Applied Technology and Instrumentation for Process Control

Douglas O.J. deSá

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APPLIED TECHNOLOGY AND INSTRUMENTATION FOR PROCESS CONTROL

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Preface

This work is an extension to the earlier publication *Instrumentation Fundamentals for Process Control (2001)* in which the basics of instrumentation were given along with some applications of instruments and control systems to real processes. Because the present work is an extension of this latter aspect, it is therefore confined mainly to the techniques of applying instrumentation and control systems to manipulate the process to give the desired results.

The topics covered in this book will expose the reader to even more actual requirements that are to be found in real process plants, as well as to some of the methods used as solutions to control them. Many complex industrial applications have several common elements. Therefore, the similarity in operation of parts of the process can allow the control philosophy developed for the control loops involved in the common elements to be applied across several different industries. The reader is encouraged to look for and exploit, where possible, this feature to advantage. As mentioned earlier, much of the instrumentation used in the systems presently discussed have been previously covered in *Instrumentation Fundamentals for Process Control (2001)*. The present text, however, has not assumed any prior knowledge, and as far as possible, steps have been taken to make this book self-sufficient.

Once again I am indebted to many of my former colleagues in the Foxboro Company, especially M.J.Cooper for his constant encouragement and cooperation, J.F. Whiting, E.A.Wright, Professor G.W.Skates, and to many other friends for their useful comments to enrich this work. I owe a particular debt of gratitude to D.R. Beeton, a personal friend and former colleague for his forbearance, patience, long hours of work, and invaluable comments in his review of this text. My patient wife Halina, also, once again deserves special mention for the warmth of her encouragement and her equanimity in tolerating the many long hours I have had to spend away from her company while this book was being prepared.

D*oug deSá*

O*ctober 2003*

Introduction

The objective of this book is not to cover only a few selected industries. Rather it is one which, via the industries covered, shows that most of the techniques are applicable (perhaps with some modification) to many diverse industries.

The things we use every day are made by a variety of processes using raw materials that in many instances do not bear any resemblance to the finished product. For example, the clothes we wear do not resemble the cotton or the wool from which they were made. The difference is even more striking if the clothes were manufactured from synthetic fibers. There is very little, if any similarity between the nylon stockings or the acrylic sweater and the crude oil from which they were produced. Even the food we eat is the subject of processing of one kind or another.

This book seeks to give the reader an insight into a number of different manufacturing processes. There are far too many processes to even contemplate covering more than a small number of process industries—but many of the topics covered are universally applicable to a much wider range of industrial plant. The examples covered represent a convenient way of giving the reader insight into how basic loops are configured and made to “hang together” to produce the control techniques (sub-applications) that can tie into the real-world overall plant philosophy

Solutions are seldom written on “tablets of stone,” for specific plant requirements will in almost all cases dictate a course of action that takes into account the prevailing circumstances. The control systems discussed represent one way that has been found to make the process manageable and able to consistently produce the product required. In order to concentrate on the regulatory control aspects for the control systems illustrated in the book, parameters that need to be recorded (i.e., a chart record to be made, and/or indicated or alarmed) have very largely not been included. These additional features, important as they are in any system, can always be added to the appropriate loop(s) quite easily when required, but only after their use and position within the control system have been discussed, defined, and agreed to with the process personnel involved.

Therefore, the challenge to the readership is to provide other solutions that are even subtler, more advantageous, and simpler when applied to the process, but most important, the solutions offered should be easily understood by all concerned. To do this effectively, the underlying principles of the process must be understood. The objective of giving a reasonably clear understanding of these process principles and the controls without demanding that the readers have tremendous familiarity with heavy math or the intricacies of physics and chemistry has been another motivation for the work. Let it be said up front, however, that on occasion readers, in the course of their work, will be called upon to give a theoretical explanation of their design. In this case, one would be compelled to make use of the knowledge gained in the hallowed halls of academia. Therefore, the advice to the reader now, as it has been in the past, is not to ignore the theoretical approach to control engineering.

Few projects can be designed and implemented under ideal conditions. Difficulties appear to be inborn and start at the “invitation to tender.” The customer’s or plant-constructor’s traditional or historical preferences and, sadly all too often today, financial constraints conspire against attaining the “best solution.” The best solution is not necessarily the cheapest in the short term but is realized by accurate, predictable, and maintainable product-throughput with minimum downtime and servicing costs. The specter of project overrun can in many instances have its origins in any impossibility of reconciling the real-plant requirements versus the as-sold contract definition. This aspect of initial or later conflict between the specification writers/purchasers and the ultimate engineering/technical implementation is particularly reflected in the project handling and is covered in Chapter 8 on Project Management.

The traditional engineering-led approach to project definition and procurement of “yesteryear” has been overtaken by the accountant-led regime—which is inevitable, but arguably detrimental. This change has led to its own set of problems, which must be allowed for in the necessary multidiscipline methods and personnel required for successful project completion.

It is the sincere hope that the present work will encourage further investigation into other processes that we are unable to cover and will serve to increase our knowledge and understanding to satisfy our natural curiosity. Exploiting the techniques described in the following chapters, and perhaps adding to or modifying some, in order to give further means of controlling other processes, will, it is hoped, benefit us all. Because of the huge diversity of industries and processes, in Chapter 1 we present control techniques that are similar to, or perhaps modifications of, some of those discussed in the succeeding chapters; they are also used in other industries or processes not specifically included in the book. We hope that the reader will gain insights into the methods whereby control techniques applied to one problem in an industry can also be used in a related or possibly unrelated industry, perhaps with a little modification or innovation.

Control systems application engineers will have to assimilate many techniques and be capable of seeing the similarities between what they know and what they are being asked to do. A very important requirement is to understand the process and how it would react to c ontrolled regulation. This is the never-ending and exciting part of the job because every day new challenges may be faced and need to be overcome.

Although the author has employed examples that he has successfully implemented on real industrial plants (where it really matters) and refers to particular items used and has suggested typical values or parameters, this does not preclude modifications or alternatives to equipment and/or fundamental methods to reach the same, but still appropriate, solution.

Notation Used in This Book

The symbolic notations shown here has been used in this book.

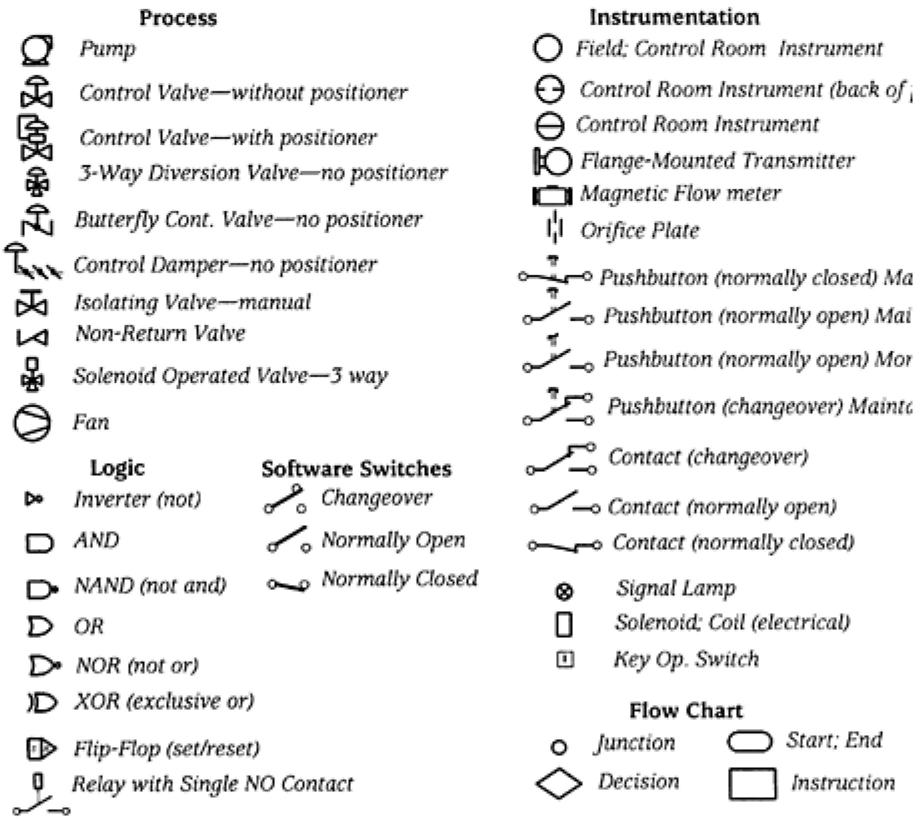
C	Consistency
C_v	Coefficient of Velocity Discharge
D	Density; Drag (as applicable)
E	Electro Potential
F	Flow
g	Gravitational Acceleration
H	Enthalpy
h	Pressure Head
I	Current
K	Constant (assigned by application)
k	Constant (assigned by application)
l	Length
n	Speed (rotational)
p	Pressure
Q	Heat Input
R	Resistance; Rush (as applicable)
S	Slip
T	Temperature; Torque (as applicable)
t	Time
V	Vapor evolved; Volume, Output (as applicable)
υ	Velocity (assigned by suffix per application)
W	Weight (assigned by suffix per application)
α	Relative volatility
Φ	Flux (magnetic)
ϕ	Phase angle
η	Efficiency
ω	Angular velocity

Subscripts

ini	initial

fin	final
ev	evolved
ind	induced
th	thermal

Instrumentation Symbols Used in This Book



Tag Number System Used in This Book

The derivation of Tag Numbers used is in general based on the ISA (Instrument Society of America) standard that is almost universally adopted. There may be some minor differences in one or two instances, e.g., ISA speed=S, in this book speed=n.

Table

	Measured Variable	Modifier	Passive Function	Output Function	Modifier
A	Analysis		Alarm		
B	Burner Flame		Users Choice	Users Choice	Users Choice
C	Conductivity			Control	
D	Density/Sp. Gravity	Differential*			
E	Voltage		Primary Element		
F	Flow Rate				
G	Gaging		Glass		
H	Hand (manual)				High
I	Current		Indicate		
J	Power				
K	Time				
L	Level		Light (Pilot)		Low
M	Moisture				
N	Users Choice		Users Choice		Users Choice
O	Users Choice		Orifice		
P	Pressure		Point		
Q	Quantity/Event	Integrate			
R	Radioactivity	Ratio*	Record		
S	Speed/Frequency	Safety		Switch	
T	Temperature			Transmit	
U	Multi-Variable		Multi-Function	Multi-Function	Multi-Function
V	Viscosity			Valve	
W	Weight		Well		

X	Unclassified	Unclassified	Unclassified	Unclassified
Y	Users Choice		Relay/Compute	
Z	Position		Drive/Final element	
	First Letter	**Second Letter**	**Third Letter**	

Notes:
The modifiers in column 3 are associated with the first letter of the tag number.
The modifiers in column 6 are associated with the third letter of the tag number.
In Europe the modifiers in column 3 with an * are usually in lower case typeface.
Depending on the circumstance, the modifier Integrate in column 3 can be used either as a noun, verb, or adjective in which case it will appear in text or speech as Integrator, Integrating. Usage will depend upon context.

Depending on the circumstance, the second letters Indicate and Record in column 4 can also be used as a noun, verb, or adjective, in which case they will appear in text or speech as Indicator, Recorder, Indicating, and Recording. Usage will depend upon context.

Depending on the circumstance, the third letters Control, Transmit, and Compute can also be used as a verb or noun, in which case they will appear in text or speech as Controller, Transmitter, and Computer, respectively. Usage will depend upon context.

Examples:
- FRRC = Flow Ratio Recorder Controller (USA)
- FrRC = Flow Ratio Recorder Controller (Europe)
- PDT = Differential Pressure Transmitter (USA)
- PdT = Differential Pressure Transmitter (Europe)
- PIC = Pressure Indicating (Indicator) Controller
- LR = Level Recorder
- TT = Temperature Transmitter
- DAH = Density Alarm High
- DAHH = Density Alarm High High—to indicate an alarm set at a value that is above the high limit that is usually associated with a shutdown or some emergency procedure

CHAPTER 1
Applicability of Miscellaneous Control Strategies—Industrywide

As noted in the Introduction, the practical world of process control largely makes use of tried and tested strategies for various types of equipment and plant, and is synonymous with the way industry in general operates, in that tried and tested methods are used time and again. These strategies can be considered as “modules” that are fitted together but, as expected in the real world, there is a slight twist in the analogy. The modules may not fit the requirement exactly; that is, a control scheme found to be workable on one plant might not, without change, work on another, which is not unusual. The modules have to be “tailored or shaped” to achieve their intended purpose. This shaping of a scheme needs an understanding of both the modules and the process. Therefore, the first objective must be to get to know the workings of as many modules as possible and to see how they are implemented and, following from that, to understand how the process—or for that matter any part of the process within our immediate sphere of interest behaves. Then, by recalling our experience and understanding of what we know about control strategies, and *applying* this to manipulate the appropriate variables we can produce the required results or product. This chapter shows some of the various ways (i.e., modules) by which control is achieved and will also indicate where similar techniques can be applied across as broad a spectrum of manufacturing industries as possible. All the remaining chapters of this book, excluding the last, show the workings of some processes and the way the instrumentation and control techniques described therein have been, and can be, applied to achieve control of the process.

Many of the control schemes in the following chapters have been described using the “block-configured” or software-based algorithms—for example, Intelligent Automation (IA) Series, or alternately TPS (TDC), Provox, Mod 300, Centum, and several other basically similar control systems, which today are increasingly being used. However, it should be remembered that hardware-only controls are still generally possible, but even with these less sophisticated hardware-based schemes, the control requirements and implementation are fundamentally still the same.

PROPORTIONING OR RATIO CONTROL

Any of us who have had the opportunity of seeing our mother baking the family loaf will be familiar with the process. All the ingredients used—flour, water, yeast, fat, salt—are carefully measured before the actual business of kneading commences. These ingredients result in a “standard” loaf of bread—there can be variations on the theme in which nuts, edible seeds, or dried fruit and, in some instances, even vegetables such as onions and tomatoes as sold in many of the large supermarkets can be included. When these “exotic” ingredients, excluding vegetables which are added as a garnish to the dough, are included, great care is taken in the production to ensure that they remain uniformly distributed (and not stratified) to prevent them being burned when subjected to the high baking temperatures. We shall go through a typical home baking process for the benefit of all readers, so that we can gain an appreciation of the industrial process, which to a large extent replicates it. When the dough has been kneaded sufficiently, it is divided into chunks that fit the baking tin or mould, and then it is allowed to *rest*—that is, to stand undisturbed but suitably protected with a cover. This is to allow the yeast to do its job of *leavening* the dough—in other words, we cause it to *prove* (rise and increase in volume). The dough increases so that it completely fills the mould, with the top having the characteristic “domed” shape. The domed tops are given a quick brushover with a light solution of egg glaze, which gives the gloss to the crust. The glossing process is not always carried out. While all this is going on, the oven is being heated to the required baking temperature. When the loaves are fully proved and the oven temperature is correct, they are quickly inserted—time is of the essence in the opening and closing of the oven door—and the loaves allowed to bake. After a predetermined time, the moulds containing the loaves are removed. A sharp knock on the side of the mould releases the loaves, which are placed on a wire tray to cool.

All the ingredients have to be measured out accurately, for each recipe will demand a variation on the amounts used. If a range of different breads is being made, some ingredients will be excluded or others added. To automate the production, one would have to consider a weighing and material-ratioing system, which would be similar in principle to that used when we discuss stock proportioning on the paper machine or fluid blending later in this book. For convenience, the illustration of the stock proportioning system has been modified (and simplified) to suit the bread-making process and is shown in Figure 1.1.

The most visible difference between Figure 1.1 and the stock proportioning system of Figure 3.3 in Chapter 3 is that the ingredients involved (apart from the added water or milk) in this case are solids and not fluids. Because of this, the metering (measuring) techniques will have to change with the use of weighing equipment in place of the fluid flowmeters as used in stock measuring.

In addition, control of the oven temperature is of particular importance; we will discuss this later in this chapter and later in the book, especially when we discuss the brewing industry.

OTHER INDUSTRIES USING SIMILAR RATIOING TECHNIQUES

Ratio control and in-line blending, as discussed in the chapter on product blending, are used to produce such goods as aviation and automobile fuels, lubricating oils, asphalt for highways, tars for building waterproofing, pesticides, household liquid detergents, hair shampoos, perfumes, nonalcoholic drinks and fruit juices, alcoholic drinks such as whiskey and wines, and many others. Every one of the industries mentioned uses the principles we have discussed, albeit with modifications to suit the particular process. One should not be so naive as to assume that the technique shown can be used directly without giving some consideration to the real process being confronted, because what is of importance is understanding the principles of operation and being able to relate a control technique to the task in hand, either directly or with modifications.

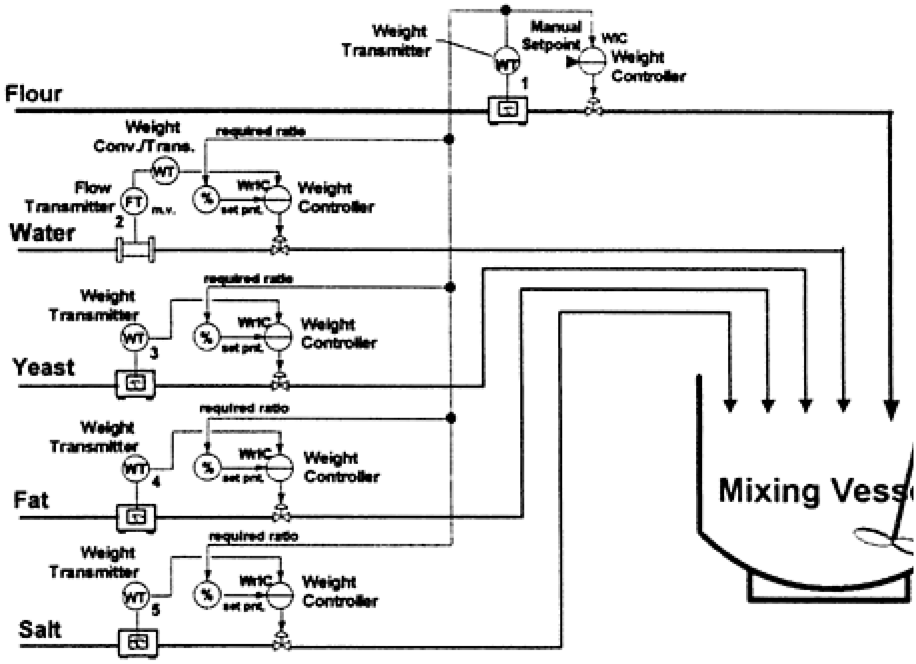


Figure 1.1: Bread ingredient proportioning control system.

SOLID MATERIAL CONVEYING SYSTEMS

When solid materials have to be moved from one place to another in a plant, conveyor systems are normally used. In these instances, the conveyors have to be started, stopped, the speed controlled, and perhaps the material on them weighed at the same time. The techniques used are described when we consider electric motor controls and discuss the pulp digester.

Figure 1.2 illustrates a basic motor control circuit, and since any motor used is always fitted on plant-located equipment, three methods—local, remote, and

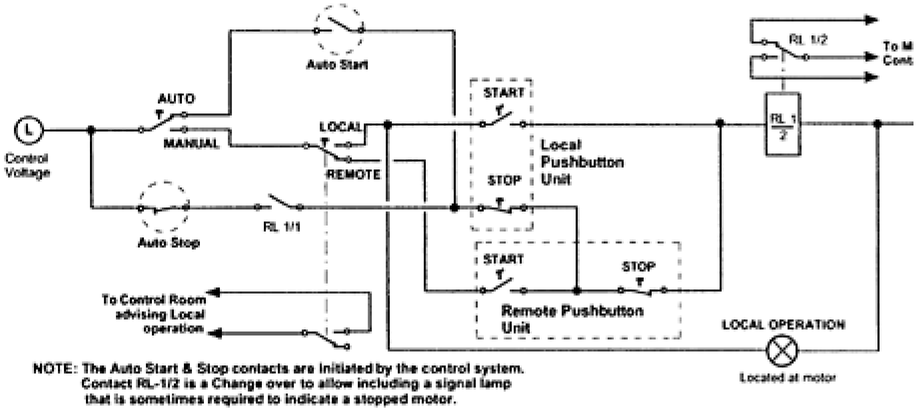


Figure 1.2: Typical motor control circuit with local/remote and automatic start/stop.

automatic—of starting and stopping the motor are provided as shown. By local, is meant that the start/stop switches are located in the vicinity of the motor; by remote, is meant the start/stop switches are located in the control room; and by automatic, is meant that the control system makes the decision to start/stop the motor when triggered by preconceived conditions that could prevail in the process at any time.

We cannot assume that the control circuit of Figure 1.2 applies to conveyor belt motors only; far from it, the technique is applicable to every electric motor, whether single or multiphase. The control circuits are always low-voltage single-phase ac or low-voltage dc. In practice, the control circuit only rarely is wired in the simple form shown because other conditions in the process will always need to influence the "state" (Start/Stop) of the motor drive and these have to be provided for. In addition, the motor will have to be protected from "adverse conditions" imposed on it while driving the equipment to which it is attached (e.g., the temperature of the windings or the motor current could rise unduly due to an increased load on the equipment, apart from catastrophic drive-stall conditions). Averting the effect of adverse conditions on the motor is implemented by "overrides," and the circuit will have to be modified to make provision for them.

All overrides that are effective while the controls are operating in automatic mode have to be generated at a particular point in, or condition of, the process, which could call for some sophisticated sequence or status monitoring facilities and measuring techniques or specialized instruments to provide the contact input(s) to the motor control circuit. Since these overrides are initiated by on-plant situations, these conditions can and will change, which will make the system implementation unique to the process being controlled.

For simplicity and understanding of the concept, all "run" overrides are collected together and shown in the figure as a single switch. In general, all process-generated overrides to start the motor automatically are connected to the auto terminal of the auto start switch as shown in Figure 1.3. This means that the motor cannot be started automatically, until the Auto/Manual switch is in the auto position. All process-generated overrides that stop the motor are connected to the common terminal of the Auto/Manual switch shown in Figure 1.3. All switches initiated by the appropriate measured parameter to achieve motor protection are wired in series with the two stop-pushbuttons.

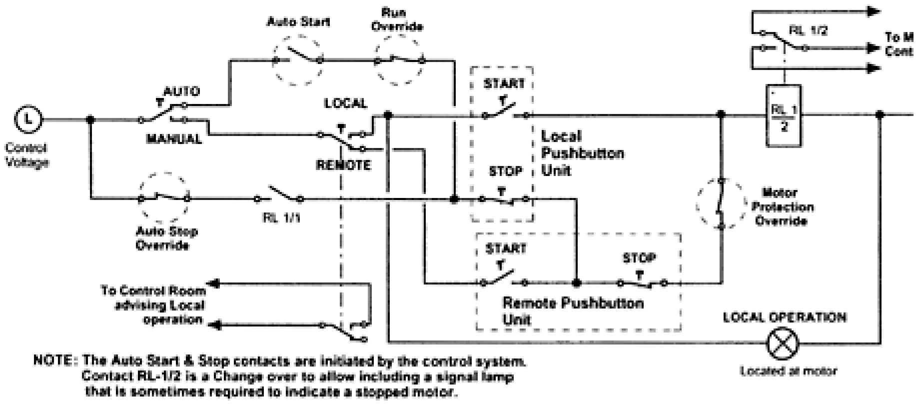


Figure 1.3: Typical motor control circuit with local/remote, automatic start/stop, and overrides.

It is said that a single picture may speak a thousand words, and Figure 1.3, which is a simplified version of that shown in Figure 2.4 in Chapter 2, is no exception because it shows very clearly what we have been saying.

Once again, the instrumentation application engineer will be called upon to provide not only the answers but an economic workable solution as well.

Since we have started discussing conveyor belt systems, it is important to appreciate that it is unusual for a single belt to run over very long traverses. This is because of the formidable power required to overcome the friction forces alone in such arrangements, which, when coupled to the power required to move the material, would involve an awesome total requirement. In such instances, the total traverse is broken down into smaller, conveniently handled, belt subsystems, which require a sequenced-start commencing with the last conveyor in the system. Having said that, what is considered to be the last conveyor in the system? This “last” has to be defined and is always considered to be the belt at the OFF-Loading end and farthest away from the point of material deposition (i.e., ONTO the conveyor). But why start with the last and not the first? The answer is that if the first conveyor in the system were to be started initially, then material would be conveyed onto the second, which was still at rest; therefore, the result would be a great embarrassing heap of material on the floor, going nowhere! With the last starting first and sequentially working forward up to the first (ON-Loading end), this would not be the case because material would be continually on the move from the point of deposition to its final destination. Stopping would be carried out in the reverse order (i.e., first to last).

OTHER INDUSTRIES USING CONVEYOR TECHNIQUES

Once again, the use of conveyors is not confined solely to process plants, for they can be found in every postal sorting office and airport baggage station where mail and baggage are handled. The very same techniques discussed in the chapter on pulp digesters are used to deal with the belts in these situations as well. There are other considerations specific to these latter industries, such as the handling of bonded mail in the postal service—those letters or packages that carry an insured financial value or mail with guaranteed time of delivery, which is referred to as Special Delivery in the United Kingdom. The means have to be implemented to ensure that the mailbags containing these items are secure from the time they are collected from the post office, through the sorting process, and up to the time they are delivered to the recipient. Mail and baggage-handling conveyor systems have highly complex logic switching and override requirements and are very interesting, challenging affairs. The mining and mineral industries also use conveyors extensively; coal mining, for example, has in addition stringent safety requirements. Consumer products such as food packaging, pottery, TV, radio/electronic entertainment equipment, and auto mobile manufacturers all use conveyor systems in their production process.

For the techniques of motor speed control, see Chapter 5 where these are discussed in detail.

HEAT GENERATION

FURNACE CONTROL

It is almost impossible to find a process plant that does not have a steam generator. Steam is one of those products that is used almost everywhere in the manufacture of the products we use every day. The three components of steam are water, fuel, and air; no steam will ever be produced in the absence of any one of these vital fundamental components. Since only three raw materials are required, the principle of steam generation is relatively easy to understand, and more so because we witness its generation every single day when we boil a kettle of water to make a drink of coffee or tea.

The steam generator, or boiler as it is commonly called, can vary quite formidably in size from relatively small ones for a small process plant to extremely large ones used in power stations to generate electricity. For all its size, relatively few loops are involved in its control, but, having said that, these loops are highly interactive, which makes the steam generator very simple to understand but very difficult to control, which on the face of it would appear to be a contradiction.

For this part of the discussion, we shall consider only the furnace and fuel combustion, leaving aside the process of generating steam, which is adequately covered in *Instrumentation Fundamentals for Process Control* by the author and elsewhere. The fuel used can vary from solid to liquid or gas. There is another fuel today (i.e., nuclear), but we shall not discuss that method of heating, for very special requirements and techniques are required to use it. For the remainder of the fuels that we have listed, the common element necessary to release the energy stored in the form of carbon (C) within them is air—or more correctly oxygen (O_2), which element forms (very generally) approximately 23 percent of the mixture we call air. The remaining 77 percent is nitrogen (N_2).

Liquid and gaseous fuels can be handled in similar ways, since both are fluids and the equipment to control the amount required is, broadly speaking, of the same design. For example, control valves are used both to regulate the amount of a fuel oil and to control the flow of a gaseous fuel. However, the differences, to list a few, between the two fuels will always be the quantity flowing, operating pressure, temperature, viscosity, and density/SG. These parameters have a significant influence on the size of the body, plug design, and materials of construction of the control valve. Solid fuels are in a separate category because special handling and measuring procedures are necessary, both of which influence the controllability of the combustion process. In addition, furnaces that will allow this fuel to be burned have to be of unique construction (especially when mechanical stokers are used), which are very different from those used for either oil or gas, in which the furnaces are generally of similar design and construction. The burner designs for pulverized coal always include diffusers to produce more stable conditions for ignition by dividing the combustion air into two streams, primary and secondary, and in this particular respect similar to those used on fuel oil.

Simplified Combustion Theory

The basic principles of combustion for the fossil fuels we are considering are the same; that is, a pound (kg) of carbon in the fuel will require a specific amount of air (oxygen) to allow it to burn completely. This amount of oxygen has to be calculated and is based on the chemistry of oxidation because carbon will (eventually) fully combine with oxygen to produce carbon dioxide, or symbolically:

$$C + O_2 = CO_2$$

To simplify the computation, we use the foregoing equation and insert the atomic weights of each element to determine the amount of oxygen to obtain complete combustion. This gives:

$$12 + (16 + 16) = 44$$

In this defined relationship, the atomic weight of carbon is 12, and that of oxygen is 16. It should therefore be clear that if a particular fuel contains 12 pounds of carbon, then we will require 32 pounds of oxygen for complete combustion, and this will produce 44 pounds of carbon dioxide as a result of the burning process.

As stated earlier, the air we breathe contains 23 percent oxygen; therefore, each pound weight of air will contain 0.23 pound weight of oxygen. Hence, for a fuel containing 12 pounds weight of carbon we shall require:

$$\frac{32}{0.23} = 139 \quad \text{lb air} \quad \text{approximately}$$

This is the nominal amount of air required for the combustible material in the fuel and is known as the *theoretical air* for the combustion. However, if we provide only the theoretical air, then we are leaving ourselves open to the possibility of having incomplete combustion since it is possible neither to ensure that the fuel used will always contain the identical amount of combustible material nor to guarantee that the measurements we make will always be absolutely accurate. With all these variables involved, it is essential to provide more than the theoretical amount of air to burn the fuel. The extra air that must be provided is called the *excess air* and is always accounted for as a percentage of the theoretical air. There are advantages in this method of operation because if we measure the amount of oxygen contained in the exhaust gases after combustion, and this is broadly speaking similar to the amount provided in the excess air, then we can be sure that all the combustible material in the fuel has in fact been burned.

Figure 1.4 shows a typical basic furnace used to raise the temperature of a heat-transfer medium that is used on other equipment in a process. Such a requirement is met when air is heated up, for example, in the brewing industry for use in a malting chamber as described in Chapter 7, or when very hot Dowtherm—a eutectic (easily melted) mixture of 26.5 percent diphenyl and 73.5 percent diphenyl oxide—used as a heat-transfer medium. When compared to heat-transfer oil, it is much more stable at high temperature and can also be used in its vapor form, which is an added

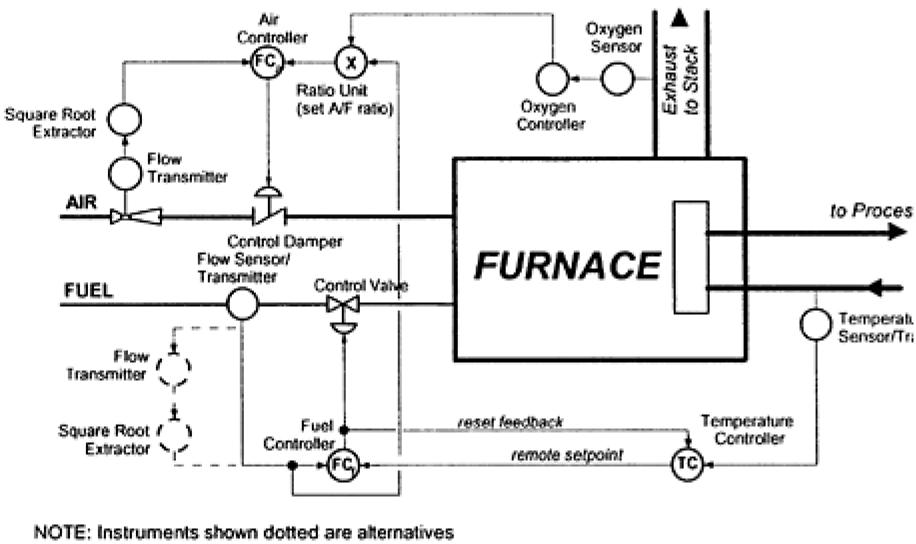


Figure 1.4: Typical single-fuel combustion control system.

advantage. Because it can be used as a vapor, both its latent heat of condensation and its sensible can be used to impart heat. Dowtherm is often used as the heat source in the reboiler of "bottoms product" when we consider petroleum distillation in Chapter 5. Both of these typical examples of fossil fuels and heat-transfer mediums occur in numerous industrial situations, that is, when direct/indirect heating is used.

From Figure 1.4 it will be seen that the temperature of the heat-transfer medium is the parameter that sets the demand on the heating system. The amount of heat required is manually set on the temperature controller TC, the output of which forms the set point of the fuel flow controller FC_f, which receives its measurement from a flow sensor/transmitter—in this case a vortex meter whose output is directly proportional to the flow. The controller output manipulates the control valve in the fuel line to regulate the amount dictated by the set point, which is in fact related to the temperature of the heat-transfer medium required by the process. One important point to note is in the fuel flow control loop where the measured and the controlled variable are the same. This situation occurs only in flow control loops and in no other. If a vortex meter is not feasible because of cost or otherwise for the application, the figure shows an alternate, which is an orifice plate and DP cell. In this case a square root extractor will be required to linearize the square law signal from the DP cell to make the air-to-fuel ratio "meaningful" because the output of a differential pressure (DP) transmitter used directly in any flow configuration has a square law relationship to the measured flow as shown by Bernoulli (see the next paragraph for the explanation).

A venturi meter measures the airflow, and, like the orifice plate, this produces a differential head across the *throat*—the narrowest part in the middle of the venturi meter. The differential created is measured by a DP cell, which again has a square law relationship to the measured flow. The signal is applied to the square root extractor and is made linear, as a result of which the final measurement is directly proportional to airflow. The airflow controller FC_a sees both this measurement and set point provided by the ratio module, and manipulates the air damper accordingly to achieve the desired value (set point). The ratio module applies a multiplying factor to give the calculated amount of combustion air in relation to the fuel flow. This calculation is trimmed by the amount of oxygen measured in the exhaust gas *(flue gas)*, which alters the ratio module output to ensure complete combustion. An oxygen analyzer measures the oxygen contained in the flue gas, using either a *katharometer* or a *paramagnetic oxygen analyzer*.

Special (Analytical) Instruments

A katharometer measures the thermal conductivity of a gas using four separate cells of equal resistance value arranged in the form of a Wheatstone bridge. Two of the cells are open to the gas being measured (measuring cells), while the other two are sealed with a sample of pure oxygen (reference cells). Each arm of the bridge contains one reference and one sample cell, and, with no sample in the measuring cells, the bridge is brought to balance with adjustable ballast resistors. When the sample cells are exposed to flue gas, the bridge will become unbalanced if the gas is not pure oxygen. A galvanometer connected across the bridge measures the amount of imbalance, which is a measure of the oxygen content of the mixture of gases in exhaust flue gas.

A paramagnetic oxygen analyzer works on the principle of the paramagnetic effect of materials established by Michael Faraday. *Paramagnetism* is the ability of some materials to align themselves along the lines of force of a magnetic field, and

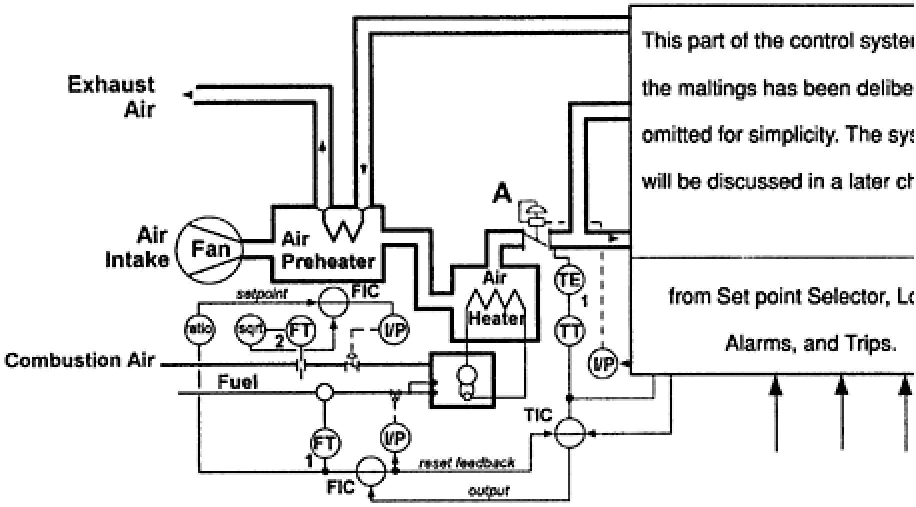


Figure 1.5: Schematic diagram of furnace control system.

diamagnetism is the ability of other materials to align themselves at right angles to the same magnetic field. Oxygen exhibits paramagnetic and nitrogen diamagnetic characteristics, and it is these characteristics of the two gases that are exploited to determine the amount of oxygen present in a gas sample. The instrument comprises a sample of pure nitrogen contained in a sealed dumbbell-shaped glass container suspended in a strong nonlinear magnetic field by one continuous suspension wire wound lengthwise as a single turn coil (feedback coil) around the dumbbell. The ends of the wire provide the suspension for the dumbbell. A very light mirror is fixed just above the dumbbell to one of the suspension wires, and both are able to rotate virtually friction free. The dumbbell sensor and mirror assembly are contained in a gas chamber with a gas-tight window through which the mirror is visible, and the suspension wires pass through the chamber walls via gas-tight seals. The chamber assembly is fitted between the pole pieces of a very strong nonlinear permanent magnet. A light source and optics, outside the measuring chamber, provide a well-defined beam of light onto the mirror. The reflected light is detected by a pair of photocell detectors connected to an auto-balancing amplifier, which drives the feedback coil in a direction to counteract any detected movement. The feedback current is a measure of the oxygen in the gas sample. For accuracy and repeatability, the sensing and measuring system is temperature controlled.

To show how the basic system is applied to a real process, it is suggested that the reader compare the systems of Figure 1.4 and the front end of Figure 1.5 and study the similarities. In this instance, as in others, the basic system discussed may have to be enhanced to comply with the individual requirements of the application involved. In this respect, it should prove a good starting point in the design development stages.

Other Industries Using Similar Space-Heating Techniques

Heating systems such as we have just discussed are also used to provide control of warm air heating in large buildings, offices, or warehouses, bread proving chambers, and climatic test chambers for equipment—in fact in any location where warm/hot air is required. Another typical example is the atmospheric “dryness” control in the region of the Fourdrinier paper machine, which is discussed in Chapter 3.

Air-cooled heat exchangers are discussed in detail in Chapter 5.

Multiple Fuel Systems

In these times when costs are critical, users of heating systems should consider the advisability of using one fuel exclusively. It should be realized that the fuels must be similar so that the same controls are capable of being used in each instance. For an introduction to the use of multiple fuels, let us consider just two fuel oils.

The system illustrated in Figure 1.4 can be modified very easily to take care of this requirement, as will be shown in Figure 1.6. For the system to work, the fuels have to be made to “appear to be the same,” although flowing in different pipelines, and this is where the summing module and the modifier are mandatory. The function of the modifier is to make fuel #1 appear to be the same as fuel #2, as far as combustible characteristics are concerned, by considering the calorific values of each fuel and using a multiplying factor to make the fuel #1 “corrected” flow rate appear equivalent to fuel #2, in terms of heating capability. Adding the two signals, one from the flow transmitter and the other from the modifier, will give the total heat supplied by the two fuels. The system then becomes one of total heat, and the fuel controller will in fact be a total heat controller. The remainder of the system will function exactly as described earlier.

Although we have considered using two fuel oils in the system shown in Figure 1.6, it is quite feasible to use the same controls for two different types of fuels, say gas and oil instead. However, in this case one would again have to take care of the calorific values of each fuel, but more important, ensure that the burners used are capable of handling the two very different fuels. Having said that, and to bring some consolation, it should be pointed out that some burners on the market are designed for just this purpose, so no difficulty should be encountered in this respect. Providing

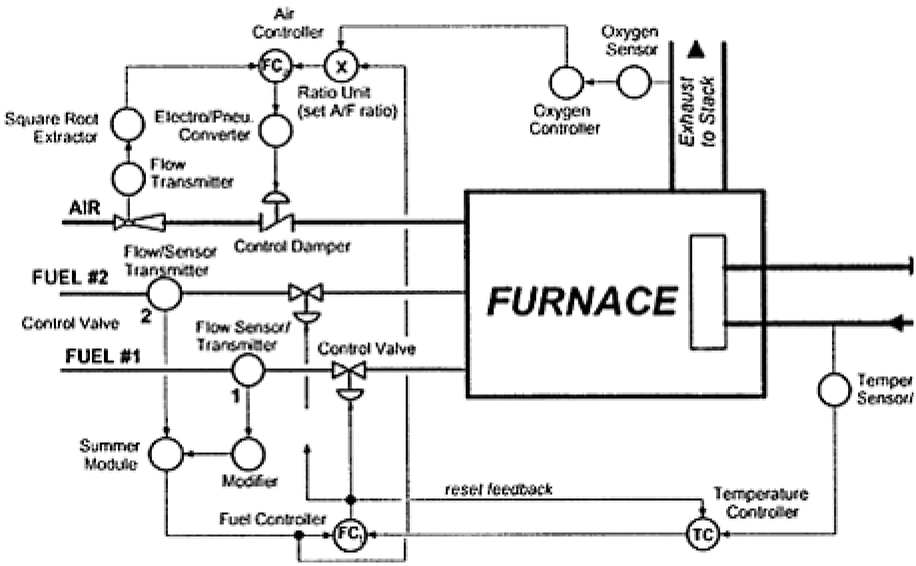


Figure 1.6: Typical multiple-fuel combustion control system.

the correct burners, of course, will be the domain of the furnace or boiler supplier and will only be of indirect concern to the control system engineer.

Considerations for a Rapidly Changing Demand

The heating systems described thus far are systems in which the process does not change rapidly because one is stretched to visualize the temperature in a building or warehouse say, changing rapidly. In the cases just mentioned, the systems shown should cope with the situation and work satisfactorily. However, if the possibilities of a rapidly changing demand were there, then it would be necessary to consider the inclusion of what is known as *cross limiting*. For the purpose of illustration, we shall use a single fuel only to make the system easier to understand. This will involve rearranging the controls shown in Figure 1.3 and adding a few additional components (i.e., two dual-input signal selectors). The reader should find no great difficulty in extending the controls to include multiple fuels if this is required.

In the system shown in Figure 1.7, the output of temperature controller TC represents the process demand, and this signal is applied as one of the inputs each to a high (>) and a low (<) signal selector block (module). The second input to the high (>) selector is obtained from the measurement of the fuel flow FT_f, and from the airflow measurement FT_a for the low (<) selector. The output from the high selector is applied as the set point of the airflow controller FC_a, and the output from the low selector is applied as the set point of the fuel flow controller FC_f. Note that the airflow measurement is applied to the ratio module X before it forms the measurement input to the airflow controller. The oxygen controller adjusts the ratio for the amount of combustion air required for complete combustion. Further note the difference from Figure 1.3 in the method and application of the oxygen trim function.

As long as the demand is constant under operating conditions, the airflow and the fuel flow controllers FC_a and FC_f, respectively, regulate their respective flows to

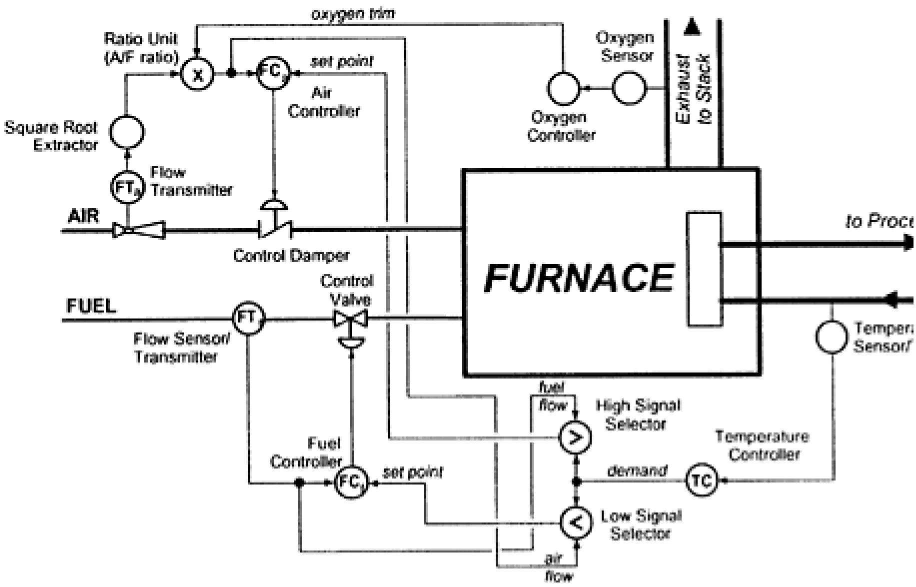


Figure 1.7: Typical single-fuel cross-limited combustion control system.

meet the demand. In other words, under steady-state conditions both control loops operate in parallel. Furthermore, it should be noted that the air controller FC_a has an output that increases with increasing measurement, and the fuel flow controller FC_f has an output that decreases with increasing measurement. The situation of parallel control loop operation changes under a process upset. Let us now consider the case of an increase in demand; that is, the output of temperature controller TC increases. This means that the temperature measurement has fallen. In the case of the high signal selector (>), the demand signal is greater than the instantaneous fuel flow FT_f signal, making the demand signal the one to be selected. This higher signal will increase the set point of the airflow controller FC_a, which will increase the airflow. At the same time in the case of the low signal selector (<), because the demand signal is greater than the airflow signal FT_a the airflow signal will be selected, but the airflow signal is always larger than the fuel flow. Because we need more air than fuel, even at steady-state conditions, the airflow measurement is always greater than fuel flow measurement; and recall that we started all this development from a steady state in the furnace. It will represent an increase in the set point of the fuel flow controller, which will increase the amount of fuel supplied to the burners. The net result will be an increase in the amount of heat from the furnace to meet the new demand. Now let us see the situation under a demand decrease. This means that the temperature measurement has increased and the output of temperature controller TC has fallen. In the case of the high signal selector (>), the demand signal is smaller than the fuel flow FT_f signal, and the fuel flow signal FT_f will be the one to be selected. This smaller signal will decrease the set point of the airflow controller FC_a, which will decrease the airflow. At the same time in the case of the low signal selector (<), because the demand signal is smaller than the airflow FT_a signal the demand signal will be selected. This smaller signal will decrease the set point of the fuel flow controller FC_f, which will decrease the fuel flow. The net result will be a decrease in the amount of heat from the furnace to meet the new demand. From the foregoing it will be seen that under process upset conditions the control loops act in series.

From what has just been said on cross limiting in combustion control, the reader should be able to visualize how the principles shown in this system can be applied to steam generators. Since it is almost impossible to visualize a manufacturing process that does not use steam, the system can be applied across the whole spectrum of manufacturing processes. However, the reader must be warned again that steam generators are not simple machines to control; there is a whole host of other systems such as burner management and shutdowns that are mandatory and must also be included for the protection and safety of personnel, plant, and property.

As stated earlier, a steam generator is an item of plant equipment that is found in almost every manufacturing site, and its output of steam has many vital uses in the various production processes. Steam has been assigned a measurement of quality and a scale based on what is known as its *dryness*, which indicates how much “free” water it contains. The scale range of dryness is 0 to 1 where 0 corresponds to being completely wet (i.e., hot water), and 1 represents completely dry (i.e., no entrained water). As we can appreciate, the drier the steam is, the greater its ability to do useful work, because it has absorbed more heat (i.e., “extra”) heat in the vaporous component), which is given up when work is done. It is very difficult to produce steam of the exact quality directly from the steam generator; therefore, what is done to meet a particular requirement is to produce steam of higher quality, that is, with excess heat, and then add a controlled amount of water to arrive at the quality required. The control is based on the temperature of the steam, as will be seen in Figure 1.7.

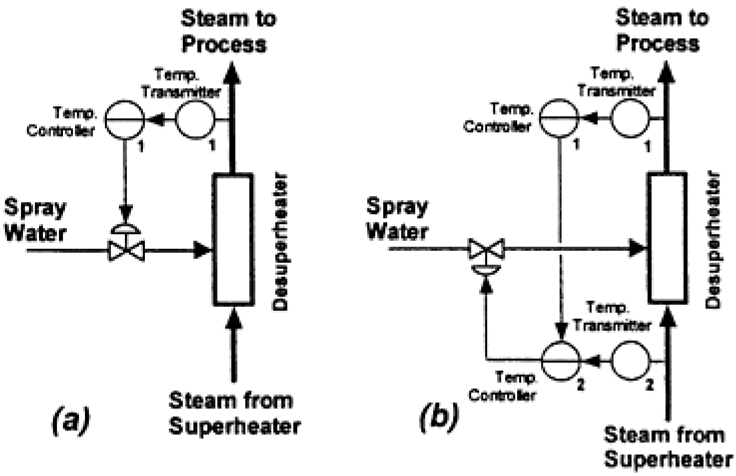


Figure 1.8: Schematic diagram of controls for a steam desuper-heater.

The technique is somewhat similar to what we do when we test the bath water before jumping in! We add cold water to the too-hot to bring it down to the desired condition—that is, an acceptable temperature. This method of operation has hidden benefits in that by adding a quantity of water we are actually increasing the mass of steam available. However, it should be remembered that it is not recommended to use cold water at any temperature to desuperheat the steam—because, for greatest all-round benefit, the spray water should be derived from already hot condensate that nearly matches the saturation temperature of the steam. In this way, by utilizing hot condensate, we require the minimum amount of superheated steam to produce the steam of the quality required. The controls shown in Figure 1.7 show different ways of how this is usually carried out.

In both the control schemes shown in Figure 1.8 temperature controllers TIC-1 have a set point that is manually adjusted by the process operator to a value that is required to give the steam quality desired. However, Figure 1.8a is a straightforward feedback control loop; the steam quality is adjusted after the spray water has been added, and therefore some of the steam will be "about" the required temperature. The average value, however, will be within the range required. The control scheme of Figure 1.8b approximates a feedforward control loop. The average value will be within a much narrower band of acceptable quality because with temperature controller TIC-2 the operator initially adjusts the set point and predicts what the outlet temperature should be, and the controller adjusts the spray water accordingly. When TIC-2 is placed with its set point in remote, then temperature controller TIC-1 monitors and adjusts the set point of TIC-2 by an amount that brings the outlet steam temperature much closer to that required—feedback stabilization. The type of control illustrated in Figure 1.8b is called cascade control. Cascade systems are very useful means of maintaining control between different loops and are widely applied across a whole range of industries. As examples, adaptations of the two control schemes are used in the control of the reboilers on distillation columns (see Chapter 5) and tank level controls, which can be cascaded onto the inlet material flow control loop to the tank (the level controller output forming the set point for the flow controller), to bring a much more refined means of level control.

PRODUCT QUALITY CONTROL

In these control systems, we are involved with the measurement and control of the overall acceptability of a product to meet a specific need, either in intermediate stages within the production cycle or in the final product sold to a consumer. The acceptability is always determined through analysis of the material concerned. This procedure could be carried out continuously (i.e., *on-line* while the material is being processed) or it can be analyzed *off-line* (i.e., by withdrawing a sample and testing it). Off-line testing will not permit corrective action to be taken immediately and could leave the manufacturer with material that is substandard. Unless the material is reprocessed, or able to be converted to another product, it will always remain substandard and a commercial liability.

The two common techniques used on liquids use the measurement of pH and/or conductivity to determine a material's suitability for its purpose. The parameter pH, which is a measure of the acidity or alkalinity of a material, is important because sometimes variations beyond very close limits can have serious consequences, for both the plant and more alarmingly for the human body. The parameter conductivity, which is a measure of a material's ability to conduct an electrical current, is more useful in an industrial setting chiefly because it is more rugged, stable, and indicative of the condition being sought, although there are applications (e.g., water treatment) outside this.

pH MEASUREMENT AND CONTROL

Let us first consider pH, which has a measurement range of 0 to 14 pH units. On the pH scale, a midscale value of 7 pH units represents neutrality—values below 7 pH are acidic, and values above 7 pH are alkaline. This parameter can be measured on-line and will therefore permit immediate correction of any variation. However, we must be aware that although pH has a linear measurement scale, it has basioally a very nonlinear characteristic. Sörensen brought out this linear representation of a nonlinear characteristic when he discovered that by using the logarithm of the reciprocal of the hydrogen-ion concentration, a linear scale resulted. Fundamentally, to regulate the pH of a material, one has to add precise amounts of a reagent, which is acidic when the material is alkaline or alkaline when the material is acidic. The typical arrangement of a pH control loop is shown in Figure 1.9, and because of the

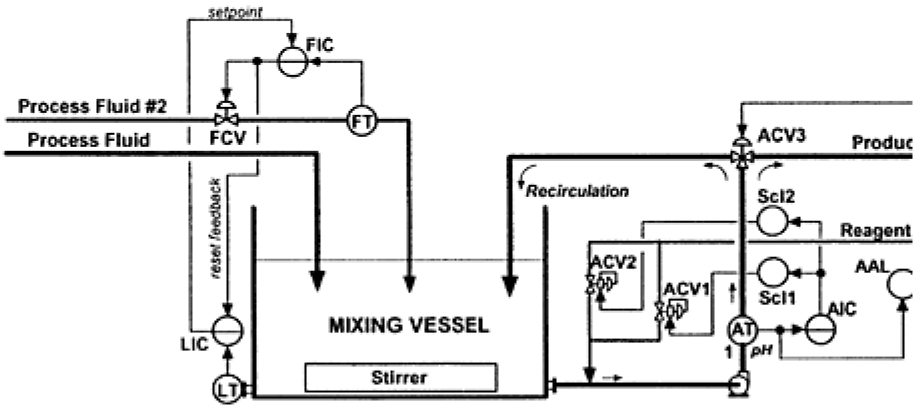


Figure 1.9: Schematic control scheme for product pH.

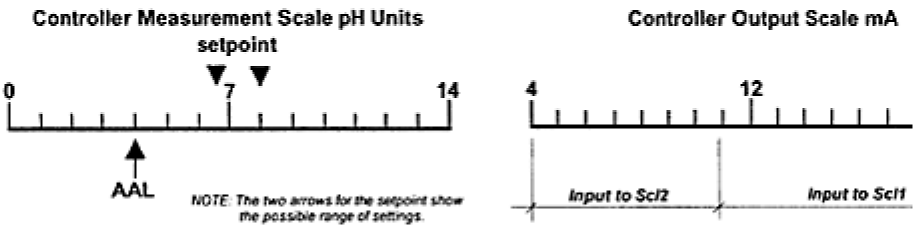


Figure 1.10: Typical settings for alarm & setpoint; typical input range for Scl1 & Scl2.

nonlinearity the control valve must have wide rangeability. This could mean using more than one valve to regulate the process.

As shown in the figure, the measurement is made in the discharge line of the pump. This is important because it allows complete dispersal of the reagent. It may not always be possible to do so, but it is important in any application that reagent dispersal is total. Since the character of pH measurement is nonlinear, it is recommended that the controllers used have a nonlinear gain. In this system we assume that because of the strength of the process fluid, reagent addition has to be made via two control valves. In operation, the pH electrode system AT makes the measurement for the nonlinear controller AIC whose output is applied to two scalers Scl1 and Scl2 and also to a high-alarm AAH. Let Scl1 be associated with the small control valve ACV1 and Scl2 with the larger control valve ACV2. Scl1 and Scl2 both accept the output from controller AIC. Scl1 is adjusted so that the lower values of the control output signal produce a full-range output signal for its partial range input, and the higher values of the control output signal applied to Scl2 produce a full-range output signal for its (partial) range of input. The control valves ACV1 and ACV2 therefore operate on full-range signals. The actual point of split for the two scaler inputs can be chosen anywhere within the controller output range. Alarm AAL is a refinement included in the measurement of controller AIC such that when the output of AIC is still within the dosing range of valve ACV2, the three-way valve ACV3 is forced by AAL to recirculate the process fluid. As soon as the measurement rises above the setting of AAL, valve ACV3 changes its ports to allow the process fluid to be discharged as product. This ensures that no highly acidic product (indicated by low pH values) is sent onward from the mixing vessel. Controller AIC has a set point such that it allows the product to tend toward neutrality or slight alkalinity, a choice to be made by the user. If the measurement falls to values within the calibrated range of Scl1, control valve ACV1 will be called into service to dose the reagent to restore balance.

Figure 1.10 shows a possible arrangement of settings for the above control scheme. The controller can only have one set point, but the figure gives the range of possible settings. It should be remembered that controlling a fluid to neutrality is a very difficult task because of the shape of the titration curve at this region, which can best be described as an S-shaped curve, with the transition from one curve of the S to the other being rather flat.

The application shown in Figure 1.9 is only typical, and it should be pointed out that pH measurement and control do not need mixing vessels every time. Depending on the application, a totally in-line system could be suitable and used.

Mixing-Vessel Level Control

In Figure 1.9, the DP cell sensor/transmitter LT senses the level of the mixing vessel and provides the measurement for controller LIC, which has a manual set point and whose output is the set point for flow controller FIC. Flow sensor/transmitter FT determines the flow in process fluid #2 line and provides the measurement for controller FIC whose output regulates the material flow via control valve FCV. This is a simple cascade loop, the form of which is used very often in process control. Reset feedback is provided to avoid saturating the integral term of controller LIC on those occasions when the operator intervenes and manually adjusts controller FIC. This phenomenon is explained in detail at the end of this chapter.

INDUSTRIES THAT USE pH AS A MEASUREMENT OF QUALITY

No pharmaceutical manufacturer can ever produce any product without using pH measurement and control somewhere in the manufacturing process of his range of products. This measurement is also very important in water and sewerage treatment; the manufacture of foods both human and animal; beverages; toiletries—soaps, hair and body shampoos, and facial creams; medicines; domestic and industrial disinfectants; domestic and industrial cleaning agents; photographic film manufacture; and industrial chemicals. It must be noted that because pH is an electrochemical measurement, different types of electrode systems are available, the most common being the glass electrode. The choice of pH electrode made and used for an application is important for success, and it is recommended that the reader seek out more detail regarding the several types available. Joint discussion with the plant chemist and the manufacturers of the pH systems will frequently be involved.

CONDUCTIVITY MEASUREMENT AND CONTROL

As stated earlier, conductivity is a measure of the electrical current-carrying ability of a fluid. It is also an electrochemical measurement that can be made in-line. One of its familiar uses is in determining the suitability of boiler feedwater for use in the generation of steam. As the reader will appreciate from his or her own experience of the havoc caused by the inefficiency or failure of a furred-up domestic kettle, this problem must be avoided at all costs in the context of a large steam generator. The consequences of a failure due to lime scale fouling can be serious, time-critical, and costly. Conductivity measurement and control also form an important part of public water treatment works when ion-exchange columns as shown in Figure 1.11 are used to demineralize the raw water. Ion-exchange columns operate on the principle of dissociation of impurities that dissolve in water to form positively *(cation)* and negatively *(anion)* charged ions. These impurities are chemical compounds and are called *electrolytes*. Ion-exchange materials have the ability to exchange one ion for another, retain it for a short while as a chemical combination, and then give it up to a strong regenerating solution.

Regeneration of a column is based on a timed cycle, for it takes a specific period first to wash and then to regenerate the exchange material. For continuous treatment, more than one set of columns is necessary because as one set is in use the other(s) could be regenerating. Usually, there are more than two sets of columns in a treatment plant. More analytical measurements are required to determine when the column exchange materials are approaching the time for being taken out of service for regeneration. However, for simplicity these instruments and the necessary timing controls have been omitted. It should also be remembered that, because water treatment is a whole industry based on the provision of a fundamental human need, several other

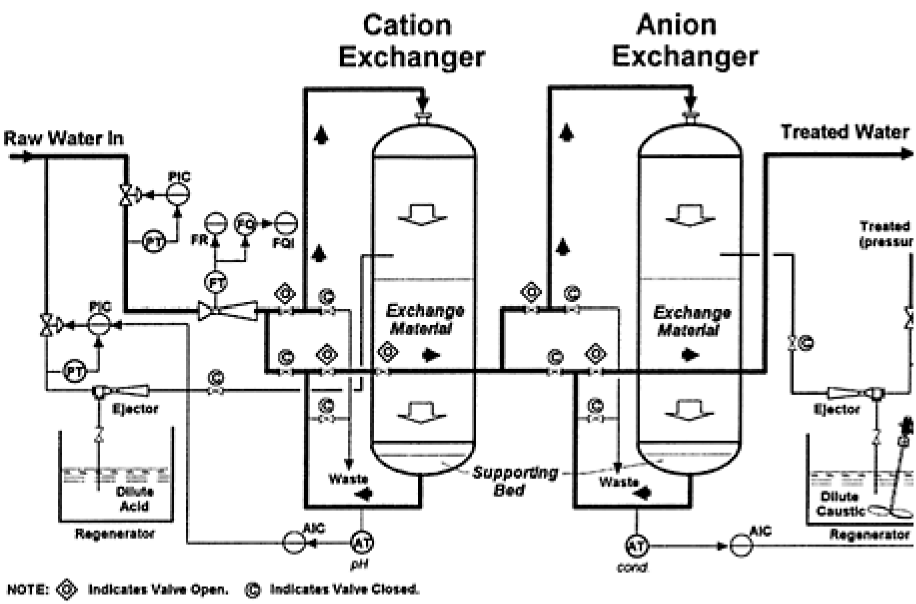


Figure 1.11: Simplified schematic of typical ion-exchange column with control system.

processes are required for the complete treatment of water. These processes have not been discussed, for this would involve much more detail than necessary for this section of the book.

A venturi meter has been shown as the raw water flow-measuring device; this can be replaced by a magnetic flowmeter if desired. The magnetic flowmeters will be particularly large, and cost will frequently be a deciding factor. The form of the conductivity controls is similar to that used on the pH loop, although no control valves are directly involved with the dosing. However, a control loop and control valve regulate the pressure to each ejector, which indirectly controls the amount of regenerating agent supplied to the exchange material. Also worth noting are the incoming water pressure and flow integration loops, which are used further on in the book (e.g., flow integration in Chapter 2). Since no regeneration takes place while the water is being processed, the pH and conductivity controllers should be placed in the manual mode and transferred to automatic when regeneration starts. This will prevent the controllers from saturating their integral term. For details of what integral saturation means, refer to the section headed Integral Saturation and Reset Windup later in this chapter.

INDUSTRIES THAT USE CONDUCTIVITY AS A MEASUREMENT OF QUALITY

No photographic film manufacturer can operate without deionized water, and we have seen conductivity measurement and control in the anion exchanger column as an integral part of it. Every desalination plant needs conductivity measurement and control to regulate the salinity of the fresh water it produces from the seawater taken in as the raw material. The desalination process is also heavily dependent on electrical power and produces a lot of salt (sodium chloride or chemically NaCl) as a result. This byproduct is commonly known as sea salt.

OTHER INDUSTRIES THAT REQUIRE CONTROL OF PARAMETERS ALREADY DISCUSSED

GLASS FURNACES

Glass and steel-making industries use heat in vast amounts for their furnaces. The principles of heat supply and regulation are substantially as we have detailed earlier, but the glass furnace has quite unique requirements, in that the heat is applied alternately from two sides of the melting chamber. The heat supply is alternated to keep the molten glass uniformly heated in the very large melting chamber, which does not have heat applied to the underside of the chamber. The process of changing the firing is called *furnace reversal*, and it is carried out on a timed cycle of about 20 minutes. Because the firing changes from one side of the furnace to the other, problems arise in ensuring the continuity of all the furnace firing controls involved; the applications engineer has to make sure that everything is coordinated correctly. The striking feature of this furnace is the installation of two flues, which change function at each furnace reversal. During the cycle, one of these acts as a flue, while the other serves as a combustion air-intake duct, and then the roles are reversed. At the time of furnace reversal, a huge damper switches the two flues around. The supply of the raw materials, typically silica, sand, and *cullet* (i.e., scrap or broken glass—the last-named component aids the conservation of the environment, by having a marked effect on the heat requirements) have to be ratioed in a manner similar to that described earlier in bread making. A radiometric detector, which uses a nuclear source, detects the level of molten glass in the furnace and regulates the amount of raw material via a cascade loop of furnace level onto the raw material supply. Temperature control plays an important part in the system strategy, and positioning of the detectors is crucial. The molten glass is withdrawn from the furnace into machinery that forms it into the end product(s). In the UK this part of the furnace is called the *working end;* and the portion of the furnace into which the raw material is fed is called the *melting end*. Both names are apt descriptions of their functionality. It should be noted that the open hearth process of steel making also uses an identical oscillating heat-applying method.

BASIC OXYGEN FURNACES—STEEL MAKING

Modern Bessemer converters use pure oxygen blowing to speed up the process of steel making, which increases the throughput and, as a result, the profitability of the manufacturing plant. The purpose of oxygen blowing is the same as it has always been: to encourage the burning of carbon, but to accomplish it much more quickly and efficiently than plain air could ever do. The oxygen-blowing furnace or, to give it its full title *Basic Oxygen Furnace* (BOF), revolutionized the steel-making industry in the mid- 1950s because it reduced the time to produce high-quality steel from hours to minutes.

Steel making still requires the smelting of the ore to be carried out in the blast furnace, which produces pig iron as the end product. In the older method, the Bessemer converter, invented by Henry Bessemer in 1856, the molten pig iron was changed into steel by blowing preheated air through the charge. The converter was charged with the molten pig iron while in a horizontal position. After charging, the converter was then rotated to the vertical position and hot air was forced through the tuyère (a series of holes arranged in a circle and connected together via a blast box) located at the base of the converter. This hot air increased the temperature considerably and burned off the carbon and other impurities. The silicon content of the pig iron is kept low to avoid producing an acid slag, which would attack the lining of the converter. In this process, which in keeping with its chemical nature is basic as opposed to acidic, manganese, carbon, and phosphorus supply the required heat of combustion to keep the charge molten during slag removal.

In the BOF, oxygen is supplied via a pipe known as a *lance*, which requires it to be at a pressure of about 150 lb/in^2 and a flow rate of 10 to 20,000 scfm (standard ft^3/min)—this means a flow of 20,000 ft^3 at 60°F and 14.7 lb/in^2 per minute, or the equivalent in metric units. These are supersonic air velocities. Because oxygen is a gas that supports combustion, it has to be protected in the high temperature of the steel furnace; hence, the lance has to be kept cool. The lance is lowered to within 4 to 8 ft of the molten steel bath, posing a formidable problem with the positioning of the lance that is very difficult to solve. The author is not aware of any satisfactory method available to do this repetitively. Cooling water is used to protect the lance, and control of both the insertion depth and the cooling water flow are purely manual operations. Any water leak can cause an explosion because of the extremely high operating temperature; therefore, leakage has to be monitored and alarmed. The most satisfactory method found is to measure the cooling water supply to and the return from the lance and compute the difference.

SOME CONSIDERATIONS ON INSTRUMENTATION AND CONTROL METHODS

INSTRUMENTATION

Selecting the measuring device can be bewildering because of the vast number available. To ease the process, we now give a few pointers—which are by no means exhaustive—on how to base the decision-making process. The comments made will not fulfill all the requirements in every specific instance but should give one a few reminders of a number of points to be taken into account.

Flow

This important parameter in any process should take into consideration the following:

1. If the material is a solid, weight is the most likely method of determining the flow rate. Weight can be determined while the material is being transported, but care is needed to ensure that the distribution on the conveyor is uniform. The speed of the conveyor is also included in determining the measurement.
2. If the material is a liquid, several options are available to make the measurement.

Volumetric Flow

When using differential creating devices, there is bound to be an overall pressure loss across the device. The orifice plate has the highest loss, which is irrecoverable, and the venturi tube has the lowest. Differential pressure cells are a necessity when such devices are used, and due consideration should be given to the mounting of these instruments, especially the heads formed by the mounting arrangement, which if not balanced out will affect the accuracy of the measurement.

Vortex meters are steadily replacing the differential creating devices and DP cell combination. These instruments are now suitable for measuring steam flow. Unlike the DP cell, the vortex meter produces an output that is directly proportional to the measurement.

Magnetic flowmeters have virtually obstructionless flow characteristics, but they do require the fluid to be electrically conductive for a measurement to be made. If particles are entrained within the (flowing) liquid, care of the electrodes must be considered.

Particles of coagulated grease as can be found in sewerage, though not erosive, are nonconductive and soon cover the electrodes, resulting in a disrupted measurement. Consideration should be given to providing a tube liner and electrodes of special material for long-term stability. Do not mount magnetic flowmeter tubes in positions that allow them to drain because burnout of the coil could ensue.

Mass Flow

Coriolis meters are invaluable for direct liquid mass measurement, but the following (two) points should be considered. The head (pressure) loss involved can be relatively high, one manufacturer, for example, states that the pressure drop for its ½ in (15 mm) meter is 13 lb/in^2 and that for its 3 in (80 mm) meter is 4.3 lb/in^2. The amount of entrained gas in the flowing process fluid can affect the measurement—if above certain defined limits the measurement is indeterminate; one should consult the manufacturer for relevant details. The mounting should avoid plant-induced vibrations in the instrument, and the measuring tube should be self-draining.

Compensating Flow Measurement

Temperature variation in a liquid fluid affects the accuracy because it influences the fluid density. Mass measurements in process lines that are above the sizes offered by the manufacturers of Coriolis meters still have to use the method of the volumetric flow of fluid times the fluid density. However, when the computations are being carried out, make sure that the volumetric flow of the fluid is corrected for pressure and temperature variations. When the fluid is a liquid, pressure only needs to be considered. In this case, fluid density will always be a separate measurement. These compensations are further detailed in the section Mass Measurement with Differential-Creating Primary Devices later in this chapter.

3. When the fluid is a gas and pressure differential methods are used, mounting of the measuring instrument is very important. Ensure the impulse piping (connections between the primary device and the measuring instrument) contains fluid of one kind only—either all liquid or all gas, but no combinations. Otherwise, errors caused by the compressibility of the trapped gas are inevitable. Pressure and temperature variation will affect the measurement (Charles and Boyles laws take effect). To obtain the best accuracy in gas flow measurement, corrections for both pressure and temperature variation should therefore be made. In many cases today, vortex meters are replacing the orifice plate and DP cell combination as stated in item 2. There are size limitations on this instrument type; consult the manufacturer to obtain the available sizes.
4. In *all* liquid and gas flow measurements the runs of straight piping upstream and downstream with respect to the primary device must be maintained—ideally 15 to 20 pipe-diameters upstream (minimum 10 pipe-diameters), and 7 to 10 pipe-diameters downstream (minimum 5 pipe-diameters). In difficult circumstances where the upstream dimensions are not feasible, a flow straightener should be used. The straight runs of pipe avoid turbulence, for it affects the measurement accuracy.
5. Public water utilities have to resort to venturi flumes because of the very large

volumes they process. Make sure the stilling wells (measuring points) are free from obstruction and ensure that any floats that are used can move freely (vertically) and avoid any sideways movement.

Pressure

1. Make low-range gauge pressure measurement using a DP cell, but keep one side open to the atmosphere.
2. Avoid pressure pulsations in any measurement line; use a pressure snubber to suppress wide fluctuations.
3. Make sure that pipe debris is kept away from the measuring point; use a filter if necessary.

Level

1. This parameter can be determined in several ways, for example, by measuring the pressure head in liquids; by determining the interface by the air reaction method using a bubble tube, air pressure regulator, and a DP cell used as a pressure transmitter; by floats; by radiometric means using a nuclear source; by radar or ultrasonic transmissions, both of which measure the time interval between the transmittal of the measuring pulse and its receipt; and by capacitance, which measures the capacitance between the electrode and the vessel side. Each method has its advantages, and the choice is important for consistent and repeatable results.
2. When using pressure, make sure the head truly reflects the level in the vessel and zero out any value that detracts from this. With floats, as stated before, make certain they are free to move vertically and are in a relatively calm situation. If necessary, use a stilling well to ensure this situation. With nuclear devices, make absolutely certain that the source is protected to the manufacturer’s recommendations, and be prepared for a large amount of paperwork to pass the certification tests required by the authorities. Radar and ultrasonic transmission are both susceptible to interference by vapor or foam; take suitable precautions. If heavy foam or vapor is a problem, then the user should be asked whether there is a solution by using an antifoaming agent; if this is not feasible, another measuring method must be sought, or the instrument maker should be asked to investigate and advise.

When making flow, pressure, and level measurements on corrosive fluids, it is sometimes advisable to use a chemical seal(s) to keep the process fluid away from the measuring instrument. A chemical seal is made from special material to suit the chemical involved, and it acts as a physical barrier. It is vital that the manufacturer of the seal be consulted to determine the viability of such an arrangement. The instrument in question will have to be prefitted with the seal, filled, and calibrated by the seal manufacturer to ensure the validity of the original (i.e., without the seal(s)) instrument specification.

Temperature

This parameter can be measured by methods ranging from mechanical, which includes filled systems and the expansion of solid material (i.e., metals); thermo-electric devices (i.e., thermocouples and resistance bulbs); and radiation pyrometers (i.e., a combination of optical and thermoelectric devices).

Mechanical Methods

1. Filled systems require that the fill fluid and the material of its containing bulb and capillary be compatible with the process material being measured. Be aware that different fill fluids have particular operating ranges; a single fill fluid is unable to measure all temperature ranges.
2. Bimetallic thermometers are widely used as a means of reading the process temperature locally at a particular point in the process. This device is chosen because of the robustness of the element, which in its simplest form consists of two metal strips joined together in the shape of a C connected to a pointer via a quadrant and pinion drive, which allows it to move across a scale. This arrangement is quite suitable for reading the temperature of a surface. When the point of measurement is below the surface, for example, fluid temperature in a pipe, the sensing element is made in the shape of a spiral of small outside diameter connected to a pointer via a lightweight shaft. The element is never exposed directly to the process medium, and it is enclosed in a protective sheath, or in the case of the C type contained within the instrument case. Two strips of metal are necessary because one is the actual material that responds quickly and directly to the temperature, and the other for stability is usually made from Invar, a trade name for an iron alloy containing 36 percent nickel, and has an extremely low coefficient of expansion. The scales are linear with respect to the temperature. Process connections can be either screwed or flanged, and the one used depends on the process pressure.

Thermoelectric Devices

3. Thermocouples (T/C) produce emfs of different magnitude, depending on the materials used; they are divided into two broad categories: base metal and rare metal. Base metal T/Cs have one wire of iron, copper, aluminum, tungsten, and the other wire alloys of these metals; also within this category are the alloy/alloy elements such as chromel/alumel (nickel-chromium/nickel-aluminum). Rare metal T/Cs have one wire of platinum, and the other wire is an alloy of platinum with specific percentages of rhodium. For the fastest response, bare thermocouples are used (i.e., without a protective sheath) so that the hot junction is directly exposed to the heat source. In such cases, the thermocouple to be used depends on the compatibility of the wire materials with the process. However, in most process applications, the thermocouple is protected either by a sheath or a thermowell (pocket), both of which slow down the response. For more detail on thermowells, see Element Protection in the next subsection.
4. Resistance temperature detectors (RTDs) are made to specific resistance values using wire of platinum or nickel. The standard resistance for an RTD in Europe is 100 ohm,

and the wire used is platinum. In the United States, the material for the wire was at one time nickel, but the trend there is also toward platinum. RTDs nearly always have a protective sheath, but wells are used for additional protection and easy uninterrupted replacement.

5. Radiation pyrometers are used for extremely high temperature measurement. These sensors use an optical system to focus the radiated light from the hot source onto a measuring thermocouple or series of thermocouples (thermopile), which respond to the heat in the transmitted light. They are seldom used for control purposes. Nascent conditions, say, in a furnace, give rise to traveling hot spots where excessively high local temperatures can be observed. These very easily upset optical pyrometers; this is one of the reasons why this type of instrument is seldom used for control. When radiation pyrometers are used, it is important that the optical objective lens be kept clean and cool; water is used for cooling and instrument air for lens cleaning.

Element Protection

To allow the process to continue uninterrupted while a replacement for failed units is being installed, pockets are always provided. A thermowell is a solid container into which the thermal measuring element snugly fits and is held in place via either a screwed or flanged connection provided on both the pocket and the element. The pocket itself is fitted permanently into the process line to be measured. The fit of the element in the pocket is important because excessive space either diametrically or lengthwise will give erroneous readings, owing to the space heating effect involved.

6. When wells are involved, both the material of construction and, if required, the coating used are important. These considerations are necessary especially when they are used on furnaces, where, apart from the temperature, the atmosphere to which the pocket is exposed is usually reducing (acidic).

Analytical

1. Generally speaking most analytical measurements (apart from pH and conductivity) are almost always slow to make, due mainly to the way they have to be carried out. Moreover, they usually involve some sort of a chemical reaction, and this always takes time to complete. Therefore, nothing or very little can be done to accelerate the process.
2. When one is involved with pH, remember that this parameter has a very nonlinear basic characteristic—although the scale is made linear by the mathematical relationship of the definition.
3. Chromatography can be, and has been, used to control a process very effectively. At least one company manufactured a pneumatic chromatograph that could be used in hazardous locations in a process plant. However, as stated earlier, the measurement is slow to make, and it is impossible to accelerate the process of component elution (the process of separating of one component in a mixture); the time taken cannot be shortened.

4. In analytical determinations, the procedure for sampling the process is very important, and great care should be exercised to ensure that the system used provides a sample that is truly representative of the process. Usually the design of the sampling system is a matter for a specialist. Some companies make this their source of business, and where necessary these experts should be called on for best results.
5. Nitrogen is often used in analytical instrumentation; for example, analytical houses are often N_2 purged. Be very careful of this material and treat it with the respect it deserves because it can be lethal. Remember: nothing living will survive in a nitrogen-filled atmosphere. Even slightly enriched N_2 atmospheres are dangerous to human life.

CONTROL

Mass Measurement with Differential-Creating Primary Devices

When a liquid mass flow has to be measured in a system and the amount flowing is beyond the range of available Coriolis meters, one is forced to resort to techniques that were used when such devices were not available. Let the flow be measured by a differential-creating primary device, in this case an orifice plate and a DP cell. The manner in which this is done is shown in Figure 1.12a. The differential head across the primary device is corrected for temperature variation in the first calculation block (module), but there is no need for pressure correction because a liquid is virtually incompressible. The square root is then extracted, and the result is the "true" volumetric flow; multiplying this by the liquid density will give the mass flow required. Of course, the corrections (including those for pressure—discussed later—use "absolute" units in the "calculation."

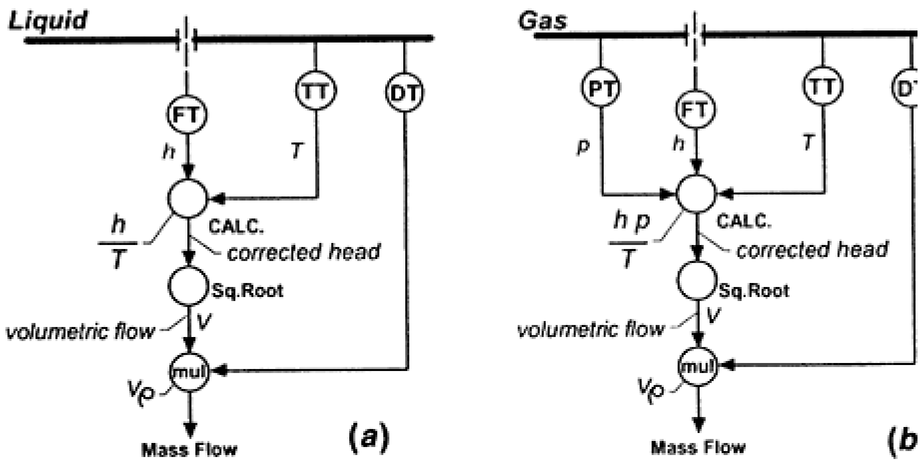


Figure 1.12: (a) Liquid mass flow; (b) gas mass flow.

The mass flow of a gas is obtained as shown in Figure 1.12b. Let the flow again be measured by a differential-creating primary device, an orifice plate, and a DP cell. The procedure is as described earlier when we considered a liquid.

Note carefully that the square root is (again) taken *after* the signal from the DP cell has been corrected for both pressure and temperature variation because the fluid is compressible. A densitometer is required for the fluid density.

Corrected Volumetric Flow with Direct Flow-Measuring Devices

When using flow-measuring primary devices that produce an output directly proportional to flow, we can omit the square root extraction in the arrangements shown in Figure 1.12a and b. The result can be used to give corrected volumetric flow measurements of either a liquid or a gas, depending on the configuration used. This corrected value of V can then be used where required.

Note: using the technique just described with either a magnetic flow meter or vortex meter and a densitometer, the mass flow can be calculated. This could replace the more expensive Coriolis meter.

Flow Integration

All measuring devices have limits to their accuracy. When we are required to integrate (totalize) the amount that has passed, we should be aware that when an instrument has its accuracy expressed as a percentage of full-scale deflection (FSD), the signal produced at the bottom end of the scale is not as accurate as that further up the scale. The best accuracy is at the very top end of the scale. As a result, integration will suffer, especially when the amounts are at the bottom end of the scale. Manufacturers of the measuring devices therefore publish the value at which the signal will be of little use because of the inaccuracy involved. This is known as low-signal cutoff and indicates that the signal below that value is suspect. An example using the vortex meter is given in Chapter 7 on the brewing industry. It should be noted that the accuracy of some instruments is given as a percentage of indicated value, in which case the statement just made is not applicable.

Signal Selection

In *all* selector systems, because every signal applied to the selector is derived from a specific, but different, part of the process or control system and therefore contributes to knowledge of the overall state of the system, a deviation of any one signal could result in a system deviation. Therefore, by using the signal that deviated most (higher or lower) as the controller measurement, the system can be made to respond in an appropriate manner to restore balance.

For example, in the case of Dowtherm heating in Chapter 5 on distillation (see Figure 5.16), if one of the fuel valves was more open than the rest, then the amount of fuel (heat) passing through that valve would be greater, and it would affect the overall heat supply to the furnace. Therefore, selecting the signal to this more widely open valve as the measurement for the valve position controller, the heat supply to the furnace will be cut back sufficiently (by an amount determined by the offending valve position) to overcome the excess that would otherwise occur if the valve position (heating effect) were ignored. The same idea of valve positioning control is used in the stock proportioning system discussed in Chapter 3 on the Fourdrinier paper machine (Figure 3.3).

In the cross-limiting system for furnace control discussed earlier in this chapter, the choice had to be made between two signals only. The process demand is directed to the fuel and air controller's set point, so that the heat supplied is sufficient to balance that demanded by the process.

Modern distributed control systems (DCSs) offer a selector with the possibility of up to eight inputs, which can be configured as either a high- or a low- or median-signal selector. In operation as a high selector, the highest of the inputs will be selected and replicated as its output, and the low selector will do the same for the lowest of the inputs applied to it. The median selector selects the signal with the median value. The values of the signals to the median selector are rearranged in ascending order at each scan, and the middle signal is selected if the number of signals applied is odd. However, if the number of signals applied is even, the design of the algorithm or module is such that a choice between the lower of the two middle signals is made, based on the values of the signals and replicated as the output. This block can alternatively be used to compute the average of up to eight inputs, in which case no selection is made, but the output is the computed average of all the applied inputs.

Integral Saturation or Reset Windup

Integral control action will produce an output as long as there is an *error*—that is, a difference between the measurement and the set point, Should the situation continue (without corrective action), eventually the controller output would be driven off-scale. Such a condition is encountered any time the control loop is “opened” (i.e., on plant shutdown), or when a very rapid and massive change takes place in the measured variable, or when the controller is transferred to manual control.

What really happens when the control loop is “opened” or the change in measurement is so massive is that the integral action, while it is trying to change the measurement in a direction toward the set point, will force the proportional band also in a direction to try and restore coincidence between the measurement and set point, but will receive no response from the loop. The integral action will continue to integrate the error, which persists because the output is going nowhere—as will be true either in an open circuit, or no further response obtained from the valve that has been driven to its limit, or when the controlled output is deliberately cut off as in manual operation. The controller reaches a point when even 100 percent output will not reduce the error to zero. This will eventually result in the output being driven to the full value of its power supply (20 lb/in^2 in the case of a pneumatic instrument, or whatever the output circuit/unit operating voltage is for an electronic instrument) and lock up at this value. The process is now out of control.

In the case of the open circuit, if the output were suddenly to be restored, the controller would then apply the full output to the controlling device. This action would not immediately restore control of the process, but would instead cause the process to make a massive “bump” as an initial response and then very, very gradually diminish. The reason for the slow and gradual return is that the reduction will be made only at the reset (integral) rate, and this could be a long time. In the case of the massive measurement change (we shall consider only one case), suppose there is a gradual reduction in the amount of change after the peak value has been reached. The controller, having already reached a value greater than the 100 percent output, will now have to commence integrating back downward toward the 100 percent value. During this time, there will still be no response from the control valve and therefore no control of the process. Transferring from manual to automatic operation will give results as described for the open circuit, but the severity will depend on the magnitude of the manual change made. The effect of the control action will begin to be seen only when the controller output goes below 100 percent of its output value, at which point the valve is able to start responding.

To overcome this serious problem, it is necessary to stop the integral action continuing to drive the output under its own dictate, but yet let the integrator take on the value of the adjusted controlled output. This latter has important implications, especially when the controller is in manual, for then the output, (e.g., to the valve) can be driven/placed anywhere within the output signal range, depending on where the operator chooses to set it (when a separate output signal generator is adjusted). The problems can be eliminated in active loops by including reset feedback, or by the operator (or automatically by the system switching to manual from auto in DCSs) transferring control to manual. The problem of balancing the signals is taken care of automatically in all modern controllers and control algorithms in DCSs with what is known as bumpless transfer. Examples of the foregoing are illustrated in many of the figures in later chapters, which deal with real-life applications.

Signal Characterizers

In are many instances, it is necessary to use signals that are nonlinear either as measurements or as outputs (e.g., the output to control dampers in air or gas ducts). In the early days, signal characterization was carried out by actually physically cutting specially shaped cams that were positioned either by a motor or a link/lever assembly, which altered the resistance of a potentiometer, or by a pneumatic needle valve. Today characterization is mainly carried out digitally. Where the relationships are difficult to define mathematically, one has to resort to the method of curve fitting, using coordinates to define the points on the curve. As will be appreciated, the greater the number of coordinates that can be used, the better will be the curve fit. However, modern instruments and DCSs also are limited in the number of coordinates permitted. The DCS system that has been used as the basis in this text provides for a maximum of 21 separate *break points* (coordinates), with the proviso that on any one block the points can either increase or decrease monotonically but not both within the same block. Other DCS systems may have similar restrictions and a greater or smaller number of break points. At least one hardware (hybrid) controller has the ability to accept four analog inputs, provides two analog outputs, and has two independent controllers. This controller has programmable digital software running internally and because of this, some advanced features such as: the instrument is provided with two characterizers, one having 16 break points and the other 11 (the latest version has only 9 break points for each characterizer) and permits direction changes of the curve.

Ramp Generators

In some control schemes, signals should increase or decrease linearly or be held at a particular value after they have been increased or decreased. This linear increase or decrease is referred to as a *ramp,* the meaning being identical to that commonly used when referring to a uniform rise or fall of a vehicle pathway. In the system we have used in the text, a ramp block or algorithm provides these features and allows the signal to rise or fall at predefined rates that are specified when the block is configured. The time unit for the rate is always in minutes; if the block output has different time units to this, another configuration parameter permits the time units of the block to be changed. As an example, suppose the output is required in hours; then a multiplying factor of 60 has to be specified for this (change implementing) parameter, and at some point in the computation the multiplication is performed. The output has high and low limits that are specifiable, and these constrain the peak-to-peak amplitude of the output ramp. The block can also be configured to follow another signal (usually a measurement) and replicates it as its output. The block can also be instructed to hold its output at a value at the time of instruction (i.e., last computed value). All instructions to make the block perform a ramp, hold, follow, or change from auto to manual mode of operation are signaled by a Boolean input to the required function parameter. Since the block can perform several different functions, there is an order of priority, which in decreasing order is Hold—Follow—Ramp, all of which are accessible when the block is in the auto mode only. In manual mode, there is no ramping, and the block output is unsecured; the manual mode overrides the Hold function.

Controller Output Bias Adjustment

We shall use a simple proportional controller to explain the reasoning behind the provision of this adjustment on most controllers. In this type of controller, the output is the result of the error multiplied by the proportional band plus the bias, or symbolically:

$$V = \frac{P}{100} Er + b$$

where V is the output, P is the proportional band in percent, Er is the error, and b is the bias.

When the controller has regulated the process and achieved steady state, the output V is equal to the bias b. When the controller is tuned correctly, the manipulated variable is driven to balance the demand of the load. We know that at steady state the output is equal to the bias; therefore, for every state of load change followed by a balancing output, there must be a specific bias. However, the bias may normally be fixed at a particular value, and this will force the operator to make the adjustment manually. This manual adjustment by the operator is called *manual reset*. The error or deviation will then be given by

$$Er = \frac{P\ (V - b)}{100}$$

In a proportional controller, this error is known as the *offset*. To avoid this offset, one has to provide a device that replicates the error and applies it to the controlled output for every change; this is called *integral action*. The system becomes a little more complicated in multiple-output systems, but the intention in this case is to avoid bumping the process when transferring to automatic operation.

SUMMARY

1. Proportioning systems are fundamentally similar, the differences being caused by the materials involved. The metering (measuring) techniques will have to change accordingly. In the case of fluids—and in such systems the fluids are always liquids—flowmeters are used. When the materials are solids, weighing equipment is used in place of the flowmeters.
2. Moving solid materials from one place to another in a plant is normally carried out by conveyor systems. The conveyors have to be started, stopped, the speed controlled, and perhaps the material on them weighed at the same time. The control circuits are always low-voltage single-phase or low-voltage dc. The motor is always fitted on equipment that is plant located and three methods—local, remote, and automatic—of starting and stopping the motor are employed. By local is meant the Start/Stop switches that are located in the vicinity of the motor, and by remote is meant the Start/Stop switches are located in the control room; and by automatic is meant that the control system makes the decision to Start/Stop the motor, which is triggered by the designer’s preconceived conditions of the process requirements that could prevail in the process at any time.
3. In practice, other conditions in the process will always need to influence the starting and stopping of the motor drive, and these have to be provided for. In addition, the motor will have to be protected from adverse conditions imposed on it while driving the equipment to which it is attached. For example, the temperature of the windings or the motor current could rise unduly as a result of an increased load on the equipment. Protecting the motor from these adverse conditions is termed overrides, and the control circuit will have to be modified to provide for them.
4. All overrides that are effective while the controls are operating in automatic mode have to be generated at a particular point in the process. This could call for sophisticated measuring techniques or specialized instruments to provide the switch input to the motor control circuit. Because these overrides are initiated by plant conditions, these can and will change and, when implemented, will make the system unique to the process being controlled.
5. It is not usual to have a single conveyor belt running over very long traverses. This is because of the formidable power required to overcome the friction forces alone in such arrangements, which, when coupled to the power required to move the material, would

involve an awesome total requirement. In such instances, the total traverse is broken down into smaller, conveniently handled, belt subsystems, which require a sequenced-start commencing with the last conveyor in the system.

6. The last conveyor is defined as the belt at the OFF-Loading end and farthest away from the point of ON-Loading material onto the conveyor. With the last conveyor starting first and sequentially working forward up to the first, the material would be continually on the move from the point of deposition to its final destination.
7. Liquid and gaseous fuels can be handled in similar ways since both are fluids and the equipment to control the amount required is generally of the same design. Control valves are used to regulate the amount of a fuel oil or the flow of a gaseous fuel. However, the parameters of flow operating pressure, temperature, viscosity, and density/SG will always have a significant influence on the size of the body, plug design, and materials of construction of the control valve for two fuels, and make them different.
8. Solid fuels are in a separate category because special handling and measuring procedures are necessary, both of which influence the controllability of the combustion process. In addition, furnaces that will allow this fuel to be burned have to be of unique construction, especially when mechanical stokers are used, and are very different from those used for either oil or gas. In the case of oil and gas fuels, the furnace is generally of similar design and construction.
9. The basic principles of combustion for fossil fuels are the same; that is, a pound (kg) of carbon in the fuel will require a specific amount of air (oxygen) to allow it to burn completely. This amount of oxygen has to be based on the chemistry of oxidation because carbon will (eventually) fully combine with oxygen to produce carbon dioxide, or symbolically: $C+O_2=CO_2$.
10. To perform the computation, we use the equation of item 9 and insert the atomic weights of each element to determine the amount of oxygen to obtain complete combustion. This gives: 12+(16+16)=44. In this defined relationship, the atomic weight of carbon is 12, and that of oxygen is 16. It should therefore be clear that if a particular fuel contains 12 pounds of carbon, then we will require 32 pounds of oxygen for complete combustion, and this will produce 44 pounds of carbon dioxide as a result of the burning process.
11. As stated earlier, the air we breathe contains 23 percent oxygen; therefore, each pound weight of air will contain 0.23 pound weight of oxygen. Hence, for a fuel containing 12 pounds weight of carbon we shall require: $\frac{32}{0.23} = 139\text{ lb}$ air approximately. This is the amount of air required for the combustible material in the fuel, and is known as the *theoretical air* for the combustion.
12. It is not possible either to ensure that the fuel used will always contain the identical amount of combustible material or to guarantee that the measurements we make will always be absolutely accurate. Therefore, to allow for the variables involved, it is essential to provide more than the theoretical amount of air to burn the fuel. The extra air that must be provided is called the *excess air* and is always accounted for as a percentage of the theoretical air.
13. If the amount of oxygen contained in the exhaust gases after combustion is measured, and it is, broadly speaking, similar to the amount provided in the excess air, then we

can be sure that all the combustible material in the fuel has in fact been burned.

14. The katharometer measures the thermal conductivity of a gas. The paramagnetic oxygen analyzer works on the principle of the paramagnetic effect of materials established by Michael Faraday.
15. *Paramagnetism* is the ability of some materials to align themselves along the lines of force of a magnetic field, and *diamagnetism* is the ability of other materials to align themselves at right angles to the same magnetic field. Oxygen exhibits paramagnetic and nitrogen diamagnetic characteristics, and it is these characteristics of the two gases that are exploited to determine the amount of oxygen present in a gas sample.
16. In order to use multiple fuels, we have to make the system think there is only a single fuel. As an example, let us consider just two fuel oils. For the system to work, it will be necessary to make the fuels appear to be the same, though flowing in different pipelines. In a two-fuel system, by considering the calorific values of each fuel and using a multiplying factor with fuel #1, it can be made to appear the same as fuel #2, or vice versa. Adding the two signals, one directly from the flow transmitter on one fuel and the other from the modifier (multiplier) on the other fuel, will give the total heat given up by the two fuels.
17. In a heating system, when a rapidly changing demand is possible, it will be necessary to consider the inclusion of what is known as *cross limiting* for controlling the combustion in the furnace. As long as the demand is constant, the airflow and the fuel flow controllers regulate their respective flows to meet the demand. Both control loops operate in parallel under this steady-state condition. The situation changes under a process upset; the demand selected through the high and low signal selectors makes the control loops then act in series.
18. Steam has a quality measurement scale based on its *dryness,* which indicates how much water it contains. The range of the dryness scale is 0 to 1 where 0 corresponds to being completely wet (i.e., hot water), and 1 represents completely dry (i.e., no entrained water). The drier the steam, the greater its ability to do useful work because it has absorbed more heat. This heat is given up when work is done.
19. It is very difficult, if not impossible, to produce steam of the exact quality directly from the steam generator. Therefore, to meet a particular requirement, it is more practical to produce steam of higher quality (i.e., with excess heat) and then add a regulated amount of (hot) water to arrive at the quality required.
20. Any source of cold water cannot be used to desuperheat steam; for the greatest benefit, the spray water should be condensate that nearly matches the saturation temperature of the steam. In this way, the minimum amount of superheated steam is required to produce steam of the requisite quality.
21. The acceptability of a product is always determined through analysis of the material concerned. This procedure can be carried out continuously while the material is being processed (i.e., on-line), or it can be tested off-line (i.e., by withdrawing a sample and testing it). Off-line testing will not permit corrective action to be taken immediately and could leave the manufacturer with material that is substandard. Unless the material is reprocessed, or able to be converted to another product, it will always remain substandard.
22. Two common techniques for use on liquids determine a material’s suitability for its

purpose: one utilizes the measurement of pH and the other measures conductivity.

23. The parameter pH, which is a measure of the acidity or alkalinity of a material, is an important one because sometimes variations beyond very close limits can have serious consequences for both the plant and more alarmingly for the human body. pH has a measurement range of 0 to 14 pH units. A midscale value of 7 pH units represents neutrality; values below this number are acidic, and values above are alkaline. However, we must be aware that, although pH has a linear measurement scale, it has basically a very nonlinear characteristic.
24. Sörensen brought about a linear representation of a nonlinear function when he discovered that by using the logarithm of the reciprocal of the hydrogen-ion concentration, a linear scale resulted.
25. Fundamentally, to regulate the pH of a material one has to add a precise amount of an acidic reagent when the material is alkaline, or a precise amount of an alkaline reagent when the material is acidic.
26. Controlling a fluid to neutrality is a very difficult task because of the shape of the titration curve at this region, which can best be described as an S-shaped curve, with the transition from one curve of the S to the other being rather flat.
27. The parameter conductivity is a measure of a material's ability to conduct an electrical current.
28. Conductivity measurement and control also form an important part of public water treatment works when ion-exchange columns are used to demineralize the raw water.
29. Ion-exchange columns operate on the principle of dissociation of impurities that dissolve in water to form positively *(cation)* and negatively *(anion)* charged ions. These impurities are chemical compounds and are called *electrolytes*. Ion-exchange materials have the ability to exchange one ion for another, retain it for a short while as a chemical combination, and then give it up to a strong regenerating solution.
30. Regeneration of the column is based on a timed cycle, as it takes a specific period first to wash and then to regenerate the exchange material. For continuous treatment, there must be more than one set of columns because as one set is in use the other(s) could be regenerating. Usually, there are more than two sets of columns in a treatment plant.
31. The mass flow of a fluid is computed as volumetric flow times the fluid density. However, for liquids, the volumetric flow must be corrected for temperature variation, and for gases, for both temperature and pressure variation.
32. For mass flow computation using differential head instruments to determine volumetric flow, always correct the differential head that represents volumetric flow for temperature when measuring liquid or pressure and temperature when measuring gas. Follow the head corrections by extracting the square root and then multiply by the fluid density.
33. For corrected volume flow using differential head instruments, always correct the differential head that represents volumetric flow for temperature when measuring liquids, or pressure and temperature when measuring gases. Follow the head corrections by extracting the square root.
34. Any time a loop having a controller with integral action is "opened," that is, on plant shutdown, or when there is a very rapid and massive change in the measured variable,

or when the controller is transferred to manual control, the integral control action will produce an output as long as there is an error—that is, a difference between the measurement and the set point. This would eventually be to drive the controller output off-scale, every time this condition is encountered.

35. If, for example, in the case of the open circuit, the output were then to be suddenly restored, the controller would apply the full output to the controlling device. This action will not immediately restore control of the process, but will instead cause the process to make a massive bump as an initial response and then very, very gradually reduce. This return could be a long time, for the return will be made only at the reset (integral) rate.

36. To overcome this serious problem, it is necessary to stop the integral action continuing to drive the output under its own dictate, and yet let the integrator assume the value of the adjusted controlled output. This latter has important implications, especially when the controller is in manual, for then the output, (e.g., to the valve) can be driven/placed anywhere within the output signal range, depending on where the operator chooses to set it.

CHAPTER 2
Digesters—Paper Pulp

CONTROL OF CONTINUOUS PULP DIGESTERS IN PAPER MAKING

The basic material of paper is fiber and the quality of the finished paper product is absolutely dependent on this raw material. In extremely simplistic terms, a sheet of paper or card is formed by laying a uniformly thick mat of a pulp slurry, formed by a mixture of very fine wood, other fibers, and water, deposited onto a mesh screen that is fine enough to trap the solid fibers, but at the same time allow the huge amount of entrained water to drain away. In ancient times, when reasonably drained of the excess liquid, the still limp mat of fibers was subjected to a press operation carried out by laying a heavy block of stone on the limp fibrous mat. Nowadays the limp mat of fibers is made to pass between a series of pairs of heated rollers that are squeezed together, with the force applied to each pair being adjusted so that they form a progressively increasing applied force. These rollers serve three important functions:

- They squeeze yet more water out at each stage as the mat passes through.
- They ensure complete uniformity of thickness.
- They dry the fibers.

When fully dry, the result is a stable and strong sheet of paper. It is easy to visualize the early process as one that permitted the formation of only a single sheet at a time—in fact this is how the whole thing began—or how the manufacturing process currently operates to make a very long continuous roll of paper.

There are many sources of fiber, but what we shall be considering here is wood as a single source, which is almost universally the most commonly used. As we all know, humans have devised many substitutes for naturally occurring materials that are difficult to obtain or expensive, but so far the making of a tree from scratch in the laboratory has eluded us. Only nature can do that and, what is more, at a pace determined by the species itself. In paper making, the wood used is usually obtained from pine and fir trees; these are softwoods and despite what has been said earlier, humans have in their own inimitable way intervened here too. With the sophistication of controlled cross fertilization, we have forcibly added to this naturally occurring process, and have now developed the means to produce fast-growing varieties. In spite of all our technology, we remain fundamentally dependent on the vital cooperation of nature, without which failure is inevitable. It must be remembered that, despite many efforts toward efficiency, humankind has not been able to overcome the basic constraint—*time,* for even the fastest growing tree requires time before it is mature enough to be useful. These days in the world's more enlightened countries, time, effort, and money are spent ensuring that the raw material—wood—is obtained mainly from forests of these specifically tailored, fast-growing varieties of trees that are managed to ensure a supply that is always available when needed, and not at the expense of denuding vast tracts of precious natural forests. Furthermore, in these modern times, paper is made not only from wood obtained from the managed forests, but also from paper waste that had at one time been processed and used and now remanufactured for reuse. This recycling technique is implemented to satisfy humanity's almost insatiable appetite for paper and to conserve our very valuable resource of natural forests. These fine words being said, it remains an indictment to humanity that we are still annually decimating millions of hectares of virgin forest to satisfy not only our basic needs but also the wants that appeal only to our vanity and require the more exotic variety of wood whose growth is very difficult to accelerate.

For paper making, the process of obtaining the vital wood fiber involves removing, by the use of either mechanical or chemical means, all the unnecessary material from the wood and yet preserving that fiber in a suitable state for use in manufacturing the finished paper. In this chapter, we consider mainly the chemical pulping process that is involved during the initial stages of paper making from natural wood.

PRE-PULPING PROCESSES

PROCESSING THE WASTE FROM LOGGING OPERATIONS

Offcut Processing

We start by looking at how the felled trees, whether from managed or virgin forests, are used initially, so that any products that can be separated are recovered and retained, hence adding to the financial viability of the operation. The offcuts, branches, and tree stumps are not discarded once they are cut off the main trunk of the tree, but instead are passed through a machine called a *hogger,* in which the solid stumps and branches are subjected to a grinding action to reduce them to a manageable size so that they can be acted on by another machine called a *shredder*. In the shredder the small but still solid pieces of wood are torn apart to produce shreds of wood that can now be conveniently processed, for it is now easier for the solvent used to penetrate the fibers and dissolve the sought-after resin contained in the splintered wood. Heating steam is applied to the first extractor vessel only, and by successively reducing the pressure in the other extractor vessels more of the inherent solvent in the wood is extracted.

Solvent Extraction

The splinters produced by the hogger and shredder are then loaded from the top into acid-resistant stainless steel extractors with perforated false bottoms on which the splinters rest. The extractors are arranged as a series of vessels and are referred to as a train. A solvent (usually naphta or some other petroleum fraction) with a boiling range between 93°C (199.4°F) and 116°C (240.8°F) and live process steam are introduced through the free space at the bottom of the extractor, thus forcing the mixture to flow upward through the perforations of the false bottom and loaded splinters. The extractors operate at a pressure in a range between 450 and 590 kPag, which allows the introduced process solvent to forcibly pass over the wood splinters washing, dissolving, and removing the sought-after residual, turpentine inherent solvent contained in the resin from the splinters as it flows past. The output from one extractor is fed to another, as shown in Figure 2.1. This figure shows the process

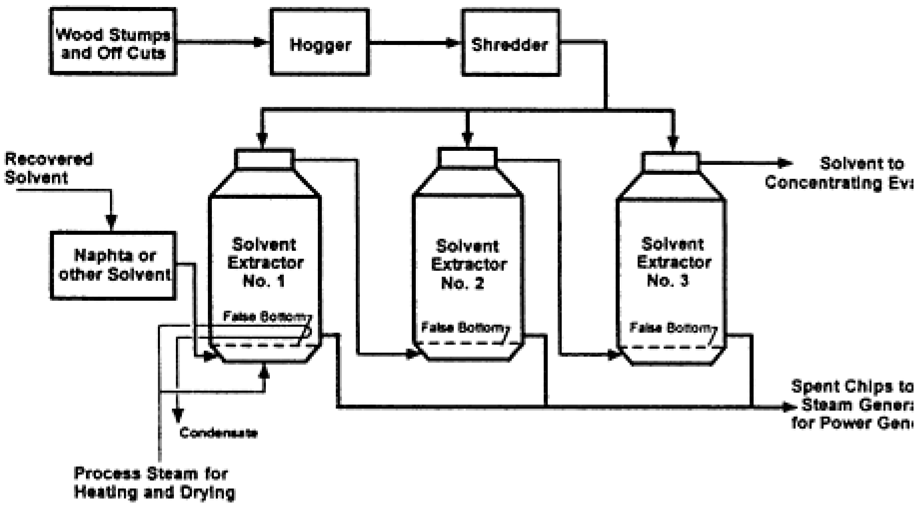


Figure 2.1: Solvent extraction process.

only up to the point of deriving the enriched solvent; it does not outline the stages involved in obtaining the other products available from it. The sale of the complex extractor train output directly to others, or continued further processing on site of the enriched solvent through evaporation and fractional distillation, results in a whole range of products such as turpentine, pine oil, tar, and many others which can then be sold and are thus a means of earning additional revenue.

PREPARING THE LOGS OF WOOD FOR PULPING

In the Western world, the trees used for paper making are pine and fir, mainly because of the length of the fibers they yield. Because fibers are the basic material for paper, it is as well to consider this now and to look at the fiber length of some of the materials used.

Cotton fiber has been used for a very long time in paper making and is the basis of almost all rag papers. The fiber lengths vary between 12 and 33 mm (0.4724 and 1.2992 in).

Flax is obtained from the outer part of the stalks of the plant. In paper making, the fiber is obtained from scraps from the textile industry. The length of the fiber is between 6 and 60 mm (0.2362 and 2.3622 in) and has thick walls with even thicker nodes at intervals along the length.

Jute is obtained from new burlap cuttings, wrapping material from bales of cotton, and washed sugar bags. It is used mostly in Kraft paper, for it is very difficult to produce a white fiber because of the lignin complex, which allows the color to be reduced to a pale yellow only. The length of the fiber is between 1.5 and 5.0 mm (0.0591 and 0.1968 in).

Cereal straws of wheat, barley, rice, oats, and especially those from wheat have been used for making paper where it finds use in the manufacture of corrugated paper, egg-case fillers, and strawboards. In the bleached state, it is also used to produce fine paper. The length of the fiber is between 0.7 and 3.1 mm (0.0276 and 0.1220 in).

Bamboo is a grass and because of its very rapid growth promises to be a good source of raw material for the papermaking industry. A vast amount of pulp from this grass is produced in India and is used in all types of paper from writing to ledger paper. The length of the fiber is between 1.5 and 4.4 mm (0.0591 and 0.1733).

As will be appreciated, several other sources of fibrous material are used to manufacture this product, and it is suggested that the reader investigate these sources.

The felled tree trimmed of all its branches and leaves results in natural logs that are of unequal length. These logs are cut to a uniform size for transportation from the forest to the mill and are then possibly reduced further in length to allow the logs to be subjected to a debarking process. The bark of a tree is removed because that bark is not fibrous and is very difficult to bleach; debarking the log is therefore a necessary pre-pulping production process. The process itself can take different forms, which can broadly be divided into two: the abrasive and hydraulic methods. Water plays an important role in the hydraulic method, for it carries away the unwanted refuse. To increase business profitability and minimize waste, the stripped bark is sometimes subjected to a process that produces a corklike material plus wax.

The Abrasive Method

This method is fundamentally a mechanical process for bark removal and depends on the friction generated by the moving logs; hence, a debarker is made up of a series of cylindrical steel sections 12 ft (3.658 m) or more in diameter approximately 22 ft (6.706 m) long fitted with rows of teeth that run around the internal periphery, the whole assembly capable of being rotated. Gaps are provided between sections of the rows of teeth to allow the loosened bark material from inside the cylinder to fall through and be carried away. A single, two, or three cylindrical sections can be coupled together to form the debarking unit, and in this form it presents a continuous drum of an overall length between 22 (6.706 m) and 66 ft (20.117 m) approximately, the most usual length being formed by two sections and therefore a minimum of 44 ft (13.411 m). In one design, the debarker is supported on freely rotating but captive trunnions, with driving ring gear fitted to the outside of the cylinder to make the whole cylinder assembly easy to rotate. The turning power is provided by geared electric motors engaging with the driving ring gear. The arrangement is shown schematically in Figure 2.2. In another design, chains from a substantial overhead structure suspend the debarker, and the drum is rotated by electric motors coupled to gearboxes driving one or more of the supporting chains.

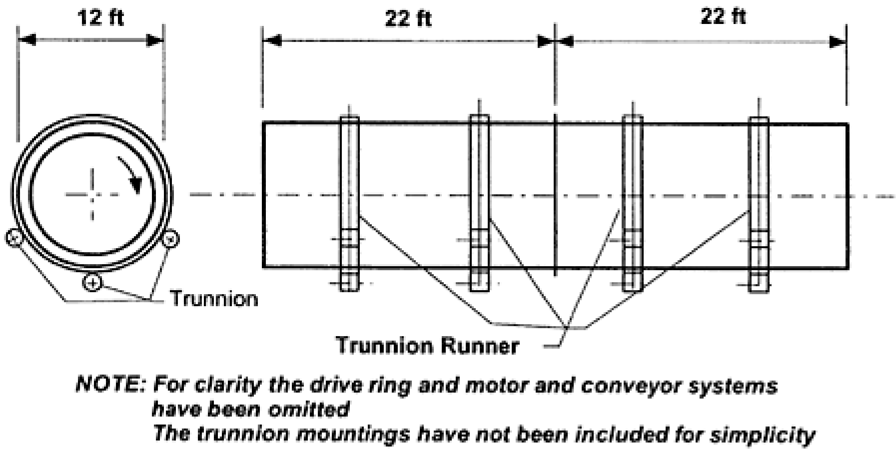


Figure 2.2: Schematic of a typical debarker.

Specially designed chain or belt conveyors that obviate damage to the belt or chain load the logs of wood into one end of the rotating cylinder. Since the debarker is rotating, its motion induces a rolling action in the logs. The abrasive action induced by the rolling logs rubbing against one another and the teeth fitted to the sides of the drum forces the removal of the bark. The cleaned-up logs are pushed out at the opposite end of the debarker. Usually process operators are stationed at the output end of the machine and visually inspect the prepared logs for remnants of bark or heavy knots. Specifically designed conveyor belt systems are fitted at the output of the machine to carry away the cleaned logs and to run underneath the debarker to remove the discarded debris for collection and processing if a cork substitute or wax making is involved. Otherwise, the bark is subjected to processes that involve shredding and compressing to remove excess water prior to using it as a fuel for steam generation. The papermaking industry is a very large user of both steam and water, and every opportunity is exploited to make it more efficient.

The Hydraulic Method

In the hydraulic process, a very high-pressure 1500 lb/in^2 (approximately 10,343 kPa) jet of water is directed tangentially against the logs. The water jet removes the bark very cleanly, breaking it up as it does so and at the same time carrying the debris off for further processing and use as described earlier. For the obvious reason of operating simplicity, the hydraulic process is used much more extensively in modern mills. The water used for the bark removal is recovered, filtered clean, and reused. As stated before, the waste is processed, these additional product(s) contributing to the financial economy of the manufacturing operation.

THE PULPING PROCESS

OPERATING PRINCIPLES

As stated earlier, the main two methods by which the pulp for paper manufacture is made are mechanical and chemical. Before we get involved with the production of paper pulp using chemicals, for completeness we will give a brief account of the mechanical method used. Of the two methods, the mechanical process of pulp making is by far the more efficient in using virtually all of the wood fiber, that is, both the cellulose and lignin, contained in the log of wood. The chemical process, on the other hand, does not do this because it dissolves the lignin and results in a pulp output that is therefore approximately half that produced by the mechanical means.

MECHANICAL PULPING

The mechanical process known as the groundwood process was invented in Germany in 1844. It involves forcing each log of wood against a fast-rotating grindstone, which results in an action that tears off the fibers from the log, but as a consequence the fiber length is not uniform. Groundwood is a mixture of fiber bundles, separate fillibrated fibers, broken fibers, and wood flour. The paper made from this material is soft, opaque, bulky, absorbent, and not strong; it also deteriorates with age. Figure 2.3 shows an arrangement of a typical early machine.

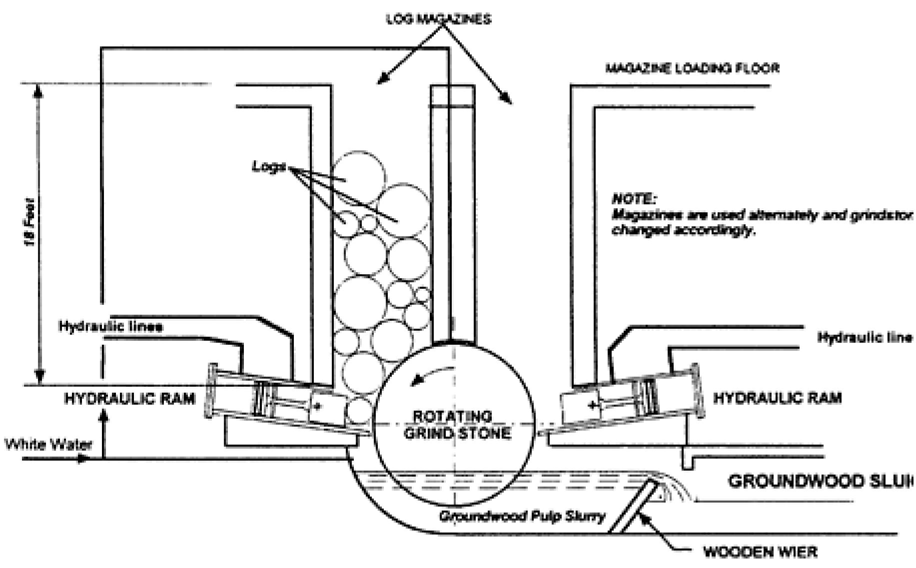


Figure 2.3: Arrangement of a typical early mechanical pulper.

The design of some of the modern versions of the mechanical pulper is based on these early machines, with the changes made being carried out mainly to the size of the log magazines. In the new machines the log magazines are much shorter: they are now only about 2 ft (0.6 m) high. Each log of wood used is 5 ft (1.5 m) in length, and the loading of these logs into the magazine, previously a heavy manual task, is now accomplished by conveyors that feed the logs directly into the magazines. The grindstones were originally fabricated from a solid sandstone boulder, with the possibility of each boulder being obtained from a different area where it was quarried. Since sandstone rocks are a natural material, they have characteristics dependent on the area from which they came, and they will therefore differ from each other. The technology in the early days was limited, and in many instances the grindstone disintegrated after only a few days' use because of the combined operational effects of heat, vibration, and deeply hidden faults in the material. Unable to withstand the uncertainty of grindstone failure, steps were taken to ensure some consistency. This effort resulted in the exploratory use of concrete to form the grindstones, but this venture had no success at all. However, a very well-known company that was involved in making artificial stones for purposes of sharpening knives and metal tools, and later on in the manufacture of the cutting tips for machine tools using silicon carbide grit along with a resin-based bonding material, exploited the business opportunity and started to produce its manufactured stones for use as pulper grindstones. The early grindstones made by this company were in one piece 2 ft (0.6 m) in diameter, but because of the combination of rapid heat generation of the grinding process and the slow expansion rate of the stone, early failure was inevitable. It was not long before the developers recognized the reason for the failure and produced a design in which the entire grinding surface was made up of a large number of small rectangular sections of stone. They started to produce these smaller rectangular shaped stones with curved upper and under faces to match the cylindrical shape of the metal core, and they held them down to it by special steel bolts. The stone sections were assembled in a manner similar to that used in building walls—that is, offset from each other—to avoid any of the unacceptable relative movement. The design included intervening spaces between each stone to allow for thermal expansion, thus eliminating one of the major causes of the early failures of the grindstone experienced previously.

Another artificial grindstone manufacturer, now seeing evidence of the success of the venture, also entered the market, but to avoid any patent infringement used a hexagonal shape for its stone sections. This gave the surface of the finished grindstones the appearance of an outsized honeycomb. Initially, the core of the grindstone was made of cast iron and was therefore costly to manufacture. To reduce the high cost of the cast iron core, it was later replaced with one made of cast concrete. Because of the mass of concrete involved, these new cores not only provided the required inertia, but were also much cheaper to produce. The advantage of an artificial stone surface lay in the fact that the abrasive quality could be varied depending on the duty for which it was intended. This flexibility was achieved by altering the amount of silicon carbide grit and the formulation of the resin-based bonding material, the actual formulation of the finished stone being dependent on the type of wood being used, as implied in the previous statement—"the duty for which it was intended".

The motive power necessary to drive the grindstone depended on the required pulp quality and its freeness, which is a measure of the amount of fibers held in suspension in the pulp. The oldest method of testing for pulp freeness is the blue glass test. For this, a small measured sample of pulp is diluted in a large measured amount of water, and the diluted specimen is poured onto a framed screen of dark blue glass, which is then held against a bright light. This allows the light-colored fibers to be easily seen against the dark blue background of the glass. It takes an experienced operator to tell from this test whether the pulp is too coarse or fine, as well as to estimate the percentage of unwanted fiber bundles contained in it. The test is very subjective and not absolutely replicable, because the results depend so heavily on the experience and eyesight of the human operator. However, technology has evolved an instrumentation system called a freeness analyzer. One company that used to produce such a system was the Bailey Meter Company in Wickliffe, Ohio. Discussion of this device is beyond the scope of this work, and so it is recommended that it be individually investigated further.

The groundwood pulp is not used directly as it comes off the grinding mill because the coarse fibers and the occasional *shim* (thin unground slivers of wood) have to be removed and be disposed of. The resulting pulp, which contains coarse as well as fine fiber, is then diluted to a suitable consistency formed by about 150 parts of water to 1 part of pulp. This dilute stock is pumped to equipment called a *knotter* where it is passed over a coarse *bull screen* having holes of openings that are 0.25 to 0.5 in (6.350 to 12.700 mm) diameter, and sometimes followed by another screening with holes of openings ranging from 0.1875 to 0.25 in (4.763 to 6.350 mm) diameter. The now fairly uniform pulp is subjected to yet another screening process; this time the hole openings are between 0.035 and 0.075 in (0.889 to 1.905 mm) diameter. The actual size of the holes in the screen used determines the quality of the finished paper; the output from this final screen is a fine pulp suitable for paper making. The largest material removed by the knotter is directed to another piece of equipment called a *refiner* where its size is reduced. The resulting pulp from the refiner is screened again to produce a pulp that is combined with that previously obtained from the fine screen. It is vital that any sand grit entrained with the pulp or obtained from the process is removed from the pulp because it can cause great damage not only to the extremely costly *wires* (screens) on the Fourdrinier paper machine, but also, if it is allowed to get that far, possibly on the expensive printing plate of the rotogravure printing presses. Today centrifugal cleaners are used in paper mills to remove the grit.

The water obtained from the grinding and screening process contains two important items:

- Very fine wood fiber pulp, which must not be wasted.
- Heat generated by the grinding process and absorbed by the cooling water.

The very fine fiber pulp is separated out either by a very fine screen or by a vacuum filter called a *decker*. These separated components are collected in the pulp storage tank, and the *white water* (cooling water) tank, respectively; the white water is so named because of its color. As stated earlier, the heat generated is mainly in the white (cooling) water, which is reused in the grinding machine. Small differences in the quantity required are made up by the addition of fresh water.

CHEMICAL PULPING

As before, the first step in this process is to debark the virgin logs of wood. The quality of the paper to be manufactured determines the amount of bark that must be removed. As a general principle, the rougher the quality of paper to be manufactured, the greater the amount of bark that can be tolerated; very fine quality paper will, as a consequence, require that all the bark be removed. The next step is to reduce the size of the log and produce reasonably uniform-sized wood chips, so that further processing can be carried out efficiently. To do this, the logs are fed at an angle into a machine called a *chipper*, which consists of a disk with protruding knives on one of its faces that is made to rotate at high speed. Since the log is at an angle, the fast-rotating knives cut the wood into the desired size of chips. It is important that the chips be neither too small nor too large because the cooking process could be affected in ways that might be undesirable. If the chips are too small, they will be overcooked, or if the chips are too large, the result will be an uncooked center in the chips. To ensure size uniformity, screening usually follows the chipping process. The fines along with the reject bark is used as fuel to fire the steam generators (boilers) that produce steam for use in other parts of the manufacturing processes in the mill. The coarse chips that have been separated out by the screen are rechipped in another machine that operates very much like the log chipper but arranged to handle chips instead of logs and returned to the screen for sizing. The acceptable chips are finally transported to chip silos ready for use in the pulping process. Recent studies have found that chip storage conditions affect the resulting pulp quality. It is therefore recommended that care and fairly uniform conditions be maintained in the chip storage silos.

ALKALINE PULPING

In 1851 the Englishman Hugh Burgess invented a process for producing wood pulp and described it as “boiling wood in caustic alkaline at high temperature,” the liquor used for pulping consisting of sodium hydroxide along with a certain quantity of sodium sulfide. The amount of sodium sulfide used varies from mill to mill; in addition, the liquor also contains some sodium carbonate and small amounts of sodium sulfate and sodium sulfite. Sodium sulfide hydrolyzes in water to form sodium hydroxide and sodium hydrosulfide according to:

$$Na_2S + H_2O \leftrightarrow NaOH + NaSH$$

The reaction is reversible, and equilibrium exists between the four constituents. Adding sodium sulfide to the liquor increases the amount of sodium hydroxide that is available and replaces the original amount of sodium hydroxide, which is used up during the cooking process. It has been found that the sodium sulfide increases the dissolution of the lignin, possibly because of the reaction between the sodium hydrosulfide and the lignin—this is a postulate only, because the actual chemistry is not fully understood.

SULFITE PULPING

The American chemist Benjamin Tilghman found that cellulose fibers could be obtained when wood was treated with solutions of bisulfite-sulfurous acid. This gave rise to the sulfite pulping process, which Tilghman patented. The initial process, which used calcium acid sulfite, ran into many difficulties and was modified later when magnesium acid sulfite, ammonia acid sulfite, and sodium acid sulfite systems were used instead. The purpose of this process is to remove the lignin where present, by the reaction with the reagent. This reaction produces lignin and hemicelluose derivatives, which are soluble in the chemical solutions introduced. When the reaction is complete, the spent liquor is drained off and the fibers are washed in water, which quite rapidly removes any liquor remnants from the surface of the fibers leaving only those within the fiber to be dissolved slowly in time and continued washing, which must be allowed for. For an ammonia-base acid sulfite pulping system, the digester tower acid consists of an aqueous solution of ammonium bisulfite along with sulfurous acid. In such a solution, a number of ionic equilibria and other basic relationships exist.

Lignin must be defined because it provides an understanding of the properties of wood and its chemistry. It is the only aromatic polymer concentrated in the middle lamella, where it functions mainly as cement and acts as a filler thereby imparting rigidity to the wood tissue. It is the 20 to 30 percent residue after the celluloses; hemicelluoses—any of several polysaccharides that are more complex than a sugar but less complex than a cellulose derived from plants, and produced commercially from seeds and plant tissue; starches; sugars; amino acids; fats; waxes; proteins; resins; tannins—any of the various chemically different substances capable of promoting tanning; flavornoids—a large group of plant pigments, including anthocynanins, that are water-soluble pigments found in sap of certain plants to give red, blue, or purple coloring to flowers, fruit, and autumn leaves; terpenes—any of the various unsaturated hydrocarbons found in essential oils and oleoresins of plants such as conifers, which are used in organic syntheses; and coloring matter or other extractives that have been removed from the wood. The exact structure of lignin has baffled chemists for more than a century, mainly for the following three reasons:

- It is a polymer, which cannot be converted to a monomer in sufficient yield without radically altering its structure. (A monomer is a small-molecule chemical from which a polymer is made; it is, so to speak, the basic building block (unit molecule) from which a polymer chain is built.)
- The structural units (molecules) containing the lignin polymer are neither identical in structure nor linked together in the same manner.
- It is almost impossible to isolate lignin completely and without structural alteration from associated wood components.

Lignin is more complex than either cellulose or certain proteins and even rivals the complexity of any known naturally occurring polymer. With a better understanding of the chemistry and properties of wood, we will be able to account for the property differences between and within different wood species; provide a better understanding of the lignin on the physical properties of the wood; have a sound basis for the improvement and development of pulp, paper, and other products; and explore new ways of using completely lignin-based byproducts. Since very large gaps remain in our understanding of lignin, we cannot yet make full use of this important polymer; until our knowledge improves, we will have to continue getting rid of it.

For a more detailed description of the chemistry involved, it is suggested that the reader consult *Pulp and Paper Science and Technology, Vol. 1,* 1962 (McGraw-Hill Book Company, New York).

THE KRAFT PROCESS

This process was discovered by chance at a Swedish paper mill where wrapping paper was being manufactured, and it came about as a result of an accident caused by a process operator when he mistakenly allowed the sulfate digester he was working on to blow up before the charge it contained was fully cooked. Rather than dump the undercooked chips to waste and lose everything, the mill manager decided to cut his losses and put the partially cooked chips through the disk refiners (called Kollergangs in Sweden). From this he thought he would produce a rough, inferior quality paper, which would return at least some revenue to pay for the damage sustained at the paper mill. The actual results were quite unexpected, and very fortuitous for the company, for it turned out that the paper produced in this way was of much higher strength than that which they normally produced. As a result, for this mill, it became standard practice thereafter to produce their *kraft* (which means strong in Swedish and German) wrapping paper from undercooked chips. Eventually, the production process was made known generally, and the product became known as Kraft, a name by which it is still known today.

SEMICHEMICAL AND CHEMIMECHANICAL PROCESSES

These processes fall between the groundwood and chemical pulping processes discussed earlier. The method involved is essentially one that uses heat plus mechanical and chemical energy to convert the wood to fibers. With this kind of process, the conversion of the wood to pulp is of the order of 55 to 95 percent—mechanical pulping gives the highest yield because almost all the wood is reduced to pulp, and the method used is generally conducted in two stages:

- A treatment with mild chemicals, which react with the bonds that lock the fibers together, to degrade and thus loosen them.
- A mechanical treatment to separate the loose fibers to make them suitable for paper manufacture.

It has been found that while undergoing chemical treatment, not only fiber loosening, but also some fiber separation occurs during this stage.

As noted earlier, the purpose of pulping is to produce fibers of cellulose, lignin, hemicelluloses, and extractives. A full chemical treatment of the wood chip, such as the alkaline and sulfate, removes almost all the lignin fibers. However, using the usual processes listed, the semichemical treatment causes the removal of lignin in amounts of decreasing order of magnitude as follows:

Most——————Least

• Acid-sulfite, neutral sulfite, Kraft, and soda

and the removal of hemicellulose fiber in amounts of decreasing order of magnitude as follows:

Most—————Least

• Soda, Kraft, neutral sulfite, and sulfite

The semichemical and chemimechanical processes are not entirely free from detractions, for there is also some attack to the cellulose fibers. It has been found that the soda semichemical process produces the heaviest attack on the cellulose fibers, and the Kraft process the least. The extractives dissolve much more easily in the alkaline than the neutral or acid reagents.

A Simplified Explanation of the Mechanisms in the Fiber/Chemical Reactions Involved

The manner in which the *neutral sulfite semichemical (NSSC) process* reacts with the lignin in the chip is by attacking the fibers mainly by sulfonation in the solid state of those sulfonable groups of the so-called A lignin-carbohydrate complex, followed by partial hydrolysis to a soluble lignin sulfonate and soluble carbohydrates. The prevailing neutral sulfite concentration and temperature within the digester will determine the amount of dissolution that will occur. The NSSC process also removes quite a lot of the hemicelluloses, for it neutralizes the acetyl and other wood acids fairly easily.

In the *acid-sulfite* and *bisulfite semichemical processes* the dissolution of the lignin under acid conditions is the main reaction. The process is thought to be similar to that obtaining in the NSSC process just described. However, the removal of the hemicelluloses is less than that obtained in the NSSC, soda, or Kraft processes. A full sulphite pulping process has been found to produce rates of dissolution of lignin proportional to the partial pressure of sulphur dioxide and a reaction that is monomolecular. In the acid or bisulfite processes, because a relatively large percentage of the solution is made up of lignin, the dissolution rates could in general apply here too.

In the *soda* and *Kraft semichemical processes,* the caustic soda in the liquid reacts with the lignin-carbohydrate complex to produce soluble sodium lignate, with hydrolysis making the carbohydrates soluble. This lignin reaction occurs only after the bulk of the caustic soda is expended in neutralizing the acetyl and methoxyl groups and dissolving the hemicellulose. This explains why lignin removal is low in alkaline semichemical pulping.

In the *cold-soda chemimechanical process,* the caustic soda reacts with the acetyl and other acid groups even at room temperature. The alkali causes the fiber to swell, thus serving to weaken the fiber bonds. The lignin is not dissolved under these conditions.

In the *sulfite chemimechanical process*, the neutral or acid sodium sulfite dissolves mainly the carbohydrates, which coupled with the high temperature at which it is operated affects the fiber bonds by weakening them.

A TYPICAL REAL PULPING PROCESS

We shall now consider a typical real process and the control systems involved with it. For convenience, the process can be considered in suitable sections: first, in order to see the progression of the raw material as obtained from nature to a state suitable for processing, and second, to make the entire process control system less confusing for the reader. The instrumentation has been shown in the ISA bubble format for simplicity and flexibility. This method has been chosen so that it is quite possible to see how the various loops can be converted easily to suit other system requirements.

RAW CHIP HANDLING AND PRE-PROCESSING

The very important and necessary preliminary processes of cutting the logs of wood to suitable size, debarking the cut logs, and producing the chips of wood all have already been described. They have not been included here because, as stated earlier, control of the processes involved during these very early stages is mainly mechanical and labor intensive. Since there usually is very little automatic control instrumentation, procedures can vary from mill to mill. (The chipping process is described earlier under the heading Chemical Pulping.) In common with all cooking processes, the size of the prepared material and length of cooking time are paramount; hence due attention must be given to these details. The cooking phase is a requirement that has to be implemented prior to the actual processing of the chips into the final product—pulp, for use in paper making. For the reader's convenience, the extra-heavy line in Figure 2.4 has been shown to define the chip flow through the various stages of the process.

The chips have to be transported from the chippers to where they will be stored and drawn upon as required for processing. Belt conveyors must be used to perform

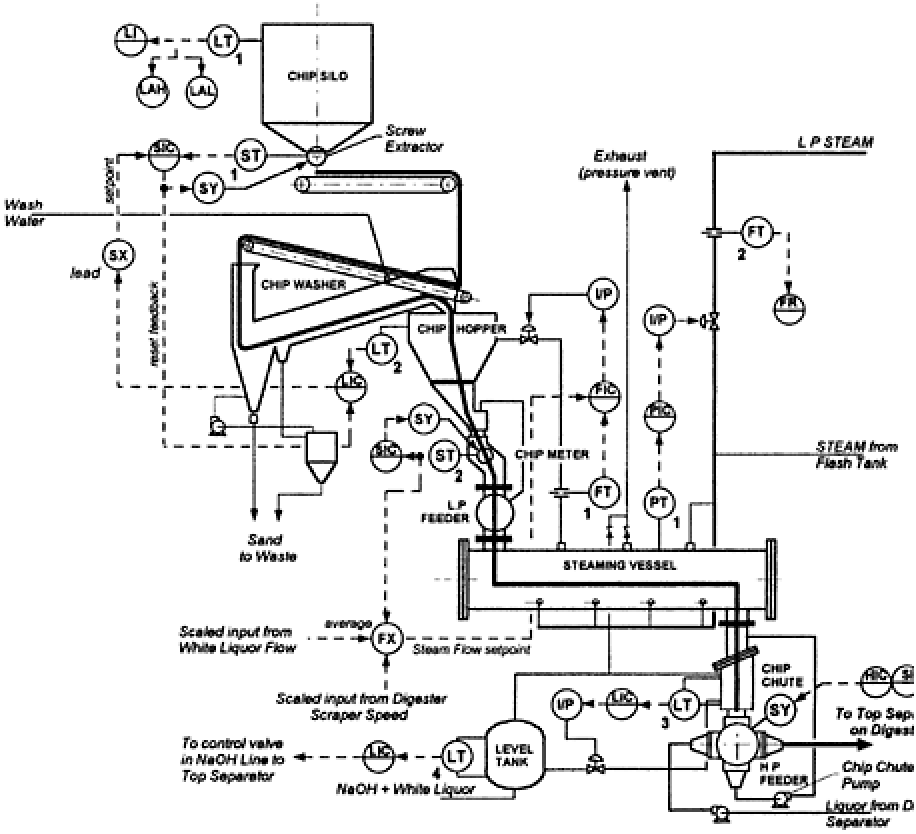


Figure 2.4: Raw chip handling and pre-processing.

the task involved, which in turn will necessitate controls to regulate the equipment used. We shall now digress a little and consider what is involved in regulating the conveyors used.

Conveyor Belt or Chain Control

The drive for this equipment is by electric motor, and therefore the controls and circuit symbols follow conventional practice. There are some minor modifications, which concern the circuit operation and the drive motor. With regard to dealing with the drive motor in the first instance, it should be noted that this can either be a separate item that drives the belt pulley through a gearbox (in which case the motor is a standard industrial motor unit of appropriate horsepower), or the motor can be in the form of the belt pulley itself and in this instance is of a specific industrial design. In the case of conveyor belts, the drive pulley is normally crowned—that is, the drive surface is not a perfect cylinder but is best described as barrel shaped, the bowed contour serving to centralize the belt as it moves. The natural tendency for a belt wrapped around a rotating cylinder is for the belt to run off the cylinder surface. Crowning the drive surface eliminates this tendency. In those instances where the drive motor cannot form part of the crowned drive pulley of the conveyor belt but has to be displaced from it, then a system comprising a grooved pulley on the motor drive shaft and vee belt(s) is used to transmit the motor drive to a similarly grooved conveyor belt pulley attached to the shaft of the crowned drive pulley of the conveyor belt. Vee belts are manufactured as a continuous ring that have a trapezoidal cross section and run in a similar-shaped groove in the pulleys, with the shortest of the parallel sides near the base of the grooves in the pulleys. The belts are designed to lie not at the bottom of the groove but at a position that allows a gap between the base of the groove and the bottom face of the belt. The load is carried entirely by a layer or layers of high-tensile, low-stretch, endless chords placed in the neutral zone that lies about the neutral axis of the belt, which is about two-thirds of the height from the base and where there is no change in speed as the belt(s) bends around the pulley. Vee belts must never be forced into the pulley grooves; the drive centers should be moved closer together so that the belt(s) can be placed in the pulley grooves. Since vee belts are made in standard sizes, more accurate results will be obtained by calculating the exact pulley center distances when using a selected belt. The approximate length of the belt can be determined from:

$$l = 2l_{c\ to\ c} + \frac{D+d}{2} \times \pi$$

where l is the approximate outside length of the belt; $l_{c\ to\ c}$ represents the center distances of the pulleys; and D and d are the pulley diameters. Note that this formula is accurate where the ratio of $D:d$ is 1:1. If this is not the case, then the formula can be modified to take care of this to give:

$$l = 2l_{c\ to\ c} + \frac{D+d}{2} \times \pi + (D+d)^2$$

From either of these two formulas, it is not difficult to calculate the center-to-center distance $l_{c\ to\ c}$ for the pulleys used.

The other important issue concerns the starting sequence of a conveyor system comprising more than one belt, and it will involve modifying the control circuit as shown in Figure 2.5 through Figure 2.10. These multiple belt systems are very common on applications where the distance between the point at which the product is loaded onto the conveyor and the point where it is off-loaded is great. It is not

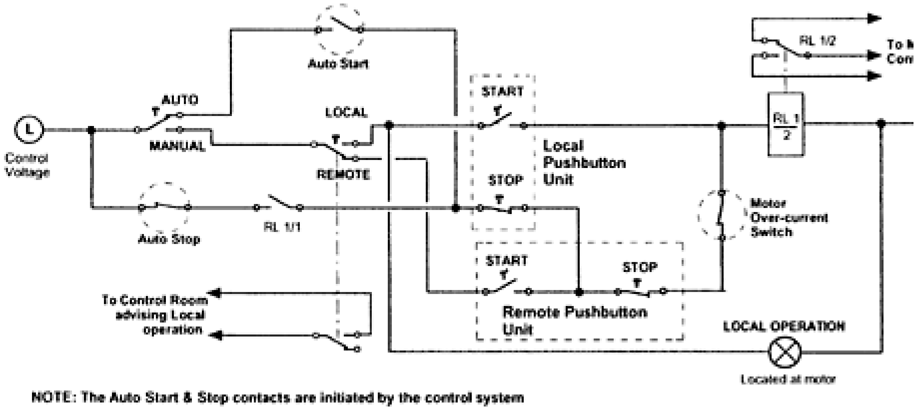


Figure 2.5: Typical motor control circuit with overrides.

unknown for some systems to be about 440 yards (400 m approximately) or more; a single belt on such applications is not recommended, because obtaining the correct belt tension becomes problematic and there will be too much drag friction, which will increase the horsepower required. Long conveyor belt runs are usually broken down into a series of conveyor belt runs of shorter length. When these multiple belt systems are used, there will have to be a number of points along the route where the material is loaded onto and unloaded from each section of the conveyor belt involved in the delivery circuit in order to get the material from its initial loading point to its final destination. It is very important that the belt furthest from the initial point of material loading be started first and then gradually worked backward from that unit up to the belt at the initial point of material loading. Belt speed is the trigger for the succeeding belt systems to be started. The simplest, and possibly the cheapest method to measure belt speed, is an instrument comprising a tachogenerator coupled to a *jockey roller* of calculated diameter that rides the belt surface

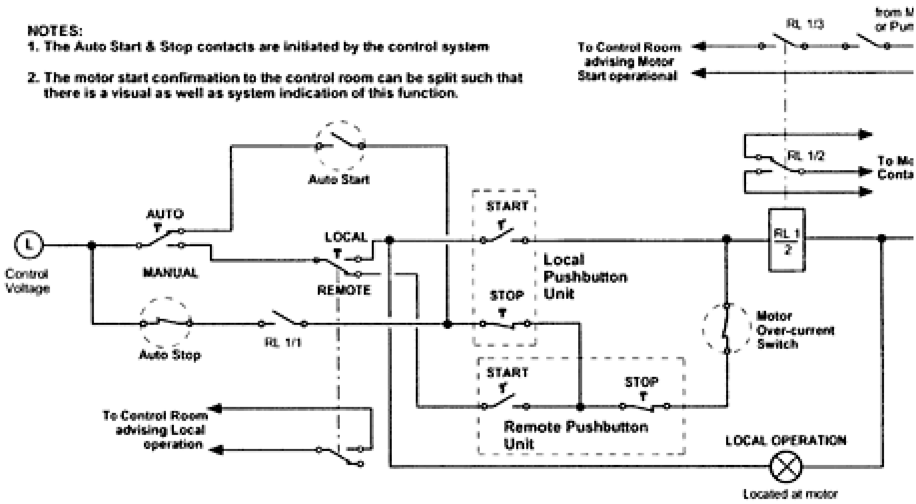


Figure 2.6: Typical motor control circuit with overrides and confirmation of motor start instruction.

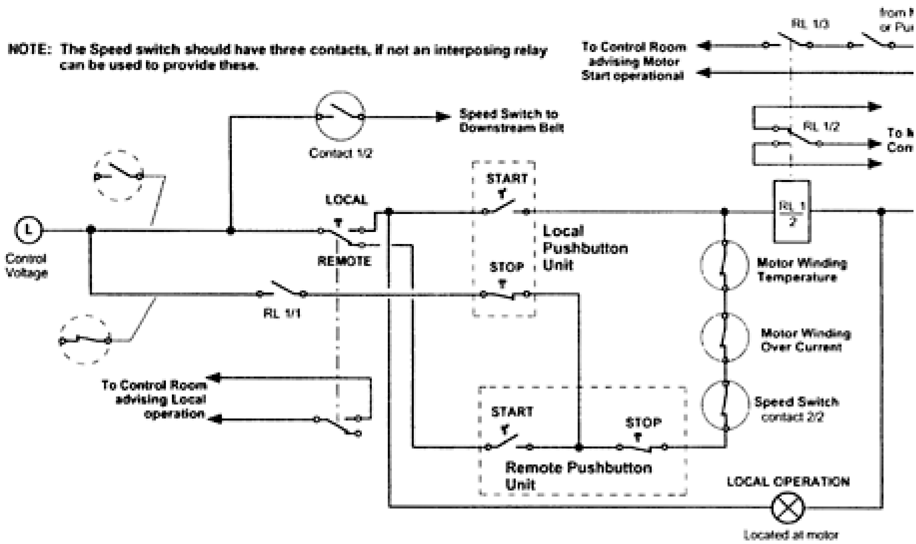


Figure 2.7: Typical last conveyor belt motor control circuit with winding temperature, winding overcurrent, and speed overrides.

and so generates a voltage or frequency proportional to the belt speed. A switch is coupled to the output from the generator and initiates a contact when a preset value corresponding to the desired speed is attained. Other methods may be used to determine the belt speed, but these are more involved and expensive to install and maintain. This speed contact is the trigger for starting the succeeding belt system. From what has been said regarding the tacho-generator system, it will be understood

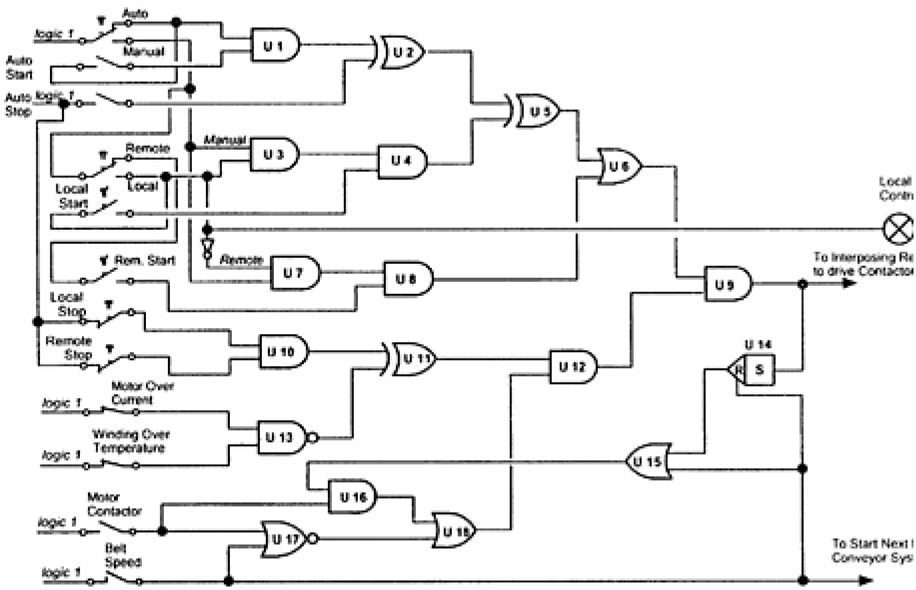


Figure 2.8: Equivalent logic diagram for motor control for the last belt in a series.

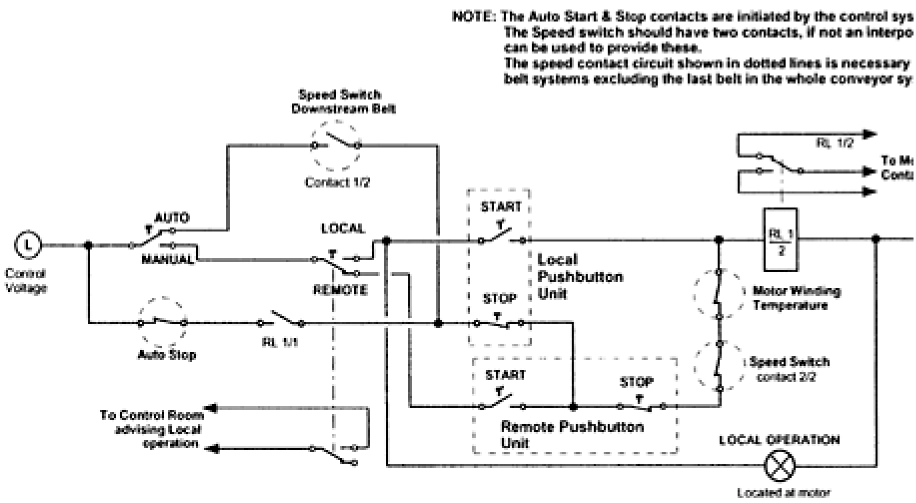


Figure 2.9: Typical first or intermediate conveyor belt motor control circuit with winding temperature and speed overrides.

that every belt system will need a speed switch to be fitted. It is important that there is no slip between the roller and the belt; otherwise errors will be introduced, and this demands that the roller be spring loaded to ensure intimate contact at all times.

As a useful and instructive exercise, the reader could simulate the digital logic circuits of Figure 2.8 and Figure 2.10 using a combination of Excel (spreadsheet) and Visual Basic or one of the proprietary logic simulation and test software packages.

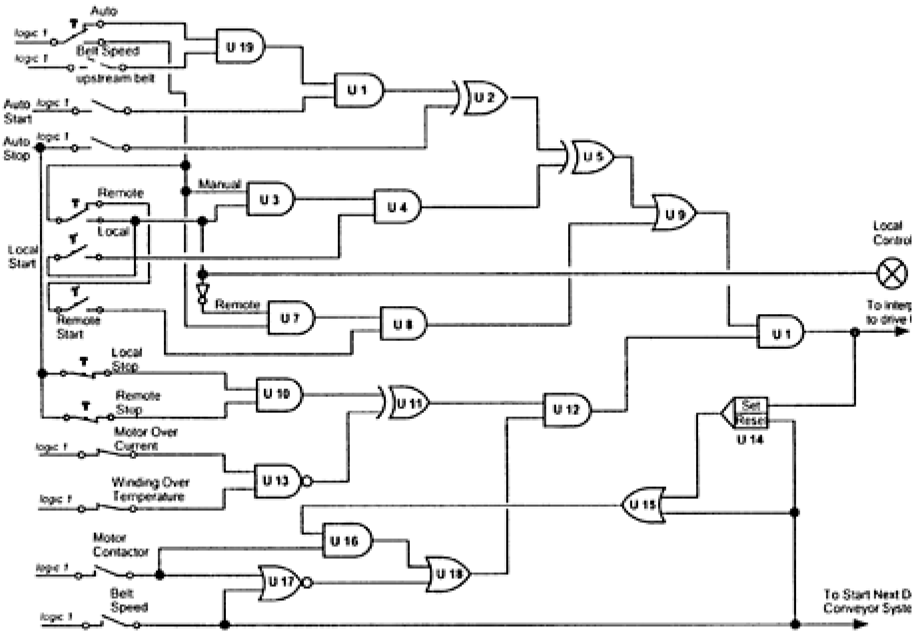


Figure 2.10: Equivalent logic diagram for motor control for belts other than the last in a series.

Motor and Conveyor Belt Controls

Motor Control—with Relay Ladder Logic

Because a number of electrically driven pumps and motors are involved in this application a motor control system is given as a guide to the basic requirements. The circuits shown here are the most basic; that is, they are the minimum required for a motor and can be modified to suit a variety of requirements demanded by the logical sequences involved in any particular application.

The circuit shown in Figure 2.5 is not specific to applications in the paper industry but could be applied wherever it is considered suitable, except where the process is hazardous, that is, susceptible to risk of explosion, and the plant is required to conform to intrinsic safety requirements. As stated earlier, what is shown can be enhanced if necessary to any level to make it suit the actual operating specification required. A few points worth noting in the above circuit are as follows.

- When inductive components are incorporated in electrical circuits, for example, relay and contactor coils, consideration must be given to the inrush current involved and suitably rated drive contacts provided. By comparison, the running current is considerably smaller in value than the inrush current. Motor start currents are similar cases.
- The circuit shown is only the *theoretical* one and is drawn as a *ladder diagram;* it is *not a physical wiring diagram*. The theoretical circuit shows how the scheme operates but not how the wiring is to be carried out. The latter diagram is quite different from this theoretical ladder diagram. The design is *not fail safe*.
- The Auto Start and Stop contacts shown are derived from the process control system, which could be a DCS (distributed control system) or PLC (programmable logic controller). In some instances, owing to the current and/or voltage handled, it may be necessary for an interposing relay to be placed between the system and the motor drive circuit contactor.
- The Local Start and Stop pushbutton switches should be of *momentary action*, that is, initiated against the action of a mechanical spring, which ensures that the unit always returns to the initial (not actuated) position. The units must be of weatherproof design and mounted in the same enclosure as the Auto/Manual and Local/Remote switches.
- Both the Auto/Manual and Local/Remote switches must have *stay-put (self-hold) action;* that is, once operated the unit will remain in the operated position and not return to the initial (not actuated) starting position. For additional protection, it is recommended that both of these switches be of the key lock type: they require a key to be inserted, and the mechanism must be mechanically unlocked before the electrical switch can be actuated.
- The Auto/Manual, Local/Remote, Local Start, and Local Stop pushbutton switches are located in the plant in the vicinity of the pump/motor involved. It is therefore important that these units be weatherproof, and for additional protection they should be mounted in a suitable field enclosure. The field enclosures are usually made from fiberglass with stainless steel hinges and fittings where appropriate.
- Following normal practice, the relay RL 1/2 and the motor contactor are usually located in the *Motor Control Center* (MCC).
- Depending on the power rating of the pump or other drive motor, the contactor could be either a single or three-phase unit. However, the initiating contact is always operated on a low-voltage supply usually 50 V ac single phase, or in some instances 24 V dc depending on the plant requirements.
- In the circuit that is *volt free,* (i.e., no voltage being switched), an initiating only contact is shown to inform the control system and the process operator in the control room that the motor/drive is under the jurisdiction of the *field personnel*—operators who are on the process plant site and not in the control room—and is being operated from the plant location. The locally mounted weatherproof signal lamp will give visual indication to others in the plant that the associated pump/motor is under manual field control. In some plants, the local visual indication is given by a flashing light, for which an additional unit is required.

Note: In general, in the following descriptions of the motor control circuit operation, the conveyor belt descriptor “upstream” means the belt system(s) either with reference to the last conveyor in the system or immediately preceding the conveyor being considered, and the descriptor “downstream” means the belt system(s) immediately following the conveyor being considered.

Enhancement to the Basic Motor Control Circuit—Motor Start/ Stop Feedback

When proof is required that the instructions given to start or stop a motor have been carried out, the relay logic control circuit of Figure 2.5 can be modified as shown in the relay logic control circuit of Figure 2.6. Relay contact RL 1/3 only advises that the instruction to start the motor/pump has been received. However, including the motor speed or pump output contact in series with contact RL 1/3 as shown in Figure 2.6 confirms that the motor/pump has actually started, since the speed or pump output contacts are associated directly with the device being started.

Motor Start/Stop Feedback Circuit with Addition of Conveyor Belt Speed

The motor control circuit of Figure 2.6 has been modified and enhanced to allow the arrangement to act as the controls for the last conveyor belt in a long conveyor system. These modifications are illustrated in the circuit of Figure 2.7 and allow the system to be stopped in the event that either the motor winding temperature rises or the current drawn by the motor goes above a defined value and the belt speed has attained a predetermined value to provide the signal to initiate the upstream conveyor belt via belt speed switch contact RL 1/2. Further enhancements, though not included in the circuit, can be added; however, to assist the reader, the position and type of contacts have been shown. The normally open contact, which is shown placed ahead of the Local/Remote switch, could be derived from, say, measurements of a series of silo levels being at an acceptable high value, and only when this condition is fulfilled is the system permitted to start. The normally closed contact shown placed ahead of contact RL 1/1 could be obtained from, say, a low-level measurement in the conveyor belt charging silo, and when this opened (on a low-level measurement) the conveyor would be stopped.

Motor Control—with Binary Logic

Note: *In all the following binary logic diagrams, it is possible to arrange the switches on the extreme left-hand side and thereby reduce the number of logic gates involved. However, to show the direct relationship between the relay and binary circuits, this has not been done.*

As an example, to show how the relay ladder logic diagram of Figure 2.7 can be converted to binary logic, we give the logic diagram of Figure 2.8 using a set of the conventional symbols used in industry and defined in Instrumentation Symbols Used in This Book. As mentioned earlier, the logic circuit could be applied to any process equipment that requires this kind of design philosophy. However, in this instance we have given the circuit to be implemented for the last belt in a conveyor system, recalling that this is normally the first to be started for the reasons given earlier, and the term *upstream* is with reference to this conveyor (see note given earlier). Another slightly modified diagram follows this one for any of the upstream conveyor belt systems; all upstream conveyor systems are initiated only when their downstream units are fully up to speed.

Circuit Functional Description—Last Belt in the Series

Automatic Operation

- The Auto/Manual switch can be a hardware or software device that needs only two states (On or Off) and a *stay put* action: when initiated, the device remains in the operated position until it is deliberately changed. When the switch is configured as a software device, it most often forms part of the process graphic. Hardware devices are usually mounted on the control console. In the preceding circuit, the Off state is the normally open contact of the Auto/Manual switch, and when switched to this state the system is in the manual mode of operation. From this it should be clear that operating the Auto/Manual switch would open the normally closed contact and change the operating mode from automatic to manual.
- The single Auto Start contact shown is one that is generated in the process, but it also could be the result of several completed subactions in the process. The subactions have not been shown for simplicity and clarity, but it can very easily be visualized as each of the subactions producing a contact output on its completion. All the subaction contacts are then connected in series (electrically) and effectively result in a single-contact closure input to the control logic.
- The automatic function command from the Auto/Manual switch and the Auto Start signals are the two inputs to gate U 1, which is operationally an AND function. U 1 will not produce an output until both inputs have a logic 1 signal on them. Note, as drawn, the signal from the Auto switch produces logic 1, and gate U 1 will wait until the Auto Start signal also is logic 1 before its output is logic 1.
- Gate U 2 is operationally an XOR (Exclusive OR) function. This is a two-input gate in which either one, but not both, of its inputs must be logic 1 to produce logic 1 at its output. If both inputs to this gate are logic 1, then the output will be logic 0. This fact is exploited to produce the Stop action for the system. If for any reason the Auto Stop (i.e., a signal generated in the process) input to gate U 2 turns into logic 1, then its output will immediately turn into logic 0.
- With the Manual input to gate U 3 held at logic 0 (remember the Auto mode select as drawn is in Auto mode), the output from this gate will be logic 0, even if the Local Operation mode switch and Local Start switch are selected inadvertently. Under this condition, the output of both gates, U 3 and U 4, will always be logic 0 and will change only if the Manual-operating mode is initially selected. In the instance where manual operation is initially selected, a separate operational description is involved.
- The logic 1 output from gate U 2 will be one input to gate U 5, which is another XOR function, and because the second input is logic 0 for reasons given in item 4, the output of gate U 5 will also be logic 1.

- Gate U 6 is operationally an OR function: any one of the inputs being logic 1 will result in the output also being logic 1. This allows the logic 1 signal to appear as one input to gate U 9, which is operationally an AND function, and therefore requires both inputs to be at logic 1 level before the output is logic 1.
- The second input to gate U 9 is derived from the output of gate U 12 that is operationally an AND function. To see how this second input is logic 1, let us look at the inputs to gate U 10. Both inputs to this gate are obtained from normally closed contacts of the Local Stop and Remote Stop switches, because before these could be hardware or software devices. Because these are both closed, each is at logic 1 level; the output of gate U 10 will therefore also be at logic 1. The motor *over current* and motor *winding over temperature* are both normally closed contacts and provide logic 1s at the inputs of the NAND gate U 13. Operationally, the output of a NAND gate will be logic 1 only if at least one of its inputs is logic 0. The over current and winding over temperature contacts operate independently and open (change state) only under adverse conditions of the monitored parameter; when both are at logic 1 level, logic 0 will be produced at the output of gate U 13. In the event of undesirable conditions at either input of gate U 13, the output will immediately change to logic 1. We first consider the situation where the motor is operationally healthy and hence neither the temperature nor motor current trip amplifiers are invoked (i.e., associated contacts are closed). Thus the conditions produce logic 1 at the output of gate U 10. Gate U 11 is yet another XOR that receives the outputs from gates U 10 and U 13 as its inputs, and because the output of gate U 10 only is logic 1, the output of gate U 11 will also be logic 1. If for any reason the output of gate U 13 were to be logic 1 owing to either the motor winding overheating or the motor current being excessive, the output from gate U 11 would immediately change to logic 0. The effect of this would be to make one of the inputs to gate U 12 (operationally an AND function) logic 0.
- Before we consider how the belt drive motor is started and/or stopped, we must see how the output of gate U 12 is made logic 1. In item 8, we described how one input to this gate is made logic 1. Let us now consider the other input, which is derived from the output of gate U 18. The inputs to gate U 17 are derived from the motor drive contactor and the belt speed. With the motor not running (the condition at start-up), both of these inputs will be at logic 0 level. Applying these contacts as inputs to gate U 17, which is operationally a NOR function, the output from this gate is logic 1. Remember, NOR gates produce logic 1 as an output only when all the inputs are at logic 0 level. Therefore, at start up logic 1 is applied to one input of gate U 18, which is operationally an OR function and hence makes its output also logic 1. This output is applied to the second input of gate U 12. Because gate U 12 is operationally an AND function, which we have seen obtained its first input as logic 1 from the output of gate U 11 (see item 8), the output from gate U 12 is logic 1. It should be remembered that the auxiliary contact associated with the drive motor contactor is used in the control system, but this contact will change state as soon as the contactor is energized and as a result forces the auxiliary contact to open and if nothing is done will stop the motor immediately. Applying the motor drive signal to gate U 14, which is operationally a flip-flop (bi-stable) function (i.e., a gate that requires logic 1 signal to set the output to logic 1 and another logic 1 signal to reset the output to logic 0) avoids this unwanted

condition. With the drive signal to the interposing relay at logic 1, gate U 14 (S) is set to logic 1 which is applied as one input to gate U 15, operationally an OR function; the second input of gate U 15 is derived from the belt speed contact. At start-up, and for a while thereafter, the belt speed contact will be open, allowing only the output from gate U 14 to be reflected in the output of U 15. This reflected output represents the drive signal to the contactor and will be held at the logic 1 level until U 14 (R) is reset. When the auxiliary contact the second input to gate U 16, which is operationally an AND function, *pulls in* (energizes), both inputs to gate U 16 are at logic 1 level, producing logic 1 at its output. The effect of this is to drive the output of gate U 17 to logic 0 (because the auxiliary contact, one of the two inputs, is at logic 1). The circuit remains operational because gate U 18, operationally an OR function, is unchanged at logic 1. When the belt is up to speed, the associated speed contact closes to apply a logic 1 signal to gate U 15 and to the reset of gate U 14 to turn its output to logic 0. The output of gate U 15 will still be logic 1, but this time will be derived from the belt speed. A change in either the state of the motor contactor or the belt speed will make the conveyor drive motor stop, by forcing the output of gate U 12 and hence gate U 9 to logic 0.

- Now let us look at how the conveyor drive motor is started and stopped. Gate U 9, which is operationally an AND function, receives its inputs from the outputs of gates U 12 and U 6; it is responsible for driving the interposing relay to the conveyor drive motor contactor. Considering the case when the output of gate U 12 is logic 1 (see item 8) and the output of gate U 6 is also logic 1 (see item 7), we see that the effect of this would be to make both the inputs logic 1 and since gate U 9 is operationally an AND function the output will also be logic 1. This would energize the interposing relay and initiate the contactor to start the conveyor drive motor. Should the output of gate U 12 be driven to logic 0 for any of the reasons given in item 8 or 9, the effect would be to make any one input to gate U 9 logic 0 and result in driving its output to logic 0. This would deenergize the interposing relay and stop the conveyor drive motor.

The foregoing shows that the controls described will automatically respond to conditions prevailing in both the process and the conveyor drive system. However, as is normal in any plant, the need for process operators to intervene at any time must also be provided; this is necessary to provide personnel and plant safety at all times.

Automatic Operation—Manual Stop

- Should it become necessary to stop the belt drive for reasons other than motor faults, then initiating (opening) either the Local Stop or the Remote Stop switches will accomplish the requirement. Opening any one of these will make the associated input signal logic 0 and will in turn force the output of gate U 10 (operationally an AND function) to logic 0. Now since both the inputs to gate U 11 (operationally an XOR function) are at logic 0, the output from this gate will also be logic 0.
- With one input to gate U 12 (operationally an AND function) being logic 0, its output will be forced to logic 0 also. This will make one input to gate U 9 (operationally an AND function) logic 0 and drive its output to logic 0 as well. The result will be a removal of drive signal to the interposing relay, forcing the conveyor drive motor to

stop.

Manual Operation—Local Start/Stop

At times it will be necessary to operate the conveyor belt systems under the control of the process operator. To do so, the control scheme has been provided with suitable facilities.

- The operator must ensure that the automatic stop input to the conveyor control system will not have an adverse influence. The Auto switch is selected first and turned off to disable the automatic start. This makes the system immune to any automatic start input from the process, and the inputs to gates U 3 and U 7 associated with this contact are set at logic 1 level.
- Manual operation can be invoked from either a Local (i.e., on the plant) or Remote (i.e., from the control room). These two options are presented because in the event of a fault with the motor, access must be available at the motor itself; therefore a facility to start and stop the motor must be made available. A selector switch that can be a hardware or software device with only two states (On or Off) and a *stay put* action is provided. When the switch is configured as a software device, it most often forms part of the process graphic. Hardware devices are usually mounted on the control console. The signal labeled Local allows on-site operation while the signal labeled Remote allows control room operation. From this it should be clear that operating the Local/Remote select switch would open the normally closed contact and change the operating mode from Remote to Local via this single contact.
- Suppose Local were selected. This would make the second input to gate U 3 change to logic 1, and as a result would make the output of the gate that is operationally an AND function change to logic 1 as well. This output is applied as one input to gate U 4. Furthermore, the selection will apply power to an interposing relay to drive a signal lamp, as shown in the figure and mounted in the vicinity of the motor; if necessary, this signal can also drive a signal lamp in the control room. However, this latter indication is not shown.
- Initiating the Local Start switch now applies logic 1 to the second input of gate U 4, which, as stated earlier, is operationally an AND function; the result is that the output of gate U 4 is changed to logic 1 and applied as one input to gate U 5.
- Gate U 5, as we have stated earlier, is operationally an XOR function requiring only one input to be at logic 1 to make its output logic 1 also. Since the system has been selected for manual operation, the Auto Start and Auto Stop inputs are not effectual. Hence, the second input to gate U 5 from these sources will be logic 0, and the signal from gate U 4 (logic 1) will appear at the output of gate U 5.
- From this point onward the system operates as described in the Automatic Operation mode items 7 through 10, and Automatic Operation—Manual Stop items 1 and 2.

Manual Operation—Remote Start/Stop

When it is necessary to operate the conveyor belt systems from the control room, then it will be a requirement to initiate the Local select switch first.

- Once again note that the operator must ensure that the automatic stop input to the conveyor control system will not have an adverse influence. The Auto switch is selected first and turned off. This makes the system immune to any automatic start input from the process, and the first input to gate U 3 and the second input to gate U 7 associated with this contact are set at logic 1 level.
- As drawn, the signal from the Local select switch in the Off state to the first input of gate U 7 is shown as an *inverted* signal (i.e., when the input is logic 1 the output is logic 0 and vice versa). When the inverted signal is used (i.e., Local select switch Off), the system is in the Remote mode of operation. When operated in Remote, this would make the first input to gate U 7 operationally an AND function, logic 1, and as a result make its output logic 1 and apply it as one input to gate U 8.
- Initiating the Remote Start switch applies logic 1 to the second input of gate U 8, which is operationally an AND function. Since both inputs to gate U 8 are now logic 1s, the output is driven to logic 1 and applied as one input to gate U 6.
- Gate U 6, as we have stated earlier, is operationally an OR function and requires only one input to be at logic 1 to make its output logic 1 also. Since the system has been selected for manual operation, the Auto Start, Auto Stop, and Local Start inputs are not effectual. The inputs to gate U 5 from these sources will be logic 0, making the output signal from gate U 5 logic 0.
- Gate U 6 receives signals from the outputs of gates U 5 and U 8, and because only the signal from gate U 8 is logic 1, this will be reflected in the output from gate U 6. This output is applied as one input to gate U 9.
- From this point onward the system operates as described in the Automatic Operation mode items 8 through 10, and Automatic Operation—Manual Stop, items 1 and 2.

First and Intermediate Conveyor Belt Control—Relay Ladder Circuit

As will be seen in the relay ladder circuit of Figure 2.9, the conveyor belt control circuit and the speed switch should have two contacts. One of these contacts is used to start the drive motor when the preceding belt has attained the correct operating speed, and the other is inserted in the power supply *hold on path* for the drive motor. This second contact in the hold on path is provided as a way to stop the system, should there be a mechanical break of the belt. The result of the belt breakage will be to stop all downstream belt systems running, but to allow the upstream systems to continue operation in order to carry away the material already deposited on the belt. If required, a motor over current contact can be inserted in series with the contact 2/2 of the speed switch. This will stop the system in the event of a motor overload, and with the same results as described earlier on the material being carried. We have also shown an interlock that will stop the system in the event the motor winding temperature rises beyond an acceptable limit. This interlock is a possibility on any motor control circuit that requires it. In this regard, it should be noted that thermocouples are inserted in the motor windings during manufacture and the cold junctions are brought out to suitable connectors to which read-out instrumentation and trip amplifiers can be added. The number of thermocouples involved will have to be determined by the manufacturers of the motor, but the instrumentation is the responsibility of the owner and the control system engineer. For the circuit shown, the winding temperature interlock is a normally closed contact that opens on abnormal conditions.

Circuit Functional Description—First and Intermediate Belt in the Series with Binary Logic

Figure 2.10 shows the binary logic control system involved in controlling the first or any intermediate belt in a conveyor system; comparing this figure with that shown in Figure 2.6, we see only one additional necessary gate, U 19, which is operationally an AND function. For the purpose of simplicity for the remainder of the circuit, the gate numbering system has been maintained as shown in the preceding figure, except in the instance where additional logic for gate U 19 is involved. By taking this course of action most of the descriptions for the circuit operation given earlier are fully compatible with that shown in Figure 2.8. The exception is that gate U 19 receives inputs from the Auto switch and upstream belt speed, both of which must be at a logic 1 level before the gate output has its effect on the operational logic. By doing this, the conveyor belt will not start until the downstream belt is fully running at the operational speed, thus ensuring that any material placed on the belt will be carried away and avoid any buildup occurring. In the case of the first belt in the series, the belt speed trigger to another belt need not be used; it would, however, be required to initiate the logic only.

Connecting the Control Circuit to the Drive Motor

For completeness Figure 2.11 is presented to show how the motor control circuit is connected to a drive motor power circuit.

The following points are worth noting:

- This circuit, in line with that given previously, is also a theoretical one.
- The initiating contact is the same *normally open* one shown as the contact of relay RL 1/2 on all the preceding control circuits.
- The circuit is drawn for a pump; hence, a *flow switch* is shown. Depending on the circumstances, however, the parameter pressure could be used as an alternative, in which case a *pressure switch* must be used instead. The same circuit can be used for control of the belt drive, but in this instance a belt speed switch should replace the flow switch shown. When modern flow instruments such as vortex, magnetic, and Coriolis are used, it will be easiest to confirm flow through a pressure switch inserted in the process line, or to use a trip amplifier in the measurement signal line from the instrument itself. When the switch (flow, pressure, or belt speed) is actuated, confirmation that the command to start or stop has in fact been carried out is obtained. It is the only way to ensure positive proof of the instruction.
- Conventionally a three-phase supply is shown. If a single phase is used on site, the schematic can be modified accordingly to reflect this.

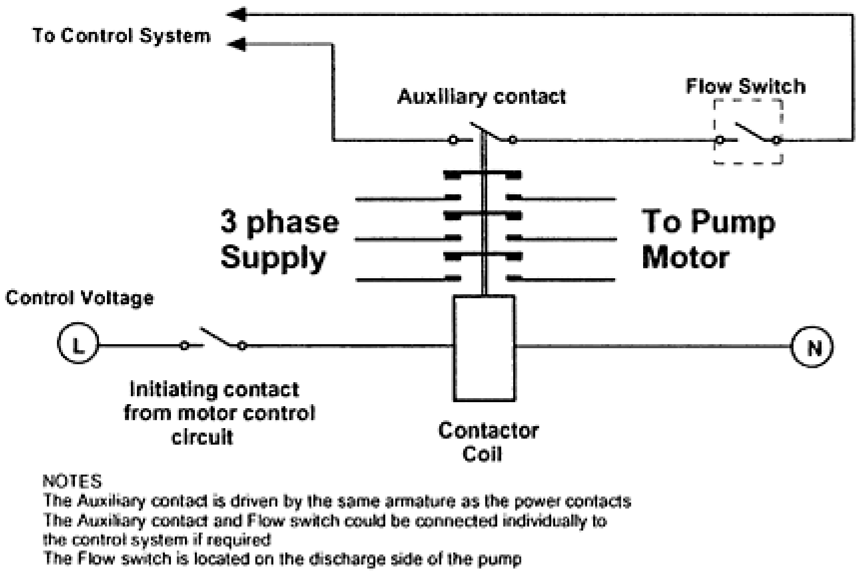


Figure 2.11: Typical three-phase motor drive circuit.

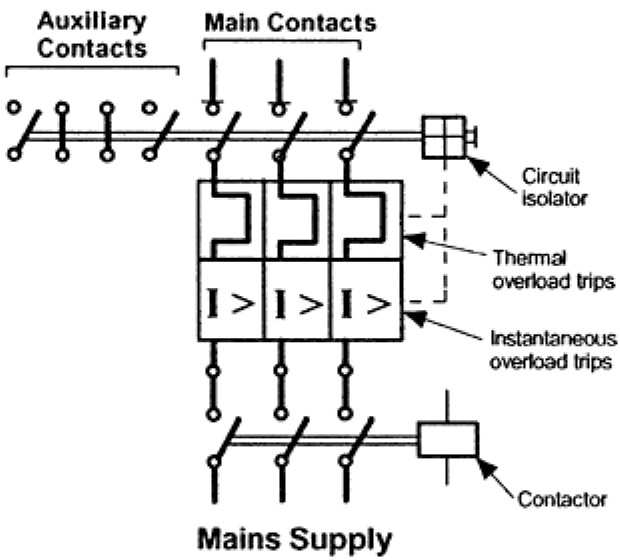


Figure 2.12: DIN 40713 SYMBOL Jan 1973.

• The auxiliary contacts on a contactor do not have as high a current rating as the main power contacts. These auxiliary contacts are not normally provided unless specifically specified to the contactor manufacturer. The number of auxiliary contacts that can be fitted to a single contactor unit varies from one maker to another. Thus, if more than one is required for a given application, this requirement must also be advised to the manufacturer.

- Other protective devices fitted to the contactor unit such as thermal overload cutouts that have not been included in the circuit diagram of Figure 2.11.

The Full Electrical Contactor Circuit

For purposes of comparison between the simplified versions of the contactor shown in the circuit diagram of Figure 2.11, the DIN (German Standard) symbol for a three-phase contactor with the additional features added is shown in Figure 2.12. It must be pointed out, however, that the symbol drawn for the DIN symbol is intentionally an earlier version. The current version of this symbol is identical, except that all the lines are of uniform thickness and all the circles presently shown in the diagram are removed. It has been said that this modification simplifies the drafting inasmuch as it involves less time to produce. However, with the current availability of computer-aided drafting, these symbols can be stored in memory and invoked when required, reducing the time immeasurably. Therefore, the choice of which symbol (old or new) to use is left with the design engineer.

Conveyor Belt Configuration and Material Weighing

In conveyor belt systems that are involved with the transport of wood chips and similar material, the belts, though flat and in a continuous loop, are forced to take up the shape of a trough so that the particulate material does not fall off. The required shape is achieved by having the idler rollers in the system made as a multiple set of freely rotating rollers arranged in such a manner that the end rollers are at an angle to the middle, thus making the normally flat belt lying on it form a trough. The instantaneous weight of material passing on the belt can be determined while the belt is moving. This is achieved by having a specially designed framework complete with idler rollers and a set of load-cells fitted to the belt support framework. The author has designed a single load-cell and idler roller conveyor belt weighing system for which his then employers took out a patent. This single load-cell design increased system stability, eliminated many of the difficulties encountered with multiple load-cell devices, and made calibration a very simple operation.

Note: For ease of recognition, each loop in the succeeding figures from this juncture showing the control systems that regulate the process have been assigned a simple serial number. This technique of sequential numbering broadly follows that used in industry. However, in practice the tag numbers assigned have much more process plant location information attached to them. The assigned numbers in the figures, though shown only once due to space limitation, are applicable to all associated components of the control loop; normally, the number is repeated at each component shown.

Control of the Chip Silo

In the process diagram of Figure 2.4 the *chip silo* shown is the one that is used to keep the digester continually operational on a daily basis. There are usually others that form part of the mill overall chip storage facility. Because wood is a natural material, it is subject to deterioration, and prolonged storage is therefore disadvantageous. The level detector and transmitter LT-1 fitted to the chip silo in the figure must be suitable for measuring solids; therefore, ultrasonic, weight, and light-based sensors (photo-cells) are possibilities to be considered for use in this application. The actual sensors used will depend on the prevailing conditions and the financial resource available. High- and low-level trip amplifier alarms LAH-1 and LAL-1, respectively, which operate on the output signal from the transmitter fitted to level sensor LT-1, as shown. These alarms provide the necessary input triggers for the logic involved with refilling the chip silo. Because several mill storage silos could be involved, it may be necessary to provide logic for the replenishing the main mill storage silos to meet the requirements of optimum storage periods. These storage silos will therefore require a level detector/transmitter and level alarms to be fitted to each silo. Because the numbers and sequence of use in practice are so variable and depend on the site requirements, the design of the logic for the rotational use of the mill storage silos to replenish the chip silo have not been shown. However, the logic involved with replenishing the duty chip silo based on the rotational use of the mill storage silos should pose no real difficult problems to define or implement. The procedural requirements must be discussed with the mill management, and their views must be taken into consideration prior to embarking on the system design or formulating any of the procedures that will be used in the plant.

The quantity of wood chips removed from the chip silo depends on how fast its screw extractor is operating. To control the amount removed from the silo, it is necessary to determine the rotational speed of the extractor drive motor and to have the means of regulating it. Motor speed is quite often measured by fitting a sensor called a tacho-generator to the motor shaft via a gearbox, or optically via an encoder, light source, and sensor. The speed sensor/transmitter is shown as ST-1. With the first method mentioned above, the tacho-generator is connected to the motor through a speed reduction transmission, and suitable circuits provide an output voltage or frequency within a calibrated range, proportional to the rotational speed of the motor.

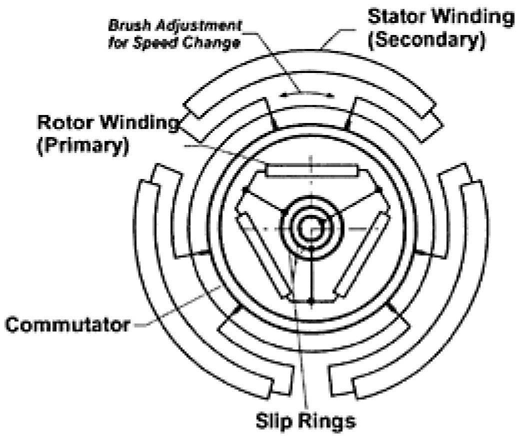


Figure 2.13: Schematic of speed control of a three-phase induction motor.

Because of the normal dirty and dusty conditions that are encountered in this part of the process and the method of measurement employed, optical instrumentation like a stroboscope and encoders are usually considered unsuitable. If this type of instrumentation were used, the results would be too unpredictable for continuous long-term operation. The mill is normally responsible for providing the drive motor together with the means of speed regulation. However, the controls have to interface, operate, and control these correctly; full details of the requirements will therefore have to be determined to ensure correct system performance. One should be aware that the only fully variable-speed three-phase motors are of the commutator type. One of the older designs of this motor as schematically illustrated in Figure 2.13 has the rotor (primary) winding normally situated on the rotor and fed by slip rings, and a second winding located on the rotor connected to the commutator in a similar way to a dc motor. In addition, there are brushes that connect, through the commutator, the stator (secondary) winding to the second winding on the rotor. Since the motor is powered through a three-phase supply, three pairs of brushes are required, on both the commutator and the slip rings. Moving each pair of brushes on the commutator relative to each other using suitable worm gear gives a range of speeds on either side of the synchronous speed of the motor. Other means of controlling speed for both ac and dc motors will be discussed later in this book. The positioning of the worm drive is determined by the output of the speed controller shown as SIC-1 acting through an appropriate signal converter shown as SY-1 interfaced to the screw extractor in the figure. Manual positioning of the worm drive can also be effected if required. The set point of the speed controller SIC-1 is derived from a signal unit named “lead” and shown as SX-1 in the figure. This has the effect of advancing (in time) the set point signal to take care of the time delay between the time of entry of the chips, including the washing process, and the measured level via level sensor/transmitter LT-2 in the *chip hopper*.

Control of the Chip Washer

The *chip washer* is an important piece of the process equipment; it is here that most of the very destructive grit that inevitably gets entrained during the preparation of the chips is removed. The controls involved in this part of the process are mainly manual and hence are operator actuated. Because belt conveyors are used, the separate discussion of their requirements already given in this chapter is applicable.

Control of the Chip Hopper

To decide on the type of level measuring instrument to be used, the following factors must be taken into account:

- The measured product is a solid.
- The product is wet, having been through a wash cycle just upstream of the hopper.
- Some entrained pockets of steam may be present in the product. This is the steam that

had been bled back into the hopper from the *steaming vessel*.

These considerations would suggest that a level measurement could be provided by any one of the following instruments: microwave detector, capacitance probe, radiometric detectors, and load-cells.

The level sensor/transmitter LT-2 fitted to the chip hopper senses the material level to provide a measure of how much material is available at any time. To maintain a constant level in the chip hopper, a level controller LIC-2, which receives its measurement signal from the level sensor/transmitter LT-2, is arranged so that its controlled output is cascaded as the set point onto the chip silo feeder speed controller SIC-1, which regulates the chip supply rate. However, as stated earlier, a delay occurs between the time the measured level change is observed and the chip supply being altered to suit. To counteract the effect of this delay, the lead module SX-1 advances the set point signal. This makes it appear as if the required change were immediate. The amount of *lead time* necessary will have to be finally determined at the site, but for testing purposes an approximate time can be set on this unit. It is suggested that the chip hopper level controller LIC-2 be a two-term (P+I) unit with *reset feedback* capability. The reset feedback signal for LIC-2 is obtained from the chip silo speed controller SIC-1 and is necessary to allow for instances when the operator decides to place the speed controller SIC-1 into manual mode. Including this reset feedback signal will prevent the chip hopper level controller LIC-2 from saturating when the chip silo speed controller SIC-1 is being manipulated manually. This saturation effect, its implications and correction are fully discussed in Chapter 1.

There is normally a continuous and uniform flow of chips from the chip hopper to the *chip meter*. If at any time the chip flow is not uniform, the likelihood of a blockage is the most likely cause. A mechanical vibrator is fitted to the hopper and is initiated on these occasions to ensure that flow continues at a uniform rate. The chip meter is a specially designed rotating wheel with pockets that deliver a specific volume of chips per revolution. A speed controller acting on the variable-speed drive motor that powers the chip meter regulates the speed of rotation. The motor speed is measured by the chip meter sensor/transmitter ST-2, and the manner in which the speed regulation is performed is the same as described earlier. The speed controller SIC-2 is a two-term (P+I) unit having a manual set point adjustment only. The volume, and hence the weight of chips flowing to the digester for any given time are calculated from the speed of the chip meter. For this calculation, the density of the wood chip is required; the value used is the density of the logs of wood from which the chips had been obtained.

The Low-Pressure Feeder

Having passed through the chip meter, the chips are then fed to the *low-pressure* (LP) *feeder*. This is specially designed equipment that consists of a rotating plug with pockets fitted with very effective pressure seals. The purpose of the seals is to maintain the pressure within the steaming vessel, which operates at about 15 lb/in^{2}g (103.4 kPa), while the chip meter and hopper operate at ambient pressure. A pipe connected between the LP feeder and the chip hopper relieves the pressure of 15 lb/in^{2}g (103.4 kPa) in the emptied plug pocket before a fresh quantity of chips is picked up from the chip meter. The design of the feeder is such that, while one of its pockets is being emptied, another is being filled. The LP feeder discharges into the steaming vessel.

Control of the Steaming Vessel

The steaming vessel is a horizontal cylinder fitted with an internally mounted screw feeder that moves the chips from the inlet to the outlet, which is located at the opposite end of the cylinder. The vessel is provided with steam and operates at about 15 lb/in^{2}g (103.4 kPa) and a temperature of about 250°F (121°C). This part of the process ensures that the moisture content of the chips is uniform. Subjecting the contents of the vessel to a temperature rise by the hot steam forces out from the chips the gases and entrained air, which are relieved into the chip hopper, thus making them more easily susceptible to impregnation by the pulping liquor to which they will be subjected further along the process. The flow of the gases and air to the chip hopper is measured by a flow transmitter FT-1 and controlled by a two-term (P+I) controller FIC-1. The controller FIC-1 is provided with a computed set point, which is the average of the conditioned and scaled values of the chip meter speed related to the delivered volume per revolution, the white liquor flow, and the digester scraper speed related to the volume it removes per revolution. (Note: For simplicity and clarity, the scaled values of white liquor flow and digester scraper speed with both signals carrying the note “To Ave. calc. on LP Feeder” are obtained from units shown as FX-5 and SX-4, respectively, in Figure 2.15.) The required averaging computations are carried out in the averaging module FX-1 (also called “average”) shown in the figure. The output from FIC-1 regulates a control valve in the line to the chip hopper through the transducer I/P. Low-pressure (LP) steam to the vessel is a combination of that obtained from the first-stage flash tank and fresh LP steam. A pressure transmitter PT-1 senses the pressure within the steaming vessel and provides the measurement signal for the pressure controller PIC-l fitted with a manual-only set point. Its controlled output, acting through a transducer I/P on a suitable control valve, regulates the amount of fresh LP steam admitted, maintaining the pressure within the steaming vessel to the manually set desired value on the controller PIC-1. A flow recorder FR-2 receives a measurement signal from the flow transmitter FT-2 inserted in the LP steam line and records the amount of steam supplied to the steaming vessel. These data are used for statistical and efficiency calculations that are carried out elsewhere.

Control of the Chip Chute and Level Tank

The Chip Chute

From the discharge outlet of the steaming vessel, the chips fall under gravity down the cylindrical *chip chute* mounted vertically and directly above the *high-pressure* (HP) *feeder*. The chip chute is piped to form a closed loop with the *level tank*, which acts as a storage header tank for the chemical pulping formulation for the chip chute. This arrangement permits a pool of pulping chemicals to be formed in the chip chute. The level of this chemical pool in the chip chute is measured by the level sensor/transmitter LT-3, which provides a measurement for the level controller LIC-3 whose output regulates through a transducer I/P a control valve placed in the line from the level tank to the chip chute. The chip chute level is maintained constant at the manually set desired value on LIC-3, which regulates the amount of chemical drawn in from the *Top Separator* through the process line labeled To HP Feeder shown in Figure 2.15. There is a top connection from the chip chute to the level tank, and because of this closed-loop arrangement, any excess process chemical from the chip chute automatically drains back to the level tank through this top connection. The first encounter between the preconditioned raw wood chips and pulping chemicals occurs within the chip chute. Although the chip chute and the level tank are connected, the wood chips are prevented from entering the level tank by a screen fitted in the chute beneath its upper connection.

The Level Tank

The amount of chemical in the level tank is measured by the level sensor/ transmitter LT-4, which provides a measurement for the level controller LIC-4 whose output regulates through a transducer I/P a control valve placed in the line from the level tank to the top separator, which is located at the top of the digester itself. (See Figure 2.15 for actual position.) The chemical pool in the chip chute initiates and facilitates the absorption of chemical by the wood chips. The pulping chemicals contained in and supplied to the level tank are in general mainly a combination of white liquor and sodium hydroxide (NaOH). The exact formulation of chemicals is most often a trade secret developed by the mill, and is prepared at another location and supplied as a mixture; it, too, has a control system most often based on ratio control that is relatively simple, but because of the commercial sensitivity is not shown for the present discussion. The level within the level tank itself, which acts as a header tank, is maintained by controlling the amount of white liquor admitted to it. The level within the level tank is the measurement of a controller that regulates the amount of NaOH admitted to the top separator.

The High Pressure Feeder

From the steaming vessel, the chips are sucked into the HP feeder as shown in Figure 2.4. This feeder is a rotating plug type, the plug having four through-holes or pockets spaced in such a way that, while one is being filled from the chip chute, another is discharging chips into the line carrying it to the top separator. To get a clearer idea of how the HP feeder works, we will consider a single pocket and describe what happens. As stated above, the pockets on the feeder are through-holes in the plug, with the bottom of the feeder housing carrying a screen. When a pocket on the feeder lines up with the discharge on the steaming vessel, the chips and liquor are sucked into the pocket under the action of the chip chute pump and the pocket fills. Because of the screen, only the liquor passes to the suction of the pump, which returns it to the top of the chip chute. The pocket rotates 90° clockwise where it is aligned with the connection of the returned liquor line pumped from the digester top. The returning liquor flushes the chips from the pocket and carries it away to the top separator on the digester. There must be a constant flow of liquor between the feeder plug and the housing, which is vital to the operation of the feeder as it lubricates and carries away any remnant sand and grit. The liquor is recovered, but the rest is discarded. The process operator manually adjusts the rotational speed of the feeder via a combined manual loading station HIC-3 and speed indicator SI-3; this instrument shows the manually adjusted speed output value applied to the drive motor.

DIGESTER CONTROL

THE TOP SEPARATOR

Having started the preconditioning of the raw wood chips and having sent them on to the top separator, we shall continue the application and direct our attention to the operation and control of the digester itself. Figure 2.14 is an enlarged view of the top separator part of the digester that is initially involved.

As will be seen, the separator being external to and at the top of the digester causes chip processing to take place in two phases. Since the separator is inclined, it is possible to have the excess liquid contained with the chips drain off easily and feed only the chips to the digester itself. However, since steam is being supplied at this point (HP steam to the top of separator), the initial cooking cycle of the pulping process commences here. What has been shown as the impregnation zone in the diagram is not totally correct, for at this point the chips are also undergoing cooking.

The level transmitter LT-4, which is a differential pressure cell that takes the difference between the liquid head and vapor pressure in the separator, displays it as a measure of the liquid level in the separator, on the indicator LI-4. Adjusting the liquor flow and padding air, which is always kept to the very minimum since its effect on the digestion process is problematic, can change pressure in the separator and the chemical level in the separator. The amount of chemical admitted is adjusted automatically, via the control valve located in the NaOH line, dependent on the level in the level tank under the direction of its associated controller LIC-4 shown in Figure 2.4.

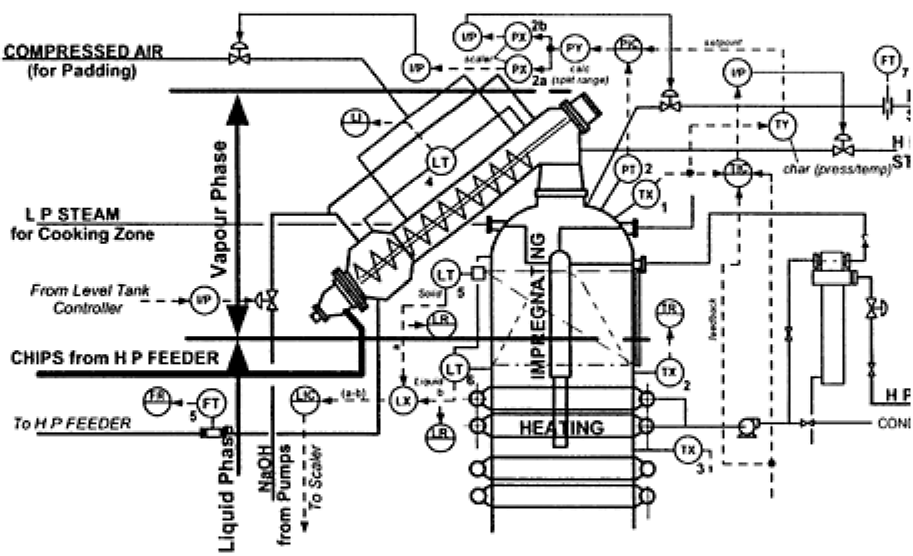


Figure 2.14: Top separator on digester.

The impregnation/cooking conditions in the upper portion of the digester should be held constant to allow uniform chip quality to be obtained. To achieve this objective both the pressure and the temperature are measured via the pressure transmitter PT-2 and the temperature sensor transmitter TX-1, respectively. These two signals are applied, respectively, as measurements to the pressure controller PIC-2 and the characterizing module TY-1. Since the temperature is dependent on the pressure, the temperature measurement is characterized in the module TY-1 to reflect this relationship. The modified temperature measurement signal is then applied as the set point to the pressure controller PIC-2 and maintains the relationship of the parameters. In this way, no matter how the temperature is altered, the pressure will follow appropriately. The output of pressure controller PIC-2 is split and used to adjust both the padding air and HP steam to the digester after separate scaling in the two modules PX-2a and PX-2b. One of the modules adjusts the padding air, and the other the HP steam admitted to the separator. The output from PIC-2 is scaled in order to

- Use that portion of the controlled output to give the maximum effect and prohibit wide fluctuation in the air pressure applied.
- Use the full signal range to drive the I/P signal converters and associated control valves.

This method of using two scaling modules and two signal converters allows each control valve to operate over its full signal range and is called *split ranging*.

The amount of HP steam used in the top separator shown in Figure 2.15 is carried out by the flow loop formed by the transmitter FT-7, flow recorder FR-7, and flow integrator FQ-7.

It can now be seen that a lot of process parameter interaction takes place in this top section of the digester. It is vital therefore to make very careful observations of the actual process conditions and to fine-tune the system accordingly for maximum response during commissioning.

It should be noted that although we are presently concerned with a vertical digester, this is not always a vertical item of equipment; other examples are the horizontal, rotary, and inclined types. When we consider controlling the digester, inevitably logical sequential operation in the control system philosophy is absolutely necessary to overcome some of the very likely *hangs* that occur when the pulping process is operating. A hang is a phenomenon that usually occurs within a vertically configured and operating digester, in which the chips that are continuously on the move and being processed all the while during their through passage suddenly stop moving. The direction of movement is downward in the case of a vertical digester and occurs as the result of gravity, combined with the action of the bottom scraper as it removes the processed chips from the digester into the *blow unit*. If the stoppage were allowed to remain unattended, the result would be the progressive formation of a plug of dewatered chips as the processing liquid freely drains away from the still somewhat solid wood chips. The plug thus formed would be subjected to increasing compressive forces exerted by the oncoming wood chips. These chips would continue to force the plug to compact even further, making it more difficult to break up. The final result, as the internal pressure increases, would possibly be an explosion of the digester itself. The reasons for the hangs, which beg explanation, are still the subject of theories. Wood chip hangs appear to be much like those that take place in a steel-making blast furnace where, discounting the temperatures and the fact that only a single furnace charge is involved, a very similar and also inexplicable condition occurs. In the steelmaking industry the phenomenon is termed *bridging*. The main

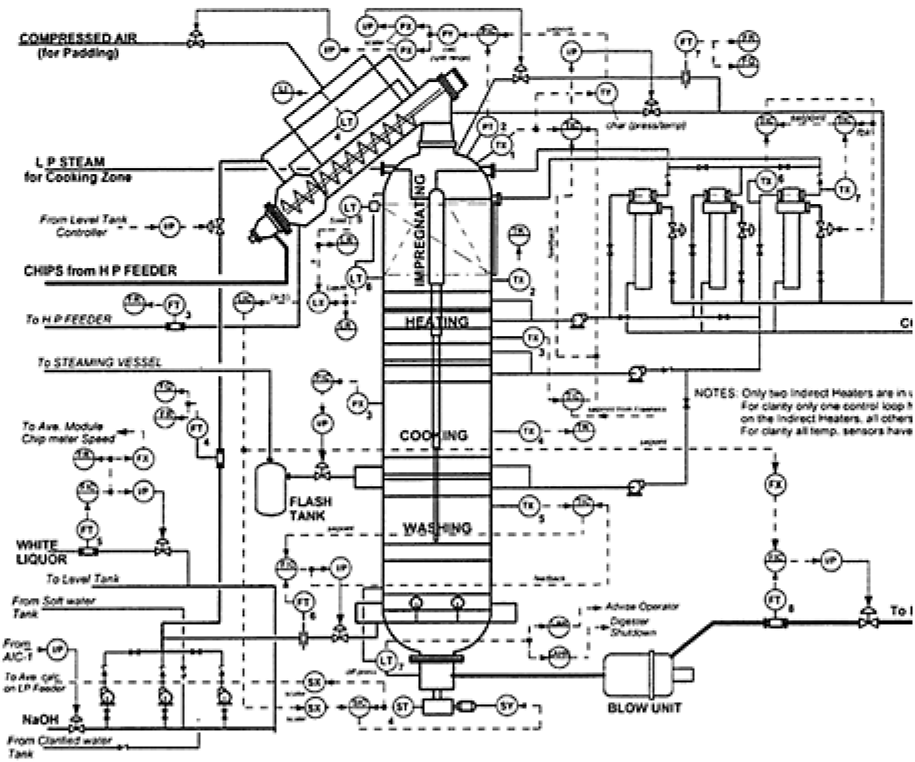


Figure 2.15: Continuous digester control system.

requirement in both the steel and paper pulping industries is to recognize the signs signaling the approach of its occurrence and to be able to implement measures that will forestall it. It is necessary in the pulp digester to invoke an *operational sequence*, which is a software routine, as soon as an approaching hang has been signaled. Under these potentially dangerous conditions, it is quite normal to:

- Immediately initiate this operational sequence. The sequence routine is one that has to be designed to replicate the evasive actions taken by an experienced human operator under similar circumstances. These operator actions most often involve admitting additional HP steam and NaOH process liquid to the top of the digester, in quantities that depend on the severity of the problem encountered at the time.
- Transfer the digester operation from automatic to manual control and supervision,

while additional provision for the process operator to apply overriding manual control of the operational sequence itself must also be available. This is necessary in order to ensure that personnel and plant safety is not compromised.

- Allow the process operator to monitor the situation continuously and transfer the digester back to automatic control as soon as stability has been achieved and maintained for a predetermined period of time. The actual time duration for the process to remain under operator supervision is the result of operating experience gained with the particular digester.

In view of the complexities of the operator action procedure that is to be undertaken under digester hang conditions, it is not possible to show this in either Figure 2.14 or Figure 2.15. The software requirements of the operational sequence involved will demand that all the danger signals given by the process are taken into account. This must be fully discussed in very minute detail with the experienced digester operators at the paper mill for which the system is being designed.

As a guide to some requirements of the operational sequence design, an incipient hang can be detected from considering the main pointers involved, some of which are as follows:

- The change in motor current of the bottom scraper
- Rapid fall of liquid level in the digester
- Rapid change in the top and bottom temperatures of the digester
- Rapid change in chip level in the digester.

This list, though only partial, should provide a good starting point for the design. In addition, process operator experience is invaluable in drawing up the design specification of the operating sequence for the individual digester. It has been found that every single one of this type of process plant equipment has unique characteristics, which will demand a specific solution.

THE CONTROL OF THE DIGESTER

We shall now consider the control involved with the rest of the digester. Figure 2.15 shows the continuation of the raw material-handling process discussed earlier and follows from it. Since the chips fed to the digester contain very little, if any, liquid, the digester may be operated at any selected liquor to wood ratio to give the required pulp. A high level of pulping liquor in the upper part of the digester allows good heat retention and will improve pulping quality. This type of digester has further advantages in that it is much simpler to operate than the hydraulic type, and it is also possible to use a poorer quality of wood chip.

Chip/Liquor Level Control

It could appear as unnecessary, or perhaps a contradiction, to supply liquor-free chips from the top separator and then immerse them once more in pulping liquid. The answer to this apparent conflict is the deliberate intention of starting the process from a known and therefore fixed base of a (virtually) liquor-free chip, which will then permit a selectable amount of pulping liquor to be added to give the desired results. To obtain consistent pulp quality for the type of paper being produced, it is vital that the liquor/chip levels be held in a fixed relation to each other. The easiest way to achieve this relation is to ensure that the height of the chips above the liquid be held constant. The method employed is to separately measure the height of the chips and the level of the liquid. (Refer to Figure 2.16 for clarity.) A radiometric level-gauge LT-5 determines the solids level, and a differential pressure cell LT-6 determines the liquid level. The position of the lower connection on the differential instrument is known because the level of liquor required is part of the digester design. The height of the chips above this will depend on the pulp quality required and is therefore based on the accumulated experience gained in operating the process. Obviously, operating limits, which form the basis of the measuring range of the radiometric level gauge, will be established.

Figure 2.16, an enlarged view of the upper part of the digester, shows the method used to determine the height of the chips above the liquid in the digester. This comprises subtracting the height of the liquor (dimension b in the figure) from the height of the chip stack (dimension a in the figure) in the subtractor module LX5/6, and making the result of this computation the measurement parameter of the two-term level controller LIC-5/6. Since the digester scraper speed and the pulp flow from the blow unit are the major influences on the liquor level, the output from the level controller LIC-5/6 is made the set point of the digester scraper speed controller SIC-4 and the pulp flow controller FIC-8, both of which are shown in Figure 2.15, which gives the full digester controls. However, this output has to be conditioned and scaled independently in modules SX-4 and FX-8 prior to it being applied to the associated controllers of each loop. In this way it will reflect the liquor level in terms of the scraper speed and volume, respectively. Here we have the situation of

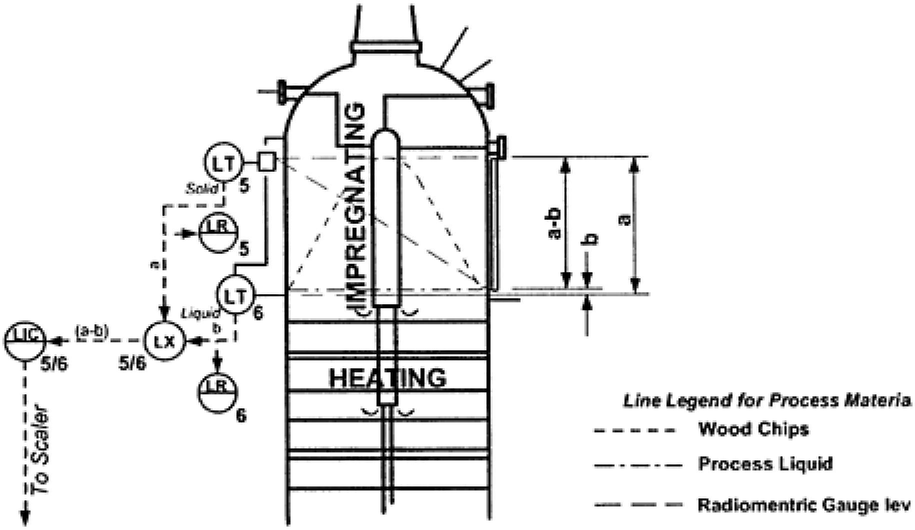


Figure 2.16: Chip level control loop.

a cascade loop where the output from the primary controller is being applied as the set point to two secondary controllers, which begs the question, how do we avoid integral saturation in the primary controller? The solution has deliberately not been shown at this stage in Figure 2.5 but will be given later in this section. As far as the level measurement for the loops is concerned, an important requirement is that the datum for both the chip (dimension a in the figure) and liquor (dimension b in the figure) level must be the same. Otherwise there will always be a disparity between the relationships of the two measurements. Should such an unwanted situation arise, the solution could lie in initially specifying a range elevation/suppression attachment to be fitted to each transmitter. In electronic instruments, this is normally carried out electronically on the output signal from the transmitter, as opposed to the mechanical adjustment that operates on the measurement made by any pneumatic instrument.

Digester Temperature Control

Reverting once more to Figure 2.15, we see that the temperature in the heating zone of the digester is affected by the steam applied at the top of the unit and by the temperature of the liquor applied to the heating coils. We shall consider each of these in turn, first the HP steam applied at the top. The measurement is obtained from the temperature sensor/transmitter TX-1 and is applied to the temperature controller TIC-1 whose set point is generated by another temperature controller TIC-3 to form a cascade loop. This cascade loop regulates the amount of heating applied to the top zone of the digester by the HP steam admitted. Saturation of the primary controller TIC-3 is avoided by assigning the reset feedback from the output of the secondary controller TIC-1, which is responsible for manipulating the HP steam control valve, back to the feedback input of TIC-3. Since the quality of the pulp depends on the type of fibers contained, the set point for the primary controller TIC-3 is derived from AX-2a, the characterized, and AX-2b, the advanced output signal from the pulp freeness controller AIC-2 shown in both Figures 2.19 and 2.21. The signal is labeled set point to Digester Temp. Note: This freeness control loop is described later in this chapter but is referred to here for completeness of the description of the digester controls. Since the arrangement of freeness controller AIC-2 providing the set point for temperature controller TIC-3 is also a cascade loop, the problem of integral term saturation will also arise. However, this situation is overcome in a relatively simple way, as shown when we discuss the freeness controls later in this chapter.

Digester Pressure Control

Digester pressure is also an important parameter, which is sensed by the pressure transmitter PT-3. It is applied as the measurement to a two-term pressure controller PIC-3, having a manually adjustable set point and its output regulates the control valve in the line to the *flash tank*.

Digester Liquor

Excess liquor from the top separator is returned to the HP feeder, the amount being measured by the flow transmitter FT-3 and recorded on the recorder FR-3. The amount of white liquor used is measured by the flow transmitter FT-5, recorded on the flow recorder FR-5, and controlled by a two-term controller FIC-5 through the signal converter I/P to a control valve placed downstream of FT-5. As mentioned earlier, the flow measurement is conditioned in module FX-5 and applied to the averaging module FX-1 (see Figure 2.4; the signal carries the label “Scaled Input

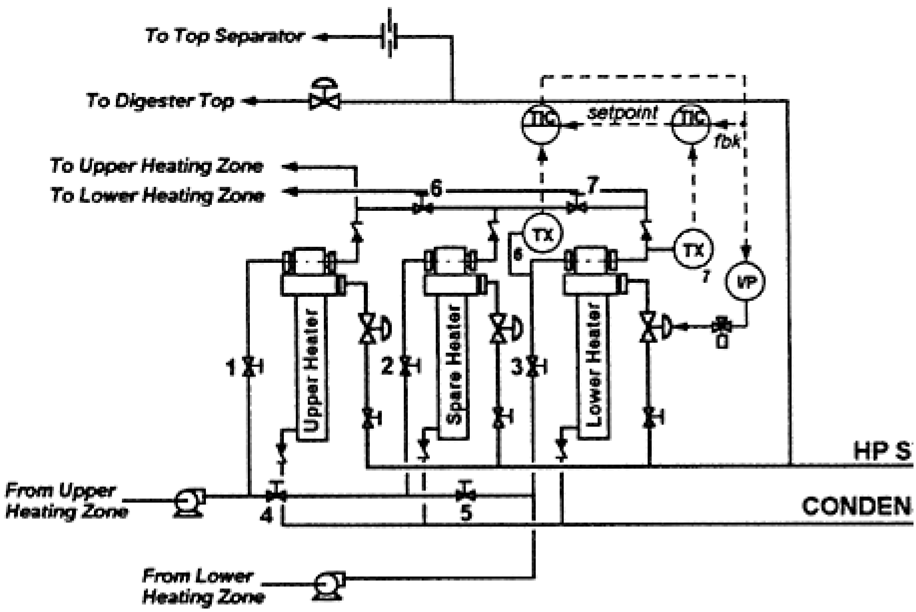


Figure 2.17: Indirect pulping chemical heaters.

from White Liquor Flow”). For performance and statistical purposes, the quantity of NaOH solution used is measured by flow transmitter FT-4, recorded on FR-4, and integrated on FQ-4.

Liguor Heating

Indirect heaters operate in pairs to provide heated pulping chemical formulation to the digester in order to add heat to the mass of wood chips undergoing processing. The cooking takes place lower down the digester at a rate determined by the amount of heat absorbed while in this zone. Any deficiencies in the heat requirement are made up in the cooking zone. Figure 2.17 is an enlargement of the liquor heaters shown in the main digester diagram of Figure 2.15 with some additional detail and valves included. For the purposes of this application, the heater selection is carried out manually, but there is no reason why the selection cannot be an automated routine. However, if the automatic selection method is chosen, additional costs will have to be considered, and mill management should be consulted on this aspect of the design. The circuit for the automated selection routine has not been shown, for this will depend on the actual mill requirements. Table 2.1 indicates how the valve selection is made for the system shown in Figure 2.17.

TABLE 2.1 Functional Operation of Heater Isolating Valve Selection

Isolating Valves							***Heaters***		
1	*2*	*3*	*4*	*5*	*6*	*7*	*Lower*	*Spare*	*Upper*
Open	Closed	Open	Open	Open	Closed	Closed	Operation		Operation
Closed	Open	Open	Open	Open	Open	Closed	Operation	Upper	
Open	Open	Closed	Open	Closed	Closed	Open		Lower	Operation

For clarity, the controls for only the lower heater involved are shown; the other heaters are controlled identically, with the important proviso that the controller of the unselected heater is placed in manual mode. This will hold the associated controller’s output either at its last value or made to stay at any predetermined position without fear of saturating the integral control term. If this latter stated option is chosen, a sequence of operation will have to be followed, which could be either software driven or an operator procedure will have to be designed to permit this to be accomplished. The control valve, which should “fail closed,” has a solenoid valve placed in the signal line to the diaphragm; this solenoid should be a three-way device that will permit the valve to fall back to its failure mode and should be initiated when the associated heater is not selected. Referring to Figure 2.17, we see that control of the heaters is carried out by two separate temperature control loops arranged in cascade. With this arrangement, the exit temperature is measured by the sensor/transmitter TX-7. It is applied as the measurement to temperature controller TIC-7, which is made the primary controller and will permit the process operator to determine the liquor temperature required for the type of chips being processed. The inlet temperature is measured by the sensor/transmitter TX-6 and is applied as the measurement to temperature controller TIC-6, which is the secondary and receives the controlled output of TIC-7 as its set point. This controller drives the control valve in the steam supply line. This cascade control arrangement gives very stable control and outlet temperature in the system. It may be advantageous to see how the heated liquor is directed to the various parts within the digester, and for this purpose Figure 2.18 is presented.

At this point, we should recall the problems of hangs occurring within the di-gester that were made under the heading Digester Control—The Top Separator in this section and we should direct the reader’s attention to the very real possibilities of this occurring. We remind the reader that operating and procedural sequences must be in place to deal with this occurrence. Moving down the digester, we shall consider the cooking zone in Figure 2.15. The chip temperature at this location is measured by the sensor/transmitter TX-5 and is applied as the measurement to a three-term (P+I+D) temperature controller TIC-5 whose output is applied as the set point of the NaOH Flow controller FIC-6 to regulate the amount of chemical being sparged (sprayed) into the digester. Controller FIC-6 receives its measurement from the flow transmitter FT-6 placed in the discharge line of the NaOH pumps. The added amount affects not only the liquid level at the bottom of the digester but also the quality of the chips being produced. A D/P cell LT-7 measures the liquid level, and its output is applied to two level alarms: a high-level alarm LAH-7 and a high/high-level alarm LAHH-7. Level alarm LAH-7 warns the process operator of a rising liquid level, but if the process operator should fail to remedy the situation, the next higher-level alarm LAHH-7 trips automatically and is used as the signal to shut down the digester. The procedures for safe shutdown are very important and can vary from plant to plant; for this reason they are not given here to avoid limiting the reader's own decisions. The safe shutdown of the digester must therefore be discussed in absolute detail with the mill management, and the appropriate procedures and (software) routines should be put in place.

DIGESTER BOTTOM SCRAPER

The rotational speed of the digester bottom scraper plays an important part in the quality of the chips produced and therefore in the control philosophy being discussed. The scraper speed is measured and regulated to a value determined by the

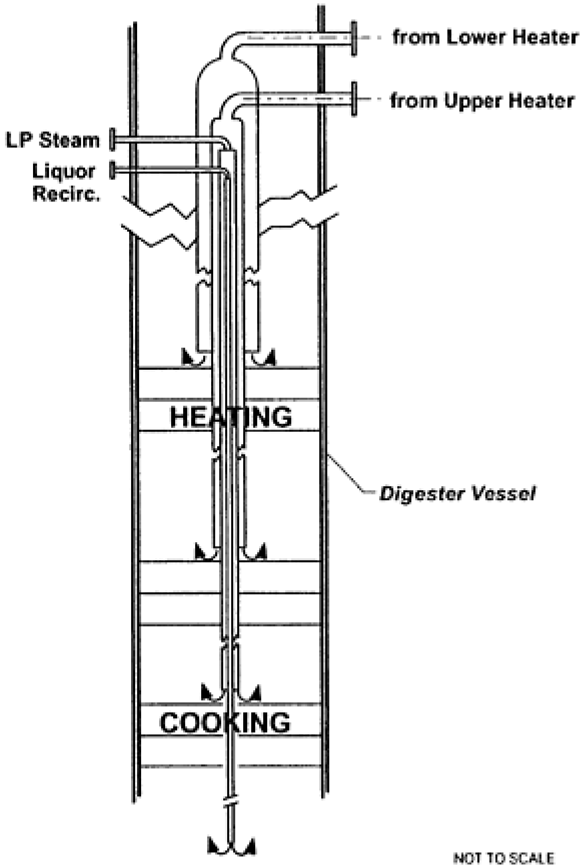


Figure 2.18: Schematic diagram of distribution pipe.

suitably scaled ratio of the chip/pulping chemical. The scraper speed also provides an input to the average computing module FX-1 shown in Figure 2.4 that supplies the set point of the controller regulating the flow of steam, which is bled from the steaming vessel.

PRIMARY PULP REFINING

The product output from the digester leaving the bottom scraper is not a mushy pulp, for it is more correctly still in a "fragile" but solid state. It is kept in this form almost throughout its time within the column which operates at a pressure of approximately 165 lb/in^2 (1138 kPa). Its form changes once the chips are introduced into the blow unit and thence the blow tank, both of which operate at atmospheric pressure. The sudden change of pressure causes the treated "fragile" chips to literally blow apart to form the required pulp. The newly formed pulp is then introduced to a process of washing and refining. The refining process can best be described as one that cuts the fibers into smaller lengths. The process from blow tank to the preliminary washed pulp is shown in Figure 2.19.

At the top of the blow tank is a cyclone separator whose purpose is to separate the stock from the liquor. The steam released during the separation is led away to

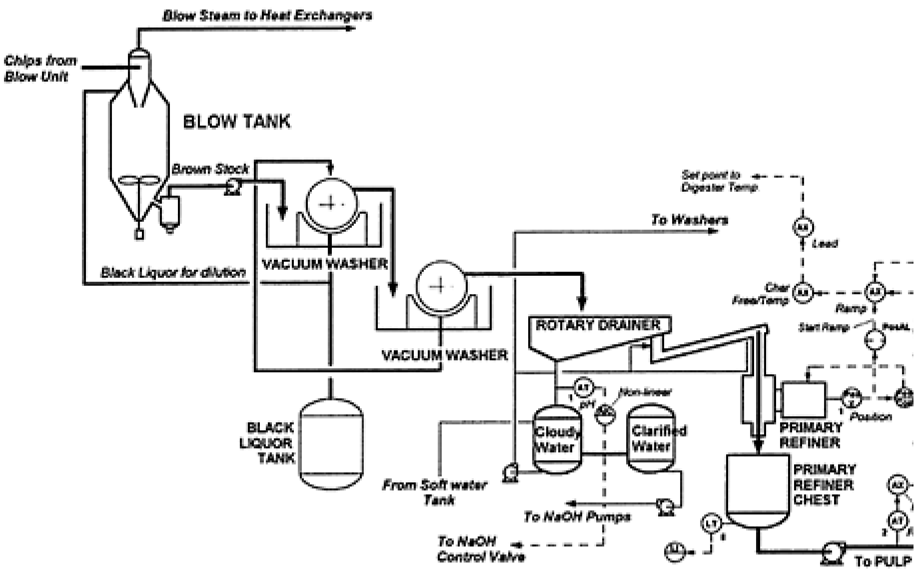


Figure 2.19: Blow tank and primary pulp refining.

heat exchangers, where it is used to heat water required for other processes in the paper mill. An agitator is located at the bottom of the blow tank, which mixes the very thick pulp with dilution liquor to produce a fluid. The fluid is first made to pass through a separator where any unwanted solid material that had escaped earlier detection is removed before the prepared stock called *brown stock* can be pumped away for washing to remove the excess chemicals it contains.

ROTARY VACUUM WASHER

Figure 2.20 shows the arrangement of a rotary vacuum washer and will be used to outline the washing operation, which is carried out in several stages owing to the number of sectors in the rotating drum. The surface of the drum is fabricated from a woven wire mesh fixed to a circular sectioned framework that is made to rotate slowly in a pool of pulp, which is fed directly from the blow tank. The pressure within the drum is reduced to produce a suction effect on the surface of the drum. Referring to the figure we see that the liquor and fibers in the pulp are sucked in and start to mat, thus beginning to form a sheet on sections a to f in response to the vacuum generated within the drum. The rotating drum carries the matted fibers on the mesh surface, and some of the excess liquor is drawn off in sectors g and h. Between sectors j and l, dilute black liquor (also called wash liquor) is sprayed onto the matted surfacel of the fiber, the liquor being drawn through the matted fiber under the action of the vacuum. The vacuum is increased between sectors m through o to draw more of the liquor through. This higher vacuum is required because the mat is more compacted at this stage. Sectors p and q have no vacuum applied, although sometimes air is admitted to these two sectors to make it easy for the sheet to come off the surface of the drum. A ribbed jockey roller or *doctor* scrapes the caked sheet off the drum and feeds it to a *repulper* where either black liquor or fresh water is added to make it a pulp once more and subject it to another wash cycle that is carried out in another similar washer.

For the remainder of this part it may be more convenient to refer to Figure 2.21 in which the detail is much clearer. The washed pulp is then fed to the *rotary drainer* where excess liquor is taken off. The liquor thus obtained is run off to the *cloudy water* tank, and after it is decanted some of it is led away to the *clarified water* tank.

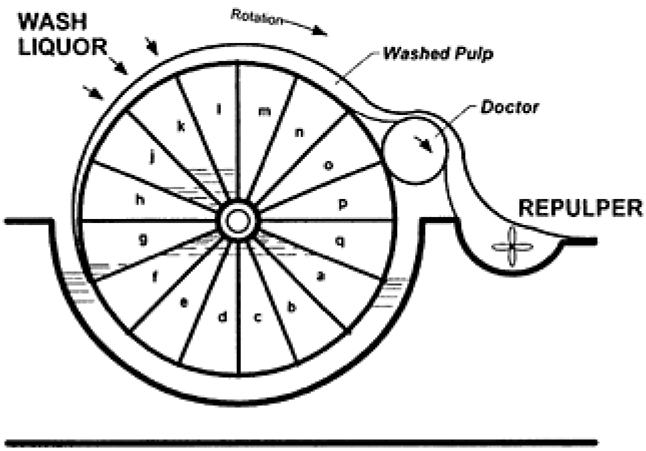


Figure 2.20: Schematic of a rotary vacuum washer.

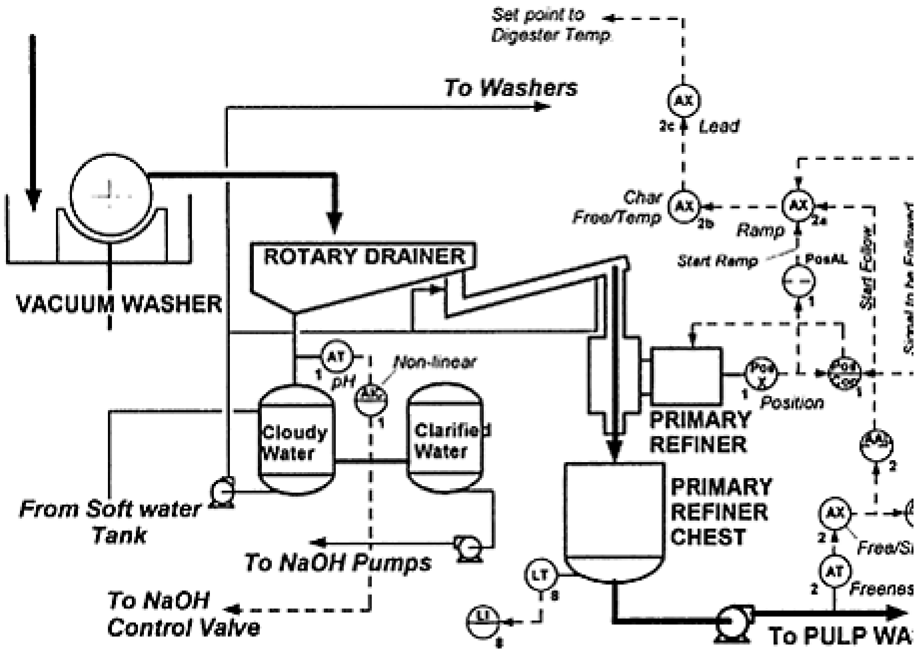


Figure 2.21: Enlarged view of primary pulp refining.

These two recovered byproducts are used to wash or thin the pulp. On its way to the cloudy water tank, a pH electrode system and transmitter AT-1 measure the pH of the liquid, and the signal is applied to a pH controller AIC-1. It is suggested that this is a three-term (P+I+D) controller, but more importantly the controller must have a nonlinear control characteristic to allow for the nonlinearity (logarithmic characteristic) of the measured parameter. The controller output is applied via a signal converter I/P to a control valve in the NaOH supply line to the pumps shown in Figure 2.15. The control valve must have a plug with an equal percentage characteristic and should be fitted with a valve positioner.

The pulp is passed from the rotary drainer to the first stage of refining. This is carried out in a machine called a *primary refiner*, which is a mechanical means of separating the fibers and dividing any fiber bundles that may exist in the pulp. Very simply described, the refiner consists essentially of a set of fixed and axially movable disks mounted on a single shaft; the disks carry serrations on the flat surfaces. There may be more than one set of disks on a refiner. Since the disks can be moved, the flat surfaces can be made to approach each other by any chosen amount. Refiner control consists in regulating the axial movement, resulting in separation of the disks to produce the quality of finished pulp required. Great care is necessary to avoid the exorbitantly expensive replacement cost of colliding rotating disks. The mechanical action involved generates friction between the rotating disks of the machine and the fibers and fiber bundles in the pulp. This process gives rise to a considerable amount of heat, which greatly aids the splitting of the chemically weakened fibrous bonds of the wood chips. It has been postulated that the actual process is carried out in three stages. The first stage involves the heating of the fiber bonds to a point at which they are ready to split. This idea has gained credence by the fact that increasing the temperature of the incoming pulp slurry increases the fibrous content of the material. The second stage is the actual disintegration of the fiber aggregates into individual fibers by the frictional forces generated as the fibrous mass is forced between the revolving disks of the machine from the center of the disk toward the peripheries by the centrifugal force of rotation. Complete fiber separation is not attainable in practice, nor is it desirable for some of the types of paper being manufactured. Greatest fiber separation is required for the bleaching process necessary to produce writing paper, for example. The third stage involves fibrillation, softening, and formation of mucilage-like colloid. In semichemical pulping, the amount produced in this last stage is dependent on the final product and can vary from small to large amounts.

The control scheme shown in Figure 2.21 consists of determining the freeness of the resulting pulp via analyzer transmitter AT-2, characterized in the freeness/shieve module AX-2, and applying the conditioned freeness measurement to a two-term or three-term controller AIC-2, whichever is required, dependent on the refiner capability. The position of the refiner disks is measured by a position sensor transmitter Pos X-1 and is applied to a position controller Pos Con-1, which is two-term, or three-term if required, dependent on the refiner capability, with time-proportioning controlled output. Note: Time-proportioning action is a pulsed output with a variable mark/space ratio that is applied to the disk positioning drive. It is discussed in detail in Chapter 3 dealing with the Fourdrinier paper machine under the heading The Time Proportioning Controller. Low-alarms PosAL-1 and AAL-2 are provided on the position and freeness measurements, respectively; these are used in conjunction with a ramp function generator AX-2a, which provides the action that will now be described. The freeness controlled output from AIC-2 is applied as the measurement input to the ramp module AX-2a. As long as the freeness is acceptable, the low-alarm AAL-2 associated with it instructs the ramp unit to provide an output of the same magnitude and phase as the freeness-controlled output from AIC-2 (i.e., the ramp output “follows” the measurement applied to it). If the refiner disk position comes too close, the alarm PosAL-1 associated with it is triggered and causes the ramp unit to cease following the freeness-controlled output from AIC-2 but to begin ramping up its output at a predetermined rate. The output from the ramp module AX 2a is passed to a signal characterizer AX-2b that is configured to reflect the chip feed/temperature relationship. The conditioned signal is then passed to a lead module AX-2c that imposes a lead time on the signal to compensate for the inevitable delay between the digester and refiner. This characterized and advanced signal from the ramp module provides the set point of the digester temperature controller TIC-3 (on Figure 2.15).

In view of the several modifications carried out to the output of the freeness controller AIC-2, it is suggested that the feedback to this controller be derived from its own unmodified controlled output, as this will minimize the amount of very complicated computations to be done should the feedback be derived from the output of the digester temperature controller TIC-3. With this arrangement, it is envisaged that whenever the operator puts the digester temperature controller TIC-3 into the Manual mode, the freeness controller AIC-2 will drive only to the value of its own output and so avoid winding itself up. The refined pulp is sent to the *primary refiner chest* and from there to more washers and refiners if required. For the purposes of this application, we have terminated the process at the output from the primary refiner chest. The process will continue, however, for the pulp will be processed further as it passes through more washers and refiners. It will have fillers, colors, and other components added to ensure that it meets the requirements of its intended use before it is charged into the machine chest as a stock ready for the headbox of the paper machine from which it will be discharged onto the wire as the first stage in developing a sheet of paper.

SUMMARY

1. There are two main methods, mechanical and chemical, by which the pulp for paper manufacture is made.
2. The mechanical process of pulp making is by far the more efficient in using virtually all of the wood fiber in the log, both cellulose and lignin. By contrast, the chemical process in fact dissolves the lignin, and as a result the output is approximately half that produced by the mechanical process.
3. The mechanical process, which is known as the groundwood process, involves forcing the wood logs against a fast-rotating grindstone that tears the fibers off; because of this action, the fiber length is not uniform. Groundwood is a mixture of fiber bundles, separate fillibrated fibers, broken fibers, and wood flour. The paper made from this material is soft, opaque, bulky, absorbent, and not strong; and it deteriorates with age. Groundwood pulp is not used directly as it comes off the grinding mill for the coarse fibers and the occasional shim—thin unground slivers of wood—has to be removed.
4. Since fibers are the basic material for paper, the following are the fiber lengths of some of the materials used: Cotton fiber, used for a very long time in paper making, is the basis of almost all rag papers; it has fiber lengths that vary between 12 and 33 mm (0.4724 and 1.2992 in); flax fiber lengths vary between 6 and 60 mm (0.2362 and 2.3622 in); jute, used mostly in Kraft paper, has a fiber length that is between 1.5 and 5.0 mm (0.0591 and 0.1968 in); cereal straws of wheat, barley, rice, oats, and especially those from wheat have fibers that vary between 0.7 and 3.1 mm (0.0276 and 0.1220 in) in length; bamboo has a fiber length that is between 1.5 and 4.4 mm (0.0591 and 0.1733).
5. The alkaline chemical process produces wood pulp described by Hugh Burgess as “boiling wood in caustic alkaline at high temperature.” The liquor used for pulping consists of sodium hydroxide, along with a quantity of sodium sulphide, the amounts used varying from mill to mill; the liquor also contains some sodium carbonate and small amounts of sodium sulphate and sodium sulphite.
6. Cellulose fibers can be obtained when wood is treated with solutions of bisulphite-sulphurous acid. This gave rise to the sulphite pulping process patented by Tilghman. The initial process, which used calcium as the base, suffered many difficulties and was modified later on when magnesium, ammonium, and sodium acid base systems were used instead. However, the intention was still to remove the lignin where present by the reaction with the reagent.

7. The Kraft process was discovered by chance at a Swedish paper mill where wrapping paper was manufactured, following an accident caused by a process operator when he inadvertently allowed the sulphate digester he was working on to blow up before the charge it contained was fully cooked. In this process, the partially cooked chips are put through the disk refiners (called Kollergangs in Sweden) and produce paper of much higher strength.
8. Semichemical and chemimechanical processes fall between the groundwood and chemical pulping processes. and essentially use heat plus mechanical and chemical energy to convert the wood to fibers. The conversion of the wood to pulp is of the order of 55 to 95 percent, and is generally conducted in two stages:

   - Treatment with mild chemicals, which reacts with the bonds that lock the fibers together, to degrade and thus loosen them.
   - Mechanical treatment to separate the loose fibers to make them suitable for paper manufacture.

   It has been found that, while undergoing chemical treatment not only fiber loosening, but also some fiber separation occurs during this stage.
9. A full chemical treatment of the wood chip, such as the alkaline and sulphate, removes almost all the lignin. The semichemical treatment causes the removal of lignin in amounts of decreasing order of magnitude as follows:

   Most——————Least
   - Acid-sulphite, neutral sulphite, Kraft, and soda.

   And the removal of hemicellulose fiber in amounts of decreasing order of magnitude as follows:

   Most——————Least
   - Soda, Kraft, neutral sulphite, and sulphite.

10. Lignin is the only aromatic polymer concentrated in the middle lamella where it functions mainly as cement and acts as a filler, thereby imparting rigidity to the wood tissue. It is the 20 to 30 percent residue after the celluloses; hemicelluoses; starches; sugars; amino acids; fats; waxes; proteins; resins; tannins; flavornoids; terpenes; coloring matter; or other extractives have been removed from the wood. Lignin is more complex than either cellulose or certain proteins and even rivals the complexity of any known naturally occurring polymer.
11. Hemicelluoses are any of several polysaccharides that are more complex than a sugar but less complex than a cellulose derived from plants, it is produced commercially from seeds and plant tissue.
12. Tannins are any of the various chemically different substances capable of promoting tanning.
13. Flavornoids are large groups of plant pigments, including anthocynanins, that are water-soluble pigments found in the sap of certain plants to give red, blue, or purple coloring to flowers, fruit, and autumn leaves.

14. Terpenes are any of the various unsaturated hydrocarbons found in essential oils and oleoresins of plants such as conifers, which are used in organic syntheses.
15. The exact structure of lignin has baffled chemists for a very long time, due mainly to three reasons:

- It is a polymer, which cannot be converted to a monomer in sufficient yield without radically altering its structure. (A monomer is a small-molecule chemical from which a polymer is made; it is, so to speak, the basic building block (unit molecule) from which a polymer chain is built.)
- The structural units (molecules) containing the lignin polymer are not identical in structure, nor are they linked together in the same manner.
- It is almost impossible to isolate lignin completely without causing structural alteration from associated wood components

16. The semichemical and chemimechanical are not entirely free from detractions, for there is also some attack to the cellulose fibers. It has been found that the soda semichemical process produces the heaviest attack on the cellulose fibers, and the Kraft process the least. The extractives dissolve much more easily in the alkaline than the neutral or acid reagents.
17. The Neutral Sulphite Semichemical (NSSC) process reaction with the lignin in the chip occurs by attacking the fibers mainly by sulphonation in the solid state of those sulphonable groups of the so-called A lignin-carbohydrate complex, followed by partial hydrolysis to soluble lignin sulphonate and carbohydrates. The prevailing conditions of neutral sulphite concentration and temperature within the digester will determine the amount of dissolution effected. The NSSC process also removes quite a lot of the hemicelluloses, for it neutralizes the acetyl and other wood acids fairly easily.
18. The dissolution of the lignin under acid conditions is the main reaction in the acid-sulphite and bisulphite semichemical processes. It is thought that the process is similar to that obtaining in the NSSC process. However, the removal of the hemicelluloses is less than that obtained in either the NSSC, soda, or Kraft processes.
19. In the soda and Kraft semichemical processes, the caustic soda in the liquid reacts with the lignin-carbohydrate complex to produce soluble sodium lignate, with hydrolysis making the carbohydrates soluble. This lignin reaction occurs only after the bulk of the caustic soda is expended in neutralizing the acetyl and methoxyl groups and in dissolving the hemicellulose. This explains why lignin removal is small in alkaline semichemical pulping.
20. In the cold-soda chemimechanical process, the caustic soda reacts with the acetyl and other acid groups even at room temperature, serving to weaken the fiber bonds and causing it to swell. The lignin is not dissolved under these conditions.
21. In the sulphite chemimechanical process, the neutral or acid sodium sulphite dissolves mainly the carbohydrates, and this, coupled with the high temperature at which it is operated, affects the fiber bonds by weakening them.
22. Freeness is a measure of the quantity of fibers held in suspension in the pulp. The oldest method of testing for pulp freeness is the blue glass test, in which a small measured sample of pulp is diluted in a large measured amount of water and the diluted specimen is poured on to a framed screen of dark blue glass that is then held against a

bright light. This allows the light-colored fibers to be easily seen against the dark blue background of the glass.

23. A hang is a phenomenon that occurs within an operating digester when the chips that are continuously moving downward in the case of a vertical digester suddenly stops moving. The reasons for their formation are not completely understood. The movement of the digester charge occurs as the result of the combined action of gravity and the bottom scraper as it removes the processed chips from digester to the blow unit. If left unattended, the final result could be an explosion of the digester itself as the internal pressure increases.
24. Some main pointers (but by no means an exhaustive listing) of an incipient hang can be obtained from:

- The bottom scraper motor current
- Rapid fall of the digester liquid level
- Rapid change in digester top and bottom temperatures
- Rapid change in chip level in the digester.

Formulating an appropriate design for dealing with the situation can only be done on an individual digester basis, and drawing on process operator experience is highly recommended as an invaluable tool in achieving a successful conclusion.

25. The product output from the digester as it leaves the bottom scraper is not a mushy pulp. It is more correctly still in a “fragile” but solid state and is kept in this form almost throughout its time within the digester column, which operates at a pressure of approximately 165 lb/in^2. Once the chips are introduced into the blow unit and the blow tank, which operate at atmospheric pressure, the physical form changes. The sudden change of pressure causes the treated fragile chips to literally blow apart to form the required pulp.
26. Long conveyor belt runs are usually broken down into a series of conveyor belt runs of shorter length. When these multiple belt systems are used, it will be appreciated that there will have to be a number of points along the route where the material is loaded onto and unloaded from each section of the conveyor belt involved in the delivery circuit in order to get the material from its initial loading point to its final destination.
27. The belt farthest from the initial point of material loading must be started first and then gradually worked backward from that unit up to the belt at the initial point of material loading. Belt speed is the trigger for the succeeding belt systems to be started.
28. Vee belts are manufactured as a continuous ring that have a trapezoidal cross section and run in a similar shaped groove in the pulleys, with the shortest of the parallel sides near the base of the grooves in the pulleys. The belts are designed not to lie at the bottom of the groove but at a position that allows a gap between the base of the groove and the bottom face of the belt.
29. Vee belts must never be forced into the pulley grooves; the drive centers should be moved closer together so that the belt(s) can be placed in the pulley grooves. Since vee

belts are made in standard sizes, more accurate results will be obtained by calculating the exact pulley center distances when using a selected belt.

30. The approximate length of the belt can be determined from:

$$l = 2l_{c\ to\ c} + \frac{D + d}{2} \times \pi$$

where *l* is the approximate outside length of the belt; $l_{c\ to\ c}$ is the center distances of the pulleys and *D* and *d* are the pulley diameters. Note that this formula is accurate where the ratio of *D:d* is 1:1. However, if this is not the case, then the formula can be modified to take care of this to give:

$$l = 2l_{c\ to\ c} + \frac{D + d}{2} \times \pi + (D + d)^2$$

From either of these two formulas it is not difficult to calculate the center-to center distance $l_{c\ to\ c}$ for the pulleys used.

CHAPTER 3
Paper Machine

THE PAPER MACHINE

In the previous chapter, we discussed the production of a pulp stock consisting of fibers, obtained mainly from wood, although other materials will also expose their fibers when subjected to appropriate treatment. The wood used can be divided into hard and soft varieties, but this division has never been specifically categorized and is mentioned now for completeness. In this section, we consider advancing the papermaking process a little further and discuss the methods used to convert the fibers into usable paper. As stated in Chapter 2, the paper manufacturing process today is confined mainly to the production of material in a continuous roll as opposed to the individual sheets that were the norm in earlier times. From our daily use of this product, we know that a variety of papers are produced today, each with particular characteristics and hence for specific use. For example, some are highly absorbent, others are translucent, and still others are greaseproof, or specifically appropriate to letter writing and are produced in a range of different colors and may even be perfumed. This very small listing of the very many different types manufactured should give a feel for the skills required in producing this huge choice. In view of the large selection available, we shall therefore have to limit our discussion to the manufacture of a basic type of paper and be aware that the variety made is the subject of variation and additions to the basic process, which in many instances involves the addition of other materials and changes in the production methods in order to impart the desired qualities to the product.

Paper making, an ancient art that goes back thousands of years, has produced many traditions over the centuries, especially in the language and names of items of equipment used. We will introduce this code that has been developed over time at the relevant point in the text. The reader must understand, however, that it is not possible to cover the whole range of the language or names of equipment in any text; the reader is therefore urged to absorb further background on the practices involved at every opportunity available.

THE WET END

The paper machine of greatest importance to our discussion is the *Fourdrinier*. This machine produces a continuous sheet of paper, which finally leaves the process as a huge and very heavy roll of paper. The weight of the finished roll of paper will depend on the thickness of the paper, its width, and the roll diameter.

Historically, the large variety of machines available today developed from only two basic systems within the last 150 years. The system from which the Fourdrinier stems had it origins in a machine originally devised in 1799 by L.Roberts, and this invention was further developed by Donkin, Didot, and Gamble. The present machines of this type owe their existence to two Englishmen, brothers Henry and Sealy Fourdrinier, who bought the patents in 1804 and further developed and enhanced the system. J.Dickinson devised the other basic system in 1809, which became known as the *cylinder* or *vat system*. Since that time, this machine, too, has undergone changes and development. In use, the Fourdrinier is a versatile machine capable of producing a wide range of papers and light boards, whereas the cylinder vat is capable of producing multi-ply papers and boards very successfully and efficiently. We focus on the Fourdrinier machine based on its versatility and its universal appeal in plants worldwide.

THE FOURDRINIER

Figure 3.1 is a simplified schematic diagram of a typical Fourdrinier paper machine. This simplification is necessary owing to the complexity of the arrangement of the *wire,* various *felts,* and drives, coupled with the fact that the equipment shown is in practice grouped together to form a compact entity. This makes it very difficult to depict the complex arrangement as it would normally appear. The grouping of the equipment saves a large amount of floor space and makes the piping arrangements much easier, thereby simplifying troubleshooting, although access for maintenance tasks may not be as simple as desirable in some instances. In the interests of gently introducing the reader to the language of paper making, the diagram and the text show only the names of some of the equipment and the major components of the material involved. These latter items will be elaborated on as required.

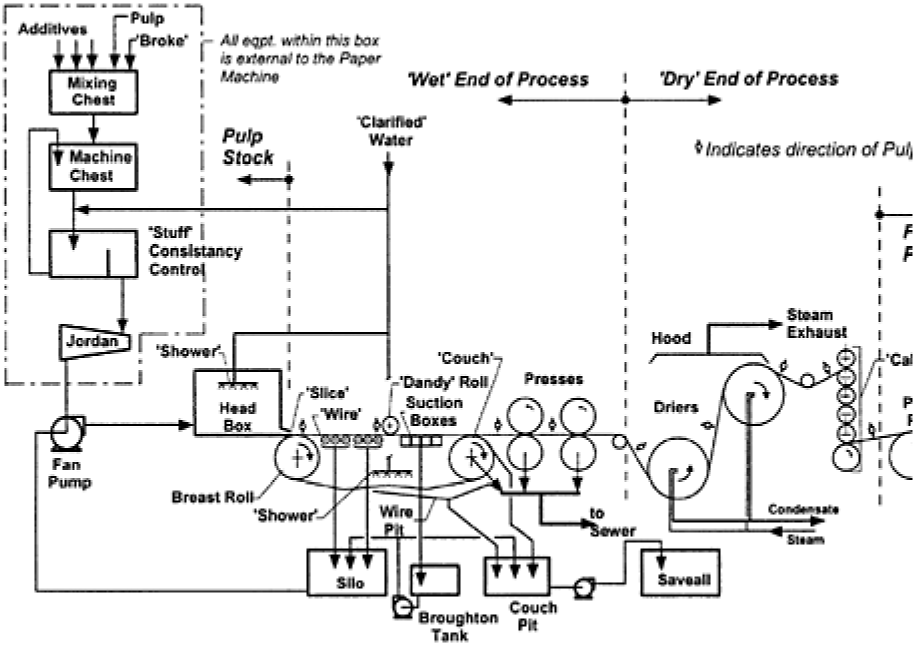


Figure 3.1: Simplified schematic diagram of a Fourdrinier paper machine.

Chapter 2 is devoted to preparation of the pulp used in the paper machine, and the reader should consult that discussion in order to understand how the bulk of material used in the *head box* is derived. Additional components are added to the *stock* during preparation, but again in the interest of simplicity and clarity, these have been shown as inputs to the *mixing chest*. The intention is to develop the system presently shown into much larger individual ones.

THE MIXING CHEST

STOCK-PROPORTIONING RATIO CONTROL

In the mixing chest the raw material or the *pulp*—as it is usually known—for the process is prepared before it is sent to the paper machine. The components added to the pulp in this discussion are chosen arbitrarily but are commonly used in the industry; however, they do not represent any specific type of paper. Figure 3.2 shows a typical schematic arrangement for a standard ratio control system associated with the components of the process raw material used in this equipment. Note that all the flow sensors have been shown as magnetic flowmeters; the choice for this type of *primary device* is the fact that these instruments are virtually obstructionless to the passage of the process material, which contains a very large proportion of solid material that would clog any other type of measuring device. It is also highly conductive because it comprises large amounts of water, thus making the magnetic flowmeter eminently

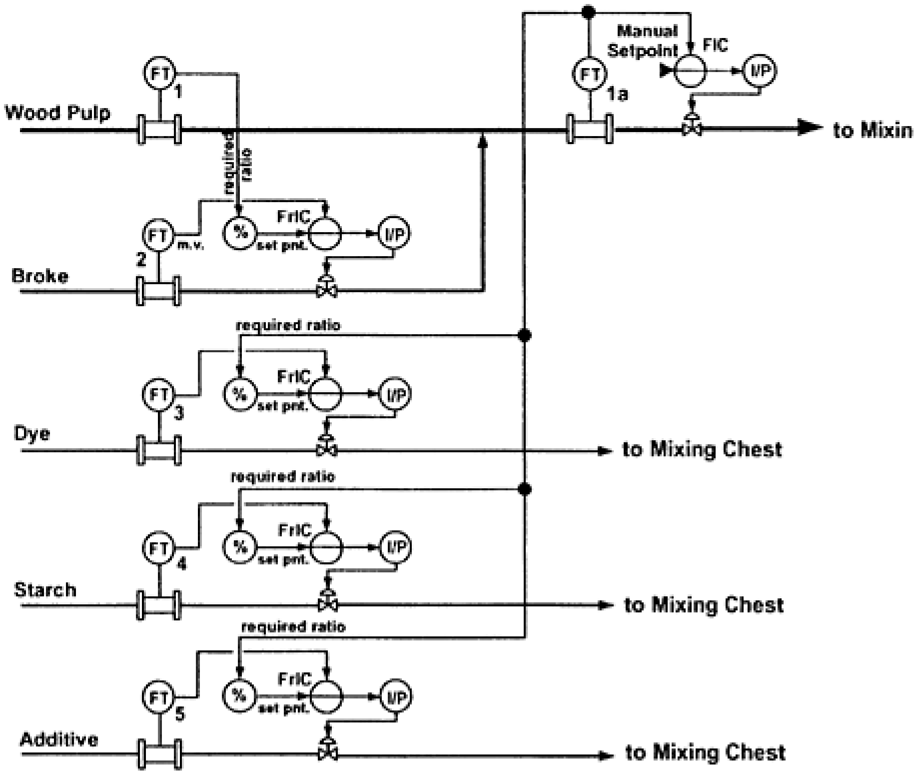


Figure 3.2: Stock-proportioning control system.

suitable for the application. In the control system there are two control loops; in the first loop, the demand is the signal produced by FT-1 as the flow measurement of the wood pulp, and the amount of *broke* regulated by controller FrIC-2 is in ratio to this measurement. When no broke is available, controller FrIC-2 must have its set point placed in local mode and manually adjusted to read zero. This will permit only the wood pulp to be pumped through the system. At all other times, when the set point of controller FrIC-2 is in remote, a combination of pulp and broke will be pumped. Although the total flow of pulp and broke is regulated by controller FrIC-1a to a value determined by the process operator, only the measurement (not the controlled output) is used as the set point or system demand. This is necessary to eliminate the effects that the control terms would have if the controlled output had been used instead. The instruments shown as tag numbers % are really multipliers that accept the demand signal as the primary input and allow it (the common demand) to be individually scaled for each constituent of the raw material. Thus, each signal applied as the set point to the constituent ratio controller (i.e., FrIC-3, FrIC-4, FrIC-5) represents the proportionate amount of the constituent to the total demand. In view of the fact that the makeup of the stock has to be consistent, it is necessary to ensure that the constituents provide the appropriate and correct fractional part of the total quantity (or 100 percent) contained in the pulp recipe—in other words, if all the multipliers have factors that are the decimal equivalent (in percentage terms) of the total demand.

In this ratio control system, it is assumed that each constituent of the stock flows at a reasonably constant rate; that is, the effect of variation in the pumping rate or any other minor temporary impediment to the flow of the material concerned is taken as part of normal running conditions. The system will take care of these variations in the makeup of the final pulp. However, the possibility of variability may pose serious problems for the production run if a restriction, which could be reasonably prolonged, in any of the additive lines occurs such that even with a wideopen associated control valve it is not possible to hold the required ratio. The pulp makeup has to be maintained under these conditions as well because the quality of the finished paper demands close adherence to the pulp recipe. Therefore, an alternative method of control that allows for the constraints of this variation and still holds the required ratio is necessary.

STOCK-PROPORTIONING PACING RATIO CONTROL

Figure 3.3 is an alternative ratio control system that takes account of the possibility of the reasonably prolonged variation in any one of the constituent flow streams just referred to and automatically adjusts the makeup of the raw material accordingly. Once again magnetic flowmeters have been shown, chosen for the reasons given earlier. In the system illustrated, one should observe that, as before, two ratio control systems are involved—one that comprises the basic raw material of wood pulp with broke in ratio to it and the other that is made up of all the additives onto total fibers. The split occurs because the pulp, which can be derived from either hard or soft wood, can be combined proportionately with the broke to impart desirable characteristics to the finished paper. Before we proceed further, it is advisable to define what *broke* is and how it is obtained. The broke is derived from the paper trimming and finishing operations, or from the waste generated when there is a paper break on the machine. A paper break could result in a huge amount of damaged paper brought about mainly by the speed at which the machine is run; typical wire

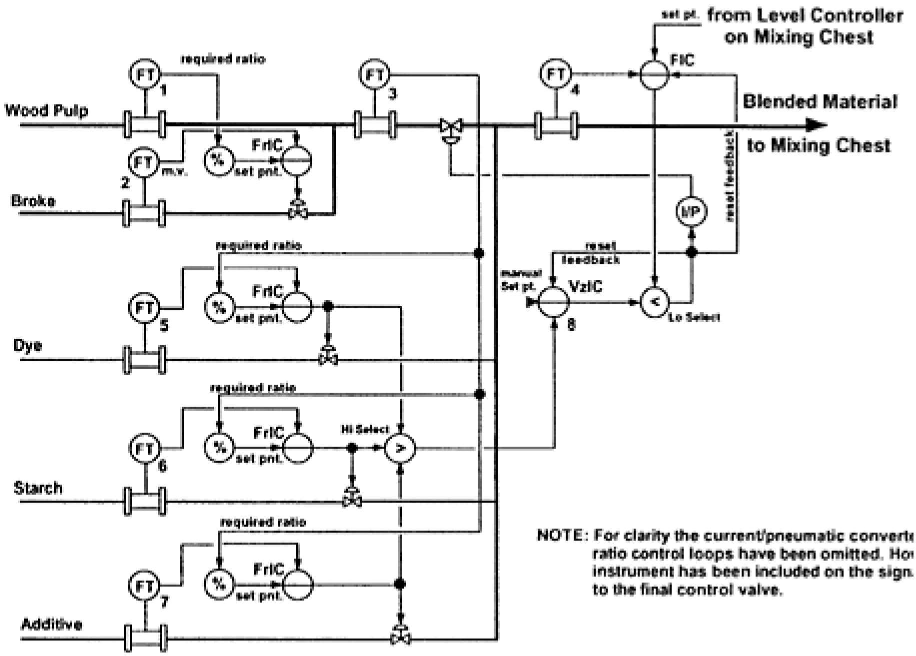


Figure 3.3: Stock-proportioning system with pacing control.

speeds are 900 to 1400 ft/m, or approximately 10 to 16 mph (16 to 26 km/hr)). The waste is returned for reprocessing, and the resulting pulp is then returned to the paper manufacturing process.

Considering for the moment the pulp ratio control system only, one can see that the demand is set by the flow of the virgin pulp measured by FT-1. This signal as before is the primary input to the multiplier tagged % (i.e., FX-2) whose output is the set point for the ratio controller FrIC-2 that regulates the broke flow accordingly. It should not be difficult for the reader to add another source of material to the system and alter the control loop to suit. The comments made earlier regarding the proportioning of the broke to virgin pulp are still valid here.

Because it is necessary to ratio the additives to the total pulp, it is necessary to include the measurement provided by FT-3 as the demand for the addition of the other constituents of the final pulp. A summing module could replace the actual measurement provided by FT-3, but this would affect the accuracy of the measurement, as we would have to consider the variations in measured value provided by FT-1 and FT-2. The choice is with the reader. As before, the set points for additive ratio controllers FrIC-5, FrIC-6, and FrIC-7 are derived as the proportionate amount of each constituent to the total demand. The system is designed to allow the final product to be of the same composition at any instant throughout the run regardless of the fact that any mechanical or pumping problems could affect any of the constituent lines to be operating at a flow rate different from that obtained without any restrictions. When a deviation in one additive from normal occurs, the system senses the change at the instant of occurrence and automatically adjusts the flow rate of the other remaining unaffected constituent lines to suit that of the problematic one, as will now be explained. In the method employed, the system detects the point at which any particular constituent is approaching a situation where control will be lost. An approaching loss of control is indicated when the control valve associated with the particular constituent is near its maximum allowable opening. The process supervisor or someone in authority determines the maximum allowable valve opening, which is usually in the range 90 to 98 percent. Since its associated ratio controller drives the valve, the amount it opens depends on the value of the control signal applied to the drive motor of the valve. The output from each ratio controller is applied to the high signal selector tag number (FX-567) shown as >. These signals are compared against the chosen amount of valve opening determined previously and set by the operator on the signal selector as the high limit value for the valves. In this instance it has been decided mainly for simplicity and clarity of explanation to show a single high signal selector as available on modern DCSs (distributed control systems). In the event that a DCS is not being used, then the usual two-input selector instruments can be a replacement and the loop arrangement can be altered to suit. The highest signal finally selected is applied as the measurement to the valve position controller tag number VzIC-8. The function of controller VzIC-8 is to reduce the flow of the base stock (i.e., wood pulp and broke in this instance) and to keep the constituent control valves from going above the chosen high limit. This is achieved by applying the output from controller VzIC-8 to a low signal selector tag number (FX-8) shown as <, where it is compared with the output of the final flow controller FIC-4, and applying the lower of the selected signal to the electropneumatic converter tag number I/P whose output drives the control valve in the pulp-broke line. The mixing chest level controller provides FIC-4 with a set point. The control valve therefore meets the requirements of both the pulp flow to and level in the mixing chest. Note that reset feedback signals are applied only to the flow and valve position controllers to avoid saturating the integral control term on these instruments when either of them is not selected.

One could argue that a process analyzer could be used instead of the pacing control system described, but in considering this alternative one should be aware of two main problems in selecting analyzers for such applications: (1) there will always be a very real possibility that an off-spec product will be manufactured before the control valve can take effective action, and (2) an analyzer (i.e., designed hardware) may well not be available for a particular constituent.

PULPERS

THE STAND-ALONE PULPER

When the pulp contains recycled paper (broke only in this discussion) in addition to the pulp produced in the digester, a *pulper* is used. The machine is aptly named, for the name fully describes its designed function. If recycled paper from other sources such as newsprint and office waste is included, then separate additional processing (e.g., deinking) of the paper will be necessary before it can be fed to the pulper. The pulper's task in this case is to reduce the recycled paper to a state that allows it to be combined with the fresh pulp. Figure 3.4 illustrates an arrangement of a typical stand-alone continuous operation pulper. As we mentioned earlier, paper machines can produce large amounts of waste whenever there is a paper break, and this waste is returned to the machine, in the interest of economy, for remanufacture. To start the remanufacturing process, it is first necessary to reduce the finished paper back to a pulp from which the whole process can be begun. This arrangement of continuous production equipment can be used for batch operations if the discharge pulp pipe

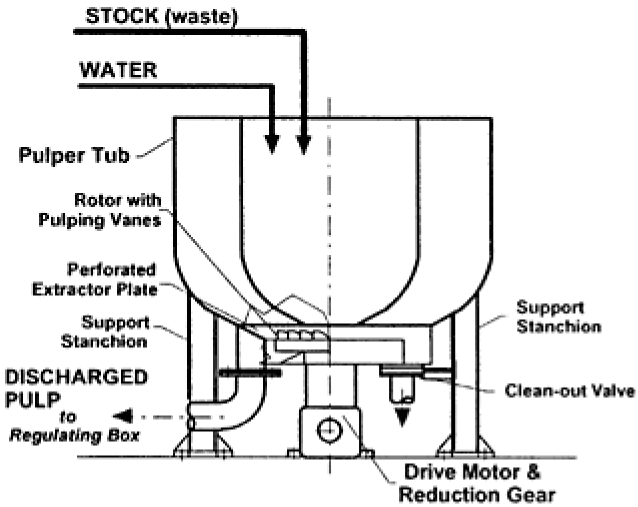


Figure 3.4: Arrangement of a typical continuous pulper.

work is modified by installing a discharge dump valve and admitting batches of bales of pulp instead. The dump valve can be either operator or *sequence logic* controlled, the choice depending on the specification of the system operation. To give the reader some idea of the quantities involved when batch pulpers are used, the batch size in some mills could be about 5000 lb or more. The pulper *tub* may be constructed from several different materials (steel, cast iron, or even concrete), which is supported all around on a framework of suitable steel stanchions. At the bottom of the tub is a heavy steel rotor carrying the pulping vanes; the whole rotor assembly is driven by a heavy-duty electric motor that is coupled to it through a reduction gearbox. The connection of the drive assembly to the rotor is either direct or indirect; in the indirect case, the drive, which once again includes a reduction gearbox, the coupling of the rotor, and drive assembly is achieved by a heavy multiple vee belt or drive chain. To extract the pulp, the periphery of the bottom is fabricated so that it provides a double skin—the outer one being solid while the inner is formed from perforated steel plate with holes ranging between 0.25 in and 1.0 in diameter, the hole size depending on the type of paper being manufactured. Pulpers are usually highly efficient and reduce the paper to slurry in a few minutes.

THE PULPER LOCATED UNDER THE FOURDRINIER MACHINE

In the Fourdrinier machine, the pulper is located under the machine in a position near the dry end where paper breaks most often occur. Because the pulper is machine-mounted, it is arranged to accept material from a number of sources on the machine itself and to deal with these efficiently when required. Figure 3.5 is a schematic arrangement of the equipment usually found; to make it easier to understand the operation, the control system is also shown in this illustration. In the interest of clarity and to give the reader a sense of the geography, the dry end of the machine has been included in the figure, together with the paper break photocell monitors on the machine. The number of monitors is such that they cover the entire area under surveillance and could be very many more than the symbolic two shown, although the actual location of these items with respect to the machine is not specifically given.

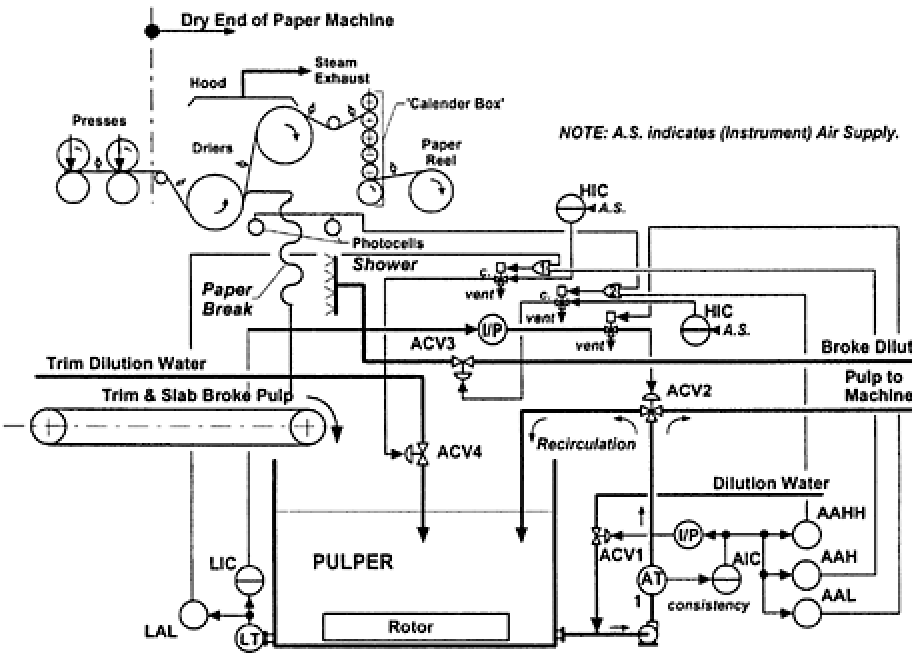


Figure 3.5: Schematic arrangement of under-machine pulper.

The Control of Pulp Consistency—Normal Operation

The consistency control loop A1 as shown in Figure 3.5 and Figure 3.7 is operational at all times to ensure that the pulp sent to the machine chest is that value required by the product specification. For this to be achieved the ports of the pneumatically operated three-way diversion valve ACV-2 located in the pulp to machine chest line valve is shown in its uninitiated (normal) state, allowing the finished product to be directed to the machine chest. That is, the flow of pulp through valve ACV-2 is from the bottom to the right-hand port. The consistency sensor/transmitter AT-1 measures the value of the pulp consistency and produces a proportional signal as the measurement for the associated consistency controller AIC-1. Controller AIC-1 manipulates the *dilution water* control valve ACV-1 to ensure that the desired consistency determined by the operator is achieved and maintained. In Figure 3.5, three alarms are also provided on the output signal of controller AIC-1. With these alarms, the following comments must be noted: while the older *trip alarm* instruments were able to carry relatively high currents (typically, 250 mA to 5.0 A using either reed relays for the lower currents or armature-actuated relays for the highest current value), in modern DCSs the alarm contacts are not themselves capable of driving any valve or other equipment directly but will require either an *interposing relay* or a high-current *solid-state switch* to handle the high initiating current of the driven item. For simplicity and clarity, the logic involved in driving the solenoids and valves has not been shown. Under normal operating conditions the *trim dilution* (ACV-4) and *broke dilution* (ACV-3) control valves are in their *failure mode,* which is closed.

Before we proceed further, we shall describe the function of the three-way solenoid valves so that the reader can follow system operation. The three-way solenoid valve is designed so that with no drive current applied to the solenoid only two of the three ports are in communication with each other. One of these ports is a *common;* that is, it is able to communicate, only one at a time, with either of the other two ports. When a drive current is applied the initial *normally open* (NO) port is shut off to discontinue communication with the common port, and the other, *normally closed* (NC) port is opened to communicate with the common port. In Figure 3.5 the *vent* is the NO port of the solenoid valve, and the common port (marked with a C on the connecting line) is that connected to the control valve diaphragm drive motor, which, as illustrated, allows the air contained in the control valve diaphragm drive motor to be vented and force the control valve to its closed failure mode.

The Control of Pulp Consistency—Abnormal Operation

Note: In the following description, where values of trip points are given, they are chosen arbitrarily and are given for description purposes only and can/will change in practice.

The consistency alarms operate as follows. When the output signal of consistency controller AIC-1 reaches a value that is just over half the output range, which is indicative of a large deviation from desired consistency, alarm AAH (consistency alarm high) is *tripped* (actuated) to provide an electrical path (it being the active input of the two-input logic OR gate #1) to initiate the three-way solenoid valve associated with the control valve ACV-4 on the trim dilution water line. This action shuts off the NO (vent) port and opens the NC port of the solenoid valve to allow air to enter the control valve diaphragm drive motor and to force the attached control valve open to a predetermined amount set by the operator on the pneumatic *manual loading station,* normally tagged HIC (hand indicating controller), thus allowing trim dilution water to flow into the pulper. Each HIC actually comprises a manually adjustable multiturn needle valve operating on its pneumatic supply line, together with a pressure indicator, that permits close adjustment of the air supply, regulated relative to the position of the valve needle. The taper of the valve needle permits fine adjustment of the output air pressure passing to the control valve diaphragm. The input to the valve diaphragm drive motor is shown on the scale of the downstream pressure indicator. The addition of trim dilution water reduces the pulp consistency and permits a return of consistency control to the consistency controller AIC-1, which will then regulate the pulp to the required consistency value by using valve ACV-1 in the dilution water line to achieve the objective. This corrective reduction in consistency is sensed by the consistency sensor/transmitter AT, and a reducing measurement is produced, which, when it is below the setting of alarm AAH, will return the alarm to its normal (uninitiated) state. The return of alarm AAH to normal deactivates the associated logic and shuts off the trim dilution water flow via control valve ACV-4.

In the event pulp of unusually high consistency is discharged into the pulper, the output signal from the consistency controller AIC-1 may rise beyond that set on alarm AAH, indicating that neither the dilution water nor the trim dilution water addition is able to cope with the resulting situation. When alarm AAHH (consistency alarm high-high) is tripped, an electrical path (it being the active input of the two input logic OR gate #2) to initiate the three-way solenoid valve associated with the control valve ACV-3 on the broke dilution water line is initiated to discharge even more water into the pulper so as to further correctively reduce the pulp consistency. As before (with ACV-4), the control valve ACV-3 on the *broke dilution water line* is driven to a predetermined position determined by its associated HIC. The water additions result in a reducing consistency measurement, which returns control to the consistency controller AIC-1 as described before. Alternatively, if the output from the consistency controller AIC-1 pulp consistency should fall so low that the pulp is not within the accepted specification, alarm AAL (consistency alarm low) trips and the pneumatically operated three-way diversion valve is initiated. As a result the control valve ACV-2 changes state to divert the pulp flow to the left-hand port and recirculate continuously (i.e., back into the pulper) until such time as the incoming pulp causes the consistency to rise above the value set on alarm AAL. The level sensor/transmitter tagged LT monitors the pulp level in the pulper, and if the level falls below that set on the low-level alarm, LAL, an electrical path is provided (it being the active input of the two-input logic OR gate #1) to the three-way solenoid valve attached to the control valve ACV-4 in the trim dilution line. LAL, through the solenoid valve in the air supply to the valve motor, then drives the control valve to the position determined by the associated HIC to admit trim dilution water to the pulper and raise the level. When this occurs, control will once more be restored to the consistency controller AIC-1.

The Control of Pulp Consistency—Under Dry End Paper-Break Conditions

A paper break on a Fourdrinier calls for immediate and focused attention because the machine runs at high speed and the amount of waste produced as a result can be enormous. Under this circumstance, the photocells that continuously monitor the integrity of the machine mat initiate the logic and through OR gate #2 provide an electrical path (it being the active input of the two-input logic OR gate #2) to the three-way solenoid valve attached to open control valve ACV-3 in the broke dilution line to the position determined by the associated HIC. This action applies water via the shower onto the paper spurting from the machine. Depending on the layout, the now wet paper falls into the pulper or onto the conveyor and then into the pulper. The amount of broke dilution water introduced is adjusted via the HIC to a value that is just short of that required for a full (i.e., when a simultaneous break in the mat also occurs in the vicinity of the wet end) paper break. Note that the different values of the output from the HIC can be preset and selected by additional logic if the system is electronic, or by a duplicate HIC adjusted to the higher output if the system is pneumatic, which, as stated earlier in the interest of simplicity, is not shown in Figure 3.5. The pulp consistency inevitably rises owing to the additional paper fed to the pulper, causing the consistency sensor/transmitter tagged AT-1 to produce an increasing measurement. This is acted on by the controller AIC-1 to make the dilution water valve open further to restore loop balance and bring the pulp pumped to the machine chest back to the required specification. If the action taken by AIC-1 and the continuing amount of broke dilution water is not sufficient to cope with the situation of reducing the consistency, then, as soon as the output from AIC-1 is about half the output scale range, alarm AAH will trip. When alarm AAH trips an electrical path is provided (it being the active input of the two-input logic OR gate #1) to the three-way solenoid valve attached to the control valve ACV-4 in the trim dilution line to activate the solenoid and drive the control valve to the position determined by its associated HIC. The additional water provided by the trim dilution line will help reduce the consistency even further. When the output of controller AIC-1 reaches a value set on AAL (about one-quarter of the output scale range), the trim dilution water valve will automatically close. This is a repetitive sequence of operations and will continue for as long as the paper break continues. As soon as normal conditions are restored (i.e., the paper has been wound onto a new reel), the photocells once again resume their monitoring role on the mat and the paper machine is returned to normal operation.

The Control of Pulp Consistency—Under Full Paper-Break Conditions

In some instances, the Fourdrinier paper machine has two pulpers located under the machine to cope with a full paper-break situation. As described earlier, one pulper is located beneath the dry end of the machine, which is considered as the *master* pulper. The other is situated at an appropriate location under the wet end of the machine; this second pulper is considered the *slave*, and usually only minimal instrumentation is used on this slave equipment. To all intents and purposes this equipment is shut down during normal operation, care being taken in the equipment design to avoid stratification or *dewatering* of any residual pulp.

For simplicity, Figure 3.6 presents a schematic only of the slave pulper and the instrumentation involved; the master pulper is the same as described earlier. As before, the control logic for the system also has not been shown in the illustration, but this can easily be designed from a specification of the start-up/shutdown procedures drawn up by and obtained from the mill.

The control system shown in Figure 3.6 operates as follows. When a paper break at the wet end is sensed by the photocells monitoring that area, the discharge pump is initiated, and the amount discharged is controlled by level controller LIC. The level controller maintains the pulp level in the pulper tub by regulating the amount passing through the control valve LCV in the discharge line to the master pulper. The photocells also initiate the three-way solenoid valve attached to the control valve CV-1 located in the broke dilution water line to convert the wet paper into slurry. A consistency sensor/transmitter tagged AT located in the discharge line from the pulper measures the consistency of the pulp and provides a measurement for the consistency indicator tagged AI. Control valve CV-1 is initially in its failure mode, which is closed, but opening the three-way solenoid valve allows air to fill the valve diaphragm motor, which drives the plug to a predetermined position set by the operator at a value indicated on the manual loading station HIC. The value set on the manual loading station is in turn determined by the process operator, based on previous experience gained by observation of the pulp consistency, which, as stated

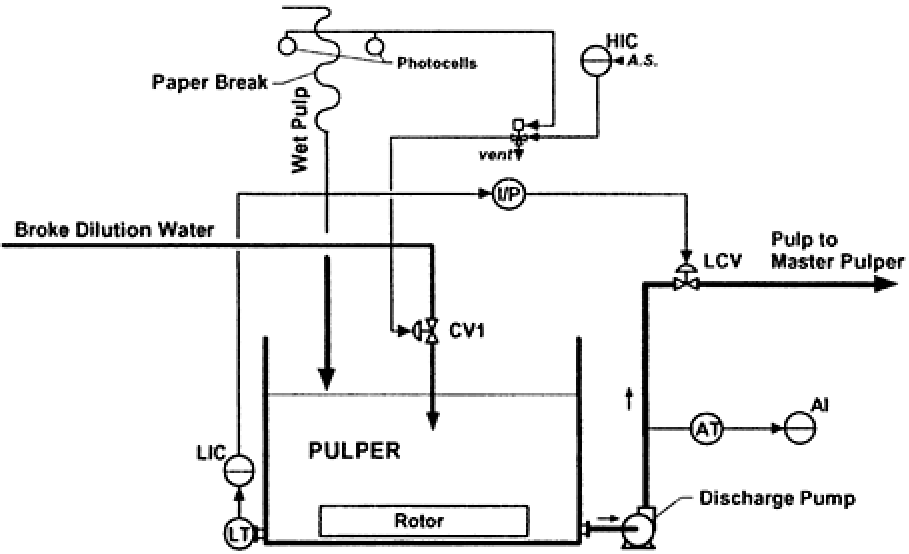


Figure 3.6: Schematic control scheme for a slave pulper.

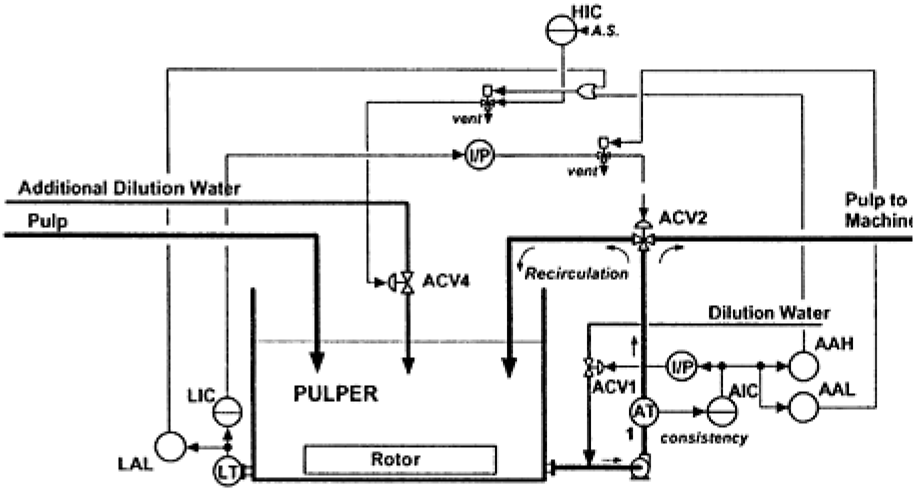


Figure 3.7: Schematic control scheme for stand-alone pulper.

earlier, is displayed on the consistency indicator AI. The operator can, if necessary, readjust the valve opening via the manual loading station HIC. The actual consistency of the discharged pulp is kept slightly higher than that required by the consistency of the final pulp that is pumped to the mixing chest. This provision of pulp from the slave pulper at a slightly higher consistency allows the material to be finely adjusted in the master pulper shown in Figure 3.5 via its consistency controller AIC-1 (also in Figure 3.5) to meet the manufacturing specification. When the photocells shown in Figure 3–6 no longer sense the paper break, the three-way solenoid valve is deenergized and the system returns to normal, with care being take to ensure that the shutdown procedure set by the mill has been met.

The Control of Pulp Consistency—Stand-Alone Pulper

Having now described the fairly complex control operation associated with the under-machine pulper, we will look at the controls usually involved with the more basic stand-alone pulper. As expected, the control system is fairly simple, and again for reasons of simplicity and clarity, is shown as a schematic arrangement in Figure 3.7. The figure has been deliberately devised from that given for control of the under-machine pulper so that the reader can deduce the modus operandi of the simplified control scheme used in the stand-alone equipment because it follows principles defined earlier for the control of pulp consistency during normal operation.

PULP ADDITIVES

As stated earlier, when we introduced the Fourdrinier machine, in addition to having the basic raw material of the pulp, the stock for paper making contained other materials as well. The reason is that the pulp produced for the mixing chest is not in itself completely suitable for converting directly into paper because in this state it is of irregular texture, high bulk, uneven formation, and low strength and would very easily disintegrate when wetted. To give it strength and make it suitable, other materials such as different types of pulp, fillers, dyes, and chemical additives are mixed in. All the added materials have to be blended in a predetermined and fixed proportion for the type of paper being manufactured. The ratios and components used are trade secrets, and control engineers should accord the data given by the paper manufacturer the security expected. We shall now consider some of the materials added to bring the pulp up to the required specification. Because this is an overall view of the Fourdrinier machine, please be aware that any real paper manufactured may or may not contain all the items now discussed, and, in addition, there may be other constituents that we have not covered but could be included.

SIZING

To be useful, paper must normally resist the absorption of liquids; it therefore has to be treated with some material that achieves this intention. In the very earliest days, this treatment was carried out after the sheet of paper had been formed, which was subjected on completion to a quick pass through a very dilute solution of glue or other adhesives and air-dried; only when fully dry was it ready for use. This treatment appeared to be satisfactory because the paper at that time was used mainly for writing. This manufacturing process has been called *external sizing*. Around 1807 Moritz Illig, a German national, developed a technique using alum which precipitated rosin size onto the pulp fibers—as the fibers circulated in the *hollander* (beater) (for a discussion, see later in this section). This technique was incorporated into the Fourdrinier machine system where it has since remained fundamentally unchanged. Because the new treatment was included at a stage when the material was still a slurry and, hence, before sheet formation, it was found to be easier, less time consuming, and satisfactory, and it became known as *internal sizing*. It should not be difficult to understand why the terms *internal* and *external* are used in naming the two sizing operations.

The original size was obtained by reacting, to neutrality, sodium or potassium salts with rosin. The resulting size or *soap* as it is called was diluted and introduced to the pulp in the hollander, where it was precipitated with alum. The chemistry of why it works is not understood completely, and many believed, and still do, that it is a double decomposition through which aluminum resinate is precipitated, leaving a soluble alkali sulfate as a waste byproduct. Other researchers—Sieber, Ostwald, and Lorenz—contradicted this theory and in the early 1920s supported the colloidial theory instead. The situation regarding the actual chemistry involved has not yet been resolved, but sizing is still being carried out to the paper user’s satisfaction in all mills. A formulation of rosin size to alum in a dry-weight ratio of 1:1·5, respectively, is used almost universally, but individual variations exist.

ROSIN SIZE

Rosin is a natural resin obtained from the wood of pine trees; it is yellow or amber in color and very brittle. It is insoluble in water but soluble (typically) in acetone, chloroform, the lower alcohols, and some oils. The rosin size is prepared by reacting rosin with sodium hydroxide or sodium carbonate to obtain a neutral size. However, preparation of rosin size today is not usually carried out on the mill site but is manufactured by others off-site as a viscous fluid and delivered to the mill in prepacked drums. Before it can be used it has to be heated, in order to reduce the viscosity, and then it is diluted with steam until a final dilution of between 3 and 5 percent solids is obtained. The paper being made determines whether neutral or free rosin size can be used with the water available at the mill site; the reason for the options available is that very hard water tends to precipitate the rosin size, with no improvement in the sizing effect. Free rosin size, on the other hand, is precipitated less in hard water. Rosin size is usually the first sizing material to be added in preparing the pulp for papermaking.

LATEX

Natural rubber in an aqueous dispersion was called latex, but this term has now come to include aqueous dispersion of resins and rubber, which are the result of emulsion polymerization. This is normally not used as an internal size because it is a special additive. Its use in its natural or synthetic form produces paper of considerable wet strength, although this is not the primary objective for its inclusion. Products such as gaskets and some artificial leathers are examples developed from its use.

STARCH

Starch is never used by itself, but instead is used along with rosin size because of the poor affinity starches have with cellulose, which makes it difficult to be retained. Partially cooking the starch improves the retention qualities, and it is prepared by turning a starch concentration of 5 to 8 percent into a slurry with water, after which it is subjected to live steam injection. Depending on the type of starch used, the temperature is raised until it attains a value in the range 87 to 95°C (189 to 203°F); keeping within this cooking temperature range is important for best results. For better control of the pulp preparation process, batch preparation of the starch has today given way to continuous injection of the starch through a steam injector system. Mechanical work has serious effects on the added starch, with wheat starches better able to withstand the mechanical work process than some others such as starches from potato or tapioca. Thus, cooked starch is added after the pulp has been put through the refiners or at the outlet of the fan pump. The addition of starch improves the surface of the paper. When starch is used as a size, the quantities based on the dry weight of the pulp are in the range 2 to 3 percent.

ALUM

This chemical is used extensively in paper manufacture where its main functions are to precipitate rosin size and to clarify the water used. In paper making, this alum is not a true alum but rather aluminum sulfate made from bauxite and sulphuric acid. Today the alum is also not manufactured at the mill site but is produced elsewhere and shipped to the mill in tankers in liquid form, normally as a 50 percent solution. The mill dilutes the pre-prepared alum to the desired strength before use in the pulp preparation process. The amount used must be in excess of that which will precipitate rosin size in the absence of pulp fibers. Should there be any ferric (iron) in the alum, it will cause the paper to have a yellow discoloration. When maximum permanent strength and maximum sizing are required, an amount of $Na_2Al_2O_4$ (sodium aluminate) is combined with the alum, which results in acceptable sizing at a pH that is nearly neutral. This neutral pH sizing has advantages for the mill in that it considerably reduces the corrosion on the plant equipment.

Several other sizes are used including emulsified waxes and bituminous emulsions; readers are advised to investigate further these other sizes to enhance their understanding.

FILLERS

The term *filler* or *pigment* is used to describe the inorganic materials similar to those materials used in paper coating and in the paint and rubber industries. The term *filler* sets the line of demarcation between white pigments that are used for *loading*, and colored pigments that are applied to give paper different colors. Loading describes a surface treatment involving the incorporation of the white pigment or other inorganic filler materials into the web of fibrous pulp to improve the paper or board quality. Fillers are necessary to produce papers with a *fine-textured* and *well-closed* surface of the web (mat), which always comprises voids randomly distributed, and an undulating discontinuous surface of minute hills and valleys. The filler plugs the cavities and reduces the unevenness of the surface of the paper, and so achieves this requirement. These two criteria are important, especially when the paper is used for printing because the filler creates a network of fine capillaries that are vital for accepting the printing ink in a uniform and controlled manner. Other effects of its inclusion are to improve the opacity of the paper because it inhibits the visibility of one printed side from the other and prevents the printing ink from penetrating very deeply, thereby causing print defects. The best particle size of a filler to give the highest opacity should be half the wavelength of light used to study the filler or approximately 0.25 μ (micron).

Excessive use of fillers can result in limpness of the paper, increased softness, dusting (whereby rubbing the finished sheet loosens the filler particles), and tacky printing inks, which allow fibers of the paper to lift off. Fillers can decrease the effectiveness of the size used; calcium carbonates are reactive and adversely change the rosin-size precipitate, and the strongly acidic zinc sulfate can cause discoloration of the paper.

SOME OF THE FILLERS USED

CLAY

This material comprising mainly kaolinite must be free of quartz, mica, and other abrasive constituents. The quartz is removed from most types of clay by dispersion in water where the heavier particles stratify out. English clay is free from titanium and iron, both of which both lower the reflectance; when used it makes it easy to attain a variety of attractive shades of paper. American clay does not have this quality and has to be *bleached* by treatment with sodium hydrosulfite or zinc compound and then spray dried to avoid formation of the grit particles that were previously obtained when the clay was dried in rotary driers.

CALCIUM SULFATE—$CaSO_4$

This material, also known as gypsum, exhibits little interference with rosin size to give high brightness and is of low cost. However, because of its high solubility in *white water,* the initial saving in cost is negated, and because its solubility decreases with rising temperature—a reversal from the norm where the solubility usually increases—the gypsum may be deposited in the pipes, which is a plant problem. Calcium sulfate has the highest specific volume of all the fillers used.

CALCIUM CARBONATE—$CaCO_3$

The common name for this material is chalk. Carefully selected natural chalk as found on the south coast of the United Kingdom or limestone deposits found in the United States is often the source of this material. However, when the sodium carbonate produced in the pulp mill recovery system is causticized with $Ca(OH)_2$—calcium hydroxide—sodium hydroxide is produced. This is the chemical product from the reaction as it is required for the paper pulping operation, where it is reused in the pulping liquor. As a result of the causticizing, calcium carbonate is precipitated as a byproduct, which can then be used as a filler. This used to be the practice when the pulping operation used the soda process where the pulp was cooked with sodium hydroxide. However, in the Kraft process whereby the pulp cooking is done in the presence of sodium hydroxide and sodium sulfide, production of the calcium carbonate is reduced because it is very difficult to produce from Kraft waste the filler needed as white calcium carbonate.

Other fillers were used at one time, but some of these were found to be detrimental either to the paper itself or to the machinery producing it. For example, even though calcium sulfite can be processed to yield very white filler, which is easy to size with rosin size and alum, it has the disadvantage in that there is a reaction between the alum and the calcium sulfite. This reaction releases sulfurous acid, which in turn corrodes the wires and wool felts on the machine, making it necessary to use corrosion-resistant wires. Felts are difficult or could be very expensive to replace with an alternate; the author is not aware of any suitable replacement. The reader is advised to investigate the subject of fillers more fully to extend his knowledge in this direction.

PULP PREPARATION EQUIPMENT

THE HOLLANDER

Fiber separation is the most important requirement in paper making. To achieve this separation the pulp was subjected to a laborious beating operation, which was later mechanized and ultimately resulted in the hollander. This was the single most important papermaking advance made about 200 years ago; the machine was designed and developed in the Netherlands whence it got its name. Although improvements have been made, the basic design remains unchanged, and some of these machines, in updated form of course, are still in use today, which bears out the solidity of the design. Figure 3.8 shows a typical hollander arrangement. The midfeather divides the beating tub into two, with the pulp circulating as shown. The tub can be fabricated from a variety of materials, such as cast iron, steel, or concrete; in some instances, the concrete is tiled over as well. The pumping action of the *beater roll* work*ing against the backfall maintains the circulatory movement of the pulp in the tub.*

The gap between the beater roll and *bedplate* can be altered through two methods; one is by maintaining the position of the beater roll and moving the bedplate toward it, and the other by maintaining the bedplate fixed and moving the roll toward it. The method chosen depends on the maker of the machine. In the illustration, the hand wheels are used to alter the position of the roll with respect to the bedplate. In some designs, hydraulic cylinders are used instead of hand wheels to change the opening

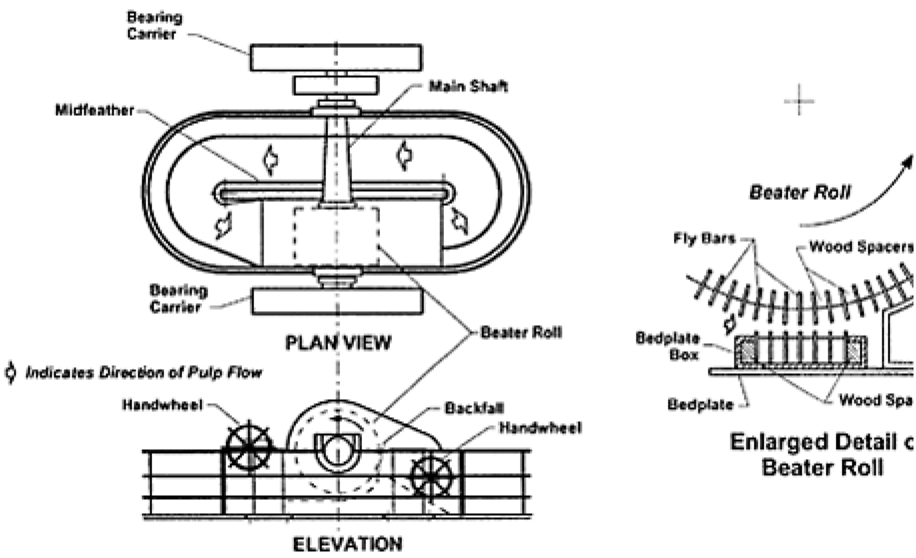


Figure 3.8: Typical arrangement of a hollander beater.

of the gap. The *fly bars* on the beater roll and the bars on the bedplate are held in position by suitable bolts or pins, with the intervening spaces wedged with wood or other suitable material dependent on the design. The enlarged view of the beater roll and the bedplate attempts to show more clearly how the pulp is beaten as it passes through the gap between the two sets of bars.

More up-to-date beating equipment is called a refiner and can be divided into two types: the *conical* refiner and the flat plate or *disk* refiner. The names given to these machines succinctly describe the design of the functional mechanism employed to achieve the results in the machine. The first equipment we consider here is the conical version, which carries the name *jordan*. Refining is the mechanical treatment of the fibers sometimes carried out after beating or on its own, in which the fibers are brushed and shortened by cutting to improve paper formation.

THE JORDAN

Figure 3.9 shows this machine, which was invented in the mid-nineteenth century and got its name from the inventor Joseph Jordan. On examining the figure, we observe that the task this machine carries out is almost identical to that done with the hollander. The idea behind the invention, however, was to increase efficiency and speed up the beating process performed by the machine it was replacing. The beating is shown to take place within the confines of the cones, the outer one of which is fixed (i.e., nonrotating), while the inner one, called the *plug,* is motor driven, rotates, and is also able to slide in or out by a required amount on a through shaft to vary the intercone spacing and thus obtain the quality of the pulp required. The inner surface of the outer cone and the outer surface of the inner cone are fitted with bars or *knives* in much the same way as they were on the hollander; however, there will be many more bars around the periphery of the base of the cones. Shaft bearings are chosen to permit the free rotation of the plug and the resulting thrust imposed when it is moved along the inside of the outer housing. The machine is very expensive in view of the complexity of manufacture, and the cost of replacing

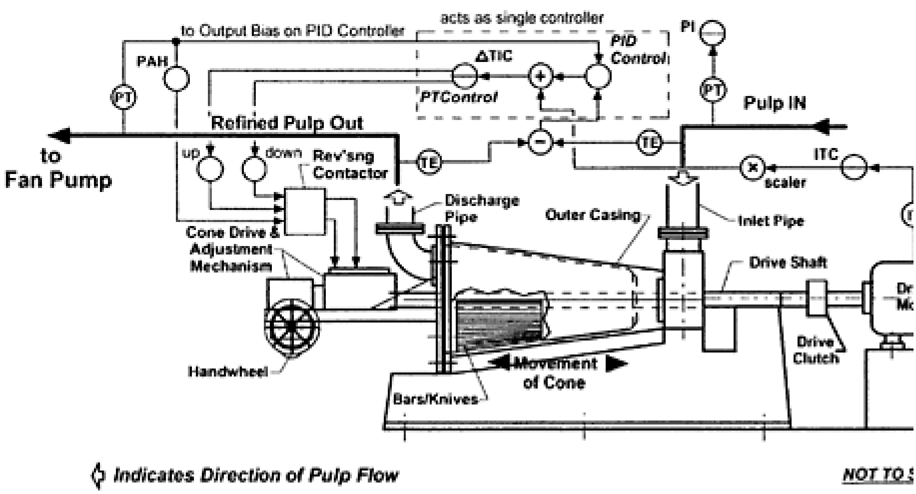


Figure 3.9: Arrangement of a typical jordan or conical refiner with control system superimposed.

the knives can be formidable. Therefore, every care must be taken to prevent any untoward circumstance.

The Time-Proportioning Controller

Before we discuss the control system, we especially need to consider the combination of controllers involved with moving the plug. In the system illustrated, the controls have for convenience been based on the control algorithms of the Foxboro I/A Series (because of the author's familiarity with the equipment), although the fundamentals apply equally to direct hardware-based controllers.

The controller tagged ΔTIC is a *proportional time control algorithm* or *block* (PTC) capable of accepting an analog measurement and producing two pulsed outputs that operate independently (i.e., each pulse train has a separate set of output terminal connections) of each other. One output drives the final actuator in one direction, and the other drives the final actuator in the reverse direction. The pulse width determines the duration of the controlled drive applied (i.e., variable *mark/space ratio*) and depends on the magnitude of the *error* (the difference between set point and measurement). As stated, the control algorithm produces an output that is *proportional only* to the magnitude of the error; no other control actions (*integral* or *derivative*) are possible. The pulses are applied via suitable reversing starter/contactors (one for each of the pulse trains generated in the PTC) to the appropriate connections on the control actuator in order to achieve the direction of the correction necessary. When the system demands control actions other than the proportional provided with the PTC algorithm, the PTC algorithm or other hardware function needs to be connected in cascade with a PID *(proportional, integral, derivative)* control algorithm (as illustrated). It is also necessary to choose the appropriate combination of control action on this latter block to give the required overall control. With the cascade arrangement, the PTC algorithm can be configured to act either as a controller (positioner) or a signal converter. For the system illustrated, the PTC is configured as a positioner that changes the PID control output to the appropriate pulse trains, the three-term

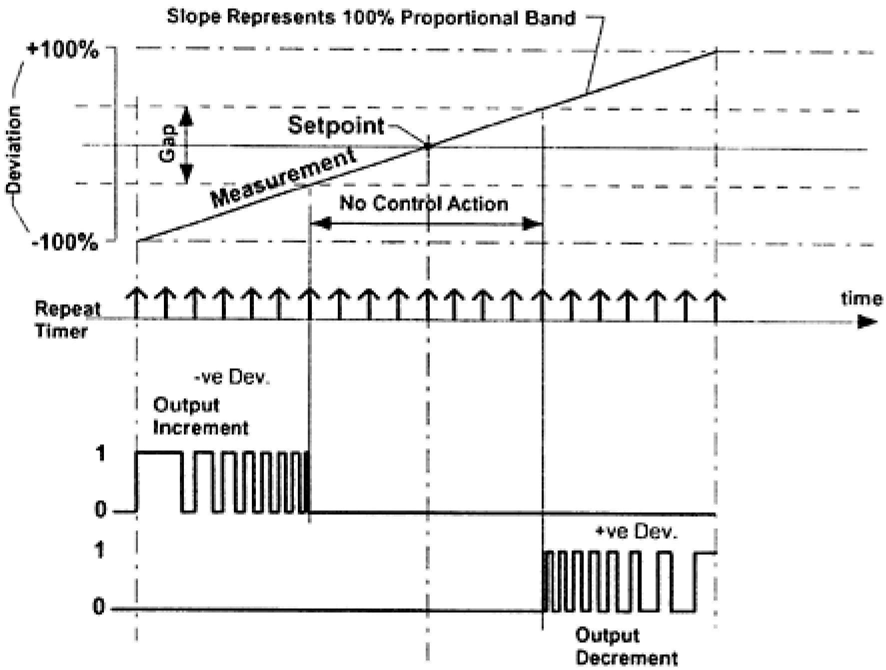


Figure 3.10: Timing diagram for the pulse duration controller.

control being performed only in the PID algorithm. It is important to always maintain the PTC algorithm in the *auto mode* when it is used as a signal converter because no time-proportioning control is performed in the *manual mode*. The selection of either auto or manual is via a boolean variable, which must be maintained at logic level 1 (i.e., auto) at all times to obtain the auto mode.

An additional feature provided in the PTC algorithm is *gap* action—the gap can be described as a *dead zone* created by an upper and lower limiting value positioned about the controller set point. The control and the process engineer jointly determine the actual limiting values of the gap. The gap is adjustable to a value desired to meet the application. When the algorithm is in operation, then as long as the measurement is within the gap created by the upper and lower limits, there is no controlled output from the algorithm. However, as soon as the measurement goes outside one of the limits, the appropriate controlled output pulse train is produced to reduce the error. Figure 3.10 shows the timing diagram for the PTC algorithm, which describes the action taken when the gap control action is configured. One can visualize the pulse train output of the PTC algorithm; if the measurement of the algorithm was below the set point, the pulses would approach the set point as it were from a value below, and more control action would be required the further away the measurement was from the lower limit. The mark/space ratio would decrease as the set point was attained. If, on the other hand, the measurement of the PTC algorithm was above the set point, it would approach the set point from a value above, and more control action would also be required the farther away the measurement was from the upper limit with the mark/space ratio decreasing as the set point was attained. The pulse trains shown in Figure 3.10 give the waveform of increasing and decreasing controller output for negative and positive deviation.

The Refiner Control System

The system shown in Figure 3.9 is used for the following description.

Any one of several different parameters, such as the vacuum in the couch, plug pressure, pulp *freeness* (which is defined as the ability of the pulp to release or retain water and the ease with which it is achieved), or differential temperature of the pulp across the refiner, can be used to control the position of the refiner plug. When pulp freeness is used, it is measured in the discharge line and can be used to control the refiner either directly or as the primary controller that produces the set point for the pulp controller illustrated. For the control scheme shown, differential temperature of the pulp has been selected as the measurement parameter for the results it gives and its ease of implementation. In the interests of simplicity and clarity, the operational logic and alarms associated with protecting the equipment have been omitted, but the reader will appreciate, for example, that driving the inner cone of the refiner too far inward could cause considerable damage to the equipment. Many other examples of protection could be given, all of which would be impossible to show in the illustration. However, the function of the alarm tagged PAH in the instrumentation shown will be detailed in this section as a typical example.

The temperature sensors located in the inlet and outlet lines are resistance bulbs tagged TE (temperature element) whose outputs, proportional to the measured temperature of the pulp, are applied to the subtractor block tagged with a minus sign. The difference is taken, and the block produces a proportional output, which is applied to the PID control block as the measurement. The set point of the PID (see the definition given earlier in the description of time-proportioning controller) block is operator determined. The output from this block is applied to the measurement input of the PTC block configured as a positioner to change the PID block output to a proportioning time pulse train necessary to drive the reversing contactor—a device designed to accept the two independent incrementing or decrementing pulse trains. Depending on the magnitude of the PID-controlled output, either the incrementing or decrementing outputs of the PTC block are invoked, and the reversing contactor is initiated accordingly to drive the plug of the refiner inward or outward to a position that brings the measurement and set point of the controller to coincidence. Note that the pulse outputs from the PTC block have been labeled as “up” and “down” only to signify an incremental or decremental drive; these must be connected to the appropriate terminals in the reversing contactor to drive the plug inward or outward.

There is an inevitable delay between the detection of a process upset by the differential temperature control system and its correction. However, since the drive motor current is more sensitive to changes in the process, this parameter is monitored via the current sensor/transmitter tagged IT and applied to a PID block tagged ITC as the measurement. The controlled output is scaled in the multiplier block tagged×and forms the second input to the summing block tagged with a plus sign, whose other input is derived from the output of the pulp PID block. Therefore, the output from the summer is under all circumstances conditioned by the motor load as well as the temperature difference and will react accordingly to reposition the refiner plug to any detected change.

Any obstruction in the discharge line will cause serious problems to both the refiner and the plant. Therefore, the pressure in the discharge line is monitored by the sensor/transmitter tagged PT whose output is applied to the bias input (to slightly increase the controlled output) of the pulp PID block, where facilities are available to have it suitably scaled and applied to the control block output. To add the bias feature to some discrete instrumentation, if used, it will be necessary to include a scaling and summing module. This arrangement allows the system to react correctly to any change in pulp discharge pressure. In the event the pressure exceeds a predetermined high value, the pressure alarm tagged PAH will be initiated, and the associated logic will override the controlled output, withdrawing the refiner plug and at the same time alerting the process operator to the prevailing condition. Again to ensure safe operation, the pressure of the inlet line is monitored in the interests of both the plant and the refiner via the pressure sensor/transmitter tagged PT, but the output is displayed as a measured value only on the indicator tagged PI.

Enhancements can be included, such as providing a display of the actual travel of the cone, but this will entail the additional cost of instrumentation. The sensors are optical devices for high accuracy, and care must be exercised when this type is considered inasmuch as pulp can be a messy product in the event of spillage, and spillage is most certainly a possibility. An alternate method is to use the recirculating ball-type sensor (identical in operation to that used for the steering system on automobiles but more accurate), which is more robust because the sensing method is mechanical. However, bearing in mind the high cost of cone repair/replacement it would be an outlay worth considering. The readers should investigate this matter for themselves when required, for a suitable means has to be found to mount the instruments and this entails study of the actual refiner equipment involved.

DISK REFINERS

Figure 3.11 is a sectional view of a single-disk refiner. This machine features two coaxial disks, one of which is held stationary while the other is motor driven. In the same way as the jordan, the rotating disk can also be made to move toward or away from the fixed disk, so that the quality of the pulp may be varied to meet the requirements of the paper being made. Some disk refiners have two active disks: two sets of fixed and rotating disks with each set independently driven by its own

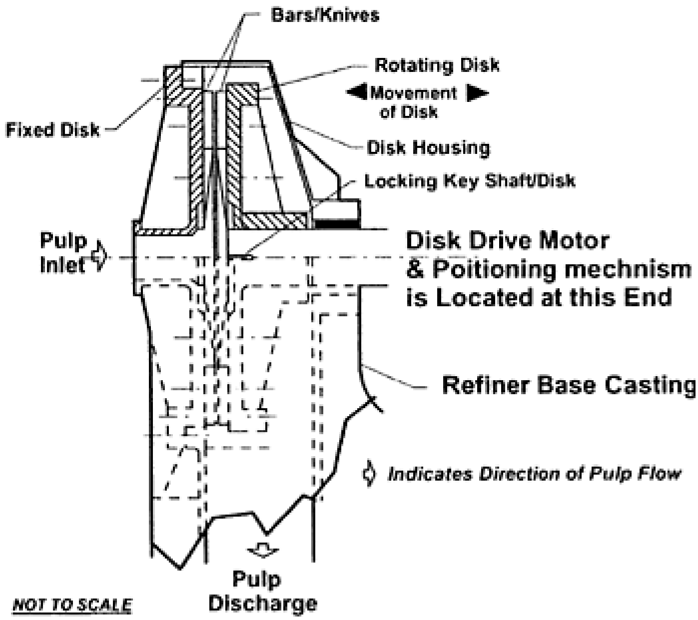


Figure 3.11: Sectional view of typical single-disk refiner.

motor. However, the important point to remember is that the disks contra-rotate. The control system for this machine will not be discussed here because it is identical to that used on the jordan. However, for these machines it is usual for the automatic controller to manipulate a hydraulic cylinder attached to the movable disk to carry out the positioning required. For operational and personnel safety, a manual override for the disk positioning is also provided. The bars/knives are made from either nickel alloys or stainless steel, and the disks are either capable of being reconditioned or are of the throwaway type.

CONTROL OF HIGH-CONSISTENCY STUFF

The term *stuff* is another traditional term used to describe the pulp, which in some mills is also called *furnish, stock,* or *pulp,* with the four names being used interchangeably. With all this varying terminology, the uninitiated will find it difficult to fully grasp the meaning of what is being discussed. The pulp proportioning operation is not the end of the processing; the pulp has to be worked on still further before it can be used on the paper machine. Stock consistency is of the utmost importance in paper making, for without it control of paper manufacture is impossible. In this connection, it is vital to realize that it is not the absolute value of stock consistency that is sought, but rather the amount of its variation about a particular value. The closer the variability of the stock about the desired consistency, the easier it will be to produce the paper required. Consistency in the paper industry is defined as the percentage by weight of fibrous material in any combination of fiber and water. Alternately, it can also be defined as the percentage by weight of dry fibrous material in any combination of stock and water, or stock (i.e., pulp+additives) and water. To give the above relationship symbols we have:

$$C = \frac{W_{fib}}{W_{sam}} \times 100$$

where C = consistency (%)

W_{fib} = weight of fibrous material in the sample

W_{sam} = weight of sample (total)

Stock consistency can be determined using either the manual or the automatic methods. The manual method is one in which the operator removes a representative sample of the material, weighs it, removes the water, and then weighs the remainder. The result gives the consistency of the stock. In this regard, it should be pointed out that very specialized connections are required for the sample withdrawal because the measurement has to be truly representative. The reader is therefore advised to investigate this aspect further. The manual procedure is not at all suitable for continuous control; therefore, on-line sampling/measuring instrumentation is necessary. Such equipment is available today from some instrument makers. One of the measuring principles involved is the determination of the stress imposed on a specially shaped steel blade or member inserted into the process line where, because of the flowing fibers in the stock, a quantity of fibers cling to the sensor and impose a stress on it. Obviously the more viscous (high fiber to water ratio) the stock, the greater will be the stress, and the less viscous (less fiber to water ratio) the stock, the lower will be the stress imposed.

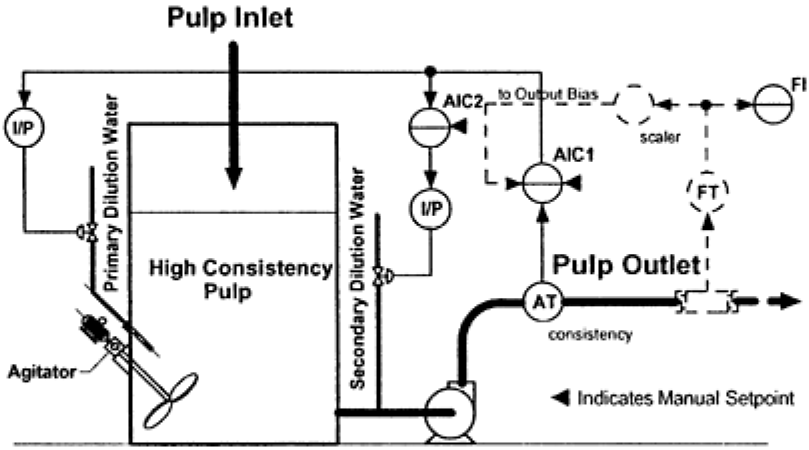


Figure 3.12: High pulp consistency control scheme.

SINGLE DILUTION OF THE STOCK

When the stock consistency is such that the controls need only to reduce the stock to the final consistency by an amount no greater than between 0.5 and 1.0 percent to achieve the specification for the machine, the consistency control scheme (minus the alarms etc.) is the same as that shown in the process discharge line of Figure 3.7 where only a single addition of dilution water is necessary.

DOUBLE DILUTION OF THE STOCK

It is very desirable, economically and production-wise, to produce the stock slurry as a high-consistency (quite often greater than 6 percent) solution, store this in a relatively small tank, and dilute it when required. Under these requirements, a double dilution as shown in Figure 3.12 is necessary.

The object of the two dilutions is as follows: adding primary dilution reduces the consistency of the lower portion of the pulp within the tank to a value (approximately 4 percent) that allows it to be pumped easily and to follow this by the addition of the secondary dilution water into the outlet to bring the pulp to the specification required by the paper machine.

Double Dilution of the Stock—System Operation

The instrumentation illustrated provides a measure of the stock consistency at the pump discharge via the sensor transmitter tagged AT. This measurement is supplied as the measured variable to the consistency controller AIC-1, which could have either a single proportional-only control term or a gap action control function. When using the I/A Series system, these control algorithms carry the names PID and DGAP, respectively, and produce a continuously varying output. As explained before, however, a gap action controller does not produce an output when the measurement is within the gap (deadband) but only when the measurement is outside the predetermined upper and lower limits of the gap. The output from AIC-1 is applied to the current/pneumatic converter I/P to manipulate the control valve in the primary dilution water line and also as the measurement to controller AIC-2, a PID control algorithm, which manipulates the control valve via the current/pneumatic converter I/P in the secondary dilution water line. Both controllers AIC-1 and AIC-2 have manual set points, which allow the process operator to determine the stock consistency required. This control system should keep the situation under scrutiny for most of the time. However, there may be occasions when the quantity demanded by the machine increases, and allowance must be made for these increases.

Should the manufacturing operation encounter occasional increased stock demands, a flow control loop is included to provide for precisely those situations. The flow loop, shown dotted in Figure 3.12, illustrates how it is incorporated into the system when required and uses a magnetic flowmeter to determine the quantity demanded. The flow measurement is applied to an indicator to advise the operator of the situation and also to a scaler (a multiplier) should this be necessary to align the two parameters (flow and consistency). The output from the scaler is applied as a positive bias to the output bias of controller AIC-1 to adjust the dilution water flow sufficiently to meet the new requirements.

THE HEADBOX

This piece of the process plant is most important, for no paper sheet will ever be formed without it. The purpose of the headbox is to:

- Reduce the turbulence brought about by the stock being pumped to the wire.
- Eradicate the effects of multiple flow velocities and unify them into a uniform effective one and hence disperse the fibers uniformly through the system.
- Direct the stock toward the slice.

We shall consider only two of the several types of headbox in use—one that is of the older design and the other a more up-to-date version. It is hoped this will give the reader a feel for the scope involved. The outlet from a pump usually terminates in a circular section pipe. The paper machine headbox is not of circular cross section because it has to produce a sheet that is rectangular and uniform in cross-section; a means must therefore be found to effect the transition. This requirement results in designs that involve having, for example:

- A single centrally located circular inlet and multiple circular outlets, which are supplied through a manifold with a double-tapered distributing section, the double taper having its widest section at the middle.
- A single circular inlet that terminates in a rectangular fan-shaped wedge, with a discharge opening width to suit the headbox dimensions. There are limits on the angle of the fan shape, and care has to be taken not to impose turbulence on the material passing through.
- Several variations on this theme.

The resulting item produced is called a *distributor*. In view of the wide choice available, the reader should investigate this aspect further. The stock is screened prior to entering the headbox as a final precaution against particles that could damage the wire or the paper being made. No single type of headbox or distributor is suitable for all the various types of paper made; each type demands a compromise to meet the machine speed and grades of paper being produced.

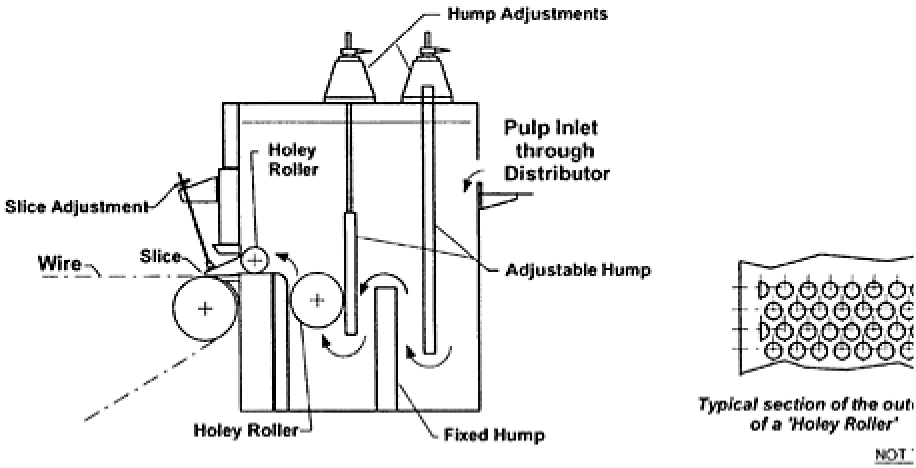


Figure 3.13: Schematic of open-type headbox.

OPEN TYPE

The open-type of headbox is the older of the two which we shall consider and is suitable for the slower paper machines where the wire speed is in the range of 600 to 800 feet per minute. Figure 3.13 is a cross-sectional view of the equipment, the *holey rolls* and *humps* providing the means of controlling the flow of the stock. The level of the stock is varied by adjusting the humps, which alter the flow to the slice and change the height of stock in the tank to suit the speed of the wire. The higher the speed, the higher the level required. For very high speeds, the height of the box sides will also have to increase, which of itself imposes restrictions on the use of such headboxes. From the illustration, it should not be difficult to visualize the effect the position of the manually adjusted variable humps has on the flow characteristic and velocity. The holey rolls with their perforated skin provide the means of reducing the inevitable turbulence, straightening out the flow of stock, and distributing the stock evenly across the entire width of the holey roll as it moves toward the slice.

CONTROL TECHNIQUES USED TO ENSURE AN EVEN DISTRIBUTION OF THE STOCK

We shall now consider some of the methods used to control the distribution of the stock evenly across the width of the wire. Since the wire is moving continuously, the stock has to emerge out of the headbox in a steady stream of predetermined thickness and at a rate dependent on the velocity of the wire. From this it can be seen that a mathematical relationship exists between the material flow and the wire velocity. This relationship is:

$$v = C_v\sqrt{2gh}$$

where v is the spouting velocity

C_v is the coefficient of velocity discharge

g is the acceleration due to gravity

h is the total pressure head

The *spouting velocity* is the velocity at which the stock issues from the slice, which must equal the wire speed. The reader should also recognize this equation as essentially the Bernoulli relationship for flow obtained when using the measuring technique of the differential head created by a restriction (the slice in this case) of calculated size.

THE HEADBOX SLICE

On any headbox, the slice is a most important item for the thickness; hence, the weight and formation of paper sheet depend on it. The slice performs the following functions:

- It acts as a metering orifice (hence the Bernoulli relationship referred to earlier) that controls the distribution of stock across the width of the wire. The slice, regardless of the sometimes erroneously held view, does not control the total flow to the machine; flow control is the function of the fan pump and its associated control valve.
- The spouting velocity is controlled by the slice opening and is effected by adjusting the average opening of the entire slice.
- In coordination with the holey rolls, the slice controls the stability of the stock flow.
- Slice geometry influences the fiber orientation.
- The slice controls the trajectory of the stock on to the wire; automatic control is a very important consideration in this respect on fast, modern machines.

A Mechanical Method

Figure 3.14 illustrates a mechanical method, using a float to ensure the correct total pressure head and stock level in a closed headbox. The system operates as follows.

Since the float chamber is so connected that the air space and the stock in the headbox are in communication with each other in the manner as illustrated, the level in the float chamber is in fact the level in the headbox. The pointer, which is attached to the float, is constrained to move in the vertical direction only and moves across a vertical scale to indicate the level in the headbox.

The description of the float-operated valve that now follows has been deliberately simplified for clarity of its operational functionality. When the system is operated such that there is a positive air pressure above the level of the stock, the operating mode is considered to be under pressure. We shall now describe the action when the system is under pressure. Valve A is a plug valve attached to the float-connecting rod and moves vertically with it; the position of the valve seat is adjustable. As we have just seen, the height of stock in the headbox is related to the spouting velocity and therefore the wire speed. The system is adjusted by physically raising the float assembly to a position that is related to the operating wire speed, and the seat is adjusted so that the plug is tight against it and valve A is therefore closed. Valves B and C are partially throttled to allow stock to enter the measuring chamber, the float position indicating the level. When there is no further float movement, valves B and C are adjusted finally to establish equilibrium between the air-padding pressure and the delivery head of the pump. This final adjustment maintains the correct spouting velocity.

Under this operating condition, as the pressure increases, the discharge head of the fan pump increases, which results in a reduction of stock delivered to the

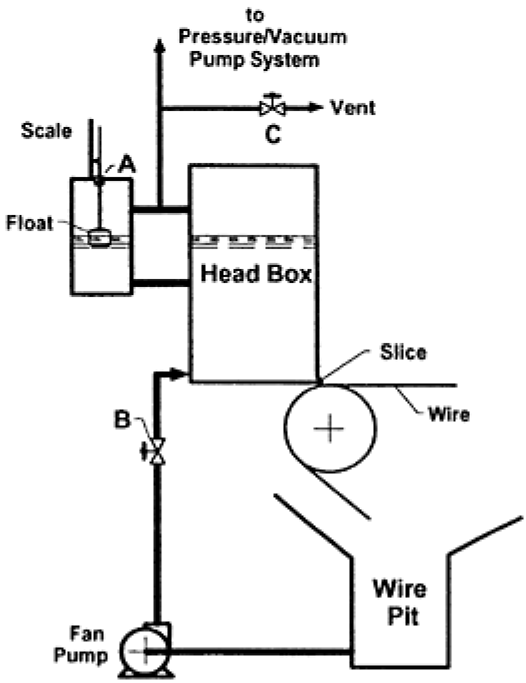


Figure 3.14: Schematic diagram of a mechanically operated float-type pressure/level headbox.

headbox. And when the level in the headbox falls, the discharge head of the fan pump decreases, resulting in more stock being delivered to the headbox. The float follows the change in stock level and opens or closes valve A to adjust the air pressure accordingly, which allows the amount of stock delivered to the headbox to vary accordingly.

When the system is operated such that there is a negative air pressure above the level of the stock, the operating mode is considered to be under vacuum. Under this mode, the initial operational adjustments are made so that when the stock is at the operating level, the plug of valve A is away from the seat. Therefore, valve A is open. When operational and the stock level rises, valve A opens to admit more air to increase the pressure and reduce the vacuum. The discharge head fan pump in turn increases and results in a reduction of stock delivered to the headbox. When the level in the headbox falls, the float follows the reduction in stock level and results in valve A closing and increase the vacuum. This in turn results in a reduction in the discharge head of the fan pump and allows more stock to be delivered to the headbox to raise the stock level.

For other mechanical methods used to control the stock level in the headbox, and the reader should investigate these independently.

Instrumentation-Assisted Stock-Level Control of the Headbox

Modern paper machines operate at very high speeds—typically 3000 feet per minute (34 mph, i.e., 55 km/h) and above; hence, mechanical methods of headbox control have had to give way to more sophistication. Figure 3.15 is a sectional view of a typical modern headbox with the instrumentation for stock-level control included.

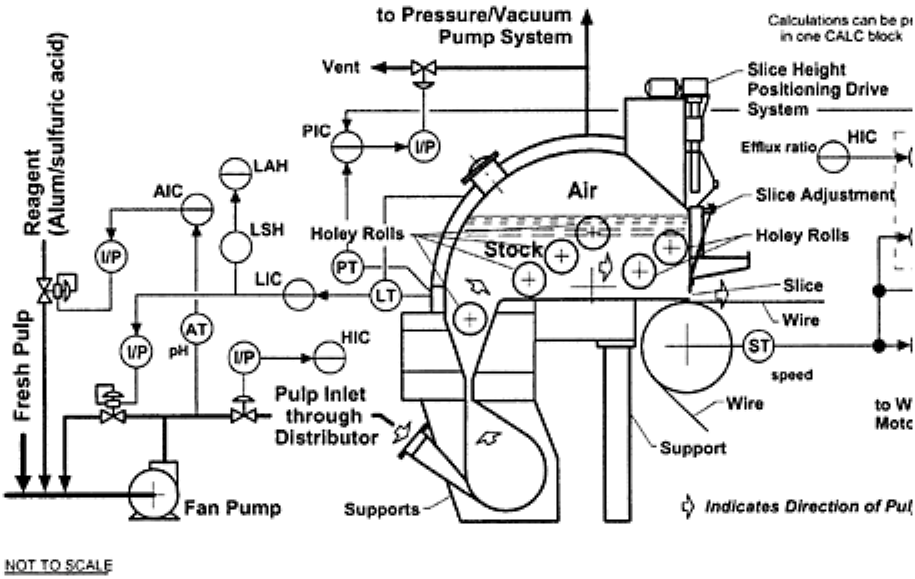


Figure 3.15: Sectional view of typical closed headbox with schematic of controls superimposed.

The bubble format for instruments superimposed on the schematic of the equipment method of depiction should give the reader an idea of what to expect in a paper mill and a better understanding of the operating principles of the system. The old method of eliminating flow turbulence by using holey rolls is still applied, but the arrangement and locations are now more precisely determined to achieve the objectives. With these machines, the pressure/vacuum headbox operation is an absolute necessity due to the wire speeds involved. The main task for the control system is to maintain the pressure/vacuum and stock level at the predetermined optimum values at all times to suit the wire speed of the machine.

The measuring instrument for level uses the differential pressure principle, and the sensor is of the extended diaphragm type. Use of the extended diaphragm on the connection in contact with the stock in this application ensures that the stock is not allowed to enter the instrument body, where otherwise the fibers would stagnate over time, coalesce to a solid mass, and impede the action of the sensing diaphragm. Since air is applied to the top of the stock, the low-pressure connection to the instrument can be made directly to the air space in the headbox. However, care must be taken to choose the connecting point so that under no circumstance can stock enter the instrument impulse line. The output signal from the level transmitter tagged LT is applied as the measurement input of a two-term (P+I control action) controller tagged LIC, whose set point is operator determined. The output of controller LIC manipulates the control valve fitted across the fan pump. The control valve is fitted with a valve positioner whose gain is used to assist the control of the process. The valve should divert only about 10 percent at most of the stock to achieve the control objective and accordingly be sized correctly, but the maximum throughput handled by the valve will have to be larger than this to ensure that the valve is not at the limit of its travel at maximum flow demanded. By adjusting the manual loading station tagged HIC, the operator determines the discharge head of the fan pump and the maximum amount diverted by the control valve. A high alarm comprising a level switch tagged LSH connected to an alarm tagged LAH is configured on the output of controller LIC, so that it trips when the control valve is diverting more than 10 percent of the stock flow allowed. The alarm calls the operator's attention to this fact and enables him or her to readjust the HIC to bring the control valve back into the operating range of 10 percent stock diversion.

The total pressure (stock+padding, i.e., the pulp plus the air pressure above it) is measured by the pressure sensor/transmitter tagged PT, which once again should be of the extended diaphragm type because the process connection is located in a situation where stock is always present. The output of PT is applied to the measurement of the controller tagged PIC whose set point is operator determined. The controller output manipulates a control valve, which vents air above the stock to the atmosphere to maintain the required pressurized conditions in the headbox. Note: changing the air pressure also influences the level in the headbox.

Rush/Drag Control

We have seen earlier that mat formation laid down (on the wire) depends on the rate at which the stock is deposited onto the wire, the speed of the wire, and the spouting velocity of the stock. Some grades of paper require that the wire speed exceed the spouting velocity; in other words, the wire so to speak *drags* the stock on to it. Other grades of paper require that the spouting velocity be greater than the wire speed or, putting it another way, the stock *rushes* on to the wire. The ratio of rush to drag or *efflux ratio* varies as the ratio of spouting velocity to wire velocity, or symbolically:

$$Eff = \frac{v_{spout}}{v_{wire}}$$

where *Eff* is the efflux ratio

v is velocity with appropriate subscripts.

From this it is clear that:

- When the efflux ratio is 1.0, the spouting velocity is equal to the wire velocity.
- When the efflux ratio is less than 1.0, the spouting velocity is less than the wire velocity and the stock is being dragged onto the wire.
- When the efflux ratio is greater than 1.0, the spouting velocity is greater than the wire velocity and the stock is being rushed onto the wire.

For the system illustrated, we use the relationship given earlier: $v = C_v\sqrt{2gh}$

Combining the constants *Cv* and 2*g* as *K* gives: $v = K\sqrt{h}$

Squaring both sides, we have: $v^2 = Kh$

This shows that the spouting velocity squared is proportional to the total pressure head of the stock in the headbox.

Measuring the wire speed with a tacho-generator tagged ST produces a signal proportional to speed, which is applied as the measurement input of the speed controller tagged SIC. The controller has a manual set point, and the controlled output is applied to the wire drive motor as the correction to regulate the wire speed and maintain it at the value determined by the operator.

The regulated wire speed signal is squared in the first multiplier to produce the value of v^2, which is the *theoretical head* required for the wire speed. The output of the manual loading station represents a bias calibrated in terms of the efflux ratio *(Eff)*, which is multiplied by a signal representing v^2 and applied as the set point of the total head pressure controller PIC. The total head pressure controller tagged PIC receives its measurement from the pressure sensor/transmitter tagged PT and compares it with the remote set point. Any error resulting produces a controlled output that manipulates the control valve in the vent line from the headbox to regulate the pressure to that demanded by the efflux ratio.

Stock pH Control

The stock prepared upstream of the headbox is monitored and corrected for its pH as it progresses through the various stages, but, because this is a very important parameter, the stock has a final check and correction just before it is put on the wire. The final pH of the stock is usually in the range 4.5 to 5.0 pH units. The most suitable place for making the measurement via the sensor/transmitter tagged AT is just after the discharge of the fan pump as illustrated in Figure 3.15—with the reagent, which could be either alum or sulphuric acid, or both, entering the stock line on the suction side of the fan pump. This arrangement will take care of the complete reagent dispersion throughout the stock, brought about by the turbulent flow taking place within the pump unit that is most necessary in every pH control loop. The choice of pH sensor is an important consideration because of the nature of the process fluid, and also because of the very real possibility of causing a blockage—another reason for the choice of sensor location. Only one reagent line has been shown for simplicity, but it should not be difficult to add a second reagent line and arrange for a switch from one reagent line to the other, or to use both reagents depending on the measurement of the pH obtained. In the case of multiple reagent use, the matter should be discussed with the technologists at the mill concerned and a solution determined. It is important that the transition from one reagent to the other is effected correctly because the control signal will have to be switched. Since pH has a nonlinear characteristic, it is vital that the controller tagged AIC is not the standard PID algorithm but the PIDX; the latter algorithm has a nonlinear gain that suits this application particularly well. The control valve should have an equal percentage characteristic, and it is suggested that it is fitted with a positioner. This arrangement of the valve will take care of the logarithmic character of the pH loop.

The reader should not conclude that the methods of controlling the headbox shown are the only ones used in the industry. The restriction is self-imposed to keep the text simple, confined, and directed to giving the reader a feel for the subject. However, many other ways of implementing headbox control are possible and it is suggested that further reading be undertaken to widen the knowledge base.

WATER DRAINAGE FROM THE STOCK ON THE WIRE

The stock discharging from the slice on the headbox onto the wire comprises the fibers, size, fillers, and so on, all held together in a vast amount of water that has to be drained off very rapidly in order to allow the sheet to be formed. This requirement of rapid water drainage becomes more acute when the wire speed is high. It had been found that, using equipment developed for the purpose of fast drainage, and from experience gained thereby, about 95 percent of the water is drained off while the continuously forming sheet is still on the wire. The sheet of paper left behind on the wire is a mat that is still quite wet and comprises 60 to 100 percent fibers. The mat is of almost uniform density across the width of the sheet and consists of interwoven fibers randomly arranged in what is called the *formation*. The meaning of the term *formation* is restricted not only to the dispersion and orientation of the fibers, but covers the quality of distribution of sizes, the fillers, and other components, used in its makeup as well. The papermaker assesses the paper by the amount of light transmitted through the sheet, giving rise to the term *look-through;* the assessment made defines the quality of the formed sheet.

Some of the main reasons why water drains from the stock are as follows:

- The force produced when the jet of stock strikes the wire at a large angle ejects a quantity of the retained water. This inertia force is used to advantage on machines making tissue paper but not for other types because of the poor formation when making heavier grades.
- The weight of the water (hydrostatic pressure) contained in the stock, which is spread on the wire, forces the water off, but this phenomenon is not of much use except on very slow machines.
- The suction forces that are developed as the wire moves over the *table rolls* discharge

the water; this force is responsible for the greatest amount of drainage on the machine.

• The suction applied to the underside of the wire by specially designed *suction boxes* working under vacuum draws large amounts of water off. The amount of water drained off with these boxes compares very favorably with the drainage achieved by the suction developed by the moving wire (i.e., by the previous item).

Note: The table rolls are located on the underside of the wire and rotate in contact with it. The maximum suction developed is numerically equal to the theoretical head, which is the head required to give the spouting velocity for the machine speed. When operating at very high speeds instead of the normal table rolls, grooved ones are used instead, or sometimes *drainage foils* or *water doctors,* as they are also often called. These are stationary water deflectors and replace the table rolls. The grooves, which are spaced along the entire length of the table roll, are normally very narrow and cut around the periphery concentrically with the roll diameter. However, spiral grooves are used occasionally instead. Suction boxes use a vacuum created by a vacuum pump in the range 5 to 8 in Hg. Using high vacuum increases the drag and reduces the life expectancy of the wire. Hence, controlling the vacuum to effect both good drainage and long wire life is an important consideration.

SUCTION BOX VACUUM CONTROL

Figure 3.16 is a schematic arrangement of vacuum boxes, which are stationary and placed under the moving wire. Because of the contact made between the two, severe wear could be experienced on both the wire and the top of the box. To minimize the wear on the wire, which is expensive to replace, the top of the suction box is of a material that is more amenable and less abrasive to the wire and hence could be made of wood, plastic, synthetic rubber, or even ceramic. Another more recent solution to the wire wear problem is to replace the fixed top of the box with a perforated belt that is free to rotate around the box and thereby to emulate the action of the table roll and minimize the friction on the wire but cause the wear to

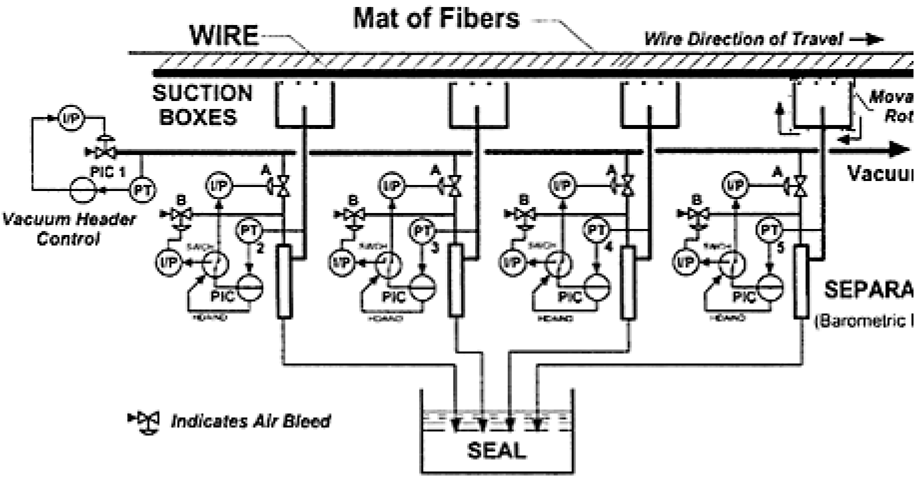


Figure 3.16: Schematic of vacuum control of suction boxes.

occur between the movable belt and the top of the box. As a license for illustration purposes, and to clarify the intent of the operation of the movable belt, only the last box in Figure 3.16 has been modified to show the action of this latest innovation.

The system operates as follows. The pressure in the vacuum header is monitored by an absolute pressure sensor/transmitter tagged PT-1 that provides the measurement to the pressure controller PID algorithm tagged PIC-1 having a manual set point adjusted by the operator to a predetermined value. The controller output manipulates the control valve via the current/pneumatic converter I/P to bleed sufficient ambient air into the header in order to maintain a steady vacuum in the header at the required value.

For the purposes of this description, four suction boxes are shown, with each box regulated by individual and identical pressure control loops numbered 2 through 5. Since all the pressure control loops are the same, the description will cover the detail functioning of one loop only and will therefore apply to the remainder. Considering loop 2 as the example, we see that the pressure in the down-comer from the suction box is measured by sensor/transmitter tagged PT-2, which provides the signal generated as the measurement for pressure controller PID algorithm tagged PIC-2 whose set point is predetermined by the operator. The controller output is connected to the common input of a changeover switch (SWCH) algorithm or unit in which the NC (normally closed) contact is connected to a current/pneumatic converter I/P-2A to manipulate control valve A in the line that connects the vacuum header to the suction box. Control valve A has a normally closed failure mode; that is, it needs a control signal to drive it open. As a result of applying the controller output via the switch, control valve A is held at a position dictated by the magnitude of the controller output. Under normal operation, the moving wire and wet mat resting on it produce an hydraulic gradient where the underside of the wire is at a slightly lower pressure than that above it, thus allowing water to drain away from the mat. Because the separator is operated at a value just slightly below atmospheric pressure (barometric loop), the water is pulled down into the separator. The head of the collected water in the separator makes it drain into the seal chamber. The controller PIC-2 modulates control valve A to ensure coincidence between measurement and set point. During configuration of the system, the operator sets HDALIM (high-deviation alarm limit), a parameter in the PID algorithm, with a real number representing the highest value of vacuum permitted in the suction box. When the value of the measured pressure produced by sensor/transmitter tagged PT-2 goes above that set on HDALIM, a boolean variable HDAIND (high-deviation alarm indicator), another parameter in the PID algorithm that is normally false (0) is set true (1). This boolean variable is applied as the toggle of the switch (SWCH) algorithm and, when true, makes (SWCH) change state. That is, the NC contact opens, and the NO (normally open) contact is forced closed. This action now directs the output of controller PIC-2 to the current/ pneumatic converter (I/P-2B) associated with the air bleed control valve B instead. Control valve B also has a normally closed failure mode. Controller PIC-2, which is now connected to control valve B, allows air to ingress and lower the vacuum in the suction box. The switch action cuts off the drive signal to control valve A, which is forced to its (closed) failure mode, allowing the pressure in the suction box to reestablish to the correct value.

THE WIRE PIT

The drained water from the mat is collected in an assembly of vessels commonly referred to as the *wire pit,* which is always under the wire. The collected water is dispersed to other vessels and ultimately back to the stock. It is therefore important that the pit does not overflow because that would create problems for the mill. For this reason level controls are appropriately implemented. Figure 3.17 is a schematic of the various segments of the pit with the controls superimposed.

The level in the white water tank is measured by the level sensor/transmitter tagged LT and the signal applied as the measurement for the controller tagged LIC whose output manipulates the control valve in the discharge of the pump to regulate the amount of white water in the tank, sending the excess to the save-all.

The temperature of the water in the wire pit is measured by the temperature sensor/transmitter tagged TT and is applied as the measurement for the controller tagged TIC whose output manipulates the control valve in the steam supply line to maintain the operator set value of temperature in the wire pit. This material will find its way via the fan pump back to the headbox where temperature has to be maintained.

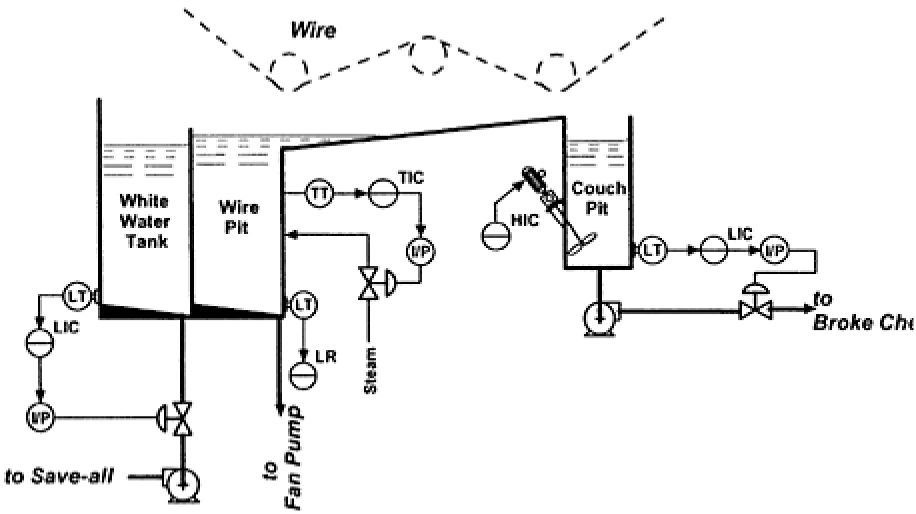


Figure 3.17: Schematic of the controls for the wire pit.

The level in the couch pit is measured by the level sensor/transmitter tagged LT and provides the measurement for the controller tagged LIC whose output manipulates the control valve in the discharge of the pump to regulate the amount of liquid in the pit, sending the excess to the broke chest.

A manual station tagged HIC is provided to allow the operator to regulate the agitator in the couch pit.

THE DRY END

Figure 3.18 illustrates a two-bank paper drier, with each bank comprising an upper and lower set of drier rolls and felts; this section of the process transforms the fragile wet mat carried on the wire into a reasonably dry sheet of paper. At the end of its traverse across the drying rolls the mat only contains about 6 percent water (94 percent dry fiber). The evaporation rate is approximately 2 lb (1 kg) per ft^2 ($0.186m^2$) of water per hour of total drier surface. This drying rate is subject to variation, dependent on the pressure of the steam used for the purpose. The diameter of the drying rolls can vary from 48 to 60 in (1.9 to 2.4 m) dependent on the machine involved. The drier rolls pose a difficult problem because the mechanical joints for steam entry on these units have to be suitable for operation at high rotational speed and at the same time must under these taxing conditions, and all circumstances, provide a proper seal for both steam and condensate (water). To add to the difficulties, the condensate that results when the steam gives up its heat is not easily removed from within the fast rotating cylinder.

One can imagine the situation on a 60 in (2.4 m) diameter drier roll; the hydraulic lift required to push the condensate out will have to be 30 in (1.2 m) wg, equivalent to a pressure of 1.08 lb/in^2 (0.076 kg/cm^2). To allow for anomalies, the pressure to lift the condensate from inside the drier roll to the condensate drain line connection on the outside of the roll is rounded up to 2.0 lb/in^2 (0.14 kg/cm^2). The problem is to ensure that the suction tube that bends down from the axis of rotation of the drier roll is always beneath the surface of the condensate held within the roll and remains in that position throughout its operational life. Figure 3.19 is a schematic of a typical arrangement of a steam-heated drier roll.

Refer once again to Figure 3.18. For the purpose of showing how the paper and felts are arranged to carry the sheet from the wet to the dry end of the machine, the drier rolls have been deliberately spaced apart. Normally these are quite closely assembled so that the transition is smooth and even. As the mat dries it will shrink; this longitudinal shrinkage will therefore affect the speed of the rolls, which will have to be adjusted to suit the reducing length to avoid a paper break.

The felt tensioners are provided to allow the felts to be adjusted because felts stretch and shrink as they go between wet to dry regions in each of the two sections. The mat is held tightly against the hot rolls at all times and can be exposed to the maximum heating surface. The illustration shows two felt driers on the upper and lower banks of the wet end also included. This is to ensure that the wet mat coming off the wire will have the excess removed by absorption, which will necessitate water removal from the felt before it comes into contact again with the continuously wet mat to keep the drying process effective.

The steam driers are of standard size, and when used on machines in mills producing paper board, the path taken by the board is still convoluted when manufacturing heavy board, but these machines are not fitted with felts because the strength of the board is sufficient to hold the board material against the rolls for effective drying to occur. However, in mills where light boards are made, there is usually a felt on the lower set of drier rolls only.

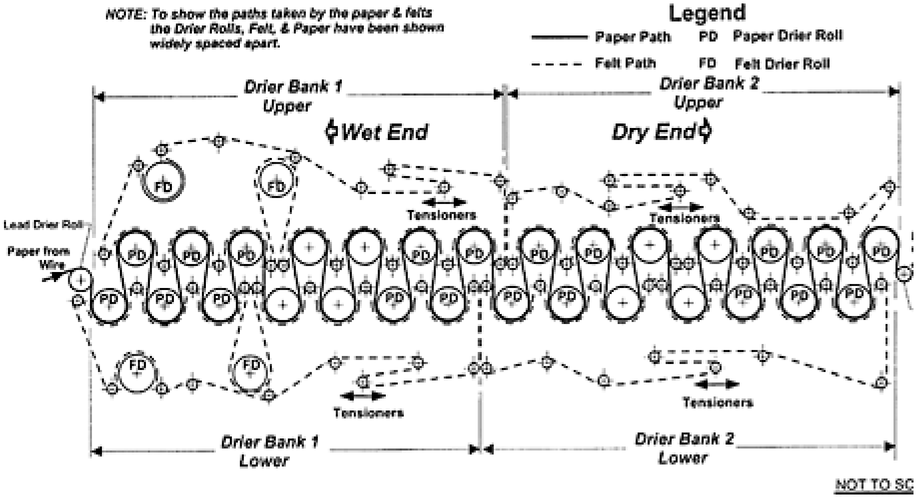


Figure 3.18: Typical arrangement of a two-bank paper drier.

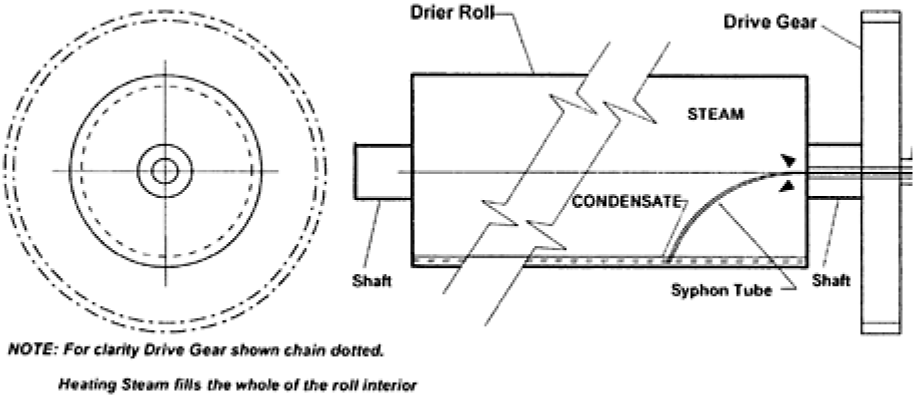


Figure 3.19: Schematic arrangement of steam heating of drier roll.

STEAM DISTRIBUTION TO THE DRIER ROLLS

Figure 3.20 presents a simplified heating steam distribution system for the drier rolls on the machine. The system illustrated is virtually the same as that shown in Figure 3.18, but for clarity and simplicity some of the intermediate rolls have been omitted. As will be seen, the machine is divided into sections; this is necessary to obtain the best and most efficient water extraction from the drying process. To achieve the maximum heat availability, the pressure to each section of driers and the differential pressure between the steam supply and the condensate is controlled. The reason behind this is to maintain the heat content constant, for if the steam pressure is held constant, then the enthalpy of the steam also remains constant. For this reason, the pressure difference between the steam and condensate headers is held as constant as possible and is controlled by the differential pressure controller. The amount of heat in the steam can be calculated using the data available in a table of the thermodynamic properties of water—commonly referred to as steam tables.

THE CONTROL SYSTEM FOR THE DRIER ROLL

The steam is introduced to the system from the dry end of the machine, and its usage is measured, recorded, and integrated (totaled) in the loop tagged FR-1/FQ-1, respectively. The instrument used to measure the steam is shown as an in-line device, which could be a vortex type flowmeter since this instrument can now be made to operate at high temperature and is available for line sizes up to 8 in (203.2 mm).

The controls operate as follows: Pressure sensors/transmitters tagged PT-1, PT-2, PT-3, PT-4, and PT-5 measure the steam pressure in each steam subheader associated with a drier section allocated to it and produce a proportional measurement signal, which is applied to the pressure controllers PIC-1, PIC-2, PIC-3, PIC-4, and PIC-5. Each of the controllers has a manual set point that the operator adjusts to a predetermined value at which it is desired to operate the machine (sections). The correction signal (i.e., controlled output) from each controller is applied, via a current/ pneumatic converter, to an associated control valve located in the steam supply line to the section of drier rolls allocated to it and modulates the valve accordingly to maintain the allocated steam subheader at the desired value.

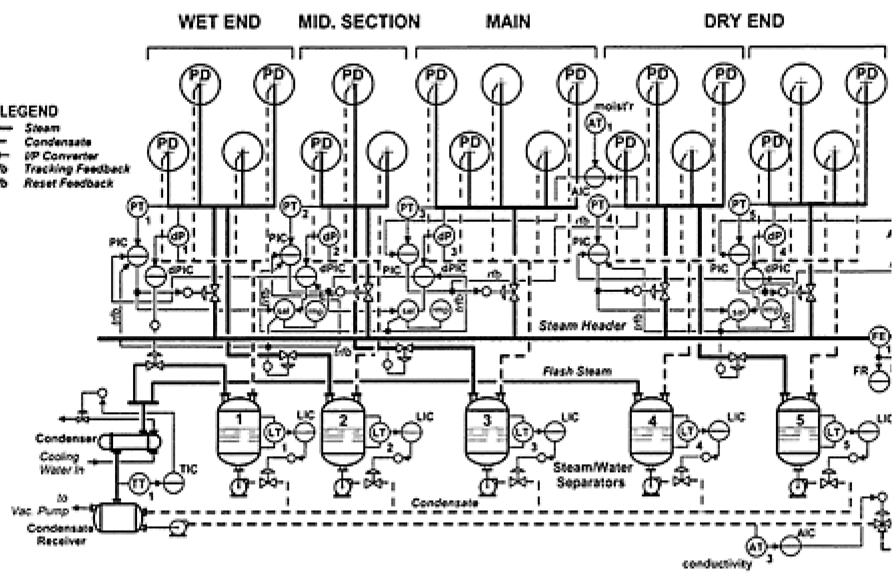


Figure 3.20: Typical simplified steam distribution system for paper drying.

The hot steam that comes in contact with the cooler drier rolls gives up some heat and condenses back to water; the condensing rate will reduce as the rolls heat up and will eventually even out to a value(s) dependent on the ambient conditions of the surroundings. This conversion of steam to water results in a pressure reduction in the condensate line. Differential pressure sensors/transmitters dPT-1, dPT-2, dPT-3, and dPT-4 measure the pressure difference between each drier section steam subheader and the associated condensate subheader, and produce a signal proportional to it. This signal is applied to differential pressure controllers dPIC-1, dPIC-2, dPIC-3, and dPIC-4. These controllers also have manual set points that the operator adjusts to a predetermined value at which it is desired to operate that section of the machine. Each correction signal from the controller dPIC-2, dPIC-3, and dPIC-4 is applied to its low signal selector tagged sel. To make a selection, a minimum of two signals is required; hence, each signal selector has as its second input the controlled output from the pressure controllers PIC-1, PIC-2, and PIC-4 respectively. Controller dPIC-1 regulates a control valve located in the exhaust steam line from the first steam/water separator to maintain the desired pressure difference in the steam subheader associated with the wet end drier section. With this arrangement, it will be seen that the pressures in and differential pressures between the drier sections have been regulated. In addition, the control valve in the steam line of steam/water separator #2 is regulated by either dPIC-2 or PIC-1; the control valve in the steam line of steam/water separator #3 is regulated by either dPIC-3 or PIC-2; and the control valve in the steam line of steam/water separator #5 is regulated by either dPIC-4 or PIC-4. To achieve this regulatory pressure control, it is necessary to select which of the two controllers will perform the regulation, and an automatic selector control system is required.

THE AUTO-SELECTOR CONTROL SYSTEM

Note: The following description of the system is as general as possible. However, to show how it relates to the particular paper-drying system, comments are made and enclosed in parentheses at appropriate places in the narrative to show the readers how the system is relevant to the paper drier.

We will now describe an automatic selection of an appropriate controller from several (either pressure or differential pressure in paper drier applications) that will maintain stable conditions of different but interrelated process parameters (the relevant steam subheaders in the paper drier application). This automatic method of selection is called an *auto-selector system;* the system to be discussed was designed and developed by the Foxboro Company. For any auto-selector system to work efficiently there must be only one control valve, which, when regulated, has a simultaneous effect on the control loops involved. (Such conditions exist in the pressure and differential pressure loops selected.) It is important that only one of the controllers has an Auto/Manual Transfer switch, and transfer of the loop from Auto to Manual is effected only through this controller. (In this specific case, the controllers with the Auto/Manual Transfer switch will be dPIC-2, dPIC-3, and dPIC-4.) The operating set point of each controller will be different for each process parameter and represents the safe operating limit for that parameter. Since we have to select an appropriate controller to bring the system under control, we must have a means of selecting the appropriate output for it.

To select the output we use a signal selector. The signal selector chosen could have either high or low selecting functions and be designed to choose either the highest or lowest—depending on the type chosen—of the signals applied to it. The choice of selector unit depends on the application. (In this particular case, a low signal selector is required and will transmit the lowest of the signals connected and apply it to the control valve to correct the process being controlled.) If the measurements are at set point, or one or more proportional bandwidths on the “safe” side of the associated set point, the output from the signal selector will be at either maximum or minimum, dependent on the selector. (In this particular case, it will be minimum because the selector is a low function, thus allowing the process to operate at maximum throughput. On the other hand, if the system had a high signal selector, then the output applied to the control valve would be the highest of those applied to the signal selector, again allowing the process to operate at full capacity.) When any of the measurements approaches its safe operating limit, the output from each associated controller will begin to change. The amount of change is dependent on the magnitude of the error (i.e., the amount of deviation from set point).

The output from the controller producing the greatest error is selected as the one that is applied to the control valve to make the correction to the system. The unselected controllers will in the interim continue to make corrections, although these are not selected for action until they go outside the safe operating limits. To do this, each controller is provided with a tracking feedback signal from the signal selector output, which permits the individual controllers to track the selected output and bring it into service at any time one of the unselected controller’s output goes outside the safe limits. When the controller with the Auto/Manual Transfer switch is transferred to Manual, the output tracking maintains the outputs of all the other associated controllers at their last value. The *ramp* function is not included in the feedback loop. When initiated, its output will continue to ramp until it reaches a maximum value, being limited only by its supply voltage, and will remain at that value until reset. After it has been reset, it will assume control again, but only if it becomes the lowest input to the signal selector. (A ramp is used to start the drier system; this is discussed further on in this section.) The logic will determine when the ramp starts and when it is reset. The schematic shown in Figure 3.21 illustrates

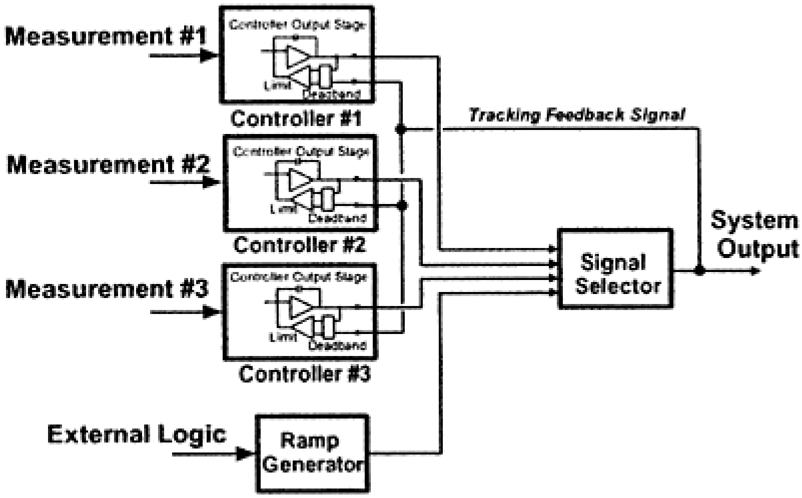


Figure 3.21: Schematic of three-variable auto-selector system.

how the control and tracking functions of the controllers involved in an auto-selector system operate.

THE CONTROL SYSTEM FOR THE DRIER ROLLS—CONTINUED

As will be seen from Figure 3.21 the tracking feedback is taken from the signal selector tagged sel output that is applied to the control valve. A ramp function tagged rmp has been provided to allow the drier roll to warm up gradually, and the rate of rise is adjustable to suit the application. The logic to initiate the ramp has not been shown, for it also has to be designed for the particular application, and it is suggested that the requirements be discussed with the paper mill engineers.

Controllers PIC-3 and PIC-5 have set points that are provided from paper moisture controllers, which receive their measurement from moisture sensor/transmitters tagged AT-1 and AT-2. The moisture content of the paper can be determined in several ways. One type of moisture-measuring instrument used works on a variable capacitance principle because the dielectric constant of moisture-laden paper is much greater than that of dry paper. The sensor—basically a capacitor—is placed in contact with the moving sheet of paper, with a pressure sufficient to prevent the sheet from leaving the sensor. The moisture in the layer of paper alters the capacitance of the sensor, which is detected, converted to a suitable workable signal, and forms the measurement to the controllers AIC-1 and AIC-2. This type of capacitance sensor has a typical measurement range of 4 to 8 percent moisture maximum and is never installed near the headbox where excessive moisture and temperature will damage the instrument. Sensor AT-1 is installed between the last main drier roll section and the first dry end roll section, and sensor AT-2 between the callender stack and the reel. Space limitation dictates that the location of the latter sensor is not shown in the figure. The outputs from the moisture controllers are the set points for the pressure controllers PIC-3 and PIC-5, respectively. These moisture control loops require a reset feedback signal that prevents the integral term on controllers AIC-1 and/or AIC-2 from saturating when the operator puts controllers PIC-3 and/or PIC-5 into manual mode. Provisions should be made with the moisture/pressure cascade loops to reduce the roll temperature by regulating the steam pressure in the event of a paper break and to restore it to normal value when the paper flow is restored. This function is not shown, however.

Level sensor/transmitters LT-1, LT-2, LT-3, LT-4, and LT-5 measure the condensate levels in the steam/water separators #1 through #5 and apply their output signal as the measurement to level controllers LIC-1, LIC-2, LIC-3, LIC-4, and LIC-5, respectively. The controllers have operator set points, adjusted to maintain a positive head on the pump suction at all times. The pump start, stop, and protection circuits are not shown in the interests of overall clarity but would be included.

The temperature sensor transmitter tagged TT-1 measures the temperature of the condensate from the vacuum condenser and the signal produced, applied as the measurement to the controller tagged TIC-1, fitted with a manual set point. The output of Controller TIC-1 manipulates the control valve installed in the cooling water discharge line to maintain the required temperature.

The conductivity sensor/transmitter tagged CT-3 measures the condensate conductivity from the condensate receiver and the signal produced, applied as the measurement to the conductivity controller tagged CIT-3 whose output manipulates the three-way diversion valve. Normally, the valve-porting arrangement allows the condensate to enter the condensate storage tank if acceptable but diverts the condensate to drain if the conductivity is too high. This is indicative of a high level of contamination.

THE YANKEE MACHINE

The drier system described earlier does not lend itself completely to the drying of lightweight, tissue, crepe, and fine papers (e.g., cigarette paper). These particular grades of paper require a specialized drying machine called a *Yankee*. Figure 3.22 illustrates the arrangement of the drier section of a typical machine of this type but omits the headbox at the front of the machine and the callender stack, together with the reeling at the back end of the machine as these are virtually the same as discussed earlier.

The main difference between this machine and the one previously considered is the massive drying roll, which can have a diameter of 8 to 12 ft (2.4 to 3.7 m) and is made from cast iron or cast steel inasmuch as rolls made of lighter construction unfortunately do not have the same performance. Since the drying roll is of such a large size, it contains a great amount of metal for stability of shape when rotating at speed and for heat retention. One can see that getting the mass of metal involved to working temperature will take considerable time, and any control system will have to take account of this fact. The outer surface of the roll is highly polished to handle the grades and type of paper produced; it must be handled with care by both the instrumentation and the process operators. On a Yankee machine, there is no felt on the drier roll, and the wet paper is tightly pressed against the highly polished surface where it clings until dry. To produce crepe paper, a type of scraper called a *creping doctor* is used; crepe napkins and absorbent towels are examples of papers that require this attachment. Both the creping doctor and the *cleaning doctor* can have detrimental effects on the roll surface, and due attention must be given to protect the surface of the drier roll. However, some crepe papers are best made while still wet, in which instances there are other drier rolls after the Yankee. When the creping doctor is not used to scrape the paper off the roll, the paper is called *machine glazed* (MG).

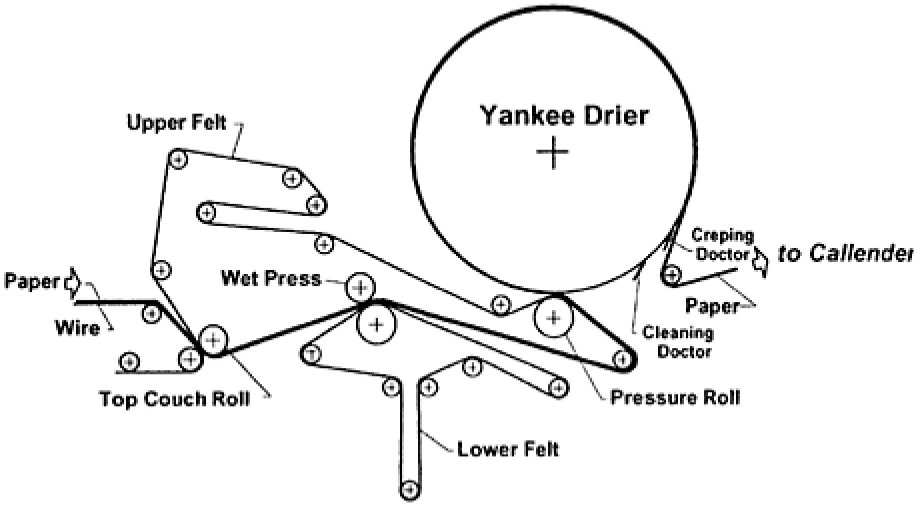


Figure 3.22: The Yankee machine.

This paper has only one side that carries a shine imparted by the polished surface of the roll.

HEAT TRANSFER AND DRIER PERFORMANCE

In machines with relatively thin drier rolls, the heat transfer across the metal shell is not too important. However, heat transfer becomes important with the Yankee when a rather thick shell is involved. Figure 3.23 presents a cross-sectional view through the shell of a typical drier roll of a machine while in active operation.

The total resistance to the transfer of heat of the roll is the sum of all the individual resistances, and resistance is the reciprocal of heat transfer (i.e., conductance computed in the same way). One would calculate the total capacitance in an electrical circuit where the capacitors are connected in series, that is:

$$\frac{1}{R_{h\,tot}} = \frac{1}{R_{h1}} + \frac{1}{R_{h2}} + \frac{1}{R_{h3}} + \frac{1}{R_{h4}} + \frac{1}{R_{h5}}$$

The value of $R_{h\,tot}$ is calculated as the product of the evaporation rate, the enthalpy of the steam at the supply pressure, and the steam rate per lb (kg) of water divided by the temperature difference between the steam supply temperature and an average paper temperature of 180°F (82°C). This makes the units for $R_{h\ tot}$—Btu/hr/ft^2/°F (kCal/hr/m^2/°C). The values of R_{h1}, R_{h2}, and R_{h3} can be obtained from published data. However, R_{h4} and R_{h5} are not usually found tabulated, but if these are combined as a single term the value can be calculated from the foregoing. The total resistance to heat transfer will then be the reciprocal of the computed result. With a Yankee drier, the outside resistance is virtually zero; that is, R_{h4} and R_{h5} can be neglected. In which case:

$$\frac{1}{R_{h\ tot}} = \frac{1}{R_{h1}} + \frac{1}{R_{h2}} + \frac{1}{R_{h3}}$$

The performance of a drier is defined in relation to the amounts of water in the paper when entering and leaving the drier(s), measured as the percentage of water to the total weight of the wet paper. For example, suppose we have 100 lb of wet paper entering the driers at the wet end, in which 60 percent was water. Then 40 percent must be dry fiber, and if at the dry end 5 percent of water remains, then there must be 95 percent dry fiber for every 100 lb of dry paper, or:

$$\frac{\%\,dry\ fiber\ leaving}{\%\,dry\ fiber\ entering} - 1 = \frac{lb\ water\ removed}{lb\ dried\ paper}$$

Or for the amounts in the example [(95/40)—1]=1.375.

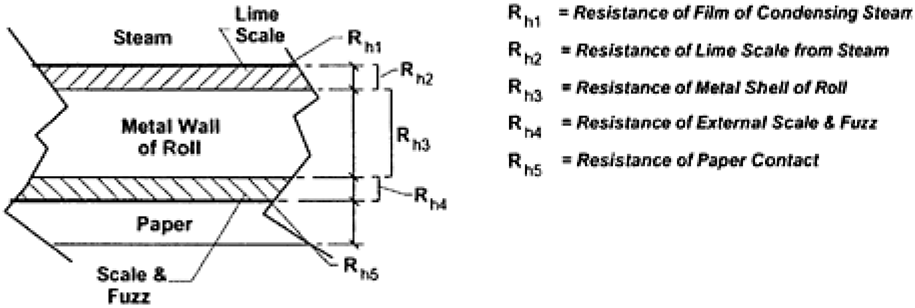


Figure 3.23: Cutaway section of a drier roll.

However, the best way to express the amount of water is in pounds of water per pound of dry fiber, which means that:

Water entering is 60/40=1.5.
Water leaving is 5/90=0.053.
Therefore, evaporation per lb dry fiber is 1.5–0.053=1.447.

Because there is 0.95 lb dry fiber in 1.0 lb dry paper, the evaporation rate per Ib dried paper is 1.447×0.95=1.375.

This verifies the calculation made earlier and is the only logical way to proceed when there is other equipment such as the size press and coater between driers, and the moisture content varies at each equipment location.

INSTRUMENTATION AND CONTROL FOR THE YANKEE DRIER

Figure 3.24 is a schematic of a control scheme overlaid on the illustration of the Yankee drier to help the reader better understand the controls involved.

The system operates as follows. The steam condition can be determined from the readings of the two pressure measurements displayed on indicators tagged PI-1 and PI-2, which indicate the value of the incoming supply via the pressure sensor/ transmitter tagged PT-1 and pressure applied to the drier roll via the pressure sensor/transmitter tagged PT-2. The amount of condensate/steam discharged to the flash tank is displayed on an in-line flow indicator tagged FI-1, an armored variable area flowmeter or similar device, fitted in the discharge line. The two main loops

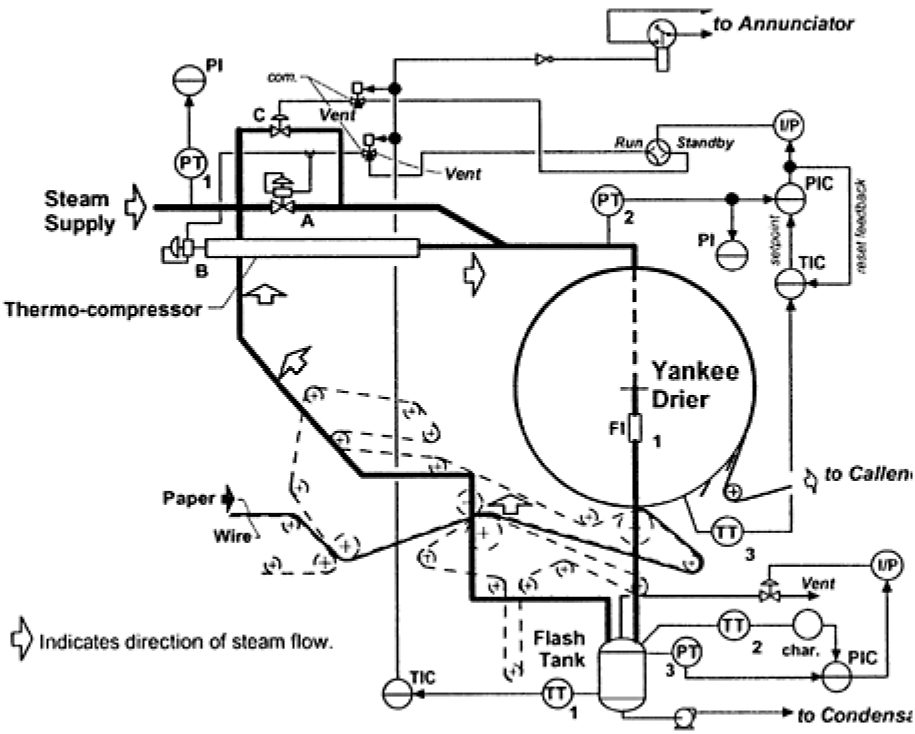


Figure 3.24: Schematic of control scheme for the Yankee machine.

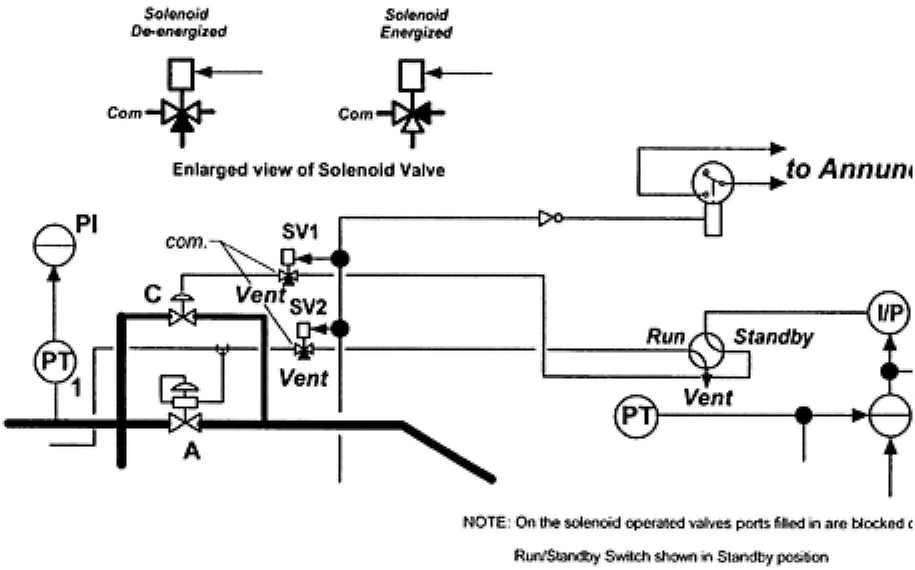


Figure 3.24A: Enlarged view of the selector switch operation.

involved in the control of the drier are the pressure loop P2 and the temperature loop T1. Pressure loop P2 obtains its measurement from a pressure sensor/transmitter PT2 located in the steam supply to the drier roll and applies it as the measurement to pressure controller PIC-2, which has a manually adjusted set point adjusted to a value determined by the operator. The controller produces an output based on the error that is applied to the two-position operator selectable Run/Standby switch. For clarity see Figure 3.24A.

This switch has a rotary action, limited to 90°, and operates on pneumatic signals only. The choice of a pneumatic device is governed by the simplicity and ease with which it allows the control action required to be achieved at the minimum cost, for only one current/pneumatic converter is necessary. The switch action is accomplished by rotating the central plug that carries only two totally independent channels machined into it; these are shown in the figure as the two solid-line right-angled curves. In either of the selected switch positions, communication is allowed between only two of the four ports on the switch. As drawn (in Standby position), the switch permits communication between controller PIC-2 and a port on the solenoid actuated valve associated with control valve tagged C, which is located in the steam bypass line. Depending on whether the solenoid is energized or deenergized, the output signal from controller PIC-2 and the connected port on solenoid-operated valve SV-1 allows control valve C to be regulated or not. For clarity the solenoid-actuated valves have been drawn deenergized to the following convention: clear ports in communication, filled-in port blocked off. The solenoid valve is a three-port device in which, operationally, one port is common and communicates with either of the other two but only one at a time. Hence, although the common is communicating with one port, the other is blocked. Selecting which of the two ports communicates with the common is determined by the action of the solenoid. With the solenoid deenergized, one port, deemed common, is connected to the open port and the other is blocked off. With the solenoid energized, the common and the blocked off port are connected while what was the open port is blocked off. In the Run position on the switch, valves A and B are connected to PIC-2 and will respond to the control signal generated. If the measurement of controller TIC-1 exceeds its set point, solenoid valve SV-2 will be energized, returning valves A and B to their failure mode closed and cutting off the steam supply. The failure mode for all the control valves is closed to avoid the undue temperature rise of the drier roll in an emergency.

Sensor/transmitter TT-1 measures the temperature of the condensate in the flash tank and produces a proportional signal that is applied as the measurement of controller TIC-1. This controller has an operator-adjusted set point and On/Off control action only. (It is in fact equivalent to a conventional domestic thermostat; an output is produced only when the measurement is above set point.) The output is applied to both the solenoid-actuated control valves but is inverted (shown by the NOT function gate—for fail-safe operation) before it is applied to drive the annunciator. With this arrangement of the annunciator drive signal, the operator is kept informed that the Yankee drier roll is below the operating temperature for as long as the measurement is below the set point because the annunciator window will be illuminated for as long as the condition exists.

Let us now consider the situation with the Run/Standby switch (note that previously we only described the switch action) in Standby and controller TIC-1 with the measurement below set point: there will be no output from TIC-1. Hence, solenoid-actuated valves A and B will not be energized, the diaphragms of the associated control valves will be vented, and as a result the control valves will fall back to closed (i.e., to the failure mode). Controller PIC-2, which receives its measurement from PT-2, could have an output (dependent on the error), which will be applied through the solenoid-actuated valve SV-1 to associated control valve C, which responds accordingly. Control valve C is very much smaller than either control valve A or B because it is sized to permit the drier roll to gently warm up to approximately 240°F (116°C) over a period of about six hours with the valve wide open. This is so arranged as to avoid the very heavy drier roll being subjected to undue thermal stresses had the temperature rise been more rapid. If now controller TIC-1 has its measurement above set point, then there will be an output from TIC-1. Hence, solenoid-actuated valve SV-2 associated with control valves A and B will be energized, the porting connections will change, but the control valves will not respond to the changed situation because the selector switch is still in Standby. The solenoid-actuated valve SV-1 associated with control valve C will be energized, the porting connections will change and allow the diaphragm of the associated control valve to be vented, and as a result control valve C will be driven closed (i.e., to the failure mode) and cut off the steam supply to the drier roll, which will lower the temperature.

Let us now consider the situation with the Run/Standby switch in the Run position. Controller PIC-2 output will now be connected to the solenoid-actuated valve SV-2 associated with control valves A and B and will modulate these accordingly to bring the measurement and set point to coincidence. In this regard, it is preferable for control to be maintained by the thermo-compressor alone, and the bypass valve should be used only sparingly when necessary. Calibrating the pneumatic positioners fitted to each device can fulfill this requirement. (The thermo-compressor will be detailed later in this section.)

With controller TIC-1 measurement below set point, there will be no output from TIC-1. Hence, solenoid-actuated valves A and B will not be energized, thereby leaving controller PIC-2 still regulating the supply steam. The solenoid-actuated valve SV-1 associated with control valve C will also not be energized allowing the diaphragm motor of the control valve to be vented and hence driven to its failure mode (closed). The action of controller PIC-2 modulating control valves A and B will carry out control under this condition, as stated earlier. If now controller TIC-1 has its measurement above set point, then there will be an output from TIC-1. Hence, solenoid-actuated valve SV-2 associated with control valves A and B will be energized, the porting connections will change, and the control valves will respond to the changed situation because the common port on the solenoid will now be connected to the normally blocked off port and thus vent the diaphragms of the control valve motors and drive them closed (i.e., to the failure mode). The solenoid-actuated valve SV-1 associated with control valve C will be energized, the porting connections will change, but the control valve will not respond to the changed situation because the selector switch is still in Run.

The description of the operation of the selector switch shows that the operator will not be able to use the drier until it has been sufficiently warmed up to a minimum operating temperature and the warmup cycle has been completed. Even after that has been done, the selector switch will have to be placed in the Run mode. Figure 3.24B illustrates the several conditions we have been discussing and should give the reader a better understanding of the control system.

As will be seen from the figure, the temperature of the surface of the roll is measured by the temperature sensor/transmitter TT-2. This is a specialized instrument in that it is important that the sensor does not scratch the highly polished surface of the roll. The measurement signal produced is applied to controller TIC-2 whose output is the remote set point for the pressure controller PIC-2. Since the operator can place PIC-2 into Manual to drive the control valves should it be necessary, it is important that controller TIC-2 be supplied with a reset feedback signal obtained from the output of controller PIC-2. This will prevent the integral term on TIC-2 from saturating. During periods of minimal production (e.g., during annual vacations and weekends) the selector switch can be placed in Standby, and the set point of controller TIC-2 can be adjusted to a low value. These actions will prohibit the roll temperature from rising excessively.

To minimize the effect of entrained air in the flash tank on the heat transfer, the pressure and temperature in the vapor space are measured by pressure sensor/transmitter PT-3 and temperature sensor/transmitter TT-3, respectively. If no air is present, the temperature will be that of saturated steam at the prevailing pressure, but if air is present it will be lower for the same pressure. The pressure/temperature condition is made to balance by characterizing the temperature signal in the module tagged char so that the temperature/pressure relationship is maintained. The output of the char module is applied as the set point for controller PIC-3, which receives its measurement from PT-3 and whose output modulates the control valve in the vent line from the flash tank to regulate the pressure/temperature relationship of the flash steam.

THE THERMO-COMPRESSOR

Figure 3.25 illustrates a typical steam jet ejector or thermo-compressor. This device has no moving parts and is the most economical way of maintaining a low pressure in the flash tank. The sources of steam supply and the destination of the discharge from the ejector have been shown to help the reader relate the equipment to the system being discussed.

The unit operates on the principle of accelerating the motive steam through the nozzle and as a direct result reducing its pressure. The reduced pressure draws the steam from the flash tank through the inlet connection, where it mixes with the motive steam and because of the increased mass is compressed in the diffuser body before being discharged at an intermediate pressure back into the drier roll. The in-line control valve regulates the amount of motive steam.

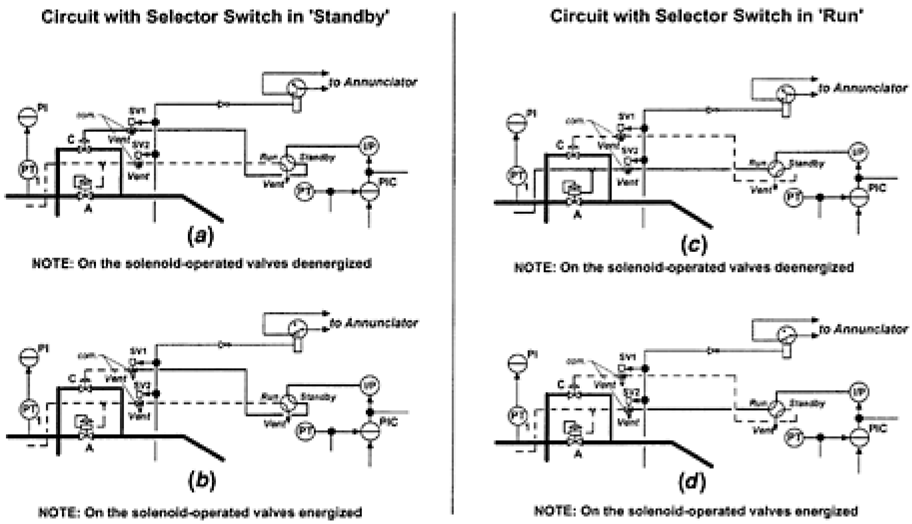


Figure 3.24B: Operational signal lines shown solid. Vented signal lines shown dotted.

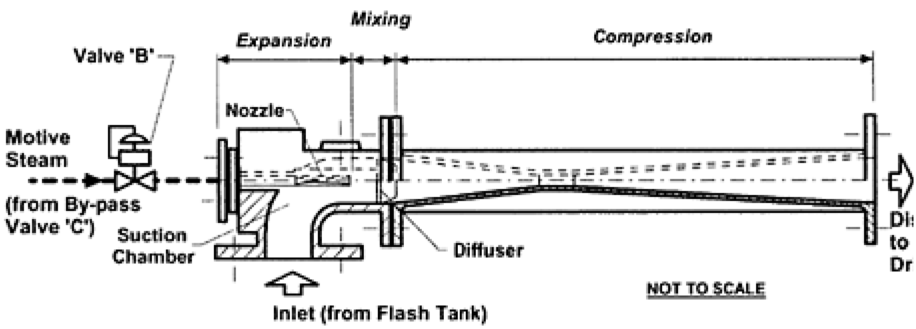


Figure 3.25: Typical arrangement of a thermo-compressor.

MACHINE ROOM VENTILATION

Obviously a vast amount of vapor is given off in the drying process, but this situation should not be permitted to go uncontrolled in the interests of not only personnel protection but product quality and protection of the machinery. To bring the amount of vapor under control, the machine is enclosed to confine the vapors; *hoods* are used to achieve this objective. These hoods could either be totally *enclosed* or *open*. The open hood, more common in mills manufacturing boards, are suspended from an overhead gantry and are arranged to be raised or lowered to suit operating conditions, while enclosed hoods are used on paper machines and are usually fixed for the most part. Figure 3.26 shows a basic plant arrangement with an enclosed hood over the machine. With this type of arrangement, the top, back, and sides are

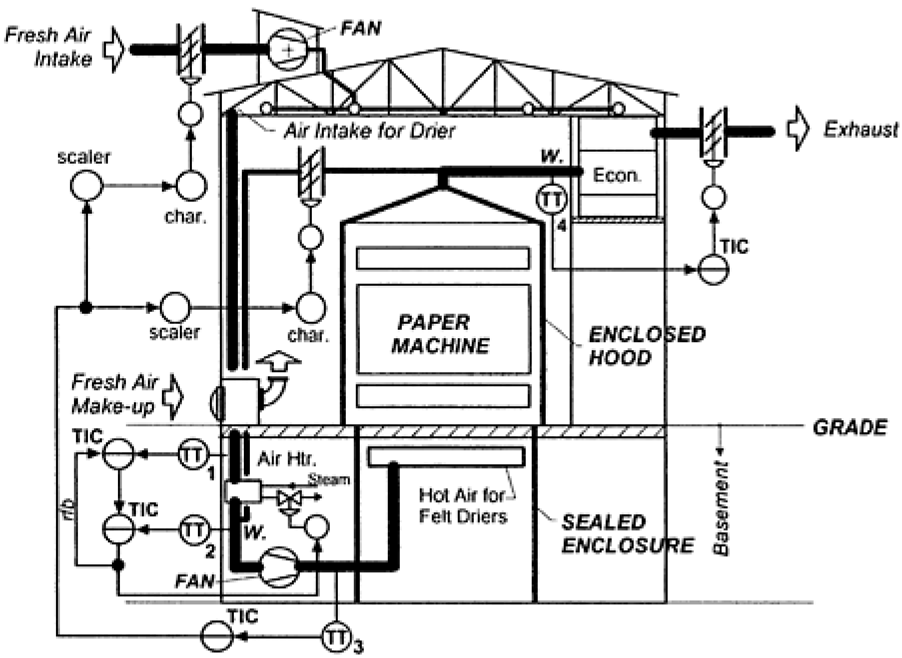


Figure 3.26: Schematic of a typical enclosed hood for a paper machine with basic instrumentation.

made of panels, most of which are fixed, although the lower section of the front is designed to slide vertically so that operating personnel can gain access to deal with a paper break or other emergency, while the back has horizontal sliding sections. Again, the control system has been superimposed to present the full picture to the reader, but it should be pointed out that the controls are the very basic required, and this can/will be modified or elaborated to suit actual requirements. When felts are used on the machine, the air used must be heated. This is usually done in basement-located heaters that must be totally enclosed to minimize the ingress of ambient air.

For operator comfort, fresh make up air is drawn in to improve conditions in the wet and dry ends of the machine and to circulate in the aisles between machines. This air picks up heat and rises or is forced up to the roof space. This region is a most suitable pickup point for the air required for felt-drying because it is important that the air used is hot in order to effectively dry the felts as quickly as possible. The heated air is forced up and along the sides of the paper machine to pick up the vapors given off by the felts and is carried up toward the roof, the air ventilating system being designed to prevent the heated air from condensing and falling back on to the machinery. While applying the hot air along the sides of the machine affects the drying process, even greater benefits to felt drying and felt-life could be obtained by blowing the hot air directly onto the felts.

INSTRUMENTATION AND CONTROL SYSTEM OPERATION

Let us start with the felt-drying. It has been stated that the air required is drawn into the air heater from points in the roof space where the air is hottest. This will therefore minimize the amount of additional heat required to bring it up to a usable temperature. The incoming air temperature to the heater is measured by a resistance temperature detector (rtd)/transmitter tagged TT-1, and the signal produced is applied as the measurement to controller TIC-1 whose output is the set point for controller TIC-2, which obtains its measurement from a *wet bulb* resistance temperature detector (rtd)/transmitter tagged TT-2. The wet bulb temperature is obtained by having the resistance bulb wrapped in a wick that is continuously soaked with water. This arrangement measures the temperature at which water evaporates with respect to the surrounding ambient temperature. In this instance, the correction applied by TIC-2 is the amount of heat required to dry the incoming air. The output of controller TIC-2 is applied as the correction signal to a current/pneumatic converter to manipulate the control valve in the condensate line of the steam heater. This is a cascade loop, hence, a reset feedback (rfb) signal must be applied to controller TIC-1 to prevent it from saturating in the event the process operator transfers controller TIC-1 to manual mode.

The temperature of the hot air from the felt-drier forced-circulation fan is measured by resistance temperature detector (rtd)/transmitter tagged TT-3, and the signal is applied as the measurement to controller TIC-3. The output from this controller manipulates two air dampers—one located in the fresh air intake and the other in a line from the hood exhaust. The latter allows an amount of very hot air to be bled into the drier air intake line, the intention once again being to minimize the heating requirements. The two dampers must be phased, and this is accomplished by providing a scaler and characterizer on each signal line. The scaler allows the operating range of the damper to be chosen, and because dampers have nonlinear characteristics, the signal characterizer enables the flow/damper opening relationship to be adjusted to meet the operating conditions.

The wet bulb temperature of the exhaust is measured by a resistance temperature detector (rtd)/transmitter tagged TT-4 and the signal produced is applied as the measurement to controller TIC-4, whose output manipulates a damper located in the exhaust line. As before, a characterizer should be used on the controlled output, but this is not shown.

VENTILATION SYSTEM FOR A YANKEE DRIER

The Yankee drier, too, has its own enclosure to maintain ambient conditions in the machine room. Figure 3.27 is an illustration of a basic arrangement with the instrumentation superimposed. In this instance, the enclosure is pressurized and draws off the vapor from the drying paper. The ducting arrangement recirculates the exhaust, and an economizer or a heat exchange is usually also included and located in the position shown in the figure.

The controls operate as follows: sensor/transmitter tagged TT-1 measures the temperature of the air entering the hood and produces a signal as the measurement input to controller TIC-1. This controller has a remote set point provided by the output of controller TIC-2, which receives its measurement from sensor/transmitter tagged TT-2 in the duct upstream of the *forced draft* (F.D.) fan. The output from controller TIC-1 is applied as the correction signal to the steam valve to regulate the temperature of the air supplied to the hood. Since the process operator can place controller TIC-1 in the manual mode, a reset feedback signal is provided to prevent the integral term on controller TIC-2 from saturating under this particular condition.

Temperature sensor/transmitter tagged TT-2 also provides the measurement signal for controller TIC-3, which manipulates the dampers in the fresh and recirculated air lines. The dampers work in opposition to each other: while one opens, the other closes, and in this way a balanced mixture of fresh and recirculated air is

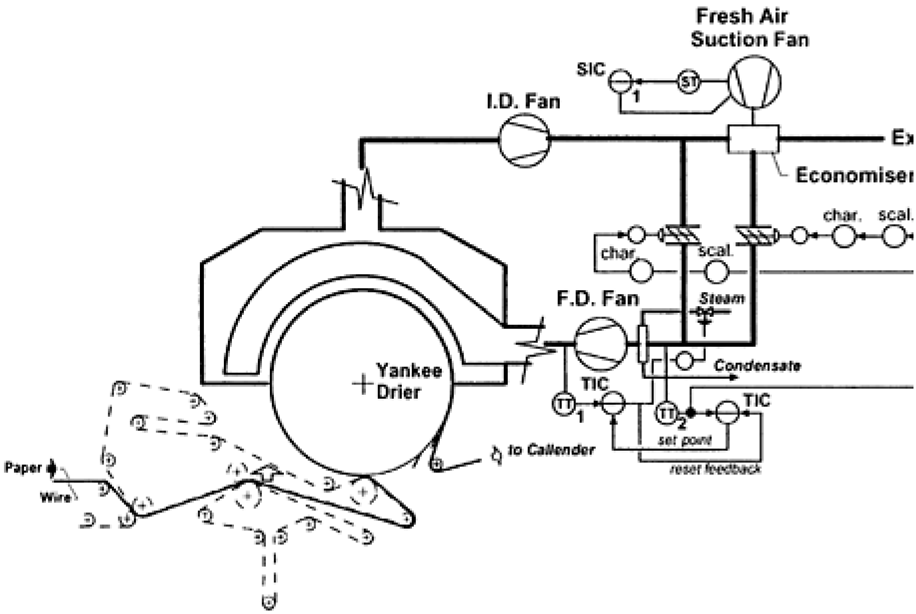


Figure 3.27: Controls for ventilating hood on a Yankee drier.

obtained, limiting the humidity of the air provided to the hood. To provide an even greater amount of control over the mixing (because dampers always have nonlinear characteristics—the amount of opening is not directly related to the amount of air admitted), signal scalers and characterizers are provided on each controlled output line to the dampers.

The process operator controls the amount of fresh air intake by adjusting the set point of speed controller SIC-1, which receives its measurement from speed sensor/transmitter ST-1.

THE VAT OR CYLINDER PAPER MACHINE

The objective in paper making is to produce a finished product that has the desired quality and sheet strength. This latter (criterion) results from having the longitudinal axis of the individual fibers lying parallel to the plane of the paper, but in a random direction to the dimensions of the sheet, in which case the paper will have strength in all directions. The papermaker normally tries to ensure that the material produced has its fibers in the direction of travel of the sheet so that the sheet is strongest in that direction. Sometimes, however, it is desirable, or even necessary, to have the longitudinal axes of the fibers perpendicular to the sheet in order to provide a thick and cushioning effect for the paper produced, for example, boxboard (cardboard in the United Kingdom). Because of the way in which the paper is formed in the vat or cylinder machines, both of these two varieties can be very easily produced. The vat has mesh screen forming the curved surface of the cylinder that is made to rotate in a vat of stock; in so doing it picks up a layer of fibers on the mesh (surface). The formed sheet is *couched off* the cylinder under the action of the couch roll.

To understand more clearly how the longitudinally aligned fiber sheet is formed, let us use an analogy. Suppose the liquid in the stock were a stream of water. The fibers contained in it could then be considered to be logs of wood floating in that stream. As the liquid flows along, the logs would then be traveling along with the liquid; but if a log happened to touch the bank, then it would stop moving forward and be aligned with the direction of flow of the liquid. With the log virtually stationary, frictional forces would also hold the liquid back. The velocity of the liquid near the bankside edge of the stream is always lower than that encountered at midstream. The log will tend to turn about the end touching the bank, and the free end will then be traveling faster (along with the liquid) than the bankside end. However, floating logs tend to rotate whether or not they actually touch the bank or the bottom of the stream and none of the logs will eventually be aligned in the direction of flow. This is an observable fact of hydraulics in any actual moving stream of water with logs floating upon it. The fibers in the stock behave in exactly the same way when the material in which they are suspended is dilute enough to allow free movement between the fibers. This is what happens in the vat machine as the sheet is formed on the rotating cylinder.

Figure 3.28 is a schematic of the vat machine and illustrates the operating principle. The mesh-covered cylinder is partially submerged and rotates continuously in a vat of stock containing the pulp fibers. The mesh, which is also called a *face*, allows the fibers to cling to the surface of the cylinder as it rotates. The clinging fibers are carried on the mesh out of suspension, and the surplus water drains back into the interior of the cylinder. The recirculating pump continuously draws off the water from the inside of the cylinder to maintain the difference in level necessary to maintain the flow of stock from the outside surface to the inside of the cylinder. Although the

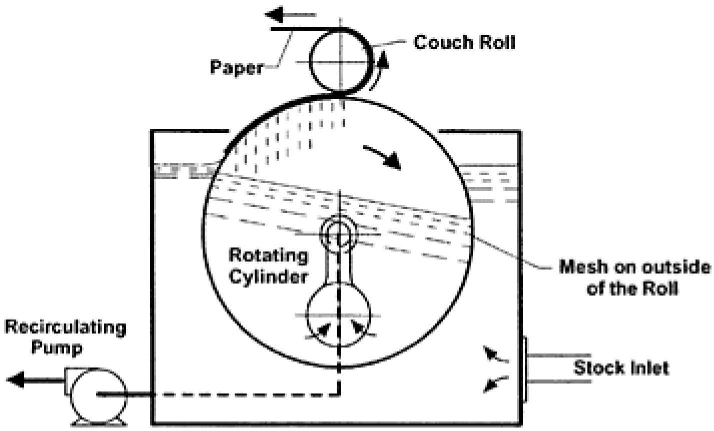


Figure 3.28: Schematic of the operating principle of a vat-type paper machine.

fibers are still held in suspension and try to cling to the mesh, considerable movement of these fibers will take place making them form areas of large amounts of fiber or clots, resulting in a very uneven surface to the forming paper. This effect can be traced to a difference in velocity between the surface of the rotating cylinder and the flow of stock, with the surface of the cylinder always moving the faster of the two. If the incoming velocity of stock remains different to the rotational speed of the cylinder, there is no way in which the fibers can be made to spread out evenly across the mesh.

To overcome the problem of clots of fiber forming, the flow of the stock is accelerated and is made to approach the velocity of the rotating cylinder. The method used to achieve this is to form a channel of reducing cross section between .the cylinder and the stock, thus forcing the stock through and increasing its velocity. Figure 3.29 illustrates the technique used.

The idea behind the design is to create a region with no relative motion between the stock and the face of the cylinder; the builtup section is called the *scroll*. The

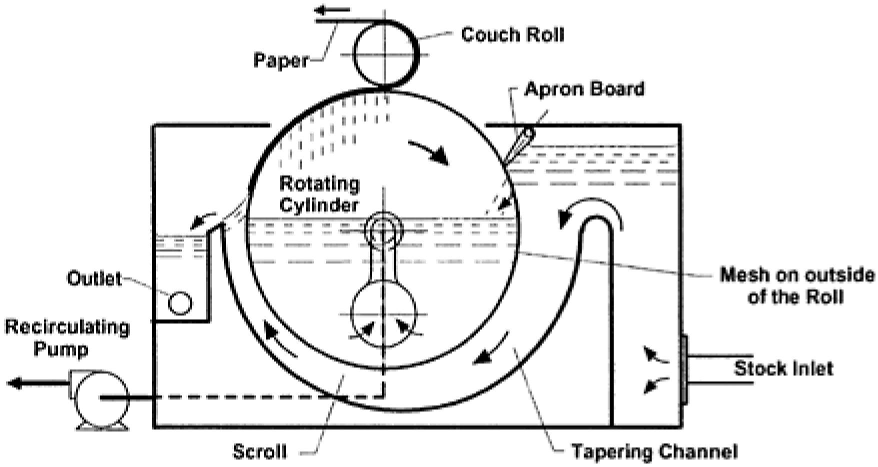


Figure 3.29: Schematic of the direct flow vat-type paper machine.

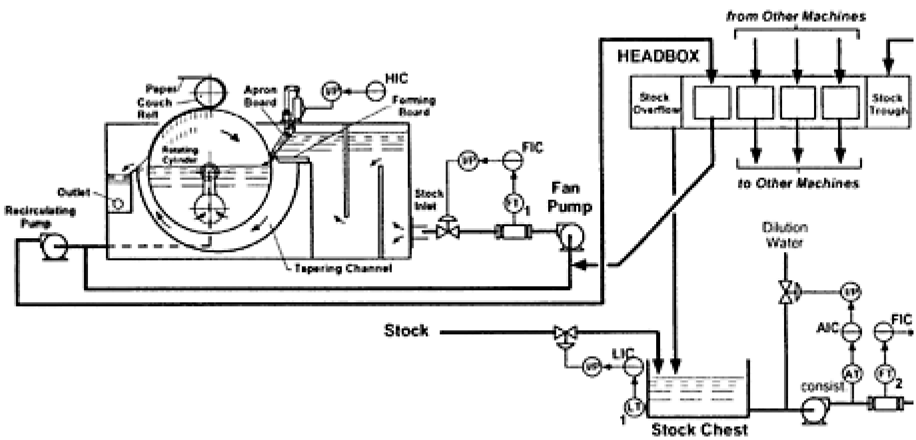


Figure 3.30: Schematic of the instrumentation and control system for a direct flow vat-type paper machine.

inclusion of the *apron board* raises the pressure head on the supply side to allow the stock velocity to increase and prevents contact between the stock and cylinder face until this acceleration has been achieved. The main disadvantage associated with this type of machine is the fact that it can operate at only one drainage rate, and since the drainage varies for different sheet weights, temperature, and stock freeness, its versatility is affected. Adding a *forming board* (shown in Figure 3.30) beneath the apron board in some ways replicates the slice on the Fourdrinier, and the inclusion of humps as employed in the open-type headbox goes some way toward increasing the machine's capability.

The couch roll is covered with a very soft rubber cover to permit pressure to be applied over the undulating surface of the formed sheet without damage and to allow the sheet to be couched off the cylinder easily. A *couch slice* or *doctor* formed from a piece of board with a strip of used felt along one edge is attached so as to face the pickup edge of the felt and is used to drain off excess water.

The direct flow vat-type paper machine does not have as much instrumentation as the Fourdrinier for it to maintain control of the process. Figure 3.30 shows the basic five loops necessary for the instrumentation and controls involved in a typical vattype paper machine, which has also been arranged to show the humps and forming board referred to earlier, together with an arrangement to alter the opening of the slice via the manual loading station tagged HIC and pneumatic *power cylinder*. Note that the actual arrangement of the link and lever system could be different from that illustrated in the figure, for while it has been decided to manipulate the apron board in this instance, it could well be the case that the forming board is manipulated instead. The arrangement required should be discussed with the mill personnel.

The level in the stock chest is measured by the sensor/transmitter tagged LT-1. This signal provides the measurement to controller LIC-1, which regulates the amount of stock discharged into the chest by manipulating the control valve via the current/pneumatic converter I/P.

Stock consistency is measured by the sensor/transmitter tagged AT, and this signal provides the measurement to controller AIC, which regulates the amount of dilution water added by manipulating the control valve via the current/pneumatic converter I/P. Note the positions of the sensor/transmitter and the entry of the dilution water, where the mixing action of the pump is used to advantage. The flow of stock from the stock chest is measured by the flow sensor/transmitter tagged FT-2, producing the measurement to controller FIC-2, which regulates the amount of stock sent to the stock trough in the headbox by manipulating the control valve via the current/ pneumatic converter.

The total amount of stock admitted to the vat is measured by flow sensor/ transmitter FT-1, and the signal produced is applied as the measurement to controller FIC-1, which regulates the amount of stock by manipulating the control valve FV-1 via its current/pneumatic converter I/P.

SUMMARY

1. The Fourdrinier machine is capable of producing a wide range of papers and light boards, whereas the cylinder vat is capable of producing multi-ply papers and boards very successfully and efficiently.
2. The stock has to be consistent. It is therefore necessary to ensure that the constituents provide the appropriate and correct fractional part of the total quantity (or 100 percent) contained in the pulp recipe. In other words, all the multipliers of the ratio control system must have factors that are the decimal equivalent (in percentage terms) of the total demand.
3. Pacing control is an alternate ratio control system that takes account of the possibility of variation in any one of the constituent flow streams and automatically adjusts the

makeup of the raw material accordingly.

4. A process analyzer could be used instead of the pacing control system, but in considering this alternate one should be aware of two main disadvantages in using analyzers for such applications: (1) there will always be a very real possibility of a situation where off-spec product is manufactured before the control valve can take effective action, and (2) there may be the real possibility of no analyzer (i.e., designed hardware) available for a particular constituent.
5. When the pulp contains recycled paper in addition to the pulp produced in the digester, a *pulper* is used. The pulper's task is to reduce the recycled paper to a state that allows it to be combined with the fresh pulp. Pulpers are usually highly efficient and reduce the paper to slurry in a few minutes.
6. In the Fourdrinier machine, the pulper is located under the machine in a position near the dry end where paper breaks most often occur. Since the pulper is machine mounted, it is arranged to accept material from a number of sources on the machine itself and to deal with these efficiently when breaks occur.
7. Stock consistency is one of the most important parameters in paper making. The consistency control loop is operational at all times to ensure that the pulp sent to the machine chest is that value required by the product specification.
8. A paper break on a Fourdrinier calls for immediate and focused attention because the machine runs at high speed and the amount of waste produced as a result can be enormous.
9. The Fourdrinier paper machine sometimes has two pulpers located under the machine to cope with the situation of a full paper break. One pulper is located beneath the dry end of the machine, which is considered the *master,* the second pulper is considered the *slave* and is situated at an appropriate location under the wet end of the machine. Usually only minimal instrumentation is used on the slave equipment, which during normal operation is to all intents and purposes shut down.
10. The stock for paper making, in addition to having the basic raw material of the pulp, contains other materials as well. The reason is that pulp produced for the mixing chest is not suitable on its own for converting directly into paper because in this state it is of irregular texture, high bulk, uneven formation, and low-strength and would very easily disintegrate when wetted.
11. To be useful, paper must resist the absorption of liquids; it therefore has to be treated with some material that achieves this intention. In the very earliest days, this treatment was carried out after the sheet of paper had been formed, after which it was subjected to a quick pass through a very dilute solution of glue or other adhesives and then air-dried. It was ready for use only when fully dry. This process has been called *external sizing*. A technique was developed that precipitated rosin size onto the pulp fibers with alum as the fibers circulated in the hollander (beater). This technique was incorporated into the Fourdrinier machine system, where it has since remained fundamentally unchanged. The new treatment, because of its inclusion at a stage when the material was still slurry and hence, before sheet formation, was easier, less time consuming, and satisfactory. It became known as *internal sizing*.
12. A formulation of rosin size to alum in a dry-weight ratio of 1:1:5, respectively, is used almost universally, although there are individual variations on this.

13. Rosin is a natural resin obtained From the wood of pine trees; it is yellow or amber in color and very brittle. Rosin is insoluble in water but soluble (typically) in acetone, chloroform, the lower alcohols, and some oils. The rosin size is prepared by reacting the resin with sodium hydroxide or sodium carbonate to obtain a neutral size. Rosin size is usually the first sizing material to be added in preparing the pulp for paper making. This size is manufactured today off-site by others and is delivered to the mill as viscous fluid in prepacked drums. Before it can be used it has to be heated to reduce the viscosity and then diluted with steam until a final dilution of between 3 and 5 percent solids is obtained. The paper being made determines whether neutral or free rosin size can be used with the water available at the mill site, the reason for the options being that very hard water tends to precipitate the rosin size, with no improvement in the sizing effect. Free rosin size, on the other hand, is precipitated less in hard water.
14. Natural rubber in an aqueous dispersion was called latex, but this term has now come to include aqueous dispersion of resins and rubber, which are the result of emulsion polymerization. This is normally not used as an internal size because it is a special additive. When used in its natural or synthetic form, it produces paper of considerable wet strength, although this is not the primary objective for its inclusion.
15. Starch is never used by itself, but rather is used together with rosin size because of the poor affinity starches have with cellulose, which makes it (starch) difficult to be retained. Partially cooking the starch improves the retention qualities, and the starch is prepared by turning a starch concentration of 5 to 8 percent to slurry with water after which it is subjected to live steam injection. Depending on the type of starch used, the temperature is raised until it attains a value in the range of 87 to 95°C. The cooking temperature is important for best results. Cooked starch is added after the pulp has been put through the refiners or at the outlet of the fan pump. Adding starch improves the surface of the paper, and when starch is used as a size, the quantities based on dry weight of pulp are in the 2 to 3 percent range.
16. Alum is used extensively in paper manufacture; its main functions are to precipitate rosin size and to clarify the water used. In paper making, the alum is not true alum, but aluminum sulfate made from bauxite and sulphuric acid. The alum is no longer manufactured at the mill site but elsewhere, and it is shipped to the mill in tankers in liquid form, normally as a 50 percent solution. The mill dilutes the pre-prepared alum to the desired strength before use in the pulp preparation process. The amount used must be in excess of that which will precipitate rosin size in the absence of pulp fibers. Any ferric (iron) in the alum will cause the paper to have a yellow discoloration. When maximum permanent strength and maximum sizing are required, an amount of $Na_2Al_2O_4$ (sodium aluminate) is combined with the alum, resulting in acceptable sizing at a pH that is nearly neutral. This neutral pH sizing has advantages for the mill in that it reduces considerably the corrosion on the plant equipment.
17. The term *filler* or pigment is used to describe the inorganic material similar to those used in the paint and rubber industries, and sets the line of demarcation between white and colored pigments, the latter being applied to give paper specific colors.
18. The term *loading* describes the incorporation of the filler into the web of fibrous pulp to improve the paper or board quality.

19. Fillers are necessary to produce papers with a fine textured and well-closed surface from the web, which always comprises voids randomly distributed, and an undulating discontinuous surface of minute hills and valleys. The filler plugs the cavities and reduces the unevenness of the surface of the paper. The best particle size of a filler to give the highest opacity should be half the wavelength of light used to study the filler, or approximately 0.25 μ (micron).
20. When used in excess, fillers can result in limp paper, increased softness, dusting—whereby rubbing the finished sheet loosens the filler particles—and makes printing inks tacky, which allows fibers of the paper to lift off. Fillers can decrease the effectiveness of the size used; calcium carbonates are reactive and change the rosin-size precipitate adversely, and the strongly acidic zinc sulfate can cause discoloration of the paper.
21. Clay for use as a filler comprises mainly kaolinite, but this must be free of quartz, mica, and other abrasive constituents. The quartz is removed from most types of clay by dispersion in water where the heavier particles stratify out. English clay is free from titanium and iron, both of which lower the reflectance, and when used makes it easy to attain a variety of attractive shades of paper. American clay does not have this quality and has to be bleached by treatment with sodium hydrosulfite or zinc and then spray dried to avoid the formation of the grit particles that were previously obtained when the clay was dried in rotary driers.
22. Calcium sulfate is also known as gypsum, and when used as a filler exhibits little interference with rosin size to give high brightness and is of low cost. However, because of its high solubility in *white water* the initial saving in cost is negated, and because its solubility decreases with rising temperature—a reversal from the norm where the solubility usually increases—there the disadvantage of possibile gypsum deposition in the pipes. Calcium sulfate has the highest specific volume of all the fillers used.
23. Calcium carbonate or chalk is also used as a filler. The natural chalk as found on the south coast of the United Kingdom or limestone deposits in the United States is often the source. When the sodium carbonate produced in the pulp mill recovery system is causticized with $Ca(OH)_2$—calcium hydroxide—sodium hydroxide is produced. This is the chemical sought by the reaction for it is necessary for the paper pulping operation where it is reused in the pulping liquor. The result of the causticizing precipitates calcium carbonate as a byproduct, which can then be used as a filler. This was the practice when the pulping operation used the soda process where the pulp was cooked with sodium hydroxide. However, in the Kraft process where pulp cooking is carried out in the presence of sodium hydroxide and sodium sulfide, the production of the calcium carbonate is reduced because it is very difficult to produce the filler needed as white calcium carbonate from Kraft waste.
24. Calcium sulfite, even though it can be processed to yield very white filler, which is easy to size with rosin and alum, has the disadvantage in that there is a reaction between the alum and the calcium sulfite. This reaction releases sulfurous acid, which in turn corrodes the wires and wool *felts* on the machine, making it necessary to use corrosion-resistant wires. Felts are difficult or could be very expensive to replace with an alternate.

25. The hollander was the single most important papermaking advance made about 200 years ago. The machine was designed and developed in the Netherlands from whence it got its name. Although improvements have been made since, the basic design remains unchanged, and there are still some of these machines in use today, though in updated form. In a hollander, the midfeather divides the beating tub into two with the pulp circulating around it. The tub can be fabricated from a variety of materials such as cast iron, steel, or concrete; in some instances, the concrete is tiled over as well. The pumping action of the *beater roll* working against the *backfall* maintains the circulatory movement of the pulp in the tub.
26. More up-to-date beating equipment is called a refiner and can be divided into two types: *conical* refiner flat plate or *disk* refiner.
27. The jordan was invented in the mid-nineteenth century and got its name from the inventor. The task this machine carries out is almost identical to that carried out by the hollander. The idea behind the invention was to increase efficiency and speed up the beating process performed by the machine it was replacing. The beating takes place within the confines of the cones, the outer one of which is fixed (i.e., nonrotating) while the inner one, called the *plug*, is motor driven, rotates, and is able to slide in or out a required amount on a through shaft and thus obtains the quality of the pulp required. The inner surface of the outer cone and the outer surface of the inner cone are fitted with bars or *knives* in much the same way as they were on the hollander. However, there will be many more bars around the periphery of the base of the cones. Shaft bearings are chosen to permit the free rotation of the plug and the resulting thrust imposed when it is moved along the inside of the outer housing.
28. A *proportional time control algorithm* (PTC) or *block* is capable of accepting an analog measurement and of producing two pulsed outputs that operate independently of each other: one is to drive the final actuator in one direction, and the other is to drive the final actuator in the reverse direction. The pulse width determines the duration of the controlled drive applied (i.e., variable *mark/space ratio*) and depends on the magnitude of the *error* (difference between set point and measurement). As stated, the control algorithm produces an output that is *proportional only* to the magnitude of the error; no other control actions (*integral* or *derivative*) are possible. When the system demands control actions other than the proportional provided with the PTC algorithm, it is necessary for the PTC algorithm to be connected in cascade with a PID *(proportional, integral, derivative)* control algorithm and choose the appropriate combination of control action on this latter block to give the required control. With the cascade arrangement, the PTC algorithm can be configured to act either as controller or as signal converter. It is important always to maintain the PTC algorithm in the *auto mode* when it is used as a signal converter because in the *manual mode* no time-proportioning control is performed.
29. Any one of several different parameters, such as the vacuum in the couch, plug pressure, pulp *freeness*, or differential temperature of the pulp across the refiner, can be used to control the position of the refiner plug. When pulp freeness is used, it is measured in the discharge line and can be used either to control the refiner directly or as the primary controller that produces the set point for the pulp controller.
30. Pulp *freeness* is defined as the ability of the pulp to release or retain water and the

ease with which it is achieved.

31. In a single-disk refiner there are a pair of disks, one of which is held stationary while the other is motor driven and rotates. In the same way as the jordan, the rotating disk can also be made to move toward or away from the fixed disk so that the quality of the pulp may be varied to meet the requirements of the paper being made. Some disk refiners have two pairs of disks: two sets of rotating and stationary disks. Each rotating disk is independently driven by its own motor. The important point to remember in machines with two sets of disks is that the movable disks contra-rotate. For disk refiners, it is usual for the automatic controller to manipulate a hydraulic cylinder attached to the movable disk to carry out the positioning required.
32. Stock consistency in paper making is of the utmost importance. Without uniform stock consistency, the control of paper manufacture will be impossible. In this connection, it is vital to realize that it is not the absolute value of stock consistency that is sought, but rather the amount of its variation about a particular value that is important. The less the variability of the stock about the desired consistency the easier it will be to produce the paper required.
33. Consistency is defined as the percentage by weight of fibrous material in any combination of fiber and water. Alternatively, it can also be defined as the percentage by weight of dry fibrous material in any combination of stock and water, or stock (i.e., pulp+additives) and water. To give the above relationship symbols we have:

$$C = \frac{W_{fib}}{W_{sam}} \times 100$$

where C = consistency (%)

W_{fib} = weight of fibrous material in the sample

W_{sam} = weight of sample (total)

34. For continuous control, on-line sampling/measuring instrumentation is necessary. Today such equipment is available from certain instrument makers. One of the measuring principles involved is the determination of the stress imposed on a specially shaped steel blade, inserted into the process line where, because of the flowing fibers in the stock, a quantity of fibers cling to the sensor and impose a stress on it. The more viscous (high fiber to water ratio) the stock, the greater will be the stress, and the less viscous (less fiber to water ratio) the stock, the lower will be the stress imposed.
35. When the stock consistency is such that the controls need only to reduce the stock to the final consistency by an amount no greater than between 0.5 and 1.0 percent to achieve the specification for the machine, only a single addition of dilution water is necessary.
36. It is very often desirable economically and productionwise to produce the stock slurry as a high-consistency (quite often greater than 6 percent) solution, store this in a relatively small tank, and dilute this solution as required. Under these requirements, a double dilution is necessary. The object of the two dilutions is as follows. The addition of primary dilution reduces the consistency of the lower portion of the pulp within the

stock preparation tank to a value of approximately 4 percent, which allows it to be pumped easily followed by the addition of the secondary dilution water to bring the pulp to the specification required by the paper machine.

37. The headbox is most important, for no paper sheet will ever be formed without it; the purpose of the headbox is to:

- Reduce the turbulence brought about by the stock being pumped to the wire.
- Eradicate the effects of multiple-flow velocities and unify them to a uniform effective one and hence disperse the fibers uniformly through the system.
- Direct the stock toward the slice.

38. The outlet from the fan pump usually terminates in a circular section pipe. Because the paper machine with an open headbox is not of circular cross section and has to produce a sheet that is rectangular in cross section, means have to be found to effect the transition. This requirement results in various designs that involve having, for example,

- A single centrally located circular inlet and multiple circular outlets which are supplied through a manifold with a double-tapered distributing section, the double taper having its widest section at the middle.
- A single circular inlet that terminates in a rectangular fan-shaped wedge with a discharge opening width to suit the headbox dimensions. There are limits on the angle of the fan shape, and care has to be taken not to impose turbulence on the material passing through.
- Several variations on this theme.

The item produced as a result is called a distributor.

39. The perforated-skin holey rolls provide the means of reducing the turbulence, straightening out the flow of stock, and distributing the stock evenly across their entire width as it moves toward the slice.

40. The open-type headbox is suitable for the slower paper machines where the wire speed is in the range of 600 to 800 feet per minute. The *holey rolls* and *humps* provide the means of controlling the flow of the stock. The level of the stock is varied to suit the speed of the wire, the higher the level the higher the speed. For very high speeds, the sides of the box will also have to increase, which impose restrictions on the use of such headboxes.

41. Since the wire is moving continuously, the stock has to be pushed out of the headbox in a steady stream of predetermined thickness at a rate dependent on the velocity of the wire. From this it can be seen that a mathematical relationship exists between the material flow and the wire velocity:

$$v = C_v\sqrt{2gh}$$

where v is the spouting velocity

C_v is the coefficient of velocity discharge

g is the acceleration due to gravity

h is the total pressure head

The *spouting velocity* is the velocity at which the stock issues from the slice. The reader should also recognize this equation as essentially the Bernoulli relationship for flow obtained when using the measuring technique of the differential head created by an obstruction of calculated bore.

42. The slice performs the following functions:

- It is a metering orifice (hence the Bernoulli relationship referred to earlier) that controls the distribution of stock across the width of the wire.
- The slice, regardless of the sometimes erroneously held view, does not control the total flow to the machine; flow control is the function of the fan pump and its associated control valve.
- The spouting velocity is controlled by the slice opening and is effected by adjusting the average opening of the entire slice.
- In coordination with the holey rolls, the slice controls the stability of the stock flow.
- Slice geometry influences the fiber orientation.
- The slice controls the trajectory of the stock on to the wire; on fast modern machines, automatic control is a very important consideration in this respect.

43. A mechanical method using a float can be used to ensure the correct total pressure head and stock level in the headbox.
44. Modern paper machines operate at very high speeds—typically, 3000 feet per minute and above. Mechanical methods of headbox control have had to give way to more sophisticated techniques. The method of eliminating flow turbulence by using holey rolls is still used, but the arrangement and location are more precisely determined to achieve the objectives. With these machines, pressure/vacuum headbox operation is an absolute necessity owing to the wire speeds involved. The main task of the control system is to maintain the pressure/vacuum and stock level at the predetermined optimum values at all times to suit the wire speed of the machine.
45. Sheet formation on the wire depends on the rate at which the stock is deposited onto the wire, the speed of the wire and the spouting velocity of the stock. Some grades of paper require the wire speed to exceed the spouting velocity. In other words, the wire so to speak *drags* the stock on to it; other grades of paper require the spouting velocity to be greater than the wire speed, or, putting it another way, the stock rushes on to the wire.
46. The ratio of rush to drag or *efflux ratio* varies as the ratio of spouting velocity to wire velocity or symbolically:

$$Eff = \frac{v_{spout}}{v_{wire}}$$

where *Eff* is the efflux ratio

υ is velocity with appropriate subscripts

From this it is clear that:

- When the efflux ratio is 1.0, the spouting velocity is equal to the wire velocity.
- When the efflux ratio is less than 1.0, the spouting velocity is less than the wire velocity, and the stock is being dragged onto the wire.
- When the efflux ratio is greater than 1.0, the spouting velocity is greater than the wire velocity and the stock is being rushed onto the wire.

47. pH is a very important parameter; the stock has a final check and correction just before it is put on the wire. The final pH of the stock is usually in the range 4.5 to 5.0 pH units.
48. Stock discharging from the slice on the headbox onto the wire comprises the fibers, size, fillers, and so on, all held together in a vast amount of water that has to be drained off very rapidly to allow the sheet to be formed. This requirement of rapid water drainage becomes more acute when the wire speed is high. Experience gained using equipment developed for the purpose of fast drainage showed that about 95 percent of the water is drained off while the continuously forming sheet is still on the wire. The sheet of paper left behind on the wire is a mat that is still quite wet and comprises 60 to 100 percent fibers. The mat is of almost uniform density across the width of the sheet and consists of interwoven fibers randomly arranged in what is called the *formation*.
49. The meaning of the term *formation* is not only restricted to the dispersion and orientation of the fibers, but covers the quality of distribution of the sizes, fillers, and so on, used in its makeup as well. The papermaker assesses the paper by the amount of light transmitted through the sheet, giving rise to the term *look-through;* the assessment made determines the quality of the formed sheet.
50. Water drains from the stock for the following reasons:

- The force produced when the jet of stock strikes the wire at a large angle ejects a quantity of the retaining water. This inertia force is used to advantage on machines making tissue paper, but not for other types because of the poor formation when making heavier grades.
- The weight of the water (hydrostatic pressure) contained in the stock spread on the wire forces the water off. This phenomenon is not of much use except on very slow machines.
- The suction forces that are developed as the wire moves over the *table rolls* discharge the water; this force is responsible for the greatest amount of the drainage on the machine.
- The suction applied to the underside of the wire by specially designed *suction boxes* working under vacuum draws large amounts of water off. With these boxes, the amount of water drained off compares very favorably with the drainage achieved by the suction developed by the moving wire.

51. When operating at very high speeds, instead of the normal table roll, a grooved one is used, or sometimes *drainage foils* or *water doctors*. These are stationary water deflectors and replace the table roll. The grooves, which are spaced along the entire length of the table roll, are very narrow and cut around the periphery concentrically with the roll diameter. Sometimes spiral groves are used instead.
52. Suction boxes use a vacuum created by a vacuum pump in the range 5 to 8 in Hg. Using high vacuum increases the drag and reduces the life expectancy of the wire. Controlling the vacuum to effect the best compromise between good drainage and long wire life is therefore important.
53. The drier section transforms the fragile wet mat carried on the wire into a reasonably dry sheet of paper. The mat contains about 94 percent dry fiber at the end of its traverse across the drying rolls. The evaporation rate is approximately 2 lb (1kg) of water per hour per ft^2 (0.19 m^2) of total drier surface; this drying rate is subject to variation, dependent on the pressure of the steam used for the purpose. The diameter of the drying rolls can vary from 48 to 60 in (1.9 to 2.4 m), dependent on the machine involved. The pressure to lift the condensate from inside the drier roll to the condensate drain line connection on the outside of the roll is rounded up to 2.0 lb/in^2 (0.14 kg/cm^2).
54. An auto-selector system is an arrangement of controllers, signal selectors, and ramp generators that permit the automatic selection of the appropriate controller from a number of available controllers that will maintain stable conditions in a process having only one control valve, but whose regulation has an effect on all the control loops involved at the same time. It is important that only one of the controllers has an Auto/Manual Transfer switch, and this controller carries out transfer of the loop from Auto to Manual only.
55. A Yankee machine is a specialized drying machine designed for the drying of lightweight, tissue, crepe, and fine papers (e.g., cigarette paper). The main difference between this machine and the others is the massive drying roll, which can have a diameter of 8 to 12 ft (2.4 to 3.6 m) made from cast iron or cast steel. Because of its large size, it contains a great amount of metal. Getting this mass of metal to working temperature will take considerable time, which the control system will have to take into account. The outer surface of the roll is highly polished to handle the grades and type of paper produced, and must be handled with care by both the instrumentation and process operators. On a Yankee machine there is no felt on the drier roll; the wet paper is tightly pressed against the highly polished surface where it clings until dry.
56. In the production of crepe paper, a type of scraper called a *creping doctor* is used. The creping doctor and the *cleaning doctor* can have detrimental effects on the roll surface. Some crepe papers are best made while still wet. In these instances there are other drier rolls after the Yankee. When the creping doctor is not used to scrape the paper off the roll, the paper is called *machine glazed* (MG). This paper has only one side that carries a shine imparted by the polished surface of the roll.
57. The total resistance to the transfer of heat of the roll is the sum of all the individual resistances, and resistance is the reciprocal of heat transfer, that is, conductance computed in the same way, as one would calculate the total capacitance in an electrical circuit where the capacitors are connected in series; that is,

$$\frac{1}{R_{h\,tot}} = \frac{1}{R_{h1}} + \frac{1}{R_{h2}} + \frac{1}{R_{h3}} + \frac{1}{R_{h4}} + \frac{1}{R_{h5}}$$

The value of $R_{h\,tot}$ is calculated as the product of the evaporation rate, the enthalpy of the steam at the supply pressure, and the steam rate per lb (kg) of water divided by the temperature difference between the steam supply temperature and an average paper temperature of 180°F (82°C). This makes the units for $R_{h\,tot}$—Btu/hr/ft^2/°F (kCal/hr/m^2/°C). The values of R_{h1}, R_{h2}, and R_{h3} can be obtained from published data. However, R_{h4} and R_{h5} are not usually tabulated, but if these are combined as a single term, the value can be calculated from the foregoing. The total resistance to heat transfer will then be the reciprocal of the computed result. With a Yankee drier, the outside resistance is virtually zero; that is, R_{h4} and R_{h5} can be neglected, in which case:

$$\frac{1}{R_{h\,tot}} = \frac{1}{R_{h1}} + \frac{1}{R_{h2}} + \frac{1}{R_{h3}}$$

58. The performance of a drier is defined in relation to the amounts of water in the paper when entering and leaving the drier(s), measured as the percentage of water to the total weight of the wet paper.

$$\frac{\%\,dry\ fiber\ leaving}{\%\,dry\ fiber\ entering} - 1 = \frac{lb\ water\ removed}{lb\ dried\ paper}$$

However, the best way of expressing the amount of water is in pounds of water per pound of dry fiber.

59. A vast amount of vapor is given off in the drying process, which must be controlled in the interests of personnel protection as well as for product quality and for protection of the machinery. Hoods are used to confine the vapors; these hoods can be either totally *enclosed* or *open*. The open hood, more common in mills manufacturing boards, are suspended from an overhead gantry and are arranged to be raised or lowered to suit operating conditions, while much of the enclosed hood used on paper machines is usually fixed.
60. The enclosure for a Yankee machine is pressurized and draws off the vapor from the drying paper. The ducting arrangement recirculates the exhaust, and an economizer or a heat exchange is usually also included.
61. The vat machine has a mesh screen cylinder that is made to rotate in a vat of stock, and in so it doing picks up a layer of fibers on the mesh surface. The formed sheet is *couched off* the cylinder under the action of the couch roll. As a result, the longitudinal axis of the individual fibers lies parallel to the plane of the paper, but in a random direction to the dimensions of the sheet, giving the paper strength in all directions. The papermaker normally tries to ensure that the material produced has its fibers in the direction of travel of the sheet so that the sheet is strongest in that direction. It is sometimes desirable, however, or even necessary, to have the longitudinal axes of the

fibers perpendicular to the sheet in order to provide a thick and cushioning effect for the paper produced.

62. The main disadvantage of the vat-type machine is its inability to operate at more than one drainage rate, and, since this drainage rate varies for different sheet weights, temperature, and stock freeness, the machine's versatility is affected. Adding a *forming board* beneath the apron board in some ways replicates the slice on the Fourdrinier, and the inclusion of humps goes some way toward increasing the machine's capability.

CHAPTER 4
Evaporators

PROCESS EVAPORATORS AND SOME TECHNIQUES TO CONTROL PRODUCTION

In this section, we shall develop the idea first suggested in the Introduction of my previous book, *Instrumentation Fundamentals for Process Control*, where only a brief and simplified view of the evaporation process was given. It is hoped that this enlarged treatment of the subject will allow the reader to understand why the complexities involved were glossed over when we first introduced the concept.

Thickening or concentration of a liquid mixture of solids dissolved in a solvent or otherwise suspended is a process that is used extensively in the food, pharmaceutical, chemical, and paper industries. In the food and pharmaceutical industries, the need to concentrate the product is governed by the demands placed on it by the product developers and the market, as being the most suitable form of delivery to the consumer or other manufacturing processors who may utilize it as an ingredient for making additional products of their own design. In the chemical and paper industries, evaporation is quite often a means of separating the solvent and the solids and so allowing use of these two components for reprocessing. Examples are solvent recovery in turpentine extraction from wood chip and the solids-enriched *black liquor* fluid, the product from the evaporators for use as a fuel in the *recovery boiler* where after it is burned the sulfite or sulfate-rich pulping chemicals contained therein is recovered for reuse in the pulping process. When fully processed, a concentrate allows the product to be transported in the most compact form, in terms of bulk volume, and is therefore the method most often used. In this section, we investigate how this change is brought about and the underlying principles involved in effecting the change.

BASIC DEFINITION OF EVAPORATION

Evaporation usually refers to the removal of water by vaporization from an aqueous solution, leaving a nonvolatile substance as residue. This basic definition has been extended with modern technology to include solutions that may not be water based but may involve a solvent. When a solvent is evaporated, because of the high cost of this component, usually the solvent must be recovered from the vapor evolved during evaporation in order to reuse it for further processing. A process fluid subjected to evaporation results in a change of density, and this is the means most often used to achieve the objective.

The Principles Involved in the Evaporation Process

Heat transfer is the single most important factor in evaporator equipment. As stated above, in almost all cases it is necessary to remove, by boiling, the water or solvent contained in the process fluid. The highest heat transfer at the lowest installed unit cost under the operating conditions, or kW/°K/(£ Sterling or $ installed), determines the choice of evaporator equipment.

Basic Definition of Vaporization

Vaporization occurs when heat is absorbed by radiation or convection, which can be either:

1. At the surface of a pool of liquid—this is how it always takes place in nature when water is evaporated from lakes and streams.
2. By natural convection from a surface beneath the disengaging surface—which is the situation when a liquid contained in a vessel is heated.
3. At the surface of falling liquid films, but because of the depth of liquid involved vaporization appears to occur instantly—in this case it can be considered as the reverse of condensation.
4. When a warm fluid is subjected to a sudden drop in pressure, which forces the fluid to become *superheated* by forced convection and made to change its *phase* from a liquid to a vapor.

When the process fluid has a high solids content, and recovery of the maximum amount of the solids is desired, then subjecting the fluid to evaporation will remove the *carrier liquid* leaving a more viscous, solids-rich fluid. This technique is used extensively in the food processing industry when syrups or concentrates are prepared either for direct consumption by the customer or for further processing, which could result in a solid product (e.g., granulated sugar or powdered milk). This technique is also employed in the papermaking industry when the *black liquor* that results mainly from the pulping process is put through several stages of a multiple-effect evaporator system before it is burned in order to recover the sulfates for reuse. In paper making, the amount of alkali charged to the digesters where the wood chip is broken down is the source of the sulfates, which amount to about 98 percent of the liquor; the remainder of the sulfate is lost in the resulting pulp. The total combustible organic matter in the black liquor is between 55 and 70 percent of the total solids content, with the solids between 15 and 22 percent of the total liquor content. The actual recovery of the salts takes place in a highly specialized steam generator specifically designed for the purpose, called a *recovery boiler*. The recovery boiler is not so much a steam generator per se—but a chemical process in its own right, with the generated steam a very valuable byproduct.

Graphical Concepts of the Evaporation Process

Figure 4.1 illustrates diagrammatically what is involved when evaporating a mixture of solids dissolved in a solvent, from which the solids content is to be extracted. For convenience and simplicity, the process is divided into two distinct stages. In the first stage, the raw material is received at the inlet of the evaporator, which is, or could be, the product resulting from a previous preparation process. In the second stage, we view the effects of the evaporating process on this raw material.

With these diagrams we are also trying to illustrate that distinct components are involved, albeit not as clearly segregated as shown but nevertheless present. For the purposes of clarification, we have divided the Stage 1 diagram into two very distinct

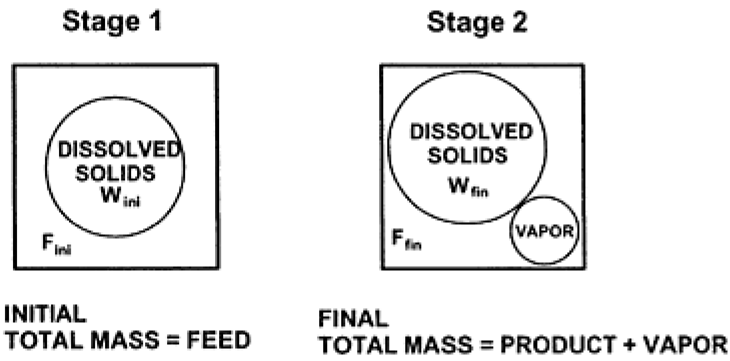


Figure 4.1: The evaporation process.

parts, with the circle containing the dissolved solids and the square representing the liquid solvent. In reality they are a completely blended uniform whole, which we will call the *feed*. If we now consider the total mass involved, we can let the mass feed flow be represented by the value F_{ini}, of which W_{ini} represents the initial weight of solids. Between Stages 1 and 2, we apply heat (not shown) to the mixture to concentrate the feed. When we have completed the concentration, let the final feed flow be F_{fin} and the final weight of solids it contains be W_{fin} with a certain amount of vapor being given off in the evaporation process. In the figure we have shown this by deliberately not changing the size of the square: the mass does not change throughout. We have however, increased the size of the *dissolved solids* circle, added the *vapor* shown as a circle, and thereby reduced the area of the feed. This is basically in keeping with what actually happens.

To derive a universally understood statement, let us draw up a material balance on the basis of the solids content only; this will yield:

$$F_{ini} \cdot W_{ini} = F_{fin} \cdot W_{fin}$$

This relationship by the Law of the Conservation of Mass shows that the amount of material available initially must be the same as the amount of material available finally, even though the amount of dissolved solids initially and finally will be different.

If V_{ev} is the amount of vapor driven off by evaporation, then we can show the complete material mass balance by rewriting the above equation as:

$$F_{ini} \cdot W_{ini} = F_{fin} \cdot W_{fin} + V_{ev}$$

There is a relationship between the amount of vapor evolved and the amount of heat applied, which in turn is based on the thermal efficiency of the evaporator itself. For a single evaporator, the heat balance can be stated as

$$V_{ev1}H_1 = \eta_{th}V_{ini}H_{ini}$$

where V is the vapor evolved, H is the enthalpy of the steam, and η is the evaporator efficiency.

The subscripts are interpreted as:

ev1	=	vapor evolved in the effect (the *1* in the subscript since there is only one stage of evaporation)
th	=	thermal
ini	=	initial

Using the equation $V_{ev1}H_1=\eta_{th}V_{ini}H_{ini}$ and writing $V_{ev1}H_1$ as V_{evS} to indicate the vapor evolved per stage denoted by S, we can represent the total result of a number of evaporator effects if we summate (add up) the amount of vapor and concentrated feed at the end of the evaporation process by:

$$\sum_{S=1}^{S=n} V_{nS} + \sum_{F=1}^{F=n} F_n$$

For a material balance, this must be equal to the initial input feed or:

$$F_{ini} = \sum_{S=1}^{S=n} V_{nS} + \sum_{F=1}^{F=n} F_n$$

Writing $\sum_{F=1}^{F=n} F_n$ as F_n we can say:

$$F_{ini} = \sum_{S=1}^{S=n} V_{nS} + F_n$$

$$\text{or } F_n = F_{ini} - \sum_{S=1}^{S=n} V_{nS}$$

This confirms that the total amount of dissolved solids in the fluid obtained from the final evaporator stage is given by the initial feed flow minus the total quantity of vapor evolved from all stages.

Using the equation

$$F_{ini} \cdot W_{ini} = F_{fin} \cdot W_{fin}$$

Because we know that F_{fin} is the same as F_n, since it is the final amount of liquid material, we can say

$$F_{ini}W_{ini} = \left(F_{ini} - \sum_{S=1}^{S=n} V_{nS}\right)W_{fin}$$

$$= F_{ini}W_{fin} - \sum_{S=1}^{S=n} V_{nS}W_{fin}$$

$$\sum_{S=1}^{S=n} V_{nS}W_{fin} = F_{ini}W_{fin} - F_{ini}W_{ini}$$

Therefore

$$\sum_{S=1}^{S=n} V_{nS} = \frac{F_{ini}W_{fin}}{W_{fin}} - \frac{F_{ini}W_{ini}}{W_{fin}} \tag{4.1}$$

$$= F_{ini} - \frac{F_{ini}W_{ini}}{W_{fin}}$$

$$= F_{ini}\left(1 - \frac{W_{ini}}{W_{fin}}\right) \ldots \text{After simplification}$$

The Results When Applied to Multiple-Effect Evaporator Systems

Let us now consider what happens in the case of a *multiple-effect* evaporator system. Before we proceed, however, it is advisable to give an idea of what the procedure entails. In this instance, the evaporation process is carried out in a series of linked evaporator vessels called *effects,* in which the process fluid and the evolved vapor are transferred from one vessel to another in succession. The vapor transferred from one effect is used as the heating medium for the following effect. The heating medium is usually applied only to the first effect in the series, and a vacuum is applied to the last, thereby forcing the vapor to be drawn through the whole series of vessels. The phenomenon of reduced pressure boiling is used for each of the following vessels in the series after the first effect to force the evolution of more vapor from the process fluid, causing it to be thickened progressively in each effect. Following this method of operation not only thickens the feed, but also preserves the quality of the product being processed, for it avoids possible damage to the product if it were to be boiled by an increasing temperature in each of the effects. To visualize what is occurring we shall once again resort to the preceding diagram, but modify it suitably to take account of the number of effects involved. For convenience we will consider a four-effect system, purely for symmetry of the diagram and nothing else. This will result in Figure 4.2. In the figure the evaporator effect numbers are shown as numerals 1 through 4 in each stage.

Once again the feed flow is F_{ini}, and we have shown this by each enclosing square. To show what happens in each evaporator effect, we have tried to convey the situation by suitably modifying the size of the dissolved solids and vapor circles. To read the figure, start at effect number 1 and proceed to effect number 4. A change occurs in each evaporator stage, which is shown by the size of the dissolved solids circle increasing and the size of the vapor circle decreasing. This represents what actually occurs in practice. However, in the interest of clarity some license has been taken; the actual volume flow from one effect to another is not necessarily equal as depicted in the figure, but the mass flow is. From this it is relatively obvious that the ratio of steam vapor volume to the mass of water it contains decreases from the first to the fourth effect because of the superheat it carries due to the boiling point elevation, which shall be shown later.

The performance of an evaporator or evaporator system is based on the amount of steam used; any economies made in this area will therefore be reflected in the performance rating. As mentioned earlier, in a multiple-effect evaporator system, the vapor produced in one effect is normally applied as the heating medium to the succeeding effect and from that one to the next and so on until the last effect is reached. However, the performance rating, important as it is, is not the only reason

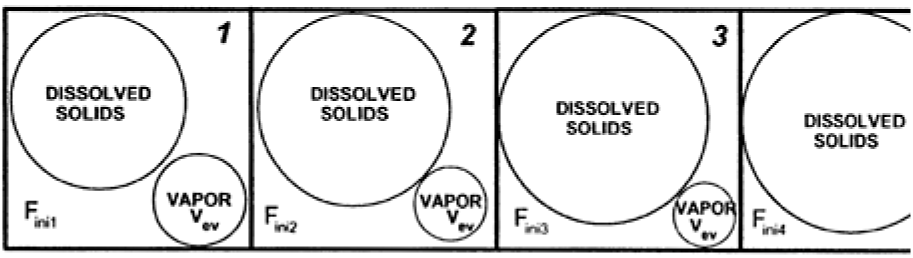


Figure 4.2: Multiple-effect evaporator having four effects.

for doing this. Steam production is an expensive business in itself, and minimizing the need to produce it separately in large quantities has a considerable effect on the economics of running the evaporator system. In some products, for instance, to preserve quality and appeal to the consumer, overheating must be precluded because the product itself may only require a relatively small heat input to ensure its production. Therefore, using the heat in the evolved vapor could be all that is necessary. Let us now consider the heating value of the evolved vapor.

As we have said before; for the first effect:

$$V_{ev1} H_1 = \eta_{th} V_{ini} H_{ini}$$

Hence for the second effect:

$$\begin{aligned} V_{ev2} H_2 &= \eta_{th} V_{ev1} H_1 \\ &= \eta_{th}^2 V_{ini} H_{ini} \end{aligned}$$

For the third effect:

$$V_{ev3}H_3 = \eta_{th}V_{ev2}H_2$$
$$= \eta_{th}^3 V_{ini}H_{ini}$$

We can continue this for *n* number of effects.

The total heating value can then be derived from summating (adding together) and rationalizing the immediately preceding expressions of the evaporator effects 1 through *n* to give:

$$\sum_{S=1}^{S=n} V_{nS} = V_{ini}H_{ini}\left(\frac{\eta_{th}}{H_1} + \frac{\eta_{th}^2}{H_2} + \frac{\eta_{th}^3}{H_3} + \ldots\ldots + \frac{\eta_{th}^n}{H_n}\right) \quad (4.2)$$

It should be noted that:

- In the above, the values of H_{ini} and V_{ini} are obtained from steam tables.
- The pressure in any evaporator effect is dependent on the temperature at which the vapor condenses.
- While the value of the total heat (enthalpy) *H* of the vapor at the absolute operating pressure in each evaporator effect obtained from steam tables is not exactly its latent heat of vaporization, for convenience without too much error, it can be used to calculate the ratio of vapor to steam for any evaporator.

As an example of how this calculation is carried out, let us consider a four-effect evaporator system in which the product being concentrated is nonedible, the heating steam in the last effect is at a temperature of, say, 130°F, and the evaporator system has an efficiency of 98 percent per effect with a temperature difference between each effect of 35°F.

From steam tables we find that for a temperature of 130°F the pressure is 2.2 lb/in^2 abs, and the enthalpy is 1020 Btu/lb. Subtracting 35 from each previous stage, we obtain the values of temperature for each of the other effects. The values of pressure and enthalpy are then easily obtained from steam tables corresponding to the temperature we have determined for each effect. It is easier if we tabulate the results, for this will enable us to see what is occurring (see Table 4.1).

The computations for the vapor/steam ratio are performed using Equation (4.2) as the basis.

Since we have to use the results of the evaporator effect thermal efficiency that is raised to increasing values of indices, it is easier if we compute the results and use

TABLE 4.1 Tabulation of Calculated Results of Steam/Vapor Ratio

Effect n	***Temperature ° F***	***Pressure Ib/in^{2}abs***	***Enthalpy Btu/lb***	***Vapor/Steam ratio*** $\frac{\sum V_n}{V_{ini}}$	***No. of Effects***
n	130	2.2	1020	(1.006866953) **1.00**	1 Last

n-1	165	5.3	999.3	(2.009795823) **2.00**	2
n-2	200	11.5	977.9	(3.01112202) **3.01**	3
n-3	235	23.3	956	(4.011425412) **4.01**	4 First
n-4	270	41.9	932		

these in turn as required. Hence, for the evaporator effect thermal efficiencies we obtain:

For each effect efficiency—η=0.98; η^2=0.96; η^3=0.94; and η^4=0.92.

Since steam is applied to only the first evaporator effect then the heat available is computed as: For each evaporator effect $(H_{ini}\eta_{th})$ term—1020×0.98=999.6; 1020×0.96=979.2; 1020×0.94=958.8; 1020×0.92=938.4.

For each evaporator effect the $(\frac{H_{ini}\eta_{th}}{H_n})$ term is computed as—999.6/999.3 = 1.00030021; 979.2/977.9=1.001329379; 958.8/956=1.00292887; 938.4/932=1.006866953.

The vapor/steam ratio for each evaporator effect is computed from the $(\frac{\sum V_n}{V_{ini}})$ term for each evaporator effect to give: 1.006866953; (1.006866953+1.00292887= 2.009795823); (2.009795823+1.001329379=3.01112202); (3.01112202+ 1.00030021=4.011425412). For simplicity we use the figures in boldface in Table 4.1.

SOME TYPES OF EVAPORATORS USED

In the following diagrams of the various evaporators, note that:

- The internally fitted baffle plates found in the vapor space directly above the heater exits have been omitted in the interest of simplicity and clarity.
- The types illustrated are only a small sample of the many available; it is by no means an exhaustive listing.

The Single-Effect Evaporator—The Short Tube Vertical Type

This is essentially a single vessel fitted with a heating element. It is used when:

- The quantity to be produced is comparatively small.
- The steam is relatively cheap.
- The material is highly corrosive.
- The vapor evolved is contaminated and therefore unsuitable for reuse.

This type of evaporator can be operated in batch, semi-batch, continuous batch, or continuous modes. We describe only the first three of the foregoing here inasmuch as the last operating mode is self-explanatory.

Batch operation is one in which filling, evaporating, and emptying operations are carried out consecutively. This mode of operation is quite rare for two important reasons:

1. The size of the vessel required. A good example of a batch evaporator is a *vacuum pan*

as in Figure 4.4 in a sugar refinery, which is quite an enormous vessel that is fed from a train of multiple-effect evaporators. However, further controlled evaporation is necessary in the vacuum pan to turn the supersaturated feed syrup into a sugar crystal-rich *massecuite* after *seeding*. Note: Seeding is the technique of adding a small quantity of refined sugar crystals to the massecuite in order to cause the whole mass to crystallize. The physics of the crystallization process in the mass of massecuite is not fully understood, but it is assumed that the small quantity of sugar crystals added acts as nodes and as a trigger to initiate crystal growth from these points. In the example quoted here, despite the earlier comments regarding the use of single-effect evaporators being used for relatively small and highly corrosive material, even though the process is a batch operation, neither batch size nor the material and the vapor evolved fit the earlier defined criteria.

2. The fact that the heating element should not be allowed to be uncovered at any time throughout the operation.

Semi-batch operation is more commonly used in industry. In this mode, the feed is continuously allowed to flow into the evaporator. To maintain a constant level in the evaporator vessel, the feed rate is adjusted accordingly and continues to be done until the entire batch has been processed. Good examples of this type are the individual effects in black liquor and raw sugar juice evaporator trains.

C*ontinuous batch* is an operation in which a continuous circulation of the material takes place between the evaporator and a separate *feed tank* that holds the full capacity of the stock to be evaporated. The important requirement is that the level in the evaporator be held constant throughout the operation. Evaporation is stopped only when the entire contents of the feed tank have attained the desired specification.

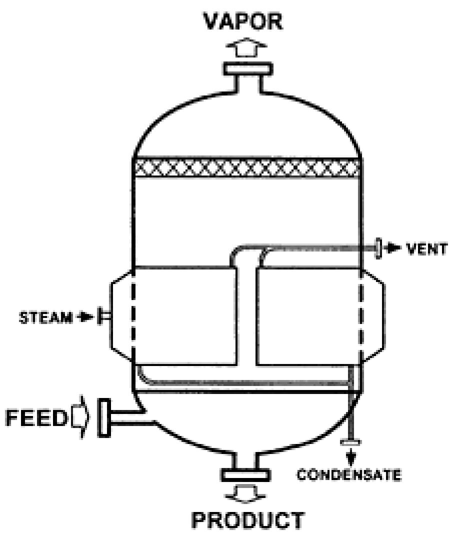


Figure 4.3: Short tube vertical evaporator (single effect).

In Figure 4.3, the size of the heating element has been exaggerated for clarity; its height should be in the region of about one-third the depth of that occupied by the batch when first introduced to ensure it is fully covered during the whole operation. The circulation and heat transfer in this type of evaporator are greatly influenced by the liquid level and are at an optimum when the level is only about halfway up the heating tubes. Circulation is entirely dependent on the boiling, and solids settle out of suspension when this stops. However, when an impeller is installed in the downtake, the evaporator can be used as a crystallizing evaporator. In this form it is used as a vacuum pan in the sugar industry. In crystallizing applications, the liquid level must be held well above the top tube.

The Vacuum Pan—As Used in the Sugar Industry (Modified Short Tube Type)

Short tube vertical evaporators are used most frequently in forming the multiple-effect evaporator train in sugar refineries. The way this type of evaporator has been modified to produce the vacuum pan so necessary in the sugar industry is illustrated in Figure 4.4. Notice the similarities and the modifications made to the vessel shown in Figure 4.3. In this enhanced equipment, the requirement is to form crystals; hence, as mentioned earlier, forced circulation of the product is included. The design of the impeller system is such that the circulation path is from the top to the bottom of the fluid, with the feed being made to enter from a point at the base of the vessel. By installing the impellers in what is effectively a *stilling tube* the circulating movement

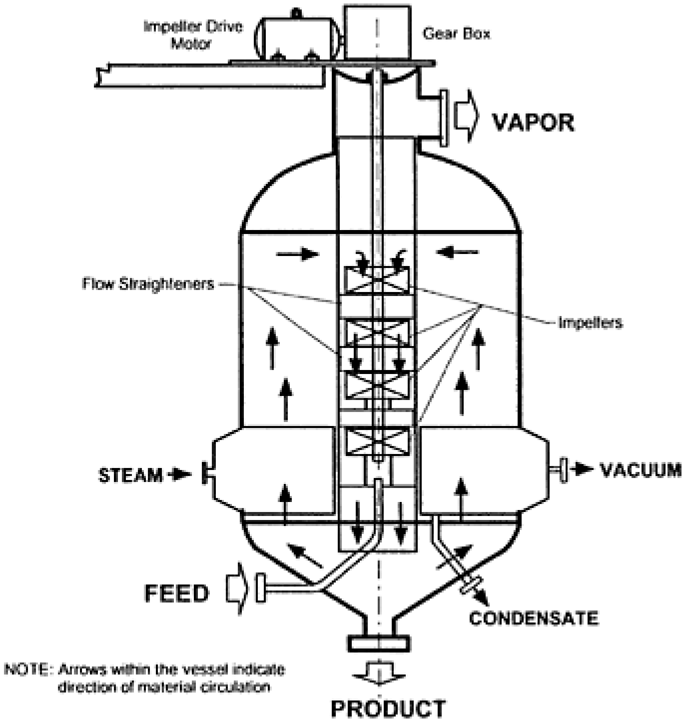


Figure 4.4: Cross section of a vacuum pan.

of the product is enhanced. This has additional benefits in that the heat is more uniformly distributed throughout the mass and crystal growth can proceed freely throughout the contents.

Forced Circulation Evaporator

The evaporator shown in Figure 4.5, is quite commonly found in industry, because the highest heat-transfer and evaporation rates are obtained using this type of evaporator. The highest heat-transfer rates are obtained when the feed is allowed to boil in the tubes with the feed level usually held at or slightly below the top of the tubes. For the equipment shown, the feed is allowed to boil in the tubes; consequently, this type is limited to evaporating feeds that do not form a salt or deposit scale during the evaporation process. If the feed does deposit scale or form a salt, then the evaporator is modified so that the heating tubes are placed far below the liquid level or return line to the flash chamber, which is the enlarged space at the top of the evaporator; the design arrangement is such that the hydrostatic head is made sufficiently large to ensure that no boiling occurs in the tubes. The usual orientation of the heating tubes is vertical as shown. In this arrangement, it is much easier to clean or re-tube the equipment and so reduce maintenance costs.

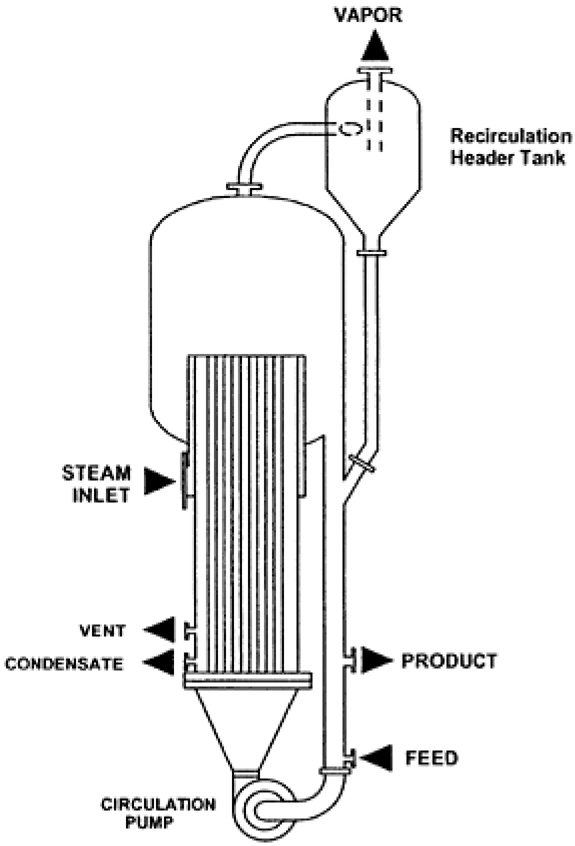


Figure 4.5: Forced circulation evaporator.

In some cases, however, where the headroom space required is restricted, the heating tubes are placed horizontally. This rearrangement has the on-site desired effect of minimizing the height and improving accessibility when compared to the vertical version. This type of evaporator is often used where a crystallization operation of the product is necessary and solids are required to be maintained at all times. Since a pump forces the feed along the heated surface of the tubes, high velocities can be obtained, although the velocities are limited by the effects of erosion on the tubes and are reflected in the power requirement of the circulation pump used.

Long Tube Vertical Evaporator

The long tube vertical type of evaporator shown in Figure 4.6 is the cheapest to run and has the highest evaporation capability. It is relatively simple and has only a one-pass heater, which feeds directly into a relatively small vapor space. The equipment is fast-acting in that the residence time is very short—on the order of seconds. The temperature in the tubes is difficult to predict because the temperatures are not uniform throughout the length of the heating tube. The vapor velocities are high; the baffle plate acts not only as a liquid/vapor separator, but also as a foam breaker. It is almost always operated as a single-pass evaporator, with virtually no liquid collected in the vapor space.

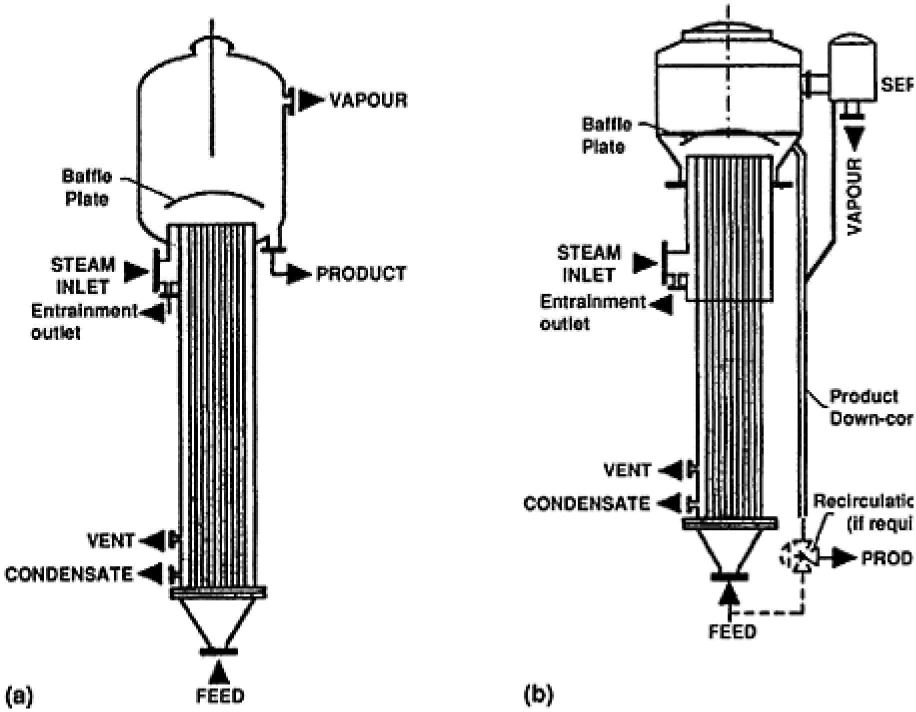


Figure 4.6: (a) Long tube vertical evaporator and (b) long tube vertical evaporator for black liquor.

Long Tube Vertical Black Liquor Evaporator—As Used in the Paper Industry

In view of its evaporating capability, the long tube vertical black liquor evaporator is commonly used in the paper industry where it is used to concentrate the black liquor before it is fired in the recovery boiler. Black liquor is so called because of its deep black color, which changes to a reddish brown when diluted. It is also very viscous and susceptible to foaming when the concentrations are high. The concentration of black liquor from the pulp washing to the evaporation system is dependent on the solids charged to the pulp digester. The composition of the liquor varies from one mill to another, but the alkalis present are in the form of carbonates, sulfates, sulfides, and other compounds related to these. There is also a possibility that sodium sulfate (Na_2SO_4) and silica (SiO_2) are present. (For details of how the pulping process operates, see Chapter 2 on digester control.) Figure 4.6 shows two versions of the equipment. When the ratio of feed to evaporation or feed to heating surface is low, recirculation of the product through the evaporator may be necessary; inserting a connection between the product and feed lines provides a solution to the problems of low feed/evaporation ratio or small heating surface. This connection is quite easy to visualize in the figure, which shows the black liquor version of the equipment. The product down-comer pipe can be joined to the feed pipe with an interposing valve normally inserted between the connections to allow recirculation of the product when necessary. The separator in the black liquor version is designed to produce a spiral action in the vapor path. This rotating flow separates out any entrained liquor from the vapor and thus minimizes any liquid carryover to the next effect.

The Falling Film Evaporator

This type of evaporator (see Figure 4.7) is used extensively in industries where highly heat-sensitive products are manufactured. It is therefore quite common in:

- The dairy industry, where it is used to process the raw milk received from the farms into a *milk concentrate* prior to it being used to produce milk powder in a vacuum drier.
- The fruit juice-producing industry.

This evaporator does not have the problem of hydrostatic head, since the process liquid is made to enter the top of the vessel, from which point it then flows downward as a film of liquid along the inner walls of the heat exchange tubes, gaining heat all the while as it does so. The vapor is usually given off at the bottom. The pressure drop along the tubes is very small, and the liquid boiling point is practically the same as the vapor head temperature. The other advantage of this evaporator is that the retention time in the evaporator is also small; hence, material processing can be carried out quickly. However, the biggest problem with the falling film type of evaporator is the distribution of the feed to the tubes, because all of the tubes must be kept continuously wet to avoid scorching and the resulting constriction of the tube bore. This type of equipment is rarely used for fluids with high solids content for reasons of the limitations already stated.

THE STEAM CONDENSER

We now turn our attention to the *steam condenser,* which is an important piece of equipment and merits some consideration before we discuss a typical control system in some detail. The condenser converts the steam back to water and in so

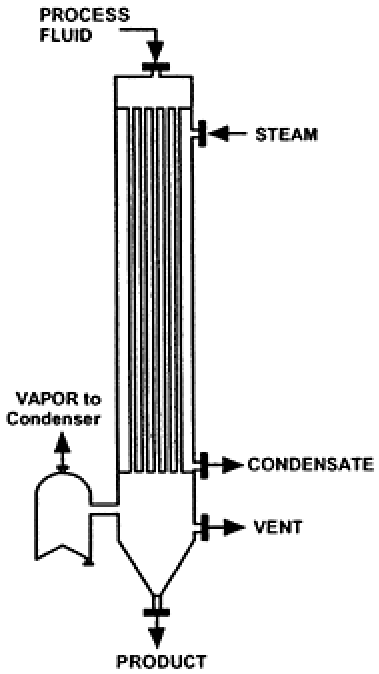


Figure 4.7: Falling film evaporator.

doing reduces its volume and thereby draws a vacuum in an evaporator, be it a single-or multiple-effect system. It is the simplest type of equipment with no mechanical moving parts and is most often used to achieve a vacuum in steam-operated systems. The condenser operates on the principle of accelerating the vapor flow through the system by providing a larger space for expansion accompanied by forced cooling and in doing so effects a pressure reduction. This is explained as follows. The reduction in the vapor temperature causes it to change state, making all or part of it revert to a liquid. Since for the same mass a liquid occupies a smaller volume, more vapor will be drawn in to replace what was liquefied; the accelerating vapor flow results in a lower pressure. A typical condenser is illustrated in Figure 4.8.

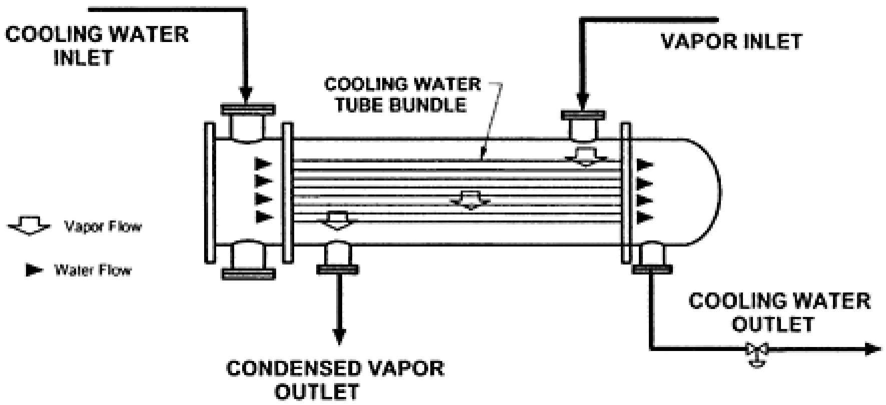


Figure 4.8: Process condenser for producing a vacuum.

Principle of Operation of the Steam Condenser

We all know that a liquid contained in a vessel occupies a particular volume at atmospheric temperature. If we put a stopper onto the containing vessel and apply heat to this volume of liquid, it will start increasing the internal energy of the liquid. If sufficient heat is applied, then the liquid will begin to change state and turn into a vapor. This vapor, together with any air trapped when the stopper was applied, fills the entire space above the liquid surface. The air mixes intimately with the vapor and is therefore at the same temperature as the vapor. The more heat that is added will not only vaporize more liquid, but will also increase the internal energy, which manifests itself in an increased pressure because of the fixed volume of the containing vessel. If at some point the heat source were to be removed and the outside of the vessel were subjected to cooling, the vapor/air mixture would give up its heat (hence energy), with the vapor starting to condense back to a liquid taking with it the air as minute entrained bubbles. The condensed vapor will occupy a much smaller volume than before (i.e., when it was a vapor) and will have less energy and will therefore, be at a reduced pressure. As a result, the stopper will be drawn even more tightly on to the vessel.

What actually happens is that as a direct result of the reduced internal pressure of the vessel (when compared to the atmospheric pressure on the outside) the pressure difference between the internal vessel pressure and external atmospheric pressure increases. This forces the stopper onto the vessel more tightly. If there were no stopper, then there would be a rush of air into the vessel to replace that which had gone into solution with the rising vapor content.

Now, if instead of having the stopper, the vessel were to be modified as shown in Figure 4.8 to have a separate chamber—shown as the volume surrounding the water tubes, into which the vapor were allowed to expand—and if this separate region were to be cooled by the water flowing through the tubes, then vapor condensation would occur there. The condensed vapor would then be continuously replaced by more vapor from the boiling vessel, drawn in by the resultant reduction of pressure. This very fast movement of vapor from the boiling vessel (at a high pressure) to the condensing vessel (at a low pressure) reduces the pressure in the boiling vessel. All we have done to achieve the pressure reduction is increase the rate of vapor flow by forcing it to change its phase from a vapor to a liquid, resulting in a reduction in the vapor volume and a lower pressure.

In practice, the vapor outlet on the evaporator is connected onto the vapor inlet of the condenser. Because it is being subjected to a reduced pressure, inevitably the liquid in the evaporator will boil even more vigorously. Reducing the pressure further lowers the boiling point of the liquid even more, causing more vigorous boiling and increased vaporization.

As we have shown before in Equation (4.1) (and repeated here for convenience)

$$\sum_{S=1}^{S=n} V_{nS} = F_{ini}\left(1 - \frac{W_{ini}}{W_{fin}}\right)$$

However, in any evaporator it has been found that the heat input and the vapor removal are constant. This can be written as:

$$\sum_{S=1}^{S=n} V_{nS} = k_{heat} Q \tag{4.3}$$

where Q is the heat input, and k_{heat} calculated from Equation (4.2) or it could be made available as part of the design data.

By substitution we can say:

$$k_{heat} Q = F_{ini}\left(1 - \frac{W_{ini}}{W_{fin}}\right) \tag{4.4}$$

This last equation will allow the approximate heat-to-feed ratio to be calculated for any given product concentration in an evaporator. It should be noted that the flow is the mass flow, which nowadays can be measured directly by a Coriolis meter. If the volumetric flow is measured, then it will have to be multiplied by the fluid density to obtain the mass flow. In instances where volumetric flow instruments are used, Equation (4.4) becomes:

$$\frac{Q}{F_{ini}} = \frac{1}{k_{heat}}\left(1 - \frac{W_{ini}}{W_{fin}}\right)$$

where $(F_{ini}Vol)$ is the volumetric flow and D is the fluid density, from which we have:

$$\frac{Q}{\left(F_{ini}Vol\right) D} = \frac{1}{k_{heat}}\left(1 - \frac{W_{ini}}{W_{fin}}\right)$$

For an orifice flow metering system, we know that:

$$Q = \frac{1}{k_{heat}} F_{ini} Vol \left\{ D \left(1 - \frac{W_{ini}}{W_{fin}} \right) \right\}$$

where *h* is the differential head produced by the primary element (orifice plate, etc.) and k_{meter} is the meter factor for the particular measuring device.

Hence, for this type of flow metering system, we can say:

$$F_{(volumetric)} = k_{meter} \sqrt{hD}$$

In order to use the above, the relationship between density and feed concentration must be known, from which a graph can be plotted. In his book *Energy Conservation through Control* (1978) F.G.Shinskey shows a plot for corn syrup and makes the statement, "These functions come out surprisingly linear with density—even the orifice function, because the square root curve does not change slope much in the region 1.0–1.2." Note the values 1.0–1.2 in the quoted statement refer to the product density. In such plots, the slope of the curve obtained from the plot between density and feed concentration is negative and varies with the solids concentration. Since the relationship is linear, it is possible to write an equation in the form:

$$Q = \frac{k_{meter}}{k_{heat}} h \left\{ \sqrt{D} \left(1 - \frac{W_{ini}}{W_{fin}} \right) \right\}$$

Since we are dealing mostly with aqueous solutions, the intercept *C* will always be 1.0, because as the feed density approaches 1.0, which is that of water, greater amounts of evaporation must take place. Under these circumstances, the feed will comprise increasing amounts of water compared to the material we are seeking. Hence, to get what we want we have to get rid of the unwanted—water—which by implication is in greater abundance. When the density of the feed is 1.0, then all the feed must be evaporated, which is as it should be. Because of the negative slope of the curve as mentioned earlier, the equation of relationship will therefore have to be modified to:

$$y = mx + C$$

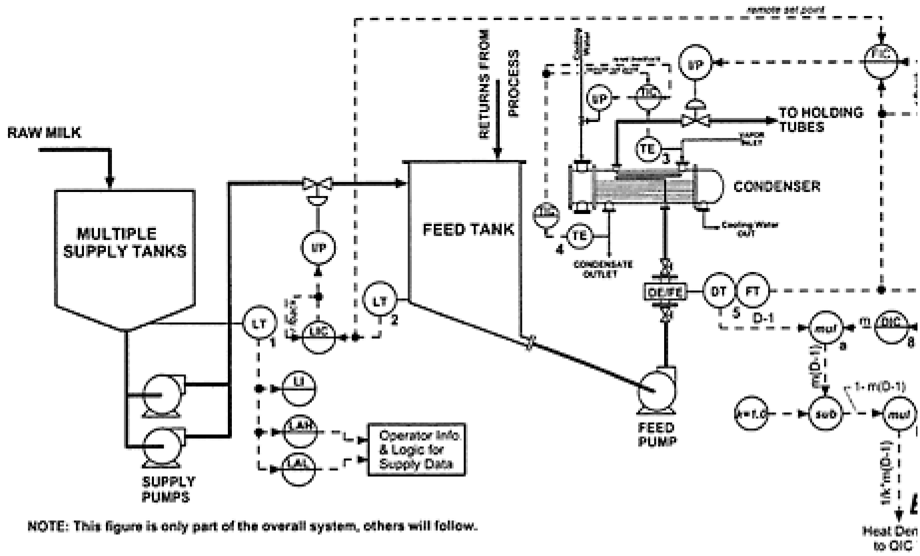


Figure 4.9: Raw milk handling system—evaporator controls.

Substituting our measurements into this equation, we have:

$$Output = 1 - \{m(D - 1)\}$$

where *Output* is the signal from the computing module and *m* is the slope of the plotted curve and is determined by the density of the final product. Hence, we can rewrite this relationship as:

$$Output = 1 - \left\{D_{final}(D - 1)\right\} \tag{4.5}$$

where D_{final} is the final product density and *D* is the density of the feed.

Equation (4.5) is what we are implementing in the instrumentation arrangement of Figure 4.9 with the signals being given their originating identity shown in the expression from which Equation (4.5) was derived.

If the heat supply to the evaporator system is to be regulated, then the feedforward system must calculate the set point for each change in the rate of product fed to the process. This requirement will result in the following relationship:

$$Q = \frac{1}{k_{heat}} F\,[1 - \{m(D - 1)\}] \tag{4.6}$$

Equation (4.6) is very similar in form to the one derived from Equation (4.4).

On the other hand, if the heat supply is to be maintained, the rate of product feed will have to be regulated, and this will result in the Following relationship:

$$F = \frac{kQ}{1 - \{m(D - 1)\}} \tag{4.7}$$

Once again there are similarities in the form of Equation (4.7) to that shown previously.

CONTROL OF A MULTIPLE-EFFECT EVAPORATOR PRODUCING A MILK CONCENTRATE

For a particular manufacturing plant with which the reader may be involved, the layout of the plant and instrumentation given in the following may not necessarily be exactly as depicted and explained. Some license for the process vessel construction and layout will remain with the plant designers. In the system descriptions that follow the tag numbers for any computational function instrumentation is shown in lower case and enclosed in square brackets for clarity.

RAW MILK RECEIPT

In this application we will first consider the bulk handling of milk as it is delivered to the creamery by the agency responsible for its collection from individual dairy cattle farms. Milk processing falls into a number of well-defined operations and products such as:

1. Milk for drinking can either be full cream—in which all the natural fats produced by the animal are contained—or skimmed—in which the bulk of the natural fats have been removed. However, manufacturers may add minerals and vitamins to both types of product to benefit the consumer.
2. Milk for processing into dairy products such as butter, cheese, and yoghurt.
3. Milk for processing into powder for wider distribution, storage, or further processing.

It should be remembered that almost all manufacturing organizations work in accordance with approved and verifiable standard specifications for the products they market.

Because the raw material is a natural product, processing must be undertaken as soon as possible after receipt. The creamery normally has a number of raw material receiving tanks into which the collected raw milk is pumped and stored. Storage tanks are necessary because the quantity delivered is usually much more than the evaporator system can process at one time. In the interest of both health and hygiene, it is necessary to clean and sanitize (the word “sterilize” is very often used to describe this process, but this usage is strictly speaking incorrect) the raw material receiving tanks after each full one is used up. The cleaning and sanitizing cycles for the raw material receiving tank are not discussed here because they are often the subject of civic health regulations whose finer details often vary between countries and the various authorities. However, this description of the general principles involved should help the reader visualize the whole cleaning process, keeping in mind that details will vary according to specific cases. Because dismantling of the plant involved cannot be contemplated, all equipment (e.g., pumps, vessels, and process connections) is specifically designed to eliminate bacteriological growth. This procedure is known as *cleaning in place (CIP)*.

PROCESS EQUIPMENT

Construction Requirements

The plant equipment has to be designed to certain requirements which experience over the years has proven to be satisfactory and to provide the necessary hygienic conditions. These requirements are as follows:

1. All process vessels must be constructed using 18/8 stainless steel, which means that the material contains 18 percent chromium and 8 percent nickel with a maximum carbon content of 0.12 percent. The carbon content is kept low because precipitated carbides in the microstructure reduce the anticorrosion property of the material. In order to retain the carbon in solid solution, the stainless steel alloy is heated to 1050°C during the manufacturing process and then quenched. Care has to be exercised during any subsequent welding during the vessel fabrication operations because areas of the metal near the weld will be held at a temperature between 650°C and 800°C long enough for carbides to be deposited, giving rise to a defect called *weld decay*. These defective areas will be the starting point for subsequent corrosion. This steel is an austenitic alloy that takes a good polish and is resistant to attack by many corrosive organic and inorganic reagents. Its tensile strength in the annealed state is between 90,000 lb/in^2 and 100,000 lb/in^2, which can be increased to between 120,000 and 125,000 lb/in^2 by cold working the material. An elongation of 60 to 70 percent can be expected. Europe does not appear to have a direct equivalent of this type of stainless steel; the nearest UK specifications for the material are EN58A and EN58B.
2. There should be no screw threads in contact with the fluid being processed.
3. All vessel ends must be sloped so that the process fluids run off easily and do not stick to the sides of the vessel.
4. Square corners must be avoided for all permanent attachments; if these are unavoidable, a minimum radius of ¼ in (6 mm) must be maintained.

Cleaning Requirements

This procedure begins with a thorough initial high-pressure wash of the vessel using hot water to eliminate some of the fat and cream in the milk, which will inevitably adhere to the sides of the raw material receiving tank. This is followed by:

1. A wash with an alkaline (or acid if it were some other product being processed) solution. The choice and strength of the wash additive depend on the product and the construction material of the containing vessel.

   The time limit for this wash is in the 10 min to 60 min range. The construction material of the vessel has an influence on this time limit because the equipment being treated must sustain no damage.

   The rate of flow of the wash is limited to the range 1 m/sec to 3 m/sec, and is most often pumped at a rate of 1.5 m/sec. The wash flow must not be dead-ended—that is, not be allowed to accumulate.

2. Sanitization of the vessel, which is the final stage of the cleaning process in the milk concentrating process, is effected with a wash using a 200 ppm (parts per million) chlorine solution. Most importantly, this sanitization wash must be carried out at least 30 min before the vessel is put into use. Under no circumstances may the vessel be used directly after the sanitization rinse.

The effluent is monitored at each stage of the cleaning process to ensure that the relevant conditions are met; thus contamination of the product by the cleansers is avoided. The procedure outlined ensures that the vessel is thoroughly clean, sanitized, and therefore bacteria free and ready for the next delivery of raw milk. Notwithstanding what has been stated earlier, every manufacturing plant has its own preferred cleansing agents and established cleaning routine. It is therefore recommended that the individual creamery's procedure be studied before any work on automating the cleaning process is undertaken.

Note: If the vessel has to be scoured to remove any unwanted material, the material used for the scourers and the vessel itself must not be dissimilar. This is to ensure that electrolytic actions are not set up that will introduce of points of corrosion, which would be the case if the recommendation were ignored.

CIP is a sequential operation and is therefore amenable to a *batch sequence procedure*. Almost all of the procedural cycles are time-based with metered quantities of water and detergent to be provided to the vessel being cleaned at appropriate points in the operating cycle. Of particular importance is the opening and closing of the appropriate valves at the correct time and for the required duration. Apart from some process analyzers and temperature and pressure measurements, very few other process measurements will be necessary. Thus the cleaning operation can in most cases be successfully automated.

RAW MILK HANDLING

The production of milk concentrate is a continuous process commencing with an arrangement of processing vessels that allow this to take place. Figure 4.9 shows a typical arrangement of such equipment.

In Figure 4.9, for simplicity and clarity the collection of a number of raw material receiving tanks has been combined and depicted as the single supply tank. In actuality, the number of raw material receiving tanks varies from one plant to another and therefore the single level-measurement shown is merely representative of individual level measurements on each receiving tank. The number of level measurements required will be appropriate for the number of raw material receiving tanks on the site.

The level transmitters used and shown as LT-1 are instruments specifically designed for use in the food and pharmaceutical industries, having internal construction that does not allow the process material to stagnate. The term used in the industry is that they do not have *dead legs*. Any D/P cell used must be provided with either an *extended diaphragm* or a *diaphragm seal*. In both instances the design must permit the measuring diaphragm to lie flush with the inside of the containing vessel, thereby eliminating the possibility of a dead leg that would otherwise be there if this method were not employed. The level alarms included in this part of the system provide initiating triggers; the high-level alarm LAH-1 is used for switching one raw material receiving tank to another, and the low-level alarm LAL-1 is used to trigger the commencement of its individual (tank) cleaning operations. Each level transmitter is located at the lowest point of the sloping bottom of its receiving vessel. Once again, because of the variation in cleaning procedures from site to site, it is not realistic to show the complete logic necessary for the system. It is assumed that sufficient attention will be paid to this aspect when one is involved with the design of such systems.

Two supply pumps have been shown to permit uninterrupted material flow during the cleaning operation. These pumps are also specifically designed to have internal pathways that eliminate even the smallest collection of stagnant fluid that would give rise to bacteriological growth and cause contamination of the product. As a result, these pumps are very expensive items. Providing a duplicate pump on every line where a pump is used is a costly affair, and it is therefore normal practice to install duplicates only on those lines that could have serious consequences for the manufacturing production cycle. The raw milk is delivered to the creamery cold (i.e., at a relatively low temperature). To minimize processing time and, more importantly, to pasteurize it, the raw product's temperature must be raised. Passing the raw milk through a heating coil contained within the specially designed condenser is the first part of the pasteurizing procedure and ensures that the raw milk will be of uniform temperature. In addition to providing heat to the milk, the condenser equipment also performs its normal function of producing the required vacuum in the evaporator system. To ensure a constant vacuum in the evaporator system and, as a direct result, a fairly uniform temperature in the raw milk, a temperature cascade loop is used; the condensate temperature is measured by the temperature sensor/transmitter TE-4 and is applied as the measurement to the primary controller TIC-4 whose set point is determined by the process operator, and its output is cascaded as the set point on to the secondary controller TIC-3. The secondary controller TIC-3 receives its measurement from the temperature sensor/transmitter TE-3 located in the vapor inlet line and monitors the temperature of the vapor entering the condenser. A reset feedback signal is important in this control loop and is provided by applying the output of TIC-4 to the feedback connection of TIC-3. This arrangement will ensure that the secondary controller TIC-3 will not saturate in the event the process operator drives the output of the primary controller manually. This cascade loop provides very stable control of the condensate temperature and also allows the operator to make fine adjustments to the vacuum, should that be required, by altering the set point of the primary controller TIC-4.

Pasteurization and First-Stage Evaporation

The heated raw milk has its temperature raised further as it passes through the evaporator effects in the following order: third, fourth, and second. The objective is to gradually raise its temperature before it is made to enter the *holding tubes* and the *pasteurizer*, where additional heat is added by applying heating steam to these two items of equipment. The path taken by the raw milk is shown in Figure 4.10. This

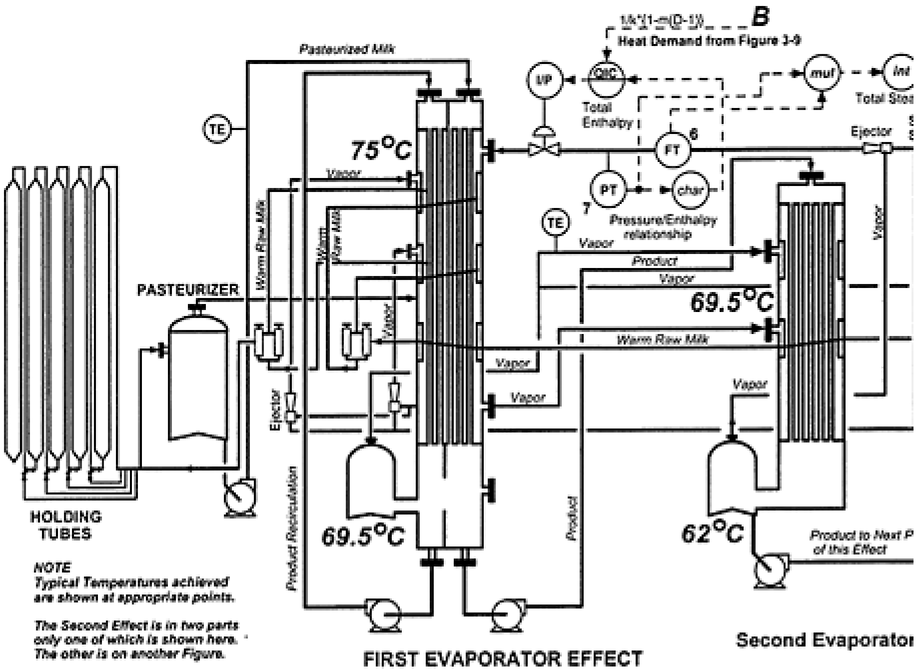


Figure 4.10: Pasteurization and first-stage evaporation control system.

fragmenting of the entire process diagram is necessary because of the large spread involved; it is hoped that by doing so the reader will obtain a better understanding of the control requirements.

Referring once again to Figure 4.9, we see that the level transmitter LT-2, which also must be similar to those used on the supply tanks, measures the level of the feed tank. Controller LIC-2 provides the set point for flow controller FIC-5 and also maintains this level to a value determined by the process operator when he sets the set point of the controller. The controller then regulates the amount of raw milk flowing through the supply line via the control valve and its electropneumatic converter I/P-2 to avoid causing the feed tank to overflow. Since this is a cascade loop, saturating the integral control term on LIC-2 must be avoided. To allow for those instances when, for operational reasons, the operator transfers the flow controller FIC-5 to Manual; reset feedback is provided from the output of the flow controller FIC-5 to the feedback input of level controller LIC-2. If required (although not shown), the feed tank level measurement could be provided with high and low alarms to give the operator ample warning of impending problems. A Coriolis mass flowmeter shown as DE/FE-5 is used to determine the amount of material that passes to the evaporators. Although high in initial cost, this instrument actually provides two measurements with a single penetration into the process line, the mass flow of material and a measure of the fluid density. Both of these measurements are used in the configuration of the control system. In the diagram of the control systems the outputs of the various computations are shown in their mathematical form so that the reader is kept informed as to the purpose and reason why the modules concerned are connected with respect to the computation. The combination of the various modules shown performs the computation shown in Equation (4.5), which is repeated here for convenience

$$Output = 1 - \left\{ D_{final} (D - 1) \right\}$$

This last equation uses the measurement of fluid density instead of the weight fraction of the solids because there is a direct relationship between the two and it is easier to measure the fluid density. There are instruments available that measure solids contents—refractometers—but these are delicate optical equipment that require much expert maintenance. It is therefore difficult to justify using them in a process production environment. Therefore, densitometers are the more usual instruments in a plant, although in some processes refractometers are needed to maintain product specification and quality.

The raw milk density is ρ (rho), but the measurement signal is transmitted and used as *D*—1, the term within parentheses in the above equation. This value is multiplied by the output from the density controller DIC-8, which obtains its measurement from the density measurement of the Coriolis flowmeter (DE/FE-8 in Figure 4.11) located in the milk concentrate line via the dynamic compensator module [dyC-8] which is set as a *lead* to allow for the delay as the process fluid passes through the several evaporator effects—the constant 1.0 being set by the constant module k=1.0 and the subtraction carried out in the module [sub-5]. The module k=1.0 has to be scaled to the full range of density expected and manually adjusted to read a value of 1.0, which is the density of water.

The Heat Demand

The incoming flow of the raw milk is determined by flow sensor/transmitter FT-5 and is applied as the measurement to the flow controller FIC-5, whose set point is provided by the feed tank level measurement derived from level transmitter LT-2. This flow control loop ensures that a known quantity is continuously provided to

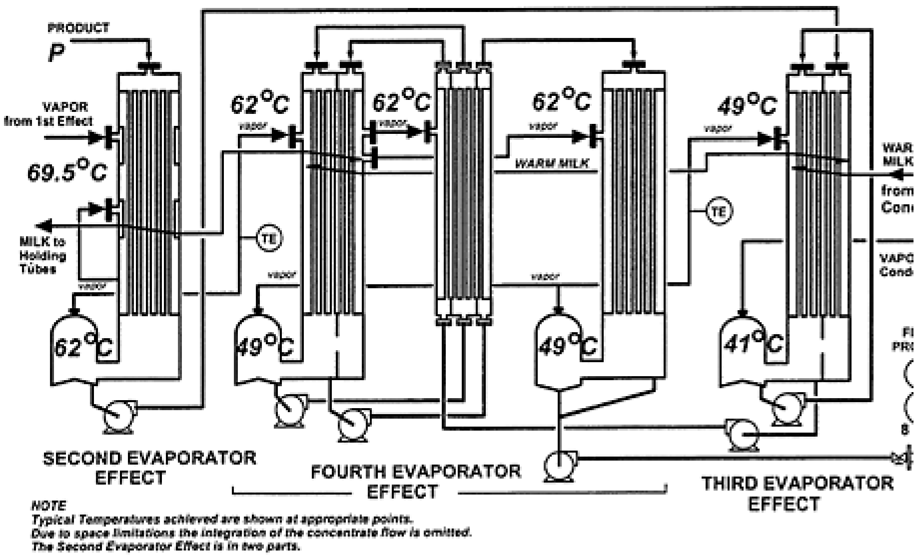


Figure 4.11: Arrangement of intermediate effects of evaporator system.

the evaporator train. Note that in this instance, the set point is taken directly from the level measurement and not the level controller output. Hence, flow controller FIC-5 responds directly to feed tank level changes, no cascade control is involved, and the both controllers LIC-2 and FIC-5 have reset feedback provided from their own outputs. This technique avoids integral saturation under all circumstances but is used only when a primary controller output is not used as the set point for the secondary. The output from controller FIC-5 regulates the amount of milk supplied to the evaporator train and ensures that this quantity is uniformly maintained. The density measurement from DT-8 (Figure 4.11) is provided with a dynamic compensator [dyC-8] (Figure 4.9), which as stated earlier is set as a *lead* device to counteract the inevitable delay that occurs as the concentrated milk passes through the evaporator effects and on to the process dryer system. The time set on the module [dyC-8] (Figure 4.9) will have to be finally determined when the control system is commissioned on site. The multiplier module [mul-5a] calculates the product of the signals it receives from DT-5 and DIC-8 to produce an output that represents the term m (D—1). The steam supply for the system (Figure 4.10) is controlled in order to produce the final product. Module [mul-5b] accepts the result of module [mul-5a] and multiplies this value by the raw milk flow from FT-5 to produce the heat demand computed from Equation (4.6) and repeated here for convenience.

$$Q = \frac{1}{k} F \left[1 - \{m(D - 1)\}\right]$$

This computed value is the set point for heat controller QIC-7. The control loop for regulating the heat supply is shown in Figure 4.10. It is also possible to vary the feed input to do the same thing, but to do this we have to obtain a measure of the amount of heat being supplied to the process and use a divider module instead of the multiplier as shown in Figure 4.9. The feed demand computed from Equation (4.7) is repeated here for convenience

$$F = \frac{kQ}{1 - \{m(D - 1)\}}$$

As before one input of the divider sees the computed value obtained from: *Output* = 1-{*m* (*D*—1)}.

The other input is the measurement of the heat supply to the system.

The amount of heat applied to the evaporator is determined as follows. The steam header pressure is measured by a pressure sensor/transmitter PT-7 and applied to a signal characterizer module [char-7]. The characterizer module relates the header pressure to the associated value of enthalpy (Btu/lb or equivalent metric unit) at that pressure. This signal is applied as the measurement to controller QIC-7, which receives its set point from the output of the computing module [mul-5b] shown in Figure 4.9. Controller QIC-7 regulates the control valve placed in the steam supply line via the signal converter I/P-7.

The steam flow is measured by a flow sensor/transmitter FT-6. For purposes of this system we have assumed that a *vortex* flowmeter is used; hence, no square root extraction is necessary. A multiplier module [mul-6] receives this flow measurement along with the output of pressure transmitter PT-7 and produces a compensated measurement of steam flow that is applied to an integrating module [int-6] the output of which is the actual totalized (i.e., with respect to time) flow of steam. Note: By compensated flow is meant that the flow is corrected for any variations in steam header pressure. Steam flow is an important measurement, and the totalized amount is used to determine the efficiency of the evaporator train.

Numerous temperature, pressure, and flow measurements continuously monitor the process and are also included on each evaporator effect. However, in the interests of simplicity and clarity Figure 4.11 shows only two temperature-measuring points and the control systems responsible for manipulating the process. Furthermore, the read-out from the temperature sensors have once again not been shown in the interests of clarity. The remaining omitted measurements, including all the readouts required, must be considered and accorded the appropriate attention to detail when dealing with a real application, as they are vital to the manufacture of the product and the functional usefulness of the operators. As an example of instruments of importance to the plant operator but omitted from Figure 4.11, pressure and temperature measurements on the evaporator effects inform the operator of possible problems caused by the tubes blocking up long before they actually occur. Steps can be taken to avoid such situations. However, the management of the creamery has to determine the procedures to be followed in such events.

THE MILK CONCENTRATING PROCESS

We shall now discuss the remainder of the evaporator system, which is shown in Figure 4.11. First, the reader should note the following:

1. Note particularly the arrangement of the effects. These are arranged as two evaporators to make up the second effect and two evaporators and a heating tube to make up the fourth effect. This arrangement is not usual but is formed as part of the design by the evaporator train manufacturer.
2. Note that the final concentrated product is derived from the fourth effect, which operates at a higher temperature than the third effect.
3. The evaporator effects do not follow in numerical sequence. This is deliberate in the interest of making it easier to follow the paths taken by the vapor as it moves from effect to effect and the raw milk as it is being warmed in its passage through the evaporator effects.

A Coriolis mass flowmeter is located in the final product line and measures the product density and flow. The density from the sensor DE-8 is used in the computations given earlier. The complete loop for the flow obtained from the flow sensor transmitter FT-8 has not been shown because of space restrictions on the diagram. However, the flow loop is required only for record, management, and financial purposes and therefore must contain a flow recorder and an integrating module to totalize the amount produced.

The controls for the heat demand process are located in the front end of the evaporator train. It is a good example of a technique known as *feedforward control,* which is extremely useful, but it depends heavily on the fact that all the mathematics and physics of the control system are absolutely correct. Figures 4.9 through 4.11 show what occurs to the incoming raw milk during processing up to the point where most of the water has been evaporated away, resulting in a fluid known as *milk concentrate*. Having now obtained some insight into the manufacture of milk concentrate, it should not be too difficult to imagine how the well-known evaporated milk and condensed milk products sold are produced. Be aware that sugar must be added to the product known as condensed milk, and this will entail carrying out further processing on the concentrate.

CONVERTING THE MILK CONCENTRATE TO POWDERED MILK

It may serve as a useful exercise to see how milk concetrate is converted into powdered milk, which is the next step. In this solid form, milk is capable of longterm storage and can also be available for distribution to millions of people in

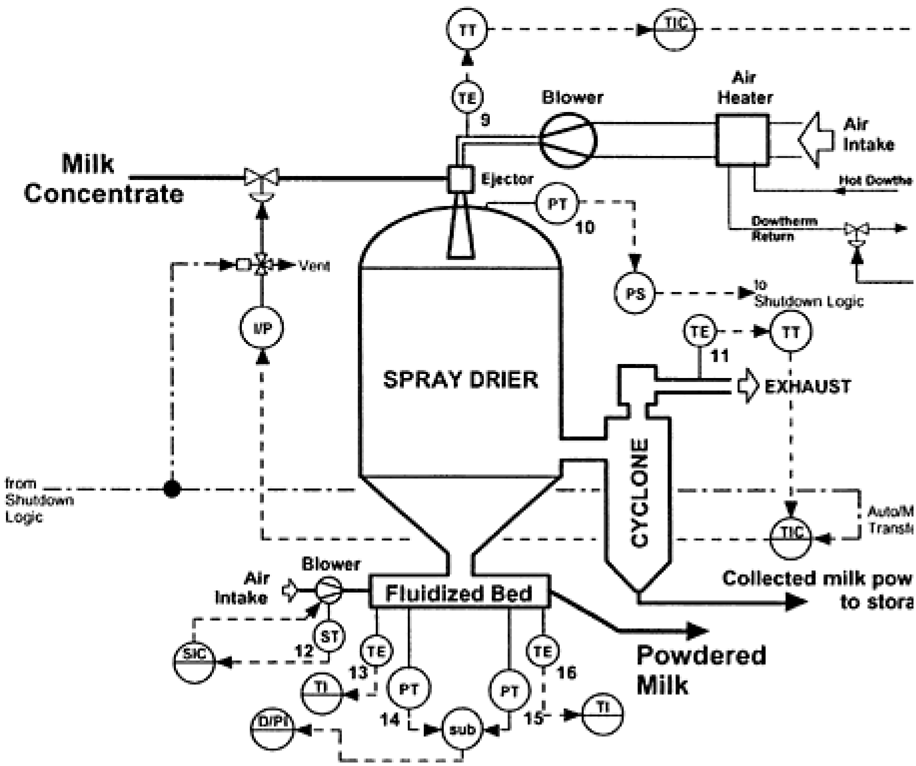


Figure 4.12: Processing milk concentrate to powdered milk.

times of a major catastrophe. The conversion is not a difficult process, and one more diagram is all that is required to illustrate the control system necessary. To this end we now give Figure 4.12.

To describe the process in its simplest terms, the milk concentrate is sprayed into a vessel carried on a stream of very hot and very fast-moving air; the velocity generated by the jet ejector shown literally drags the milk concentrate along, breaking the liquid up into a mist as it does so. This is the exact same action as occurs in a manually operated perfume spray. The solids entrained in the very fine droplets of liquid contained in the spray are released from suspension when the hot air contacts the droplets and vaporizes their containing liquid, allowing the solid particles to fall out because there is no liquid to bind them together. The vessel in which this process is carried out is known as a *spray drier*.

Figure 4.12 shows that only three control loops are involved: (1) the regulation of the drying air temperature; (2) the control of the amount of milk concentrate supplied to the drier; and (3) the control of the air velocity in the fluidized bed.

For the drying air temperature control loop, the blower unit draws in ambient air into the air heater where it passes over a radiator system; in doing so its temperature is raised. Very hot Dowtherm, which is a proprietary heating medium, flowing in the radiator system imparts most of its heat to the incoming air. For a typical arrangement of a Dowtherm heating system see *The Dowtherm Heating System* in Chapter 5. The Dowtherm heating medium is used extensively throughout industry for similar purposes. Temperature sensor TE-9 measures the temperature of the hot incoming air. The measured temperature is applied to a controller TIC-9 and compared with an operator-adjusted set point; the controller output is applied to a control valve in the Dowtherm return line via a signal converter I/P-9. By controlling the amount of Dowtherm returned, the temperature of the hot air is regulated to the value set by the process operator. The hot air is then applied to an ejector, which draws in the milk concentrate (by the venturi effect) and forces it into the drying chamber. Because of the very high air velocity and the attending low pressure, the concentrate is sucked into the jet stream and atomizes immediately. The heat of the air stream vaporizes the remaining water in the concentrate, allowing the solids to fall out of suspension into the bottom of the drier. Any remaining particles held in the hot air are drawn into the cyclone. This unit is designed so that the incoming solid-particle laden air is forced into a spiralling swirl; the centrifugal action of the swirling air stream forces the solid particles to the outside of the rotating mass of air and onto the vessel walls. The particles are stopped and fall to the bottom of the cyclone unit. The collected solid milk residue from the bottom of the cyclone is carried off along with the powdered milk from the drier to the packaging and storage areas of the plant while the cleaned-up air is exhausted.

Measuring airflow by the cooling effect of the exhaust air from the cyclone unit on a resistance temperature-sensing element TE-11 and transmitter TT-11 enables concentrate control to be effected. The measurement is applied to a controller TIC-11, which has its set point determined by the process operator. The controlled output is applied via a signal converter I/P-11 to a control valve in the concentrate supply line to the drier and regulates the amount of concentrate fed to the ejector. An important safety system is built into this loop, which ensures that when the concentrate supply has to be interrupted either through operator intervention or automatically through specifically designed control logic, the pneumatic drive signal to the control valve is vented and controller TIC-11 automatically placed in the manual operating mode. This feature is provided on the controller if specifically requested at the time of purchase and is known as *Auto/Manual transfer*. For the purpose of this description, the control logic is not included, although in a real system such requirements connected with the operation must be considered and the system designed accordingly.

A tacho-generator sensor SE-12, which produces a proportional dc voltage or frequency signal measures the speed of the blower supplying the transport-air to the fluidized bed. The measured speed is related to the air velocity and is applied to the speed controller SIC-12, which produces a controlled output to regulate it to the value set by the process operator. There is a relationship between the transport-air velocity and its solid pickup capability defined by *Stokes Law*. This relationship will not be discussed here; suffice it to say that it exists, and is used for instance when solids such as grain or any powdered particulate such as pulverized coal dust for furnace firing have to be moved. To guide the operator in the choice of set point for SIC-12, the differential pressure across the fluidized bed is determined. In this instance, a D/P cell is not used to make the measurement, but individual pressure sensors are employed instead, and the outputs from which are applied to a subtractor module and indicator to compute and indicate the differential pressure. Individual pressure sampling points are used because a good average value must be obtained for each measurement. Hence, there may be several pressure sampling points for each pressure sensor/transmitter with all the pressure sampling points joined together and a single connection made to the associated pressure measuring instrument. The pipe connection that makes up each sampling point is made to project (i.e., proud of the internal face of the containing walls of the chamber) a little way into the bed. The other important consideration is the method used in obtaining the measurement. Since there is a combination of solids and gas in the process fluid, an air reaction technique is employed, as this will keep the measuring point free of solid particles and provide a good measurement. The bed temperature is sensed by temperature elements TE-13 and TE-16 and is indicated on display instruments TI-13 and TI-16, respectively.

Pressure sensor/transmitter PT-10 measures the pressure in the drying chamber, and its output is applied to a pressure switch PS-10. This switch produces a contact closure when the pressure in the drier exceeds a predetermined operator set value and is used to provide an input to the shutdown logic system.

THE MULTIPLE-EFFECT BLACK LIQUOR EVAPORATOR—FOR THE PAPER INDUSTRY

We shall now consider another multiple-effect evaporator system, one that is used in the paper industry to concentrate the liquor produced in the first stage in paper making by the semichemical pulping process and recover these expensive chemicals that are reused. The evaporator unit employed in this application is the long vertical tube (Figure 4.6) type previously illustrated and quite different from the one shown in the milk processing application where the falling film type (Figure 4.7) is employed. In this section we show the overall control system only. The controls used are different from those used on the milk concentrate application that we discussed earlier. For this multiple-effect processing unit, we must ensure that the level in each evaporator effect is held constant; therefore we employ individual level control loops for each effect. However, the reuse of steam vapor generated in each effect is exactly the same as previously discussed, and the methods for evaluating the system efficiency are identical for all evaporator systems.

The byproduct *tall oil* is obtained by skimming off the upper layer and foam in the *soap tank*. This is a useful source of revenue for the paper mill. The word *tall* (not pronounced as you would to indicate height, but rather as in tallow), is of Scandinavian origin, where it means pine; the name has been adopted in Europe and North America since most papers manufactured in these regions use pine trees as the raw material. From this waste output from the evaporation process, we can obtain adhesives, disinfectants, lubricants, paint varnishes, rosin, and wetting agents, to name but a few. The relief gases, which are another waste material from the pulping process, also yield the valuable solvent, turpentine. Pulping as we have seen is carried out in a *digester*, which in processing terms is an upstream process unit to the evaporator system (i.e., pulp processing must occur before the black liquor is obtained). The unwanted waste process liquid provides a rich source of the thin liquor that is the feed stock of the evaporator system we are presently discussing. The pulp digester is discussed in more detail in Chapter 2.

Figure 4.13 does not include several of the pressure and temperature measurements on each effect. The measurements of the changing conditions prevailing in each effect during the evaporation cycle are important, for they provide the process operators with valuable information on their plant behavior and allow timely intervention should that be required.

THE BOILING POINT RISE SENSOR/TRANSMITTER

As is apparent in the figure, the feed and heat flows are counter to each other, and the condenser in the vapor exit of evaporator effect #6 brings about the vacuum. In the diagram, the amount of heat required is measured by a specialized

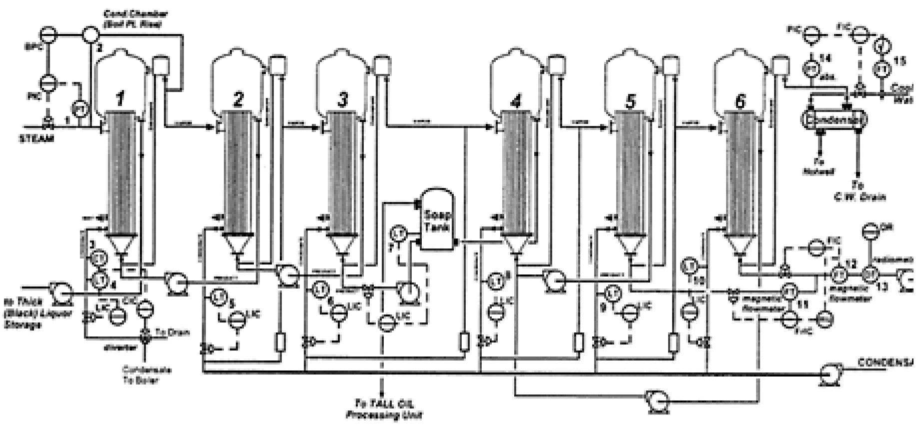


Figure 4.13: Typical controls for a black liquor evaporator system.

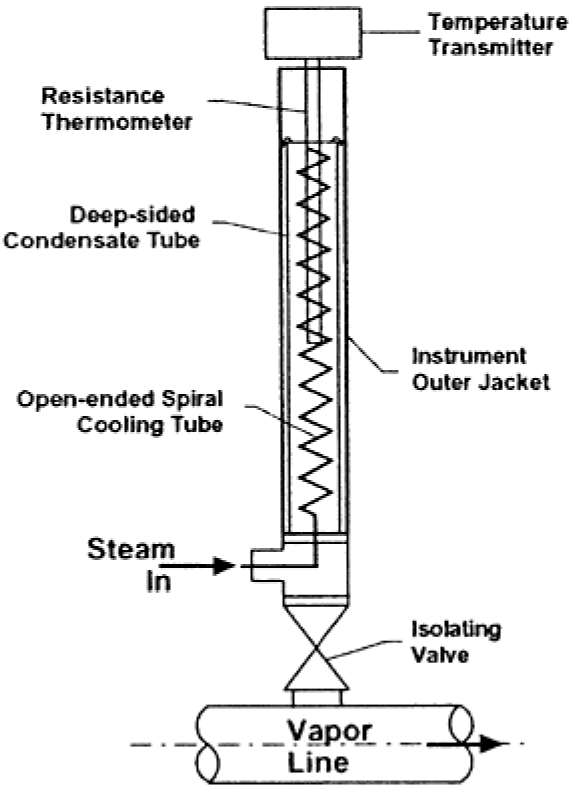


Figure 4.14: Schematic of boiling point rise sensor/transmitter.

instrument called a *condensing chamber*, which was designed and patented by the Foxboro Company to determine the *boiling point rise* (see Figure 4.14).

This instrument, shown as part of loop BP-2 in Figure 4.13 uses the steam into effect #1 and allows it to condense in the deep-sided inner condensate tube and drain back into the vapor line through holes in the base of the annular ring formed by condensate tube and the outer jacket of the instrument. The loss of heat from the walls of the tube by radiation results in steam condensation, which is effected by the difference between the temperature of the liquor boiling at the pressure existing in the evaporator itself and saturated steam at the same pressure. The condensate temperature measured by a resistance thermometer is the boiling point rise, which in turn is related to product density. This relationship is determined by careful experiment for specific liquors, or it can be established on site for a particular liquor. Controller BPC-2 receives the measurement from the instrument and compares it with the operator-determined set point and produces an output that is used as the set point for the pressure controller PIC-1. This controller adjusts the pressure of the steam supply to maintain it at a value determined by the density of the product from the evaporator. Alternate methods of determining the density could be employed; these make use of refractometers or radiometric instruments on the product line from effect #1, but they may not be as specifically relevant to this application. In this figure, all the signal converters associated with the control valves have intentionally been omitted in the interests of clarity and ease of understanding.

CONTROLLING THE MULTIPLE-EFFECT BLACK LIQUOR EVAPORATOR TRAIN

The level of condensate in effect #1 is measured by level transmitter LT-4, which provides controller LIC-4 with a measurement, and the controlled output regulates the control valve, which sends the bulk of the condensate directly to the boiler house since this is quite pure. The objective of the level control loop is to keep the condensate level below the tubes in the evaporator itself and thereby avoid the condensate being contaminated by the black liquor. To ensure that there is no contamination, a conductivity analyzer CT-3, which provides the measurement for conductivity controller CIC-3, whose set point is selected by the process operator, continuously monitors the conductivity of the condensate. When a detrimental change of conductivity from the acceptable is detected, a three-way diverter valve is initiated to send the "bad" condensate to the drainage system for disposal. Note carefully that the level control is effected by a control valve, which is manipulated by LIC-4, and the flow diversion is implemented by the conductivity controller. Recall that control is not possible with a three-way valve, which is designed for flow diversion purposes only. The level control loops L5, L6, L8, L9, and L10 associated with evaporator effect #2 through effect #6, respectively, ensure that a condensate seal is maintained in each of the effects, which also permits any *flashed* (vaporized) condensate from the control valves to reenter the effect via the vapor inlet. The term flashing of a process liquid in control valves describes an extremely rapid change in phase of the liquid to a vapor.

A flow ratio control system shown on the feed to the evaporator train ensures that effects #1 and #2 are adequately supplied with raw material. This control is effected as follows. The total inflow of the thin *green liquor* is split between evaporator effects #5 and #6. Magnetic flowmeters are used to determine the flow rate as these instruments provide obstructionless measurements of the incoming liquor. Flowmeter FT-12 measures the amount to evaporator effect #6 and flowmeter FT-11 the amount to evaporator effect #5. The signal from FT-12 is applied to a flow controller FIC-12 as well as to a multiplier module, where it is multiplied by an operator-determined constant and used as the set point for flow ratio controller FrIC-11, whose measurement is the output from flow transmitter FT-11. Controller FIC-12 has an operator-determined set point, and both controllers regulate their respective control valves to ensure that the required flow ratio between the two lines is maintained. Once again, notice that only the measurements signals from the two flow transmitters are used to determine the flow ratio required. The density of the incoming thin green liquor is continuously measured by a radiometric densitometer DT-13. Because this instrument uses a radioactive source to determine the measurement, it requires stringent maintenance and accurate records to be maintained to comply with safety regulations of respective countries. The fluid density is recorded on a recorder DR-13 and provides the process operator the data on which to decide when and by how much the feed should be adjusted to cope with the changing makeup of the feedstock.

The resin *soap tank* is located between effects #3 and #4, at about the middle of the evaporator train; this allows the liquor to cool a little and thereby permit the resins to separate out. This is necessary to avoid the occurrence of foaming in the evaporators. It is suggested that a flanged-type extended diaphragm, differential pressure instrument is used to measure the level in this vessel. These instruments are similar to those mentioned earlier where the measuring diaphragm is made to lie flush with the vessel walls.

The *black liquor* produced by the evaporator train also presents problems to the mill owners in that the volatile and unstable sulfide compounds, hydrogen sulfide, mercaptans, and methyl sulfides formed in the sulfate process can easily escape into the atmosphere. These compounds, if allowed to escape, cause an offensive odor unacceptable to people living in the vicinity of the mill. One process used to counteract this problem is to oxidize the liquor by exposing it to air. In most instances, this is carried out before the liquor is allowed to enter the evaporator system, but doing so gives rise to excessive foaming in the evaporators unless defoamers are used to minimize this occurrence. Some paper mills reduce the problem by subjecting the black liquor to oxidation at the point where it is removed for soap separation.

THE RECOVERY BOILER FOR THE PAPER INDUSTRY—FUNCTIONALITY AND CONTROL INSTRUMENTATION

As mentioned earlier, the recovery boiler is not so much a steam-raising plant per se but is specifically a process unit designed to recover the very valuable chemicals used in the wood pulping process of paper making.

Figure 4.15 shows the recovery boiler and the instrumentation involved. This very simplified version has been drawn to give the reader a general idea of how the plant is designed and operates. Because the chemical recovery is easily accomplished by combustion, it is advantageous to use the heat of combustion as a means of steam generation, inasmuch as the paper industry uses vast quantities of steam, together with huge amounts of water, to produce paper. The recovery boiler is never used as a stand-alone steam generator, but is always paired with another specific steam-generating plant called a *power boiler*. This latter plant copes with the load swings and demands of the papermaking process to which the pair is attached. In this respect, the recovery boiler can be considered to be a *base load* provider. Since the prime function of the equipment is chemical recovery, the amount of steam generated by the recovery boiler is largely uncontrolled. Thus, the amount of steam from the steam drum is not regulated by the demands of the papermaking process but is fed directly as it is produced to the steam header. Accordingly, one will not find a *master pressure controller* on this boiler to coordinate the fuel firing in response to steam demand. A recovery boiler must be provided with an auxiliary fuel that is used during start-up to enable the temperature of the *smelt bed* (the area immediately below the combustion chamber where the sought-after recovered chemicals, which are the products of combustion, collect) to attain a high enough value to be sustained by the burning black liquor alone, or when the boiler must generate additional steam to meet plant demand, or when problems arise with supplying it with sufficient black liquor. The topic of firing multiple fuels is also discussed in

Multiple Fuel Systems in Chapter 1.

THE REDUCTION ZONE

The recovery furnace is generally divided into two main sections: the upper portion called the *oxidation zone* and the lower portion called the *reduction zone*. In the oxidation zone, the remaining water in the black liquor is evaporated, and this is the area in which complete combustion is effected. The reduction zone provides the reducing agents, carbon, and carbon monoxide, owing to the incomplete combustion of the organics in the liquor. The carbon and carbon monoxide reduce the sodium sulfate to sodium sulfide plus impurities, which is referred to as the *smelt*. The reduction takes place in a limited amount of primary air that is fed around the smelt bed. The smelt is withdrawn from the bottom of the bed into the smelt-dissolving tank at temperatures typically between 1500° F and 1800°F (about 820°C and 980°C). The density of the outgoing strong green liquor from the dissolving tank is controlled to

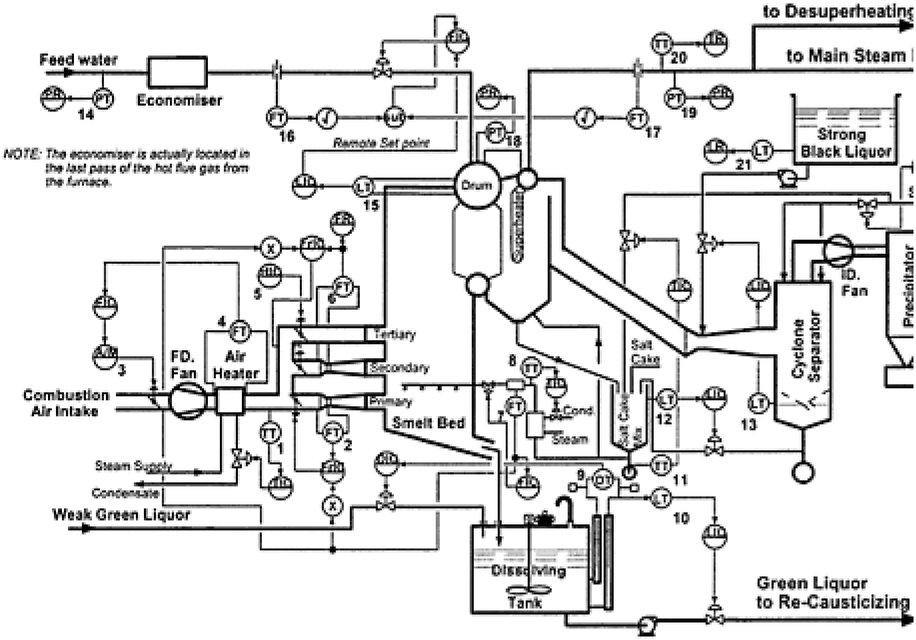


Figure 4.15: Simplified control system diagram for a recovery boiler.

a predetermined value by the addition of weak green liquor into the dissolved smelt. The heat generated sustains the chemical reaction of the smelt bed. It is this heat that is used to produce the steam. Any inorganic ash is collected in the precipitator from the flue gas as it passes to the stack.

Some liberties are taken in Figure 4.15 purely in the interest of clarity and simplicity of presentation, namely:

1. The alternate fuel line and controls associated with it have been omitted.
2. The several pressure and temperature-measuring points on an actual plant have been very much reduced, with only a few of the more important ones being included in the figure.
3. Many of the measurement points shown are also recorded, but this aspect has again been omitted. It is easy to visualize these if necessary, bearing in mind that records are necessary for performance calculations, inventory, and statistical purposes.
4. All the electropneumatic signal converters that produce the drive signals for the control valves and damper actuators have been omitted for clarity. The diagram therefore shows the control outputs being applied directly to the final actuators directly, which will certainly not be the case.
5. For clarity each *loop tag number* is stated only once, whereas in practice this serial tag number is repeated for each module in the control circuit.

THE WATER/STEAM CIRCUIT

Figure 4.15 shows that the control of the water level in the boiler drum is maintained using *three-element feedwater control*. This control strategy is necessary for all recovery boilers, for it gives stable results. The pressure of the feedwater supply is sensed and measured by pressure sensor/transmitter PT-14 and recorded on PR-14 for record and statistical purposes because the boiler is primarily a processing unit. A differential pressure transmitter LT-15 determines the drum level, and this measurement is applied to level controller LIC-15, which regulates its output which is used as the remote set point for flow feedwater controller FIC-16. Orifice plates FE-16 and FE-17 measure the feedwater flow and the steam flow in each respective line, and signals from differential pressure transmitters FT-16 and FT-17 connected to these primary differential-creating devices represent these measurements, respectively. In this regard it should be noted that instead of orifice plates and D/P cells, more expensive vortex meters could be used, but if this option is taken it will not be necessary to have the square root extractor modules (v) shown, as the output from vortex meters is inherently directly proportional to flow. The module [sub-16] takes the difference between the two flow measurements and applies it to a flow controller FIC-16 as the measurement input. This measured variable is compared against the set point generated by the output from level controller LIC-15, and the resulting signal is applied as the correction to the feedwater flow control valve. Drum pressure is an important measurement, therefore, pressure sensor/transmitter PT-18 measures the drum pressure and applies it to recorder PR-18. Steam temperature and pressure are determined by temperature/pressure sensor/transmitters TT-20 and PT-19, respectively. Both of these measurements are important; hence, they are recorded on TR-20 and PR-19. The typical range of values of the steam temperature produced in a recovery boiler is 560°F to 750°F (290°C to 400°C). Records of drum pressure, header pressure, and header temperature are used to locate possible steam header failures since the recovery boiler provides the base load for the plant.

The phenomenon of *shrink and swell* in steam generators is also observed in the drum of this boiler. For this reason conventional three-element control on the feedwater circuit is used.

The Fuel/Air Control Circuit

Since the recovery boiler cannot inherently follow load changes for the reasons already given, a master pressure control loop and *air/fuel cross limiting* are excluded because both of these techniques are designed specifically to allow the steam-generating plant to respond to steam demand.

The resulting fuel/air circuit is much simpler and as one can see in Figure 4.15 the total air requirement is set by the process operator adjusting the set point of FIC-4. Note, however, that this loop can be made to operate in manual mode continuously by transferring the Auto/Manual station A/M-3 to Manual. However, to avoid saturating its integral term, the output of FIC-4 must be applied to its own reset feedback connection. A ratio control loop formed by the black liquor flow is measured by the electromagnetic flowmeter FT-7 and regulated by the associated flow controller FIC-7 to a manually adjusted operator determined set point. The amount of this fuel sets the amount of primary and secondary air supplied to the smelt bed. Flow sensor/transmitters FT-2 and FT-6 measure the amount of primary and secondary air, respectively, and apply these measurements to flow ratio controllers FrIC-2 and FrIC-6 as measurement inputs. The set point for each controller is derived from FT-7, the measurement of fuel flow, and is modified by the multiplier modules [mul-2] and [mul-6] respectively, both shown as×in the figure. The process engineer determines the range of the multiplying factor for each module and the process operator sets a specific value to suit the prevailing conditions in the plant. The secondary and tertiary air applied to the oxidation zone is used to ensure complete combustion. Although not shown, an oxygen analyzer is normally used to ensure that combustion is complete, although a combustibles analyzer can, if preferred, be used instead for this purpose. Either of these (analytical) measurements is made in the boiler stack and is usually applied to a controller, the output of which automatically adjusts the air/fuel ratio. However, in this particular application, the information is made available as a readout only and from the information given allows the operator to make the necessary fuel adjustments, depending on the prevailing conditions.

THE MULTIPLE-EFFECT EVAPORATOR—FOR THE CANE SUGAR INDUSTRY

Before we leave this section, we present a typical multiple evaporator system that is often found in a cane sugar refinery. The system shown in Figure 4.16 is a much-simplified version of the process and is given for comparison purposes.

In the system illustrated, the level within each effect is vital and therefore controlled. The reasons for the importance of feed level in the effect are twofold. On the one hand, if the level were too low, the cane juice would burn on to the heating surface, reduce the heat transfer, and give inefficient evaporation. If this condition was allowed to continue it would certainly result in eventual shutdown and a very expensive cleanout operation. On the other hand, if the level were too high, there would also be a loss in evaporation, accompanied by entrainment and the very real possibility of flooding, which also involves additional cost. In all process control applications, the objectives are to minimize material use and operational cost and to maximize the return on the investment made. In this multiple-effect evaporator

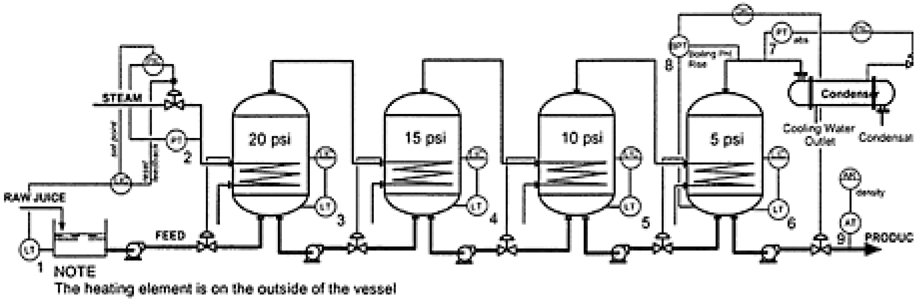


Figure 4.16: Simplified schematic of a quadrupule effect co-current evaporator.

system the heating and feed run co-currently—that is, in the same direction—as opposed to that shown in the black liquor multiple-effect evaporator system where heating and feed are countercurrent.

SYSTEM OPERATION

The level of the raw cane juice feed tank is measured by a differential pressure cell level sensor/transmitter LT-1, which provides a measurement to a level controller LIC-1 whose output is the remote set point for the heating steam pressure controller PIC-2. The pressure of the heating steam applied to the first effect is measured by pressure sensor/transmitter PT-2, which provides the measurement for pressure controller PIC-2 whose output manipulates the control valve in the heating steam supply line. The juice level in each effect is measured by level sensor/transmitters LT-3, LT-4, LT-5, and LT-6, which provide the measurements for level controllers LIC-3, LIC-4, LIC-5, and LIC-6, respectively. The level controller for each effect regulates a control valve in the discharge line of the pump that supplies the raw juice to the associated effect. This may not always be the case, however, because in the event the raw cane juice feed pump is a positive displacement (PD) type, the control valve on the discharge side is not provided, and the pressure controller output manipulates the speed of the pump directly. This latter case has not been shown, but it should be realized that the controller output cannot be applied directly to the pump motor. Both the controller output signal and the motor speed regulator input requirements must be compatible, and care must be taken to ensure that this requirement is met.

In the multiple-effect evaporator system, the evaporation rate is a function of the temperature difference between the steam jacket temperature of the first effect and the dome temperature of the last effect. This means that the evaporation rate of the system is the sum of the evaporation rates of each effect, with the temperature in each effect automatically adjusting itself to suit. Hence, it is inappropriate to attempt to regulate the temperature in the intermediate effects of such a system. All that is required is that the steam jacket temperature of the first effect and the vapor temperature of the last effect be controlled. In the system shown, the temperature of the first effect is regulated by ensuring that the steam pressure is held constant at a value dictated by the feed level via the pressure controller PIC-2. The temperature of the last effect is maintained by regulating the absolute pressure in the last effect, where an absolute pressure sensor/transmitter PT-7 provides the measurement for the pressure controller PIC-7, which manipulates a valve in the incoming cooling water supply.

A density controller DIC-8 receives its measurement from a boiling point rise sensor transmitter BPT-8 and controls the density of the product. For record purposes, a density analyzer AT-9 is included in the product outlet line and the data are recorded on AR-9. Note that the sugar industry density is always referred to and given as a *Brix* value. The final product is then sent to the vacuum pans for further processing. For information on the vacuum pan, see details given earlier in *The Vacuum Pan—As Used in the Sugar Industry (Modified Short Tube Type)* in this chapter.

SUMMARY

1. Evaporation, in very general terms, usually refers to the removal of water by vaporization from an aqueous solution, leaving a nonvolatile substance as residue. Evaporation is the means used to effect a density change in the process fluid.
2. The choice of evaporator equipment is determined by the highest heat transfer at the lowest installed unit cost under the operating conditions, or kW/°K/£ Sterling installed.
3. Vaporization occurs when heat is absorbed by radiation or convection: At the surface of a pool of liquid.

   By natural convection from a surface beneath the disengaging surface.

   At the surface of falling liquid films.

   When a warm fluid is subjected to a sudden drop in pressure, which forces the fluid to become superheated by forced convection and made to change its phase from a liquid to a vapor.
4. A material balance on the basis of the solids content only, will yield:

$$F_{ini} {}^{*} W_{ini} = F_{fin} {}^{*} W_{fin}$$

   where *F* is the mass feed flow, *W* the weight of solids, subscripts *ini* the initial and *fin* the final conditions, and * indicates a multiplication symbol.

   The Law of the Conservation of Mass shows that the initial amount of material must be the same as the final amount of material, even though the amount of dissolved solids initially and finally will be different.
5. A relationship exists between the amount of vapor evolved and the amount of heat applied, which in turn is based on the thermal efficiency of the evaporator itself. For a single evaporator, this can be stated as

$$V_{ev1} H_1 = \eta_{th} V_{ini} H_{ini}$$

where V is the vapor evolved, H is the enthalpy of the steam, and η is the efficiency. The subscripts are interpreted as:

ev1	=	vapor evolved in the effect, *1* since there is only one stage of evaporation
th	=	thermal
ini	=	initial

6. Writing the term $V_{ev1}H_1$ of the equation of item 5 as V_{evS} indicates the vapor evolved per stage. We can represent the total result of a number of evaporator effects by a summation (adding together) of the amount of vapor and concentrated feed at the end of the evaporation process, or:

$$\sum_{S=1}^{S=n} V_{nS} + \sum_{F=1}^{F=n} F_n$$

7. For a material balance, the amount of vapor evolved plus concentrated feed must be equal to the initial input feed, or:

$$F_{ini} = \sum_{S=1}^{S=n} V_{nS} + \sum_{F=1}^{F=n} F_n \text{ and writing } \sum_{F=1}^{F=n} F_n \text{ as } F_n \text{ we can say:}$$

$$F_n = F_{ini} - \sum_{S=1}^{S=n} V_{nS}$$

8. Using the equation

$$F_{ini}{}^{*} W_{ini} = F_{fin}{}^{*} W_{fin}$$

where F is the mass feed flow, W the weight of solids, subscripts *ini* the initial and *fin* the final conditions, and * indicates a multiplication symbol. Because F_{fin} is the same as F_n and since it is the final amount of liquid material, we can say

$$F_{ini}W_{ini} = \left(F_{ini} - \sum_{S=1}^{S=n} V_{nS}\right) W_{fin}$$

$$= F_{ini}W_{fin} - \sum_{S=1}^{S=n} V_{nS}W_{fin}$$

$$\therefore \sum_{S=1}^{S=n} V_{nS} = \frac{F_{ini}W_{fin}}{W_{fin}} - \frac{F_{ini}W_{ini}}{W_{fin}}$$

$$= F_{ini}\left(1 - \frac{W_{ini}}{W_{fin}}\right) \text{ after simplification}$$

9. In a multiple-effect evaporator system, it is normal practice for the vapor produced in one effect to be applied as the heating medium to the succeeding effect and from that one to the next and so on until the last effect is reached.
10. Considering the heating value of the evolved vapor. For the first effect:

$$V_{ev1}H_1 = \eta_{th}V_{ini}H_{ini}$$

For the second effect:

$$V_{ev2}H_2 = \eta_{th}V_{ev1}H_1$$
$$= \eta_{th}^2 V_{ini}H_{ini}, \quad \text{etc.}$$

For *n* number of effects, the total heating value can then be derived from:

$$\sum_{S=1}^{S=n} V_{nS} = V_{ini}H_{ini}\left(\frac{\eta_{th}}{H_1} + \frac{\eta_{th}^2}{H_2} + \frac{\eta_{th}^3}{H_3} + \ldots\ldots + \frac{\eta_{th}^n}{H_n}\right)$$

11. Some of the types of evaporators used in industry are:

The *single effect evaporator,* which is essentially a single vessel fitted with a heating element; they are comparatively small, used when steam is relatively cheap, the material is highly corrosive, but the vapor evolved is contaminated and therefore unsuitable for reuse. This type of evaporator can be operated in batch, semi-batch, continuous batch, or continuous modes.

The *forced circulation evaporator,* an evaporator that is quite commonly found in industry, because the highest heat-transfer rates and evaporation rates are obtained using this type of evaporator.

Long tube vertical evaporator, the cheapest to run and the highest evaporation capability. It is simple and has only a one-pass heater, which feeds directly into a relatively small vapor space.

The *falling film evaporator,* used extensively in industries where highly heat-sensitive products are manufactured, and is therefore quite common in:

- The dairy industry where it is used to process the milk received from the farms to a milk concentrate prior to it being used to produce milk powder in a vacuum drier.
- The fruit juice-producing industry.

12. A condenser is a plant equipment item that converts a vapor to a liquid and in doing so lowers the operating pressure. In practice, it is usually connected to a heated and vapor-filled process vessel within which a low pressure or vacuum is required. A low pressure lowers the boiling point of a material.

CHAPTER 5
Product Distillation

A large number of the materials and items we use daily are the result of extraction and/or separation from a basic mixture that contains a number of discrete components. As an example, one need only consider the gasoline that is so freely available and that we take for granted. This fuel is not a single, simple substance; rather, it is only one of many other important components—not all of them exclusively fuels—contained in the evil-smelling crude oil that has lain over many centuries in the Earth’s crust. The origin of the oil goes back to countless billions of living animals (plankton and other marine life) who were trapped and killed by the movement of the crust caused by earthquakes and as a result subjected to increasing temperature, pressure, and the exclusion of oxygen. The combined effect of the enclosing rock substances and these two parameters is mainly responsible for the gradual transformation of the dead animals over the ages into the crude oil we know today. Vegetation in the form of countless thousands of trees and other organic substances also was not left untouched. It, too, was subjected to entrapment and treatment by the increasing temperature, pressure, and oxygen exclusion, resulting in other materials being formed. The most common and well known of these materials is coal. Most theories on the origins of crude oil and coal appear to postulate a very close affinity between the two. Initially, coal was likely exploited as a means of providing heat, but later it became the source of other useful products as technology advanced. It is also documented that some ancient tribes found crude oil on the surface of the Earth and used it in the first instance for medicinal purposes and for providing light. They found it readily and easily transportable and very easy to ignite. Unbelievable as it may appear, coal is still the largest raw material source from which chemicals and fuel can be extracted. Both of these raw materials are made up largely of the elements carbon and hydrogen and thus fall under the general heading of hydrocarbons.

THE BASICS OF THE DISTILLATION PROCESS

In their raw state, crude oil and coal have limited uses as exemplified by the (limited) use the ancients made of them. However, when they are subjected to processing of a particular kind, namely, distillation, many much more exotic and useful products are obtained. Distillation is essentially a separation process used in extracting the different products from both coal and crude oil. It is achieved by deliberately creating two or more coexisting zones that differ in temperature, pressure, composition, and phase or state. In the case of coal, the process of separation is known as destructive distillation and is carried out without air being present. This process is described as thermal pyrolyzation. For the present we will not pursue the destructive distillation of coal but will limit our discussion to the process involved in the separation of crude oil products.

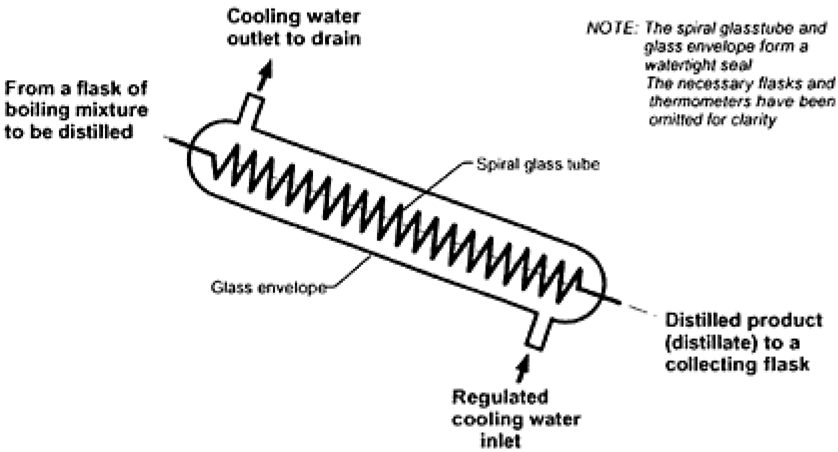


Figure 5.1: Laboratory distillation tube arrangement.

LABORATORY EQUIPMENT

The laboratory method used to distill a material is shown in Figure 5.1. In the arrangement shown, it should be noted that:

1. The flow of cooling water is countercurrent to the flow of distilled product to allow the vapors to condense fully.
2. The cooling water flow is regulated to achieve the objective of complete condensation.
3. To present a large surface area for the vapors to contact the cooling water, the enclosing tube for the hot vapor is wound in the form of a continuous spiral.
4. The distillate will arrive at the collection flask as a continuous stream, where, because of density changes, the various components will separate out, provided they are not miscible. In the presence of component solubility, they will blend into one another.
5. The heat applied to the boiling flask must be adjusted so that its temperature must rise at a uniform rate, and the heat input (and by implication the temperature) can be maintained at a specific value. No intermediate changes should be made to the heat input to accelerate or slow down the boiling and hence the distillation process.
6. The temperature of the various components at the collection flask upon arrival must be noted to indicate the component involved.
7. The boiling flask must be watched closely to avoid any untoward occurrence such as material decomposition. This is especially important when the material being distilled is a volatile one.

INDUSTRIAL EQUIPMENT

The industrial distillation column uses the same principles as in the laboratory column but does not replicate it exactly. The equipment is designed to produce the distilled products as separate entities or fractions, from which the common descriptive name

Fractionating Column originates. The column can be visualized very simply as a number of trays or plates that are in communication with each other and are stacked vertically one above the other; vapor and liquid (in the trays) occupy the intervening spaces between each tray. The transfer of heat to the metal enclosure, and hence to the surrounding atmosphere, cools the vapors; this makes the industrial distillation process a little dependent on prevailing weather conditions. The complete tray assembly is held together and contained in a cylindrical steel shell. The vapor and liquid at a particular level are at the same temperature and pressure but change for different levels because each different component must be drawn off as a specific entity. Suitable offtake connections are provided at very specific points along the length of the column. The positions of the offtakes are calculated and form part of the design of the distillation column. As control engineers, however, we are not concerned with this aspect of the work, although we should know why the connections are located in their specific positions (on the equipment). A typical column is shown in Figure 5.2, which illustrates how the process works.

Each molecular species of the mixture to be distilled reacts in a unique way to the differences prevailing in each coexisting zone. As equilibrium is approached, each of the species establishes a different concentration in each zone, resulting in a separation of each species contained in the mixture.

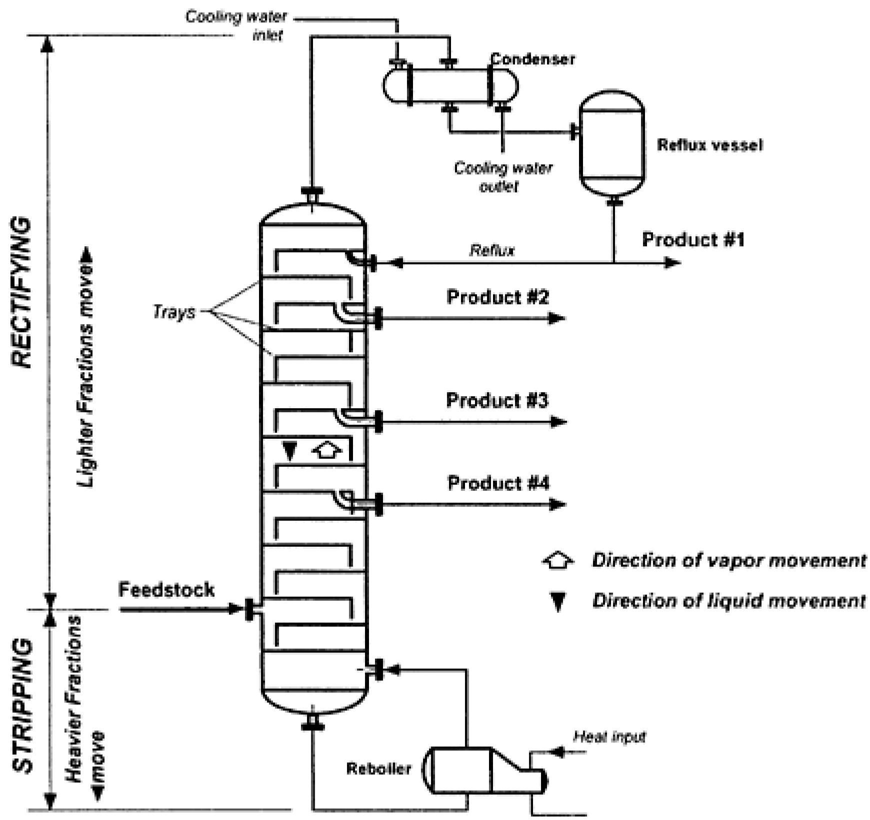


Figure 5.2: Typical distillation or fractionating column.

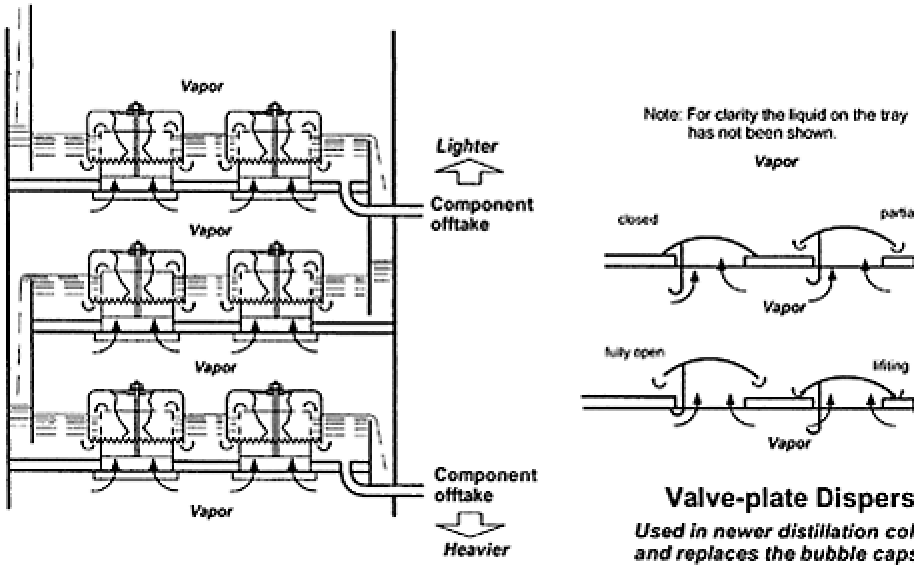


Figure 5.3: Schematic of trays with bubble caps.

How does the separation of the liquid and vapor occur at/on the trays involved? Each tray is basically a large, flat plate with a large number of holes punched in it; the early designs had what are known as *bubble caps* fitted to each hole. This design has since been modified so that each plate now contains either a large number of plain and simple holes or a large number of holes having a very simple valve arrangement. Figure 5.3 shows the alternative bubble cap and the valve arrangements only (the simplicity of the plain-holed plates does not warrant an illustration). Each tray is so fitted to the containing shell that it slopes gently toward the liquid drain for that tray level.

Only a limited number of enlarged views of bubble caps and *valve-plate dispersers* are shown in Figure 5.3, though, as stated earlier, there are many more per plate. A simplified depiction is presented to provide a clear insight into how the separation process actually works. Hole sizes used with bubble caps can vary from 3 to 6 in (75 to 150 mm)—from 2 to 4 in (50 to 100 mm) for valve-plate dispersers, and from 0.125 to 0.5 in (3.175 to 12.7 mm) for the plain hole. The actual sizes used depend on the plate design. Bubble cap and valve-plate dispersers have the advantage that both can be operated at very low gas flow rates, the former because of the seal arrangement and the latter because of the closing of the valve. In the plain hole design, the limit is the point where the liquid begins to drain through the perforations, at which point the plate efficiency is severely affected. In all the designs, there is a definite minimum gas flow rate below which dispersion for intimate contact is not possible; a similar limitation applies to liquid flow rates, below which good distribution is not possible.

Distillation is carried out in more than one column because the range of temperatures necessary to obtain all the products being sought after would exceed that obtainable in one *fractionating tower*. The liquid drawn off from each tray is received by *side strippers,* which distill each fraction in a small tower of its own. During the distillation process no chemical change occurs; only a separation of each fraction that exists in the feedstock takes place. The resulting total products are therefore in the same proportions as originally existed.

THE CONVERSION PROCESS

In order to obtain the more important and useful products contained in the various separated fractions, it is necessary to break down the heavy hydrocarbons they contain into a whole range of lighter ones. The process of carrying this out is called *cracking,* a process in which chemical changes take place. To understand these changes we will consider a molecule—the smallest imaginable particle—of the hydrocarbons involved in order to begin to appreciate the chemistry associated with it.

As stated earlier, the hydrocarbon molecules are made up of atoms of carbon and hydrogen. How these combine with one another can best be visualized as the carbon atom having four points of attachment by which it can bond to another atom (i.e., it is *quadrivalent*). The hydrogen atom, on the other hand, has only a single point of attachment (i.e., it is *monovalent*); this is shown in Figure 5.4a. This figure also shows that molecules with up to 4 carbon atoms are gases at normal temperatures and pressures; molecules having 5 to 19 carbon atoms are usually liquids; and molecules with 19 and more carbon atoms are products that are solids or semi-solids. Arrangements of the atoms that give rise to molecules that have names ending with an *ane* are a series of *paraffins,* some of which are shown in Figure 5.4b, Figure 5.4c, and Figure 5.4d. Note: The name *paraffin* or *paraffin-oil* as used in the United Kingdom for a heating fuel is incorrect. The actual name for this fuel is *kerosine,* which is the name by which it is known in the industry and commonly used elsewhere in the world.

In the naming of the molecular arrangements of the compounds (c) and (d) in Figure 5.4 the names butane and octane are preceded by the letter n; this is an abbreviation for the word normal and refers to the continuous chain arrangement of the molecules. If we take a particular paraffin and crack it further in the presence of a catalyst, we can obtain an isomer (defined further on in this paragraph) of the paraffin that was used. An example is presented in Figure 5.5a. There the paraffin used was butane, with the molecular arrangement given in Figure 5.4c. The carbon atoms are now branched, but the number of carbon and hydrogen atoms involved has not changed because there are still 4 carbon and 10 hydrogen atoms, although the arrangement of these has indeed changed. This leads us to a definition of an isomer, which states that the compound formed has the same percentage composition and molecular weight as that compound from which it was formed, but differs in chemical and physical properties. This is illustrated in Figure 5.5a for iso-butane, or to give it its chemical name—2-methylpropane—which is called a *structural isomer* because of the change in the linking arrangement only.

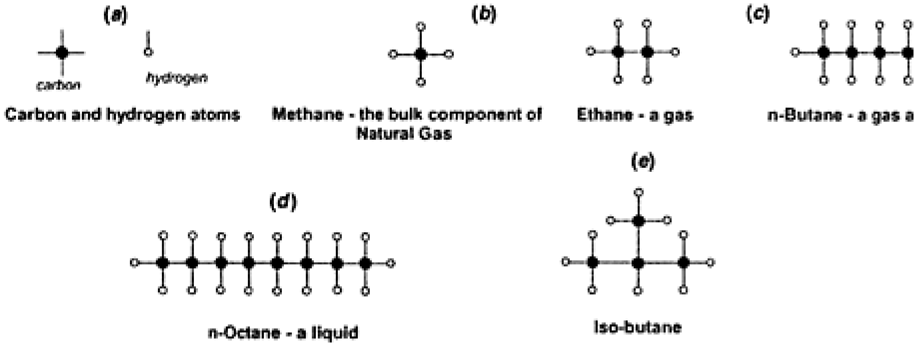


Figure 5.4: The atomic structure of carbon and hydrogen and the molecular arrangement of some paraffin.

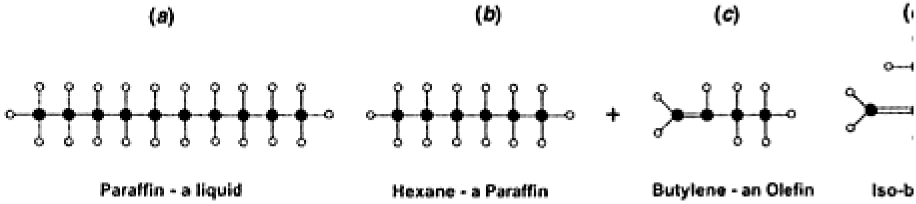


Figure 5.5: The molecular arrangement of some isomers derived from the catalytic cracking of paraffin.

If we take the paraffin $C_{10}H_{22}$ of in Figure 5.5a and crack it to yield hexane and butylene, the molecular arrangements of which are shown in Figure 5.5b and Figure 5.5c, we notice that once again the total number of atoms of carbon and hydrogen in the now two compounds has not changed. This time, however, the *linkages* have altered, and in the carbon atom of the compound butylene there is now a *double bond*. If we then crack the butylene in the presence of a catalyst, we will obtain another isomer called iso-butylene, whose molecular arrangement is shown in Figure 5.5d. The double bond of the carbon atoms in both of these cases indicates that the compounds are unstable relative to the saturated hydrocarbons (with single bonds) and can therefore easily react, that is, be capable of picking up another atom. In general, double or *triple bonds* signify the reactivity of the compound. This is not a hard and fast rule, for some compounds with double bonds are reasonably stable. Such compounds are usually formed from what is called the *benzene ring*.

The French chemist Louis Pasteur discovered another kind of isomer, called a *stereoisomer*, long after the structural isomer was known. The difference in the spatial arrangement of the atoms or groups of atoms from one another within molecules that have the same structural formula is called *stereoisomerism*. This difference occurs because there are limitations on the movement of the atoms brought about by several factors. Stereoisomerism is important when we consider polymerization, but it is not intended to proceed further with this aspect of the complex chemistry involved.

At the start of this section we spoke of cracking, and although there are many variants of this process, it can take two main forms: (1) *thermal cracking* where the variables that bring about the changes are temperature, pressure, and time; (2) *catalytic cracking* (see Figure 5.6), in which the temperature plays the same important role, but not as high a pressure as that required for thermal cracking. Catalytic cracking does require a catalyst—a substance that assists, but does not itself get used up in the cracking process. Catalysts do, however, need to be regenerated for optimum performance. Modern catalysts take the form of a very fine powder, usually produced from a mixture of aluminum oxide and silica that is spray dried, producing a large

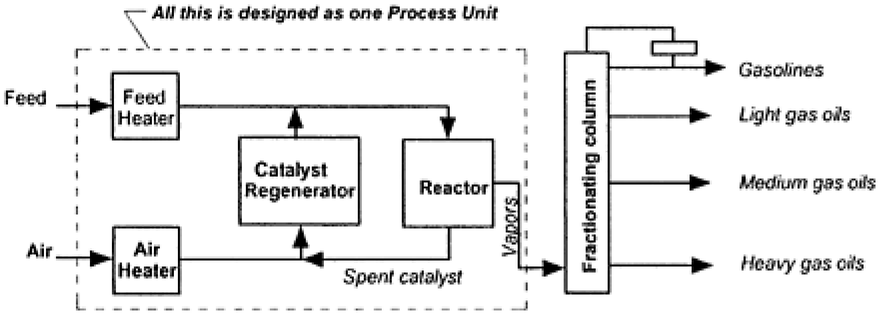


Figure 5.6: Block schematic of catalytic cracking.

number of extremely small spheres. The object of having the catalyst as minute spheres is to present an enormously large surface area on which the reaction can take place. Typically, 1 ounce (28 gm) of this powder provides a surface area of approximately 20,000 square yards (17,000 m^2). This very fine powder behaves as a liquid when mixed with an air or vapor stream and can be handled in exactly the same way, thus avoiding any mechanical handling. The other important difference between the two methods of cracking is the fact that the thermal process can be employed for any heavy oil, be it distillate or residue, but the catalytic process can only be used on a distillate. The main advantage of the catalytic process is its ability to produce more *iso-paraffins* and *aromatics* than is possible without their use.

Not all crude oil is the same. The percentage composition that makes it up may vary from one oilfield to another and provides a number of valuable products, the most common ones being the variety of fuels we use every day. The most widely found impurity of a crude oil is the amount of sulfur it contains. Much of it is in the form of a colorless gas, hydrogen sulfide (H_2S), which smells of rotten eggs and is almost as poisonous as hydrogen cyanide; mercaptans, another sulfur compound, also has a vile smell. Both H_2S and mercaptans can corrode metals; mercaptans is often present in some fractions. An initial distillation process known as *sweetening* removes the sulfur.

Not all catalysts used are solids. For example, hydrogen was once used in the process called *hydrocracking*, but the original process became very uneconomical to run and was therefore rejected. However, since the early founding days of the 1930s, the hydrogen process has been reassessed and revised. The updated technology is now used to produce high-grade gasoline, to change light oils into gases, or to change heavier oils into aviation jet fuel and diesel oils.

The gasolines we use today have been subjected to a process called *reforming*, which is a cracking process to improve the *anti-knock* properties of the fuel. Knocking is the phenomenon in the cylinder of an internal combustion engine brought about by adhering glowing carbon deposits on the valve gear that are left from the ignition of the fuel of the previous ignition cycle (and not purged by the exhaust stroke). This causes the fuel/air mixture of the new present cycle to ignite earlier in the combustion cycle than is actually required. The source of the carbon deposits is the fuel itself. This pre-ignition, apart from doing considerable physical damage, makes the engine run “bumpily” and backfire. By cracking the heavier gasoline in the presence of a catalyst, of which there are several, the knocking effect is reduced or eliminated completely. In some processes, platinum is used as the catalyst; the process equipment used is then called a *platformer*—a term combining the words platinum and reformer. Another method of eliminating engine knocking is to use the *alkylation* process which is the reverse of cracking. In this process two dissimilar light hydrocarbons are made to combine, once again in the presence of a catalyst, to produce a high-grade anti-knock gasoline, typically *iso-octane*, a combination of iso-butane and *isobutylene*.

THE PRACTICAL DISTILLATION COLUMN

Let us now consider what happens within the distillation column, which can be considered as a series of equilibrium stages. The transfer of energy and mass is extremely complicated and cannot easily be modeled mathematically. To avoid the difficulty of mathematical modeling a technique called the *equilibrium stage model* is used. With this concept, each stage of the series of individual equilibrium stages is considered to be operating at a particular pressure; hence, the vapor and liquid streams leaving one stage for another are in complete equilibrium with each other. Thermodynamic principles are then applied to relate this to the temperature and concentration of the component involved. As the separation process advances, zones of different pressure, temperature, and composition are created; these coexist with each other. *Dalton’s Law of Partial Pressures* states that in a mixture of gaseous substances the total pressure exerted by the mixture, provided there is no interaction between the components, is the sum of the partial pressures exerted by each individual component, or symbolically:

$$P_{total} = \sum_{1}^{n} p_{individual}$$

where *p* is pressure and *n* the number of components of the gas.

Each of the molecular species in the mixture to be separated reacts in a unique way to the conditions prevailing in each zone. As the system moves toward equilibrium, each of the species establishes a different concentration in each zone and in this way brings about a separation of the components in the mixture. In an ideal mixture, the partial pressure exerted by a species within the mixture is proportional to its concentration.

LIQUID/LIQUID SOLUTIONS

For simplicity, we shall consider a two-component mixture in which one liquid is completely dissolved in another, in which case it is called a homogeneous solution. Because only two liquids are involved, the solution is termed a *binary solution*. The saturated vapor pressure exerted by the solution is dependent on the composition of the mixture and the saturated vapor pressure of each component. If *A* and *B* are the components of a mixture, one way of expressing the composition is to state the mole fraction of each component; hence, for component *A:*

$$\textit{Mole fraction of A} = \frac{\textit{Number of moles of A}}{\textit{Total number of moles in the mixture}}$$

Note: A *mole*—derived from the German word *Moleculargewicht* meaning molecular weight—is defined as the basic amount of substance that contains the same number of entities (atoms, ions, molecules, photons, etc.) as there are atoms in 0.012 kg (=12 g) of the isotope of carbon with a mass number 12. If the symbol *x* is used to define the mole fraction of the liquid phase and *n* the number of moles, and the subscripts refer to each of the components, then for the component *A*, the equation can be written as:

$$x_A = \frac{n_A}{n_A + n_B}$$

The same method can be applied to determine the mole fraction of the component *B*.

In the mixture *A* and *B*, the vapor above the liquid will contain both *A* and *B*. *Raoult's Law* states that the saturated vapor pressure of each component in a mixture is equal to the product of the mole fraction of the component and the saturated vapor pressure of that pure component, or symbolically:

$$p_A = x_A p_A^0 \quad \text{for component } A$$

and

$$p_B = x_B p_B^0 \quad \text{for component } B$$

where p is the saturated vapor pressure of the component in the mixture, p^0 is the saturated vapor pressure of the pure component; x is the mole fraction, and the subscripts define each of the components. Figure 5.7 depicts the situation diagrammatically.

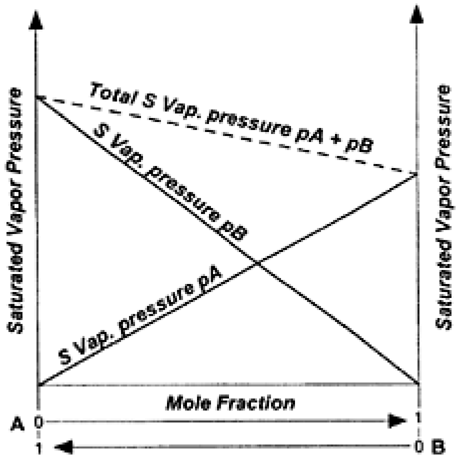


Figure 5.7: Mole fraction vs. SVP for liquid mixture of A & B.

The vapors above the mixture of liquid *A* and *B* do not have the same composition of the liquid. Hence, if y_A *and* y_B are the mole fractions of *A* and *B* in the vapor phase, then:

$$\frac{y_A}{y_B} = \frac{p_A}{p_B} = \frac{x_A p_A^0}{x_B p_B^0}$$

If one of the components of the mixture is more volatile than the other, then the vapor above the mixture is richer in the more volatile component (i.e., the one with the higher saturated vapor pressure) than the liquid. In this diagram, F is the more volatile (see Figure 5.8). The liquid and vapor composition curves are exaggerated to emphasize the difference.

For a binary mixture, the pressure and temperature determine the composition of the liquid and vapor. This experimental data for the mole fraction *y* of the vapor

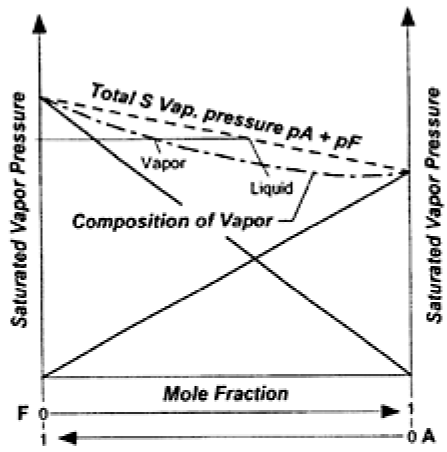


Figure 5.8: Mole fraction vs. SVP for liquid/vapor mixture of A & F where A is more volatile.

and the mole fraction *x* of the liquid is available in the form of tables, either for a range of pressures for a fixed temperature or over a range of temperatures for a fixed pressure of 1 atm (1.013 bar, 101.3 kPa). However, because of the difficulty and/or the impossibility of obtaining equilibrium data for multicomponent feedstock, the calculations are based on a *vapor-liquid equilibrium vaporization ratio* or a *K* value. This value for one of the components is defined as:

$$K_A = \frac{\textit{mole fraction of A in vap. phase}}{\textit{mole fraction of A in liq. phase}} = \frac{y_A}{x_A}$$

where, as before, the subscript *A* indicates one of the components of the mixture.

Let us consider a binary mixture of components *A* and *F*. In most binary mixtures, the system consists of components in which only one of the two is more volatile than the other over the entire composition range. However, in some binary mixtures one of the components can be more volatile than the other over only, say, the upper part of the composition range and the other component can be more volatile over the lower part. At the point of changeover the composition of the vapor and liquid is the same. Such mixtures are called *azeotropic (constant boiling) mixtures*. The deviations from the ideal can be either positive or negative.

The ratio of the *K* value of each of the two species is called the *relative volatility*, shown symbolically as:

$$K_{AF} = \frac{K_A}{K_F}$$

where the subscripts *A* and *F* indicate the two species, of which, say, *A* is more volatile than *F*.

To avoid confusion, it may be advisable to rename the symbol for the relative volatility as *α* (alpha), which is used conventionally in chemical engineering. Hence, the preceding equation can then be written as:

$$\alpha_{AF} = \frac{K_A}{K_F}$$

If the relative volatility is less than 1.05, then large-scale distillation is seldom used with *A* more volatile that F. Researchers have produced nomographs that relate the K (or *α*) value to the pressure and temperature of various individual light hydrocarbon fractions. Column designers refer to these data when they commence the design of a distillation column. It has been found that for similar components the vapor pressure curves converge as the temperature is increased. This tendency causes the value of *α* to decrease with increasing temperature. Hence, separation is best at the minimum temperature possible. We shall now write the foregoing equation in a form easily recognizable by chemical engineers as:

$$\alpha_{ij} = \frac{K_i}{K_j}$$

where *i* and *j* directly replace the *A* and *F* used before.

OPERATING A COLUMN IN TOTAL REFLUX MODE

Figure 5.9 shows a distillation column in the total reflux mode, which is an operating mode in which the entire vapor is condensed and returned to the column and there is no product withdrawn or feed provided to the column. In this arrangement, sufficient material is charged to completely fill the reboiler, the trays, and the overhead

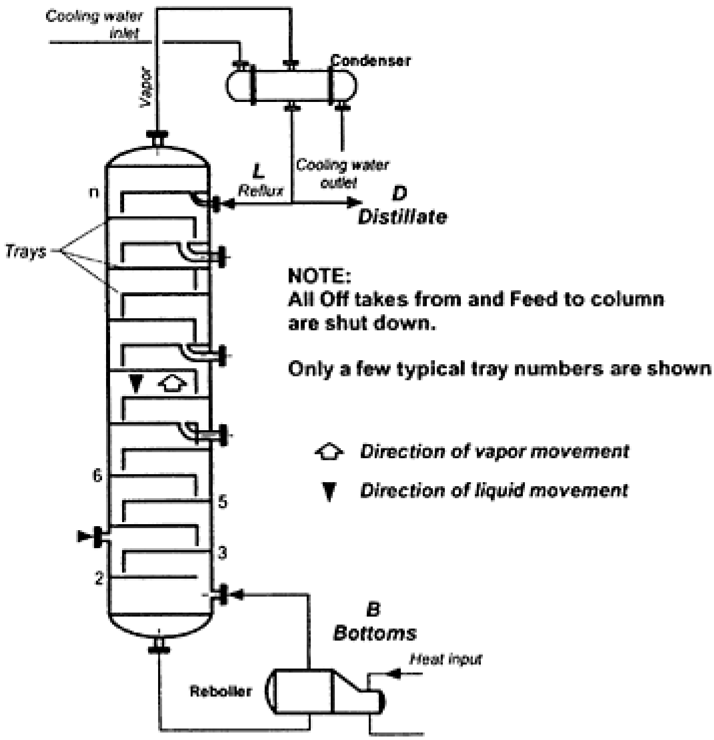


Figure 5.9: Distillation column in total reflux mode.

condenser to their working levels, and no further feed is then provided. If a column is operated in this mode, then no product (distillate) will be available because the entire vapor from the top will be returned as liquid condensate (reflux) via the condenser. Note: The reflux vessel (as seen in Figure 5.2) has been removed as it adds a capacity to the system. The product from the bottom is returned as the feed to the column. It is therefore entirely possible for a column operating in total reflux to reach equilibrium, in which case no net movement of product takes place up or down the column. A column operating in the total reflux mode will give the minimum number of trays necessary to effect a specified separation between x_B and x_D, of a material x that is to be separated, the subscripts B and D denoting the Bottoms and Distillate products, respectively. In this arrangement we can say:

$$L_{n+1} = V_n \quad and \quad D = 0$$

where L is the liquid phase, V is the vapor phase, D is the distillate, and n is the number of trays.

The reboiler is equivalent to a tray, and hence we have n+1 as the total number of trays involved. Under the total reflux condition the liquid to vapor ratio *(L/V)* or *reflux ratio,* is unity at any point in the column.

The *minimum reflux ratio* is that ratio which, if reduced by an infinitesimally small amount, will require an infinite number of trays to effect a specified separation. However, the minimum reflux ratio has meaning only when separation between two components is specified and the number of trays is not.

The *optimum reflux ratio* is that ratio which has the least effect on the fixed and operating costs of the column. The minimum generally occurs at an operating ratio of between 1.1 and 1.5 times the minimum, with the lower value corresponding to a relative volatility near 1.

When feed is added and products are removed from the column, the *L/V* ratio in the tray above the feed-introduction decreases and the *L/V* ratio in the tray below the feed-introduction increases.

DESIGN OF A DISTILLATION COLUMN

The design aspects of a column will not be discussed in detail here; nevertheless it is useful to understand how the plant itself has come about. To produce the products required, it is necessary to ensure that the feedstock enters at the correct position and the number of trays involved will produce the correct components. In all the following it should be noted that:

1. Only the basic data are given; for a complete version of the necessary information, *Perry's Chemical Engineers Handbook* should be consulted.
2. Where applicable, the heat supply to the reboiler is shown as steam. This may not necessarily be the case in every circumstance, for in some instances the heating medium Dowtherm (for a definition, see Chapter 1) is used instead. Steam is shown because it is easier for the reader to appreciate the intent. In this regard, although superheated steam is of a much higher energy level than saturated steam, it is not suitable for heating purposes and its most useful application is in driving machinery.
3. The symbols used in the *Methods of Calculation* are not the same as those used elsewhere in this discussion.

METHODS OF CALCULATION

The *Kremser* method is the classical but approximate way to determine the number of equilibrium stages for a countercurrent cascade of simple absorbers and strippers (these equipments will be defined later). In *Perry's Chemical Engineers Handbook* this method is given as:

$$(v_i)_N = (v_i)_0\,(\Phi_i)_A + (l_i)_A + (l_i)_{N+1}\,[1 - (\Phi_i)_S]$$

where $(\Phi_i)_A = \dfrac{(A_i)_e - 1}{(A_i)_e^{N+1} - 1}$ is the fraction of component *i* in the entering vapor not absorbed

$(\Phi_i)_S = \frac{(S_i)_e - 1}{(S_i)_e^{N+1} - 1}$ is the fraction of component *i* in the entering liquid not stripped

$(A_i)_e = \left(\frac{L}{K_i V}\right)_e$ is the effective or average absorption for component *i*

and $(S_i)_e = \frac{1}{(A_i)_e}$ is the effective or average stripping factor for component *i*

The *Smith-Brinkley* (SB) method is a development from the Kremser and can be applied to distillation, absorption, and extraction processes. *Perry's Chemical Engineers Handbook* shows that this equation is applicable to a distillation column, illustrated in Figure 5.9 as:

$$f = \frac{\left(1 + S_n^{N-M}\right) + R\,(1 - S_n)}{\left(1 + S_n^{N-M}\right) + R\,(1 - S_n) + hS_n^{N-M}\left(1 - S_m^{M+1}\right)}$$

where *R* is the external reflux ratio $\frac{L_{N+1}}{D}$

$f = \left(\frac{B x_B}{F x_F}\right)_i$ is the fraction of *i* leaving in the bottoms product

S is the stripping factor for component *i* and is defined for each group of stages in the column as:

$$S_{n,i} = \frac{K_i V}{L} \quad and \quad S_{m,i} = \frac{K_i' V'}{L'}$$

in which *K*, *V*, and *L* are effective values at the top column section and K_i' *V'*, and *L'* are effective values at the sections below the feed stage.

The *Fenske-Underwood-Gilliland* (FUG) method is used to calculate the number of plates N_m to make a specified separation at total reflux, which, as mentioned earlier, is actually the minimum value of *N*. The Fenske total-reflux equations, which are rigorous relationships in the splits obtained for components *i* and *r*, are given in *Perry's Chemical Engineers Handbook* as either:

$$\frac{x_i}{x_r} = (\alpha)^{N_m}\left(\frac{x_i}{x_r}\right)_B$$

or

$$N_m = \frac{\log\left[\left(\frac{D x_D}{B x_B}\right)_i \left(\frac{B x_B}{D x_D}\right)_r\right]}{\log \alpha_i}$$

where i is any component and r is an arbitary selected reference component in the definition of relative volatilities, and $\alpha_i = \frac{K_i}{K_r} = \frac{y_i x_r}{y_r x_i}$

The correct value of α_i however, must always be estimated, and it is usually from:

$$\text{Either } \alpha = (\alpha_{top}\,\alpha_{bottom})^{\frac{1}{2}} \quad \text{or} \quad \alpha = (\alpha_{top}\,\alpha_{middle}\,\alpha_{bottom})^{\frac{1}{3}}$$

The Underwood minimum-reflux equations are those that apply when some components do not appear in either the reflux or bottoms product at minimum reflux. These are given in *Perry's Chemical Engineers Handbook* as:

$$\sum_i \frac{\alpha_i (x_{i,D})_m}{\alpha_i - \theta} = R_m + 1$$

and

$$\sum_i \frac{\alpha_i x_{i,F}}{\alpha_i - \theta} = 1 - q$$

where $\alpha_i = \frac{K_i}{K_r} = \frac{y_i x_r}{y_r x_i}$ R_m is the minimum-reflux ratio $(\frac{L_{N+1}}{D})_{min}$ q is the thermal condition of the feed, which is

1.0 for bubble-point feed, and 0.0 for saturated-vapor feed.

X_{iF} are values available from the given feed composition.

θ is the common root for the top section and the bottom section developed by Underwood for a column at minimum reflux and separate zones of constant composition in each section. The common root must fall between α_{hk} and α_{lk}, where subscripts *hk* and *lk* stand for high and low key, respectively. The key components are those the designer wants to separate.

The α_i values are effective values obtained from either $\alpha = (\alpha_{top}\,\alpha_{bottom})^{\frac{1}{2}}$ or $\alpha = (\alpha_{top}\,\alpha_{middle}\,\alpha_{bottom})^{\frac{1}{3}}$.

Gilliland produced a graphical correlation between the Fenske and Underwood equations that relates actual column performance to total and minimum-reflux conditions for a specified separation between two key components.

The SB and FUG methods work best when the feed mixtures are nearly ideal, with the FUG method being more convenient for the study of new columns and the SB method for existing ones.

TYPICAL ARRANGEMENTS OF DISTILLATION COLUMNS

To give a feel for what might be found on a refinery process plant, in Figures 5.10 to 5.15 we show some typical arrangements of the columns involved. These are not intended to give specific practical details of the equipment, but only to show basically how the equipment operates and how or where the various process connections and ancillary items of equipment are located.

THE FLASH DRUM

The equipment shown in Figure 5.10 is a single-stage, continuous adiabatic distillation process; it is used when:

1. Two components have a large separation between their relative volatilities.
2. Only a partial separation between the two is required.

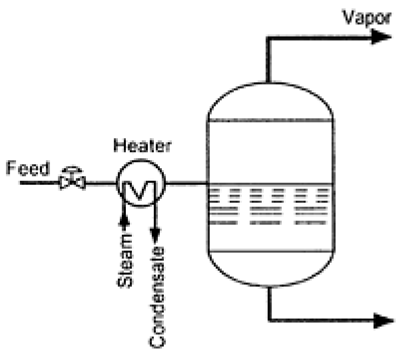


Figure 5.10: Flash drum.

3. The recovery of only one component is required regardless of any other components in one of the two product streams.

Figure 5.10 shows only a feed heater; a valve in the feed line (not shown) is also usually involved to establish the temperature and pressure of the flash. In operation, the temperature and pressure drop across the valve is adjusted to vaporize the feed to the required amount, with the drum providing the space that allows the vapor to disengage and separate out from the other component (liquid). The feed expands at constant enthalpy (i.e., constant heat content) across the valve, thus allowing the inlet or outlet feed temperatures to be calculated. The temperature at which the vapor-to feed ratio V/F=0.0 and the first vapor bubble forms is the *bubble point*, whereas the temperature at which V/F=1.0 and the first droplet of liquid forms is the *dew point*. For a given feed composition, pressure, and temperature, the temperature range that encompasses the bubble and dew point is the range of the equilibrium flash.

THE ABSORPTION AND RECTIFICATION COLUMNS

When the mixture to be separated comprises two components of adjacent volatilities and only one component is to be recovered, then absorption or stripping in a single column may be sufficient. If the feed is a vapor at separation conditions, then a *mass separating agent* (MSA) of relatively low volatility and the *absorption column* as shown in Figure

5.11 a can be used. This column makes the recovery and recycling of the absorbent easier. However, if partially condensing the overhead vapor and using the reflux produced make it easier to obtain the required product, then the *rectification column* shown in Figure 5.11b is used instead. The choice of which method and column to use is either between the ease of partial condensation of the overhead or of recovering and recycling the absorbent.

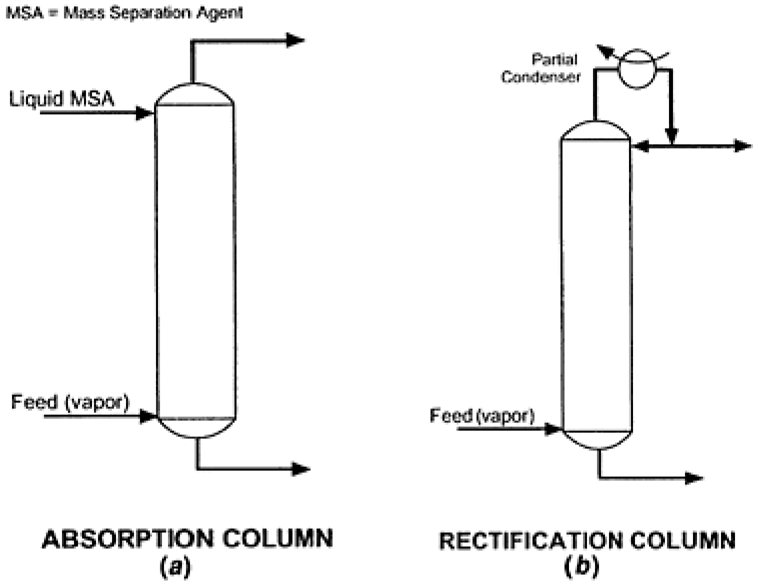


Figure 5.11: Schematics of absorption and rectification columns.

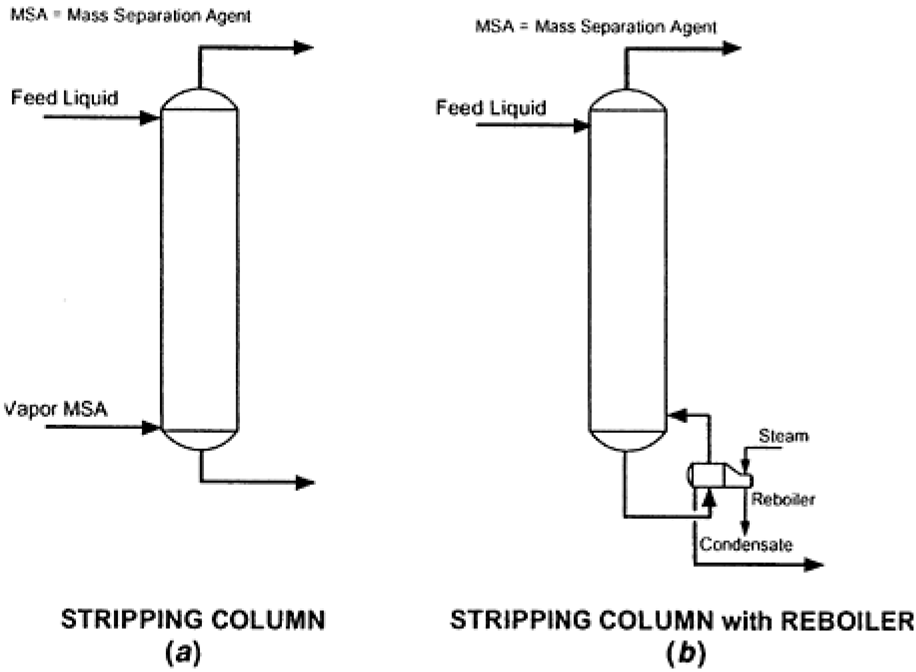


Figure 5.12: Schematics of stripping columns.

STRIPPING COLUMNS WITH AND WITHOUT REBOILER

The main function of the simplest stripping column shown in Figure 5.12a is to achieve a reduction in the content of the volatile component in the liquid product. When the feed is a liquid at separating conditions, the choice is between using either an externally supplied relatively high-volatility vapor stripping agent as shown in Figure 5.12a or using the boil-up produced in a partial reboiler as shown in Figure 5.12b. As before, the choice of which column to use is again between the ease of recovering and recycling the stripping agent or the ease of reboiling the bottoms product.

When two components of relatively close volatility are to be separated reasonably sharply but one either requires a high temperature to produce a boil-up or a low temperature to produce reflux at the column operating pressure, then the reboiled absorption column shown in Figure 5.13a or the refluxed stripping column shown in Figure 5.13b may be used. In both cases, the choice of the MSA depends on whether the feed is a vapor or a liquid and must be given the same consideration, as mentioned earlier.

THE AZEOTROPIC DISTILLATION COLUMN

An azeotrope is defined as a mixture of two or more volatile components that have identical liquid and vapor compositions at equilibrium. From this it will be appreciated that it is a constant boiling-point mixture whose composition does not change as distillation proceeds. Simple distillation techniques are not suitable for azeotropes because only one component will be removed. The other remaining component(s) will be the azeotrope. In every instance for separating such a mixture, a column dedicated to each component of the azeotropic mixture will be required. Hence, two columns will be necessary for a binary mixture.

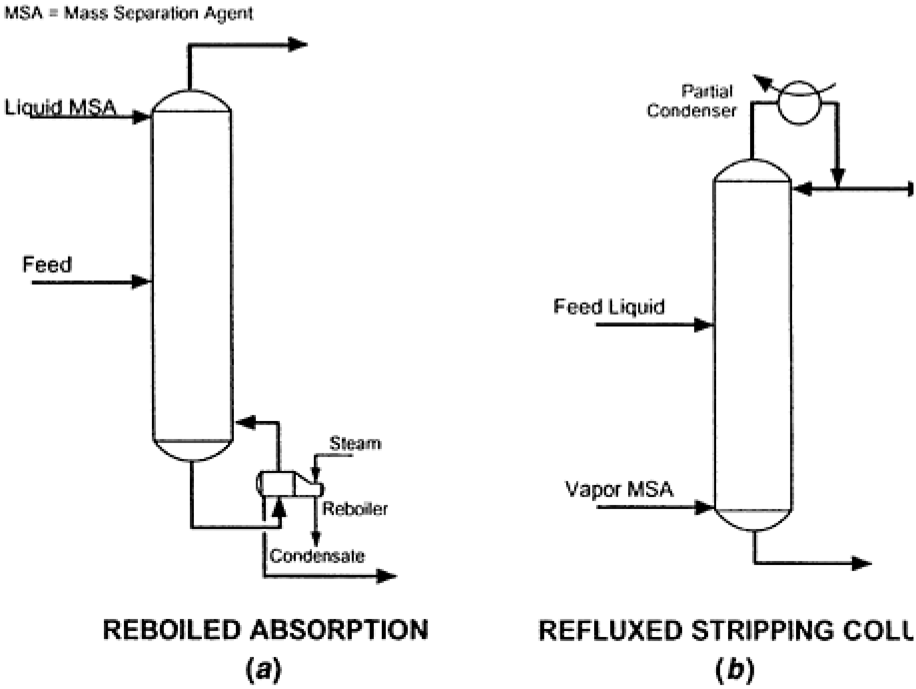


Figure 5.13: Schematics of reboiled absorption and refluxed stripping columns.

Figure 5.14 shows the azeotropic column in one of its many modes; this column can be used as an alternative to the extractive column we show in Figure 5.15. The MSA used is one that forms a heterogeneous minimum-boiling azeotrope, with one or more of the components in the feed. The azeotrope is taken overhead, and the MSA-rich phase is decanted and returned as reflux to the top of the column.

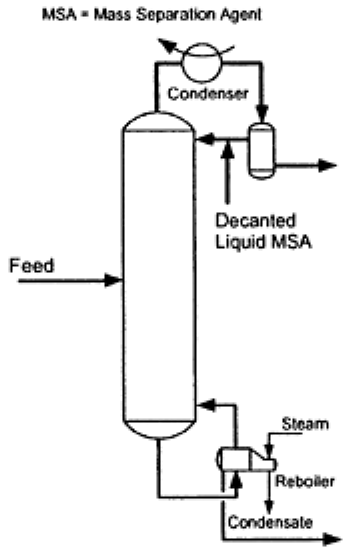


Figure 5.14: Azeotropic distillation.

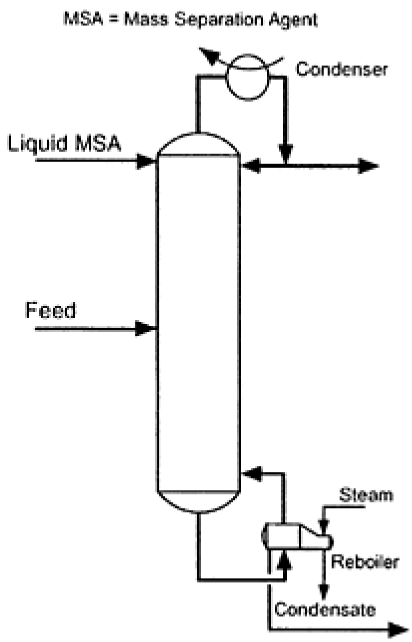


Figure 5.15: Extractive distillation.

EXTRACTIVE DISTILLATION COLUMN

The extractive distillation column is used when the difference in volatility between two components is so small that a large number of stages are required to effect the separation. The choice of MSA, which is usually a compound of low volatility, is made on the basis of its ability to increase the difference in volatility by an amount that reduces the number of stages to an acceptable value. The MSA is introduced in quite large quantities at the top of the column from where it affects almost all the stages in the column. To minimize the MSA content in the distillate, some reflux is used in the top stage. The bottoms product contains the MSA, from which it is recovered and recycled. This method of distillation is suitable to homogeneous azeotropes, which are difficult to separate by any other means.

DISTILLATION COLUMN CONTROL SYSTEMS

The control of a distillation column is complex because of the almost simultaneously occurring number of changes made to the incoming feed material. Moreover, the changes occur, with small variations in the parameters that affect them. Weather conditions around the plant also have a considerable effect, and, because of the inconsistency experienced in some parts of the world, controlling the process becomes that much more difficult. In view of the variations present, no single control strategy can be applicable to all columns; rather, it will depend on the plant and the finesse of the control engineer’s solutions against which success will be measured. The following give some of the basic strategies that can be, and have been, used. Inevitably, of course, variations of these strategies will have to be applied in particular instances, but at least one can have something with which to commence the initial design of the control system. Several discussions will have to be held with the appropriate plant personnel before the final control system can be implemented, but one should be prepared to offer sound reasons for the choice of proposals offered for consideration.

PROCESS HEATERS—CONTROL OF THE INFLOW OF ENERGY

Distillation is a process in which energy is applied to achieve the desired results. It follows that this energy input has to be regulated throughout its application in the process; that is, both the supply and outflow from the process have to be considered. In every case, we must provide the means to get results at the least cost in terms of both fuel used and finance in running the process. We shall first consider the energy supply side. Among the several heating mediums used are steam, salt, or oil, and Dowtherm.

THE DOWTHERM HEATING SYSTEM

One well-known product is Dowtherm, which is made to flow continuously and is supplied to the various users through a number of parallel loops around the plant. The Dowtherm has its temperature raised via a directly fired vaporizing heater, which is specialized equipment whose arrangement of heating tubes is similar to that in steam generators. The vaporizing heater is situated at some central location. When Dowtherm is used as the heating medium, the fluid is in vapor form at a typical value of 600°F (at the heater exit) and on the supply side (i.e., heat input) to the reboilers. Pumps, which are capable of handling fluids at high temperature, force the cooler returning Dowtherm, which is now a liquid, back to the directly fired vaporizing heater where its temperature is raised once more (re-vaporized) in a continuous cycle. The full system has been divided into two for convenience of description: combustion control and heat distribution. However, only the fuel/air ratio control on the process fluid heating in Figure 5.17 is applicable to Dowtherm vaporization, while the remainder should be derived from the scheme illustrated in Figure 5.16. A typical heat-distribution system for Dowtherm and some of the controls involved are shown in the arrangement of Figure 5.16. The pipe work shown in the dotted box is known as the *Hartford Loop* and this inclusion is used only when a gravity-fed system instead of the pumped return is implemented. The idea behind the loop arrangement is to ensure that it will never be possible to create a vapor lock in the system.

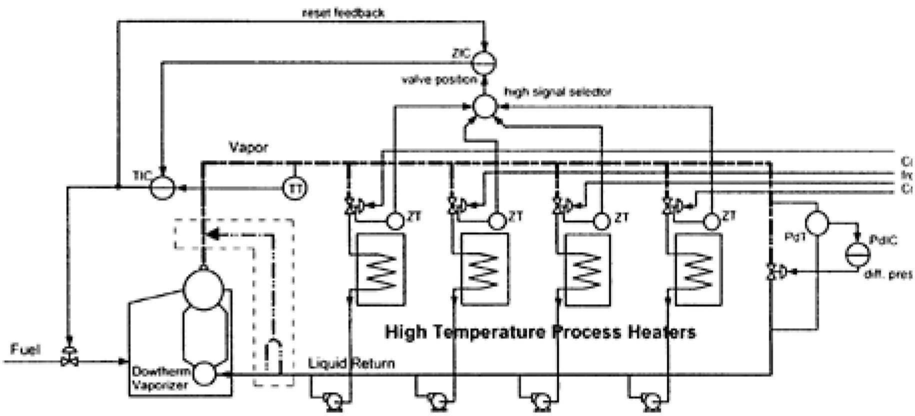


Figure 5.16: Typical vapor heating system with Dowtherm.

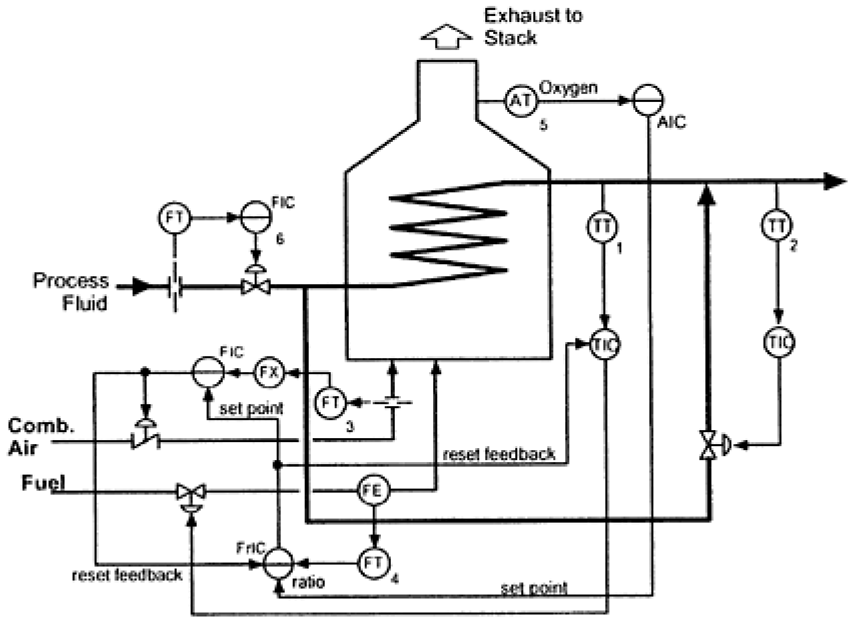


Figure 5.17: Combustion and temperature control on direct-fired heater.

The control system illustrated in Figure 5.16 operates as follows. Since each heater is associated with a column, the demands of that column regulate the amount of heat required by modulating the control valve involved. Each control valve is fitted with a *position transmitter* tagged ZT, attached to the valve stem. The action of changing the valve plug to suit the demands of the column temperature controller alters the position of the transmitter ZT commensurately. From this it is clear that each position transmitter will be at a different position dependent on the dictates of the associated column temperature controller. The outputs from the position transmitters are applied to a high signal selector, which selects the highest and applies it as the measurement to the *valve position controller* tagged ZIC, the output of which is used as the set point of the *vapor temperature controller* tagged TIC, whose measurement is derived from the *temperature transmitter* tagged TT located in the vapor supply line to the heaters. The vapor temperature controller TIC output regulates the fuel supply to the vaporizer to ensure that the correct temperature is achieved. Note that the output of the vapor temperature controller TIC is also applied to the valve position controller ZIC as the reset feedback signal to avoid saturating the integral term in the event the operator puts vapor temperature controller TIC into manual mode and drives the fuel valve directly. In this way, the system ensures that the reboiler demanding the most heat obtains it, with the other valves throttling the demand accordingly. This type of reboiler is said to have *forced circulation*.

To protect against loss of flow through the vaporizer, the bypass with a control valve is included. The differential pressure between the hot and cold heating medium lines regulates this valve. When the reboilers demand less heat, the *differential pressure transmitter* tagged PdT senses the change, and the *differential pressure controller* tagged PdIC alters its output to ensure a constant flow through the vaporizer. Although, strictly speaking, the bypass line in this particular control scheme is not necessary because one reboiler heating valve is always almost fully open, it is included as a backup to allow for control system failure.

COMBUSTION CONTROL OF A DIRECT-FIRED PROCESS HEATER

Figure 5.17 shows the control schemes applied to a direct-fired process heater. In this equipment the heat from the burning fuel is applied directly to the tubes carrying the process fluid in the same way as the water tubes in a steam generator. This type of heater is often used as a reboiler in columns distilling crude oil, and in these instances the process fluid (i.e., the feed) is always controlled to ensure maximum heat transfer to it. The rate of flow is set such that at the same time it prevents the internals of the process heating coils from fouling with any deposits precipitated from the process fluid. The arrangement of mixing some unheated process fluid with the heated process material via temperature control loop T2 to achieve the required temperature is commonly found in domestic water heating systems. However, it is somewhat wasteful of the energy produced in the combustion chamber as the losses depend on the stack temperature.

The principles of combustion described in Chapter 1 are valid in this instance as well. The temperature of the heated feed is monitored by sensor/transmitter tagged TT-1 and applied as the measurement to controller tagged TIC-1, which has a manual set point and whose output regulates the fuel supply to the heater. The amount of fuel to the burners is monitored by an in-line flowmeter tagged FT-4 and applied as the measurement to a ratio controller tagged FrIC-4. The ratio of air to fuel to effect combustion is set on the ratio controller FrIC-4, and this value is finely adjusted by the amount of oxygen in the exhaust gas. The oxygen in the exhaust gas is measured by the oxygen analyzer tagged AT-5 and applied as the measurement to the controller tagged AIC 5 whose output is applied as the set point of controller FrIC-4 and, hence, indirectly adjusts the position of the air damper. The ratio controller FrIC-4 operates on a calculated ratio range, and its remote set point driven by the output signal from the oxygen controller AIC-5 is also referred to as the *oxygen trim,* which precisely corrects the air requirements (including the mandatory “excess air”) for complete combustion. The reset feedback connections to controllers TIC-1 and FrIC-4 are important to avoid saturating the integral term of these controllers, when the operator puts either FIC-3 or FrIC-4 into manual mode. Attention is also drawn to the fact that there is a square root extractor tagged FX-3 in the output from the differential pressure transmitter FT-3 in the combustion air supply, but the fuel flow transmitter FT-4 is an in-line instrument, which has a linear output with respect to flow.

Figure 5.18 is a composite of the two preceding diagrams in which the type of heater, valve position, and Dowtherm differential pressure controls of Figure 5.16 are used, along with the air/fuel controls and oxygen trim of Figure 5.17. Figure 5.18 is given for completeness to show how the two systems are combined. The remarks made earlier in connection with Figures 5.16 and 5.17 individually are still valid in this instance, with the exception of the reset feedback connections of Figure 5.17. These feedback connections have been altered in Figure 5.18 because of the different process piping arrangement for the heated vapor and the associated control system involved.

INDIRECT HEATERS

The temperature of the process fluid in heaters shown in Figures 5.19a and 5.19b is raised by contact with the hot surface of the heater tubes carrying a very hot heat-transfer medium through them.

With the controls shown in Figure 5.19 one should notice the location of the temperature sensors tagged TT-1 and TT-2. In Figure 5.19a, temperature control loop 1 will ensure that the fluid passing out of the heater is generally at the value set

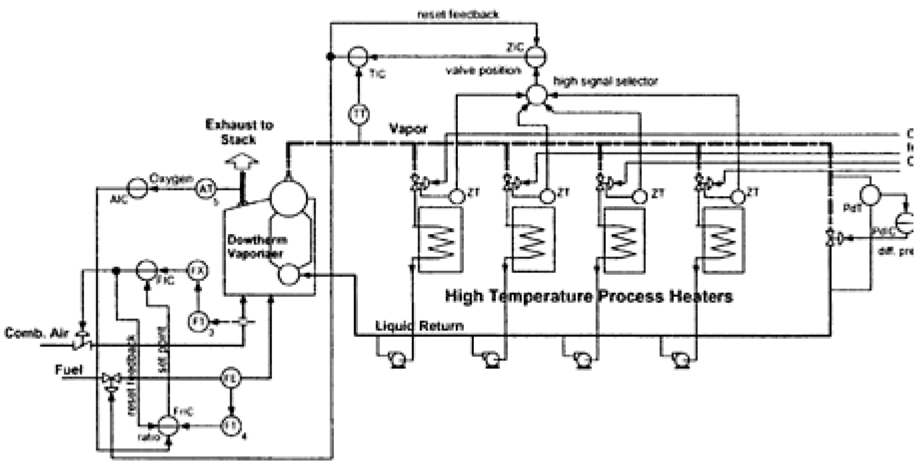


Figure 5.18: Dowtherm vaporizer control system.

on the controller tagged TIC-1, which is dependent on the temperature of the incoming process fluid and the heat-transfer rate. With control loop T1 only implemented, the desired condition will lie somewhere within a band that has maximum and minimum values with a relatively wide separation. To increase the possibility of attaining the desired condition more closely, the controller tagged TIC-2 is included, and some unheated incoming fluid is mixed with the outgoing material. This increases the effective process gain and narrows the amount of process temperature variations. Obtaining this result requires two control valves as shown.

In the system illustrated in Figure 5.19b, notice once again the location of the two temperature sensors tagged TT-1 and TT-2. This will give better results; using only one control valve eliminates the bypass pipeline but provides the same degree of flexibility as before. The system is a combination of feedforward and feedback

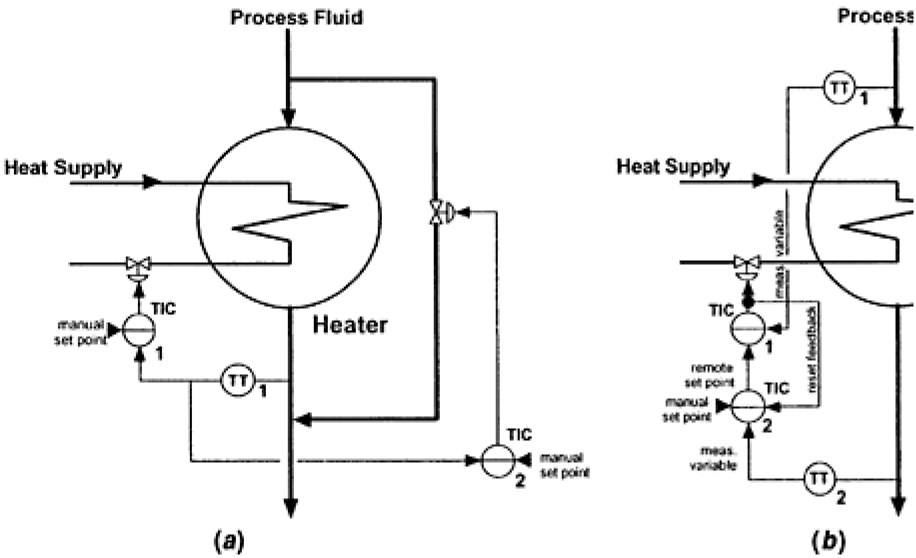


Figure 5.19: Temperature control.

control, the (anticipatory) feedforward aspect provided by loop T1 and the feedback by loop T2. Notice also that controller TIC-2 requires a reset feedback input derived from the output of controller TIC-1. This feedback prevents the integral control term of controller TIC-2 from saturating when or if the operator transfers controller TIC-1 into the manual mode and drives the process directly. Note the subtle way in which the change in temperature is effected in Figure 5.19b where both the incoming and outgoing temperatures are used to adjust the heat supply.

One very important aspect of the blending systems depicted in Figures 5.19a and 5.19b is the fact that they are irreversible. Once the process fluid has been acted upon, no simple change can be applied to the fluid to make it revert to the original condition.

Steam-Heated Reboilers

When steam-heated reboilers are used on distillation columns and the heating medium is steam, the arrangements shown are modified to include a steam flow control loop. The control valve can then be placed either in the steam or condensate line. Steam pressure compensation is always recommended in these cases, and the controls will be as shown in Figure 5.20. Note that there are two possible locations for the control valve: either in the steam supply line or in the steam condensate line. When the control valve is placed in the steam supply line, it is important that a *steam trap* is used to drain the condensate away but retain the steam. However, when the control valve is located in the condensate line, no steam trap is required, but the valve should be fitted with a positioner because the loop behaves more like a level (because of its response to a control signal) than a flow control loop. A positioner assists in stabilizing it, but when the control valve is placed in the steam supply line, a positioner is not required. A positioner is not fitted to the valve located in the steam line because it would destabilize the control loop, making the steam flow respond immediately to the controlled output and precede the heat transfer. On the other hand, changes in condensate have no direct effect on the steam flow but only on the heat transfer,

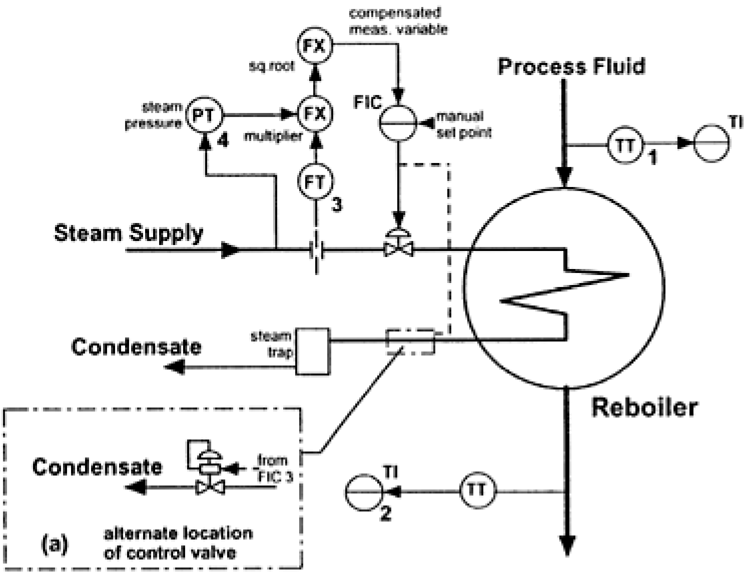


Figure 5.20: Steam-heated reboiler control.

which has a much slower response. The other big advantage is the fact that the valve located in the condensate line can be considerably smaller in size—approximately one-third smaller because of the square law relationship between valve C_v and pipe diameter—and also this valve is of a lower temperature grade and therefore of lower cost. Moreover, as mentioned earlier, there is no need for a steam trap that restricts the removal of condensate and causes the heater shell to flood. In addition, since the steam reaches the reboiler at a higher pressure than that obtained with the valve in the steam line, the heat-transfer rate increases and the thermal economy improves.

Note: For simplicity, the alternate location and controller output for the control valve in the condensate line are shown as an insert view in Figure 5.20. The symbol for a control valve fitted with a positioner is as illustrated; the reader should notice the difference between the symbols used for the two types of control valve shown.

Reboiler Control

The equipment shown in Figure 5.21 is called a *kettle reboiler*, which is normally connected to the bottom of a column from where it receives the liquid bottoms product. Under normal circumstances, only a small amount of liquid is held at the bottom of a column and reboiling whatever amount remains allows the lighter components to be extracted. The unit shown is mounted externally to the column; however, the heating element can sometimes be fitted directly into the base of the column where it accomplishes the same function of vaporizing the liquid. The design of the equipment shown ensures that no liquid is discharged along with the vapor. The figure also shows that the liquid collects in the section formed by the weir, from where it is pumped away as the final bottoms product. In the event of a failure of the level controller, the weir is intended to prevent the heating tubes from being uncovered and therefore damaged. However, when a loss of column pressure occurs, rapid changes in boil-up result in the liquid vaporizing faster than it is returned, thus allowing the tubes to become uncovered. Suitable precautions should therefore be taken to

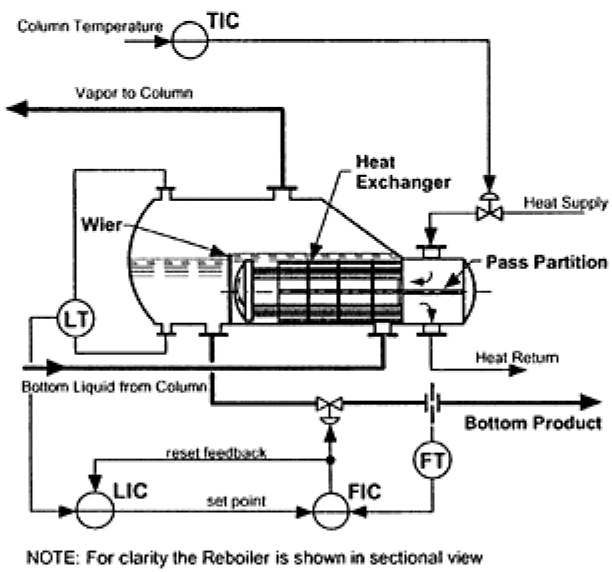


Figure 5.21: Kettle reboiler control.

minimize these occurrences. This type of reboiler is referred to an *immersed type* inasmuch as liquid covers the tubes.

COLUMN FEED PREHEAT

Product quality is affected by variations in material flow through the column, which in turn is dependent on the feed enthalpy; the total heat of the feed should therefore be regulated to meet this demand. When steam is used for either feed preheating or reboiling, the principles involved are basically the same. However, because the preheated feed passes through only part of the trays, the energy used is less useful than if it were to be passed through a reboiler instead. Preheaters are very valuable in recovering the lower heat level that the reboiler is unable to handle and are also suitable in balancing the vapor load of the column. Figure 5.22 shows two arrangements, in both of which the feed is not manipulated. In Figure 5.22a the feed is bypassed, and in Figure 5.22b the heat is bypassed. This aspect of not interfering too much with the feed flow is of importance when dealing with distillation column feed. In both schemes, the objective is achieved by using a three-way valve, which is a “diverting or proportioning” device and not a controlling one. In this application advantage is taken of its characteristic minimal pressure loss without unduly affecting the flow through the valve. Remember that two-way (two connection ports only) valves can be used instead of the three-way valve, but there are the penalties of greater pressure loss across the valve and the inevitability of some flow passing through the device at all times.

The response of the two systems illustrated in Figure 5.22 is not the same, with the scheme of Figure 5.22a being the faster of the two. When columns are subject to variable pressure, it is important that the temperature of the feed is compensated for these pressure variations. Although Figures 5.22a and 5.22b show a manual set point for the temperature controllers TIC-1, this can alternatively be derived as a remote set point from the output of a controller that obtains its measurement from the differential pressure across the column, which responds very rapidly to a change in heat supply to the column.

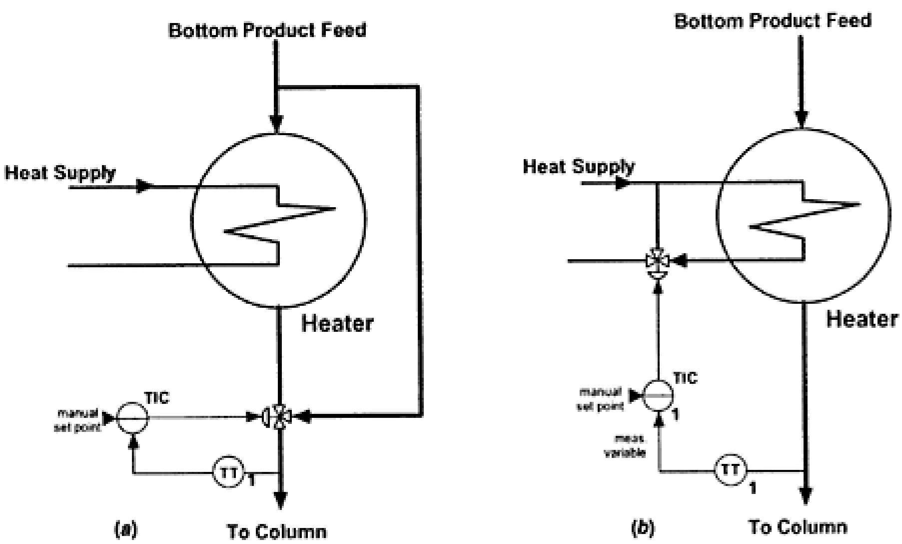


Figure 5.22: Feed preheating temperature control.

COLUMN DIFFERENTIAL PRESSURE

As mentioned earlier, one way of ensuring that the feed is provided at the most favorable conditions for the column is to use the differential pressure across the column as the driving mechanism. The difficulty lies in the fact that because a distillation column could typically be 30 m (100 ft approximately) or taller, considerable problems could arise in making the appropriate process connections. Orifice plates can, and have been, fitted between the top of the column and the condenser to provide a solution, but these are expensive due to the size of the device and the location necessary. However, since the column internals comprise a series of horizontal trays that are in communication with each other to allow the passage of vapor and liquid under normal operation, they behave in a constricting manner similar to the bore of the orifice plate and can be used instead. More fortuitously, the column with its trays follows the Bernoulli relationship $F = \sqrt{2gh}$ as well. The situation of the wide separation between process connections for the measurement is alleviated because the condenser and reflux vessel are usually located at the base of the column at grade (ground level) or first level. The major obstacle is the presence of a vapor within the column which will condense in the process lines because of the piping arrangement, thereby affecting the accuracy of the measurement. In *Distillation Control for Productivity and Energy Conservation,* Shinskey describes how the process connections and mounting of the differential pressure transmitter should be carried out; his instructions should be followed to ensure a good measurement is obtained.

CONDENSERS—CONTROL OF THE OUTFLOW OF ENERGY

Everyone involved in controlling the amount of heat removed from a system recognizes that it is a much more difficult proposition than adding heat to it. This is because the rejected heat has different places to which it is dispersed and, in a manner of speaking, involuntarily. More importantly, the heat dispersal takes place simultaneously in the various directions, for example, to the medium carrying out the cooling. At the same time, it is being dispersed to the surroundings and the containing enclosure, which can carry it away. It is impossible to regulate the amount being taken up by each of the cooling agencies involved. The fundamental reason for this state of affairs is that too many and uncontrollable variables are involved in heat dispersion. Since all the unnecessary heat has to be gotten rid of, it ultimately finishes up in the environment; and how does one exercise control over such a formidable heat sink?

The two types of equipment involved in regulating heat outflow are the airand the water-cooled condensers. In some instances, refrigerants are also used as the cooling medium, and these are liquids other than CFCs. In view of the current emphasis on environmental protection, water-cooled equipment is not used as extensively these days as it once was. In some situations, however, as in vacuum distillation, water-cooling is imperative since the very low pressure loss of a direct contact condenser maintains the low system pressure.

The Air-Cooled Condenser

Figure 5.23 presents a schematic arrangement of this type of equipment and the controls involved. In petroleum refineries, the American Petroleum Institute (API) usually determines the design specification. Only one fan is shown on the suction side in the illustration. This fan is usually referred to as the *forced draft* fan. There could be another fan located on the exhaust as well, in which case it is called the *induced draft* fan, where these names are identical to those used on the furnace side

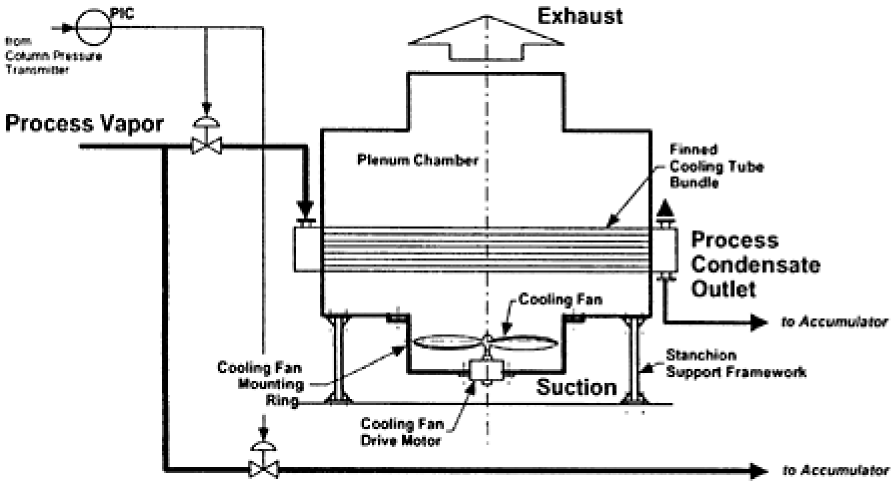


Figure 5.23: Schematic arrangement of the air-cooled heat exchanger.

of steam generators. Sometimes more than one fan may be involved; the process itself determines the actual number required. Louvers are not often used in this equipment because of the physical size involved, and although trimming the fan blades to regulate the airflow across them has been attempted, the results have not been particularly satisfactory because of the mechanical problems involved with the trimming devices. With multiple fan units, varying the airflow can sometimes be achieved by selecting the number operating at any given time. The fan control is implemented to regulate the temperature of the reflux; it is never used to control the pressure of the column or the level in the accumulator drum. Under normal conditions without any control being applied, the temperature of the condensate will vary with the heat load and will affect the pressure within the column as a result. One of the easiest ways to regulate the temperature is to flood the cooling tubes, but this has associated problems too, since the tubes are of large bore and they contain a considerable amount of condensate. Because of the volume involved, this has the effect of reducing the response of the system.

Since the equipment is of considerable size and uses dry air to effect the necessary cooling, if there is any rain, it will naturally fall on the cooling tubes and affect performance by reducing the heat flow. As expected, the performance of the associated column will also suffer as a result of the rainfall. To remedy the situation, the solution is to regulate the process, since manipulating the fan under these circumstances is of little use in handling the new conditions that the wet weather has brought about.

Two control valves are shown in Figure 5.23 and both are necessary because the process vapor stream is split to allow mixing and thereby achieve the desired temperature. However, the two streams must not be joined together on the outlet side of the cooling tube bundle so that a single entry to the accumulator can be made. If the two streams are joined on the outlet, the arrangement will induce water hammer in the piping. The vapor in the bypass line condenses when it contacts the cooler walls of the vessel and the surface of the condensate in the accumulator. If two pressure controllers—one on the column that manipulates the main vapor line and the other on the accumulator that regulates the bypass—were to be used to control the pressure, interaction would follow. To avoid controller interaction, only a single controller that monitors the column pressure is employed to ensure stable pressure conditions. Use of a single controller however, requires that the control valves work in opposite directions—that is, one opens as the other closes. Selecting the failure mode of each valve properly and applying the output of the single pressure controller PIC to the valve motors achieve this requirement of opposite direction operation.

The Cooling Fan

It is useful at this point to consider the basis on which a fan is selected. The purpose of a fan is to establish and maintain a pressure difference between the suction and the discharge sides of the device, and as a result it permits a volume of gas to flow through the equipment connected to it. Resistance to the gas flow arises out of several unavoidable circumstances—eddies generated by the construction of the ducting and obstructions caused by having to insert equipment such as heaters and coolers in the flow path. It follows, therefore, that the pressure difference generated by the fan must be sufficient to overcome the resistance of the system as a whole. Air is rarely, if ever, uniformly distributed across a section of ductwork. Hence, to evaluate the average velocity within the duct, it is necessary to measure the flow at distributed points across the ducting and therefrom compute the average static and total pressures and derive the average gas velocity from these measurements. Two methods of computation are available:

1. Take the square root of each velocity pressure reading and determine the arithmetic average and square this value to give the average velocity. This is the root mean square (rms) value.
2. Convert each velocity head to a corresponding velocity and then determine the arithmetic average of the velocities to give the average velocity.

Note: The formulas for a fan following on immediately are given in imperial units.

Determining Gas Velocity from Velocity Pressure

$$v = 1096.2\sqrt{\frac{p_{vel}}{\rho}}$$

where v is the gas velocity in feet per minute (ft/min)

p_{vel} is the velocity pressure in inches water gauge (in wg)

ρ is the gas density in pounds per cubic foot (lb/ft^3)

Velocity of Gases Other Than Air:

If the gas is air at 60°F and a pressure of 30.0 in Hg, the velocity corresponding to a 1.0 in wg pressure is 3970 feet per minute, from which we can say that for any gas at any condition other than that given, the velocity can be determined from

$$v = 3970\sqrt{p_{vel}\,\frac{460 + T_{act}}{460 + 60}\,\frac{30}{p_{bar}}}$$

where v is the gas velocity in feet per minute (ft/min)

p_{vel} is the velocity pressure in inches water gauge (in wg)

T_{act} is the actual temperature of the gas in °F

p_{bar} is the barometric pressure in inches mercury (in Hg)

Determining the Horsepower of the Fan

If a fan in a duct handles a volume V ft^3 per minute of air against a pressure measured as in water gauge, we can consider the ducting configuration to be represented by and equivalent to a cylinder of 1.0 ft^2 cross section with a frictionless piston of 5.2 p lbs weight, where p is the pressure in in water.

(Note: 1 ft^3 water=62.4 lb; therefore, a 12 in cube of water exerts a pressure of 62.4 lb/ft^2 and hence, a pressure of 1 in water=5.2 lb/ft^2)

Then the work done per minute will be given by:

$$V\ 5.2\ p\ \text{ft.lb}$$

from which the horsepower will be:

$$\frac{V\ 5.2\ p}{33{,}000}$$

If η were the percentage efficiency of the fan, then the power would be given by:

$$B.H.P = \frac{V \times 5.2 \times p \times 100}{33{,}000 \times \eta}$$

where V is the gas volume in ft^3 per minute

p is the pressure in in water

Fundamental Fan Rules

Two important rules determine the performance of any fan. These rules are used to make any adjustments required when the equipment is commissioned in a plant.

1. For a given speed and a given constant volume of gas, the static pressure, total pressure, velocity pressure, and power are all directly proportional to the density of the gas involved.
2. For a constant ducting system resistance:

 a. The volume of gas handled is directly proportional to the fan speed.
 b. The static pressure, total pressure, and velocity pressure will vary as the square of the fan speed.
 c. The power will vary as the cube of the fan speed.

Since the density of a gas is dependent on the gas involved, the first rule enables us to calculate the change involved when the gas handled is changed. This is so because of the gas laws, which state that the gas density is directly proportional to the barometric pressure and inversely proportional to the absolute temperature.

As an example of what is involved when considering differing gas densities, let us consider the air supplied to a furnace of a steam generator. Let the air be supplied at a temperature of 60.0°F, and a pressure of 30.0 in Hg, and let the static pressure (delivered pressure) on the discharge side be 2.5 in wg. An air heater raises the temperature of the incoming air to 150.0°F, which causes the pressure to fall to 24 in Hg. Let us determine the new static pressure (delivered pressure) under these conditions. (Note: Since the temperature has changed, the density of the incoming air also has changed.)

The static pressure (delivered pressure) can be evaluated from 2.5 $\frac{(460+60)}{(460+150)}\,\frac{24}{30}$ to yield a static pressure (delivered pressure) of 1.705 in wg.

Note that the term *static pressure* used to describe the pressure delivered by the fan is commonly used by fan engineers and is repeated here for accuracy of teminology.

Measurement of Sound/Noise Intensity

Fans generate a considerable amount of noise, and steps have to be taken to restrict the noise to an acceptable level. Important as they are, however, the methods of sound reduction or noise control are outside the scope of this text. This subject is adequately covered in specialist literature and by the availability of contract service organizations. Having said that, still we must have a means of measuring the amount of noise generated, so that a basis for a definition or comparison can be determined. The fundamental unit of measurement is the *bel,* which was introduced in 1923 and named after Alexander Graham Bell, the inventor of the telephone. The bel is a large unit of measurement, and it is more conventional and convenient to use a smaller unit in computations and specifications, in which case the unit is called a *decibel*= 0.1 bel and written as *dB*. The intensity of a sound wave is measured by the passage of energy or power resulting from a sound-pressure wave. However, the decibel may be used to express the ratio of other power sources, including related quantities such as electrical current and voltage. If W_1 and W_2 are two sources of power in which $W_2 > W_1$, then:

$$n = 10 \log_{10} \frac{W_2}{W_1}$$

where n is the intensity of W_2 relative to W_1 in decibels.

Sound pressure (noise) is given by n=20 log 10 $\left(\frac{p_2}{p_1}\right)$ where p is the sound pressure.

If we consider electrical voltage, then from Ohm's law the power is given by $P=v^2 R^{-1}$, in which case n is given by:

$$n = 10 \log_{10} \frac{V_2^2 R_2^{-1}}{V_1^2 R_1^{-1}} = 10 \log_{10} \left(\frac{V_2}{V_1}\right)^2 \left(\frac{R_1}{R_2}\right)$$
$$= 20 \log_{10} \frac{V_2}{V_1} + 10 \log_{10} \frac{R_1}{R_2}$$

If we consider electrical current, then from Ohm's law the power is given by $P=I^2 R$, in which case n is given by:

$$n = 20 \log_{10} \frac{I_2}{I_1} + 10 \log_{10} \frac{R_2}{R_1}$$

Since the decibel is a unit obtained from a ratio of power sources, it is necessary to define a reference level when just stating a "level of sound" existing at any measurement location. In acoustic work, the "zero" or reference pressure level is set at 2×10^{-5} pascals (conventionally as 0.0002 dynes/cm^2), in which case the reference level (p_1 or W_1) is usually given as p_0 for pressure or W_0 for power. For the "normal ear" this (ref) level is the minimum audible sound at a frequency of 1 kHz.

ELECTRIC MOTOR SPEED CONTROL

As mentioned earlier, the volume of air through the fan is dependent on the speed of rotation and the number and pitch of the blades. Hence, we will now present some ways of regulating the motor speed. A motor is under load when it overcomes a torque opposing its rotation, which in the real world is represented by the equipment that is being driven by it.

The Direct Current (dc) Machine

In the following, we make the assumption that the power supply is constant and the magnetic flux per pole is independent of the load. For an unloaded motor, the rotational speed is due to the armature current, which is small because the torque to be overcome is that due to the friction in the bearings, windage, and iron losses in the armature. Under these conditions, the back emf is almost equal and opposite to that of the power supply. Since we have introduced back emf, it is as well to discuss its meaning. This meaning can be envisaged as follows. As soon as the armature rotates, an emf is generated because the armature is rotating in a magnetic field; therefore, in accordance with Lenz's law, this generated emf has a direction that is opposite to the current. Hence, it is called the back emf. To maintain the current, the power supply has to overcome not only the armature winding resistance, but also the back emf. We can therefore write the relationship in voltage terms as:

$$E_{sup} = R_{arm}\, I + E_{back}$$

where E_{sup} is the power supply

R_{arm} is the resistance of the armature

E_{back} is the back emf

From this equation it can be seen that the resistance of the armature interpoles and so on, are designed to be small. The *numerical value of the back emf* under normal conditions is *never very different from the power supply*, but more importantly it must always be *less than the power supply*. The armature current can be considered as being due to the excess of power supply p.d. over the back emf or:

$$I_{arm} = \frac{E_{sup} - E_{back}}{R_{arm}}$$

where I_{arm} is the armature current with all other terms as defined earlier.

As a load is applied, the armature slows down immediately, and in doing so the back emf decreases to allow a larger electrical current to flow. This expectation is confirmed when we consider the result obtained from the immediately preceding equation in which if we allow E_{back} to decrease, I_{arm} will immediately increase. The slowing of the rotational speed is just sufficient to permit the increase in current to produce the necessary torque to drive the load. However, when the load is reduced or removed, the existing torque is greater than that required, and the excess immediately accelerates the armature. This causes the back emf to increase and reduce the current to a value required by the new condition. In this way of operation, the back emf makes the dc motor self-regulating.

It has been found that the magnetic flux per pole is not independent of the load, but since the back emf is the one that is generated by the rotation of the armature, then:

$$E_{back} \propto n\,\Phi$$

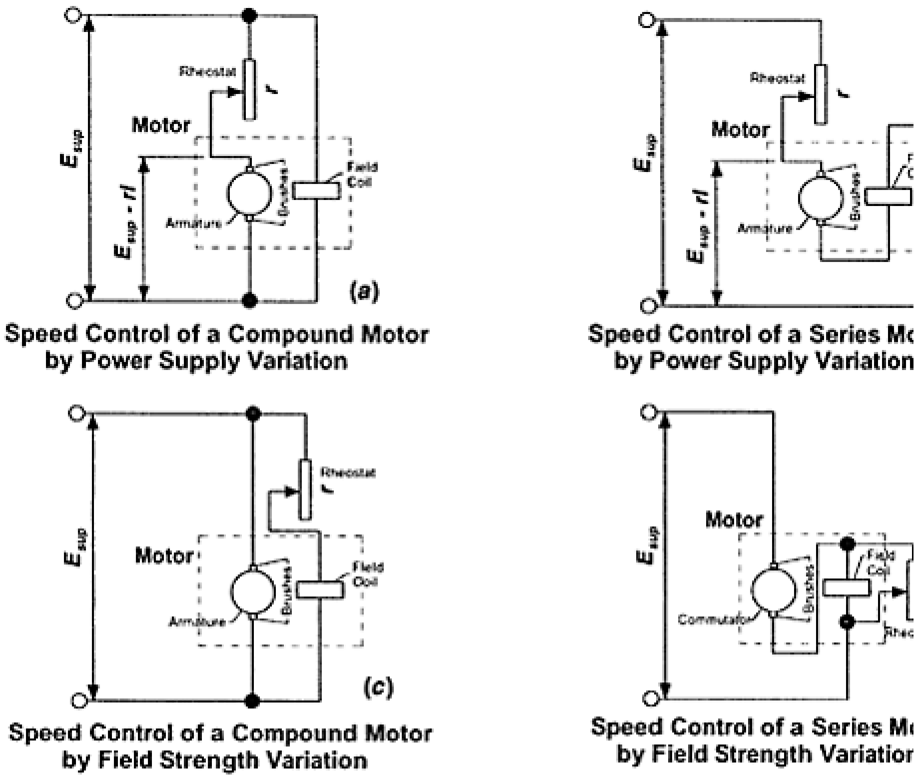


Figure 5.24: dc motor speed control.

where n is the rotational speed in rpm

Φ is the flux per pole

From which we can say: $n \propto \frac{E_{back}}{\Phi} \propto \frac{E_{sup}}{\Phi}$ (approximately). Therefore, the motor speed may be varied by altering the values of either the armature p.d., that is, power supply E_{sup} or the flux per pole **Φ**.

The whole of the field circuit is a loss-making arrangement; these losses are therefore always designed to be as small as possible. With the arrangements shown in Figure 5.24 (for speed control using the technique of power supply variation), one must be aware that in the case of the compound motor (Figure 5.24a) and series motor (Figure 5.24b) the shunt rheostat will see the full supply current and will tend to get very hot as the resistance is increased. The resulting armature p.d. is decreased in order to slow the rotation until the back emf has decreased enough to allow the current required to give the necessary torque. This arrangement is suitable for only short-duration operations but it is inefficient, owing to the large losses incurred in the rheostat. Nonetheless, it will give rotational speeds capable of varying from very slow to full speed, but the attendant problem of heat generation referred to earlier is unavoidable. By placing the rheostat in series with the field circuit as shown in Figure 5.24c for the compound motor controlled by field strength variation, the large current and heat generation seen before is reduced to that required by the shunt/field arrangement. This has the benefit of making the motor available for a wide variation in above-normal rotational speeds. The arrangement of placing the rheostat in parallel

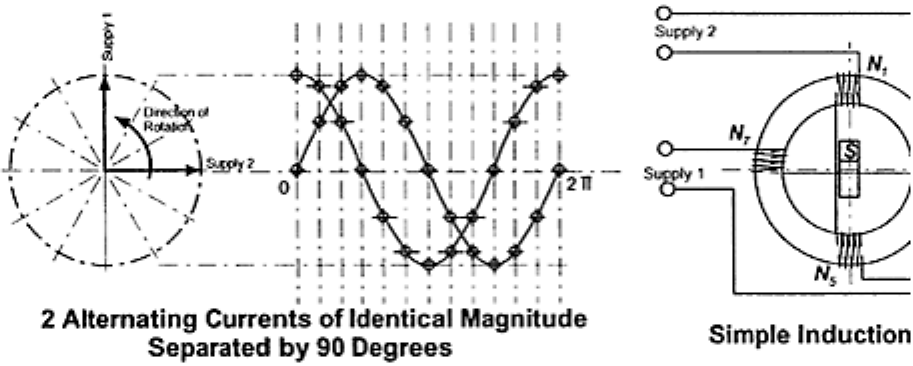


Figure 5.25: Alternating current wave and simple induction motor.

with the field circuit, as in Figure 5.24d, diverts a portion of the field current through it and so weakens the field strength, thereby also permitting the rotational speed to be regulated.

The Alternating Current Machine

The alternating current (ac) motor poses a different set of problems to give a variable rotational speed due to the manner in which the motor windings are excited. The ac motor is a device that operates on the induction principles propounded by Faraday. In this motor, there is no electrical connection between the fixed (stator) and the rotating (rotor) part of the machine, but these two parts are coupled together magnetically by the induced emf. To understand the principle involved, we now refer to Figure 5.25. In this illustration we make the following arbitrary, but nonetheless, conventional choices

1. All values above the central horizontal axis designated 0 to 2π are considered positive.
2. All values below the central horizontal axis designated 0 to 2π are considered negative.
3. The direction of rotation of the voltage vectors is counterclockwise.
4. The zero or start position is on the horizontal axis.

The Induction Motor

Let the current from two power supplies be of the same magnitude and be shown as vectors placed 90° apart, with one vector located at the zero (horizontal) or the start position. To simulate the two alternating currents, let the two vectors commence rotating at the same time and speed from this position, as shown in Figure 5.25. We are interested only in a single revolution since the results obtained for each revolution made are infinitely repeatable. In the illustration, by using standard drawing projection techniques we can obtain the two curves shown to the right of the rotating vectors. From the curves it is clear that the vector shown horizontal produces the well-recognized sinusoidal trace, and the other vector shown at 90° produces the equally familiar cosine trace. Since the two vectors are displaced by 90° from each other, it should be evident that after one revolution there will be a delay (lag) between them before each once again attains the starting positions illustrated.

To show how this phenomenon is used, a simple induction motor is also included in Figure 5.25. The motor comprises a torus that has only a pair of windings wound on it, which are also located 90° apart, and a freely rotatable permanent magnet mounted in the center of the ring. The torus is made from soft iron because this material can easily be magnetized under the influence of the current carried by the coils wound on it. As we apply two ac sources of power, one to each winding, and use the right-hand helix (corkscrew) rule to the winding attached to supply #1 (to determine the direction of both the emf, and hence, the current, flowing and the magnetic flux in the circuit), we shall see that the top of the soft iron torus behaves as the N pole of a magnet and the bottom (inner surface) of the soft iron torus as its S pole. This makes the N pole of the freely rotatable permanent magnet move toward the S pole of the ring (because dissimilar magnetic poles attract). The same phenomenon occurs with supply #2. Now, because there is a separation of 90° between the two windings, as mentioned earlier, the value of the current supply #2 will be increasing as the current of supply #1 is decreasing, thus making the N pole on the torus appear to rotate. This change in value of the current (hence, the magnetic flux) will after, say, one-eighth of a revolution, shift the N pole on the torus to an apparent position halfway between the positions marked N_1 and N_3 in Figure 5.25. This virtual shifting of the N pole around the soft iron torus forces the permanent magnet to actually rotate.

In a practical machine, the rotating permanent magnet is replaced by a *rotor*, constructed from a series of rectangular copper or aluminum conductor bars mounted in slots on a cylindrical soft iron core, with both ends of all the conductor bars joined together by two heavy copper or aluminum rings to form a short-circuited winding. As the rotating field moves across the bar winding of the rotor, it induces very strong currents that magnetize the soft iron core and allows the rotating field to pull the rotor round continuously. From what has just been said, it should be evident that the speed of rotation will be entirely dependent on and fixed by the frequency of the alternating current that is applied. This type of motor is called a *squirrel cage* because of the rotor construction, which resembles the exercise cage of the pet animal.

Torque/Rotor Power Factor Relationship

Figure 5.26 illustrates the way in which the voltage, torque, and power in the rotor circuit are related. Faraday's law of magnetic induction states that the electromotive force generated when a conductor passes through a magnetic field is proportional to the product of field density, conductor length, and velocity of traverse or $emf \propto Blv$. In the case of the motor, the conductor length and velocity are constant; hence, *emf* α *B*. In the case of the motor, the flux distribution over one pole pitch can be represented very closely by a sine wave, so that the emf distribution can also be represented by the same sine wave. If we assume that in the first instance the rotor is totally noninductive, then the current can also be represented by another sine wave *in phase* (i.e., both start and finish at the same points) with each other. These two sine waves are shown in Figure 5.26a. Since the conductor length is constant, the torque acting on each conductor at any instant is proportional to the product of the flux density and the induced current, or $T \propto B\ I_{ind}$, where *T* is the torque and I_{ind} is the induced current. Plotting the product of *B* and I_{ind} for each conductor results in the torque distribution curve over the pole pitch also shown in the figure. Despite the fact that the torque falls to zero at certain points, this curve is always in the same direction (positive) and is brought about by the reversal of both the flux and the current in the next pole pitch.

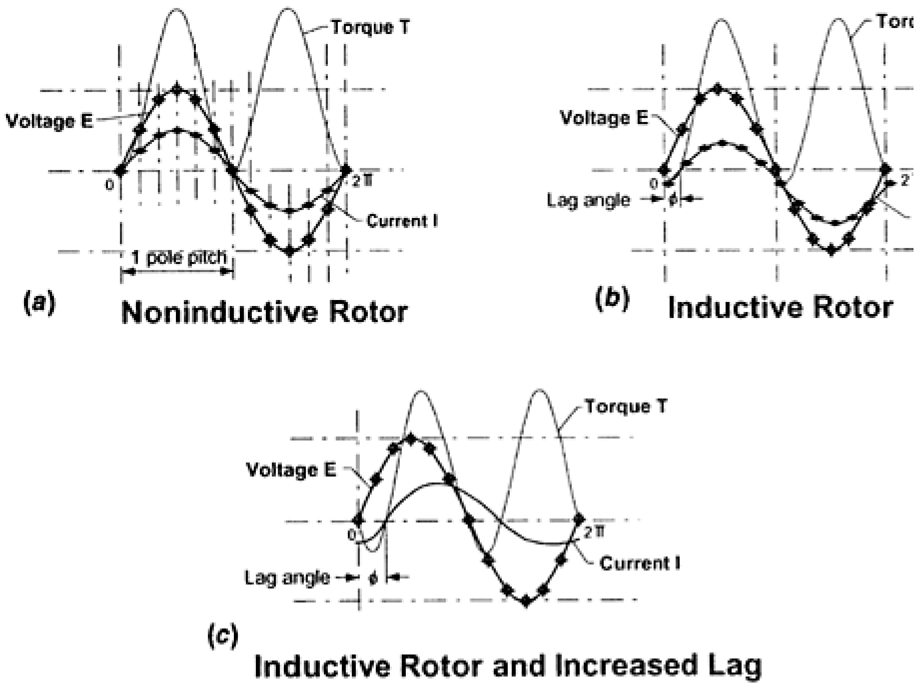


Figure 5.26: Torque/power factor relationship in an ac motor.

It is virtually impossible to make a totally noninductive rotor; hence, we shall now investigate the effect that some inductance has on the situation. Figure 5.26b shows the inductive effect; the emf and flux can still be represented by the same sine wave, but we can see that the current now lags behind the emf by an angle **Φ** The inductance makes the torque in a portion of the pole pitch encompassing the lag angle reverse because the current is reversed between this part of the pole pitch as well. The overall effect is that the resultant torque, (i.e., the difference between the forward and backward torques) is reduced by a large amount.

If the inductance of the rotor increases, the lag increases; that is, **Φ** gets larger, and a greater proportion of the conductors exert a backward torque. This situation is shown in Figure 5.26c. If we allow the inductance to continue to increase until the forward and backward torques are equal, the power factor and the resultant torque will be zero.

We can summarize the foregoing as follows:

The resultant torque is proportional to the product of the rotor emf, rotor current, and rotor power factor, or:

$$T_{res} \propto E_{ind}\, I_{ind} \cos \phi_{ind}$$

If **Φ** is the flux per pole, then E_{ind} is proportional to **Φ** in which case

$$T_{res} = k\, \Phi\, I_{ind} \cos \phi_{ind}$$

Starting Torque

A multiphase induction motor at the instant of starting is subject to the emf induced in each phase of the rotor, the reactance per phase, and the resistance per

phase. Hence, at starting, the following apply:

$$\text{Rotor current:} \qquad I_{ind} = \frac{E_{ind}}{\sqrt{R_{ind}^2 + X_{ind}^2}}$$

$$\text{Rotor power factor:} \qquad \cos \phi_{ind} = \frac{R_{ind}}{\sqrt{R_{ind}^2 + X_{ind}^2}}$$

where E_{ind} is the emf induced in each phase of the rotor at starting

X_{ind} is the reactance per phase at starting

R_{ind} is the resistance per phase

Therefore, the starting torque:

$$T_{start} = k \frac{\Phi\, E_{ind}\, R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

But normally the power supply is constant, and as a result the flux per pole is also constant. Hence, we can say:

$$T_{start} = k_1 \frac{R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

The rotor, because of its construction, is highly inductive, and at the time of starting, the frequency of both the rotor and stator are equal so that the reactance is larger than the resistance, which makes the rotor current lag the emf by a large angle. The result is a power factor that is low and a torque that is small. Either increasing the resistance or reducing the reactance in any inductive circuit can achieve a reduction in the phase angle. It is very difficult, however, to reduce the reactance of an induction motor; but by increasing the resistance, the emf and current can be brought more into phase. There are disadvantages associated with increasing resistance, for by doing so, the impedance increases thereby reducing the value of the current, but the improvement in power factor and starting torque is of more significance. As an illustration, suppose we carry on increasing the resistance in the rotor continuously; will this as expected, give a continually increasing starting torque as a result? The answer is “No,” for the maximum torque is achieved when the resistance and the reactance are equal. Any increase in resistance beyond this value actually results in a decrease in torque owing to a reduction in current, but there is an improvement in the power factor, as we have said earlier.

We now turn to normal running; the motor will require a low resistance for efficient and satisfactory operation during this period, which contradicts the starting requirements. To overcome the dilemma, a *wound* or *slip-ring rotor* is used; when employed, this allows external resistances to be inserted at starting and cut out—by short-circuiting, as the motor runs up to speed. This technique makes the slip-ring rotor fully short-circuited during normal full-speed running.

The Effect of Supply Voltage Variation

To visualize the effect of a changing power supply voltage on the motor let us use the equation derived previously:

$$T_{start} = k\frac{\Phi E_{ind} R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

We are aware that E_{ind} is proportional to **Φ** and that **Φ** is very nearly proportional to E_{sup}. Now if E_{sup} is not constant then we can say:

$$T_{start} = k_2 E_{sup}^2 \frac{R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

From this equation it is clear that the starting torque is extremely sensitive to supply voltage variation.

Rotor Slip

The speed of the rotor must always be less than the synchronous speed of the motor. The difference between these two speeds is called the *slip,* which is expressed as either a fraction or percentage of the synchronous speed and is denoted by the symbol *s*.

$$s = \frac{N_{syn} - N_{act}}{N_{syn}}$$

where N is the rotational speed and the subscripts *syn* and *act* denote synchronous and actual speeds, respectively.

When the motor is standing still, s=1.0 and the slip is therefore 100%. The machine then behaves as a transformer, with the induced emf (Eind) in the rotor having the same frequency as the power supply.

Speed Control of an Induction Motor

By Rotor Resistance Change:

As we have seen earlier, altering the resistance of the rotor circuit can change the rotational speed of the motor. Inserting external resistances into the rotor via the slip rings effects the change in rotor resistance. However, the speed regulation at low rpm is very poor because at low speeds a small change in resistance produces a large change in rotational speed.

By Pole Changing:

This technique changes the speed by changing the number of poles by a switching operation, but the speed-changes are limited to simple ratios such as 1:2 and are confined mainly to small motors. In some cases, confined generally to larger motors, two separate windings are provided—one that provides, say, 4 and 8 poles and the other 6 and 12 poles—to give four synchronous speed of 1500, 1000, 750, and 500 rpm.

Infinitely Variable Speed Control

For an infinite variation of fan speed, the only solution using this type of constant speed motor is to include a hydraulic-coupled speed-changing gear unit in the system. The attendant efficiency of the hydraulic coupling itself and its demand on motor power must also be taken into account. In this arrangement, the induction motor is allowed to run at its constant design speed, with all other changes in speed being made via the hydraulically coupled speed-changing gear. Suitable provisions will therefore have to be made to enable the control signal output of the system to mechanically alter the speed-changing gear smoothly for each change in demand.

TABLE 5.1 Basis of Sound Measurement *(NOTE: There is no correlation between data in Tables 5.1 and 5.2.)*

Relative Energy $\frac{P_2}{P_1}$	***log_{10} Rel. Energy***	***dB $10 \times log_{10}$ Rel. Energy***

1,000,000,000,000	12	120
100,000,000,000	11	110
10,000,000,000	10	100
1,000,000,000	9	90
100,000,000	8	80
10,000,000	7	70
1 ,000,000	6	60
100,000	5	50
10,000	4	40
1,000	3	30
100	2	20
10	1	10
1	0	0

The Recirculating Dry Air-Cooled Condenser

The following points should be taken into account of when air-cooled units are involved:

- All the exchangers in a bank should be of the same type.
- The effects that prevailing wind, surrounding buildings, and other structures have on the units should be considered.

TABLE 5.2 Sound Increase for dB difference *(NOTE: There is no correlation between data in Tables 5.1 and 5.2.)*

Difference in dB rating of two component sounds	*Add to greater sound*
0	3.01
1	2.54
2	2.12
3	1.76
4	1.46
5	1.19
6	0.97
7	0.79
8	0.64
9	0.52

	10	0.41
	11	0.33
	12	0.27
	13	0.21
	14	0.17
	15	0.14
	16	0.11
	1 7 and above	Negligible

- The noise generated by the fans should be given due consideration. (See Tables 5.1 and 5.2 for points 3 and 4.)
- The energy of two or more uncorrelated sound sources is additive. The difference in noise level between a single and two identical sources is 3.01 dB. This applies whether one is combining physical units, such as fans, or adding fan noise to background noise. When adding a second (quieter) unit, if the difference between the individual sound levels amounts to a value above 17 dB, very little increase takes place in the overall resultant sound level.
- The exhaust from the heat exchanger is directly to the surrounding atmosphere; care should be taken to ensure that the exhaust is not located over equipment or in the direction of personnel, and/or can cause a hazard.
- The units should not be installed where corrosive vapors or fumes can be drawn in through the inlet.
- The heat flow is approximately proportional to the flow of air through the exchanger.

Figure 5.27 shows a schematic of a typical internal recirculating dry air-cooled heat exchanger. In these exchangers, recirculating some of the warm exhaust air prevents the problems that arise when operating the unit at low inlet temperature conditions. Wind skirts and louvers limit the mount of cold air drawn in via the inlet, although it should be noted that, despite these precautions, and assuming they “fail-open,” any failure of the louvers or skirts allows the cold air direct access to the process tube bundle.

Since the dB rating of equipment should always be available from the manufacturers, it is suggested that all computations start with figures that match the values of the equipment from column 3 in Table 5.1.

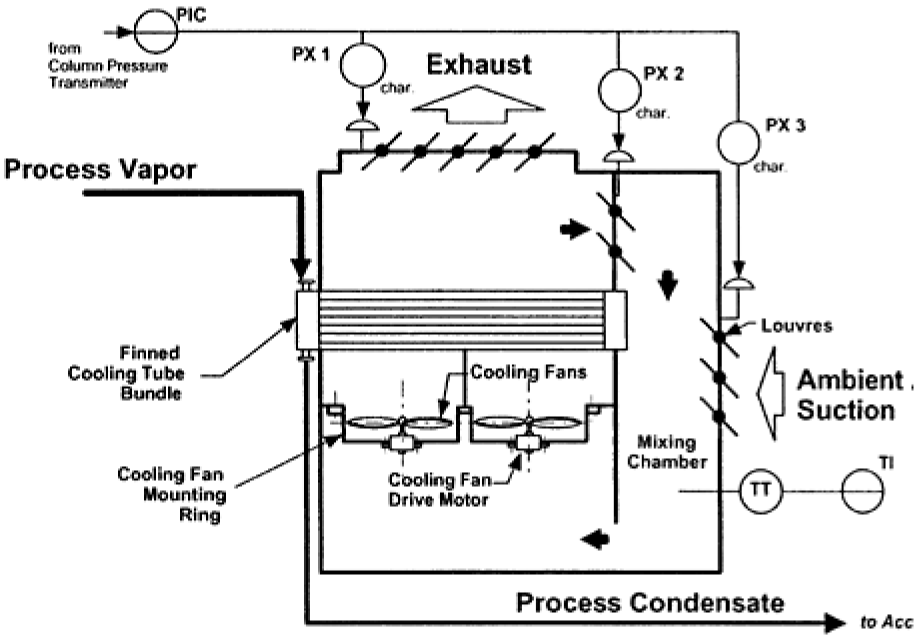


Figure 5.27: Schematic arrangement of recirculating dry air-cooled heat exchanger.

EXAMPLE (a)

If a 50 dB noise is added to a 50 dB background noise, the relative energy is (100,000+100,000) or 200,000. Log_{10} 200,000=5.30103 from which we calculate the sound intensity as 10×5.30103=53.0103. From this it will be seen that the change in sound intensity is 3.01 above either sources of the sound since both sources have identical intensities.

EXAMPLE (b)

If a 50 dB noise is added to a 30 dB background, the relative energy is (100,000+ 1,000) or 101,000. Now, $\log_{10}$ 101,000=5.00432 from which we calculate the sound intensity as 10×5.00432=50.0432 dB. From this it will be seen that the change in sound intensity is just 0.04 above the source of the higher sound level and hence can, to all intents, be neglected.

EXAMPLE (c)

To save time in carrying out the computations, it is possible to calculate only the difference in the energy levels of the two sources of sound, refer to the relevant integer in the “Difference in dB” column, and add the associated numerical value in the extreme right-hand column to the higher source of sound. For instance, in Example (a) the difference between the two sources is 20 dB. Hence, referring to the “Difference in dB” for “17 and above,” the amount to be added is negligible, so the resultant sound intensity is 50 dB; and for Example (a) the difference is 0 (zero). Therefore, the resultant to be added is 3.01 to 50 dB to give 53.01 dB as the resultant sound intensity. Despite the apparently low increase, it (nominally 3 dB) still represents an increase to twice the power.

The operation and controls for the recirculating dry air heat exchanger shown in Figure 5.27 are essentially the same as those shown for the evaporative condenser equipment shown in Figure 5.28.

The Evaporative Condenser

Figure 5.28 is a schematic of this type of equipment. In principle, it is very similar to the recirculating air unit of Figure 5.27 but with the addition of a cooling water spray over the tube bundle. This small change has advantages in that it makes the conditions more stable, which results in a much improved heat transfer. When the unit is operating at steady state, the heat is transferred to the air by evaporation, brought about by the difference between the temperature of the water and the wet bulb temperature of the air. The wet bulb temperature is not subject to the rapid changes or wide fluctuations in the same way as the dry bulb temperature, but it does increase with both humidity and dry bulb temperature. Any rainfall, although it cools the air, increases the humidity at the same time and hence does not affect the wet bulb temperature to any great extent. In fact, by increasing the humidity, the efficiency of heat transfer is improved over that obtained with a dry air recirculating unit. The effect of the improvements using water to assist the cooling makes it possible to use units that are physically smaller in size (compared to the dry air recirculating unit), obtain lower condensate temperatures, and, as a result of the size reductions, use control dampers to advantage for control purposes. Since water is used to effect the cooling, precautions must be taken to avoid the possibilities of freezing when such

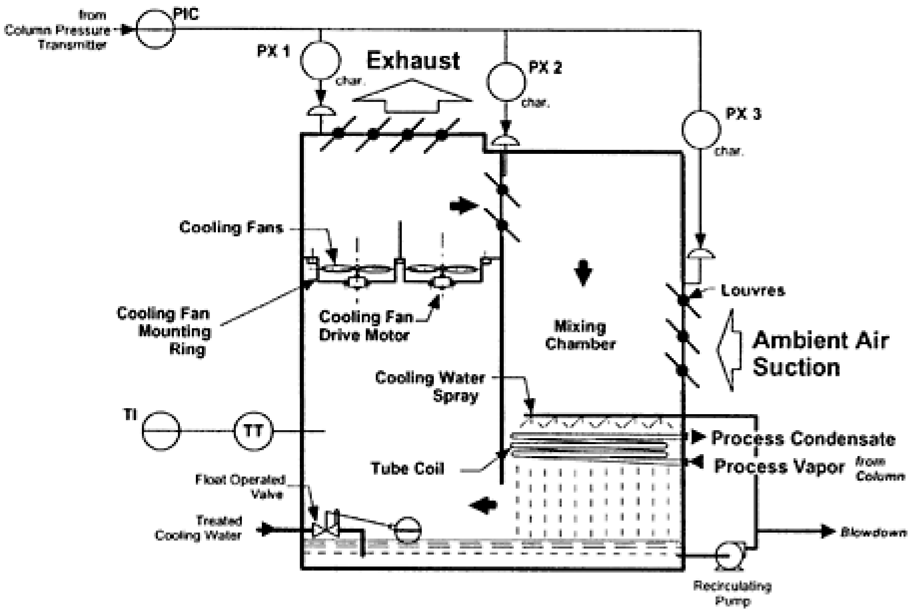


Figure 5.28: Schematic arrangement of evaporative heat exchanger.

units are installed in locations that are subject to low ambient temperatures. Low ambient temperature operation entails providing a source of heating for the water during the cold weather. With these units, the heat flow is nearly proportional to fresh airflow.

Signal characterizers have been shown in both Figures 5.27 and 5.28 in order to allow for the fact that all dampers are very nonlinear and follow curves that are roughly similar to those obtained with butterfly control valves, which operate in exactly the same way. The characterizers can be trimmed to allow the opening of dampers to match the amount of air permitted for the magnitude of the driving control signal. The relationship between the volume of air versus damper opening must be ascertained prior to installation, with details of the damper characteristic obtained from the manufacturer. From these data the configuration of the characterizers is determined, although the results must be finely adjusted on site.

Low-Pressure Columns

With some products it is necessary to operate the column at very low pressures or even vacuum and to use condensers in which the vapor is made to contact the cooling medium directly. Figure 5.29 is a schematic of such an arrangement. The distillate is sub-cooled (to a value below its condensing temperature) and recirculated through a pump and a spray condenser. Any noncondensable gases are to be removed continuously, in order to maintain the low column pressure. To allow this system to work, heat removal is required, and the column temperature is used as the measurement to a controller to regulate the amount of heat removed. The composition of the overhead product is maintained by controlling both the pressure and temperature.

In the system shown in Figure 5.29, the level controller LIC determines the amount of reflux returned to the column to maintain the level by providing the set point for the flow controller tagged FIC. Note the square root extractor provided on the

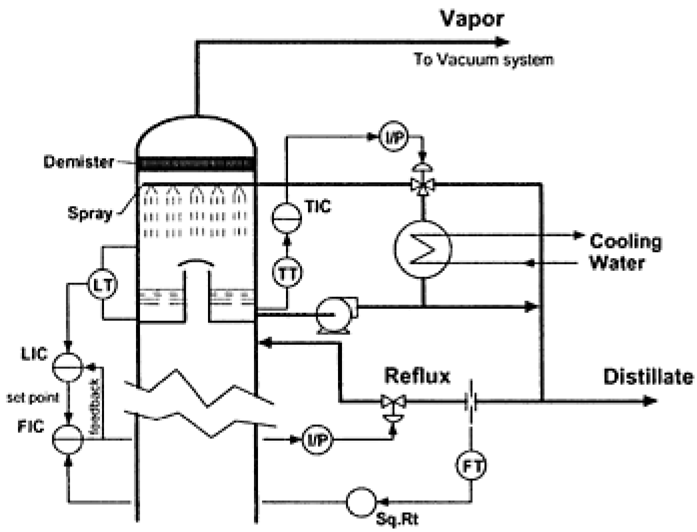


Figure 5.29: Schematic of direct contact condensing.

output of the D/P transmitter. Its purpose is to linearize the differential pressure signal, making it compatible with the linear signal produced by the level measurement. The column temperature measured by the temperature sensor transmitter tagged TT provides the input to the controller tagged TIC, which manipulates the three-way diversion valve. The vacuum system has not been shown and is best determined by the equipment actually available. This could be provided by either a vacuum pump or an arrangement of steam ejectors connected to the top of the column.

Floating Pressure Control of a Column

We have seen that the pressure in the column is an important measurement and is used in the control systems we have so far discussed. It is, however, necessary to appreciate why this is so. It is mainly because a stable temperature lies at the root of product quality, and maintaining this parameter constant is of greater significance. Because the two parameters, temperature and pressure, are intimately bound together in the context of material boiling points, maintaining one is therefore reflected in the stability of the other. Today process analyzers—chromatographs in several instances—are increasingly taking over the determination of product quality that used to be made via the parameter temperature. Process analyzers are not as influenced by the pressure in the column.

Implementing a Practical Floating Pressure Controller

In his *Distillation Control for Production and Energy Conservation,* Shinskey outlined a system for allowing a column to follow pressure variations under full control. When involved with air-cooled and water-cooled condensers, the present author has successfully implemented the method suggested and the technique is now described. Since any column will be subject to process variations and upsets, it will be necessary to provide some means of detecting these changes and at the same time smooth out any upsets whenever they occur. To do so, it will be necessary to provide a control scheme that will have fast detection and response and, at the same time, follow any

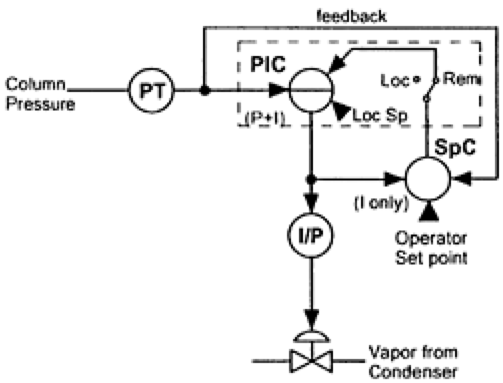


Figure 5.30: Arrangement of controllers for floating pressure control.

changes smoothly under full control without causing the process to fluctuate unduly. Figure 5.30 shows the arrangement we shall discuss.

The fast detection and response can be provided by including the usual two-term (P+I) controller (instrument or algorithm) tagged PIC for column pressure control, which is tuned to produce a controlled output to correct the process upset as soon as it is detected and providing another controller—tagged SpC (set point, or valve position controller)—that produces a much slower changing output, which is used as the demand (set point) for the column pressure. The controller (SpC) with the slower changing output has as its measurement the controlled output from the column pressure controller (PIC). Feedback is provided from the column pressure measurement (PT) to avoid saturating the integral control term. With this arrangement, the column pressure demand signal is maintained as long as there is an *error*, that is, a difference between the measurement (column pressure) and the set point determined by the operator. A single-term integral-only (I) controller (instrument or algorithm) for the controller tagged SpC produces just this type of control action, with its output changing at a rate determined by the integral time setting. The column pressure controller tagged PIC is required to accept an operator set demand to allow either the column operating pressure to be set at a specific value or by the slower changing output generated by the other controller tagged SpC-1 but not shown in Figure 5.30. This arrangement provides the classic Local/Remote set point operation for the column pressure controller. To avoid bumping the process when changing the set point from local to remote operation, the controller tagged PIC must be in the manual mode. With the combination of control characteristics described for the two controllers involved, any process upsets will be tracked and responded to directly as they occur, and at the same time they will be continuously corrected for the duration that they exist.

Since it is not wise to allow the control valve to be driven to its extreme position to avoid damage to the product, a limit must be set on the integral-only controller. The operator sets this limit by adjusting the set point of the controller tagged SpC to a definite value and thus allows the system to respond to falling column pressure only. Whether the valve is driven open or closed depends on the control requirement of flooding, bypassing, or throttling the condenser. In any event, the condenser must be fully loaded at all times.

The dotted line in Figure 5.30 encloses the components of the column pressure controller tagged PIC, with the Local/Remote set point being operator-selected via

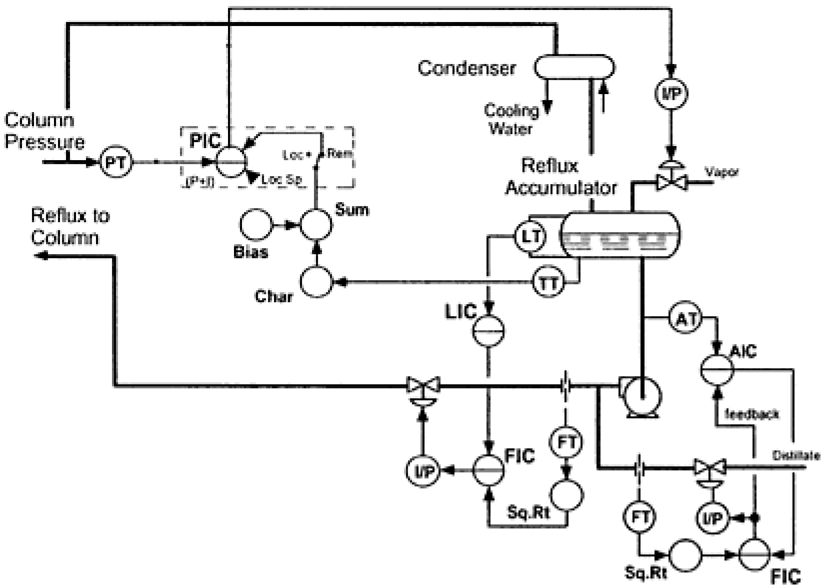


Figure 5.31: Schematic control loop for two-phase overhead product.

the switch shown. For simplicity and clarity, the Auto/Manual operation switch has not been included in the figure, although this switch will have to be located in the signal line to the control valve.

Vapor-Pressure Control System for Two-Phase Overhead Products

Figure 5.31 is the complete control loop for overhead products in both phases in the column. This figure shows that a characterizer is included to relate the temperature of the condensate to the vapor pressure in the column at the associated product composition and that a multiplier is included to provide the necessary temperature correction. The temperature and pressure curves are approximately linear over the range obtained with condensers, but although the slopes of the vapor pressure curves for various product compositions are to all intents and purposes very nearly the same, they are displaced from each other. Therefore, bias adjustment on the multiplier output is provided as a means of shifting the temperature correction curve (which in this case is produced by the characterizer/summer/bias arrangement) dependent on the product composition.

Control of Internal Reflux in a Column

Flow of the vapors upward and the liquids down, the internals of a distillation column comprise the internal reflux that constantly takes place. The boiling of the material being distilled, as we have described, brings about this flow of the two phases. Because of the column construction, however, the flow rates of these two phases within the column are unmeasurable. Nonetheless, flow-rate constancy is vital in order to obtain stable column operation. One of the means available to ensure this constancy is to ensure very stable boiling conditions (i.e., by holding the heat input to the column constant and closing the heat balance by regulating the reflux), through column pressure; or by accumulator level control if floating pressure control is implemented, as shown in Figure 5.32.

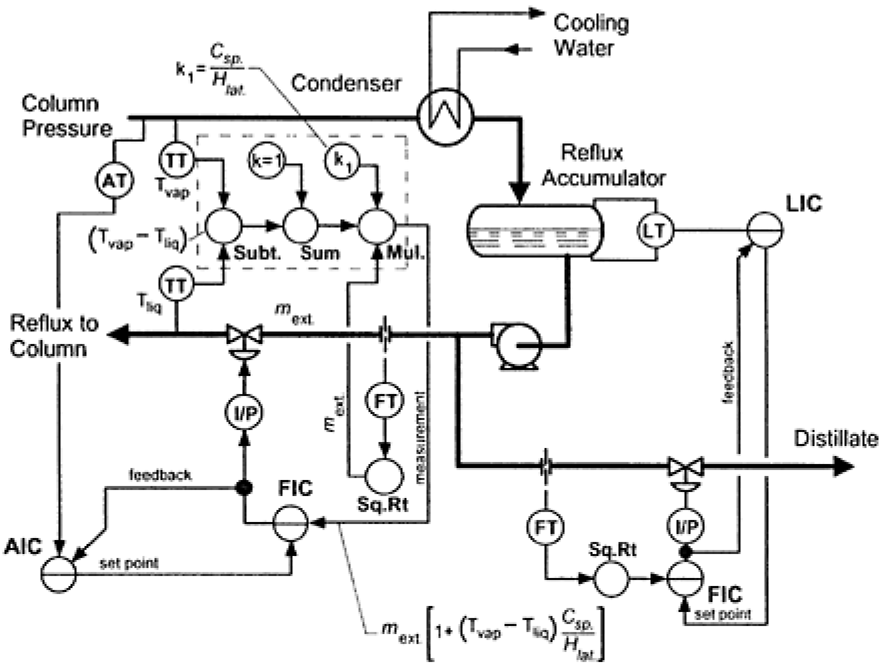


Figure 5.32: Schematic loop to control internal reflux.

Figure 5.32 is a schematic to control the internal reflux by inferring the amount flowing internally and using measurements obtained from the parameters easily accessible on the exterior of the column. The computation shown is similar to the one given in *Perry's Chemical Engineers Handbook*, where it is given as:

$$R_i = R_e\,[1. + k\ (T_{ov} - T_{re})]$$

where R_i is the internal reflux flow rate in mass units

R_e is the external reflux flow rate in mass units

k is the ratio of specific (C_p) to latent (H) heat of liquid in the top tray C_p/H

T_{ov} is the temperature of the overhead vapor

T_{re} is the temperature of the external reflux

The symbols in the figure differ slightly, where for clarity and simplicity the subscripts used have been made to represent the measurements almost directly. Although the computation of the internal reflux flow rate has been shown as being the result obtained using individual mathematical function modules, it is normally accomplished in a single calculation block when the system is implemented in a *distributed control system* (DCS). The dotted line around the computations shows the case when a DCS is used.

Without the stabilizing influence of the analyzer feedback, control would still be provided when the reflux is subcooled, but it would become unstable if the overhead vapor temperature changed to a higher value or the vapor composition changed. The instability in the case of higher overhead temperature would make the temperature difference term $(T_{ov}-T_{re})$ increase and introduce positive feedback under these conditions, thereby exacerbating the situation. The feedback from either a temperature or analyzer controller provides the necessary negative feedback to stabilize the system under these conditions.

It is unlikely that there will be any sub-cooling of the reflux if floating pressure control is implemented on the column, for in this case the system will balance out without the need for internal reflux control.

Basic Controls for a Distillation Column

Figure 5.33 illustrates the very basic controls that are required on a distillation column. As we have stated, no two columns are identical. Therefore, it is absolutely vital that each column is given individual attention. As a result, the controls to be used must be based on the outcome of the study involved. In view of what has just been said, it is not possible to determine a universal solution that is applicable to all distillation control systems. The information on individual control loops presented previously is an attempt to show the several variations that are possible; even these cannot be considered in any way to be exhaustive. It is therefore essential that the reader use this basic scheme only as an interim arrangement to further the study of

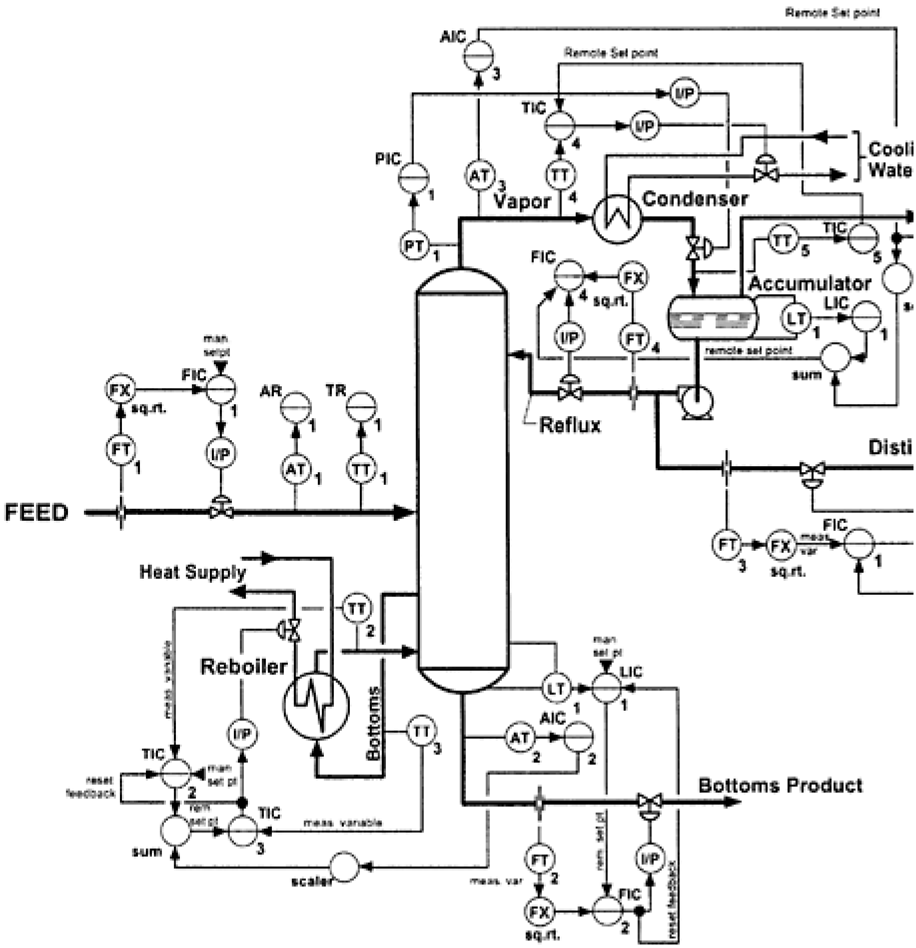


Figure 5.33: Typical basic control system for a distillation column.

the controls involved. Because our intention is to illustrate the system in very broad terms only, no attempt has been made in Figure 5.33 to show how to decouple interactive loops.

Other Methods to Control a Distillation Column

What we have seen so far are the techniques for implementing control of a distillation process using a number of individual control loops, each performing a particular function (s) and coordinating these loops into a composite whole. This concept has been the procedure for a very long time, and the results have thus far been acceptable. However, in the interest of increasing the return on investment, financially and economically, we must reconsider the situation in these terms and make our objective the attainment of consistent product quality conforming to the minimal product specification. Hence, any product of a higher specification therefore means we are not getting the profitability from the manufacturing operation. Profitability maximizes the use of raw materials, consequently resulting in products at the most economical price. For this part, we shall investigate the possibility of regulating the material flow principally within the confines of the column. This yields the surest way to give the results required, for whatever we do to regulate material flow external to the distillation column will have little or only marginal effect on the product quality. In a material balance system, the flow of a product is used to regulate the product quality, that is, its composition. The amount flowing and quality usually refer to the product being manipulated, but this may not always be the case. Before we go any further, let us see what this technique entails. Figure 5.34 describes in simple terms what happens when a feed material is distilled.

If we consider the material flows only, we can say that the sum of the distillate and bottoms product flows must equal the flow of the feed material to achieve material mass balance, or symbolically:

$$F = D + B$$

where *F* is the feed flow, *D* is the distillate flow, and *B* is the flow of bottoms product.

Let the fraction of any given component in the feed *(F)* be *z,* in the distillate *(D)* be *y,* and in the bottoms product *(B)* be *x;* if we consider the component balance, we have:

$$F_z = D_y + B_x$$

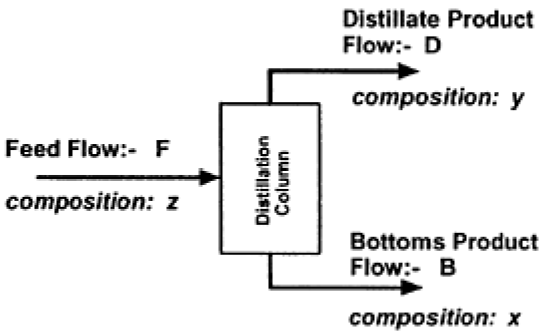


Figure 5.34: Basic split of distillation feed material.

Note: In the component balance, the composition is given in terms of the most volatile component, from which the composition of the feed is composition of the distillate minus composition of the bottoms product or

$$F = y - x$$

from which the composition of the distillate is composition of the feed minus composition of the bottoms product or

$$D = z - x$$

from which the composition of the bottoms product is composition of the distillate minus composition of the feed or

$$B = y - z$$

As observed earlier, when we change the feed flow *(F),* the change is reflected in changes of flow in both the distillate *(D)* and the bottoms product *(B).* In the same way, any change in composition of the feed *(z)* is reflected in the changes of composition in both the distillate *(y)* and the bottoms product *(x),* and results in the following relationships (when we rewrite the feed, distillate, and bottoms in terms of composition):

$$\frac{D}{F} = \frac{z - x}{y - x}$$

$$\frac{B}{F} = \frac{y - x}{y - x}$$

From this it will be seen that the composition of both the distillate and bottoms product is determined by the ratio *D/F* or *B/F*. To maintain product quality, we therefore need to maintain the ratio of *D/F* or *B/F* at any chosen desired value. How well this is done is a measure of the effectiveness of the flow controls involved and ultimately of the product quality.

The equations $F=D+B$ and $F_z=D_y+B_x$ are unable to provide a solution because basically each has two unknowns. To effect control of the distillate or bottoms product quality, our only option is to manipulate (as individual entities) the two ratios *D/F* and *B/F,* depending on the composition *z* of the feed. Treating these as partial derivatives and writing this symbolically, we have:

$$\frac{\partial\, D/F}{\partial z} = -\frac{\partial\, B/F}{\partial z} = \frac{1}{y - x}$$

The composition of either distillate or bottoms product can only lie between 0 and 1 (where 1 represents 100 percent purity). Therefore, the change in the ratios *D/F* and *B/F* must always be greater than the feed composition *z.*

Control System for Material (Mass) Balance

Figure 5.35 is a schematic diagram of a typical material balance control system for a distillation column. If we compare this illustration and the control loops shown in Figure 5.33 we will see that only minor differences separate the two arrangements. For easy comparison of the two diagrams the overall format has been kept largely the same. In Figure 5.35 we see that the analyzer controller tagged AIC-2, whose set point is determined by the process operator, determines the quality of the distillate and sets the distillate flow accordingly via the flow controller tagged FIC-4 to meet this demand. The cascade control loop LIC-2/FIC-5 formed by the accumulator level and reflux flow automatically maintains the internal flow of material within the

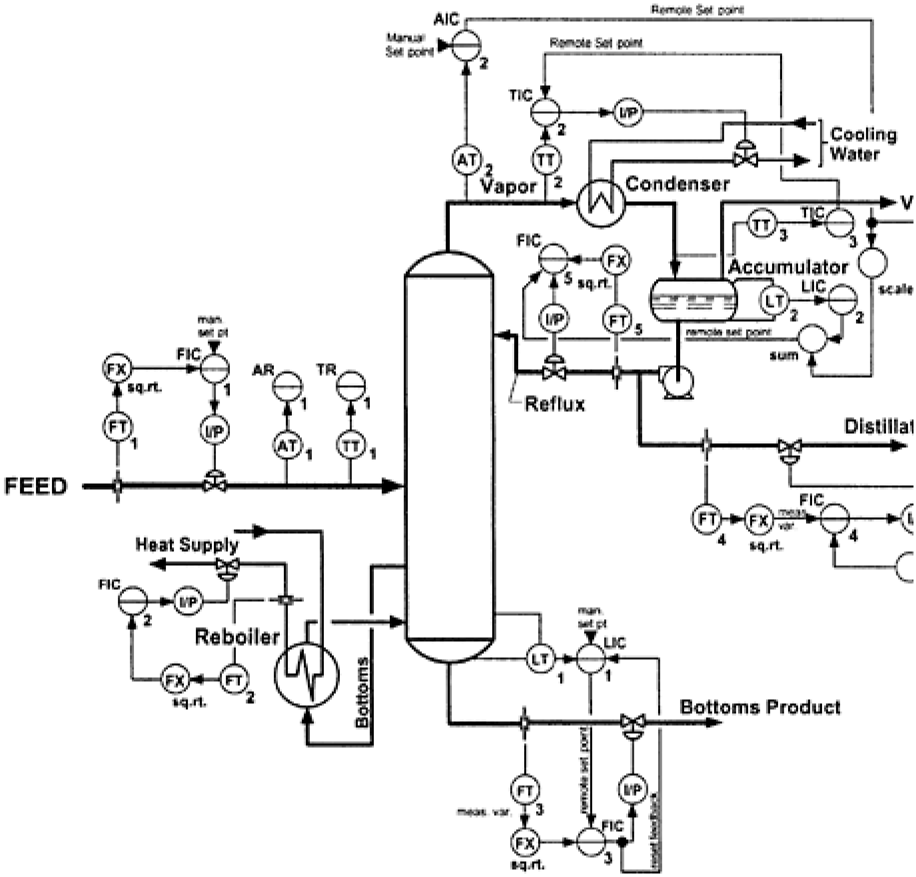


Figure 5.35: Typical material balance control system for a distillation column.

column in response to the dictates of the analyzer controller tagged AIC-2. The other advantage is that this cascade loop also has an effect on the heat supply. For any change in the amount of heat provided results in an increase in accumulator level, which will automatically be adjusted by the cascade arrangement because the reflux flow will alter to suit the new demand. In this arrangement, we see how one product flow is manipulated to achieve the quality of the final distillate product.

Controls Applied When Bottoms Product Is Less Than Distillate

In the event that the distillate flow exceeds the bottoms product flow, the system shown in Figure 5.35 should be modified to that shown in Figure 5.36. In this arrangement, we are intent on collecting as much distillate as possible, which we ensure by regulating the bottoms product quality. Hence, an analyzer in the vapor phase is not necessary. In this diagram we have shown the bottoms product quality being monitored by an analyzer/transmitter tagged AT-3 and controlled by the output from controller tagged AIC-3 cascaded as the set point of flow controller tagged FIC-3 to produce consistent quality.

In the system illustrated the distillate flow control loop F4 and accumulator level control loop L2 are arranged as a cascade loop. This arrangement provides not only

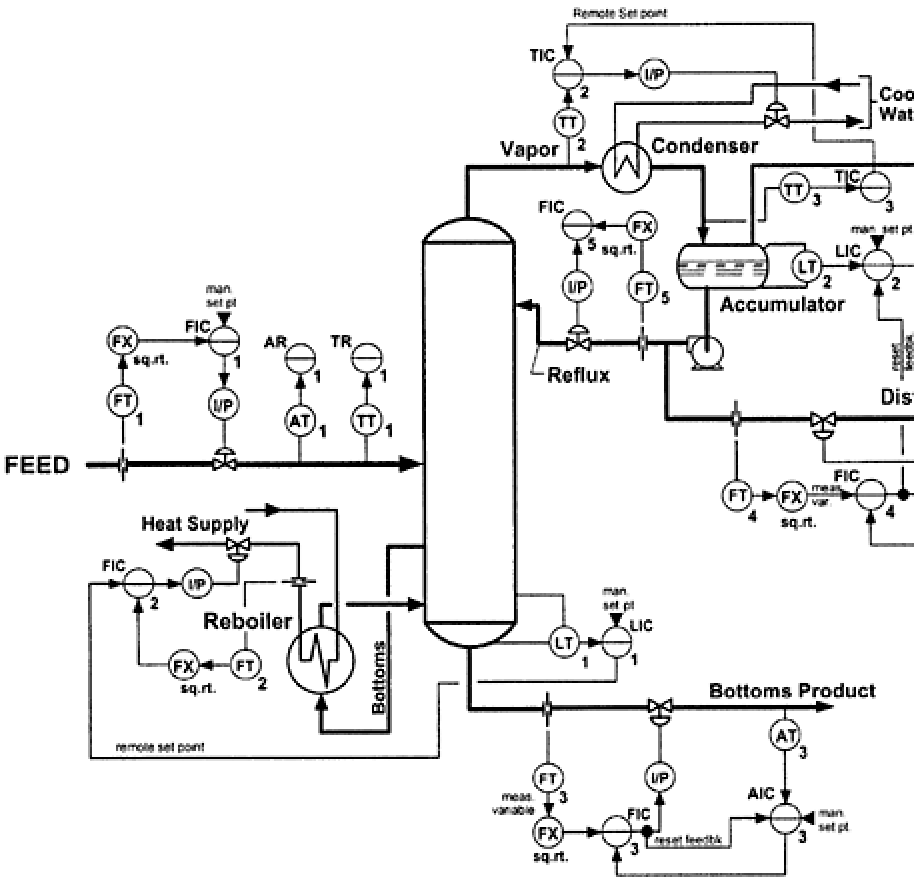


Figure 5.36: Typical material balance control system when bottoms product flow is less than distillate flow.

an automatic means of maintaining the accumulator level, but also enables the operator to adjust the flow manually in the event any difficulty arises. However, when the operator intervenes, the level controller tagged LIC-2 is always made aware of the intervention, and the feedback signal shown will prevent the integral term of the level controller LIC-2 from saturating under these conditions. The flow control loop F4 could, if desired, be replaced with a slightly less sophisticated loop in which an Auto/Manual station is provided instead. This instrument, when set to Auto, will apply the output of level controller LIC-2 directly to the distillate control valve to regulate the amount flowing in the distillate line. When set to Manual, it will allow the operator to adjust the amount passing through.

Controls Applied When Distillate Flow Regulates Bottoms Product Quality

Figure 5.37 illustrates the controls used to regulate the quality of the bottoms product by manipulating the distillate flow via flow control loop F4. This loop is a cascade arrangement, with the composition controller tagged AIC-2 providing the

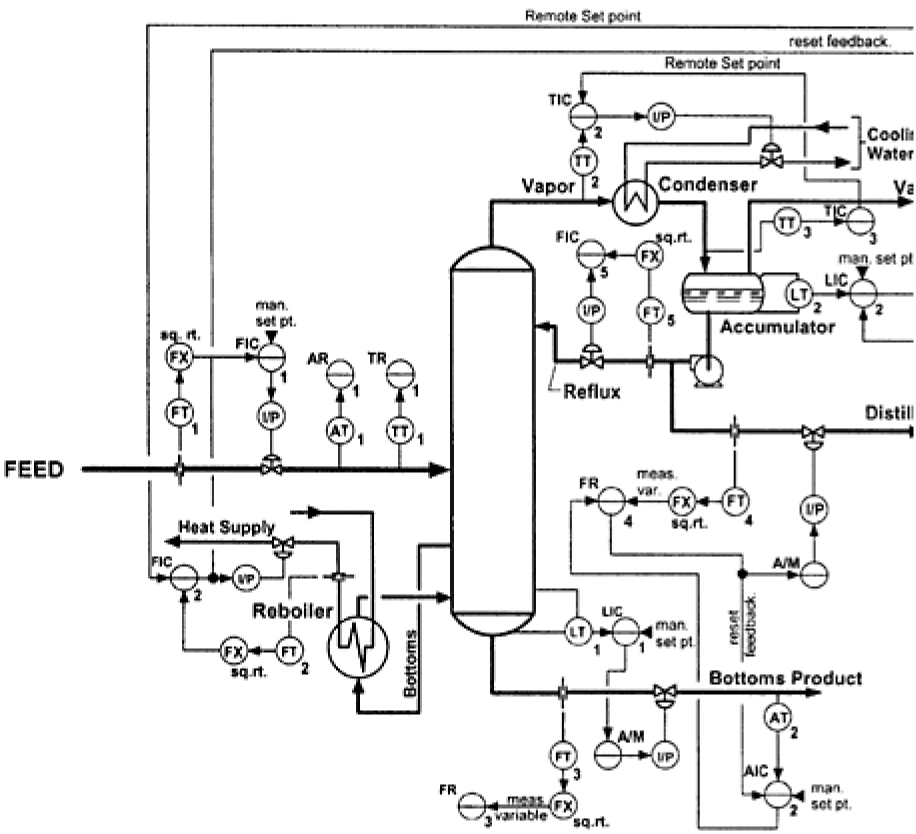


Figure 5.37: Typical material balance control system when bottoms product quality is controlled by distillate flow.

set point for the distillate flow controller tagged FIC-4. The loop behaves in much the same way as the cascade loop in Figure 5.36 where the level controller tagged LIC-2 was maintaining the accumulator level by manipulating the distillate flow controller tagged FIC-4. A modified version of this figure is also used to describe the Start-up and Shutdown procedure following this section. The main advantage of distillate flow control over reflux flow control is the fact that reflux flow control is slower to respond because of the time it takes the reflux to reach the bottom of the column. In contrast, the change in boil-up is felt throughout the column in a very short time when the distillate flow rate is altered.

When the *D/F* (distillate to feed) ratio is smaller than the *B/F* (bottoms to feed) ratio and the bottoms product composition has to be regulated to a specific desired value, the heat input has to be influenced by the level of the product in the accumulator. However, if the *B/F* ratio is much smaller than the *D/F* ratio, it is advantageous to regulate the flow of bottoms product to maintain product quality, leaving the level of the column base to be made responsive to the amount of heat added. Even under these conditions the need to control the heat input by the accumulator level is vital because controlling the flow of bottoms product does not by itself maintain product quality. The change in the amount of heat added to the reboiler is affected by its thermal capacity, and this in turn affects the response of the accumulator level. Using heat input to determine the level of the column base gives rise to other problems—typically turbulence brought about by the product boiling. This and other problems associated with it result in an unstable column base level control loop.

STARTING UP AND SHUTTING DOWN A DISTILLATION COLUMN

The demands of starting up a distillation column are a very different proposition from the demands required when the column is in continuous operation. For the purposes of this description, we will use the system shown in Figure 5.38, which as stated earlier is basically the same as Figure 5.37, with suitable modifications appropriate to these specific operational requirements. A start-up, other than the occasion after a column is installed, is carried out only infrequently, perhaps once a year after a shutdown for essential maintenance requirements. One additional reason for the infrequency of the procedures is that, while the column is being started up, the process cannot make any product(s), thereby creating serious consequences for the business. Any plant downtime is reflected in a loss of revenue and should therefore be kept to a minimum.

Let us first consider an empty column. The switch tagged Sw-1 is placed in the Start-up position; it should be noted that Sw-1 is a 5-ganged unit with changeover contacts for each switch (even though not all the changeover contacts are used). That is, a manual actuation of the operating handle will change the position of all five individual switches coupled to it. For convenience, the (five) separate switch contacts of switch Sw-1 have been drawn in appropriate positions that show most clearly their action on the control system. The Auto/Manual stations tagged A/M-1 and A/M-2 associated with the level controller tagged LIC-1 and analyzer controller tagged AIC2, respectively, are placed in manual and are adjusted to close off their connected control valves tagged LV-1 and FV-4. Sufficient material is held in the accumulator to prevent damage to the pump, which would occur if the suction head dropped too low. A low limit is applied via the level switch tagged LS-2 that is used to inhibit the pump running under these conditions. The feed is introduced into the column by placing the controller tagged FIC-1 in manual and driving valve tagged FCV-1 and observing the level in the column on the controller tagged LIC-1. A five-input low-signal selector tagged SSL-1 provides the set point of the controller tagged FIC-2 during start-up. Since the column is empty, the output signals from the pressure controller tagged PIC-1, differential pressure controller tagged dPIC-1, and level controller LIC-1 are all large because the measurements are low (although limits (not shown) must be applied to guard against excessive column differential pressure or loss of base level—feed supplied at base of the column). The output from the ramp block (module) only is initially low and will therefore be selected by the low selector SSL-1. This occurs through the ramp block, which operates as follows. A normally open switch tagged Sw-2, attached to an operator-initiated faceplate on the console tagged Ind—shows the status of Sw-2, which when actuated applies a logic 1 to both the Auto/Manual parameter “MA” and the “ramp” parameter of the ramp block. The MA parameter changes the block to automatic mode, and the ramp parameter initiates the ramp. The ramp always starts from zero, which is configured as 0.00 in the “rampin” parameter, and is operative as soon as the ramp function is invoked. The rate of rise is engineer-configurable by the parameter “uprate,” which always has a time base in minutes. The ramp signal is applied via the closed (S) contact of the Start/Run switch Sw-1 as the set point of controller FIC-2 (which had been left at a minimum value from a previous shutdown operation), and begins to apply heat to the reboiler. The ramped set point raises the temperature gradually to avoid thermal shock and to prevent leakage through the connections on the reboiler. Heat will continue to be

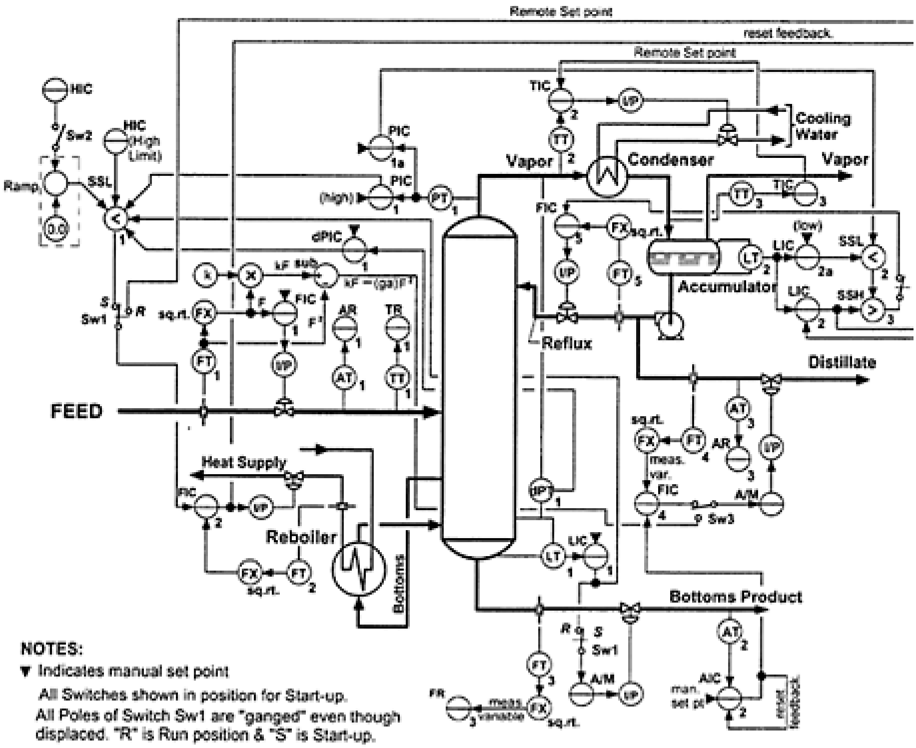


Figure 5.38: Typical start-up of material balance control system.

applied by this arrangement until one of the other inputs to the selector SSL-1 takes over the control and continues the heating. Once the feed in the base begins to boil, the pressure within the column will begin to change. The pressure rise will continue until reflux begins to flow into the reflux accumulator. In this connection, it should be noted that the accumulator and the associated condenser, though operationally appearing at the top of the column and shown as such on the figure, are in fact physically located somewhere near the base of the column, either at grade (ground level) or at the first level up. (Note that opening switch Sw-2 changes the mode from Auto to Manual to allow the next ramp to start from zero for the next start-up.)

Since the pressure in the column starts to rise, the output from the pressure controller tagged PIC-1 a will be lower than that from the level controller tagged LIC2a and will be selected by the low selector tagged SSL-2 and be compared with the signal from level controller LIC-2. The output from the high signal selector tagged SSH-2 provides the set point for reflux flow controller FIC-5, which regulates the flow back to the column. The reflux flow will control the pressure in the column. When the level in the accumulator reaches the normal level for continuous operation, level LIC-2 will take over control.

The feed is allowed to continue while heat is being applied; the feed is required because the levels in the trays have to be established and come to equilibrium within the column. Once all the levels in the trays and accumulator have been established, reflux will begin to flow; the feed is then shut off via FCV-1 being driven closed. Since there is no product (because the distillate valve FV-4 is shut, as stated earlier) or feed flowing in (because the feed through FCV-1 has been stopped), the column is in total reflux mode. Total reflux is continued for a while, to allow the column to settle. The quality of the product is indeterminate and impossible to control because it depends on the material balance. The feed is then gradually increased at the same time as increasing the distillate or bottoms flow (all under manual control). In this case the distillate flow is increased, with the operator making the adjustments while the feed controller is in manual mode. The switch tagged Sw-3 is then initiated, which allows the feed flow (signal from the FC1 complex) to influence the distillate flow and regulate it via FCV-4. This feedforward loop permits the operator to set the final product quality. The first products will in most cases not be suitable and will have to be diverted to the feed-holding tanks and be reprocessed. The feedforward model is based on the Shinskey parabolic form given in his *Distillation Control for Productivity and Energy Conservation,* where it is given as:

$$D^* = mF - bF^2$$

In the equation shown in Figure 5.38 the gain of the subtractor module shown as (ga) replaces the coefficient b and the constant shown as k replaces m in the Shinskey model.

When satisfied that the column is operating satisfactorily, the switches are changed for continuous operation.

Shutting down the column is the reverse of starting up. The feed is reduced until the column is in total reflux mode, care being taken to ensure that the product does not go off-specification. The heat input can then be reduced, which will be followed by a reduction in reflux flow until the amount passing is so very small that it can be considered to be weeping. When this occurs, the level in the base of the column will begin to rise due to the lighter components from the top of the column condensing and falling downward to the base. The material in the base must be diverted back to the feed storage tanks for reprocessing, while the product in the accumulator, which is not affected, can be transferred to the product tanks.

Conditions for Normal Running

Switch Sw-1 being in the R run position provides the conditions for normal running. Switch Sw-2 is left open to put the ramp block into the manual mode, set the ramp parameter to off, and the rampin parameter to 0.0. Switch Sw-3 is set to permit the output of controller FIC-4, as directed by the set point from AIC-2 to manipulate control valve FCV-4 via the A/M station, which is set to Auto. Pressure controller PIC-1, level controller LIC-2a, and differential pressure controller dPIC-1 are set to manual mode.

SUMMARY

1. Distillation is essentially a separation process achieved by deliberately creating two or

more coexisting zones that differ in temperature, pressure, composition, and phase or state and using the conditions to extract the different products from both coal and crude oil.

2. The industrial distillation column uses the principle of the laboratory distillation, but does not replicate it exactly. The equipment is designed to produce the distilled products as separate entities and can be visualized simply as a number of trays or plates that are in communication with each other and stacked vertically one above the other; vapor and liquid fill the intervening spaces between each of the trays. The transfer of heat to the metal enclosure, and hence to the surrounding atmosphere, cools the vapors; this process makes industrial distillation a little dependent on prevailing weather conditions.
3. The vapor and liquid at each level within the column are at the same temperature and pressure, but because each different component as a specific entity must be drawn off, suitable offtake connections are provided at specific points along the length of the column. The position of the offtakes is calculated and forms part of the design of the distillation column.
4. Separation of the liquid and vapor occurs at/on the trays involved. A tray is basically a large flat plate with a large number of holes punched in it. In the early designs, so-called *bubble caps* were fitted to each hole. This design has since been modified so that at the present time the plate contains either a large number of plain, simple holes or a large number of holes that have a simple valve arrangement.
5. Hydrocarbon molecules are made up of carbon and hydrogen atoms. How these combine with one another can best be visualized as the carbon atom having four points of attachment by which it is capable of being bonded to another atom (i.e., it is *quadrivalent*). The hydrogen atom, on the other hand, has only a single point of attachment (i.e., it is *monovalent*).
6. Molecules with up to 4 carbon atoms are gases at normal temperatures and pressures; molecules having 5 to 19 carbon atoms are usually liquids; and molecules having 19 and over carbon atoms are products that are solids or semi-solids. Arrangements of the atoms that give rise to molecules whose names end with an *"ane"* are a series of paraffins. The name "paraffin" as used in the United Kingdom for a heating fuel is incorrect; the actual name for this fuel is *kerosine,* which is the name by which it is known in the industry and commonly used elsewhere in the world.
7. Names such as butane and octane are preceded by the letter n; this is an abbreviation for the word "normal" and refers to the continuous-chain arrangement of the molecules. If we take a particular paraffin, say butane, and crack it further in the presence of a catalyst, we can obtain an isomer of the paraffin that was used. The arrangement of the carbon atoms has altered because they are branched, but the number of carbon and hydrogen atoms involved has not changed. There are still 4 carbon and 10 hydrogen atoms. This gives us a definition of an isomer, which states that the compound formed has the same percentage composition and molecular weight as that compound from which it was formed, but differs in chemical and physical properties.
8. When a change takes place in the linking arrangement only in a compound, the isomer is called a *structural isomer* (e.g., iso-butane or, to give it its chemical name, 2-

methylpropane).

9. The double bond of carbon atoms indicates that the compound is unstable relative to the saturated hydrocarbons and can therefore easily react, that is, be capable of picking up another atom. In general, *double* or *triple bonds* signify the reactivity of the compound. However, this is not a hard and fast rule. Some compounds with double bonds are reasonably stable; such compounds are usually formed from what is called the *benzene ring*.
10. Louis Pasteur discovered another kind of isomer called a *stereoisomer* a long time after the structural isomer was known. *Stereoisomerism* is the difference in the spatial arrangement of the atoms or groups of atoms to one another within molecules that have the same structural formula. This occurrence is explained by the limitations on the movement of the atoms brought about by several factors and is of importance when we consider polymerization.
11. Although many variants of the cracking process are available, it can take two main forms. The first is *thermal cracking* in which the variables that bring about the changes are temperature, pressure, and time; the second is *catalytic cracking* in which temperature plays the same important role but the pressure required is not as high as in thermal cracking. However, it does require a catalyst (i.e., a substance that assists in the cracking process), although it does not itself get used up while doing so. Catalysts do need to be regenerated to perform at their best.
12. Modern catalysts take the form of a very fine powder, usually produced from a mixture of aluminum oxide and silica that is spray dried and that then results in a very large number of extremely small spheres. The object of these small spheres is to present an enormously large surface area on which the reaction can take place.
13. The important difference between the two methods of cracking is the fact that the thermal process can be employed for any heavy oil, be it distillate or residue, but the catalytic process can only be used on a distillate. The main advantage of the catalytic process is its ability to produce more *iso-paraffins* and *aromatics*.
14. Not all catalysts used are solids; hydrogen was used in the past, and the process that makes use of it is called *hydrocracking*. The original process became very uneconomic to run and was rejected. However, since the early 1930s the hydrogen process has been reassessed and revised, and the updated technology is now used to produce high-grade gasoline, to change light oils into gases, or to change heavier oils into aviation jet fuel and diesel oils.
15. The gasolines we use are subjected to a process called *reforming;* this cracking process improves the *anti-knock* properties of the fuel. In some processes, platinum is used as the catalyst, and the process equipment used is then called a *platformer*—combining the words platinum and reformer.
16. The knocking phenomenon is brought about by carbon deposits on the valve gear in the cylinder of an internal combustion engine. These deposits are left glowing by the ignition of the fuel of the previous ignition cycle that causes the fuel/air mixture of the present cycle to ignite at a time in the combustion cycle that is earlier than is actually required. The source of the carbon deposits is mainly the fuel itself.
17. Another method of eliminating engine knocking is to use a process called *alkylation*. This is really the reverse of cracking in which two dissimilar light hydrocarbons, again

in the presence of a catalyst, are made to combine to produce a high-grade anti-knock gasoline.

18. The transfer of energy and mass is extremely complicated and cannot easily be modeled mathematically. Instead a technique called the *equilibrium stage model* is used; with this concept, each stage of the series of individual equilibrium stages is considered to be operating at a particular pressure. Hence, the vapor and liquid streams leaving one stage for another are in complete equilibrium with each other. Thermodynamic principles are then applied to relate the equilibrium state to the temperature and concentration of the component involved.
19. As the separation process advances, zones of different pressure, temperature, and composition are created; these zones coexist with each other. *Dalton's Law of Partial Pressures* states that in a mixture of gaseous substances the total pressure exerted by the mixture, provided no interaction takes place between the components, is the sum of the partial pressures exerted by each individual component, or symbolically:

$$P_{total} = \sum_{1}^{n} p_{individual}$$

where p is pressure and n the number of components of the gas.

20. Each molecular species in the mixture to be separated reacts in a unique way to the conditions prevailing in each zone. As the system moves toward equilibrium, each species establishes a different concentration in each zone and in this way brings about a separation of the components in the mixture. In an ideal mixture, the partial pressure exerted by a species within the mixture is proportional to its concentration.
21. A two-component liquid/liquid mixture in which one liquid is completely dissolved in another is called a homogeneous solution. Since only two liquids are involved, the solution is termed a *binary solution*. The saturated vapor pressure exerted by the solution is dependent on the composition of the mixture and the vapor pressure of each component. If A and B are the components of a mixture, one way of expressing the composition is to state the mole fraction of each component. Hence, for component A:

$$Mole\ fraction\ of\ A = \frac{Number\ of\ moles\ of\ A}{Total\ number\ of\ moles\ in\ the\ mixture}$$

22. A *mole*—derived from the German word *Moleculargewicht* meaning molecular weight—is defined as the basic amount of substance that contains the same number of entities (atoms, ions, molecules, photons, etc.) as there are atoms in 0.012 kg of the isotope of carbon with a mass number 12. If the symbol x is used to define the mole fraction of the liquid phase, n indicates the number of moles, and the subscripts define each of the components, then for the component A, the equation can be written as:

$$x_A = \frac{n_A}{n_A + n_B}$$

The same method can be applied to determine the mole fraction of the component *B*.

23. In the mixture *AB*, the vapor above the liquid will contain both *A* and *B*. *Raults Law* states that the saturated vapor pressure of each component in a mixture is equal to the product of the mole fraction of the component and the saturated vapor pressure of that pure component, or symbolically:

    $p_A = x_A p_A^0$ for component A

    and

    $p_B = x_B p_B^0$ for component B

    where *p* is the saturated vapor pressure of components in the mixture; p^0 is the vapor pressure of the pure component; *x* is the mole fraction; and the subscripts define each of the components.

24. The vapors above the mixture of liquid *AB* do not have the same composition of the liquid. Hence, if y_A and y_B are the mole fractions of *A* and *B* in the vapor phase, then:

$$\frac{y_A}{y_B} = \frac{p_A}{p_B} = \frac{x_A p_A^0}{x_B p_B^0}$$

25. In a binary mixture, the pressure and temperature determine the composition of the liquid and vapor; this experimental data for the mole fraction *y* of the vapor and the mole fraction *x* of the liquid is available in the form of tables either for a range of pressure for a fixed temperature or a fixed pressure of 1 atm (1.013 bar, 101.3 kPa) over a range of temperatures. However, because of the difficulty and/or the impossibility of obtaining equilibrium data for multicomponent feedstock the calculations are based on a *vapor-liquid equilibrium vaporization ratio* or a *K* value. This value for one of the components is defined as:

$$K_A = \frac{\textit{mole fraction of A in the vap. phase}}{\textit{mole fraction of A in the liq. phase}} = \frac{y_A}{x_A}$$

    where the subscript *A* indicates one of the components of the mixture.

26. Most binary systems consist of components in which only one of the two is more volatile than the other over the entire composition range. However, in some binary mixtures one of the components may be more volatile than the other over only, say, the upper part of the composition range, and the other component may be more volatile over the lower part. At the point of changeover the composition of the vapor and liquid is the same. Such mixtures are called *azeotropic (constant boiling) mixtures*. The deviations from the ideal can be either positive or negative.

    The ratio of the *K* value of each of the two species is called the *relative volatility,* shown symbolically as:

$$K_{AF} = \frac{K_A}{K_F}$$

    where the subscripts *A* and *F* indicate the two species, of which say *A* is more volatile than *F*.

27. A distillation column operated in total reflux mode has sufficient material charged to completely fill the reboiler, trays, and overhead condenser to their working levels, with no further feed being provided. In this mode, no product (distillate) will be available because the entire vapor from the top will be returned as liquid condensate (reflux) via the condenser. The product from the bottom is returned as the feed to the column. It is therefore entirely possible for a column operating in total reflux to reach equilibrium, in which case there is no net movement of product up or down the column.
28. A column operating in the total reflux mode will give the minimum number of trays necessary to effect a specified separation between x_B and x_D of a material x that is to be separated. The subscripts *B* and *D* denote the bottoms and distillate products, respectively. In this arrangement we can say:

$$L_{n+1} = V_n \text{ and } D = 0$$

where *L* is the liquid phase, *V* is the vapor phase, *D* is the distillate, and *n* is the number of trays.

The reboiler is equivalent to a tray; hence we have n+1 as the total number of trays involved. Under the total reflux condition, the liquid to vapor ratio *(L/V)* is unity at any point in the column.

29. The *minimum reflux ratio* is that ratio which, if reduced by an infinitesimally small amount, will require an infinite number of trays to effect a specified separation. However, the minimum reflux ratio has meaning only when separation between two components is specified and the number of trays is not.
30. The *optimum reflux ratio* is that ratio which has the least effect on the fixed and operating costs of the column. The minimum generally occurs at an operating ratio of between 1.1 and 1.5 times the minimum, with the lower value corresponding to a relative volatility near 1.
31. The *Kremser* method is the classical but approximate way to determine the number of equilibrium stages for a countercurrent cascade of simple absorbers and strippers. In *Perry's Chemical Engineers Handbook* this is given as:

$$(v_i)_N = (v_i)_0 (\Phi_i)_A + (l_i)_A + (l_i)_{N+1} [1 - (\Phi_i)_S]$$

where $(\Phi_i)_A = \frac{(A_i)_e - 1}{(A_i)_e^{N+1} - 1}$ is the fraction of component *i* in the entering vapor not absorbed.

$(\Phi_i)_S = \frac{(S_i)_e - 1}{(S_i)_e^{N+1} - 1}$ is the fraction of component *i* in the entering liquid not stripped.

$(A_i)_e = (\frac{L}{K_i V})_e$ is the effective or average absorption for component *i*.

and $(S_i)_e = \frac{1}{(A_i)_e}$ is the effective or average stripping factor for component *i*.

32. The *Smith-Brinkley* (SB) method developed from the Kremser and can be applied to distillation, absorption, and extraction processes. *Perry's Chemical Engineers Handbook* shows this equation applicable to a distillation column as:

$$f = \frac{\left(1 + S_n^{N-M}\right) + R\left(1 - S_n\right)}{\left(1 + S_n^{N-M}\right) + R\left(1 - S_n\right) + hS_n^{N-M}\left(1 - S_m^{M+1}\right)}$$

where *R* is the external reflux ratio $\frac{L_{N+1}}{D}$

$f = (\frac{Bx_B}{Fx_F})_i$ is the fraction of *i* leaving in the bottoms product

S is the stripping factor for component *i* and is defined for each group of stages in the column as: $S_{n,i} = \frac{K_i V}{L}$ and $S_{m,i} = \frac{K_i' V'}{L'}$ in which *K*, *V*, and *L* are effective values at the top column section and *K'*, *V'*, and *L'* are effective values at the sections below the feed stage.

33. The *Fenske-Underwood-Gilliland* (FUG) method is used to calculate the number of plates N_m needed to make a specified separation at total reflux, which is actually the minimum value of *N*. The Fenske total-reflux equations, which are rigorous relationships in the splits obtained for components *i* and *r*, are given in *Perry's Chemical Engineers Handbook* as:

$$\text{Either } \frac{x_i}{x_r} = (\alpha)^{N_m}\left(\frac{x_i}{x_r}\right)_B \quad \text{or} \quad N_m = \frac{\log\left[\left(\frac{Dx_D}{Bx_B}\right)_i\left(\frac{Bx_B}{Dx_D}\right)_r\right]}{\log \alpha_i}$$

where *i* is any component and *r* is an arbitary selected reference component in the definition of relative volatilities and $\alpha_i = \frac{K_i}{K_r} = \frac{y_i x_r}{y_r x_i}$

The correct value of α_i, must always be estimated, however, and it is usually from:

$$\text{Either } \alpha = (\alpha_{top}\,\alpha_{bottom})^{1/2} \quad \text{or} \quad \alpha = (\alpha_{top}\,\alpha_{middle}\,\alpha_{bottom})^{1/3}$$

34. The Underwood minimum-reflux equations are those that apply when some components do not appear in either the reflux or bottoms product at minimum reflux. These are given in *Perry's Chemical Engineers Handbook* as:

$$\sum_i \frac{\alpha_i (x_{i,D})_m}{\alpha_i - \theta} = R_m + 1 \quad \text{and} \quad \sum_i \frac{\alpha_i x_{i,F}}{\alpha_i - \theta} = 1 - q$$

where $\alpha_i = \frac{K_i}{K_r} = \frac{y_i x_r}{y_r x_i}$ R_m is the minimum-reflux ratio $(\frac{L_{N+1}}{D})_{min}$ q is the thermal condition of the feed 1.0 for bubble-point feed, and 0.0 for saturated-vapor feed. x_{iF} are values available from the given feed composition.

θ is the common root for the top section and the bottom section developed by Underwood for a column at minimum reflux and separate zones of constant composition in each section. The common root must fall between α_{hk} and α_{lk} where subscripts *hk* and *lk* stand for high and low key, respectively. The key components are those the designer wants to separate.

The α_i values are effective values obtained from either $\alpha=(\alpha_{top}\alpha_{bottom})1/2$ *or* $\alpha= (\alpha_{top}\alpha_{middle}\ \alpha_{bottom})^{1/3}$.

35. Gilliland produced a graphical correlation between the Fenske and Underwood equations that relates actual column performance to total and minimum-reflux conditions for a specified separation between two key components.
36. The SB and FUG methods work best when the feed mixtures are nearly ideal, with the FUG method being more convenient for the study of new columns and the SB method for existing ones.
37. The flash drum is a single-stage, continuous, adiabatic distillation process and is used when:

a. Two components have a large separation between their relative volatilities.
b. Only a partial separation between the two is required.
c. The recovery of only one component is required regardless of any other component in one of the two product streams.

A feed heater and a valve are usually in the feed line to establish the temperature and pressure of the flash. In operation, the temperature and the pressure drop across the valve are adjusted to vaporize the feed to the required amount, with the drum providing the space to allow the vapor to disengage and separate out. The feed expands at constant enthalpy across the valve, thus allowing the inlet or outlet feed temperatures to be calculated. The temperature at which the vapor to feed ratio V/F=0.0 and the first vapor bubble forms is the bubble point, whereas the temperature at which V/F=1.0 and the first droplet of liquid forms is the dew point. For a given feed composition, pressure, and temperature, the temperature range that encompasses the bubble and dew point is the range of the equilibrium flash.

38. When a mixture having two components of adjacent volatilities is to be separated and only one component is to be recovered, then absorption or stripping in a single column may be sufficient. If the feed is a vapor at separation conditions, then a *mass separating agent* (MSA) of relatively low volatility and an *absorption column* can be used. This column makes the recovery and recycling of the absorbent easier.
39. A *rectification column* is used as an alternative to an absorption or stripping column in situations when partially condensing the overhead vapor and using the reflux produced make it easier to obtain the required product. The choice of which method and column to use is either between the ease of partial condensation of the overhead or the recovery and recycling of the absorbent.
40. The main function of a simple stripping column is to achieve a reduction in the

content of the volatile component in a liquid product. When the feed is a liquid at separating conditions, the choice lies between using either an externally supplied relatively high-volatility vapor stripping agent or the boil-up produced in a partial reboiler. The type of column to use is determined by the ease of recovering and recycling the stripping agent or the ease of reboiling the bottoms product.

41. When two components of relatively close volatility are to be separated reasonably sharply but one requires either a high temperature to produce a boil-up or a low temperature to produce reflux at the column operating pressure, then the reboiled absorption column or the refluxed stripping column may be used. The choice of the MSA in both cases depends on whether the feed is a vapor or a liquid.
42. Simple distillation techniques are not suitable for azeotropes, for only one component will be removed, the other(s) remaining will be the azeotrope. In every instance for separating such a mixture, a column dedicated to each component of the azeotropic mixture will be required; hence, for a binary mixture two columns will be necessary. The azeotropic column can be used as an alternate to the extractive column. The MSA, when used, forms a heterogeneous minimum-boiling azeotrope with one or more of the components in the feed. The azeotrope is taken overhead, and the MSA-rich phase is decanted and returned as reflux to the top of the column.
43. The extractive distillation column is used when the difference in volatility between two components is so small that a large number of stages are required to effect the separation. This method of distillation is suitable for homogeneous azeotropes, which are difficult to separate by any other means. The choice of MSA, which is usually a compound of low volatility, is made on the basis of its ability to increase the difference in volatility by an amount that reduces the number of stages to an acceptable value. The MSA is introduced in quite large quantities at the top of the column from where it affects almost all the stages in the column. To minimize the MSA content in the distillate, some reflux is used in the top stage. The bottoms product contains the MSA, from which it is recovered and recycled.
44. Distillation is a process in which energy is applied to achieve the desired results. It follows that this energy input has to be regulated throughout its application in the process. That is, both the supply and outflow from the process have to be considered. In every case we must provide the means to get results at the least cost in terms of both fuel used and finance in running the process.
45. Several heating mediums are used (e.g., steam, salt, or oil). One well-known oil-based product is Dowtherm, which is made to flow continuously and is supplied to the various users through a number of parallel loops around the plant. The Dowtherm temperature is raised via a directly fired vaporizing heater. This heater is specialized equipment having an arrangement of heating tubes similar to those shown on steam generators. The vaporizing heater is situated at some central location. When Dowtherm is used, the fluid is in vapor form at a typical value of 600° F on the supply side to the reboilers. Pumps capable of handling fluids at high temperature force the cooler returning Dowtherm, which is now a liquid, back to the directly fired vaporizing heater where its temperature is raised once more and the cycle is repeated.
46. When steam-heated reboilers are used on distillation columns, the arrangements include a steam flow control loop. The control valve can then be placed either in the

steam or condensate line. Steam pressure compensation is always recommended in these cases. The two possible locations for the control valve are either in the steam supply line, or in the steam condensate line.

47. When the control valve is placed in the steam supply line, it is important that a *steam trap* be included to drain the condensate but retain the steam; a valve positioner is not required. A positioner is not fitted to the control valve located in the steam supply line because it would destabilize the control loop, inasmuch as the flow will respond immediately to the controlled output and precede the heat transfer. On the other hand, changes in condensate have no direct effect on the steam flow but only on the heat transfer, which has a much slower response.
48. The valve located in the condensate line does not need a steam trap and can be considerably smaller in size—approximately one-third—and therefore is of lower cost. The valve should be fitted with a positioner, for the loop behaves more like a level than a flow control loop, and a positioner assists in stabilizing it. In addition, because the steam reaches the reboiler at a higher pressure than that obtained with the valve in the steam line, the heat-transfer rate is also higher.
49. A *kettle reboiler* is normally connected to the bottom of a column from where it receives the liquid bottoms product. Normally, there is not a large amount of liquid held at the bottom of a column, and reboiling what remains allows the lighter components to be extracted. The design ensures that no liquid is discharged along with the vapor. The unit is usually mounted externally to the column, but the heating element can sometimes be fitted directly into the base of the column to accomplish the same function of vaporizing the liquid. In the external design reboiler, the liquid collects in the section formed by the weir from where it is pumped away as final bottoms product. The weir is intended to prevent the heating tubes from being uncovered and becoming damaged in the event of a failure of the level controller. When a loss of column pressure occurs, rapid changes in boil-up result in the liquid vaporizing faster than it is returned thus allowing the tubes to become uncovered. Suitable precautions should therefore be taken to minimize these occurrences. Since liquid covers the tubes, this type of reboiler is referred to as an *immersed type*.
50. Feed preheaters are valuable in recovering the lower heat level that the reboiler is unable to handle and they are also suitable in balancing the vapor load of the column. Product quality is affected by variations in material flow through the column, which in turn is dependent on the feed enthalpy. Hence, the total heat of the feed should be regulated to meet the demand. This objective is achieved using a three-way valve, although it is a “diverting or proportioning” and not a controlling device. In this application, however, advantage is taken of its characteristic of minimal pressure loss without affecting the flow through the valve. Alternately, two-way valves can be used instead of the three-way valve, but there are the penalties of greater pressure loss across the valves and the inevitability of some flow passing through the device at all times. When columns are subject to variable pressure, the temperature of the feed must be compensated for these variations.
51. One way of ensuring that the feed is provided at the most favorable conditions for the column is to use the differential pressure across the column as the mechanism. Because a distillation column could typically be 30 meters (100 ft approximately) or taller, it

poses considerable problems in making the appropriate process connections. Orifice plates can be fitted between the top of the column and the condenser to provide a solution, but these plates are expensive because of the size and location of the device. Since the column internals comprise a series of horizontal trays that are in communication with each other, they behave under normal operation similar to the bore of the orifice plate following the Bernoulli relationship $F = \sqrt{2gh}$ and can be used instead. The wide separation between process connections for the measurement is overcome because in most instances the condenser and reflux vessel are usually located at the base of the column—usually at grade or first level. The major obstacle is the presence of a vapor within the column. Because of the piping arrangement, this will condense in the process lines where it will affect the accuracy of the measurement. This problem must be addressed.

52. Controlling the amount of heat removed from a system is a much more difficult proposition than adding heat to it. Heat dispersal to different places occurs involuntarily and simultaneously, and it is difficult or even impossible, to regulate the amount taken up by each cooling agency involved. Basically, two types of equipment are involved in regulating heat outflow: the air and water-cooled condensers. In some instances, too, refrigerants are used, and these use liquids other than CFCs as the cooling medium. In view of the emphasis on environmental protection, water-cooled equipment is not used extensively these days. But in some situations (e.g., vacuum distillation), water-cooling is imperative since the very low pressure-loss of a direct contact condenser maintains the low system pressure.
53. Air-cooled condensers in petroleum refineries have a design specification that is usually determined by the American Petroleum Institute (API). A fan on the suction side is usually referred to as the *forced draft fan;* another located on the exhaust is called the *induced draft fan*. These names are identical to those used on the furnace side of steam generators. Sometimes more than one fan may be involved; the process itself determines the actual number required. In air-cooled condensers, louvers are not often used because of the physical size involved. Trimming the fan blades to regulate the airflow across them has been attempted, but the results have not been satisfactory thanks to the mechanical problems associated with the trimming devices.
54. With multiple fan units, the airflow can sometimes be varied by selecting the number operating at any given time. Fan controls are implemented to regulate the temperature of the reflux; they are never used to control the pressure of the column or the level in the accumulator drum. Under normal conditions without any control being applied, the temperature of the condensate will vary with the heat load and as a result will affect the pressure within the column. One of the easiest ways to regulate the temperature is to flood the cooling tubes, but this method has associated problems too. Since the tubes are of large bore, they contain a considerable amount of condensate, and because of the volume involved they have the effect of reducing the system response.
55. A fan establishes and maintains a pressure difference between the suction and discharge sides of the device and thus permits a volume of gas to flow through the equipment connected to it. There is resistance to the gas flow brought about by several unavoidable circumstances—eddies generated by the construction of the ducting and obstructions caused by having to insert equipment such as heaters and coolers in the

flow path. It follows, therefore, that the pressure difference generated by the fan must be sufficient to overcome the resistance of the system as a whole.

56. Air is rarely, if ever, uniformly distributed across a section of ductwork. To evaluate the average velocity within the duct, it is necessary to compute the average static and total pressures and to relate these to the average gas velocity. Two methods of computation are available:

1. Take the square root of each velocity pressure reading and determine the arithmetic average and square this value to give the average velocity. Note that this is the root mean square (rms) value.
2. Convert each velocity head to a corresponding velocity and then determine the arithmetic average of the velocities to give the average velocity.

57. To determine gas velocity from velocity pressure in imperial units

$$\upsilon = 1096.2\sqrt{\frac{p_{vel}}{\rho}}$$

where υ is the gas velocity in feet per minute (ft/min)

p_{vel} is the velocity pressure in inches water gauge (in wg)

ρ is the gas density in pounds per cubic foot (lb/ft^3)

58. To determine the velocity of gases other than air in imperial units:

If the gas was air at 60°F at a pressure of 30.0 in Hg, the velocity corresponding to a 1.0 in. wg pressure is 3970 feet per minute. From this we can say for any gas at any other condition than that given, the velocity can be determined from:

$$\upsilon = 3970\sqrt{p_{vel}\,\frac{460 + T_{act}}{460 + 60}\,\frac{30}{p_{bar}}}$$

where υ is the gas velocity in feet per minute (ft/min)

p_{vel} is the velocity pressure in inches water gauge (in wg)

T_{act} is the actual temperature of the gas in °F

P_{bar} is the barometric pressure in inches mercury (in Hg)

59. To determine the horsepower of a fan in imperial units:

If a fan in a duct handles a volume V ft^3 per minute of air against a pressure measured in inches Hg, we can consider the ducting configuration to be represented by and equivalent to a frictionless cylinder of 1.0 ft^2 cross section with a frictionless piston of 5.2 P_{bar} lbs wt. Then the work done per minute will be given by:

$$V\,5.2\,p_{bar} \qquad \text{ft lb}$$

From which the horsepower will be:

$$\frac{V5.2\ p_{bar}}{33{,}000}$$

If η were the percentage efficiency of the fan, then the power would be given by:

$$B.H.P = \frac{5.2V\ p_{bar}\ 100}{33{,}000\ \eta}$$

where V is the gas volume in ft^3 per minute

p_{bar} is the pressure in in Hg

60. There are two important rules that determine the performance of any fan; these rules are used to make any adjustments required when the equipment is commissioned.

1. For a given speed and a given constant volume of gas, the static pressure, total pressure, velocity pressure, and the power are directly proportional to the density of the gas involved.
2. For a constant external resistance:

   a. The volume of gas handled is directly proportional to the fan speed.
   b. The static pressure, total pressure, and velocity pressure will vary as the square of the fan speed.
   c. The power will vary as the cube of the fan speed.

Because the density of a gas is dependent on the gas involved, rule 1 enables us to calculate the change involved when the gas handled is changed, because the gas laws state that the gas density is directly proportional to the barometric pressure and inversely proportional to the absolute temperature.

61. The unit of measuring the amount of noise generated so that a basis for a comparison can be determined is the *bel*, which was introduced in 1923 and named after Alexander Graham Bell, the inventor of the telephone. The bel is a large unit of measurement, and it is more common to use a tenth part of the unit in computations and specifications, in which case the unit is called a *decibel* and is written as dB. The intensity of a sound wave is measured by the passage of energy or power. Hence, the decibel may be used to express the ratio of all power sources and such related quantities as electrical current and voltage. If p_1 and p_2 are two sources of power in which $p_2 > p_1$, then:

$$n = 10\ \log_{10}\ \frac{p_2}{p_1}$$

where n is the intensity in decibels.

Since the decibel is a unit obtained from a ratio of power sources, it is necessary to define a reference level; in acoustic work, the zero or reference level is set at 2×10^{-5} pascals.

62. If we consider electrical voltage, then from Ohm's law the power is given by $p=V^2 R^{-1}$. In this case n is given by:

$$n = 10\ \log_{10} \frac{V_2^2\ R_2^{-1}}{V_1^2\ R_1^{-1}} = 10\ \log_{10} \left(\frac{V_2}{V_1}\right)^2 \left(\frac{R_1}{R_2}\right)$$
$$= 20\ \log_{10} \frac{V_2}{V_1} + 10\ \log_{10} \frac{R_1}{R_2}$$

If we consider electrical current, then from Ohm's law the power is given by $p=I^2 R$. in this case n is given by:

$$n = 20\ \log_{10} \frac{I_2}{I_1} + 10\ \log_{10} \frac{R_2}{R_1}$$

63. A motor is loaded when it overcomes a torque opposing its motion, which in the real world is represented by the equipment that is being driven by it. For an unloaded dc motor, the rotational speed is due to the armature current, which is small because the torque to be overcome is due to the friction in the bearings, windage, and iron losses in the armature. Under these conditions, the back emf is almost equal and opposite to that of the power supply. For this we make the assumption that the power supply is constant and the magnetic flux per pole is independent of the load.
64. As soon as the armature rotates, an emf is generated because the armature is rotating in a magnetic field. Therefore, in accordance with Lenz's law this generated emf has a direction that is opposite to the current; hence, it is called the back emf.
65. To maintain the current, the power supply has to overcome not only the armature winding resistance but also the back emf. In other words, writing the relationship in voltage terms, we have:

$$E_{sup} = R_{arm}\ I + E_{back}$$

Where E_{sup} is the power supply

R_{arm} is the resistance of the armature

E_{back} is the back emf

66. The armature current can be considered as being due to the excess of power supply p.d. over the back emf, or:

$$I_{arm} = \frac{E_{sup} - E_{back}}{R_{arm}}$$

where I_{arm} is the armature current, with all other terms as defined in item 65.

67. It has been found that the magnetic flux per pole is not independent of the load, but since the back emf is the one that is generated by the rotation of the armature, then:

$$E_{back} \propto n \Phi$$

where n is the rotational speed in rpm

Φ is the flux per pole

from which we can say: $n \propto \frac{E_{back}}{\Phi} \propto \frac{E_{sup}}{\Phi}$ (approximately). Therefore, the speed may be varied by altering the values of the armature p.d., that is, power supply E_{sup} or the flux per pole **Φ**

68. The alternating current motor poses a different set of problems to give a variable rotational speed due to the manner in which the motor windings are excited. The ac motor is a device that operates on the induction principles propounded by Faraday. In this motor there is no electrical connection between the fixed (stator) and the rotating (rotor) parts of the machine; these two parts are coupled together magnetically by the induced emf.

69. In a practical machine, the rotor is constructed from a series of rectangular copper or aluminum conductor bars mounted in slots on a cylindrical soft iron core, with both ends of all the conductor bars joined together by two heavy copper or aluminum rings to form a short-circuited winding. As the rotating field moves across the bar winding of the rotor it induces very strong currents that magnetize the soft iron core and allows the rotating field to pull the rotor round continuously. From what has been said, the speed of rotation will be entirely dependent on and fixed by the frequency of the alternating current that is applied. This type of motor is called a *squirrel cage* because of the rotor construction.

70. Faraday’s law of magnetic induction states that the electromotive force generated when a conductor passes through a magnetic field is proportional to the product of field density, conductor length, and velocity of traverse or $emf \; \alpha \; Blv$. In the case of the motor, the conductor length and velocity are constant; hence, $emf \; \alpha \; B$. The flux distribution over one pole pitch can be represented very closely by a sine wave, so that the emf distribution can also be represented by the same sine wave. If the rotor is totally noninductive, the current can also be represented by another sine wave *in phase* (i.e., both start and finish at the same points) with each other. Since the conductor length is constant, the torque acting on each conductor at any instant is proportional to the product of the flux density and the induced current, or $T \; \alpha \; B \, I_{ind}$, where T is the torque and I_{ind} the induced current.

71. It is virtually impossible to make a totally noninductive rotor. The emf and flux can

still be represented by the same sine wave, but we can see that the current now lags behind the emf by an angle **Φ**. This makes the torque in a portion of the pole pitch encompassing the lag angle reverse because the current is also reversed between this part of the pole pitch. As a consequence, the resultant torque (i.e., the difference between the forward and backward torques) is reduced. If the inductance of the rotor increases, the lag increases—that is, **Φ** gets larger and a greater portion of the conductors exert a backward torque. If we allow the inductance to continue to increase until the forward and backward torques are equal, the power factor and the resultant torque will be zero.

72. The resultant torque is proportional to the product of the rotor emf, rotor current, and rotor power factor, or:

$$T_{res} = E_{ind}\ I_{ind}\ \cos\phi$$

If **Φ** is the flux per pole, then E_{ind} is proportional to **Φ**, in which case

$$T_{ind} = k\ \Phi\ I_{ind}\ \cos\phi$$

73. A multiphase induction motor at the instant of starting is subject to the emf induced in each phase of the rotor, the reactance per phase, and the resistance per phase. Hence, at starting the following apply:

$$\text{Rotor current:}\quad I_{ind} = \frac{E_{ind}}{\sqrt{R_{ind}^2 + X_{ind}^2}}$$

$$\text{Rotor power factor:}\quad \cos\phi = \frac{R_{ind}}{\sqrt{R_{ind}^2 + X_{ind}^2}}$$

where E_{ind} is the emf induced in each phase of the rotor at starting

X_{ind} is the reactance per phase at starting

R_{ind} is the resistance per phase

Therefore, the starting torque:

$$T_{start} = k\frac{\Phi\ E_{ind}\ R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

But normally the power supply is constant and as a result the flux per pole is also constant. Hence, we can say:

$$T_{start} = k_1\frac{R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

74. To visualize the effect that a changing power supply voltage has on the motor, let us use the equation:

$$T_{start} = k\frac{\Phi E_{ind} R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

But E_{ind} is proportional to **Φ**, and **Φ** is very nearly proportional to E_{sup}; now if E_{sup} is not constant, then we can say:

$$T_{start} = k_2 E_{sup}^2 \frac{R_{ind}}{R_{ind}^2 + X_{ind}^2}$$

From this, we see that the starting torque is extremely sensitive to supply voltage variation.

75. The speed of the rotor must always be less than the synchronous speed of the motor. The difference between these two speeds is called the *slip;* it is expressed as either a fraction or percentage of the synchronous speed and is denoted by the symbol *s:*

$$s = \frac{N_{syn} - N_{act}}{N_{syn}}$$

where *N* is the rotational speed and the subscripts *syn* and *act* denote synchronous and actual speeds, respectively.

When the motor is standing still, $s=1.0$ and the slip is therefore 100 percent; the machine then behaves as a transformer, with the induced emf (E_{ind}) in the rotor having the same frequency as the power supply.

76. The speed of an ac motor can be changed by:

a. Altering the resistance of the rotor circuit, which is effected by inserting external resistances into the rotor via slip rings. Speed regulation at low rpm using this technique is very poor because at low speeds a small change in resistance produces a large change in rotational speed.
b. By changing the number of poles with a switching operation. The speeds are limited to simple ratios such as 1:2 and are confined mainly to small motors.
c. In some cases, two separate windings are provided—one that provides, say, 4 and 8 poles and the other 6 and 12 poles—to give four synchronous speeds of 1500, 1000, 750, and 500 rpm.
d. For infinite variation of fan speed, using an ac induction motor we find that the only solution is to include a hydraulic-coupled speed-changing gear unit in the system. This allows the induction motor to run at its constant design speed, all other speed changes being made via the speed-changing gear. The efficiency of the hydraulic coupling itself and its demand on motor power must also be considered. Provisions to enable the control signal output of the system to mechanically alter the speed-changing gear smoothly will have to be made.

77. In recirculationg dry air-cooled exchangers, some of the warm exhaust air is recirculated to prevent problems when operating the unit at low inlet temperature conditions. Wind skirts and louvers limit the amount of cold air drawn in via the inlet; any failure of the louvers or skirts allows the cold air direct access to the process tube bundle. Attention must be paid to the following points when air-cooled units are involved:

a. All the exchangers in a bank should be of the same type, and the effect that prevailing wind, surrounding buildings, and other structures have on the units should be allowed for.
b. The noise generated by the fans should be considered.
c. The exhaust from the heat exchanger goes directly to the surrounding atmosphere; therefore, it must not be located over equipment that can cause a hazard.
d. The units should not be installed where corrosive vapors or fumes can be drawn in through the inlet
e. The heat flow is approximately proportional to the flow of air through the exchanger.

78. In principle, the evaporative condenser is very similar to the recirculating air unit but with the addition of a cooling water spray over the tube bundle. With these units, the heat flow is nearly proportional to fresh airflow. When the unit is operating at steady state, the heat is transferred to the air by evaporation brought about by the difference between the temperature of the water and the wet bulb temperature of the air. A cooling water spray has advantages:

- It makes the conditions more stable and improves the heat transfer.
- The wet bulb temperature is not subject to the rapid changes or wide fluctuations as the dry bulb temperature but increases with both humidity and dry bulb temperature.
- Rainfall, though cooling the air, increases the humidity at the same time. It therefore does not affect the wet bulb temperature to any great extent. In fact, heat-transfer efficiency is improved with increasing humidity.
- Water-cooling makes these units physically smaller in size (compared to the dry air recirculating unit), allows control dampers to be used for control purposes, and obtains lower condensate temperatures.

There are disadvantages:

- Since water is used to effect the cooling, precautions must be taken to prevent it from freezing when these units are installed in locations subject to low ambient temperatures.
- A source of heating for the water must be provided during the cold weather.

79. With some products the column must be operated at very low pressures or vacuum and condensers should be used in which the vapor is made to contact the cooling medium directly. The distillate is sub-cooled and recirculated through a pump and a spray condenser. Any noncondensable gases are removed continuously to maintain the low column pressure. For this system to work, heat removal is required. The column temperature is used as the measurement to a controller to regulate the amount of heat removed. By controlling both the pressure and the temperature, the composition of the overhead product is maintained.

80. Column pressure is an important measurement used in the control systems, mainly because a stable temperature lies at the root of product quality and maintaining this parameter constant is of greater significance. Since the two parameters in the context of material boiling points are intimately bound to gether, maintaining one is reflected in the stability of the other. Today the parameter temperature for determining product quality is increasingly being taken over by process analyzers, which in several instances are chromatographs. Chromatographs are not so heavily influenced by the column pressure.
81. Vapors flowing up and the liquids flowing down the internals of a distillation column comprise the internal reflux that constantly takes place. The boiling of the material being distilled brings about the flow of these two phases. Because of column construction, the flow rates of these two phases within the column are immeasurable, but flow rate constancy is vital to obtaining stable column operation. One means to ensure constancy is to provide very stable boiling conditions—that is, by holding the heat input to the column constant and closing the heat balance by regulating the reflux through either column pressure or by accumulator level control if floating pressure control is implemented.
82. The computation for internal reflux in *Perry's Chemical Engineers Handbook* is given as:

$$R_i = R_e [1. + k (T_{ov} - T_{re})]$$

where R_i is the internal reflux flow rate in mass units

R_e is the external reflux flow rate in mass units

k is the ratio of specific (C_p) to latent (H) heat of liquid in the top

tray C_p/H

T_{ov} is the temperature of the overhead vapor

T_{re} is the temperature of the external reflux

83. In a material balance system, flow of a product is used to regulate the product quality, that is, its composition. The amount flowing and quality usually refer to the product being manipulated, but this may not always be the case. In simple terms when a feed material is distilled and we consider the material flows only, we can say that to achieve material mass balance the sum of distillate and bottoms product flow must equal the flow of the feed material, or symbolically:

$$F = D + B$$

where F is the feed flow, D is the distillate flow, and B is the flow of bottoms product.

Let the fraction of any given component in the feed *(F)* be z, in the distillate *(D)* be y, and in the bottoms product *(B)* be x; and considering the component balance, we have:

$$F_z = D_y + B_x$$

Note: In the component balance, the composition is given in terms of the most volatile component.

84. The composition of the feed is composition of the distillate minus composition of the bottoms product or

$$F = y - x$$

the composition of the distillate is composition of the feed minus composition of the bottoms product or

$$D = z - x$$

the composition of the bottoms product is composition of the distillate minus composition of the feed or

$$B = y - z$$

When we change the feed flow *(F),* the change is reflected in changes of flow in both the distillate *(D)* and the bottoms product *(B).* In the same way, any change in composition of the feed *(z)* is reflected in the changes of composition in both the distillate *(y)* and the bottoms product *(x),* and results in the following relationships (when we rewrite the feed distillate and bottoms in terms of composition):

$$\frac{D}{F} = \frac{z - x}{y - x}$$

$$\frac{B}{F} = \frac{y - x}{y - x}$$

From this the composition of both the distillate and bottoms product is determined by the ratio *D/F* or *B/F.* To maintain product quality, we therefore need to maintain the ratio of *D/F* or *B/F* at any chosen desired value.

85. Equations $F=D+B$ and $F_z=D_y+B_x$ are unable to provide a solution, for they basically have two unknowns each. To effect control of the distillate or bottoms product quality, we have no option but to manipulate (as individual entities) the two ratios *D/F* and *B/F* dependent on the composition z of the feed. Treating these as partial derivatives and writing this symbolically, we have:

$$\frac{\partial D/F}{\partial z} = -\frac{\partial B/F}{\partial z} = \frac{1}{y - x}$$

The composition of either distillate or bottoms product can only lie between 0 and 1 (where 1 represents 100 percent purity). Therefore the change in the ratios *D/F* and *B/F* must always be greater than the feed composition *z*.

CHAPTER 6
Product Blending

IN-LINE PRODUCT BLENDING

Many of the products we use in our daily lives are the result of combining two or more pre-prepared products into a single entity ready for the marketplace This combination process is normally referred to as blending and applies across the whole spectrum of use from edible to nonedible products. Blending should always be considered a nonreversible process, which means that once two or more separate products are brought together, it is virtually impossible to separate them back into their original states, using simple methods. The reversal process can be done, but at great additional expense because it will involve completely reprocessing the entire amount produced. What usually happens under these circumstances when an error occurs in product blending (always assuming that the blended product is capable of being reworked easily, without being reprocessed completely) is that the product with the unacceptable specification will be either up- or downgraded to another "saleable" product of similar but not equal specification. Both upgrading and downgrading require additional time, material, labor costs, and hence some net loss of revenue, which will inevitably affect the overall profitability. Considering the severe penalties to be paid for avoidable errors, it is no wonder that all processors of blended products will demand a means of getting the product right the first time around. The systems provided must therefore meet the criteria set and perform the task satisfactorily throughout their working life.

In this chapter, we will first show the basic configuration of an elemental flow loop typical of several employed in liquid blending applications, and then we will develop a simple combination of such loops under the control of a blend master controller in order to give a single multistream blending system such as might be configured using conventional hardware instrumentation throughout. As a progressive development from these basic elements, the adaptation using a software block-configured system will be detailed. Further expansion using submasters, each with control over a group of process streams via their component loops, but under the control of a system master will follow. As a further, more detailed extension, linking such a complex (system) to a computer to organize both recipe definition/handling and system status cohesion plus related documentation will be explained.

Later in this chapter we will discuss a system that makes use of a proprietary stand-alone digital microprocessor-based blender, originally designed to meet the demands of a single 24-stream blending unit. In this instance, however, it is modified to meet the requirements of four separate, individual blending units and at the same time produce commercial documentation associated with the operation. The original stand-alone blender did not have the capability of recipe storage, printout of blended output, or invoices associated with the delivery. In this way, the requirement was a complete departure from the normal method of operation of the original equipment unit. All the required modifications were carried out externally to the original blender equipment and did not involve any changes to the internal circuitry of the proprietary unit. Hence, the integrity of the original unit's blending functions was preserved, and it was capable of fulfilling its design criteria within its specified operational limits. This application is presented to demonstrate the possibilities of exploiting the capabilities of proprietary equipment to advantage in order to meet new challenges.

BASIC BLEND-LOOP REQUIREMENTS

The Blending System in a Nonhazardous Environment

Figure 6.1 is a simple overall view of a typical loop that can be directly manipulated by the blender/master controller. Although Figures 6.1 and 6.2 show loop control via a microprocessor, as detailed later, the fundamental configuration is no different from that for any hardware-only system. The precursor of the blender as we know it today was the analog flow ratio control loop. This system was quite adequate for simple two-stream blending operations but became quite unwieldy when the number of streams increased and the requirements for the individual blend master controllers became more demanding. Digital electronics came to the rescue, for it was able to cope much better with the demands made. The stand-alone digital controllers have been almost entirely supplanted by microprocessor-based systems. To be meaningful, there will have to be more than one loop in the system that produces a product. However, it is not unknown for a single loop to be used to totalize the transfer of a process component. Each loop is devoted to manipulating a different component of the final product in a manner that fulfills the specification requirement of the final product. In the system illustrated, it will be seen that the measurement and controlled signals from and to the process are derived from interface modules that change the transmitted analog signals to digital ones so that they are comprehensible to the hardware or microprocessor within the blending controller. However, it should be emphasized that some flow-measuring instruments can produce pulsed signals that can be applied to input interfaces and need no signal conversion. To be useful, all measurement signals need to be scaled, that is, to have a common basis for the relationship to each other.

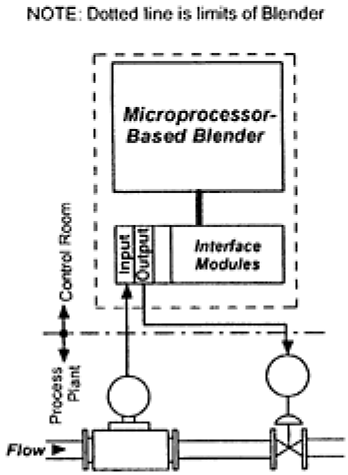


Figure 6.1: A typical blend loop.

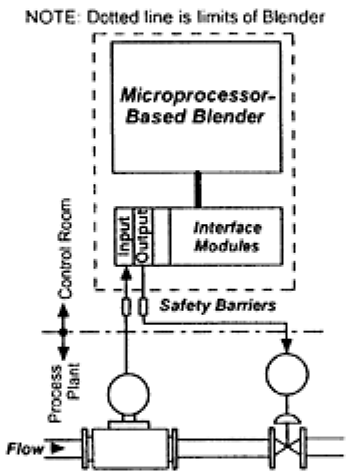


Figure 6.2: A typical blend loop in a hazardous location.

The system shown in Figure 6.1 is one in which the process plant is nonhazardous—that is, the material being processed does not easily ignite or explode, and therefore the normal good practice of instrument installation will apply. When the process plant produces or handles hazardous material, other more rigid precautions have to be taken to ensure the safety of the personnel and equipment associated with the manufacturing operation. These precautions are of paramount importance when life and property are involved. The measures adopted are achieved by inserting *safety barriers* between the blender unit in the control room and the field-mounted equipment via the interface modules.

THE BLENDING SYSTEM IN A HAZARDOUS ENVIRONMENT

Figure 6.1 will be altered to show the safety barriers in their normal position. We show detailed information on the safety barriers later in this chapter.

The safety devices shown in Figure 6.2 are designed to limit the energy in the electrical circuit to levels at which any sudden release of energy will not be able to cause a spark and ignite flammable gases that could be surrounding the instruments. Details of intrinsic safety, power, and grounding are discussed in more depth in national standards, related literature, and elsewhere.

GENERAL OVERVIEW OF A MICROPROCESSOR BASED BLENDING SYSTEM

As we have already seen, the equipment we are discussing accepts measurements from the transmitters of the loops to be blended and provides controlled outputs to the control valve or proportioning pump, with the submaster controlling the rate at which the various streams are assigned to its supervision. A maximum of 24 blend loops and a system master can be employed in the blending system. Additional control and functionality are provided to control the process via software algorithms or blocks. These blocks are powerful software routines, which can be broken down into the general categories of signal interfaces, signal processing, and control. The blocks are connected by software links to signal interfaces or other blocks to produce the control strategy required. A total of 48 blocks is available and these are divided into 16 types covering the general categories stated earlier. The 16 types are as follows:

Inputs:	Analog; Contact
Signal Processing:	Equation; Constant; Switch; Lead/Lag (dynamic compensation); Dead time; Dead-time Extension; Compare; Nonlinear Curve (characterizer); Boolean; Delay
Control:	PID Control; Local Master
Outputs:	Analog; Contact

Block configuration follows a procedure similar to all microprocessor-based control systems. In distributed control systems (DCS) the system configurator puts up a block selection list from which the system implementor (person) makes a choice. The system configurator (microprocessor firmware) displays a page(s) of data requests associated with the selection against which the implementor inputs the appropriate data normally via a keyboard. The procedure using this equipment is a little different because in this case there is no keyboard. All data are entered via a numeric keypad embedded on the face of the instrument. Since there is only a numeric keypad, all data entry has to be made via a program code; the system is alerted to accept the data as soon as the program code pushbutton is initiated. The procedural steps for data entry are: (1) initiate program code pushbutton; (2) initiate keypad pushbutton, for example, 53 (code)—for an analog input, which is a block type 5; (3) initiate “Enter” push-button—to put the data into memory.

For alpha data there is a separate push-button, and program code pushbutton initiation is not needed. The alpha pushbutton has to be initiated prior to entering the code for the alpha character required. For the example cited in (2), when code 53 is entered, the system configurator displays the block requested as a list of required data, which must be completed using the data entry procedure outlined.

With regard to the way calculations are performed in the equation block, which uses the Reverse Polish notation (eliminates the necessity of parentheses and brackets), for example, suppose one wishes to perform a subtraction. The number from which the amount is to be subtracted is entered, and this operation is followed by the subtrahend, and following that the minus sign. From this it will be seen that the math function to be performed is always the last entry for the calculation. The block allows "+"; "—"; "*" -multiply; "/"-divide; SQR-square root; EXP-exponentiate (x^y); ABSabsolute value. Each calculation permits 13 "elements," 7 of which can be constants or outputs from other blocks.

Configuring a Basic Blend Loop

A blend loop is configured using a single block called the *blend loop*. The functions of this block combine with the functions of other blocks, which the user links together to perform the control strategy to suit the application. The blend loop performs no computation itself but can be considered as the data input for a control algorithm and must therefore be linked to it. The control algorithm serves a number of blend loop blocks and as a result depends on the data contained in the blend loop block to carry out the appropriate instructions. The information to the blend loop is updated 10 (or 5) times a second as specified, which means that the function of the control algorithm is carried out every 100 (or 200) milliseconds, depending on the requirement specified. The controller calculates the outputs for each blend loop assigned to it using the master demand rate defined and the flow rate of each blend loop that occurs at the time of each "pass". A pass is defined as the computations for each loop, starting at loop #1 and finishing with loop #x the last in the number assigned to the master.

Each blend loop requires 43 separate bits of data to be entered; the full complement is detailed in Table 6.3. With regard to just one item of these data, the controller, it should be noted that for this item only the proportional band and integral time are required to be specified. Derivative action is never included on flow control loops because of the problem of noise, which upsets the stability of the control, the plus and minus error shutdown trips, and the block number that provides the measurement and the associated master number.

All blocks follow the rule that the inputs to it always cite the origin of the signal. As examples, an analog input block will require the hardware address of the input module to which the transmitted measurement signal is connected; the analog output block will require the block number from which it receives its input, and the output module that connects the system output (analog or contact) to the field device will require the block number from which it obtains its input.

Functional Detail of the Blender—Single Master

To simplify explanation, Figure 6.4 uses a single *system-master,* which is called *master 0*. The figure is a functional illustration of the way the incoming and outgoing signals between the flow loop and the blender are generated. The error calculation will not be correct unless the measurement and demand have common engineering units. When analog flowmeters are used, the flow rate is usually stated in volume or mass per unit time. This proprietary blender can only be provided in volumetric units, which is specifically in U.S. gallons. Hence, every measurement and demand must be converted to and computed in gallons and used internally. The display, however, can be shown in the units required.

If a pulse-generating instrument such as a turbine flowmeter—commonly installed—is used to provide the flow rate measurement, it will be necessary to compute the correct amount that is represented by a single pulse generated by the flowmeter. The computed amount of flow is transferred to the instrument by correctly defining the "loop *K*" factor, for the demand represented by the ratioed amount, when configuring the blender. Only then will it be possible to determine the error, which is the difference between the measurement and the demand. The error computation is identical to that used in a conventional controller, even to the extent of the terminology used, because the terms set point (in a conventional controller) and demand (in the blender) are in fact interchangeable.

Scaling

The following are examples of the method of scaling used. For convenience, we use a pulse input, which is more commonly found in blending applications.

1. Suppose the flowmeter output is 30 pulses/U.S. gallon and the full-scale flow rate is 500 U.S. gallons/minute.

Then the pulse rate/second is given by:	(pulses/U.S. gallon×U.S. gallons/minute)/60 (where 60 is the number of seconds in a minute)
The meter *k* factor is:	30

Since the measurement and the demand have the same units (i.e., U.S. gallons), the loop *K* factor is: 1
The input pulse rate is given by inserting the data into the equation: $V=kQ/60$
where V is the volumetric flow rate; k is the meter factor; and Q is the full-scale flow rate.

This gives:	(30×500)/60
	250 pulses/second

2. Suppose the flowmeter output is 4000 pulses/U.S. barrel and the full-scale flow rate is 500 U.S. gallons/minute.

The meter *k* factor is:	4000
Then 4000 pulses/U.S. barrel	= 4000/42 because there are 42 U.S. gallons in a U.S. barrel
	= 95.24 pulses/U.S. gallon

since we have made the measurement and the demand have the same units (i.e., U.S. gallons).
The loop *K* factor is: 1
The input pulse rate is given by inserting the data into the equation: $V=kQ/60$
where V is the volumetric flow rate; k is the meter factor; and Q is the full-scale flow rate.

This gives:	(95.24×500)/60
	795 pulses/second

The technique can be applied to analog signals as well. Figure 6.3 illustrates the procedure. In all scaling requirements, three methods are used:

1. Changing the "meter *k*" units to make the measurement units the same as the demand units. In this case the totalization will be in the same units as the demand. (This is shown in Example 2.)
2. Changing the "loop *K*" units to make the demand units the same as the measurement units. In this case the totalization will be in the same units as the measurement.
3. Changing both the meter *k* and loop *K* units to make the totalization units the same as that required. In this case the units will be neither those of the measurement nor those of the demand.

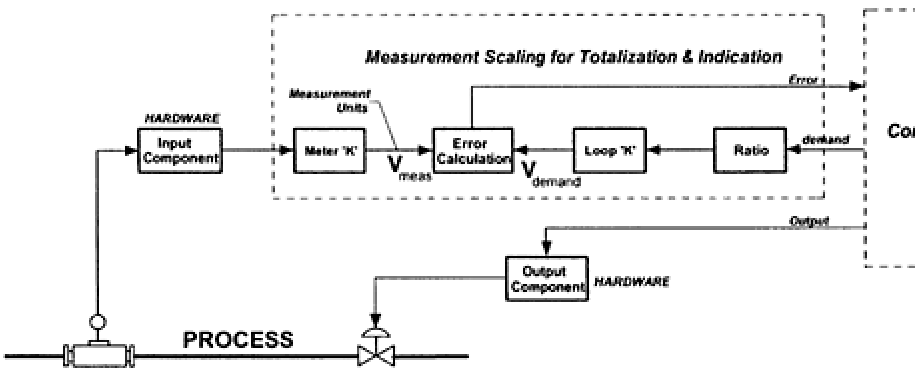


Figure 6.3: Schematic for measurement and loop scaling.

Two calculations are required to determine the loop *K:* the first is to determine the measured quantity, and the second to determine the loop K.

The number of loops that can be assigned to a single master is 24 (or a combination of other masters), which represents a maximum of a 24-component stream blender. It is possible to assign other masters called *local masters*, each to monitor and to control a smaller number of loops, but these local masters will have to report to the system master (master 0). With this specific blending control equipment there is a maximum total of 24 flow loops for the whole system. A supervisory computer can be included, and communications between the blender and PC are carried out over the RS 232 C serial communications link.

Functional Detail of the Blender—Multimaster

Figure 6.5 is an enhancement of the system shown in Figure 6.4 and, to emphasize the similarities, the basic illustration has been used with the enhancements added on. This enhancement is deliberately done to show the reader the progressive complexity that can be achieved. The field circuit, as far as the flow measurement and control are concerned, has not changed at all. However, it should be also be noted that the process temperature is now measured and forms another input from the field, and will require an additional temperature sensor to be included. This additional sensor will automatically compensate the flow measurement for variations in process temperature; the alterations now made are included in system operation. The temperature loop is shown with a dotted line to indicate that it is an added feature, and compensation of the measurement will be made as shown within the loop diagram.

The temperature sensor must be fitted with a signal converter (ideally head-mounted on the sensor itself) that will transmit the measurement using the standard 4 to 20 mA signal instead of the normal signal produced by the sensor. This step is taken for uniformity of input interfaces required and to facilitate long-distance

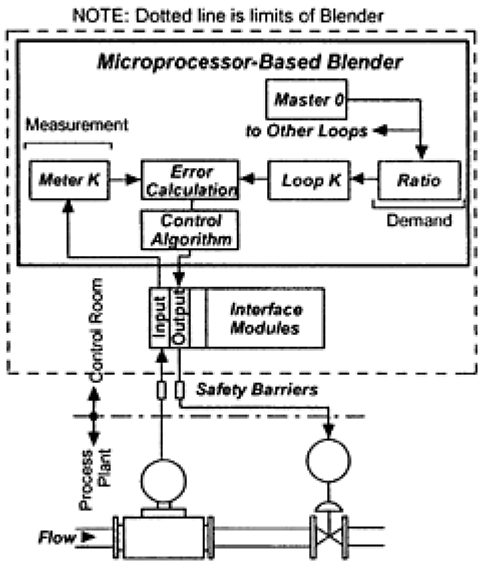


Figure 6.4: Detail of a single master blend loop in a hazardous location.

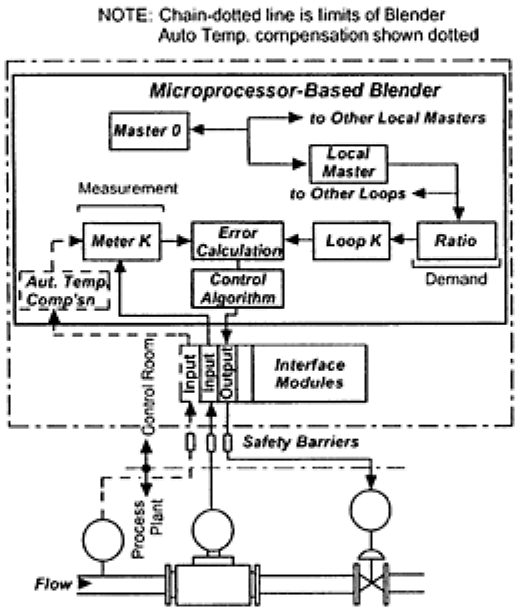


Figure 6.5: Detail of a multimaster blender in a hazardous location.

transmission because the signal produced by the temperature sensor will depend on the type of sensor used and could be mV for a thermocouple or a resistance change for a resistance bulb.

Functional Detail of the Multimaster Blender with Supervisory Computer

Figure 6.6 shows the blending system with a supervisory computer added. This arrangement allows the system far greater operational flexibility and permits records and documentation to be handled and hard copies to be produced on demand. The blending system we will be discussing later in this section uses this arrangement, along with other enhancements that make the instrument more versatile than the standard stand-alone product.

THE VITAL BLENDING SOFTWARE BLOCKS

The blender performs three vital functions of monitoring and coordinating the entire blending system, monitoring and coordinating groups of control loops, and controlling individual flow loops without which it would not be possible to carry out a blending function. Other blocks can be connected to these blocks; the functionality of these other blocks (48 in total), can be selected from 16 different types. They are substantially similar to those used in the DCSs throughout this book (e.g., the Foxboro I/A Series).

Master 0 Display

All systems have an overall master called the *master 0* controller implemented; through this controller, the system is organized and maintained on track while a

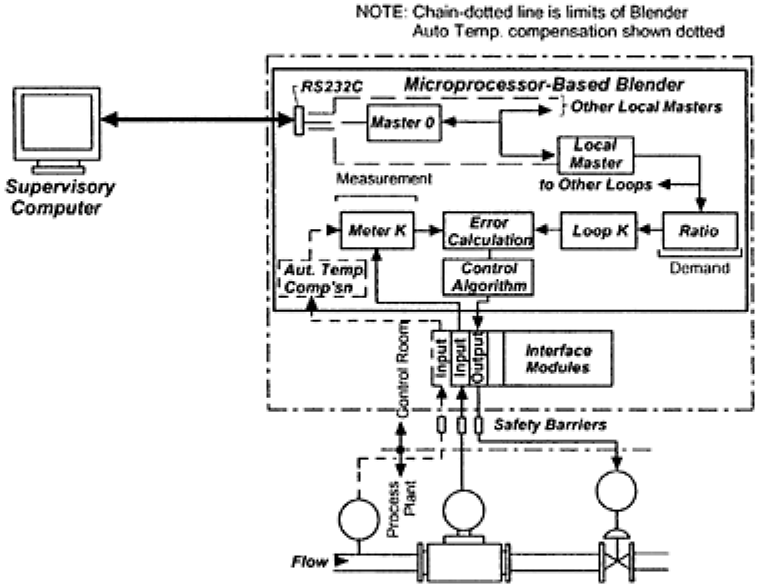


Figure 6.6: Detail of multimaster blender with a supervisory computer and process in a hazardous location.

blending operation is in progress. All overall high-level supervisory alarm reporting is carried out through this controller, and for the system we are discussing each blender has an immediate master called a *local master* to which all assigned component loops report. Each local master in turn reports to the master 0; hence, at any time master 0 is updated with data concerning the prevailing conditions. Additional alarms are also included specific to local master(s) and individual loops.

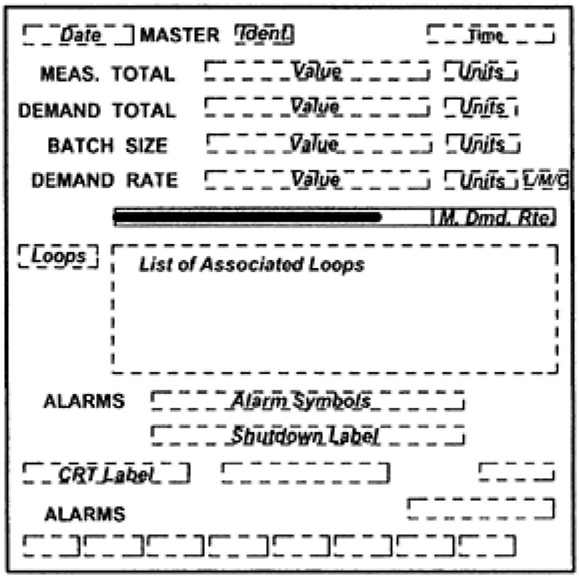


Figure 6.7: Standard master 0 display.

Figure 6.7 shows the display associated with the master 0 controller. In this display, the information shown in capital letters appears on the CRT as part of the fixed design of the display, whereas the information shown in italic typeface depends on the situation at the time the blender is running, for it will obtain these data from the live system. In this regard, it is important that apart from the obvious (e.g., date and time) the meaning of the various individual items will now be given.

The areas shown in Figure 6.7 are as follows:

- In the displayed information for a single-master system, the master appears as 00 under the heading Ident., while an appropriate number is displayed for a multimaster—more than one blender system (this is not to be confused with multiple local masters).
- The information displayed in the areas assigned to Value is obtained from a live system with Meas. Total being the *current master total* and M.Dmd. Rte the *current master demand rate*. The Demand Total is the *calculated master demand total*. The Batch Size is the *master batch size,* and the Demand Rate is the *preset demand rate*.
- The area covered by L/M/C (located alongside the value of the demand rate) indicates whether the blender is on *local, manual,* or *computer* control.
- The thick horizontal line is an analog bar graph of the master demand flow rate and will change as the process changes in response to the regulation applied by the controls.
- The upper area of alarms covered by alarm symbols displays the symbol *OVL* for cpu (central processing unit) overload, *PSD* for pre-shutdown, and *BSD* for batch shutdown when appropriate conditions demand that they be shown.
- The lower area of alarms covered by the shutdown label displays the symbol *SD1* for the shutdown label from shutdown input #1, *SD2* for shutdown input #2, *SD3* for

shutdown input #3, and *SD4* for shutdown input #4, when appropriate conditions demand that they be shown.

- The area covered by the CRT label displays the appropriate program code functions when data values are entered or accessed.

Master 0 Operation

There are a number of pushbuttons on the actual instrument faceplate, one of which is labeled Run and the other Local. Initiating the Run button starts the blend algorithm regardless of what the display on the instrument CRT is showing. However, if there are any active shutdowns, that is , SD1 through SD4 in operation, the system will not start. Provided the instrument CRT display is showing a particular local master (of which there can be a total of 24), or its block summary or its master summary, then initiating the Local button causes the algorithm of that particular local master to begin. A supervisory computer can also initiate the local master, but only if the external Auto/Manual input is enabled and active.

The program codes (listed in Table 6.1) referred to are code numbers that must be entered by the person configuring the system. These codes permit access to the parameter of a particular block, which is to be assigned with specific process data. Once the above conditions are met, the following will occur:

1. The master demand rate starts at zero and will ramp up in a linear manner to the rate (a value shown in a maximum of six digits) set by program code 01 (Max

TABLE 6.1 Program Codes for Master 0 Block

Program Code #	*Function*	*CRT Label*	*Remarks*
01	Maximum Demand Rate	MAX MDR	Max 6 digits plus decimal point
02	Address Key Lockout	ADDR DIS	0=enable 1=inhibit via instrument
03	Demand Rate Time Units	FR TIME	0=sec, 1=min, 2=hr, 3=days
04	Pre-shutdown Value	P S DOWN	Max 6 digits plus decimal point
05	Ramp-up Time in sec	RAMP UP	Sec up to 32767
06	Ramp-down Time in sec	RAMP DN	Sec up to 32767
07	Holding Rate	HOLD RT	Max 6 digits plus decimal point
08	Number of Loops (0 through 24)	LOOPS	Max 24

09	Shutdown on Master Demand	MD SDOWN	0=on MD Tot., 1=on sum of meas. Tots
10	Number of Blocks (0 through 40)	BLOCKS	Max 40
11	Shutdown ramp	SD RAMP	0=immediately, 1=Ramp-down time
12	External demand Source	EXT DMND	0 or any legal output pointer
13	Loop Period (1 or 2)	LOOP PER	01 =0.1 sec, 02=0.2 sec
14	Totalizer Resolution	TOT RES	0=000, 1=00.0, 2=0.00, 3=.000
15	Total Label	TOT LBL	Max 4 alpha characters
16	Rate Label	F RATE L	Max 4 alpha characters
17	External Shutdown Mask	SD MASK	8 digit binary number* see note
18	External Shutdown Horn Mask	HN MASK	8 digit binary number* see note
19	100% Check	% CHECK	Must sum of ratio=100? 0=No, 1=Yes
20	Date	DATE	DD=01-to 31-, MM=01- to 12-, YY=2 digits
21	Time	TIME	HH=01—to 24-, MM=00- to 59-, SS=00 to 59
22	Power Line Frequency (50, 60 Hz)	50/60 HZ	
23	Blender Number (for communications)	BLENDER	1 through 99
24	External Shutdown Label #1	SD LABEL 1	Max 4 alphanumeric characters
25	External Shutdown Label #2	SD LABEL 2	Max 4 alphanumeric characters
26	External Shutdown Label #3	SD LABEL 3	Max 4 alphanumeric characters
27	External Shutdown Label #4	SD LABEL 4	Max 4 alphanumeric characters
28	Master Ratio Label	M % LBL	Max 4 alphanumeric characters
29	External Measurement source	EXT MEAS	0=int’l sum or any legal output pointer
30	Up/down Load Inhibit	U/D IHN	1=inhibit computer read or write

Note: Only the four rightmost digits are recognized. If the four rightmost digits of the eight-digit binary number comprises all zeros, contact closure will not cause a shutdown; but if the four rightmost digits are all 1s (ones) contact closure will cause a shutdown. The 8-bit number is user generated from binary values 00000000 through 00001111, with the leftmost four digits always 0.

Example: If only SD1 and SD are to be active, the number must read 00001100.

MDR). The time in seconds to ramp from zero to the maximum value is that set by program code 05 (Ramp Up).

2. The error for each loop is calculated as the difference between the measurement input (flow rate) and the demand. The demand is evaluated from the algorithm—MDR×the scan period in sec (either 0.1 or 0.2 sec) set in program code 13× the ratio setting for that loop. Each time the calculation is made, the resulting error of this computation is added to the sum of the previous errors and applied to the control algorithm, which comprises proportional and integral action terms.
3. Depending on the system configuration defined by data in program code 29 (which allows either the internal/summed total of the assigned loops or a real number output from an external measurement source), the demand flow rate begins to ramp down in a linear fashion to a holding rate defined by a value entered using program code 7 once the demand total reaches the pre-shutdown point. Preshutdown in turn is defined as the batch size minus the pre-shutdown value set by an entered value using program code 4.
4. When the holding value is attained, the demand flow rate will hold at this value until either the demand total or the measured total (configuration dependent—see item 3) reaches the value set in the batch size. When this occurs, the demand rate (normally) goes to zero immediately. However, there are exceptions to this train of events:

- When an external demand in program code 12 has been defined, the demand rate ramps up either as if starting from zero to the maximum demand rate or the difference between two subsequent values calculated once per second, and uses the lesser of the two. While a blend is in operation, the demand rate always ramps (up or down) to the difference between two subsequent external values.
- When the holding rate is defined in program code 07 as zero, the system uses the current demand as the holding rate when pre-shutdown occurs.
- When the shutdown ramp is defined in program code 11, the demand flow rate ramps down to zero from the holding rate at the ramp down rate. To avoid slamming the valve shut, which would occur if program code were specified as 0, this should be specified as 1, in which case the valve will shut at the ramp-down time.

Table 6.1 lists the full program codes available for the master 0 block. This arrangement shows their meaning, the code appearing in the area CRT label on the display, and added comments on the functionality of the program code.

Local Master

Any system can have up to a maximum of 24 individual local masters but only 24 loops in total. In general, these operate in a manner similar to the master 0 in that each local master controls the loops assigned to it. The loops in turn are arranged to form control schemes and report back to the assigned local master but are still “overlooked” by the system master.

Figure 6.8 shows the display associated with the local master controller. In this display, the information shown in capitals appears on the CRT as part of the fixed

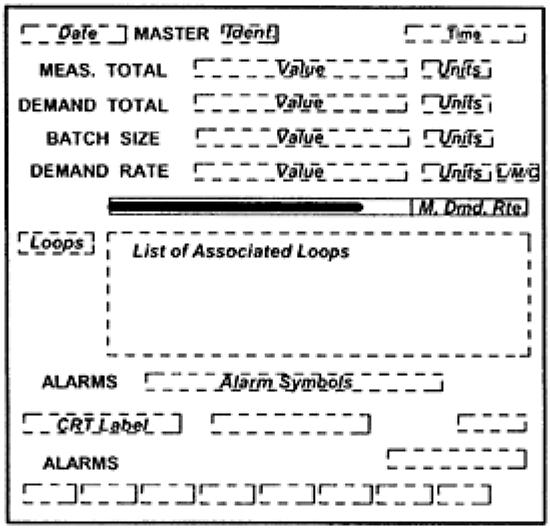


Figure 6.8: Standard local master display.

design of the display, whereas the information shown in italics depends on the situation at the time the blender is running, for it will obtain these data from the live system. In this regard it is important that, apart from the obvious, for example, date and time, the meaning of the various individual be given.

Local Master Operation

The areas shown in Figure 6.8 are as follows:

- In the displayed information under the heading Ident. for the local master appears as 01 for a single local master system, or as an appropriate number for a multiple local-master blender system.
- The information displayed in the areas assigned to Value is obtained from a live system, with Meas. Total being the *current master total* and M.Dmd. Rte the *current master demand rate*. The Demand Total is the *calculated master demand total*. The Batch Size is the master batch size, and the Demand Rate is the *preset demand rate.*
- The area covered by "L/M/C" indicates whether the blender is on *local,* or *manual,* or *computer* control.
- The thick horizontal line is an analog bar graph of the master demand flow rate and will change as the process changes in response to the regulation applied by the controls.
- The area of alarms covered by alarm symbols displays the symbol *PSD* for pre-shutdown and *BSD* for batch shutdown when appropriate conditions demand that they be shown.

• The area covered by CRT label displays the appropriate program code functions.
• The only external shutdown is achieved by external auto/manual switching. The system is triggered via a contact input module wired to the initiating switch.
• The block is started and stopped by the Local and Manual switches on the instrument. However, the master can be started and stopped with external auto/manual switching, but the Manual switch on the instrument overrides the external switching.

Table 6.2 presents the full program codes available for the local master block. This arrangement shows their meaning, the code appearing in the area CRT label on the display, and added comments on the functionality of the program code.

TABLE 6.2 Program Codes for Local Master Block

Program Code #	***Function***	***CRT Label***	***Remarks***
01	BlockType=16	TYPE	Max 2 digits
02	Address Key Lockout	ADDR DIS	0=enable 1=disabled
03	Maximum Demand Rate	MAX MDR	Max 6 digits plus decimal point
04	Demand Rate Time Units	FR TIME	0=sec, 1=min, 2=hr, 3=days
05	Pre-shutdown Value	P S DOWN	Max 6 digits plus decimal point
06	Ramp-up Time in sec	RAMP UP	Sec up to 32767
07	Ramp-down Time in sec	RAMP DN	Sec up to 32767
08	Holding Rate	HOLD RT	Max 6 digits plus decimal point
09	External Demand Block Number	EXT DMND	0=Undefined or any valid real number pointer
10	Shutdown on Master Demand	MD SDOWN	0=BSC on demand Tot., 1= BSC on sum. Tots
11	Shutdown Ramp	SD RAMP	0=immediately, 1=Ramp-down from PC7 rate
12	Totalizer Resolution	TOT RES	0=000, 1=00.0, 2=0.00, 3=0.000
13	Total Label	TOT LBL	Max 4 alpha characters
14	Rate Label	M % LBL	Max 4 alpha characters
15	Flow Rate Label	F RATE L	Max 4 alpha characters (eng. units)
16	External A/M Switch Enable	E A/M E	0=Disable, 1=Enable
17	External A/M Contact Number	E A/M C	0=Undefined, or 1 through 8* see note
18	External A/M Block Pointer	E A/M B	0=Undefined, or valid 8 bit word pointer

19	External Clear Enable	E CLR E	0=Disable, 1=Enable
20	External Clear Contact Number	E CLR C	0=Undefined, or 1 through 8** see note
21	External Clear Block Pointer	E CLR B	0=Undefined, or valid 8 bit word pointer
22	100% Check	% CHECK	0=Start at any ratio val., 1=Start at ratio val.

Notes:

* Bit value from contact switches block to manual.

** Bit value from contact clears totals.

The Blend Loop

The blend loop is any one of the 24 inbuilt regulatory control and totalizing blocks, which when linked with the functions of an Input, Output (plus possibly logic or Calc blocks) from the 48 additional blocks provided produce a control loop that manipulates the process under the direction of the assigned master. Using the master's demand rate setting with the appropriate loop ratio, the controller calculates the loop output on each pass. A pass consists of performing all the output calculations for all the loops and all other blocks or other functions associated with the complete system starting with the first and ending with the last. Each loop output is updated every 100 ms or 200 ms (milliseconds)—that is, 10 or 5 times per second.

If the master demand rate changes for any reason—for example, operator intervention, ramp up or down, or pacing control—and occurs while the controller in the midst of a pass, the change will be ignored for the duration of the pass. The change will be implemented only after the output calculation of the last loop (i.e., at the end of the full pass), at which time a new pass will be started and all the outputs will be recalculated with the new change in place.

Figure 6.9 shows the loop controller display. In this display the information shown in capitals appears on the CRT as part of the fixed design of the display, whereas the information shown in italics depends on the situation at the time the blender is running, for it will obtain this data from the live system.

Blend Loop Operation

The areas shown in Figure 6.9 are as follows:

- In the displayed information under the heading Num. is a unique numeric assigned to the loop. This will dictate the sequence of loop information on the display page(s), as well, of course, relating to the loop elements, blocks and so on, and the assignment to any local master.

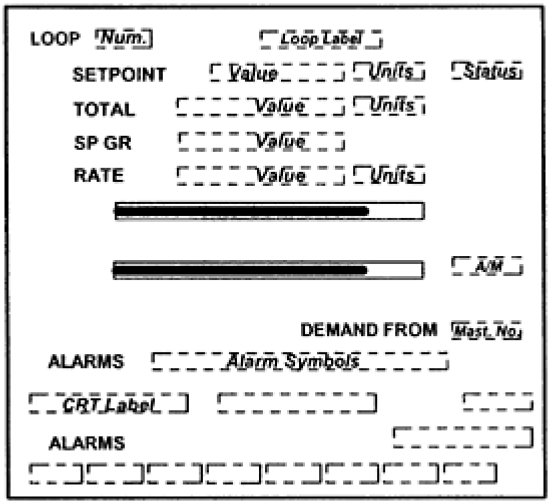


Figure 6.9: Standard loop display.

TABLE 6.3 Program Codes for Blend Loop Block

Program Code #	***Function***	***CRT Label***	***Remarks***
01	Pulse Input K Factor	METER K	Max 6 digits plus decimal point
02	Address Key Lockout	ADDR DIS	0=Enabled 1=Disabled
03	Loop Normalization Factor	LOOP K	Max 6 digits plus decimal point
04	Full Scale Flow Rate	FS FLOW	Max 6 digits plus decimal point
05	Flow-Rate Time Units	FR TIME	0=sec, 1=min, 2=hr, 3=days
06	Low-Flow Alarm Set Point	L FLOW A	Range 0 to 999999. Same units as meter K
07	High-Flow Alarm Set Point	H FLOW A	Range 0 to 999999. Same units as meter K
08	Plus Alarm Set Point	PLUS A	Range 0 to 327.67
09	Minus Alarm Set Point	MINUS A	Range 0 to 327.67
10	Plus-Error Shutdown Set Point	PLUS SD	Range 0 to 327.67
11	Minus-Error Shutdown Set Point	MINUS SD	Range 0 to 327.67
12	Proportional Band Setting	PR BAND	0 to 32767

13	Integral (reset) Setting	RESET	0 to 3276. To eliminate Integral enter 0
14	Totalizer Resolution	TOT RES	0=000, 1=00.0, 2=0.00, 3=0.000
15	Remote Totalizer Output	REM TOT	1=Rem Tot. 0=No Rem.Tot
16	Proportioning Pump Loop	PR PUMP	1=Pump. 0=No Pump. Loops 9 to 12 only
17	Memory or Pace Loop	MEM/PACE	0=Memory Loop 1=Pace Loop
18	Single or Dual Range Loop	SGL/DUAL	0=Single Range 1=Dual Range
19	Inventory Totals	INV TOT	0=No, 1=Yes
20	Trim or ATC Selection	TRIM/ATC	0=None 1=Trim 2=ATC
21	Minimum Temperature for ATC	MIN TEMP	Range 0 to 3276 °C/°F 0=No ATC
22	Maximum Temperature for ATC	MAX TEMP	Range 0 to 3276 °C/°F 0=No ATC
23	Reference Temperature for ATC	REF TEMP	Range 0 to 3276 °C/°F 0=No ATC

24	Coefficient of Expansion	EX COEFF	%/°C or °F. 7 digits 6 dec. places 0=No ATC
25	Loop Label	LOOP LBL	Max 6 alphanumeric characters
26	Total Label	TOT LBL	Max 4 alphanumeric characters
27	Rate Label %	%LBL	Max 4 alphanumeric characters
28	Flow Rate Label	F RATE L	Max 4 alphanumeric characters
29	External A/M Switch Enable	E A/M EN	0=Disable 1=Enable
30	External A/M Contact Number	E A/M C#	0=Not implemented, or 1 through 8* see note
31	External On/Off Switch Enable	E O/O EN	0=Disable 1=Enable
32	External On/Off Contact Number	E O/O C#	0=Not implemented, or 1 to 8** see note
33	External Totalizer Inhibit Enable	E INH EN	0=Disable 1=Enable
34	External Totalizer Inhibit Cont. Num.	E INH C#	0=Not implemented, or 1 to 8*** see note
35	External Clear Enable	E CLR EN	0=Disable 1=Enable
36	External Clear Contact Number	E CLR C#	0=Not implemented, or 1 to 8**** see note
37	External Measurement Pointer	EXT MEAS	May be 0 or any legal output pointer
38	External Demand Pointer	EXT	May be 0 or any legal output pointer

		DMND	
39	External Ratio Pointer	EX RATIO	May be 0 or any legal output pointer 0 to 1
40	Specific Gravity Label	SG LABEL	Max 6 alphanumeric characters
41	Associated Master	A MASTER	0=master 0 or MO 1–6 through M24–6
42	External Contacts Pointer	EX C BLK	0=disabled or cont. input block -1/-2 pointers
43	Measurement Loop	MEAS LP	0=Std. Blend control 1=measurement only

Notes:

*	Bit value of 1 switches block to Manual.
**	Bit value of 1 turns the loop Off.
***	Bit value of 1 inhibits totalization.
****	Bit value of 1 clears total.

- The information displayed in the areas assigned to Loop Label is a unique name of six alphanumeric characters assigned to the loop.
- The information displayed in the areas assigned to Value is obtained from a live system, with Setpoint being the *loop ratio setting* and Total the *current loop total*. The Sp Gr is the *specific gravity*. The Rate is the *loop flow rate*. The areas assigned to Units are the *engineering units,* which are individually associated with each of the foregoing.
- The area covered by Status is the status word showing whether the loop is being manipulated *locally* or by *computer*.
- The area covered by A/M is the status word showing whether the loop is on *automatic* or *manual* control.
- The two thick horizontal lines are analog bar graphs. The upper one gives the loop flow rate and the lower one the controlled loop output. Both graphs are scaled 0 to 100 percent and have a 2 percent resolution.
- The area covered by Mast.No. defines the loop master number. In a single-master system, Master 0 is always displayed as an M. Otherwise the relevant Local Master is identified.
- The area of alarms covered by alarm symbols displays the symbols when appropriate conditions demand that they be shown: +for a plus alarm,−for a minus alarm, *SD* for plus or minus shutdown, *P* for pace alarm, *LF* for low flow alarm, *HF* for high flow alarm, and MM for manual alarm.
- The area covered by CRT label displays the appropriate program code functions.

Table 6.3 lists the full program codes available for the blend loop block. This arrangement shows their meaning, the codes appearing in the area CRT labels on the display, and added comments on the functionality of the program coded entries.

DESIGN AND IMPLEMENTATION OF A (SPECIFIC) BLENDING SYSTEM

SYSTEM APPLICATION—OBJECTIVES AND OVERVIEW, BRIEF SYSTEM SPECIFICATION—PHYSICAL REQUIREMENTS

As stated earlier when we introduced the subject of this chapter, the blender was a proprietary instrument with the basic capability of running a single blender having 24 independent product streams, but with other features, including multimaster configuration. The requirement in this instance was to have this single blender reconfigured to provide for four independent blenders, with each blender having the following combinations of associated streams:

Blender #l	5 active streams
Blender #2	4 active streams; with one stream sharing a common source with blender #1 plus one spare stream
Blender #3	5 active streams; two streams that shared common sources with blender #1
Blender #4	3 active streams

The number of streams for blenders #1 and #2 was initially defined; however, the system was to be capable of providing the addition of two component streams for #1 in the future.

The components of the product were highly flammable; therefore, all circuits were to be designed to meet the safety standards of a hazardous process plant.

Product Requirements

In addition to the basic blending controls, the system had to be capable of working to pre-defined products and of storing and adding new recipes for the various blended products to the product repertoire. The products were to be assigned to and prepared by specific blenders. Moreover, each product would comprise a base component with a fixed ratio of the others to make up the required blend. Once the product and the blender had been initially defined, the system was to be capable henceforth of determining the blender necessary, the required components, and the ratio of the whole blended product from only a single input of the product name and the total quantity of the product required.

Operational Requirements

The delivery was to be made directly into road tankers, the vehicle driver being responsible for preparing the vehicle for accepting the product at the point of delivery, filling the on-board tank compartments, and ensuring the delivery system was ready for the next driver to use.

On completion of the delivery, the system was to produce a waybill for signature by the tanker driver showing the date, product name, and total quantity delivered. Separate documents were also required for:

- The invoice, which would be dispatched to the customer separately. The price shown on this document was to be capable of being modified to allow for market fluctuation in each component cost.
- Detailed product inventory. The internal administration of the company would use the inventory data and stock control to provide timely replenishment of those items running low.

System Overview

Figure 6.10 presents a general overview of the blending system. Since it is not possible to show all the information on such a diagram because of the split necessary in the technical and commercial requirements, the diagram concentrates on the technical aspects only.

Additional Equipment

In order to meet the system requirements of recipe handling and production of commercial documentation, it was necessary to provide the following equipment:

- A personal computer with a serial port (RS-232) connection, high-capacity hard disk drive, two floppy disk drives, and sufficient RAM (random access memory).
- A printer to work with the personal computer.
- Bar code reader and associated printout equipment.

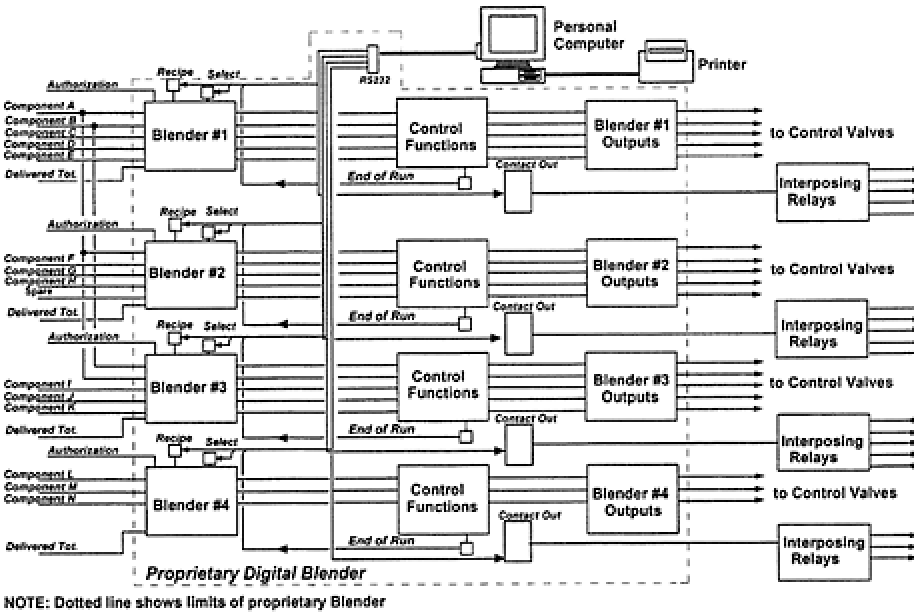


Figure 6.10: Overview schematic of blending system.

• Various pushbuttons and selector switches, relays, and signal lamps.
• A small PLC (programmable logic controller) to implement the pump selection logic.

System Inputs and Outputs

Figure 6.11 shows the arrangement of the inputs and outputs associated with blender #1, together with a partial view of the interfaces with blender #2. This type of arrangement is repeated for the other blenders in the system. The communications between the blender and the personal computer are carried out over the RS-232 serial link.

The signals from and to the field-mounted instrumentation are: analog 4 to 20 mA for target flow transmitters and for current/pneumatic converters for the control valves; and discrete contact output closures for solenoid operated valves. The interconnections for each type of instrument are carried out as shown in Figure 6.12.

Since the plant is considered a hazardous location, all signals to and from it (i.e., between the Field and the Control-room area) must be rendered safe; that is, the signals must not be capable of causing a release of energy liable to ignite any flammable gases that might be present. This requirement also applies to all other plant equipment on the site, although instrument and control engineers are not responsible for these items. Their only role is to ensure that any connections made to such equipment will not infringe on safety requirements. The types of safety barrier used were galvanically isolated units. These safety barriers have the advantage of not requiring an equipotential earth connection. However, care must be taken to avoid

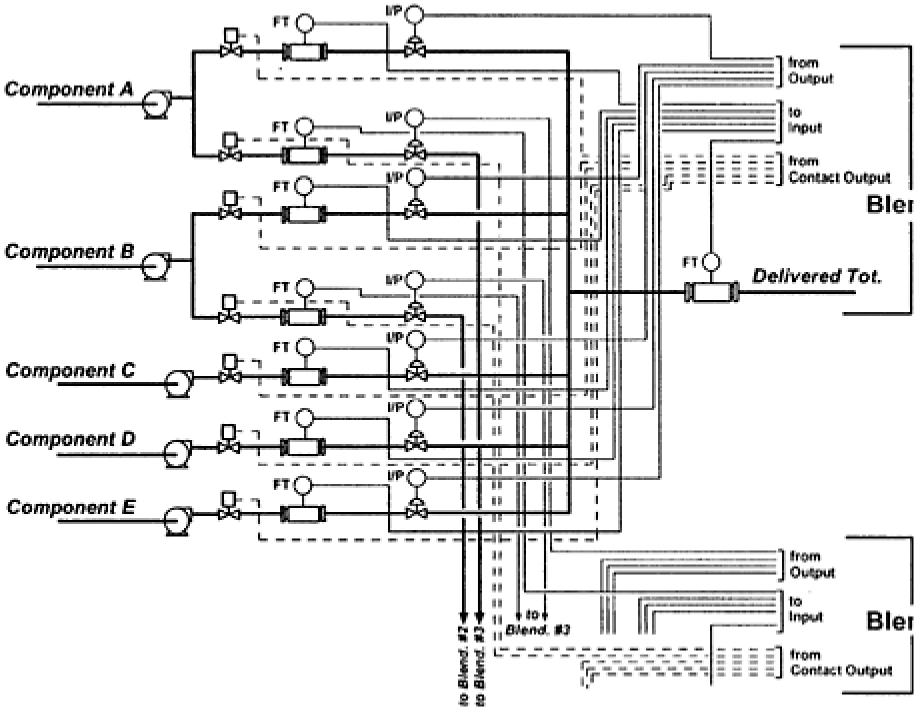


Figure 6.11: Schematic of measurement input/control output signals for blender #1

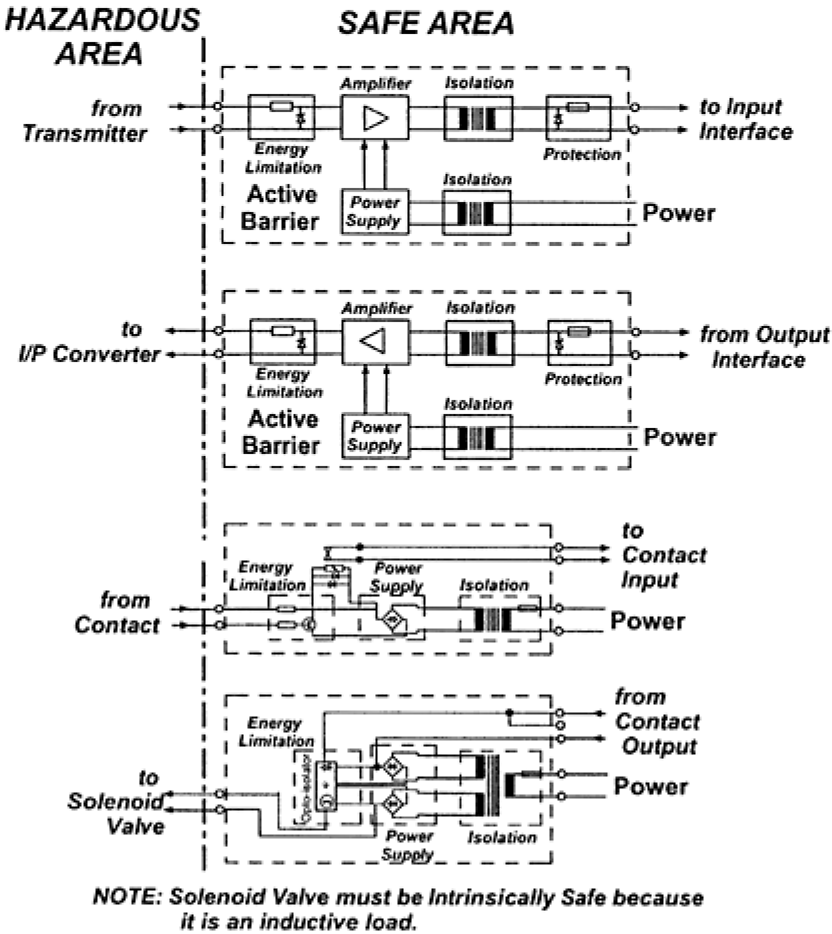


Figure 6.12: Typical connection detail for galvanically isolated safety barriers.

the field cables running parallel to other current-carrying cables, thereby precluding the possibilities of pickup and capacitance effects on the safety of the plant and the control system. Details of intrinsic safety, power, and grounding are discussed in more detail in national standards, related literature, and elsewhere.

The blender we are considering has specific locations for the interfaces to which all incoming and outgoing signals are connected. Therefore adherence to these locations is necessary. To provide for the requirement that some product component lines are shared between the individual blenders, each individual blender stream is provided with separate flow-measuring and transmitting instruments. The user should note that all pumps should be duplicated per component to allow for motor failures that would otherwise interrupt product delivery. A separate PLC (programmable logic controller) to handle the logic for pump selection is therefore to be provided.

COMPONENT PUMP SELECTION

Figure 6.13 shows a typical two-pump selection logic circuit. The arrangement shown is not the only way of implementing the selection; there may be other ways appropriate to individual requirements and local-plant practice.

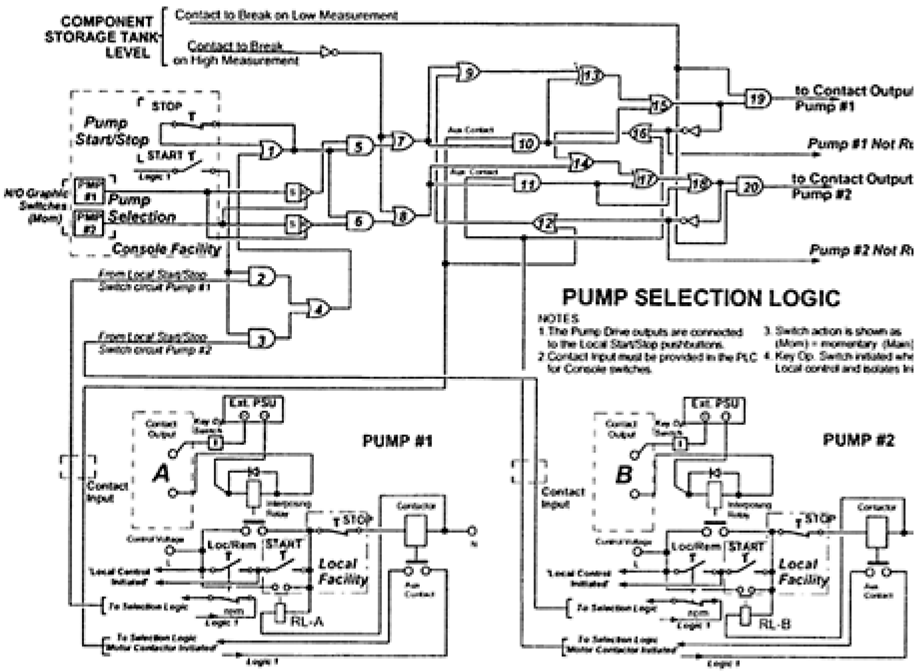


Figure 6.13: Typical local start/stop circuit.

Design Criteria for Pump Selection

The basis for the design of the selection logic is as follows:

- Only one pump is to be in service at a given time.
- In the event of pump failure, the standby pump shall be started automatically. However, the standby pump shall only be stopped from the local Start/Stop facility to permit investigation of the original failure.
- In the event of a pump malfunction, the pump shall be stopped at any time from the local Start/Stop facility. Remote start of the pump from the control room is not possible under this circumstance.
- A low-level alarm on the storage tank shall stop the selected pump. The process operator after investigating the cause shall be required to manually start the pump.
- A high-level alarm on the storage tank shall start the standby pump automatically. The two pumps shall run but only for the duration that allows the tank level to return to a

safe value.

Pump Selection Circuit Operation

The following operational description is confined to the selection and running of pump #1. However, it should be noted that pump #2 operates in identically the same way. It is suggested that the reader follow through the paths for pump #2 to understand the reasoning and circuit operation. For clarity, the types of gates are shown in italics.

No Pump Selection Made:

The *FLIP-FLOP* for both pumps are at logic 0 on the *set* and *reset* inputs.

The *AND* gates 2 and 3 have logic 0 on one input associated with the remote startpush button but logic 1 on the input from the Loc/Rem switch input. The output for both gates will therefore be at logic 0.

As a result, neither of the pumps will start.

Pump Selection and Pump Start from the Control Console (Remote Facility):

Select pump #1 through the pump selection switch unit, which is an interlocked device, usually referred to in the United Kingdom as a *ganged switch*, such that selecting one switch mechanically releases the other, thus allowing only one switch to be selected and initiated at any time. The *FLIP-FLOP* for pump #1 will have logic 1 on the *set* input and the *FLIP-FLOP* for pump #2 will have logic 1 on the *reset* input to ensure that pump #2 will not be started.

A*ND* gate 2 has logic 1 on the input from the Loc/Rem switch. Initiating the console start pushbutton puts logic 1 on the second input of gate 2, with the result that gate 2 output is turned on to logic 1.

O*R* gate 4 having a logic 1 applied to its input from gate 2 is turned on and makes its output logic 1. The output of gate 2 is applied to one input of *OR* gate 1. Gate 1 is held at logic 1 indefinitely through the stop switch and is released only when the switch is opened.

The *FLIP-FLOP* for pump #1 has logic 1 on the *set* input, which is applied to one input of *AND* gate 5 whose second input is derived from the output of *OR* gate 1, which is also at logic 1. This turns *AND* gate 5 on and makes its output logic 1, which is applied to one input of *OR* gate 7. This turns gate 7 on and applies logic 1 to one input of *OR* gate 9 and one input of *AND* gate 10.

O*R* gate 9 is turned on and applies a logic 1 to one input of *XOR* (exclusive or) gate 13. The second input of this gate is logic level 0; hence, gate 13 is turned on and has logic 1 on its output, which is applied to one input of *OR* gate 15 to turn it on.

The output of gate 15 is applied to one input of *AND* gate 19, the second input of which is at logic 1. This turns gate 19 on and applies logic 1 to the contact output.

The contact output module has an interposing relay coil and power supply connected across its terminals. When the module is turned on, the relay is energized to close its associated contact and energize the pump contactor and start pump #1.

The contactor for pump #1 being energized closes its auxiliary contact. This applies logic 1 to the second input of *AND* gate 10 and turns it on. Logic 1 appearing on the output of gate 10 also puts logic 1 on the second input of *XOR* gate 13; this turns gate 13 off, making its output logic 0. At the same time, the second input of *OR* gate 15 has logic 1 applied to its second input to maintain gate 15 in its on state. The remainder of the circuit operates as described earlier and allows pump #1 to continue running, but this time dependent on the state of the auxiliary contact in the motor contactor which will trip if any untoward incidents occur, for example, the thermal cut-out operates, or motor current exceeds its prescribed limits.

Automatic Start of Standby Pump #2:

In the event pump #1 fails, the auxiliary contact associated with it will open. This will make the output of *OR* gate 15 logic 0, but since this is inverted and applied to one input of *OR* gate 16, it will turn gate 16 on because the second input to the gate is logic 0 as it is derived from the auxiliary contact of pump #2, which is not running. As suggested in the figure, the inverted output can also be used to inform the control room operator that the selected pump has failed. The output of gate 16 is applied to one input of *OR* gate 14, which will turn the gate on. The output of gate 14 is applied to one input of *XOR* gate 17, which will turn it on. The second input of gate 17 is at logic 0 because pump #2 is unselected. The output of gate 17 is applied to one input of *OR* gate 18, which will turn it on; at this time the second input of gate is at logic 0. The output of gate 18 is applied to one input of *AND* gate 20 and will turn it on because the second input of gate 22 is at logic 0, for it is assumed that the component storage tank has sufficient product and is above the low-level alarm trip point. Gate 20 being turned on applies logic 1 to the contact output.

The contact output module has an interposing relay coil and power supply connected across its terminals. When the module is turned on, the relay is energized to close its associated contact and energize the pump contactor and start pump #2. The auxiliary contact on the pump contactor is made once the motor starts and will continue to run because the path is provided through gates 16, 14, 17, 18, and 20. Pump #2 can be stopped only through process operator intervention at the local facility. This has been chosen because it gives plant personnel the opportunity to investigate the cause of the initially selected pump failure.

Local Start/Stop Facility:

The plant on-site process operator has been allowed the facility of manipulating any of the component pumps from a location adjacent to the pump motors. This facility has been given to enable timely intervention in case of emergencies. However, it does not preclude the on-site operator contacting his or her counterpart in the control room to advise any on-site action being undertaken.

When the Loc/Rem switch, which has a *maintained action* (i.e., the device holds its last operating condition indefinitely until changed), is transferred to the local operating position, the normally open (NO) contact on the switch is closed, and the normally closed

(NC) contact is opened. This action can also be used to initiate a signal lamp in the control room, as suggested in the figure, to advise that the pump is under the control of the on-site process operator. Under this condition and as a safety measure, the control room operating personnel are prevented from manipulating the pump. With the Loc/Rem switch in the local position, a path is provided to permit the contactor to be energized when the Start pushbutton is initiated.

Initiating the Start pushbutton provides a supply to reach the contactor coil through the normally closed contact of the Stop pushbutton and energizes it. At the same time, power is applied to the coil of relay RL-A and this too is energized, allowing its associated contact to close to continue providing the path and power to the contactor coil, thereby keeping it energized and the pump motor running for as long as the path exists.

Initiating the Stop pushbutton opens the circuit established when the Start push-button was actuated and breaks the power supply to the contactor coil, allowing it to deenergize and thus stop the pump motor from running.

Component Storage Tank Level

Each component storage tank is provided with a level sensor/transmitter that has high- and low-level alarm changeover contacts. The contacts are implemented as fail-safe; that is, they are “energized” and break on an alarm condition. This does not assume that the contact closure is actuated electromechanically only, but it could also be completely mechanical. However, the important point is that in both instances the contact break (separation) is initiated by the action of the sensing device when it reaches a predetermined high level. The reason for this is to permit the system to recognize the fact that a parameter has departed from its assigned operational limit. If the contacts were to make (close) on an alarm condition and the initiating unit had failed for whatever reason, then the system would not be aware of it. The system would assume that the contact was behaving as normal and hence would ignore it. The result in this instance could be disastrous.

Tank Low-Level Alarm:

As stated earlier, the contacts are fail-safe and therefore produce logic 1 as an output, which is applied to one input of *AND* gate 19. Hence, when the component tank goes below the setting of the low-level alarm the output will change to logic 0 and turn gate 19 off and produce logic 0 on its output. Since gate 19 is an *AND*, when one of its inputs is logic 0, its output will be logic 0, which when applied to the contactor of pump #1 will stop the pump motor from running.

Tank High-Level Alarm:

The operational specification of this situation as stated before requires that both pumps operate simultaneously and return to normal when the level has been reduced under the action of the two pumps working in unison. The scenario as described will be the situation when neither of the pumps has been selected. However, when one pump has been selected, the chosen pump will continue to run as normal and only the standby pump will be started.

Neither Component Pump Selected:

The circuit operates in the following way: the normally closed alarm contact is inverted and applied to one input of *OR* gate 7 and also one input of *OR* gate 8. As a result, when the component storage tank level goes high, the alarm contact opens, which makes the inputs to *OR* gates 7 and 8 logic 1s. The logic 1 outputs from these gates are assigned to one input of *OR* gates 9 and 14, which turns these gates on and produces logic 1 on their outputs. The output from gate 9 is applied to one input of *XOR* gate 13, and the output of *OR* gate 14 is applied to one input of *XOR* gate 17. This turns the gates on and makes their output logic 1. *OR* gates 15 and 18 having logic 1 on one of their inputs are both turned on. The output of *OR* gate 15 is applied to one input of *AND* gate 19 and will turn it on to make pump #1 start. The output of *OR* gate 18 turns it on to make its output logic 1, which is applied to one input of *AND* gate 20 to make its output logic 1 and start pump #2 also.

When the high-level alarm on the component storage tank returns to a value below its high setting, the circuit is unable to sustain itself and the pumps stop running. This fulfills the operational specification for the condition when neither of the pumps is selected.

One Component Pump Selected:

If a component pump has been selected, then the chosen pump will continue to run in the normal manner under the dictate of the path of the chosen pump described earlier. The standby pump will be started as described in the immediately preceding section.

THE MICROPROCESSOR BLENDING CONTROL UNIT

As stated earlier, the equipment used on this application was a proprietary controller that had to be configured to allow the instrument to depart from its customary arrangement of a single blending controller and perform the function of four independent blenders. No internal circuit alterations were carried out on the instrument, and all the connections to and from the field-mounted measuring and control devices conformed, as far as physical location was concerned, to the controller's original requirements. The types of input/output interface modules and the actual arrangement of the units are shown in Figure 6.14. The pulse input module allows the use of flow sensors that produce a pulse train proportional to the flow-rate measurement (e.g., turbine flowmeters). This type of flowmeter is used extensively in gasoline blending because of its high accuracy and the fact that the process fluid has an extremely low viscosity. A turbine meter is quite unsuitable in applications where the process fluid is viscous. When pulsed flowmeters are not used, position 1 has to be left empty.

It is always considered desirable to include an isolation transformer between the power source and any (similar) control system, for this arrangement avoids undesirable pick-up of interference that could affect the proper working of the system. On some installations, a dedicated uninterruptible power supply (UPS) is sometimes used; this equipment has the isolation transformer and battery backup built in, and all that is necessary is to connect the UPS to the power source. In case of power failure, the switchover from one to the other is automatic, and when the situation is over, the unit recharges the batteries ready for the next time. As will be appreciated, the expected duration of power outage to be covered has to be specified as this affects the cost of the equipment.

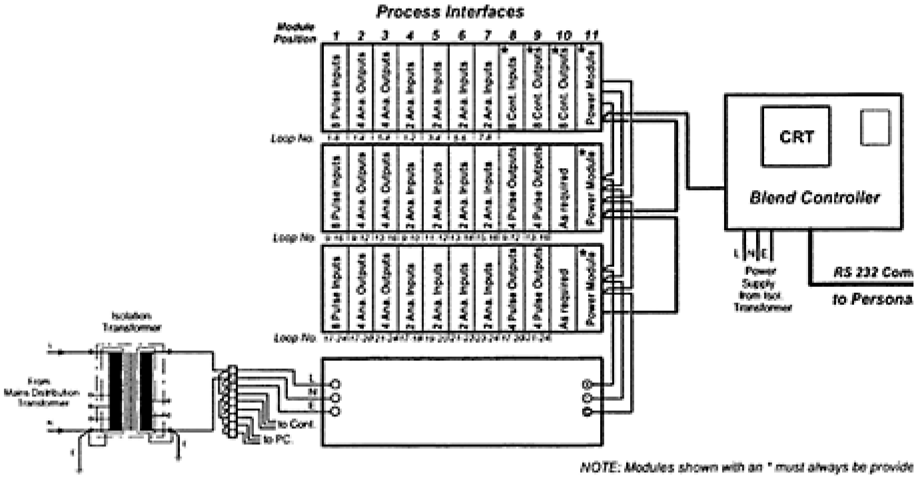
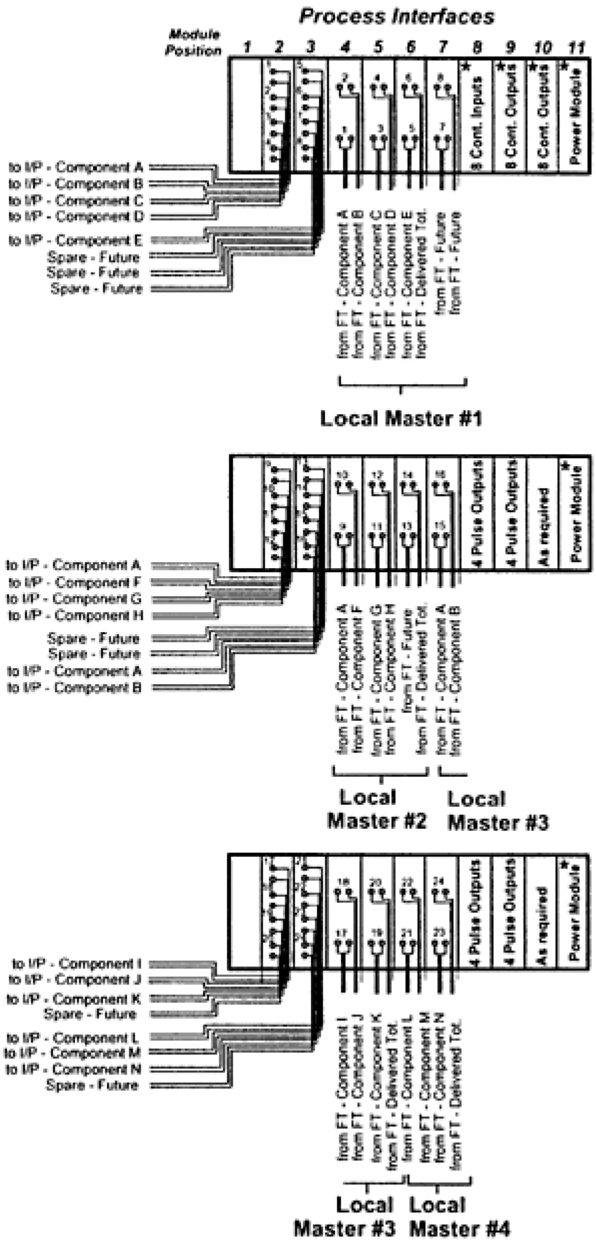


Figure 6.14: Arrangement of microprocessor-based blender.



***NOTE:** The loop numbers recognized by the blending controller are shown near the connection terminals.*
The tag numbers associated with the loop numbers are also shown.
Local Master #3 is split over two nests.

Figure 6.15: Measurement and output signal connections to the blending controller.

Allocation of Input and Output Interfaces

The blending controller is designed as a dedicated instrument. Therefore, all interface module types and connections to and from the instrument are allocated specific locations in relation to the loop references. It is not possible to interchange these fundamental functional arrangements, although some leeway does exist in the card module model selection for the dedicated functions.

The measurement inputs to each interface of the blenders are arranged to run consecutively, with each spare loop allocated to the end of the series. This results in an arrangement where blender #1 is assigned to blend loop numbers 1 through 8; blender #2 to blend loop numbers 9 through 14; blender #3 to blend loop numbers 15 through 20; and blender #4 to blend loop numbers 21 through 24. This arrangement ensures meaningful page-displays for the operators on the CRT (including potential provision for "Spare" loops for later expansion without major reconfiguration and disruptive and costly display changes) and obviously a logical wiring layout.

The viscosity of the process fluid in this particular application precluded the use of turbine flowmeters. Hence, other types of meter that performed the measurement were used. These alternate instruments could only provide analog signals in the range 4 to 20 mA for the measurement. Therefore, the analog current input interfaces had to be used instead. The equipment is actually mounted in a framework as in Figure 6.15. Cable-trunking is provided between each nest to carry the interconnection cables. The trunking that served the galvanically isolated safety barrier units carried a physical barrier along its length to separate the intrinsic safe wiring—from and to the field—from any others that did have to comply with the regulations. The intrinsic safe wiring used the normal red and black color for the insulation to identify the polarity of the conductor, but there was a light-blue colored sleeve over the exposed cable where it was fixed to the connection terminals of the barrier module.

Blender Control System Hierarchy

The controls in this system are arranged in the order shown in Figure 6.16. The data from the PC are transferred to the local master, which coordinates the working of all the individual loops assigned to it, especially those involved with the product being made at any given time. This last statement implies that not all the component streams are used to make a particular product; in those instances where a component(s) is (are) not required, a batch size is not downloaded from the PC. The coordination ensures that the blended product is at all times in full agreement with the product specification. In this respect, the control involves the correct ratio being maintained, and the flow rates are paced accordingly. For details on how pacing controls operate, refer to the information given on this subject in Chapter 3 where an analog system is shown. The pacing control technique shown for the analog system should be studied to understand the principles involved, for these are fundamentally applicable in all such instances, albeit the present system operates in digital form.

The RS232-C Serial Communications Link:

The blending controller had this facility provided as part of the original instrument specification. Hence, the protocol used when connecting the controller to other instrumentation had to be adhered to

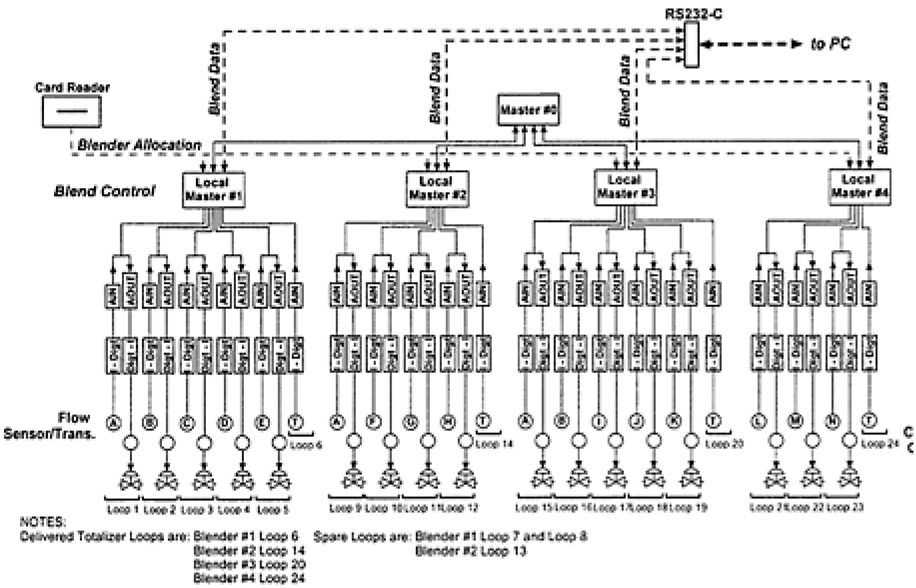


Figure 6.16: Schematic of blending unit control hierarchy.

for meaningful communication. This link was also usable for down/uploading configuration databases via the personal computer.

SOFTWARE DESIGN REQUIREMENTS

COMMUNICATION BETWEEN THE BLENDING CONTROLLER AND THE PERSONAL COMPUTER

The system described in this section applies only to the specific project and the equipment involved and should therefore be used solely as a model. It is not recommended that it be duplicated, although some of the techniques can be applied in principle only to other systems. The details discussed, however, do show how system enhancements can be incorporated by progressive analysis of the user's requirements and developed therefrom between project definition and handover.

The communications and operations package is broken into two modes. The one shown in Figure 6.17 is called *on-line* because the system is operational in the sense of blending the required end-product, and the other is called *off-line*, a name chosen to indicate that neither the blending controller nor the PC is yet manipulating the process.

The On-Line Mode

The on-line mode is the normal production-operating mode of the blender. As will be seen from the flowchart of Figure 6.17, the system allows two methods of defining a product. The first is for a Standard, Predefined Recipe by entering the product name along with the required quantity, and the system takes over from there. The system gets ready to load the recipe and associated blender—if available (i.e., not running)—and instructs the operator to initiate the Run pushbutton on the blender; else it advises that the blender is running. The second method allows the manufacture of a special product, not already included in the database Product List. This second procedure is a little more time consuming with regard to operator entry time and initiation and plant interruption; the extra time is reflected in the price of the product. If the demand is later found to be high enough, the product can be included in the repertoire of standard recipes and allocated a product name. This inclusion will have to be carried out in the off-line mode as will be shown in Figure 6.20.

When preparing a special recipe, the operator must enter the percentage of each component required; the system checks whether the totals add up to 100 percent. The final total to be delivered is also entered, together with the blender in which the product is to be prepared. The operator must then enter his or her initials so that the manufacture of the product can be recorded. This special facility may be restricted to particular personnel via the security passwording.

In the case of a standard (recipe) product, once selection of the operation, declaration of the product name, and the quantity required to be made are completed, the system takes over from there. The operator remains present to take care of any untoward situation that may arise. In the event of a problem, the operator aborts the blend, and the system shuts down in an orderly fashion, allowing the documentation (up to the time of stoppage) to be produced for record and stock control purposes.

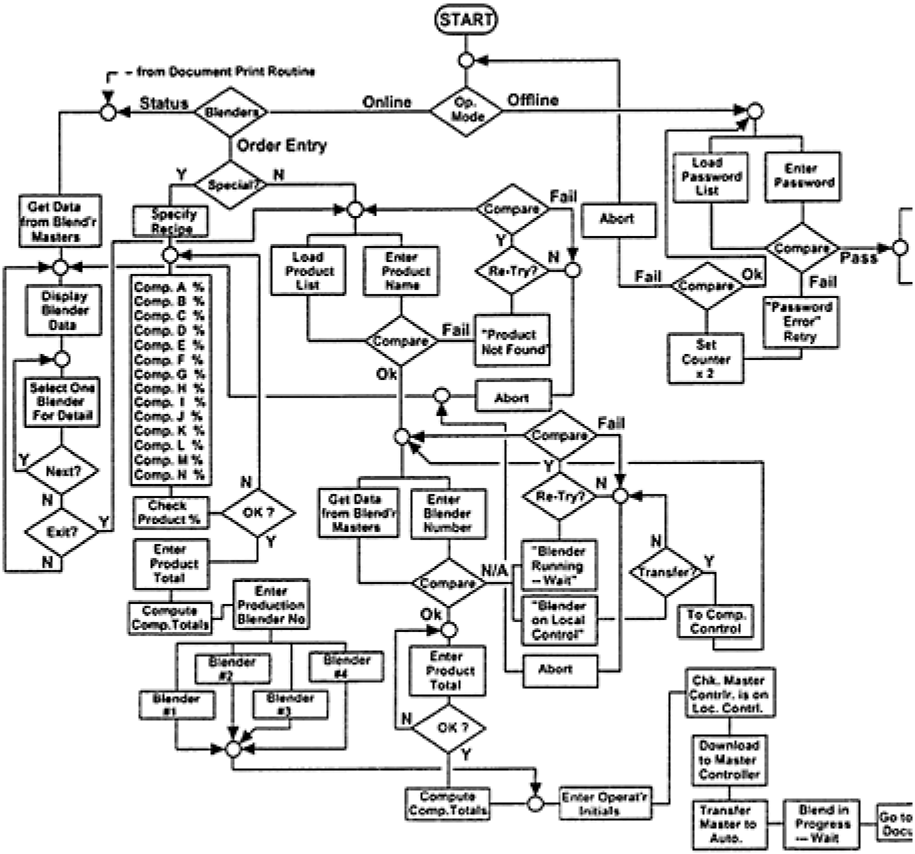


Figure 6.17: Flowchart for blending system working in on-line mode.

Because the product is delivered directly to the tanker, the vehicle is emptied to a safe store and then made ready for the next correct delivery to be made.

Product Delivery

The operator who receives the request for the supply of a product has to go through the formality of entering the product name, quantity, and allocating the delivery point. This procedure is necessary because each blender has a particular area under the delivery gantry beneath which the tanker driver has to place his vehicle, ready to accept the discharged product. The procedure involves the receiving-operator issuing the tanker driver a bar-coded delivery card defining the delivery point. The tanker driver has to perform the following task before the delivery can be effected. On arrival at the delivery point:

• Insert the bar-coded card into the card reader, which, if accepted, will illuminate a green signal lamp and set up a path for the next operation.

- Once permitted, the driver has to electrically discharge the vehicle to ensure that there is no residual static charge on the truck. The driver discharges the vehicle by connecting the grounding point on the vehicle with an earth-connected metallic bar.
- With the two initial requirements complete, the path is clear for the product delivery to commence, which is signaled by a contact closure to the blender. Throughout the discharge procedure, the driver has to maintain the product discharge nozzle contact attached to the gantry; a contact break will stop the delivery and illuminate a red signal lamp at the gantry.

On-Line Manufactured Product Documentation

As shown in Figure 6.18, the system is capable of producing a variety of documentation. Two of the standard documents required in any such operation are a delivery note and an invoice, both of these are allowed for. In the delivery note document, all that has been allowed for is the record of the product name, total amount delivered, plus the date and time. Additional information such as space for acceptance signatures, and delivery vehicle reference will be provided.

Allowance has also been made for the component usage to be evaluated; this provides the process administration department with sufficient information to maintain adequate stock control of the raw material inventory and to ensure that sufficient material is available to meet the demand placed on it. The system automatically updates the values shown as zz in the component registers in Figure 6.18 and produces a suitable report when required. The format of the report has to be decided by the appropriate plant authority.

The system will also produce an invoice, which will give the product, total quantity delivered, and the price. Additional provision is made in the invoice for the unit costs to be adjusted to suit the changing state of the marketplace. This facility is catered for in the step where provision is made to change the individual component price factor shown as xx in Figure 6.18. The factor includes an amount that represents the handling and profit margin allowed for. However, the amount is not declared in the document because it is financially sensitive and is therefore not divulged.

In all the documentation discussed, please note that the printout format of the document is the subject of separate discussion and agreement by management, and suitable steps have to be taken to meet the document print format.

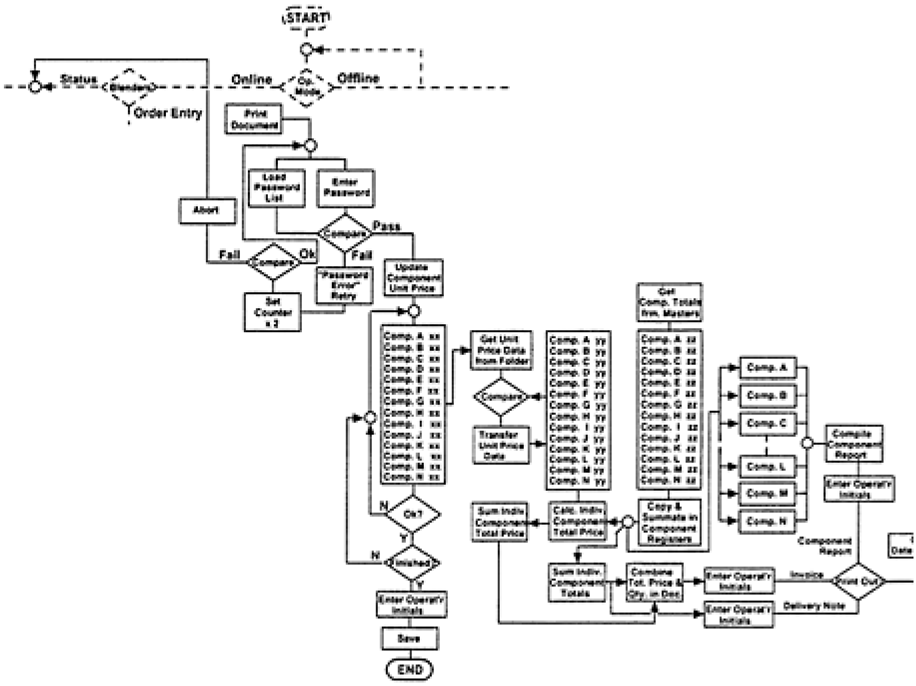


Figure 6.18: Flowchart for documentation printout in on-line mode.

The Off-Line Mode

Uploading and Downloading the Blending Controller Database

The off-line mode is applicable for allowing changes to the configuration database to be made. This functional requirement cannot be accomplished when the system is actually regulating the process. It is as well to define the meaning of the terms *upload* and *download* when used in connection with this system. In this system arrangement, the PC is considered to be at an hierarchical level above the blending controller, and any data transfer from blend controller to the PC therefore has to be made in an upward direction, whereas any data transfer from PC to blend controller will, by implication, be made in a downward direction. The system (hardware configuration) database is held in the blending controller itself (as always in the case of a stand-alone blending controller). The PC has access to any database using the up/download facility via the Serial RS-232 port. Based on the preceding information, however, it follows that the initial data entry must be carried out on the blend controller itself because under this condition no database exists and up/download has no meaning. Once configured and a database is entered, up/downloading does become a useful means of implementing changes.

Database Modification

To modify a controller database requires verification that the person seeking to make the changes is authorized to do so. This is one level of protection that is essential to preserve the integrity of the system. The person wanting to gain access to modify the information is given two opportunities to obtain entry, after which the entry system is aborted and returned to the starting condition. To add yet even greater security, a second level of checking has been added, and this level requires a unique access code to be entered before the system will permit the information to be altered. The security passwords and access codes have to be initially declared and stored within the PC system, but facilities have been included to change these, if necessary, to cater for conditions that would warrant future updating. The procedures that permit alterations are included in the modification routines; these are shown later in Figure 6.21.

Hard Copies of the Database, Configuration, and Products

Figure 6.19 shows the provisions that are included to permit a printout of all the information contained in the (hardware=blender) system so that the personnel involved can resolve any issues that require attention. It cannot be emphasized enough that any copies obtained (suitably dated and identified) must be stored carefully, for they could affect system and commercial security if they fell in the wrong hands. The figure also shows that a limited number of attempts are allowed for password and access code entry; this prevents unlimited code-breaking attempts by personnel. Although not included in this system, an additional feature could be implemented that would log all attempts made to gain entry to the system and provide evidence of any violation, and require even more stringent alerting security measures if commercially or otherwise deemed appropriate.

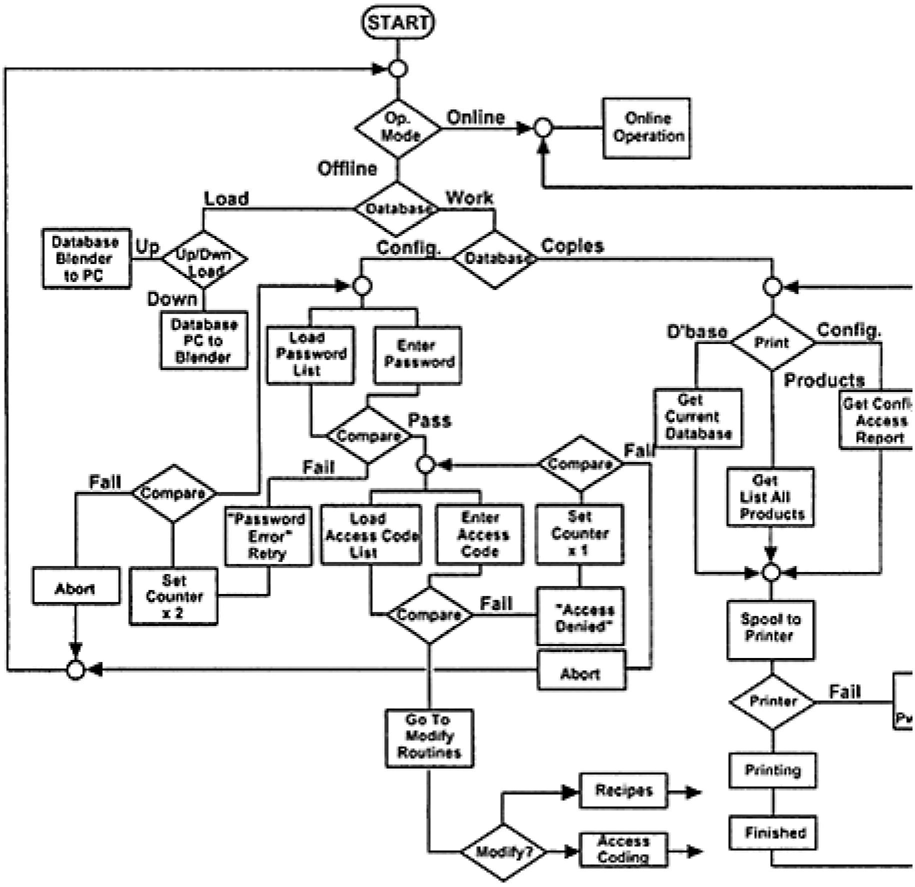


Figure 6.19: Flowchart for system working in off-line mode selection of up/download, on-off-line operation, and printout of products, configuration, and database.

Database Configuration

The controller database is configured at the instrument, using a series of entry *program codes* to give the required configuration. Printed blank forms for each type of control function required can be prepared from the manufacturer's published information, and the required data can be manually added to it as an aid to data entry. However, as stated earlier, each applicable piece of data has to be initially entered individually.

Recipe Handling

Figure 6.20 is a flowchart outlining the procedures that permit product recipes to be added, modified, or deleted. Any changes made are automatically saved and stored in the appropriate locations. The person making the changes will need password authorization, and must initial the changes or additions, which are date and time stamped by the system. When additions are made, the blender that will be used must be specified. This information will be required when a product is prepared in the future.

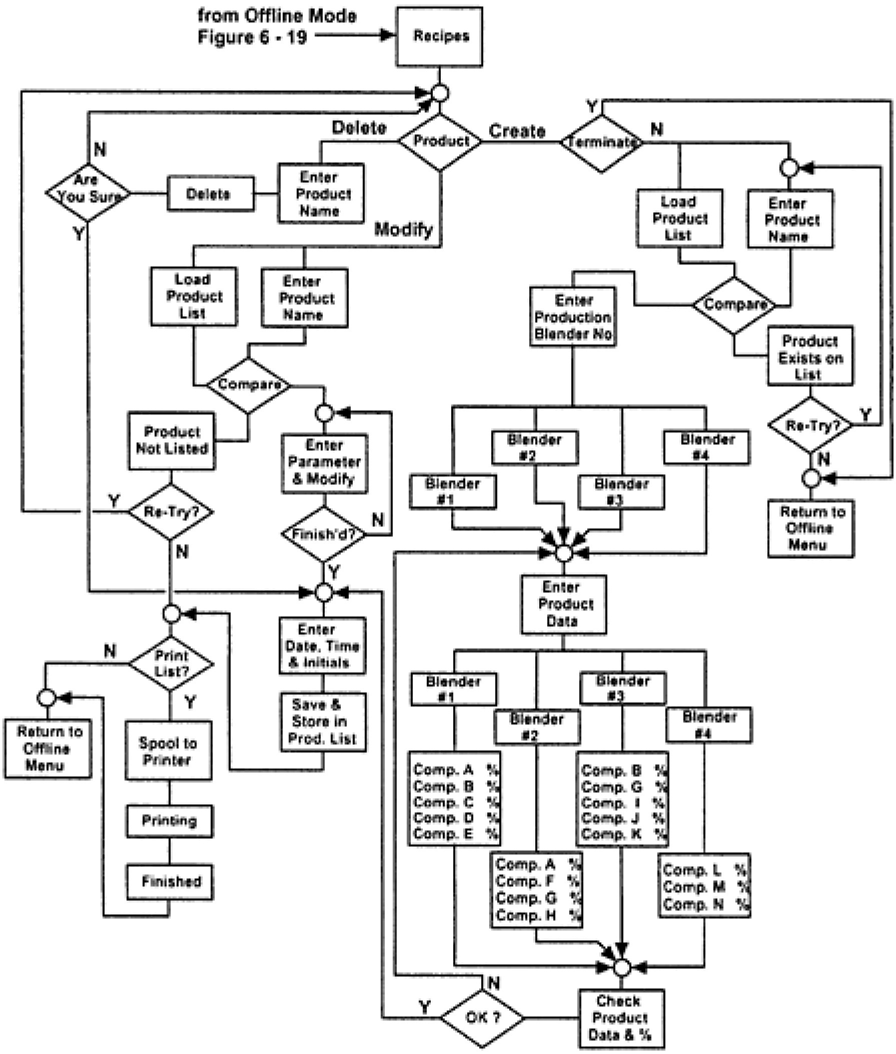


Figure 6.20: Flowchart for system recipe handling in off-line mode.

Formulating new recipes is carried out when the blender is not on-line. However, the process supervisor may make changes to a recipe if required, but this is an on-line function, as described earlier, and is recorded when done. Plant management may include this altered recipe in the list of products if it is thought to be a viable product.

Implementing Changes

Figure 6.21 outlines the methods of changing the various security codes used. The facility to alter security codes is necessary to allow for changes in operating circumstances that could adversely or otherwise affect the operating personnel, procedures, or the business in general. The changes must always be carried out in the off-line mode so as not to affect the production runs.

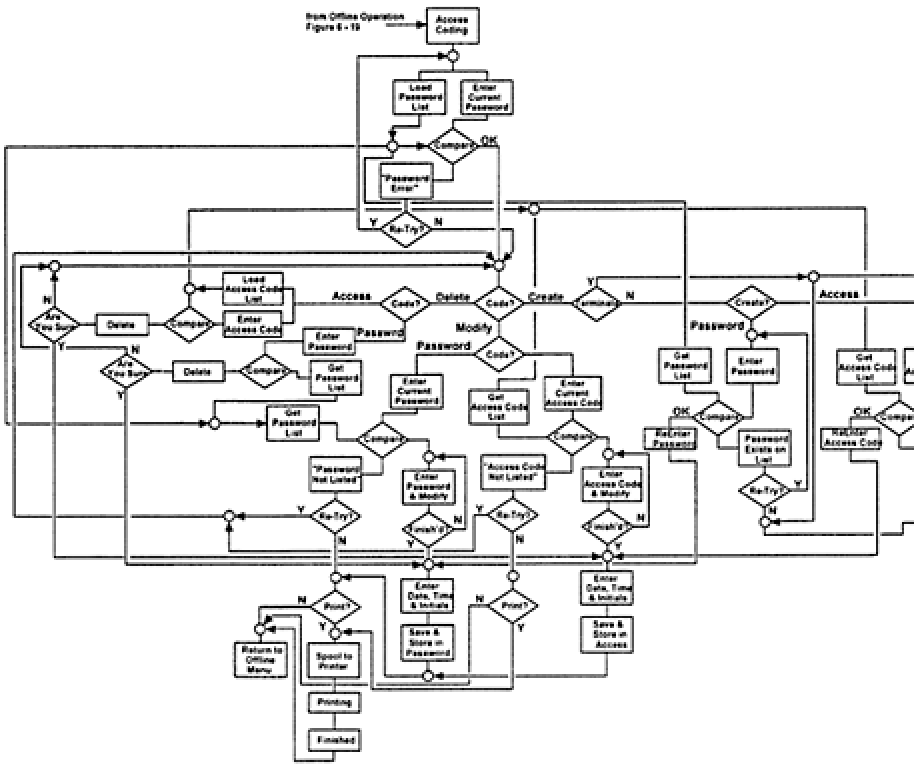


Figure 6.21: Flowchart for system security code handling in off-line mode.

SUMMARY

1. In any blending system, more than one loop produces a product. Each loop is devoted to manipulating a different component of the final product in a manner that fulfills the specification requirement of the final product.
2. In the system discussed, the measurement and controlled signals from and to the process are derived from interface modules that change analog-transmitted signals to digital ones that are comprehensible to the microprocessor within the blending controller.

3. The process plant can be nonhazardous; that is, the material being processed does not easily ignite or explode, and therefore normal good practice of instrument installation will apply. When the process plant produces or handles hazardous material, other more rigid precautions have to be taken to ensure the safety of personnel and equipment associated with the manufacturing operation.
4. The measures adopted to achieve safe operation are obtained by inserting safety barriers between the blender interface modules and the field-mounted equipment. These safety devices are designed to limit the energy in the electrical circuit to levels at which any sudden release of energy is incapable of causing a spark to ignite flammable gases that could be surrounding the instruments.
5. Any blending system must have a system master to which all assigned component loops report. The master is the means of initiating any control action. For the system discussed, the number of loops that can be assigned to a single master is 24, and this represents a maximum of a 24-component stream blender. The engineering units of the measurement and demand must be the same; otherwise it will not be possible to accomplish anything correctly due to the mismatch of the units.
6. Instructions to produce a particular product are given to the master as a total quantity of the product required, the name of each component to be used in the recipe, and the ratio of each component in the product recipe.
7. Not all the components assigned to the master have to be used every time to produce a particular product.
8. For the system discussed, it is possible to assign other masters called local masters. Each local master monitors and controls a smaller number of loops, but these local masters will have to report to the system master.
9. For the system discussed, the normal arrangement is for the blender to be a stand-alone controller. However, a supervisory computer can be included, and the communications between the blender and PC carried out over the RS 232-C serial communications link
10. For the system discussed, configuration of the blender must be carried out manually on the blender itself as a series of data entries on a standard electronic form, with each entry initiated by a unique program code.
11. Once configured, the database entered can be modified via the computer initiated by actions called uploading and downloading. Uploading means the data from the blender are transferred from the blender to the computer, and downloading means the data from the computer are transferred to the blender.

CHAPTER 7
The Brewing Industry

From the very earliest of times, humankind has been involved with making intoxicating drinks of one kind or another. The procedures involved in producing these beverages, which had such a euphoric effect on the psyche, gradually took on the ceremonial ritual of a religious act of worship. In most cases, making the brew was the prerogative of either a group of elders or a highly respected member of the tribe. These people looked on their role with such jealousy that they were willing to commit murder to safeguard their right to secrecy of the recipe. Much of the production process was open to be witnessed by the rank-and-file members who were generally involved with procuring and readying the basic raw materials. However, some of the ingredients used had always been a closely guarded secret, with perhaps certain components being known to only one person alone. In many cases, the brew was usually not fermented in the way we know it today, even to the extent that the fermentation process of the concoction took place within the imbiber's digestive system. This sometimes had very serious consequences, in some cases even resulting in the death of the person involved.

In those early times, neither chemistry nor distillation was known, and there must have been occasions when the elders got the formulation wrong, with dire effects for the rest of the tribe. Humans have learned by their errors, and over centuries of use, the formulations have been documented and refined, leaving us today with an abundance of data to be used or modified to suit our much more sophisticated taste. In this section we discuss beer manufacture, which is much more complicated than wine making.

Perhaps it is advisable to clarify the meaning of the different names used to identify the product so familiar to all of us. Historically, in Britain beer was produced by a *top fermentation* process and was called *ale,* but this was only to separate it from those beers called *lager* produced in continental Europe by a *bottom fermentation* process. Today, however, the majority of beers manufactured in Britain use the cylindroconical fermenting vessel (we shall discuss this equipment later) in which the fermentation process is always at the bottom, but the British still cling to tradition and call the brew ale. Beer making has been carried out by a number of ancient civilizations, and accounts of the Babylonians making a brew are a matter of record. Instrumentation and control systems are of assistance, but we will never be able to dispense with the expertise of the brew master.

THE RAW MATERIALS

BARLEY (AND THE MALTING PROCESS)

Barley is a widely cultivated cereal grass of the genus *Hordeum,* and in particular

Hordeum vulgare, which bears bearded flower spikes and edible seeds. The grains of this plant are the most important basic raw material used in beer, ale, and whiskey making. The unprocessed grain is unsuitable for making beer, but subjecting it to a malting (controlled germination) process achieves a radical change. Malting brings about changes in the chemical, biological, and physical properties of the grain. Barley is a very hardy cereal, which is grown extensively for the brewing industry and to a lesser extent for animal feed. *Malt* and a range of malt extracts are made from germinating barley. The barley is deliberately allowed to sprout under moist, warm conditions so that the α- and *β-amylases* become active and start to break down the starch *endosperm*—nutritive tissue surrounding and absorbed by the embryo in flowering plants. Amylases are enzymes that break down starch. The α-amylases (or dextrimorganic amylases) randomly attack starch molecules to produce dextrins, and the β-amylase systematically removes maltose from starch molecules. These two enzymes together are called *diastase*—because they convert starch to maltose in the germinating grains (malt). Dextrin, a white or yellow powder formed by the hydrolysis of starch, has colloidal properties and is used mainly as an adhesive and thickening agent. When the desired amount of maltose has been produced, the grain or the malt is extracted for use in beer making, malt whiskey (whisky), and vinegar. Pearl barley is grain that has been rubbed into spherical shapes and from which most of the bran and the germ have been removed and is used mainly in the food industry as a thickening agent.

The American Malting Barley Association (AMBA) in the United States has specifically bred malting varieties of barley. These strains do not produce as much grain per acre as does barley for animal feed, and as a result maltsters pay farmers a premium to grow malting varieties. The United Kingdom and Europe have no specific malting varieties of barley, but maltsters prefer some varieties to others. The Nutritional Information and Analysis Center (NIAC) allocates quality numbers for malting varieties of grain as they are developed. The United Kingdom and European malsters search animal feed crops for grain that meets the quality requirement, and they also pay a premium for this grain. The requirements for the malting variety of barley are as follows:

The barley sample must be at least 96 percent alive; dry (considered to retain approximately 12 percent moisture); free of infestation, disease, discoloration, and debris—generally comprising weeds, dust, and broken corns; and low in nitrogen.

The nitrogen content requirement is low because excessive N_2 slows down the modification (starch conversion) and lowers the malt extract yield.

Figure 7.1 is a schematic of a single grain of barley: the regional names shown on the outer boundaries of the figure define the areas into which the grain is botanically divided, making it easier to reference then.

WATER

Traditionally, water is known as *liquor* in the U.K. brewing industry; a fact we will have to recall when dealing with U.K. breweries in the future. Since beer is

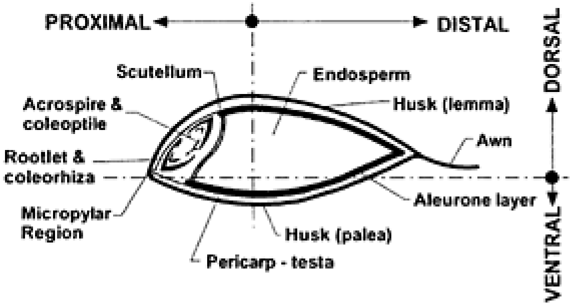


Figure 7.1: Schematic longitudinal section of a barley corn.

composed of almost 95 percent water, the water used in its manufacture must be of the utmost purity, and it is vital that it not impart any unacceptable taste to the brew. In the majority of instances, the brew master—a U.S. title, equivalent to brewer/head brewer in the United Kingdom, and brewmeister in Germany—is the person who decides on the quality of the product made at the brewery. However, in view of the competition in the marketplace the brew master must also take into account this quality aspect. The term *quality* is one of those esoteric terms that will vary from one person to another, hence, an absolute definition is impossible. In the context of beer, however, quality depends on several factors, the main ones being: aroma, flavor, color, and clarity. In the final analysis, one has to concede that the ultimate test for quality rests with the consumer and is reflected in the volume of sales of the product. To maintain the quality decided upon, the pH of the water must be maintained because the pH of the final brew is ultimately related to the initial pH of the water used, despite the several changes in value it undergoes during preparation. The treated water used is known as sweet water (liquor) and it is retained in large storage tanks from which it is drawn and used in the process.

Other materials added to the recipe—additional cereals—are called *adjuncts* and are included to give the desired; flavor to the beer. For instance, rice and millet are included as components in China; flaked rice, oats, and corn in the United States; and wheat in Germany.

WHEAT

Wheat is more familiar for its use in the powdered seed form of flour, which is used extensively in the preparation of cakes, bread, and pasta in which it is the basic ingredient. Botanically speaking, it is any of a variety of grasses of the genus *Triticum* and in particular *Triticum aestivum*. It is widely cultivated in many varieties for its edible grain. As mentioned earlier, it also finds use in the beer brewing process in Germany where it is one of the adjuncts used.

OATS

Oata are another of the several grasses of the genus *Avena*, in particular *Avena sativa*, which is also widely cultivated for its edible seeds and is used as food and animal feed. In the United States, the seed is processed to obtain a flaked form (which is basically the flattened seed) and then used in the brewing of beer.

MILLET

A grass, whose botanical name is *Panicum miliaceum,* is widely cultivated in Asia and Africa for its seed and in the United States, Canada, and Europe for hay. In Asia and Africa the white seeds of the plant are used as food.

CORN

This is the general term for seed or fruit of any of several plants that produce edible seeds, especially with the main crop of a region such as wheat in England, oats in Scotland, and maize in the United States and Australia. Maize is the New World grass, *Zea mays,* grown extensively as animal feed and for its light yellow to medium orange-colored cob. It is also known as Indian corn, which can be cooked and eaten as a vegetable.

YEAST AND OTHER INGREDIENTS

Before we proceed further, we will define the ingredient "yeast," which permits the formation of alcohol through fermentation.

YEAST

Yeast is a *fungus,* usually involved with fermentation and spoilage of sweetened and salted products. The two forms of yeast important in the brewing industry are:

1. *Saccharomyces cereisiae,* used in beer making and bread baking
2. *S. ellipsoideus,* used in wine making.

Of the two, we are particularly interested in *Saccharomyces cereisiae* in beer manufacture, which is further classified into *S. cereisiae* for ale making and *S. carlsbergenisis* for lager making. The separation is not of much use when comparing the strains, but the manufacturing process and the materials used influence the beer types produced from them. Yeasts are a useful source of proteins and B vitamins. Yeast extracts and hydrolysates—products of hydrolysis (i.e., the decomposition of a chemical compound by reaction with water such as the dissociation of a dissolved salt or the catalytic conversion of glucose to starch)—are used as flavors in soups and meat products.

HOPS

Any of several twining vines of the genus *Humulus,* in particular *humulus lupulus,* having hooked leaves and green cones, like female flowers. It is a native flora of Europe, Asia, and North America, but it has been successfully grown in Australia. The female plant is the cultivated variety.

The brewing value lies in the resins and oils contained in the lupulin glands at the base of each bracteole. The mature cones are harvested and processed; the resins impart the bitterness, and the oils supply the aroma of the beer made from it. In modern beers the level at which the antimicrobial character of the resin content is effective is lower, whereas the formulas of older beer had higher hop content. Boiling is necessary for extraction, as well as for killing all vegetable microbes contained in the raw material. Thus, processing improves the microbiological stability of the beer, providing that the overall hygiene of the plant is maintained.

The hops are harvested and kiln dried to reduce the moisture content to about 10 percent, which will then enable them to be satisfactorily and stably stored. Storage is effected by packaging the dried hops in bags made from either jute or woven polypropylene. The packages have a special name, which in Germany is a *ballot* of approximately 90 kg, in the United States a *bale,* and in the United Kingdom a *pocket* of approximately 80 kg in weight. In the United Kingdom, hops were formerly processed in circular brick houses having an inverted conical-shaped roof called an *oast-house* and which were to be found in great numbers in the county of Kent. Today the traditional oast-house has been replaced by a modern, more efficient structure.

The remaining ingredients of brewing sugars and syrups (corn or glucose) complete the list of requirements needed to proceed with the manufacture of beer.

ADDITIVES

Modern technology has also facilitated the inclusion of specific chemical additives to improve shelf life, taste, and color; and some of these permitted additives

are as follows:

E150 Caramel

E212 Potassium benzoate

E213 Calcium benzoate

E214 Ethyl 4-hydroxybenzoate (ethyl para-hydroxybenzoate)

E215 Ethyl 4-hydroxybenzoate, sodium salt (sodium ethyl para-hydroxybenzoate)

E216 Propyl 4-hydroxybenzoate (propyl para-hydroxybenzoate)

E217 Propyl 4-hydroxybenzoate, sodium salt (sodium propyl para-hydroxybenzoate)

E218 Methyl 4-hydroxybenzoate (methyl para-hydroxybenzoate) methyl 4

E219 Hydroxybenzoate, sodium salt (sodium methyl para-hydroxybenzoate)

Each manufacturer chooses the additive(s) that will enhance his product and thereby increase sales.

THE CHEMISTRY

Beer brewing is much more complex than making wine because fermentable sugars must be extracted from the grain, especially from the barley used. To accomplish this extraction the barley must be prepared through a process called *malting*—in which the grain is allowed to sprout—to produce maltose, which is a sugar whose structural formula is $C_{12}H_{22}O_{11}$ (it is also known as *malt sugar*) and other fermentable sugars. Other grain can be used to extend the malt since the amylase content of malt is capable of breaking down more starch than is present in the barley itself. These grains, usually boiled, modify the flavor of the beer and minimize the formation of protein bases.

DISACCHARIDES

Disaccharides are sugars such as sucrose, lactose, and maltose which are formed by a combination of two monosaccharide units with the elimination of a molecule of water:

Sucrose=fructose+glucose
Lactose=galactose+glucose
Maltose=glucose+glucose

A glucose unit has a molecular arrangement as shown in Figure 7.2. The figures within brackets make reference to the carbon atoms easier.

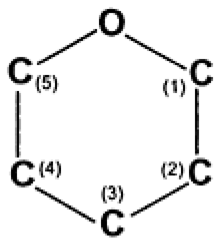


Figure 7.2: A glucose unit.

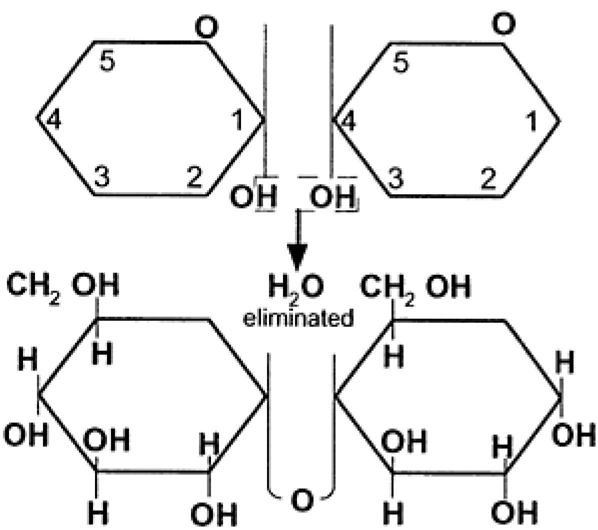


Figure 7.3: *α* maltose and *β* maltose.

MALTOSE

As stated above and shown in Figure 7.3, maltose or malt sugar is a simple disaccharide made from two glucose units which are linked across a carbon atom (1) on the left-hand glucose unit and the carbon atom (4) on the right-hand glucose unit.

A *β* maltose does exist but is less common; its structure is the same except the OH on the carbon on the right-hand side is at the top.

When the two glucose units condense together, water is eliminated and the remaining oxygen atom forms a bridge between the two glucoses as shown in Figure 7.4. This bridge is called the *glycosidic link*. In this case, the glycosidic link is called an *α*, 1–4 link because the left-hand sugar is an *α* form and the link is between carbon atom 1 and 4 of the two sugars joined.

Maltose is a reducing sugar and is produced when starch is broken down by the action of enzymes (amylases), particularly in the malting process of barley for beer making.

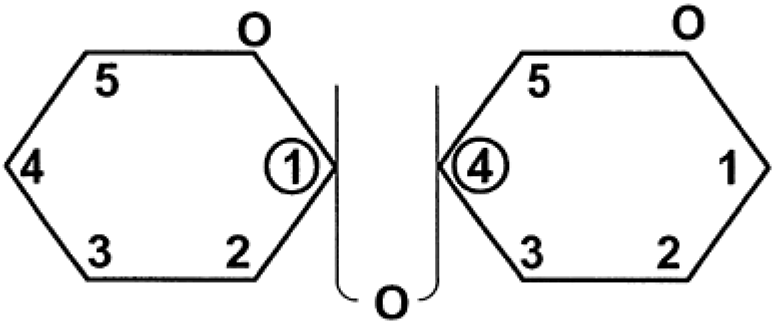


Figure 7.4: *α,* 1–4.

A BRIEF GENERAL PROCESS OVERVIEW

BEERS—ALES AND LAGERS

The malt and cereal grain are roughly milled, and hot water (the mixture is called *wort*) is added in a large container—the *mash tun*. The word “tun” is used quite extensively within the brewing industry in the United Kingdom and is defined as a large cask for liquids, especially beer and wine (per Old English *tunne,* cask, or vat from medieval Latin *tunna*). In the United States these vessels are referred to as *tubs*. The temperature is controlled at about 65°C and the mashing takes about three hours. After this period the wort, which is now rich in dissolved sugars, is separated from the grain by being allowed to drain away. The wort is passed to a *copper* where hops are added and the mixture is boiled. The hops, in addition to giving flavor to the wort, also add bitterness, natural preservatives, and protein coagulants as well. The wort is then filtered and cooled very rapidly, and fermentation is allowed to proceed at a temperature of about 15°C. In typical British ales, the carbon dioxide produced during fermentation carries the yeast to the top, and therefore it is called top fermentation. The situation is reversed in the manufacture of lagers because the yeast is bottom fermenting, and these are characteristics of the specific yeast used for the different end products. *Finings* or clarifying agents may be added to clarify the beer, or the beer can be filtered to remove the yeast after which it can then be either bottled or put into kegs, which are under pressure. Carbonization is carried out either by sugaring the barrels in a traditional process or by injecting carbon dioxide. Compared with wine, the alcohol content of beer as served in public houses (pubs) is much lower at about 3 percent to 5 percent. In some instances ales sold in the United Kingdom can have an alcohol content that is higher than 5 percent; however, lagers are always above 5 percent. Heavier beers (those of higher specific gravity) are said to have more body, and these beverages are richer in carbohydrates and proteins; they also contain more minerals and are therefore nutritionally good for one's health. Filtration is not the only method used for removing solids from a liquid, for the process of centrifuging may instead also be employed to separate them. Centrifuges are used in sugar refining and purifying oils, as well as in clarifying beer, and separating yeast.

THE PRODUCTION OF MALT

Before the barley is processed, it has to be washed and steeped in water to soften the husk and to make the grain ready to germinate, but once softened up the excess water is drained off. As we have mentioned before, the germinated barley produces malt, but it takes time since germination is a natural process—usually a period of about eight days, with the grain spread out in large rooms where it is encouraged to sprout. During this time it is turned over regularly to remove the grain that has germinated sufficiently to be processed. To assist growth, the barley grain is subjected to the effects of circulating warm, moist air at a maintained constant temperature. While the grain is sprouting, oxygen is absorbed, and carbon dioxide is given off, and the enzyme diastase is formed. This enzyme is the biological catalyst that converts the starch in the grain to the disaccharide maltose, which, when transformed to monosaccharide glucose by maltase, is directly fermentable by yeast. Once all the grain has germinated, it is subjected to a malting operation under controlled conditions in a kiln.

KILN INSTRUMENTATION AND CONTROL

Figure 7.5 is a schematic of a typical kiln control system in which the instrumentation shown defines the function required. The time periods and temperatures given are typical only, and the system operates as follows:

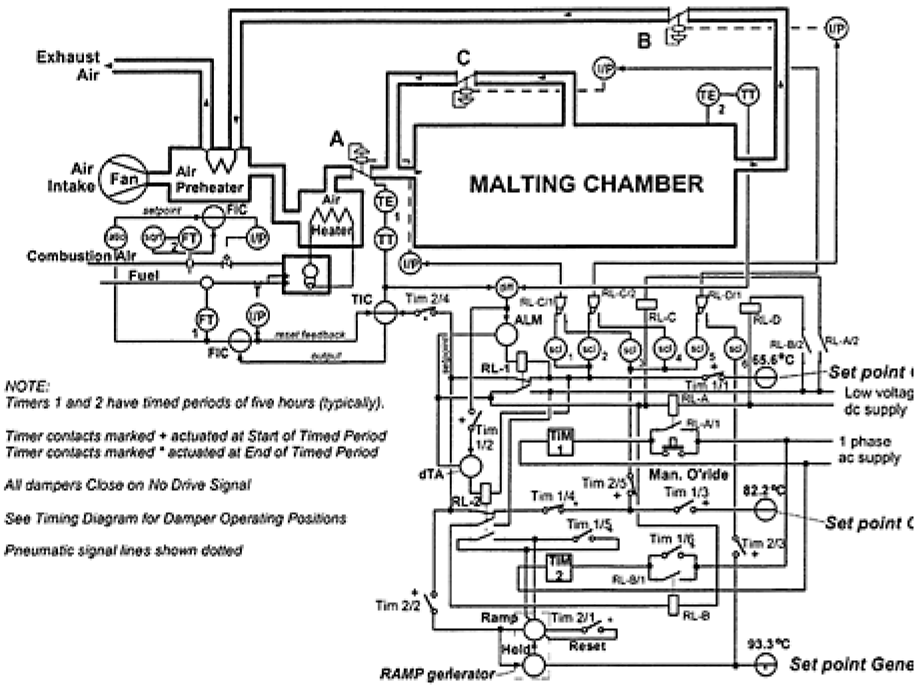


Figure 7.5: Schematic diagram of control system for makings.

The kiln malting chamber is a large room arranged so that the hot air is forced through from beneath a perforated false floor with a layer of germinated barley above. As a result, the hot air is driven upward through the barley layer, taking with it moisture as it does so. Averaging resistance thermometers tagged TE-1 and TE-2 measure the temperature of the incoming hot air and the outgoing cooler air. These averaging thermometers are usually made in the form of a closely wound spiral, one end of which terminates in an eye that can be fixed to a wall-mounted hook. The spiral is stretched across the room whose temperature is to be measured. This arrangement ensures that the temperature variations that always exist across such a location are accounted for in the measurement signal produced by the transmitter. The difference between the two measurements is taken in the module tagged “diff.” and the signal is applied to a high alarm module whose trip point is set by the process engineer in collaboration with the brew master to a value that gives the required condition for the barley being malted. As will be appreciated from the arrangement, the hot air will be applied for as long as the difference is below the setting of the trip point set on the alarm tagged ALM and as soon as the alarm ALM trips, relay RL-1 will be initiated. Throughout the period that the difference is below the alarm trip point, a set point of 65.6°C (150°F) derived from the module tagged (upper) set point generator is applied to the temperature controller tagged TIC (via the timer start contact tagged Tim 1/1).

FUEL/AIR RATIO CONTROL (HEAT INPUT)

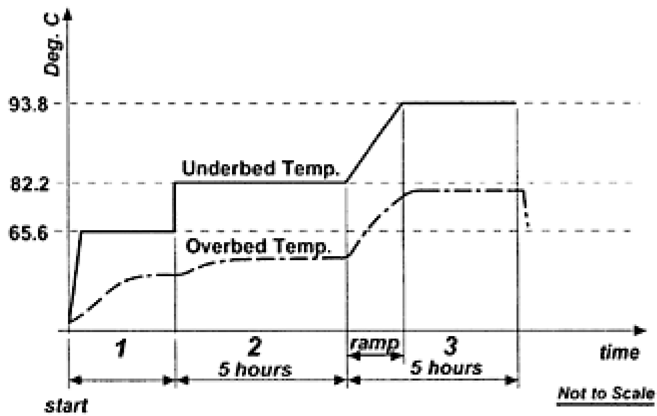
Temperature controller TIC receives its measurement from the averaging resistance thermometer/transmitter TT-1, and its output is the set point for the fuel flow controller tagged FIC (classical Cascade system). In this instance, the fuel dictates the amount of combustion air required and is necessary because the heat must be available immediately when demanded. This would not be the case if the combustion air would lead the fuel. However, in all cases whether fuel leads air or vice versa, we also require sufficient air to completely burn all the fuel, plus a small amount in excess to ensure that this is the case. This technique of fuel leading air is used extensively in steam-driven naval ships where the required steam demand has to be met at very short notice. Since the amount of air to burn an amount of fuel is always larger (volume for volume), as a result, the module tagged ratio will have a much larger value for the multiplying factor than that required when the fuel is manipulated. The multiplier is larger because much more air per unit quantity fuel burned is necessary.

The fuel/air circuit operates in the following way. The measurement from the fuel flow sensor/transmitter tagged FT-1 is obtained from an inline primary device, which could be a vortex flowmeter (a linear device), and is applied to the module tagged ratio where it is multiplied and used as the set point for the combustion air controller tagged FIC-1. Note particularly that the fuel measurement and not the fuel controller output is used to generate the set point for the combustion air controller tagged FIC-2. The combustion air controller receives its measurement from the flow sensor/transmitter tagged FT-2 that has an orifice plate as the primary device. It is therefore necessary to extract the square root of the signal in the module tagged sqrt before using it in controller FIC-2. Extracting the square root is required to make the characteristics of the two flow signals—fuel and air—the same (both linear with respect to flow rate for meaningful ratioing). The combustion air controller FIC-2 manipulates the damper accordingly. This is a straightforward system that controls the preset air-to-fuel ratio, but like all combustion systems it requires the (theoretical) amount of air to support complete combustion to be calculated correctly before applying a small additional amount *(excess air)* to ensure that complete combustion is achieved.

POSITION OF THE DAMPERS AT THE START OF THE MALT FINISHING OPERATION

Three dampers, A, B, and C direct the flow of the hot air in the malting chamber. At the start of the operation, dampers A and B are open while damper C is closed. This arrangement allows the chamber outlet hot air to pass to the exhaust but not before any remaining heat it has is imparted to the incoming fresh air via the air pre-heater shown. The table in Figure 7.6 shows the damper positions as the malting process proceeds.

The dampers are driven to the required positions by signals generated and set in the modules tagged scl-1 through scl-6, which are scaling modules each of which may be engineer-set at any desired output value for a given signal input and will hold that output value for as long as the given input signal exists. With no input signal or a minimum signal available at the scaler, its output falls to either a minimum value (e.g., 4 mA) or zero percent. The damper is arranged to close under these conditions. The closure is achieved mechanically under spring action; this is similar to what happens when a control valve reverts back to its failure or fail-safe mode. For dampers A and B, two sets of changeover contacts tagged RL-C/1 and RL-C/2 attached to relay coil tagged RL-C direct the output of either the 65.6°C (150°F) or the 82.2°C (180°F) set point generators via the scalers tagged scl-1, scl-2 scl-3, and scl-4, respectively, to the relevant current to pneumatic converters tagged (I/P) associated with the dampers. Damper C is driven via contact tagged RL-D/1 associated



Period	Damper Opening		
	A	B	C
1	Open	Open	Closed
2	Part Open	Part Open	Part Open
3	Closed	Closed	Closed

Figure 7.6: Timing diagram and damper position for malting.

with relay coil tagged RL-D. We shall discuss the action of this damper later in this chapter.

DETAILED OPERATION AND TERMINATING THE MALTING PROCESS

As the hot incoming air passes under and upward through the bed of germinated barley, it also heats the barley as it does so, an action that drives moisture from the grain. The hot air loses heat as it gains moisture, and its temperature is lowered as a result. Figure 7.5 tries to depict the result graphically. Since damper C is closed, the air is forced to pass through the duct containing damper B. Therefore, the air passes across the resistance thermometer tagged TE-1, which produces a signal proportional to the average temperature, as explained earlier. The actions described now give more detail on the operation of the controls of the malting process and elaborate on the system described earlier. As stated before, the difference between the incoming and outgoing air temperatures is determined and applied to an alarm module tagged ALM, which is set at a predetermined (High) value. As long as the temperature difference is below the trip point of alarm module ALM, the coil of relay RL-C is not energized and the signal from the 65.6°C set point generator is applied via the NC (normally closed) contacts of RL-C/1 and RL-C/2 and scalers scl-1 and scl-2, respectively to dampers A and B. With a signal representing 65.6°C from the set point generator the output from scl-1 and scl-2 is set at 20 mA; this keeps dampers A and B open. Scaler scl-5 will not have a signal on its input, hence, as stated earlier its output will be at 4 mA resulting in damper C reverting to its failure mode closed. Once the output signal from the temperature difference module diff exceeds the alarm setting on ALM, the alarm trips and initiates relay RL-1. This action applies the low-voltage dc supply to the coil of relay RL-A to energize it and cause contact RL-A/1 to close to initiate the timer TIM-1 to start Period 2, and contact RL-A/2 to initiate relay coil RL-C.

Since timer TIM-1 is initiated, contact Tim 1/1 opens immediately and isolates the original set point of 65.6°C (150°F) to controller TIC-1. The changes are held for the period of five hours set on TIM-1 as shown in the upper part of Figure 7.6. Timer-contact Tim 1/2 closes immediately to provide a path for the temperature difference signal from module tagged diff to be applied to the rate of change alarm block (algorithm) tagged dTA. The dTA alarm monitors the rate at which the temperature difference is changing and is provided with high and low trip points that are set at predetermined values.

Timer-contact Tim 1/3 also closes immediately, and a new set point of 82.2°C is applied to temperature controller TIC-1 via timer-contact Tim 1/4, NC contact of relay RL-2 and timer-contact Tim 2/4 resulting in new values for the set point to fuel flow controller FIC-1 and also for the airflow controller FIC-2. This set point change is made stepwise to controller TIC-1 and implies a change for a larger amount of fuel and air supplied to the burners, which will inevitably mean a higher temperature of the incoming air.

The signal from the 82.2°C (180°F) set point generator is also applied to the scalers scl-3, scl-4, and scl-5 via timer-contacts Tim 1/3, and Tim 2/5. As a result of relay coil RL-C being energized its contacts RL-C/1 and RL-C/2 will change over and drive dampers A and B partly open. Because the signal from the 82.2°C (180°F) set point generator is applied to scaler scl-5 damper C is also partly opened via RLD/l the NC contact of relay RL-D—the actual amount of opening being determined by the experience of the master brewer and set on scalers scl-3, scl-4, and scl-5. Since dampers A, B, and C are open partially, some of the hot air is recirculated through damper C, together with some being exhausted via damper B and the air preheater. Some fresh air is also drawn via damper A into the malting chamber. The partly open positions of A, B, and C are held until timer-contact Tim 2/5 is initiated.

At the end of the timed period of five hours timer TIM-1 contacts Tim 1/4 opens, and Tim-1/5 closes. With contact Tim 1/4 opening, the set point of 82.2°C (180°F) is no longer applied to controller TIC-1. The NO (normally open) contact of relay RL-2 that is connected in series with timer contact Tim 1/5 are now both closed and provide a path to invoke the signal ramp generator and start the set point ramp. Also at the end of the timed period of five hours, timer TIM-1 contacts Tim 1/6 closes and starts timer TIM-2, which closes associated timer contact Tim 2/3 immediately and applies the set point of 93.3°C to scaler scl-6 input. Scaler scl-6 is set so that with an input of 93.6°C its output is at 20 mA. Differential temperature alarm dTA trips when the rate of change of the temperature difference is zero and energizes the coil of relay RL-2, causing the associated contacts to change state. The second NO contact of relay RL-2 closes and energizes the coil of relay RL-B, which provides the hold on path for timer TIM-2 via relay contact RL-B/1 that is connected in parallel across timer contact Tim 1/6. NO relay contact RL-B/2 closes to energize the coil of relay RL-D and force relay-contact RL-D/1 to change over.

Timer-contact Tim 2/2 closes immediately; timer TIM-2 is initiated to start Period 3 and provides a path for the ramping set point from the 93.8°C (200°F) set point generator to be applied to temperature controller TIC-1 via timer contacts Tim 2/2 and Tim 2/4. This results in new values for the set point to fuel flow controller FIC-1, and as a consequence, a new set point value for airflow controller FIC-2.

As soon as timer TIM-2 is initiated, timer-contact Tim 2/5 opens immediately causing the signal to scalers scl-3 and scl-4 to be removed and allowing dampers A and B to revert to their failure mode closed under spring action. As stated earlier the output of scaler scl-6 is 20 mA, and the NO relay-contact RL-D/1 is connected to it. Damper C will be driven open and will allow the hot air in the malting chamber to circulate until timer-contact Tim 2/3 opens once again at the end of the period set on TIM-2.

At the end of the timed period set on timer TIM-2, timer-contact Tim 2/1 closes to reset the ramp generator block, and timer-contact Tim 2/4 opens to drive the set point of controller TIC-1 to zero in preparation for the next malting session.

No instrumentation for direct measurements of the grain is made because it is difficult to measure the condition of the malt as it is being processed. For instance, the color and the aroma of the malting grain will ultimately determine the quality of the finished product. Much reliance is placed on the skill and experience of the process operators and the master brewer, who is responsible for the quality of the beer produced. This in turn depends on the allotted time and the temperature at which the germinated barley is exposed to the effect of the warm air.

MILLING

After the barley has been malted, it is subjected to a process called *milling*, which is carried out in machines called roll mills. The objective of this operation is to leave the husk of the barley intact but crush the grain within it. Leaving the husk intact assists the separation of the wort and also reduces the possibility of extracting unwanted components such as tannins. The grain is drawn through a space between pairs of fluted rolls that are adjusted to a gap sufficient to crush the grain but not split the husk. However, the crushing operation is carried out not in one pass through the rolls but by several passes through the set of rolls. Some mills can have three pairs of rolls; these are called six-roll mills. Each pair of rolls is followed by a set of vibrating mesh screens, which are graded from coarse to fine, the coarsest being placed first in the train and the finest last.

THE MASHING OPERATION

The process described hereafter follows the procedure carried out in America and is known as *double mashing*. In the United Kingdom and Europe, the mashing process is different and is called *decoction mashing,* which will be discussed later in this section.

GRAIN WEIGHING

Having now obtained the malt, the process can continue, which involves preparing the *mash* from which, following completion of its fermentation, beer is the product. The malt and cereal used are measured in specially designed weigh vessels, which are stainless steel tanks to which load cells have been fitted. The vessels are fabricated with a conical base—the angle of the cone being greater than the *angle of repose* of the materials for which it is used—which allows all the loaded material to be discharged completely. The vessel and its supporting framework are designed to enable the vessel to move vertically (the actual movement involved is of the order of micro inches) but to retain its (locational) stability. Load cells operate on the strain gauge principle, and in this instance the area of location of the strain gauge within the load cell is generally indicated in Figure 7.7. A load cell consists of a solid cylindrical steel billet to which is cemented a *strain gauge rosette* in a position along the *neutral axis* of the billet. This positioning allows the strain in the billet due to any imposed compressional load to be detected. The billet and the strain gauge are housed in a totally sealed circular steel housing, with the gauge connecting wires brought out through a watertight cable gland. The base to which the steel housing is permanently fixed is arranged so that it is used as the method by which the cell

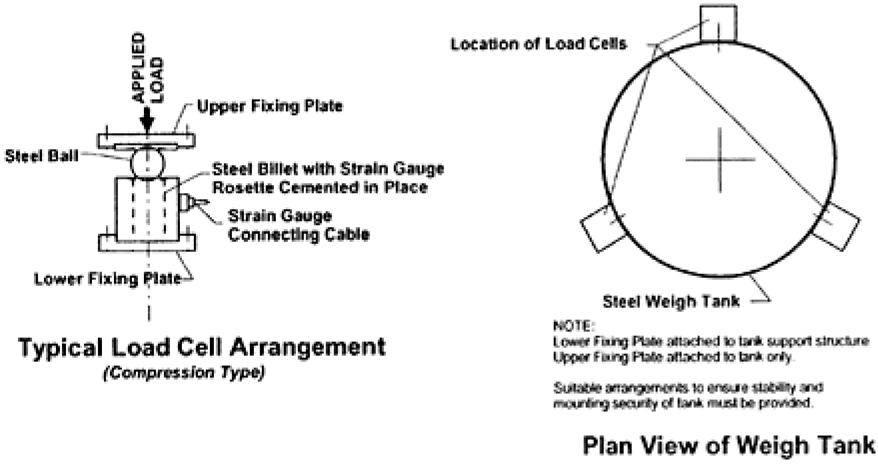
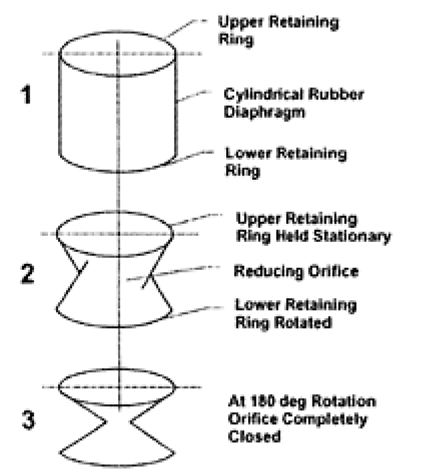


Figure 7.7: Grain weight tank and weight sensor.

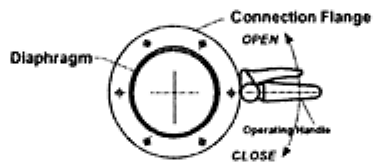
is fitted to the mounting framework. The top of the billet is machined to provide a central saucer-like recess, which enables the steel ball to rest on the centerline of the billet. A similar arrangement is provided for the top mounting plate, which enables the line of action of the applied force to be axially through the center of the steel billet without lateral restraint. Three load cells are used to obtain the total weight by summation. When commissioned, the weight of the empty tank is *tared off* (i.e., zeroed out) to allow only the net weight of the loaded material to be obtained.

As with all recipes, the ingredients have to conform to very specific quantities in order to yield the required results. This means that the cereals malt and hops have to be measured out accurately. Figure 7.7 is a typical arrangement of the *load cell* and the cell mounting arrangement only.

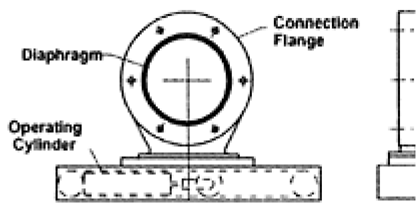
The discharge valve at the bottom of the lower conical section is usually either a *disk* or *iris diaphragm* type. The disk-type valve has a horizontal sliding metal disk that can be either manually operated or moved via a pneumatic cylinder. The iris diaphragm valve uses a cylindrical rubber sleeve, one end of which is fixed and the other end rotated through 180 degrees to completely close it off. Again this valve can be either manually operated or moved via a pneumatic cylinder. *Kemutec* in the United Kingdom manufactures these valves, and the principle of operation is shown in Figure 7.8 which illustrates the manual and pneumatic versions. This type of valve is ideal for the application of dispensing granular or powdered material, for no obstruction to the flow is involved because of the cylindrical rubber diaphragm. When required to shut off while a solid object is encountered passing through, the cylindrical diaphragm is flexible enough to wrap itself tightly around the solid object and inhibit the flow. An electric motor-driven version of the iris valve is available but has not been shown here because it looks similar to the pneumatic model. The sliding disk valve has not been illustrated because it is easy to visualize a horizontal disk constrained to slide between two flanges and in so doing cutting off the discharge of material from the vessel to which it is fitted.



Principle of Operation of Iris Valve



Plan View of Manually Operated Iris Diaphragm Valve



Plan View of Pneumatically Operat
Iris Diaphragm Valve

Figure 7.8: Operating principle and detail of an iris diaphragm valve.

CEREAL COOKING

The cereal cooking and mashing operations are run in parallel, so that the *lauter tun* receives the complete mash in one discharge from the mash tun. This procedure, as mentioned earlier, is known as double mashing. The cereals used in the preparation must be cooked (gelatinized) prior to being included in the mash. The amount is carefully weighed in the weigh tank and passed to the cereal cooker along with a metered amount of water. Figure 7.9 is a schematic diagram of the control system involved; not included in the illustration is the weigh tank preceding the cereal input line because presumably the reader can easily visualize this being included. The cereal cooker in this instance is a vessel fitted with a heating jacket, although, as an alternate, heating coils or direct steam injection can be found on these vessels. An agitator is also provided to facilitate heat distribution throughout the cereal mass. Also included is a motor current sensor/transmitter tagged IT-1, which monitors the current drawn by the agitator drive and provides a signal that is recorded on recorder tagged IR-1, This is necessary so that the operator can reduce the current by diluting the cereal with hot water in the event it becomes too thick. Figure 7.10 shows typical time/temperature profiles for both the cereal cooker and the mash tun. These profiles should be consulted while one is reading the operating description. The amount of hot water is measured by an in-line flowmeter (e.g., vortex type), or preferably a magnetic flowmeter to allow for low flow cutoff in a batch operation. The reasoning behind this recommendation is the way the vortex meter works. We know that the vortex meter uses a bluff body to shed vortices; these vortices are shed alternately from either side of the bluff body that is placed in the middle of the flow stream. The flow rate is determined by counting the number of vortices generated per unit time.

Using an analogy to visualize the situation, let us consider a flag on a flagpole and assume a moderately brisk wind is blowing. The flag reacts to the wind flowing past and rises, its full rectangular shape being displayed. There is something subtle, however, about the horizontal sides of the rectangle, which appear to be straight when viewed in elevation, because what we are looking edge-on at are curves (i.e., similar to the open end of a teacup viewed in elevation). When the flag is seen in plain view, these sides are definitely not uniformly straight; rather, they are undulating in an almost sinusoidal way about an axis normal to the pole. The peaks of the curves representing the vortices, counting the peaks on either side of this normal axis, will give us the wind speed. If the wind increases, the number of peaks increases indicating a faster airflow; a less brisk wind results in a limper flag, that is, one with a much-reduced number of peaks. If the wind speed drops severely, the flag will not move but will just hang about the flagpole. If now we enclose the flag and the pole in a horizontal tube of uniform cross section (the pole appears as a diameter) and allow the same things to happen, then it is relatively easy to relate the number of peaks to the airflow. When the airflow is so low that the flag tends to hang limp, counting peaks becomes extremely difficult, making the accuracy of the determined airflow suspect. Hence, if we are using the vortex meter to determine the size of a batch of material, then as the batch size nears its end and the flow of material is reduced, the frequency of the output is so reduced (i.e., the start and finish of successive curves is indeterminate) that the accuracy of the amount passed will be hopelessly incorrect.

The same is not applicable to the magnetic meter because, being based on Faraday's law of induction, this meter produces an emf measurement signal that is dependent on the rate (speed) at which the conductor, which is the fluid in this case, cuts a uniform magnetic field that is developed by the electromagnetic coil wound around the containing pipe. (Note that almost all water is sufficiently conductive for satisfactory operation.) Hence, lowering rates of cutting the magnetic field will yield

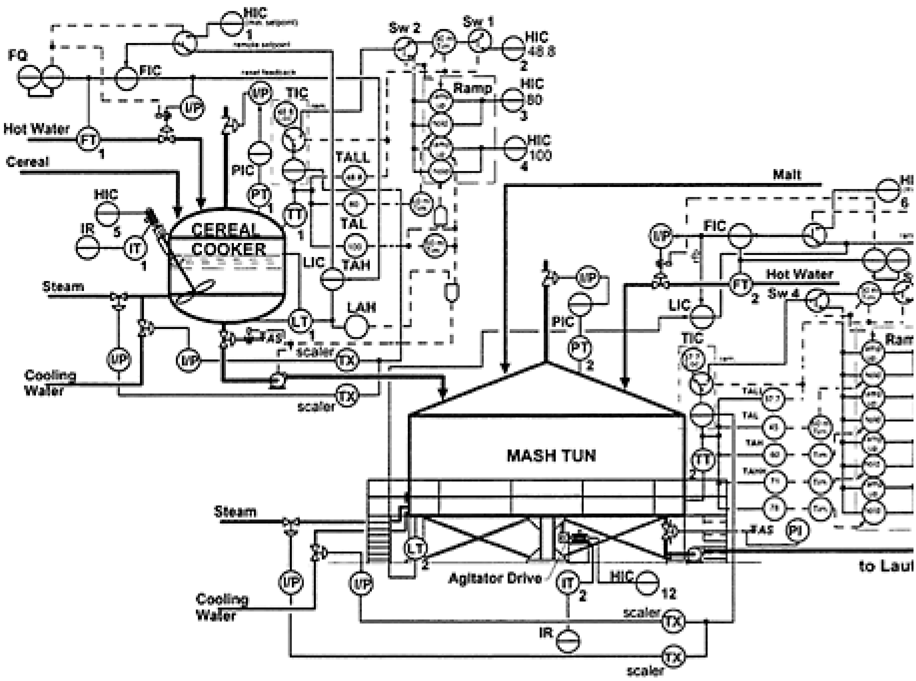


Figure 7.9: Control system schematics for cereal cooking and mashing operations in beer brewing.

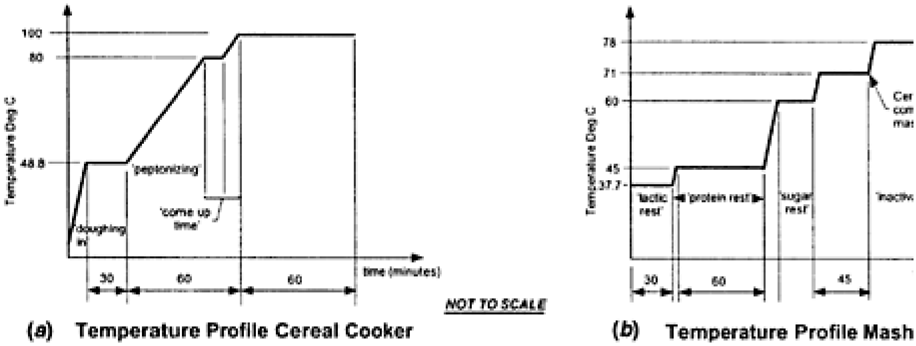


Figure 7.10: Time/temperature curves for cereal cooker and mash tun.

lowering values of generated emf. When the signal goes so low that it affects the accuracy, it is the cutoff point for the measurement, and is normally referred to as the *low signal cutoff*. The measurement produced by the inline flowmeter is applied to a predetermining counter tagged FQ-1 and a flow controller tagged FIC-1. The flow controller FIC-1 regulates a control valve in the hot water line. The predetermining counter operates as follows: the operator dials in (via thumbwheels in the case of a hardware device) or programs in (when a software device is used) the amount of hot water required. The incoming flow rate is continually totalized and compared with the predefined amount, and when there is agreement between the two amounts (the totalized and the pre-determined), a contact is initiated. This contact is the toggle of a switch that changes the remote set point of the flow controller, which is set at a minimum value to drive the control valve shut. The contact also initiates the solenoid valve in the pneumatic signal line to the control valve, which will drive the valve to its failure mode (closed). These two actions of closing the control valve are taken to ensure that the vessel cannot be inadvertently filled with water after the required amount has been admitted. The level in the cooker is monitored by level sensor/transmitter tagged LT-1, and the measurement produced is applied to a level controller tagged LIC-1 whose output is the set point of the hot water flow controller tagged FIC-1. This cascade loop is provided with a reset feedback signal derived from the output of flow controller FIC-1, to prevent the level controller LIC-1 from saturating should the process operator transfer the flow controller to manual mode while cereal cooking is in operation.

The pressure within the cereal cooker is monitored by the pressure sensor/ transmitter tagged PT-1, and the measurement produced is applied to a pressure controller tagged PIC-1 that regulates a control valve placed in the exhaust line from the cooker. This will maintain pressure conditions within the cooker to a value set by the operator on controller PIC-1.

The temperature of the cereal cooker is an important measurement that is monitored by sensor/transmitter tagged TT-1. The measurement signal is applied to a controller tagged TIC-1 and three temperature alarms tagged TALL-1 (low-low alarm), TAL-1 (low alarm), and TAH-1 (high alarm) whose trip points are set at 48.8°C (120°F), 80.0° (176° F) C, and 100.0°C (212°F), respectively. Controller TIC-1 output is *split ranged* by the two scalers TX-s (steam) and TX-w (water) and thereby manipulates the two valves, one in the steam supply line and the other in the cooling water line. The time/temperature profile of the cereal cook is shown in Figure 7.10a. At the start of the cooking cycle, controller TIC-1 provides control under its own local set point of 48.8°C (120°F) to allow the temperature of the cereal to rise. From what follows it may appear strange that a lot of switching is involved at the initial stage of the cooking operation, but this is necessary to comply with the specific request that the operations should start in manual mode. When the temperature of 48.8°C (120°F) is attained, temperature alarm TALL-1 goes open (untrips): the controller set point is switched from local to remote operation; the 30-minute timer is started; and switch Sw-1 is initiated. This allows the set point of 48.8°C (120°F) generated on the associated HIC to continue to be applied for the time set on the timer. This period—runup and 30-minute timed period—is referred to as the *doughing-in* period. However, it must be remembered that the master brewer decides on the actual length of time permitted. When the 30-minute timer completes its set timed period, it initiates switch Sw-2 causing it to change state, and it starts the set point ramp up to 80.0° C (176°F). The period it takes to ramp the temperature up is called *peptonizing*. The total time allocated for this next multistage, including the ramp period, is of the order of 60 minutes, but the master brewer decides the rate of ramp and the hold period. The hold period within the *come up time* is another interval determined by the master brewer and set on the hold period on the ramp module. At the end of this period, the temperature is again ramped to a value of 100°C (212°F). When the temperature reaches 100°C, the temperature alarm TAH-1 is tripped, which initiates the 60-minute timer. Then the timer sets the hold input of the ramp module for the second 60-minute period via the AND gate and applies another set point of 100°C to the temperature controller TIC-1, allowing the adjuncts to cook to their final condition. At the end of the timed period and the level within the cooker at its maximum, both inputs of the second AND gate are logic 1. This initiates the solenoid valve in the discharge line from the cooker and the discharge pump, thereby enabling the contents of the cereal cooker to be discharged into the mash tun.

THE MASHING OPERATION IN PRACTICE

As stated earlier, the mashing operation is in progress while the contents of the cereal cooker are being prepared. The mash tun originally did not have an agitator because the dense wort was effectively pushed through the thick mash bed by a series of hot sparge water flushes. This technique was known as *infusion mashing* and was the original classic British method of mashing. Modern mash tun designers used the data obtained from the infusion mashers to modify the technique and now fit knives and rakes that cut and lift the mash to make the dense wort collection a little easier and faster.

Double Mashing

We refer once again to Figure 7.9 and also to Figure 7.10 for system operation and the temperature profile applicable to the mash tun. The mash tun has a perforated false bottom and is free-draining throughout the mashing process. However, initially the outlet connection is shut off by a valve fitted with a pressure regulator and indicator tagged PI located at the base of the mash tun and opened after all the malt has been admitted. The malt is weighed and discharged into the mash tun where it is combined with a metered quantity of water that had already been admitted to the vessel in order to cushion the load imposed when the malt is discharged. The quantity of water delivered is measured by the flow sensor/transmitter tagged FT-2 and integrated by the integrator FQ-2, which, as before, is a predetermining counter that initiates a solenoid valve in the pneumatic signal line to the control valve, driving it closed when the preset quantity has been loaded. The level in the mash tun is monitored by level sensor/transmitter tagged LT-2 as the measurement to a level controller tagged LIC-2 whose output is the set point of the hot water flow controller tagged FIC-2. This cascade loop is provided with a reset feedback signal (marked rfb), derived from the output of flow controller FIC-2, which will prevent the level controller LIC-2 from saturating should the process operator transfer the flow controller to manual mode.

The pressure within the mash tun is monitored by the pressure sensor/transmitter tagged PT-2, as the measurement to a pressure controller tagged PIC-2 that regulates a control valve in the exhaust line from the mash tun. This will maintain pressure conditions within the mash tun to a value manually set by the operator on the pressure controller PIC-2.

As before, the temperature of the mash tun is the most important measurement that is made and is monitored and measured by sensor/transmitter tagged TT-2. The measurement signal is applied to a controller tagged TIC-2 and to five temperature alarms, with trip points set at the values shown, TALL-2 (low-low alarm) 37.7°C (100° F), TAL-2 (low alarm) 45.0°C (113°F), TAH-2 (high alarm) 60.0°C (140°F), TAHH-2 (high-high alarm) 71.0°C (159.8°F), and TA-2 78.0°C (1 72.4°F). As described before in the case of the cereal cooker, controller TIC-2 output is *split ranged* via two scalers to manipulate two valves, one in the steam supply line and another in the cooling water line. A separate alarm (unit or) block provides the fifth temperature alarm TA-2 because most controller blocks (algorithms) can only provide a maximum of four alarms. The time/temperature profile of the mashing is shown in Figure 7.10b. At the start of the mashing cycle, a local set point of 37.7°C (100°F) is applied to the controller TIC-2 to allow the temperature of the mash to rise. When the temperature of 37.7°C (100°F) is attained alarm TALL-2 untrips: the controller TIC-2 set point is switched from local to remote operation; the 30-minute timer is started; and switch Sw-3 is initiated. This allows the set point of 37.7°C (100°F) generated on the associated HIC-7 to continue to be applied for the time set on the timer—the reasons for the switching are the same as given before on the cereal cooker. This period is referred to as the *lactic rest* period, during which time the enzyme activity produces lactic acid; the master brewer however, determines the actual length of time permitted. On completion of the allocated period, the 30-minute timer initiates switch Sw-4 causing it to change state, and start the set point ramp up to 45.0°C (113°F). The total hold time allocated, for this next multistage, is of the order of 60 minutes. However, once again the master brewer decides the rate of ramp and the hold period; the period it takes to ramp and hold the temperature is called the *protein rest*. During this period, the enzyme proteinase reaches its maximum activity and reduces the large protein molecules to compounds of lower molecular weight. The next ramp to the temperature 60.0°C (140°F) and hold period, known as the *sugar rest*, is also determined by the master brewer and configured on the hold period on the ramp module. It is during this period that the sugar maltose is formed by the action of the enzyme β-amylase. At the end of the sugar rest period, the temperature is ramped again to 71 °C (159.8°F) and held for a period of 45 minutes. As before, the master brewer determines the ramp rate and hold period. At the end of the hold period, the mash from the cereal cooker is combined with that in the mash tun, and samples are taken to check and ensure that the starch has been completely converted. The temperature is once again ramped to a value of 78.0°C (172.4°F) when alarm TA-2 is tripped. The mash tun is held at this value for a master brewer determined period in order to inactivate the conversion process. The wort that is continually being processed is then discharged into the lauter tun.

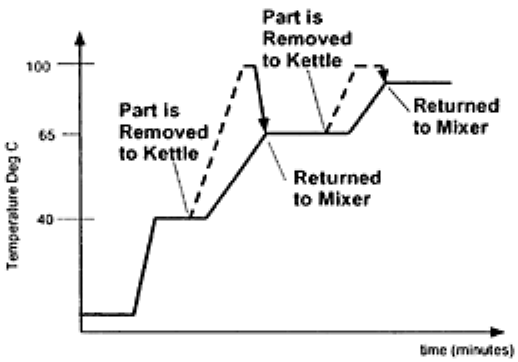


Figure 7.11: Typical temperature profile decoction mashing.

Decoction Mashing

When this procedure is used in the mashing process, two vessels are required to prepare the mash. A small vessel called the *mash kettle* and a larger one called the *mash mixer* are fitted with agitators and heaters. A typical temperature profile obtained is shown in Figure 7.11. As described before, when we dealt with double mashing, hot water is placed in the mash mixer, and the agitator is started prior to adding the malt. Part of the first charge is quickly transferred to the mash kettle where it is brought to the boil and the temperature held for a period before it is returned to the mash mixer. The main mash in the mash mixer is at a lower temperature during this period; this stage is referred to as the protein rest. Introducing the boiling mash from the mash kettle to the mash mixer raises the temperature of the latter. A period is allowed for the conversion of some of the starch to take place before again part of the mash is withdrawn from the mixer and transferred to the mash kettle. There it undergoes another period of boiling, after which it is returned once again to the mash mixer, which further raises the temperature of the mash once again to a final value called the *mash-off*.

Calculating the Resulting Temperature When Mash and Hot Water Are Mixed

It is important to determine the temperature of the contents when a relatively cool mash and hot water are combined. The calculation is based on the fundamental evaluation of heat, which states that the total heat gained by a body is the product of its mass multiplied by specific heat multiplied by the change in temperature, or Actual heat=Mass×Sp Ht×Actual temperature. This results in the following relationship:

$$T_{mixture} = \frac{W_{water} \times Sp.Ht_{water} \times T_{water} + W_{malt} \times Sp.Ht_{malt} \times T_{malt}}{W_{water} \times Sp.Ht_{water} + W_{malt} \times Sp.Ht_{malt}}$$

$$= \frac{W_{water} \times 1.0 \times T_{water} + W_{malt} \times 0.4 \times T_{malt}}{W_{water} \times 1.0 + W_{malt} \times 0.4}$$

where *T* is the temperature, *W* is the weight, and *Sp.Ht* is the specific heat. The subscripts define the component involved.

LAUTERING

After the conversion of the starch to sugars that occurs in the mash tun is complete, the mash is transferred to the lauter tun. Separation of the insoluble constituents is effected in this vessel. The lauter vessel comprises a very large cylindrical container much larger than the mash tun; the lauter tun has a perforated false bottom and a highly specialized agitator comprising a horizontal bar with vertical rakes (sometimes also called knives), the pitch of which can be altered. The false bottom of the vessel has perforated slots that are narrower and pitched farther apart than those found on the mash tun. The real bottom of the vessel has a number of outlets fitted to it so that the liquor can be drained off. There is also a horizontal sparge tube at the top of the assembly through which water can be sprayed. The complete agitator assembly can be raised or lowered either mechanically or hydraulically. Figure 7.12 illustrates the lauter tun and the control system. In view of the complexity of the control requirements (e.g., typically the amount of sparge water and the amount of agitation), this aspect should be discussed with the master brewer and others at the brewery to determine the actual requirements of the system. The following will give a brief idea of what is required, but these requirements will have to be modified when the system is being designed and implemented.

The mash delivered to the lauter tun is in a well-mixed condition owing to the combined actions of the mash agitator and the pump. When the complete quantity has been delivered, it is allowed to stand for a short while, during which time the larger and therefore heavier components will stratify and settle down on the false bottom, with the lighter components at the top. If the liquor is drawn off rapidly, one can easily see that the lighter components will tend to consolidate because they are accelerated more easily and as a result will tend to bind together, clog up, and inhibit the easy flow of liquor through the remainder. Therefore, the rake assembly will have to be started and, depending on the severity of the coagulation of the mash charge, both the amount of rake on the knives and the depth it has to be lowered into the bed of mash will have to be decided. These adjustments are small indeed and can only be determined by experience gained working with the equipment and observation of the parameters of density and clarity of the liquor. In the United States, the rakes are run continuously, and hence the bed is in a constant state of agitation.

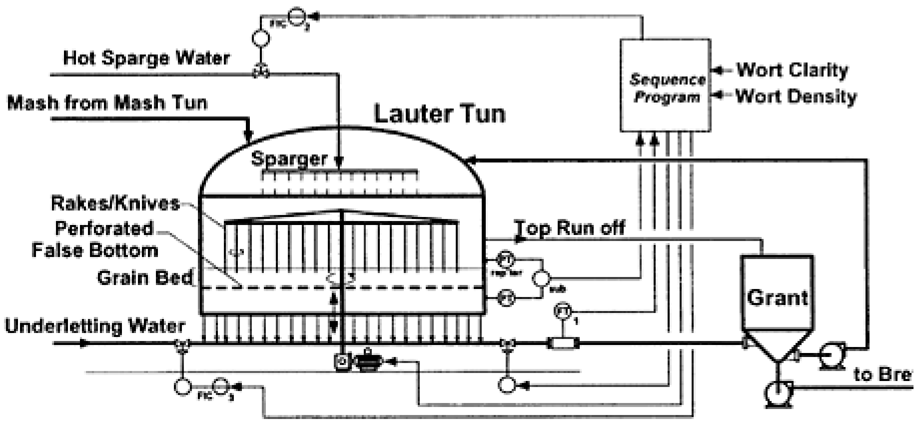


Figure 7.12: Schematic of lauter tun and control system.

A good idea as to the degree of consolidation of the bed can be derived from measuring the differential pressure across it. The instrument normally used to make the measurement is a differential pressure cell. However, in this instance it is preferable to use two flanged-type differential pressure sensing instruments instead. These instruments are arranged as follows: the low-pressure connection on the sensor/ transmitters is left open to atmosphere. This will allow the instruments to perform as very low-range pressure sensor/transmitters instead of the differential pressure instruments that they are. The pressure difference is calculated externally using the signals from the two pressure transmitters. This method is adopted because of the strange effects experienced when a DP cell with diaphragm seals is subjected to CIP (cleaning in place) operations. The measurement range should be given careful consideration inasmuch as the variations will be small and sensitivity is important. The magnetic flowmeter and transmitter tagged FT-1 measure the liquor runoff and the underletting water when used. This instrument is chosen because it is virtually obstructionless and is available in a hygienic construction, which is vital when used in the food industry. A drop in outflow rate indicates approaching problems with the bed due to consolidation, which can be forestalled by initiating a period of sparging with hot water. Sometimes it is necessary to admit water flow from the underside of the bed (underletting) when the bed has consolidated; this action arouses the bed and restores liquor flow. The wort density and clarity are measurements made on samples drawn off at regular intervals. These measurements could be made on-line but the equipment used (called refractometers, which use optical techniques) are delicate and difficult to maintain. Furthermore, the author is not aware that they are manufactured in hygienic versions, which would be a requirement in this application. The initial quantity of liquor after the lauter tun is first charged is allowed to discharge, but thereafter the wort is recycled and stopped when the liquor runs clear. The runoffs are collected in a vessel called a *grant*.

The total amount of time required for the wort to be obtained from the lautering process is of the order of 90 to 120 minutes.

An alternate to the lauter tun is to install a mash filter. These devices are much more labor intensive and involve the use of filter cloths, which today are made from some form of plastic material. When these filters are used, the controls involved require a magnetic flowmeter to measure the flow and determine when the filter is clogging, indicated by a lowering of the flow rate, and a flow controller, which regulates a variable speed pump. This latter equipment is necessary because maximum filtration is obtained at constant flow rate and this is achieved by controlling the pump speed.

THE BREW KETTLE

Figure 7.13 shows a typical vessel and the controls involved for this part of the process. The vessels are large and, though in different form than those found today, have been part of brewing from the earliest of times. Originally, they were constructed from copper, and as a result they carried the name *coppers*. Selection of this construction material was based on the good thermal transfer afforded by copper. However, modern kettles are made from stainless steel, even though the material has much poorer heat-transfer capabilities. All the same, this material is stronger and is better able to withstand the harsh cleaning chemicals used today. Since the heating coils or calandria are always mounted internally, the heat-retaining properties of stainless steel are exploited to advantage. Some brewers still include some copper items in part of

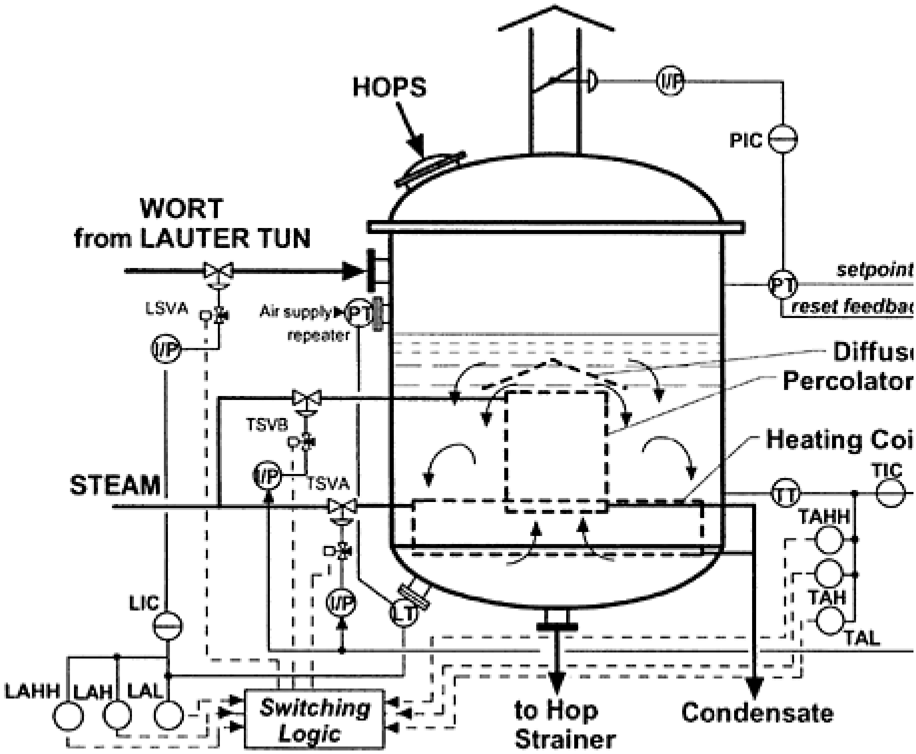


Figure 7.13: Schematic of brew kettle control system.

the wort processing equipment, for they believe that the beer picks up some traces of this metallic element to enhance the flavor and quality of the product. There are basically three reasons for boiling:

1. It inactivates any enzymes that manage to survive the mashing process.
2. It precipitates a complex protein/tannin/carbohydrate compound called *hot trub,* which could render the beer subject to chill haze.
3. Boiling is a sterilizing process for the wort, which renders it stable from a bacteriological standpoint since it kills off all vegetative microbes contained in the raw materials.

Hops that are so vital in giving the beer its characteristic bitter taste are introduced to the wort in the brew kettle. The hops are added in one of two ways: either the full measure required for the quantity of wort is included at the start, or it is added in small quantities at several stages during the entire processing operation. When the latter procedure is adopted, the master brewer must define the exact time of hop addition as the quality is most certainly affected.

The vessel is designed so that the vessel concentrates the heat at the center of the wort contained therein. This ensures that the boiling becomes a *full rolling boil* which means an intense and rapid motion of the heated charge by convection currents and the evolution and removal of the steam generated by the boil. Thus, the percolator or vertical calanderia is mounted centrally within the body of the vessel. With the arrangement of the heating elements shown, filling the kettle with wort is carried out in two stages. The first stage allows the wort to cover the heating coil only, and steam is then allowed to circulate and heat the wort. Next, once this initial material attains the desired temperature, the steam to the coil is shut off, and more wort is introduced until the level covers the entire percolator. At this point, steam is applied to the percolator and the wort is boiled.

The Kettle Control System and Logic

The controls for the system shown in Figure 7.13 operate as follows, and the operation of the associated (selection) logic, shown in Figure 7.14, should also be referred to. The temperature of the wort is measured by sensor/transmitter tagged TT, and the sensor is installed in a thermowell, which will ensure that hygienic conditions are maintained at all times. The temperature is the measurement applied to the controller tagged TIC and temperature alarms tagged TAH (high), TAHH (high/high), and TAL (low) are also connected to the measurement input. The output of temperature controller TIC is applied to three-way solenoid valves under the control of the logic fitted in the pneumatic signal line to each control valve via its I/P converter, which are installed in the steam supply to both the kettle heating coil and to the percolator. The pressure sensor/transmitter tagged PT measures the pressure in the vapor space as the measurement signal for the controller tagged PIC, which receives its set point from the output of temperature controller TIC via a characterizer block tagged char. The function of this block is to relate the relevant pressure to the temperature because these two parameters are intimately interdependent. Reset feedback is provided for the pressure controller PIC for those instances when the operator puts the temperature controller into the manual mode. This arrangement, which is common in cascade loops, will prevent the integral term of the pressure controller PIC saturating. Two instruments measure the level of the wort in the kettle, one of which is a differential

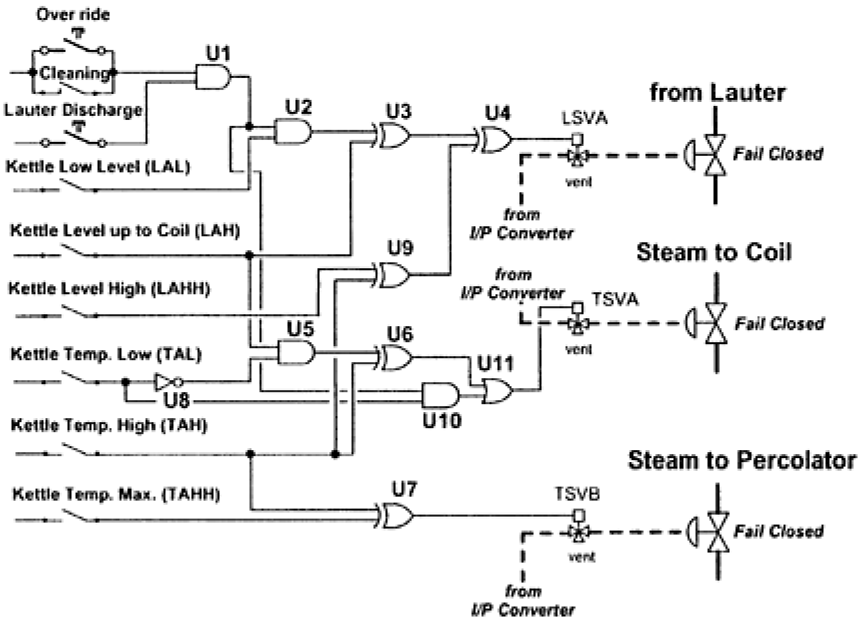


Figure 7.14: Typical kettle switching logic.

pressure transmitter with extended diaphragm, tagged LT, located at the base of the kettle; the other instrument, a pneumatic repeater tagged PT, is located at the top of the kettle with its input connection made to the vapor space. The signal produced by the repeater PT is applied to the low-pressure connection of the level transmitter LT primarily to avoid the problems that would occur due to the temperature of the kettle and its contents influencing the level measurement if chemical seals with interconnecting filled capillaries were used, as these would behave as a liquid-filled thermometer. The pneumatic repeater is an instrument that produces a pneumatic signal that exactly replicates the pressure applied to its sensing diaphragm by the process fluid. The pressure of the pneumatic supply to the instrument transmission mechanism therefore limits the range of the instrument. Since, as stated, the repeater instrument exactly replicates its input, care must be taken to ensure that the correct range is specified when initially defining and later calibrating the transmitter when fitting it to the kettle. The level measurement is applied to a controller LIC and level alarms tagged LAL (low), LAH (high), and LAHH (high/high) are configured on the measurement input. The level controller regulates the control valve in the wort supply line via a three-way solenoid valve fitted to its pneumatic signal; it is also under control of the logic switching circuit shown in Figure 7.14.

The Switching Logic

The operation of the switching logic shown in Figure 7.14 is as follows. The kettle "cleaning complete" contact is configured as part of the cleaning procedure and is initiated automatically at the end of the cleaning cycle. The operator initiating the override switch can bypass the cleaning cycle if the kettle is in use continuously. The cleaning override function must, however, be designed into the cleaning procedure to allow it to be operated as described. When the lauter is ready to be discharged, the operator initiates the Lauter Discharge switch. The cleaning complete/override and the Lauter Discharge are the two inputs to AND gate U1, which will have logic 1 on its output only when both inputs are also logic 1. AND gate U2 accepts the output of gate U1 and the low-level alarm LAL output. With the kettle empty, the kettle low-level alarm LAL will be closed and therefore at logic 1, which will make the output of gate U2 also logic 1. XOR gate U3 accepts the output of gate U2, and since this is at logic 1 and the high level alarm LAH "kettle level up to coil" at logic 0 the output of gate U3 will also be logic 1. XOR gate U4 accepts the logic 1 output of gate U3, and, since neither alarm LAHH nor alarm TAH is tripped, XOR gate U9 output must be at logic 0 making the output of gate U4 also logic 1. As a result, the solenoid of the three-way valve LSVA (located as shown in Figure 7.13) will be energized and allow the output of the I/P converter, which is driven by controller LIC to be applied to the control valve and start admitting the contents from the lauter into the kettle. Since gate U3 and U4 are XOR functions, either the kettle level up to coil (LAH) or the output of XOR gate U9 going to logic 1 will deenergize the three-way solenoid valve LSVA, and vent the diaphragm motor. The associated control valve will therefore be driven to its "closed" failure mode.

Under normal operation, the kettle level up to coil (LAH) will be initiated first as the kettle fills up and inhibit the further ingress of material from the lauter by deenergizing the three-way solenoid valve LSVA, but it will also make one input of AND gate U5 logic 1. Since the kettle is always empty at the start of the operation, the temperature is low making the kettle temp. low (TAL) close, but the inverter NOT gate U8 will force the signal to appear open. As soon as the material from the lauter is introduced, both inputs to AND gate U10 will be at logic 1 to turn the gate on. This output is applied to the second input of OR gate U11 to make its output logic 1 and thus energize the three-way solenoid valve TSVA to allow steam to the heating coils. The temperature of the kettle will start to rise, and when it goes above the setting of kettle temp. low (TAL), the signal from the inverter U8 will go to logic 1 and make the output of AND gate U5 logic 1. The result of this will make the output of XOR gate U6 logic 1, which is applied to the first input of OR gate U11 and alternatively energize the three-way solenoid valve TSVA associated with control valve in the steam supply to the heating coil to drive it open to an amount determined by the output of temperature controller TIC. The temperature of the material in the kettle will continue to rise, and if the setting of the alarm kettle temp. high is close to boiling point, then the material will be brought up to that level. When the alarm kettle temp. high is tripped, the second input to XOR gate U6 goes to logic 1, making the output from this gate logic 0 as AND gate U5 will still be at logic 1—the specific characteristic of XOR gates—and thus deenergizing the three-way solenoid valve TSVA associated with the control valve in the steam supply to the heating coil to shut it off. At the same time, the input to XOR gate U9 from the alarm kettle temp. high (TAH) makes the output from gate U9 go to logic 1 (as TAHH is logic 0) and once again energize the three-way solenoid valve LSVA associated with control valve in the lauter material supply line to open and admit more wort to the kettle.

As a memory aid, the truth table given in Table 7.1 defines the logic involved in the working of a two-input XOR gate. One can see from the listing that when both inputs are at logic 1, the output from the gate will always be logic 0, but when either of the inputs is logic 1, then the output is also logic 1.

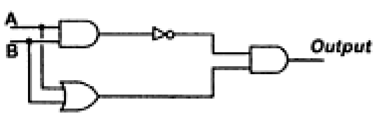
In response, the level in the kettle will begin to rise and will continue to do so until the kettle level high (LAHH) alarm setting is initiated. This will make the second input of XOR gate U9 logic 1 and drive the output from the gate to logic 0, which will result in deenergizing the three-way solenoid valve LSVA associated with control valve in the lauter material supply line, forcing it to close, terminating the loading. As a result the temperature in the kettle will fall because of the increased material added to the kettle. This will make the temperature alarms TAH and TAHH revert to normal and allow steam to be admitted to the heating coil and the percolator to raise the temperature once again via the drive to the three-way solenoids from gate U6 and gate U7.

The master brewer determines the time the wort is allowed to boil and, as mentioned earlier, the points at which the hops are added to the brew. This must be allowed for in the design of the sequence.

The contents of the kettle are passed on, being discharged to a strainer as quickly as possible where the hops are removed. The strained wort is then stored in tanks where the proteins (trub) are allowed to settle out. The temperature is allowed to fall, after which the clearer wort is passed through frame and plate coolers where

TABLE 7.1 Truth Table and Logic Circuit for an XOR Logic Gate

A	B	A.B	$\overline{A.B}$	A+B	$\overline{A.B}.A+B$
0	0	0	1	0	0
1	0	0	1	1	1
0	1	0	1	1	1
1	1	1	0	1	0



Equivalent Logic Circuit

NOTE:'.' indicates an 'AND' function

'+' indicates an 'OR' function

A bar over an input or group of inputs indicates an INVERSION

the temperature is lowered even more. Not all the solids are removed by the settling tanks, and a *whirlpool separator* is used to remove even more of the remaining solids. A whirlpool separator is a circular vessel in which the height is roughly equal to the diameter. The wort is pumped tangentially into the vessel, resulting in *a* centrifugal force being set up, which forces the particles to the periphery where they meet the sides and slip down toward the base of the vessel. They are then propelled toward the center, from which point they are easily removed. The time taken is of the order of 20 minutes.

Wort Cooling

Figure 7.15 illustrates a typical plate and frame cooler, a form of construction that is useful as it allows the number of cooling plates to be chosen to give the necessary cooling required. All the plates are made from stainless steel, and, though not shown, the surface of those involved with carrying the fluid is usually corrugated. This provides the means of adding stiffness to the construction of the plate and forces the flow to be turbulent and therefore distributed across the entire surface of the plate. For simplicity, the detail of the end connections, covers, and plate clamping is not shown, but it should be pointed out that more clamping bolts are involved than the four shown. To seal the plate and frame interface, an elastomer gasket is located and held in a groove. This type of cooler cannot be used for gases or very high-temperature applications. For simplicity also, the fitting of the plates to the retainer is shown as a simple dovetail. This may not necessarily be the case but is used to explain the ease with which the plates are assembled and retained. The end covers are usually also provided with a means of fixing the whole assembly to the chosen location. This detail has once again, for clarity, not been included inasmuch as we are concentrating mainly on the way the cooler works.

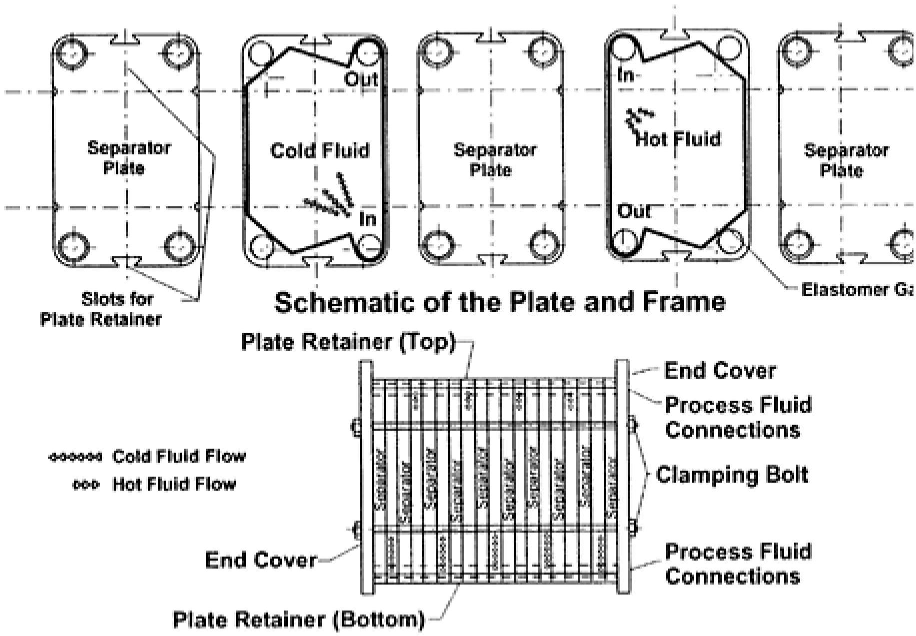


Figure 7.15: Schematic assembly of plate and frame cooler.

The cooler modules operate in the following way: The hot wort is pumped into the cooler through the top connection and flows downward toward the outlet connection of the hot-fluid plate. The cooling fluid is pumped into the cooler through the bottom connection of each cold-fluid plate located on the opposite side of that used for the hot wort and flows upward toward the outlet connection. Since the two fluid flows are counter to each other and the fluid has been forced to disperse as a relatively thin film across the entire surface of the plate, there is ample opportunity for the hot fluid to give up its heat to the coolant. This makes the system quite efficient in lowering the temperature of the wort.

FERMENTATION

Fermentation is an exothermic process. Therefore cooling is needed to get rid of the heat generated and thus retain the activity of the yeast. However, yeast is a living organism that acts on the sugars contained in the wort. The metabolic process cannot be separated from the growth and multiplication of the organism, and as a result it produces alcohol—ethanol actually—and a whole lot of other products, giving off carbon dioxide in the process. The result of the metabolic action of the yeast makes a significant contribution to the flavor of the final product. As stated very early on, the yeast used is, for scientific purposes rather than brewing, taken from strains of the genus *Saccharomyces* and species *cerevisiae*. The brewing industry, however, retains the two earlier classifications, one for ales—*S. cerevisiae*—and the other for lagers—*S. carlsbergensis.* With today's fermentation equipment, the two classifications are retained for purely traditional reasons because all fermentation takes place at the bottom. Yeast is kept fresh at a temperature of 2 to 4°C, but for ale-yeast propagation, a temperature of 25°C using a wort of 1.045 sg and a precisely controlled air aeration rate is best. To obtain the maximum alcohol with minimum growth, the fermentation temperature is 9 to 20°C with a restricted supply of oxygen. For maximum growth, yeast prefers an ample supply of oxygen and a temperature of 25 to 28°C. The sugar-to-ethanol conversion process takes about 6 to 10 days to complete.

The fermentation is brought about by the addition of yeast to the wort. The fermentation that occurs when the first amount of yeast is added is called the *primary fermentation,* which is followed by another period of fermentation with a smaller quantity of yeast, which is called *secondary fermentation*. The final processing consists of removing the remaining yeast and *ageing* the beer at a low temperature. A brewery will customarily use the yeast several times over, and, because it is a living organism, care must be exercised to maintain conditions suitable for the yeast to continue living and even reproduce. To continue its action and survival, the yeast must be provided with fermentable carbohydrates, assimilable nitrogen (ammonium salts), molecular oxygen, biotin (a vitamin), phosphorus, sulfur, magnesium, calcium, and traces of copper and zinc. The wort is subjected to routine testing for fermentable sugars and assimilable nitrogen (ammonium salts) in order to ensure that these criteria are met. Dissolved oxygen in the wort is a very important requirement, and sufficient amounts must be available at the start of the fermentation. Once the fermentation has started, however, no more oxygen is required, and any excess will ruin the beer by causing an oxidation reaction. The quantity of dissolved oxgen is inversely proportional to both temperature and specific gravity (s.g.). An excess of dissolved oxygen results in a strong fermentation and excessive yeast growth, with a commensurate reduction in alcohol content and change in the flavor of the beer.

Figure 7.16 illustrates the foregoing more explicitly and should be used to identify the trends of the parameters involved in the fermentation of beers/ales only; lagers

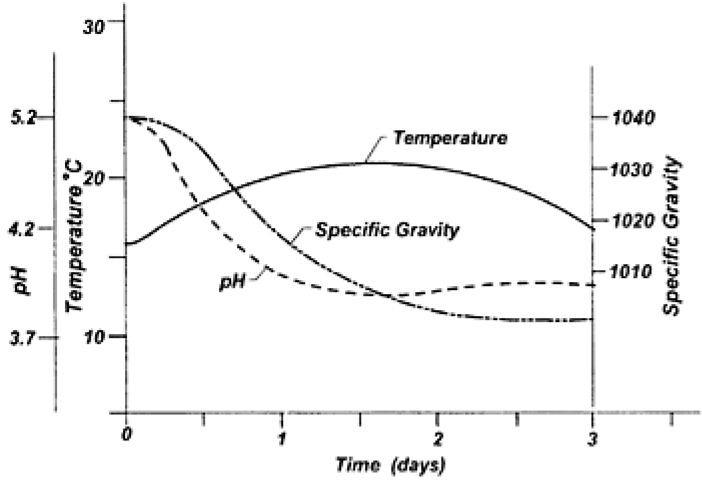


Figure 7.16: Beer fermentation parameters.

have a different set of trend patterns. The figure shows a pattern only; it is not to scale, and therefore readings should not be taken directly from it.

In most modern breweries, the old fermenters are being replaced with the cylindroconical type illustrated in Figure 7.17. These vessels are constructed from stainless steel with a cone-shaped bottom, the cone having an included angle of 65° to 75°

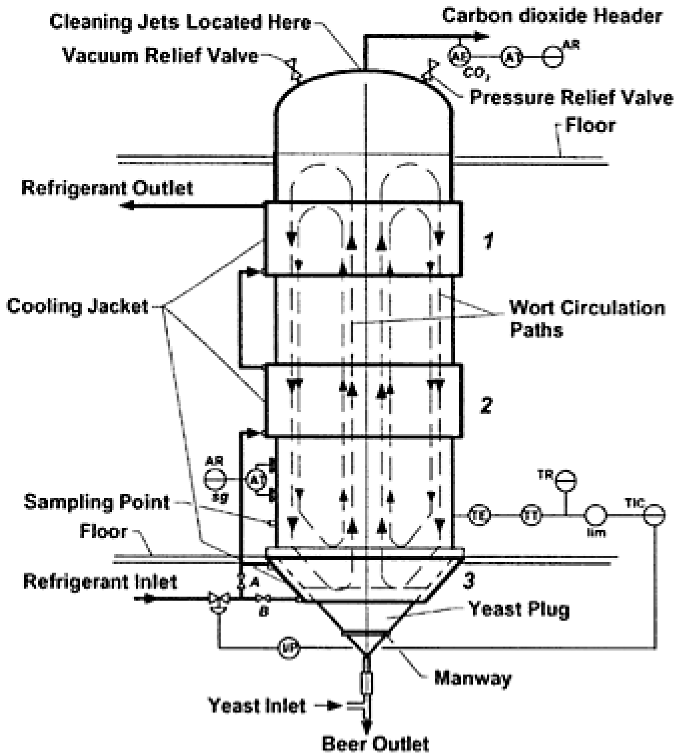


Figure 7.17: Schematic of a cylindroconical fermenter.

maximum. CO_2 gas is evolved as the wort ferments and the temperature starts to rise. The evolution of CO_2 increases as fermentation progresses, and a wort circulation path is formed as illustrated. The gas bubbles rise up through the middle of the two paths, giving the appearance of the wort boiling. As fermentation progresses, the yeast will flocculate (form lumpy masses) and settle in the cone of the vessel, making it easier to remove. Over the range 2°C to 30°C, the fermentation rate is directly dependent on the temperature; hence, a very effective way to control the fermentation rate is to regulate the temperature. The control loop consists of a resistance thermometer tagged TE that senses the wort temperature, and the transmitter tagged TT produces a proportional signal. This measurement is applied to a *rate of change* limiting block (algorithm) tagged lim, which allows the engineer to set acceptable rate of change limits. It monitors the measurement and applies rate-limiting to it to produce the module output. This block operates as follows: If the input rate of change is less than the configured rate of change limit, the output tracks the input (measurement). If the input rate of change is greater than the configured rate of change limit, the output will attempt to track the measurement, but its rate of change will be limited to the configured rate of change limit. As soon as the measurement rate of change becomes less than the configured limit, the output will continue to change at the linear rate of change configured until it eventually tracks the measurement. The output of the rate of change limit block is the measurement input of a PID (three term) control block tagged TIC whose output is applied to an electro/pneumatic converter, which regulates the control valve placed in the coolant inlet line.

Figure 7.17 shows a fermenter with three cooling jackets (#1 through #3), which is not always the case because usually there are only two (#1 and #2). Jacket #3 will be used when the yeast from the fermenter is used to *pitch* (provide the yeast for) other fermenters, and valves A and B direct or block the coolant flow appropriately. The greatest wort circulation is achieved when cooling jacket #1 only is used. It is usual for the yeast to be removed at the end of the fermentation process and to transfer it to a chilled slurry tank.

The temperature of the incoming wort at the start of the fermentation is in the range 15°C (59°F) to 17°C (62.6°F), and the maximum it is allowed to reach during fermentation is in the range 20°C (68°F) to 23°C (71.6°F). As fermentation nears completion, the amount of CO2 generated decreases, and the temperature falls. Additional cooling can be applied to allow more yeast to settle in the cone, the temperature now being slightly below that at which it was when the wort was first introduced to the fermenter. It is then held in the vessel for *warm conditioning*. The master brewer decides the period to hold the wort, after which the beer is cooled to 4°C (39.2°F), and no lower, because the beer—now called *green beer*—is at its densest condition and is transferred to other tanks—usually horizontal vessels—for maturing at a temperature in the range 0°C (32.0°F) to −1°C (30.2°F). This low temperature is achieved by heat exchangers or cooling coils in the vessels.

SPECIFIC GRAVITY MEASUREMENT

The following description of specific gravity measurement is used for many process applications. When used on wort, however, Europe has other more sophisticated methods available, which the reader is advised to investigate.

To guide the process operator in her task, the CO_2 evolved, the specific gravity, and the pH of the wort are all measured and recorded on the same chart recorder. This will give a trace similar in character to that shown in Figure 7.16 and will allow the process operator to visualize clearly the result of her actions. The specific gravity, or more correctly the density, is measured when using a differential pressure

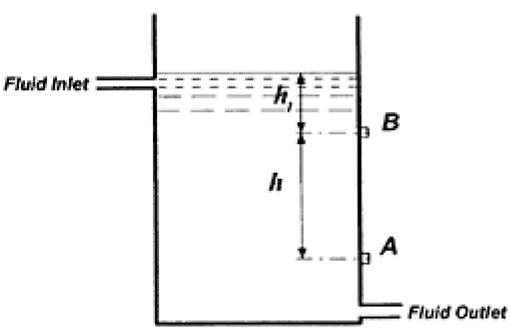


Figure 7.18: Hydrostatic method of measuring liquid density.

cell fitted with filled capillaries attached extended diaphragms on both process connections. The interconnecting capillary tubes should be of minimum length for the application, well insulated, and kept close to the vessel to minimize the heat loss, thus preventing the filled systems from behaving as thermometers as well, thereby ensuring measurement validity. It is absolutely essential that the process fluid covers both the process connections on the DP cell at all times with this type of measurement.

The principle on which the measurement is made is as follows: Figure 7.18 shows there are two connections A and B in a vessel, separated by a fixed distance *h*, and the vessel is filled with a liquid so that the liquid level can never come below the upper connection B. Then the difference in pressure between the two connections A and B is equal to the difference between the liquid head pressures between these two points. This liquid head pressure difference between the two points under consideration is true regardless of the head h_1 of liquid above the upper connection B. If h is the distance between the two connections, then multiplying h by the relative density will give the differential head between the two connections. To measure a change in pressure head that results from a change in density from ρ_1 to ρ_2 all we have to do is multiply h by the difference between ρ_1 and ρ_2 or symbolically:

$$p_{diff} = h(\rho_1 - \rho_2)$$

$$\frac{p_{diff}}{h} = (\rho_1 - \rho_2)$$

where p_{diff} is the pressure difference; h is the separation; ρ is the density; and subscripts 1 and 2 are the change in density. In this type of measurement, the actual span of the density change only is always considered. Therefore, the zero of the instrument is suppressed.

The meaning of zero suppression is easiest to explain if we consider a level measurement using a DP cell. Let us assume we need to measure a liquid level in a vessel with an open top with respect to the lower vessel connection, but we mount the instrument below the lower process connection on the vessel. Here we have a situation where even when the level in the vessel goes below the lower process connection, a column of liquid is always standing at the measurement connection of the instrument. If this situation is not taken care of, the level we shall be measuring will be with respect to the location of the instrument connection where the “true zero” of the measurement is now located rather than the “zero of the lower vessel connection” as required. The true measurement span of the arrangement will be the upper range value minus the true zero value (lying some distance below the lower vessel connection), which makes the span greater than that required. To overcome this problem, we must now “artificially” push the instrument connection up to the location of the lower connection on the vessel. In other words we have to elevate the zero of the measurement, and as a direct result we have reduced the true measurement span or in instrument parlance, carried out a “span suppression.” Elevating the zero always results in a change in the lower range value, and for the level measurement in question, the range will certainly not be zero based.

We now consider the situation where the instrument is located (for practical convenience, say) above the lower process connection. In this case, the true zero as before will be at the position of the instrument connection, and therefore the true zero will have to be "artificially" lowered to the position of the process connection. In other words, we have to suppress the zero and as a result increase or "elevate the span." A useful *aide memoire:* "Zero elevation results in span suppression" and "Zero suppression results in span elevation." In closed vessels, the pressure above the liquid face must always be accounted for in the calculations for instrument range and span. In the case of the measurement of density, the density span can never be zero based, so we have to suppress the zero. This allows the full span of the instrument to represent the change in density.

To choose the instrument, we must consider the span given by $h(\rho_1—\rho_2)$ and the zero suppression given by $h\ \rho_1$. As a result, it will be seen that for a given instrument span, a low-density span requires a large value of *h* and for a given density span, a measuring instrument with a low span will require a small value of *h*—this is instinctive and does not need a formula!

Since density and temperature are directly interrelated, and since we are controlling the temperature within the fermenter, the variation will be directly related to changes in density of the wort and vice versa.

There are other methods of measuring specific gravity. However, we must be aware that when the process concerns the food industry, then hygiene is of paramount importance. Any device that contains a quantity of stationary fluid is unacceptable for it could be a source of bacterial growth. For this reason we have suggested using a DP cell with extended diaphragms because this arrangement permits the measuring diaphragms to be flush with the inner wall of the fermenter and to be cleaned very effectively. Cleaning the vessel is carried out in situ, a procedure called cleaning in place (CIP). Every company has a specific procedure and chemicals that are used for the purpose, and these must be strictly followed.

CARBON DIOXIDE STORAGE

The carbon dioxide that evolves during the fermentation process is collected and used to carbonate the beer at a later stage. The carbon dioxide is purified and compressed before being stored in pressurized tanks. Only one tank and controls have been shown in Figure 7.19, but there are usually many more such tanks on a site. If necessary, the individual systems can be easily organized into a composite single one, but the requirements must be discussed fully with the plant management. The gas is not only used for the carbonation of the beer but is required for the bottling/canning operation as well. The storage pressure is such that there is always a large proportion of the gas in liquid form because this does not demand large amounts of storage capacity. The tanks are always lagged and placed within protective housings to minimize heat loss and for safety reasons. It is therefore necessary to have local tank-level indicators to give the plant operators an indication of the quantities available. The level alarm tagged LAL shown will be initiated and give an audible/visual warning when the contents drop below a predetermined value. This alarm can also be used to initiate a replenishing operation if desired. This additional feature has

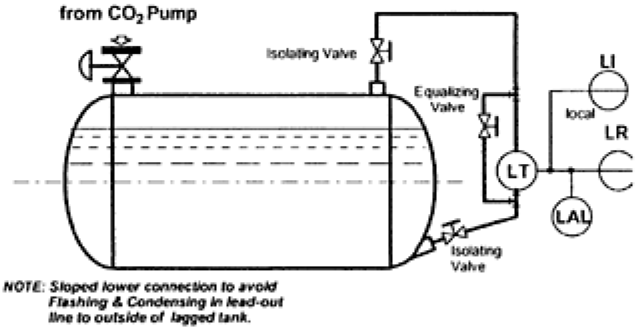


Figure 7.19: Schematic of carbon dioxide storage.

not been illustrated but can be designed quite easily. In the example illustrated in Figure 7.18, it is assumed that the process operators will initiate the tank replenishing when necessary from the information available to them. It is important that the block (isolating) valves on the impulse lines to the measuring instrument be (diaphragm types) suitable for refrigeration service, for this type will avoid leakage occurring.

FINISHING THE FERMENTED BEER

The product that is drawn off the fermenter is beer, but unfortunately it is not completely suitable for consumption. It needs to be processed further to remove the suspended particles that still exist, making the beer appear cloudy. It also lacks enough carbonization and needs flavor and color adjustment; in other words it needs to be matured. To bring about the mature flavor, yeast, acting as a catalyst, needs to be present. The two means of producing this maturation are called *secondary fermentation* and *storage-aging*.

SECONDARY FERMENTATION

In this process, fermentation by the yeast is allowed to continue, albeit at a very reduced rate, owing to the small amount of yeast involved and a low temperature. Such processes are krausen fermentations, lagering, and cask. In each case, to mature the beer, some sugar is added to start the fermentation, and the resultant carbon dioxide gas produced carbonates the product. The cask process is the shortest, in terms of time required; in some operations, hops or hop products for additional bitterness and fragrance, and sometimes potassium metabisulfite (to restrict bacteria) are added before the casks are sealed. The casks are then held for a few days, or up to a week, to allow the beer to clarify before being served.

The krausen process is very much like the cask; the added sugar, or *krausen,* comprises about 10 percent volume, but in the case of high-gravity beer up to 17 percent volume can be added to the fresh fermented wort. The beer is then put into horizontal tanks, which for the first day are left open to permit the sulphurous aroma, gas, and other volatile material to escape. The tanks are then sealed and held at about 8°C for a period of one to three weeks, within which period sedimentation occurs and the carbon dioxide produced carbonates the beer.

The lagering process is by far the longest of the three in terms of time; the sugar for the secondary fermentation is part of the original wort. However, before the first fermentation is complete, the wort is cooled to about 8°C and transferred to a secondary vessel, where the secondary fermentation occurs. The wort is held here for many weeks, sometimes months, after which it is fully fermented, mature and clarified.

CLARIFICATION

Once the wort has been fermented, it is transferred to storage tanks to age for a period up to a week or a week and a half, during which time the temperature is maintained within the range −1°C (30°F) to −4°C (39°F). This is carried out in order that the remaining yeast can combine with any remaining oxygen and settle out, as well as to encourage the formation of particles of chill haze (a protein-carbohydrate/tannin/metal ion complex made visible when the beer is chilled and re-dissolves when the beer warms up), so that these can be removed too.

Dense particles settle out in accordance with the terminal settling velocity from Stokes law, which is given by *Perry's Chemical Engineers Handbook* as:

$$v_t = \frac{g D_p^2 (\rho_p - \rho)}{18 \mu}$$

where v_t=free settling velocity

D_p=particle diameter

μ=fluid viscosity

ρ_p=particle density

ρ=liquid density

g=gravitational acceleration

Note that in *Perry's Chemical Engineers Handbook* the terminal settling velocity is stated as u_t. This has been modified to align with the notation used in this book.

In some smaller breweries that produce ales as the only product, because the process of ale making takes a much shorter period of time than lager, the cylindroconical fermenter is used as a multipurpose vessel. The secondary fermentation is started in the same vessel after the primary fermentation is complete. This is followed by yeast removal, flavor adjustment, and cold storage. When the cylindroconical fermenter is used in this way, the vessel is sealed to trap the carbon dioxide after the primary fermentation is complete and the hops have been added. The pressure within the vessel begins to rise as fermentation proceeds and steadies as the fermentable extract is exhausted. The vessel is then cooled—slowly at the start—to age the product, and then rapidly to a value within the range 1°C (34°F) to 3°C (37°F) for clarification and stabilization. The instrumentation shown in Figure 7.17 will have to be modified accordingly to take care of this method of operation. (This has not been shown but should not be too difficult to incorporate.)

PASTEURIZATION

Pasteurization always follows the filling operation, the objective being to minimize the possibility of microorganisms surviving in the beer. This process depends on several factors such as the type of beer, the number of microbes present, the level of confidence the brewers have in using the least amount of pasteurization treatment, and the size of the beer container.

In brewing, a Pasteurizing Unit (PU) is defined as 1 minute (time) at 60°C (140°F), or equivalent based on the death rate of the microorganisms in the beer. At the reference temperature of 60°C (140°F), the kill time obtained by empirical observation is 5.6 minutes, or 5.6 PU, and is the minimum safe heat treatment for the beer. The heat must be received at the center of the container. Brewers, however, operate in the range 5 to 15 PU. To meet the requirement of heat to be as measured at the center, containers could be forced to remain for long periods in the pasteurizer. But at the same time the beer that is near the walls of the container will receive more than the required amount of the applied heat. With an excessive amount of time spent in the heat, there is every possibility that the flavor of the beer will be affected. These considerations greatly influence the size of the container itself.

Bulk pasteurizing is one in which a relatively thin stream of beer is made to flow through a heat exchanger. Operating in a similar way to that shown in Figure 7.15 would allow it to heat up and cool down relatively quickly. This minimizes the time the beer is exposed to the heat of pasteurization and will preserve its flavor. The bulk pasteurizing method is also much more energy efficient.

SUMMARY

1. Barley is a widely cultivated cereal grass of the genus *Hordeum* and in particular *Hordeum vulgare,* which bears bearded flower spikes and edible seeds. The grains of this plant are the most important basic raw material used in beer, ale, and whiskey making.
2. Barley grain itself as harvested is unsuitable for making beer, but subjecting it to a malting (controlled germination) process achieves a radical change. Malting brings about changes in the chemical, biological, and physical properties of the grain.
3. Malt and a range of malt extracts are made from germinating barley, a process in which the barley is deliberately allowed to sprout under moist, warm conditions so that the α- and *β-amylases* become active and start to break down the starch endosperm.

4. The endosperm is the nutritive tissue surrounding and absorbed by the embryo in flowering plants.
5. Amylases are enzymes, which break down starch. The α-amylases (or dextrimorganic amylases) attack starch molecules randomly to produce dextrins, and the β-amylases systematically remove maltose from starch molecules. These two enzymes together are called *diastase*—because they convert starch to maltose in the germinating grains (malt).
6. Dextrin is a white or yellow powder formed by the hydrolysis of starch and has colloidal properties. It is used mainly as an adhesive and thickening agent.
7. For brewing, the barley sample must be at least 96 percent alive; dry, that is, retain approximately 12 percent moisture; free of infestation, disease, discoloration, and debris, which generally comprises weeds, dust, and broken corns; and low in nitrogen. The reason for the low nitrogen content requirement is that excessive N_2 slows down the modification (starch conversion) and lowers the malt-extract yield.
8. Since beer is composed of almost 95 percent water, the water used in its manufacture must be of the utmost purity, and it is vital that it does not impart any unacceptable taste to the brew. To maintain the quality of the beer, it is essential that the pH of the water be maintained because the pH of the final brew, despite the several changes in value it undergoes during preparation, is ultimately related to the initial pH of the water used. The treated water used is known as sweet water and is retained in large storage tanks.
9. Other materials are often added to the formula; for instance rice and millet are included in China as components, flaked rice, oats, and corn in the United States, while wheat is used in Germany. These additional cereals are called adjuncts and are included to provide the desired flavor to the beer.
10. Wheat is any of a variety of grasses of the genus *Triticum,* and in particular *Triticum aestivum,* widely cultivated in many varieties for its edible grain and best known for its use in the powdered seed form of flour used extensively in the preparation of cakes, bread, and pasta in which it is the basic ingredient. In Germany it also finds use in the beer brewing process, where it is one of the adjuncts used.
11. Oats are another of the several grasses of the genus *Avena* and in particular *Avena sativa,* also widely cultivated for its edible seeds, used as food and animal feed. In the United States the seed is processed to obtain a flaked form (which is basically the flattened seed) and then used in the brewing of beer.
12. Millet is a grass whose botanical name is *Panicum miliaceum*. It is widely cultivated in Asia and Africa for its seed and in the United States, Canada, and Europe for hay. In Asia and Africa, the white seeds of the plant are used as food.
13. Corn is the general name for the seed or fruit of any of several plants that produce edible seeds, especially when grown as the main crop of a region, such as wheat in England, oats in Scotland, and maize in the United States and Australia. Maize is a New World grass, *Zea mays,* grown extensively as animal feed and for its light yellow to medium orange colored cob, which is also known as Indian corn and can be cooked and eaten as a vegetable.
14. Other ingredients required to proceed with the manufacture of beer are brewing sugars and syrups (corn or glucose) plus yeast.

15. Hops are any of several twining vines of the genus Humulus and in particular *humulus lupulus* having hooked leaves and green cones like female flowers. It is a native flora of Europe, Asia, and North America, but it has nevertheless been successfully grown in Australia. It is the female plant that is cultivated. The brewing value lies in the resins and oils that are contained in the lupulin glands at the base of each bracteole. The mature cones are harvested and processed; the resins impart the bitterness and the oils produce the aroma of the beer made from it.
16. Boiling the hops is necessary for extracting the resins and oils, and also because it kills all vegetable microbes contained in the raw material. Thus, processing improves the microbiological stability of the beer, providing that the overall hygiene of the plant is maintained.
17. Hops are harvested and kiln dried to reduce the moisture content to about 10 percent for this will then enable the hops to be stored. The dried hops are packaged in bags made from either jute or woven polypropylene. The packages have a special name—in Germany they are called a ballot, in the United States a bale, and in the United Kingdom a pocket. The weight of a ballot is approximately 90 kg, and a pocket is approximately 80 kg. In the United Kingdom hops used to be processed in circular brick houses having an inverted circular, cone-shaped roof called an oast-house. Today the traditional oast-house has been replaced by a modern structure that is more efficient.
18. Yeast is a *fungus*, usually involved with fermentation and spoilage of sweetened and salted products. The two forms of interest with respect to the drinks industries are *Saccharomyces cereisiae*, which is used for bread and beer making and *S. ellipsoideus*, which is used in wine making.
19. In beer manufacture, we are in particular concerned with *Saccharomyces cereisiae*. Yeasts are a useful source of proteins and B vitamins. Yeast extracts and hydrolysates—products of hydrolysis, that is, the decomposition of a chemical compound by reaction with water such as the dissociation of a dissolved salt or the catalytic conversion of glucose to starch—are used as flavors in soups and meat products.
20. Technology has also allowed the inclusion of chemical additives to improve shelf life, taste, and color. Each manufacturer chooses the additive(s) that will enhance his product. Refer to the main text under the heading Additives for details of the chemical additives used.
21. Disaccharides are sugars such as sucrose, lactose, and maltose that are formed by a combination of two monosaccharide units with the elimination of a molecule of water.

    Sucrose=fructose+glucose
    Lactose=galactose+glucose
    Maltose=glucose+glucose

22. Maltose or malt sugar is a simple disaccharide made from two glucose units. Refer to Figure 7.3 when reading the following. The two glucose units are linked across a carbon atom (1) on the left-hand glucose unit and the carbon atom (4) on the right-hand glucose unit. Maltose is a reducing sugar and is produced when starch is broken down

by the action of enzymes (amylases), particularly in the malting process of barley for beer making.

23. Refer to Figure 7.3 when reading the following. A *β* maltose does exist but is less common; its structure is the same except the OH on the carbon on the right-hand side is at the top.
24. Refer to Figure 7.3 when reading the following. When the two glucose units condense together, water is eliminated and the remaining oxygen atom forms a bridge between the two glucoses. This bridge is called the *glycosidic link*. In this case, the glycosidic link is called an *α*, 1–4 link because the left-hand sugar is an *α* form and the link is between carbon atom 1 and 4 of the two sugars joined.
25. Before the barley is processed, it has to be washed and steeped in water to soften the husk and make the grain ready to germinate, but once softened up the excess water is drained off. Germination is a natural process and takes time, usually a period of about eight days. The grain is spread out in large rooms where it is encouraged to sprout. During this time it is turned over regularly to remove the grain that has developed sufficiently to be processed. To assist growth, the barley grain is subjected to the effects of circulating warm moist air whose temperature is maintained constant. Oxygen is absorbed, and carbon dioxide is given off while the grain is sprouting and the enzyme diastase is formed. Once all the grain has germinated, it is subjected to a malting operation under controlled conditions in a kiln.
26. The enzyme diastase is the biological catalyst that converts the starch in the grain to the disaccharide maltose, which is directly fermentable by yeast after it is transformed to monosaccharide glucose by maltase.
27. No instrumentation-assisted measurements of the grain are made because it is difficult to measure the condition of the malt as it is being processed. The color and the aroma of the malting grain will ultimately determine the quality of the finished product, and to a very large extent these are extremely difficult to determine or define. Much reliance is placed on the skill and experience of the process operators and the master brewer who is responsible for the overall quality of the beer produced.
28. After the barley has been malted, it is subjected to a milling process carried out in machines called roll mills. The grain is drawn through a space between pairs of fluted rolls adjusted to a gap sufficient to crush the grain but not split the husk. The crushing operation is not carried out in one pass but in several passes through the set of rolls. The mills can have multiple pairs of rolls; a mill with three pairs of rolls is then called a six-roll mill. Each pair of rolls is followed by a set of vibrating screens, the mesh of which is graded from coarse to fine, the coarsest being placed first in the train and the finest last.
29. The objective of the milling operation is to leave the husk of the barley intact but crush the grain within it. Leaving the husk intact assists the separation of the wort and also reduces the possibility of extracting unwanted components such as tannins.
30. Mashing is a process that allows the sugars to be dissolved. There are basically two forms of mashing. The procedure carried out in America is known as double mashing. In the United Kingdom and Europe the mashing process is different and is called decoction mashing.
31. Double mashing requires the use of two vessels: a cereal cooker and a mash tun. The

cereal cooking and mashing operation are run in parallel, so that the lauter tun receives the complete mash in a single discharge from the mash tun. The cereals used must be cooked (gelatinized) prior to being included in the mash. The amount of cereal used is carefully weighed in a weigh tank and passed to the cereal cooker along with a metered amount of water.

32. The cereal cooker is a vessel fitted with a heating facility, which could be a jacket, heating coils, or direct steam injection. An agitator is also provided in order to facilitate heat distribution throughout the cereal mass.
33. The mash tun has a perforated false bottom and is free-draining throughout the mashing process, but initially the outlet connection is shut off by a valve located at the base of the mash tun and opened after all the malt has been admitted. Refer to Figure 7.9.
34. The mash tun originally did not have an agitator because the dense wort was pushed through the thick mash bed by a series of hot sparge water flushes. This technique was known as infusion mashing and was the original classic British method of mashing. Modern mash tun designers used the data obtained from the infusion mashers to modify the technique and now fit knives and rakes that cut and lift the mash to make the dense wort collection a little easier and faster.
35. The lactic rest is a period during which the mash is allowed to stand to permit the enzyme activity to produce lactic acid. Refer to Figure 7.10b.
36. The protein rest is a period during which the mash is allowed to stand to allow the enzyme proteinase to reach its maximum activity and reduce the large protein molecules to compounds of lower molecular weight. Refer to Figure 7.10b.
37. The sugar rest is a period during which the mash is allowed to stand to allow the sugar maltose to be formed by the action of the enzyme β-amylase. Refer to Figure 7.10b.
38. All rest periods are determined by the master brewer and configured as hold-periods in the sequence of control system stages.
39. Two vessels are also required to prepare the mash in the decoction mashing process: a small vessel called the mash kettle and a larger one called the mash mixer. Both vessels are fitted with agitators and heaters. Part of the charge is transferred from the mash mixer to the mash kettle at specific times where it is brought up to the boil and the temperature is held for a period before it is returned to the mash mixer to continue being processed.
40. The temperature of the contents is determined when a relatively cool mash and hot water are combined. The calculation is based on the fundamental evaluation of heat, which states that the total heat of a body is its mass multiplied by specific heat multiplied by the change in temperature.

$$
\begin{aligned}
T_{mixture} &= \frac{W_{water} \times Sp.Ht_{water} \times T_{water} + W_{malt} \times Sp.Ht_{malt} \times T_{malt}}{W_{water} \times Sp.Ht_{water} + W_{malt} \times Sp.Ht_{malt}} \\
&= \frac{W_{water} \times 1.0 \times T_{water} + W_{malt} \times 0.4 \times T_{malt}}{W_{water} \times 1.0 + W_{malt} \times 0.4}
\end{aligned}
$$

41. After the conversion of the starch to sugars in the mash tun is complete, the mash is transferred to the lauter tun where the separation of the insoluble constituents is effected. The lauter vessel is a very large cylindrical container much bigger than the mash tun, with a perforated false bottom comprising slots that are narrower and pitched further apart than those found on the mash tun. The real bottom of the vessel has a number of outlets fitted to it so that the liquor can be drained off. It has a highly specialized agitator comprising a horizontal bar with vertical rakes called knives whose pitch can be altered. There is also a horizontal sparge tube at the top of the rake assembly through which water can be sprayed. The complete agitator assembly can be raised or lowered either mechanically or hydraulically. The runoffs are collected in a vessel called a grant. Refer to Figure 7.12.
42. The brew kettle is large and of a different form from kettles involved with brewing in earlier times. Originally they were constructed from copper and as a result carried the name *coppers*. Copper was chosen as the construction material because of its good thermal transfer. Modern kettles are made from stainless steel even though the material has much poorer heat-transfer capabilities. Stainless steel is now the choice because it is sturdier and better able to withstand the harsh cleaning chemicals used today. Since the heating coils or calandria are always mounted internally, the heat-retaining properties of stainless steel are exploited to advantage. The design of the vessel is such that it concentrates the heat at the center of the wort contained therein to ensure that the boiling is what is called a full rolling boil. This means the intense, rapid motion of the heated convection currents and the evolution and removal of the steam generated by the boil.
43. There are basically three reasons for boiling. It inactivates any enzymes that manage to survive the mashing process; it precipitates a complex protein/tannin/ carbohydrate compound called *hot trub,* which could render the beer subject to chill haze; and it sterilizes the wort, which renders it stable from a bacteriological standpoint since it kills off all vegetative microbes contained in the raw materials.
44. Hops, which are vital in giving beer its characteristic bitter taste, are introduced to the wort in the brew kettle. Hops are added in one of two ways: either the full measure required for the quantity of wort is included at the start, or it is added in small quantities at several stages during the entire processing operation.
45. When boiling is complete, the contents of the kettle are passed to a strainer as quickly as possible where the hops are removed and the strained wort is then stored in tanks where the proteins (trub) are allowed to settle out and the temperature can fall. Afterward, the clearer wort is passed through frame and plate coolers where the temperature is lowered even more.
46. Not all the solids are removed by the settling tanks, and usually a whirlpool separator is used to remove even more of the remaining solids. A whirlpool separator is a circular vessel into which the wort is pumped tangentially. Because of the centrifugal force set up, the particles are forced to the periphery where they meet the sides and slip down toward the base of the vessel and are then propelled toward the center, from which point they are easily removed. The time taken is of the order of 20 minutes.
47. Since fermentation is an exothermic process, it is necessary to provide cooling to get rid of the generated heat and retain the activity of the yeast. Yeast is a living organism

that acts on the sugars contained in the wort, converting it to alcohol and giving off carbon dioxide in the process. It is usual for a brewery to use the yeast several times over; hence, care must be exercised to maintain conditions suitable for the yeast to continue living and even reproduce. Yeast is kept fresh at a temperature of 2 to 4°C, but for ale-yeast propagation, a temperature of 25°C using a wort of 1.045 s.g. and a precisely controlled air aeration rate is best. To obtain the maximum alcohol with minimum growth, the temperature of fermentation is 9 to 20°C with a restricted supply of oxygen. For maximum growth, yeast prefers an ample supply of oxygen and a temperature of 25 to 28°C. The conversion of the sugars to alcohol takes about 6 to 10 days to complete.

48. The fermentation that occurs when the first amount of yeast is added is called the primary fermentation, which is followed by another period of fermentation with a lesser quantity of yeast, called secondary fermentation.
49. Dissolved oxygen in the wort is very important, and sufficient amounts must be available at the start of the fermentation. However, once the fermentation has started, no more oxygen is necessary, as any excess will ruin the beer by causing an oxidation reaction. The quantity of dissolved oxgen is inversely proportional to both temperature and specific gravity. An excess of dissolved oxygen results in a strong fermentation and excessive yeast growth, with a commensurate reduction in alcohol content and change in flavor of the beer.
50. The cylindroconical fermenter is the modern version of the old fermenting vessel. Some of these modern vessels have three cooling jackets. The yeast from one fermenter can be used to pitch another once the fermentation in the first fermenter has been completed. In smaller breweries the cylindroconical fermenter is a multiuse vessel for fermentation, warm conditioning, and clarification, which are all carried out in the same vessel.
51. The carbon dioxide evolved during the fermentation process is collected and used later to carbonate the beer. The carbon dioxide is purified, compressed, and then stored in pressurized tanks. The gas is not only used for the carbonating the beer but is also required for the bottling/canning operation. The storage pressure is such that much of the contained gas is in liquid form because this requires less storage capacity. The tanks are always lagged and placed within protective housing to minimize heat loss.
52. After fermentation, the wort is transferred to storage tanks to age for a period of 7 to 10 days, during which time the temperature is maintained within the range −1°C (30°F) to −4°C (39°F). This is so that the remaining yeast can combine with any remaining oxygen and settle out, as well as to encourage the formation of particles of chill haze so that these too can be removed.
53. Dense particles settle out in accordance with the terminal settling velocity from Stokes law given by *Perry's Chemical Engineers Handbook* as:

$$v_t = \frac{g\, D_p^2\, (\rho_{p} - \rho)}{18\, \mu}$$

where v_t=free settling velocity

g=gravitational acceleration

D_p=particle diameter

ρ=liquid density

ρ_p=particle density

μ=fluid viscosity

CHAPTER 8
Project Management and Administration

At first sight, the business of managing a project regardless of size or complexity appears to be a simple matter. This cursory view of the subject could not be further from the truth. The reality is that the path to a successful conclusion of any project is strewn with pitfalls for the unwary, some of which could spell disaster both technically and financially. The result of such mishaps, if allowed to occur, can be severe for all parties involved, whether they are individuals or the company itself. Project management is primarily a function involving the interaction with people as much as it is with equipment and technology. Never forget that all equipment is produced by the joint efforts of several individual human beings, each of whom has a unique personality that has to be respected.

This chapter focuses on the essential project management needs of the systems supplier, but to fully understand this aspect, it is necessary also to be aware of the project management methods of the user and contractor.

For most major projects at least three project managers could be involved, each with a different set of priorities, depending upon their position within the overall project structure. The first project manager representing the end user has the principal aim of completing the project within the defined schedule and fulfilling the design criteria. The second project manager representing the contractor is usually working from a fixed price contract with the end user and a schedule that incorporates constructions other than that directly applicable to the control system. This manager's priorities therefore become more complicated in that the client's satisfaction has to be met and at the same time oversee and coordinate the actions of the various suppliers to the overall contract. The system supplier has a third project manager who interacts directly with the main contractor and indirectly with the end user. This third manager would normally be working from a fixed price contract arrived at by bidding against the contractor's specification and a delivery schedule agreed to prior to the contract being awarded. The priorities for this manager are, therefore, to complete the contract technically within the agreed time schedule and at the minimum cost, thereby maximizing profit for the company.

THE TECHNOLOGIST VERSUS THE MANAGER (ADMINISTRATOR)

A project, depending on its size and the amount of personnel and expertise required, can be handled in two ways. First, there is the method that uses the knowledge and capability of a dedicated (and by this is meant an assigned) project manager, whose sole task is to administer the project efficiently and manage it within budget and to schedule. In this duty, a team of technical and administrative members, all of whom interact to produce the desired result, assists the project manager. It is quite common for the end user to appoint a technologist as its project manager so that detailed knowledge of the process can be fully utilized in any detailed discussions with the contractor's project manager. The contractor also makes use of an experienced, capable technologist, who in addition to the technical ability has the talent and competence to fulfill the duties of project manager.

THE MANAGER (ADMINISTRATOR)

The project manager, by virtue of specific business administration, academic qualification, and experience, in addition to technical qualifications, is often allocated the task of project management. However, those who have the academic qualifications sometimes lack the important "people managing" (interpersonal) skills and experience that are an intrinsic part of the job. It is also not unknown for project managers to be in charge of the most demanding large-scale projects even though they do not possess qualification in business administration. These individuals are successful because, despite their lack of specific academic business qualification, they have technical ability as well as interpersonal skills. Most importantly, they have acquired this business acumen through experience in the industry, having spent a considerable time learning their trade, and their self-acquired diplomatic ability sharpened over years of using it.

Project management is an area of practical concern that, while requiring a good understanding of technology, does not demand a continual and deep involvement in the sometimes fundamental and difficult aspects of science that are called for in getting the task done. However, the manager must be sufficiently knowledgeable to realize when a project is going astray and must have the necessary risk management skills to bring it back on track.

THE TECHNOLOGIST

For the professional engineer, it appears as an unnecessary intrusion to be called upon to perform functions that are mostly administrative and have very little technical content. This aspect of technology interspersed with bureaucracy is not of major concern to those of us who are dedicated technologists. Our initial reaction is to avoid, or if possible, have only minimal involvement in these important and sometimes vital administrative tasks. However, technologists understand that sometimes it is necessary to become involved with purely clerical functions in order to maintain a check on matters of real concern to the professional engineer. The involvement becomes greater the more complex and/or larger the size of the task—hence, presenting a greater risk.

THE REQUIREMENTS OF THE ADMINISTRATOR

A good project manager (PM) is a person with a multifaceted personality. This demanding job requires a persona of openness to and approachability by others in terms of both technical and commercial input and advice. The other important functions of this position are to be sleuth, diplomat, and coach as well. In the role of investigator, the PM has to be able to discern the legal implications of those ostensibly innocuous statements or requirements that, if overlooked, could spell serious trouble. If necessary, the PM has to be humble enough to put the thoughts provoked by these highly complex statements to those who are more versed and qualified in these matters and, in so doing heed the advice given. Since the PM is intimately involved with people, he or she must possess the ability to accept the foibles, occasional arrogance, and some idiosyncrasies of individuals with grace, but yet be able to deliver his or her logically considered opinion firmly and fairly in all dealings. The PM is the one who in the final analysis carries the responsibility, and who will eventually be held accountable by management, for all aspects of the assigned project. In these duties, the PM displays the characteristic ingredients of the professional diplomat because producing a smooth and seamless project performance despite any upset is the ultimate goal. The PM must at all times avoid altering factual information at the expense of the other party's integrity. This practice in any case is highly unethical, and merits castigation.

STARTING OFF A PROJECT

The ultimate aim of most projects is to increase the profits of the end user. This aim can generally be achieved by:

1. An improvement in the quality of the product, thereby increasing the saleability of that product.
2. Improved productivity by producing more at a reduced unit cost.
3. Lower product cost.

Every project has a very definite point of inception, and in the case of a project dealing with control systems, experience has taught that the end user of the process has very definite ideas on how the process and various control systems should behave. Depending on the size of the plant involved and its complexity, the project can usually be broken down into very specific areas of responsibility. For example if, say, the process involves a chemical plant, a major plant construction company could be involved. This organization would be responsible for the whole plant and would therefore be allowed to manage the work involved with the entire job. The construction company (or contractor), which usually has particular expertise in certain types of manufacturing processes, has several specialist departments dealing with different aspects of the project. Such an organization is broadly illustrated in Figure 8.1.

There are, of course, many different types of contracts between end users and contractors, such as the "turnkey." This means that the contractor is responsible for the entire project, from basic process design right through all plant equipment and control systems. Profit comes from completing the project within budget in both time and money, and, hence, at minimal cost to the company. Another is the "cost plus," which means that, while the contractor is still responsible for the design, providing the plant equipment and the control systems for which they are paid by the end user, in addition the contracting company is also awarded an amount of money based on a fixed percentage of the overall contract value. In other words, for the cost plus contract, the contractor is guaranteed a profit.

A similar organizational setup as operated by the contractor can be found in an instrument and control system manufacturing company. Of necessity there are going to be differences between the two companies, because they are involved in different aspects of the project. What they have in common are the completion of the project and the safe running of the process when it is finally handed over to the end user (the product manufacturer) on whose behalf the constructor and the instrument supplier work together to achieve a successful conclusion.

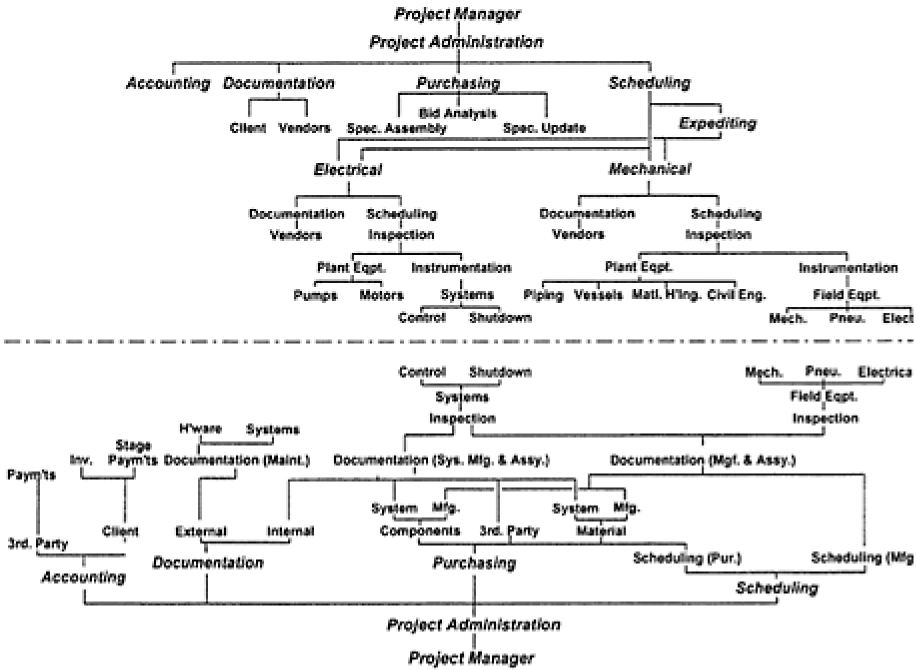


Figure 8.1: Simplified chart of the organizational setup of a typical process/instrumentation industry construction project.

For simplicity of the diagram, the interaction of the several departments involved in both organizations internally and with each other has been omitted; these interconnections will be included where appropriate (see Figure 8.2) to give a better understanding. To see how the arrangement works, let us consider a typical project right from its inception—with the end user's (product manufacturer's) justification, through the assignment of a process plant constructor, down to the choice of an instrumentation and control system manufacturer.

We will discuss in general terms the considerations the end user (the product manufacturer) takes into account and the operation and function of the process plant constructor. Our emphasis, however, will be on the workings of the instrumentation and system manufacturer and on how this organization interfaces and interacts with the process plant constructor. The particular emphasis is on the roles the PM of the instrumentation and system manufacturer play in achieving the project objectives.

An understanding of the end user and the contractor's project management methods is needed to explain the different functions of each party in the overall project.

PRE-PROJECT INVOLVEMENT FOR THE PRODUCT MANUFACTURER

To briefly trace the start of a typical large project, let us assume that a particular chemical manufacturer (end user) has conducted its investigations on the need for an addition to its existing manufacturing capability.

THE MANUFACTURING SITE

The manufacturer has fundamentally two options:

1. Use the existing plant with the additions placed near where required, in available positions.
2. Develop a new processing area for the additional plant.

The first option makes use of the plant as it stands, with the additions suitably placed to give the desired result. For this option to be considered, the existing plant must have space available for the new equipment to be incorporated. However, a considerable amount of alterations to the process piping could be involved and in some instances access could be limited. The second option could involve using some vacant land that currently exists on the site, or it could mean acquiring additional land adjacent to the plant. This latter development is called a *greenfield* development. Used in this sense, the term *greenfield* explicitly describes the land required for the needed plant.

Let us assume for this example that the plant currently exists and has the necessary space to include the proposed expansion without incurring too great a problem. This, is not the same as the development of a greenfield site because in this latter case the project discussions between the manufacturer and the construction company will have to be more elaborate. In the United Kingdom, government departments (Department of the Environment, and Health and Safety to cite only two) would also be involved because the proposed plant will have to comply with government regulations. This intervention is unavoidable in most European countries and the United States. Unfortunately, however, the rules for compliance vary from country to country.

PROJECT JUSTIFICATIONS

Before any work is undertaken, every aspect of the involvement has to be considered. These studies, termed *feasibility studies,* include the justification of the needs.

Process Aspects

1. The projected market—the necessity of the new product, together with an estimate of

the demand for it.

2. The feasibility of the additions interfacing with the existing plant, either through the additions utilizing existing space and being able to join the process with minimal disruption, or the expansion needing new additional space for the new plant and equipment.
3. The ability to continue manufacturing the current range of product(s) while the additional capability is being constructed.
4. The effect of the inevitable shutdown of existing or affected parts of the processes, when the new capability is brought *on stream*, and the amount of time required for the shutdown and the clearance of any associated difficulties to be achieved.

Financial and Legal Aspects

1. Financing of the project.
2. The projected *return on investment* (ROI), including the period over which this return will be realized. In these harsh economic times, the financial commitment and the recuperation of the monies involved are vitally important. Any lapses in considering this aspect will carry a heavy penalty, possibly even threatening the organization's very survival.
3. The legal requirements regarding the site together with equipment delivery will also have to be considered, and any penalties for late or noncompletion will be considered. Standard terms and conditions are available from many professional institutions; these can be used in totality or in a modified form to provide the basis of the contract.

PREPARATION OF THE PROCESS PLANT SPECIFICATION

1. Bearing in mind that the matter had been given active consideration long before this stage had been reached, the technical specification of the proposed additions would have been in the form of detailed notes prepared by the management, engineering, financial, and legal departments which will then be coordinated into a final document.
2. The engineering involved will also have been scrutinized, and appropriate drawings produced; these will be included in the specification package.
3. The construction specification and tender document will once more be assigned to the financial and legal departments for their final approval before it is sent out for tender.

SELECTION OF THE PROCESS PLANT CONSTRUCTOR

1. Some construction companies specialize in particular types of manufacturing processes. The manufacturer will be aware of these companies and their ability to fulfill the proposed task and will draw up a short list of prospective constructors.
2. The final specification and invitation to tender will then be sent out to those companies on the short list.
3. Again, depending on the size of the project, the construction companies may be invited to discussions and a survey of the site.
4. In most instances, the manufacturer normally seeks and obtains process guarantees

from the construction company awarded the contract to build.

CONSIDERATIONS GIVEN BY THE CONSTRUCTION COMPANY

A site visit by the construction company will almost certainly be made, so that the client's specification can be compared with the actual prevailing site conditions. This visit will allow the organization involved in providing the construction to gain a comprehensive idea of the degree of involvement. During this meeting, the construction company ascertains whether the client (end user) has any particular preferences as to equipment or suppliers. This preference of supplier most often concerns analytical measurements where the choice of manufacturers and technique used is fairly restricted. The constructor's right to abide by these preferences will also be discussed, for no company will be willing to surrender anything that might jeopardize the smooth running of a project, especially when the capital investment is large. Also discussed will be the allocated time scheduled to prepare and submit the tender documentation. This aspect is important when the amount of work involved in its preparation is unrealistically constrictive. Any changes in the time allocated will be the subject of a confirmatory statement acceptable to both parties.

TECHNICAL ASPECTS

1. The project specification and tender document are reviewed overall, and specific aspects of the technical requirements are copied and circulated to the various engineering disciplines that will be involved. Each engineering discipline will be asked to review the requirements for its feasibility and to prepare an estimate of the time required to complete the specification requirements.
2. Since a final date is usually prescribed for submission of the bid document, each engineering discipline will be allocated a specific time within which to return the results of its review.
3. In parallel with the technical reviews, a study is also conducted to determine the exact requirements being requested and whether these match others the corporation had dealt with in the past or whether a previous client had requested a similar, or broadly similar, specification. This study can save an enormous amount of time and effort, and will certainly result in a more competitive bid.

PROCESS ENGINEERING ASPECTS

1. Assuming a likely match is found, no matter how similar any two specifications might appear to be, some differences will always exist and will require addressing. These differences usually make considerable changes in the actual requirements. To allow for these differences, the process engineers employed by the construction company will also review the previous specification to estimate how far the similarities go and what has to be done to achieve the present client's specification.
2. Based on the findings of the review, a workable process specification is drawn up defining the conditions that will meet the original request and, if necessary, put

forward guarantees of delivered product totals.

3. Any departures from the client (end user) specification will also be defined, and the reasons for these departures will be given. In this way, the client will be able to verify or disagree.
4. Options are proposed in the process system design, which takes into account the variations in the manufacturer's (end user's) product that may exist between that specified and their (contractor's) standard product.
5. In the event no match is found, work on the client (end user) specification will have to be started from scratch. Under most circumstances, this is unlikely to happen, but the possibilities exist. This stage of the work is time consuming, and steps for bid extension will be taken.

COMMERCIAL ASPECTS

The Project Bureaucracy

1. The amount of clerical involvement in running the project, including the amount of paperwork to be generated and coordinated will be assessed. This will involve generating project-specific documents, labels, and stationery, and allocating filing ability and space to house the files that will be generated.
2. The amount of floor space necessary to house all the staff that the project would demand, and the cost thereof, will be determined.
3. Provision of an IT (Information Technology) infrastructure will be investigated, and all the equipment and labor needed to implement it will be assessed.

Legal and Financial Aspects

Legal Input

1. The legal department will be given a full copy of the client's specification for review and comment. The attorneys will scrutinize the document thoroughly for all aspects of compliance or nonconformance, recommending the most suitable manner in which the client's requirements should be modified to permit acceptance.
2. Where disagreements are great, a meeting will be held prior to the final presentation of the bid document in order to discuss the affected areas and possible compromises needed to achieve the desired objectives.
3. The method of arbitration to be used will be defined, should arbitration be necessary.
4. The protection of intellectual property, patent, and copyright issues will be defined.

Financial Input

1. The payment strategy will be defined and will include, in addition to the normal payment for the project management costs, the methods by which the required plant equipment is to be paid for or whether constructors will purchase items on behalf of the

client and be reimbursed on a regular basis. This latter method of payment for items will undoubtedly involve interest charges. In all cases, guarantees for payment will be required.

2. The payment strategy to recover the cost from the client for the staff required in running the project will be defined. Such a strategy is required on large projects because the numbers of personnel are not constant, but vary depending on the project status. In most instances, the number of employees is initially relatively small and is gradually built up as progress is made. The numbers decrease gradually as the project draws nearer conclusion. A core number of staff is retained before and after any project to handle any unforeseen occurrences.
3. To enable cost comparisons from the various bidders for a particular aspect of the project to be made easily, the format of the expected responses will be defined. This format, among other requirements, will set out the expected form of pricing to be followed and the form of the bidder's compliance with the specification. This procedure will allow the contractor to draw up a compliance matrix to short-list the prospective bidders.
4. In some instances the client agrees to meet all financing directly, but in these cases the constructor's cost will be increased because of the additional clerical and accountancy involvement. Each request will have to be supported by approved authorization and justification, all of which need scrutiny and preparation.
5. The payment method for unforeseen and additional items or equipment will be proposed.
6. Although not seen at this stage as likely, it is nonetheless important to specify the amount and method for payment to be made to the contractor in the event of client default and hence noncompletion of the contracted project.

CONSTRUCTOR'S INVITATION TO BID—ISSUED TO SUBCONTRACTORS

Under normal circumstances, a construction company does not manufacture any of the material required for a plant, although some constructors do have subsidiary organizations involved with the manufacture of some items. The only items produced by a construction company are design calculations and drawings associated with the process: plant piping; vessels; structural arrangements of supports for every item such as vessels, pipe tracks, conveyor systems, and so on; electrical distribution for power and lighting; and pneumatic and hydraulic systems. In several process plants there are items of equipment that comprise a complete process in themselves (e.g., steam generation, liquid oxygen, and air plant). These items, being the specialty of dedicated specialist companies, are always purchased as a complete unit. In at least one case, the liquid oxygen and air plant is never sold to the user but is available on lease only, with the terms of the lease subject to negotiation. The maintenance of this plant is the responsibility of the plant owner, who maintains his own staff on the user's site. In view of the multiple types of contracts to be handled, the constructors will have to deal with each individually, and obtain terms and prices for the supply of all items of plant equipment, such as process vessels, pipe work, pumps, motors, conveyor systems, instrumentation, and control equipment. In many instances, a *construction crew* (manpower) will also have to be employed and the terms of employment, as well as the envisaged time and duration they will be needed on site, will have to be determined. All of these deliberations will involve seeking bids from individual manufacturers or suppliers of the services.

A specification document for each particular equipment is prepared, which gives the relevant data for producing a realistic cost to be determined by the subcontractor. If drawings are required for the document, they should be appended to the specification. As would be expected, the drawings and specifications may not be in their final state because the full requirements will only become known as the project unfolds. Therefore, subcontractors usually insert clauses in their proposal documents that allow for variations. In some instances, the construction company may ask for a fixed price for the work. Doing so presents a very difficult situation, and in the last analysis the price is usually increased significantly to allow for variations. In any case, when this situation arises, the subcontractor will often insist that the information and design be complete and invariable at the time the contract is awarded, with suitable provisions for cost recovery if this is not so. Negotiations that take place under these circumstances are quite delicate for the construction company because their client usually applies some very stringent conditions as well. The construction company will therefore be seeking to obtain a deal that does not expose them to excessive financial and technical hardship.

THE CONSTRUCTION SPECIFICATION

In the case of instrumentation and control equipment and associated services, since there can be several suppliers, the document has to be equipment specific. We shall consider only this requirement for the project. The specification is split into individual sections dealing with a particular aspect of the project, as follows.

1. Scope of the project and its construction period.
2. Financial arrangements including method of reimbursement for costs incurred, for example, staged (if this is specified, then the milestones to be achieved prior to any payment will also be defined); terms of payment; method of submitting claims for payment; liabilities for late or nondelivery of equipment.
3. Legal aspects that typically define the conditions for protecting intellectual rights, the law under which any litigation will be dealt with (e.g., English or U.S., or any other), responsibilities for the operation of equipment, and the extent of claims for damages, if incurred.
4. Guarantees for the equipment and system. In some instances there may be a request for process guarantees as well.
5. Technical requirements for the instrumentation and control system and, where a special process is involved, a description of the system operation. Conformance to recognized standards, for example, the NAMUR (Normenarbeitsgemeinschaft für Mess-und Regeltechnik in der Chemischen Industrie zur Interessengeimeinschaft Prozessleittechnik der chemischen und pharmazeutischen Industrie) standard, or UOP (Universal Oil Products—a very large and world-renowned U.S.-based process research organization that holds the patent and copyright to many manufacturing

processes) specifications.

6. Instrumentation and system inspection, acceptance, and testing. In some instances, there may be a requirement that the tests be carried out by a recognized testing organization (e.g., Bureaux Veritas in the United Kingdom and Europe). The requirements for the test could also be defined.
7. Set of project drawings, which typically could include a site plan, a set of P&IDs (Piping and Instrument Diagrams), control console layouts, single-line (describes the functionality of the circuit only) electrical power distribution diagrams, and any other relevant ones.
8. Closing date and time for the receipt of offers, which could include conditions and the manner in which the bid document should be presented.

RESPONSE OF THE INSTRUMENTATION AND CONTROL SYSTEM MANUFACTURERS

The sales organization of the instrumentation and system manufacturer is the recipient of the inquiry document prepared by the construction company. The manner by which this document comes about may vary: the sales personnel may have been invited by the construction company to collect the inquiry, or the inquiry may have been mailed directly to the sales division of the instrument and system manufacturer. Most large projects have the inquiry handed over on a personal basis at a short informal meeting. At these meetings, the sales personnel will endeavor to obtain as much information as possible that will facilitate the preparation of the bid document. This information could in fact define more clearly the user requirements and/or expectations. The sales personnel will also try to ascertain (most discreetly) the possibilities of success.

On receipt, copies are made and issued to the heads of various departments, who, after reading the document, gather together a team comprising selected members of the engineering and sales organizations. The team is under the direction of an assigned project manager who is made responsible for coordinating and preparing the proposal. The combination of several engineering and sales personnel is necessary because in most large projects, a single person will soon be overwhelmed by the amount of work required to be done within a relatively short time. It is sometimes possible for the contractor ask to be introduced to the main instrument vendor’s personnel who will be involved on the project. The initially assigned project manager usually continues in this position in the event the contract is won. The other team members may or may not follow the project in the same way, but on large projects the senior member of the team usually carries on in that position. This ensures continuity of the project. The specification is usually split into two general spheres of interest and expertise, one that deals with field equipment and the other with controls and systems.

On completion of the study of the specification, the heads of the sales, engineering, and financial teams decide whether or not to proceed. This decision will be taken when the joint effects of all disciplines involved on the project are considered for the immediate and the long-term future—if the bid is successful. The immediate future is considered because producing a bid is very costly indeed, and the likelihood of it coming to fruition is indeterminate. If unsuccessful, the bid is a drain on vital company financial resources. In this respect, the decision makers will be guided by the valuable input from the sales team. The long-term profitability for the company will be determined by the success achieved by the project manager and his team.

THE FIELD EQUIPMENT

The requirement is analyzed and, if the construction company provides a summary of instruments, this task is made easier. Otherwise a list is prepared under the headings of (a) process area and (b) associated process parameters (i.e., Flow, Pressure, Temperature, Level, and Analysis). Under each process parameter heading, a brief specification of the actual instrument is drawn up that must, at least for the most part, conform to the inquiry specification. This instrument specification states the model number together with an abbreviated summary of the salient points of the device and references to supporting documents. The supporting literature elaborates on the abbreviated summary, thereby enabling the technologists at the construction company to ascertain how closely the proposed instruments match the inquiry specification.

If final actuators (control valves, drives etc.) are required, these also are included. Since not all instrument manufacturers make such equipment, these items might have to be the subject of another inquiry, this time generated by the instrumentation and system manufacturer to a selected supplier. Depending on the time allowed, the issue of a formal written inquiry and specification may be dispensed with, and the final actuator supplier may be invited to attend a meeting at which the requirement is discussed and copies of the constructors specification are handed over. Suitable precautions are taken to ensure that information divulged is not disclosed to others. These precautions normally take the form of a *gentleman's agreement,* which almost always works very well. The same procedure is adopted for any instruments and equipment that fall outside the company's manufacturing remit No single instrument manufacturer, regardless of its size, can ever hope to manufacture within its organization every item required by a process plant. This explains some of the reasons behind the takeovers, mergers, and strategic alliances entered into within the instrument industry.

INSTALLATION AND COMMISSIONING

If the systems supplier is also required to install and commission his equipment, a site visit will be needed to determine the conditions under which this work would be carried out and to determine the local costs involved in undertaking this work.

THE CONTROL SYSTEM

As far as possible, the instrument and control system manufacturer bases its offering on its current system, which in most instances today is a DCS (distributed control system). However, occasionally when the plant is located abroad in a less sophisticated country where older types of systems already exist, this may not be the case. An older system is specified and therefore (if possible) offered. Most instrument manufacturers usually ensure backward compatibility (i.e., modern systems interfacing with older instrumentation to allow implementation of a planned migration to modern techniques). The P&IDs for the project are studied, and a suitable method of meeting the requirement is decided upon. In the event of special control applications, these applications are designed and notes are made of the arrangements so that they can be commented on in the offering. This enables the contractor to recognize that the system will in general comply with the specification requirements requested. There could, however, be minor differences between the offering and the request. In any event, such differences are normal, due to the subtle changes in interpretation of the written specification, but they are not pursued, only when the divergence is too great. The differences must be resolved at the appropriate time in the future.

Engineering Drawings

Engineering drawings present the layout of the display consoles, power distribution diagram(s), arrangement of the equipment racks, layout of the control room and equipment room, and drawings of the solution to the special applications for the entire system. In addition to the commercial and basic instrumentation and system specifications, all the technical information regarding divergences from the inquiry specification and description of the special applications are prepared and form part of the offering.

THE PROPOSAL

The Systems Content

The project manager supervises the compilation of the hardware components of the system to meet the specification and is responsible for evaluating the time expected to implement the project both administratively and technically. This task is referred to as compiling the *man-hour* requirement for the project. The senior or the *lead engineer* makes the man-hour assessment for the technical aspect of the project, which is subject to approval by the project manager who may require justification of the figures presented. In this task, it is always important to ensure that any formulas used by the project manager and lead engineer have the approval of the company’s higher management. It is therefore not unusual for most organizations to have a set method of determining costs, leaving only the compilation of the man-hours to be evaluated, which is normally based on past experience. The period required for project completion is determined from the duration set by the construction company and the manufacturing schedule of the company and their subsuppliers, if any. The project manager also determines the number and hiring of project specific personnel, the finance involved, and the time at which these additional personnel will be required.

The Instrumentation Content

The project manager, who will be in close contact with the department(s) preparing the proposal for the field instrumentation, will be aware of the content of the offering being made, together with any special requirements that may be necessary. One should be aware that analytical measurements have very special requirements both for the measurement itself, which could involve sampling systems, and the control if required. In some instances, a sampling system will require the involvement of specialists in the field, and these are expensive. When the proposal is complete, the project manager will obtain the data prepared for the field equipment and will organize a meeting of all parties concerned to finalize the complete proposal that will be presented to the construction company. At this meeting, a chart for the project organization will also be determined, with names of individual personnel and their function in working the project. The choice of personnel is subject to approval by the heads of the departments concerned. The final organizational chart will then be prepared for submission, along with the proposal of the hardware and technical content of the project.

The Commercial Content

The commercial content should include a clause-by-clause response to the inquiry document to ensure that all aspects of the commercial terms have been considered and accepted or rejected. In addition to the contract pricing, the following specific commercial points must be addressed.

1. Payment terms.
2. Penalty clause definition and exceptions.
3. System options.
4. Delivery schedule with *cutoff dates* (final dates) for the supply of information and approval of the system designs.
5. Escalation clause for extended contract periods.
6. Currency parity protection (if applicable).
7. Procedure for management system specification changes.
8. Warranties.

Other commercial points may also need to be addressed; it is essential that at this stage of a contract any possible financial risk be avoided. This assessment of the financial risks involved is formalized into a study called the *risk analysis*. The risk analysis includes the effect that technical, scheduling, financial and business decisions have on running the project to a successful conclusion; it also documents any mitigating actions that have to be taken.

OPENING OF THE TENDER DOCUMENTS FROM CONTRACTORS—BY THE END USER

On large projects it is quite normal for all the contractors (construction companies) assembled to witness the formal opening of the tenders, all of which are delivered sealed. The end user and his team will be the host and will announce the price submitted by each party invited to make an offering.

Since each bid is sealed, there will of necessity have to be a period during which the end user will study the documents, make comparisons, and arrive at a decision. The end user may approach particular constructors to ascertain clarification of points of concern or ambiguity that had arisen in the course of their study. When the end user completes his study, the successful contractor is awarded the contract to build.

AWARD OF THE CONTRACT TO THE SUCCESSFUL INSTRUMENT AND SYSTEM VENDOR—BY THE CONTRACTOR

Upon completion of the study of all the proposals submitted by the instrument and system vendors for the project, a final meeting of all parties is organized at which the construction company will announce the name of the successful bidder. At this meeting, all the candidates will be thanked for efforts made, and the company winning the contract will then begin negotiations on the manner in which the project will be managed and delivered. Only the project manager and higher management from the instrument and systems manufacturer will usually be present at this meeting. At this time, a request for a site visit is made, which will allow certain members of the technical team to familarize themselves with the actual project requirements. The visit also lets them meet their counterparts on the construction company's side to establish working relationships.

Setting Up the Project Team

At the instrument manufacturer's offices, the first or *kickoff* meeting is called at which all the team members will be established. It is assumed that the project engineer and administrator, who have already been involved, will therefore continue in these positions. The project manager will normally be the only point of contact between the two organizations (i.e., the contractor and the instrument manufacturer), and all communications and instructions will be made through this link. Should contact between other members of the team and the client be necessary, the project manager must always be informed. All dealings with the client are recorded. Figure 8.2 illustrates in general terms the hierarchy and organizational links within the instrument manufacturer's company. Note that in this illustration the project engineer, project administrator, and project draftsperson have each been allocated assistance, which indicates that the project scope is quite large and these extra personnel will be necessary. On projects of lesser technical and commercial involvement, the team membership is much reduced, with perhaps only the project engineer, project administrator, and a drafts person required.

Processing the Manufacture of Project Equipment

The relevant parts of the proposal will be copied and handed to the senior team members concerned, and the associated drawings will be given to the project engineer. In some organizations, the field equipment is handled by another set of personnel whose only task is the preparation of the appropriate manufacturing documentation. This method of operation has its limitations, in spite of the burden of specifying that field equipment be removed from the jurisdiction of the control and systems engineer(s). The subtle requirements of compatible material of construction for the instrument, or the possibility of some control loops being overlooked, may become the source of later difficulties. If this method is adopted, the systems engineer involved must be made fully aware of the equipment being specified for manufacture *before* it is sent for client review and finally issued for production. These statements are made in the light of considerable experience with construction companies, who always have a clause (a controversial one in the view of the author) in their stamp of approval, which puts the onus of responsibility entirely on the instrument manufacturer or supplier—if others make the instrument. The reason for the author's disagreement lies in the wording used on the stamp of approval; the facts are that the construction company, despite having prepared the original instrument specification and having reviewed the associated manufacturing specification, and possibly the manufacturing document (if no trade secrets are involved) and given its approval, accepts no responsibility for its suitability for the task!

Equipment Supplied by Other Manufacturers—Third-Party Suppliers

As mentioned earlier, no individual instrument manufacturer can ever meet the needs of an entire process plant from his range of products; hence, other suppliers of the required instruments lying outside the product range will be involved. These

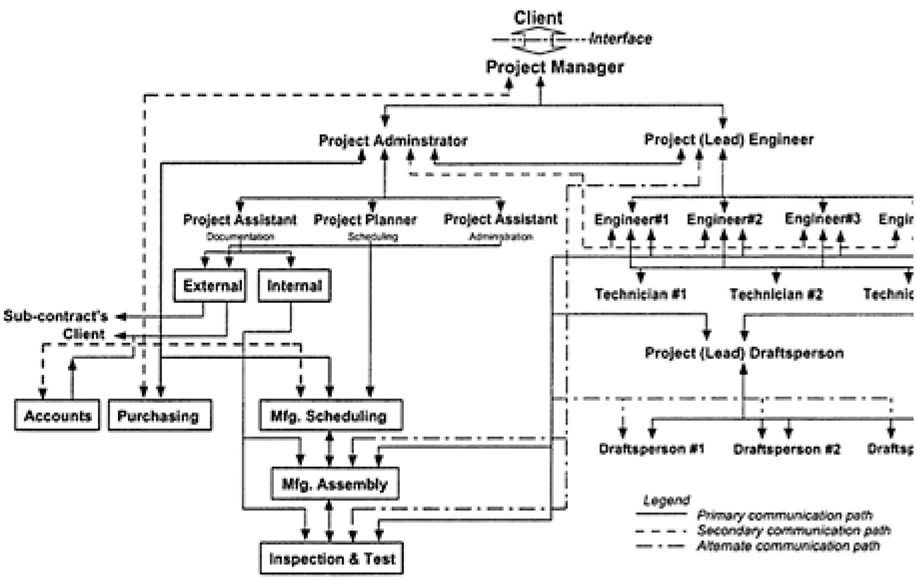


Figure 8.2: Typical hierarchical structure of a project management function in an instrumentation and control system manufacturing organization.

other suppliers (usually referred to as third-party) would already have been aware of the situation because they would have been approached when the initial inquiry was being investigated and a suitable response was compiled. The project manager will have to produce for each supplier a final purchase order and equipment specification for each of the *bought out items* (instruments involved). As can be expected the purchase agreement will contain:

1. The delivery schedule and guarantees.
2. The legal implications in the event of a dispute and the laws of arbitration to be invoked.
3. Financial and other penalties for late or nondelivery.
4. Inspection and test requirements.
5. Maintenance and installation documents.
6. Installation and commissioning support required.
7. Acceptance by the supplier of all commercial terms contained within the original (that issued by the contractor) contract.

The project manager calls a meeting with each supplier in order to establish working arrangements. The project engineer and project administrator are required to attend these meetings because they will be involved during the course of the project and may have to receive information well in advance of the agreed schedule.

THE PROJECT SCHEDULE AND ADMINISTRATION

Assisted by the project administrator, the project manager develops the project schedule based on the total man-hours sold, which is almost always evaluated at the proposal stage and recorded under specific headings for just this purpose. To assist in managing a large project, several tools are available; these are almost always software based and considerably reduce the mundane task of chart preparation and determination of the *critical path* without excessive effort by the project manager. The user can adapt the charts to depict every function (e.g., preparation of equipment order documents, orders for power distribution equipment) and the allocated time for completion. Based on the data provided, the software plots the critical path, which is so named because any failure to meet the defined targets will almost certainly mean a man-hour overrun, which combined with the attendant cost overrun that is inevitable and departure from scheduled delivery, will spell disaster for the project. The target dates are usually referred to as *milestones*, and for obvious reasons the project manager and the project assistant keep a very close watch on these dates. Every means available is taken to avoid missing a milestone, if necessary (depending on the resulting severity of the envisaged failure), to avoid financial or other penalties. If penalties for noncompliance with published data is part of the agreed contract, higher management of the company may also become involved as early as possible, in order to salvage a bad situation.

Figure 8.3 shows a schedule of project activities that occur prior to and after a contract has been awarded. In the interest of brevity, the pre-order activities have been minimized, and the post-order activities have been shown in general terms only. This method will give the reader an overall “feel” of the situation; experience will inevitably enhance that knowledge.

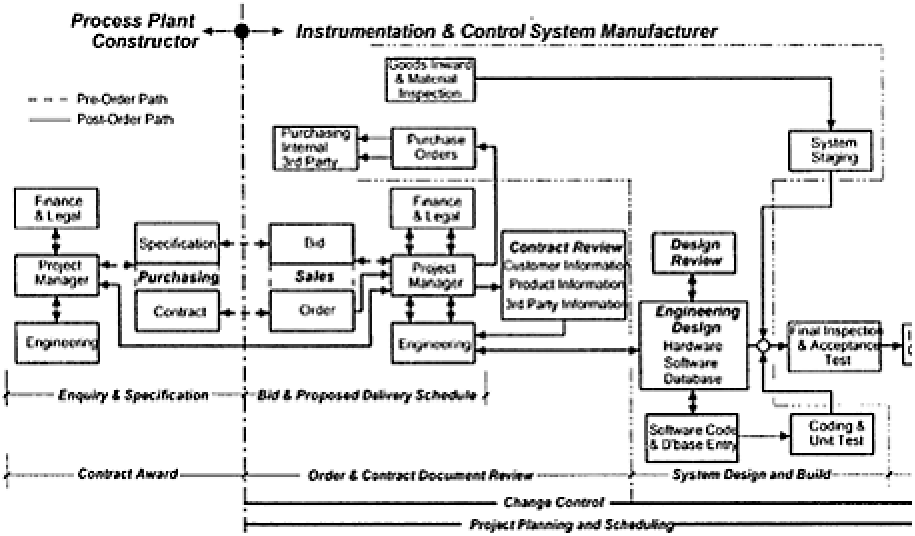


Figure 8.3: Schedule of project activities.

As also mentioned earlier, when the bid is being prepared, most companies involved in this kind of work have an automated method of determining man-hour costs, and the auto-computed results can be altered to suit particularly difficult or unusual control requirements. The project manager has the prerogative to reallocate the personnel involved and the sold man-hours, within the price limits, to suit what he or she believes to be required by the task. However, the project manager is not allowed to change the total number of hours (and hence by implication, the cost) sold. The cost per hour does vary according to the personnel involved; the scale used is a sliding one that ranges from most expensive to not so expensive. To facilitate the foregoing, every team member, including the project manager, has to complete a weekly time sheet that gives a detailed account of the activities in which they have been involved. Every activity that has to be accounted for is given a specific identity code to simplify data entry and to enable rapid assessment of the situation to be made. There are whole ranges of these codes, which are a company standard, but the project manager chooses only those to be used on the project. The choice of the range of useable codes is made known to the whole project team, and every group of team members has restrictions on its full use placed on them. The team member's job function defines the admissible codes applicable. The project administrator is responsible for collecting, entering, and presenting these data to the project manager in a weekly report on the situation. Since the man-hours and the task(s) on which these are expended are important, closely monitored items, the project manager takes corrective steps if these are found to be changing too rapidly without yielding real results.

The project manager is involved not only with the internal costs of the project, but also with the cost of all equipment being supplied on the project. The delivery time scale for all purchased equipment will also fall under the PM's remit. The project administrator is responsible for monitoring the situation developing with all external suppliers and for providing the project manager with regular and timely reports. Thus, any required action can be taken to forestall the development of an untoward occurrence. The project manager has to make a monthly financial review of the project, which will be presented to the company's higher management, with the financial controller taking a specific interest in this report. The project manager must be prepared to answer questions that management raises on how the project is being handled and to justify the forecasts made.

The project manager, or his appointed deputy, attends every meeting, and, depending on whether the discussions are technical, the project engineer will also be invited. The project manager prepares the minutes and circulates them to all parties. *All* points should be noted in detail because experience has shown that many important issues discussed are very often overlooked—and, sadly, most often by the instrument and system manufacturer, simply because at the time they do not appear to be important enough. This "devil in the details" could have serious consequences for the project both technically and commercially.

Perhaps the most important, and sometimes the most overlooked, aspect of project management is the administration and management of system changes, which has a direct impact on the cost and delivery of the system. It is essential that any changes be identified immediately after they occur; therefore, it is imperative that a system be established with the contractor defining how these modifications are to be handled. In the case of major changes, it may be necessary to halt the contract and to agree on a revised (extended) delivery date, based on obtaining approval of the changes both technically and commercially prior to resuming work.

In a similar vein, the contractor's supply of missing data can also have a direct effect on the project schedule and hence the costs. It is vital that missing data be identified as early as possible within the project schedule and that the implications for any delay in providing the data, and/or the associated additional costs be conveyed to the contractor as soon as possible.

The Role of the Project Engineer

The project engineer (Proj.Eng) fills a very important function on a large project because all technical decisions have to be taken at this level. The entire scope of the contract has to be made known to the Proj.Eng, and it is imperative that all technical decisions outside those specified in the contract be taken with the Proj.Eng's full agreement. In the event of the Proj.Eng's absence, for whatever reason, the project manager must not bypass this important link. The other engineers on the team must make the project engineer fully aware of the situation as far as their area of responsibility is concerned. This is important because only when one is fully aware of all the facts, and is not forced to work on assumptions, can correct decisions be taken. This exchange of information is best achieved at regular (preferably on a specific day of the week) weekly meetings of the group, or, if really urgent, a meeting with the individual engineer concerned should be called at the appropriate time. Information exchange flows not only upward from the engineers on the team, but also from the project engineer downward, since the first link between project manager and technologists is through the project engineer. All project documentation should be approved by the project engineer, but not before the relevant engineer has fully checked the document and signed it off as being approved.

The project engineer should handle equipment that is common to the whole control system (e.g., the power distribution, control room and equipment rack room layout, and voice communications). For simplicity here, only the procedure for managing the procurement of the power distribution system will be described in some detail; all other purchases will be handled in a similar manner. The basic design of the power distribution system is determined by the project engineer based on data provided by each engineer on the project who is responsible for ensuring the correct load current for each part of the process areas allocated. The design is then circulated to the team for comment and, if necessary, any modifications are made. The vendor for this equipment, which is chosen at the initial bid preparation stage, is now approached, with the final specification prepared by the project manager and requested to provide a confirmation of the bid price. However, on this occasion the specification is based on real information now provided. The kickoff meeting with the vendor, attended by the project manager and project engineer, sets the working relationships, makes requests for confirming the dates for the receipt of equipment, dates for the supply of preliminary review and final drawings, and sets up the protocol for equipment inspection, test, and delivery. The project administrator adds the information to the project schedule. The inspection department makes regular scheduled visits to the vendor's works and prepares a report outlining progress. The project administrator uses the reported data to update the project schedule, and the project manager can now take any necessary action to keep the project on track. The project engineer, along with the checkout engineer, carries out the final inspection and testing of the power distribution system at the manufacturer's site and, if the system is found to be in order, they are authorized to sign the acceptance documentation.

If permitted, most plant constructors will continually ask for changes to be made, based on what they claim to be the evolving design of the process. At the same time, they will insist on maintaining the agreed-on completion date! These changes don't only affect the power distribution but they most often have serious consequences for other aspects of the project as well. The project manager has to be very firm and call a halt when foresight shows that these changes are jeopardizing the target completion date; otherwise, project scheduling has no meaning. Some agreement has to be arrived at, mandating that any change requested after a defined point in the schedule will be attended to after project completion. This will inevitably cost more to implement, and the author is convinced that it is primarily for this reason plant constructors want changes to be made during the normal life of the contract.

All changes required during the life of the project will inevitably cost money and time; the project engineer must have an input for both of these aspects. It is the project manager's duty to ensure that all realistic costs brought about by the constractor's action are paid for. This financial recovery aspect of project management can be very demanding and usually involves shrewd negotiating ability. Construction companies, due to their very considerable size and influence, believe that everything should go the way they dictate; this is far from the reality. Instrument manufacturers and system houses also have considerable power, although in most instances they are reluctant to use it. However, a well-timed intervention by the instrument and system supplier can bring rewards—for instance, calling a project halt when the contractor ignores several timely and repeated requests for important information. But the circumstances and timing have to be right; the effect of intervention can be salutary.

The project engineer must attend all weekly project meetings convened by the project manager; the other members of the team if they are available, should also, also be present. The objective of these weekly meetings is to let the team know the current situation and to give advance warning of any foreseeable problems.

As expected, a close working relationship develops between the engineers and the drafting personnel; the draftspersons give expression to the engineer's ideas and provide the means of carrying them out in a practical way. The most important means of communication between these two disciplines is the engineering sketch. This document must be clear and precise if the results of the finished drawing are to be meaningful. It will pay dividends for all engineers to prepare neat, fully documented sketches (freehand if possible; tool-assisted sketches take too much time to prepare) that leave little room for interpretation by anyone who sees it. The author has found that a sheet of cartridge-quality graph paper with deep colored lines that show through when placed under a normal sheet of paper greatly assists in preparing good sketches and allows reasonably straight lines to be drawn freehand. It is suggested that information on the arrangement of control loops be prepared using the bubble format similar to that seen in all loop diagrams in this book. This format for loop diagrams permits the system to be implemented using any type of instrumentation, be it single case (individual instruments) or DCS. Loop diagrams, combined with process data and the tag number, will enable the technician to implement on a DCS the controls for the process that the engineer requires.

As mentioned earlier, it is vital that the engineer be fully aware of the field instruments because the system with which he is involved has to interface with them. Since the signals produced by the field instrument have to be meaningful to the system, the measurement has to be correct. Remember: a bad measurement must give bad control, and if one cannot measure the parameter (even inferentially) then one should give up any hope of controlling it. The idea of instrument compatibility is given realism, albeit it is a simple problem to solve, if we consider, for example, a split range loop where one control valve is manipulated over one part of the split range of the control signal, and another control valve is manipulated over the remainder. Under this condition of split responsibility for the control signal, each final actuator has to be calibrated to suit the signal applied to it. The range splitting becomes a little more difficult when using discrete instruments. To simplify the complexity and provide a workable solution, a scaler module for each part of the controlled output signal that is split, can be included in the system. Note that in this example the scaler module suggested accepts the partial range of the control output signal as its input and produces a full-range control signal output that is proportional to it. The scaler module output, when applied to the final actuator, will drive it correctly. The final actuators need no calibration because they will be standard instruments and will work over their entire input signal range.

The Role of the Technician

On large projects, of which Figure 8.2 is one, each of the engineers #1 through #3 is allocated specific plant areas for which they individually are totally responsible. It must be realized, however, that some overlap between areas is bound to exist, and, for the control to be seamless, all engineers must collaborate. The task of the project engineer is to ensure that those loops that are split between the assigned areas referred to earlier are aligned correctly and that all aspects of the plant instrumentation and control are covered. The role of the technician is to ensure that:

1. The technical requirements specified by the engineer are met; these tasks could be placing on order all the components that will make up the control system.
2. All drawings are updated in a timely way—though final responsibility for correctness rests with the engineer.
3. Assisting with the assembly wiring and cabling of the system is provided.
4. Assisting with the preliminary system checkout and testing is provided.
5. Entering data into the database (once again the responsibility for all data used lies with the assigned engineer) after the system has been fully assembled (mechanically) and checked out (electrically) and preliminary tests have been completed.

On some very large projects, it could prove advantageous to assign an engineer to coordinate and manage the system database and process graphics. This will allow the entire system to run efficiently by minimizing repetition and decreasing the time needed to access a desired parameter on the process. It will also make presentation of all the plant information and behavior to the process operators and engineers readily available.

SYSTEM CHECKOUT AND FINAL ACCEPTANCE TEST

There are two principal forms of system testing, and these are usually carried out at the system builder's works: (1) the internal test procedure carried out by the system builder (unwitnessed), and (2) a witnessed demonstration of the system carried out in the presence of the contractor and the end user. The system engineers satisfy themselves that the product meets the design specification and conduct the unwitnessed test on the entire system. The cost for this test is included in the original bid price. However, the witnessed tests also have to be paid for, and normally the testing of a percentage of the total number of control loops is allowed for in the offering. This percentage is defined to the contractor in the bid document. In the event tests need to be carried out on the whole system, additional costs are involved and are usually based on an hourly rate, which is also defined in the bid document.

In every instance upon completion of the database entry, the engineering team subjects the entire system to a series of tests. If necessary, any adjustments to the control schemes are made; each change is recorded so that the contractor and the end user are alerted to the situation, and the modifications are fed back and recorded on the system documentation. During these tests, it may sometimes be necessary for the contractor and/or the end user to be contacted and apprised of the situation. In all such instances, the project manager must be the interface. Only after the engineering team is satisfied that the system performs correctly are the contractor and the end user invited to witness the system performance. If the standard percentage number of tests is required, the witnesses choose the loops to be demonstrated. In these tests (as with all the others already performed), the entire loop is simulated so that the results of its behavior can be seen.

When satisfied that the system meets the specification requirement, the project manager presents documents stating the approval, and appropriate signatures are obtained, allowing the equipment to be released for shipment.

SYSTEM DOCUMENTATION

It is always necessary to provide the contractor, and by implication the end user, a complete set of system documentation. Experience has shown that when contractors are involved, the quantity required is phenomenal, and the resulting cost must be included in the bid. In addition, individual engineers with contractors can sometimes be quite demanding, and project managers must be on their guard against them. Some of these engineers have been known to interpret the statement "documentation to be project specific" as applying to *all* documentation! One should remember that instruction manuals for equipment are produced to allow *any buyer* of the item to use it correctly. It cannot therefore be produced as a project-specific document—not unless the contractor is willing to pay an exorbitant amount of money to have it done specially. A discreet word by the project manager in the appropriate ear in the contractor's organization can work miracles.

It is always advantageous for the project engineer to produce an additional set of project manuals for use by his own service organization that will in almost every case be involved in maintenance of the system, or even be called on when the plant is being commissioned. Once again, experience has shown that project manuals are seldom available when required on site, despite the huge number supplied.

SYSTEM PACKAGING AND SHIPPING

Packaging of the equipment for transport to site takes two forms. The first involves the transfer to sites within the country of manufacture and the other for export. For shipments to sites within the country of origin, the type of packing used may not be as restricted as that required for shipment abroad. The instrument and system supplier normally state that prices for goods are *ex works;* that is, the price for goods are those charged solely for the equipment as available at the shipping bay of the company's works for collection by the customer. If delivery is required to a site within the country, the cost will be that charged by a reputable shipping company for delivery to the nominated site and will be invoiced accordingly. This shipping cost does not include any insurance for the goods either when loading at the supplier's works, while in transit, or while offloading at the site. All these costs are additional and are usually referred to as C.I.F. (carriage insurance freight) charges. Usually the instrument and system supplier adds a management charge, which is calculated as a percentage of the C.I.F. that is levied on the delivery to cover the bureaucracy involved. Sometimes, however, C.I.F. costs are invoiced to the contractor without any value added to them. They are referred to as *at-cost charges*. When the latter course is taken, usually an undisclosed amount somewhere in the factors enables the C.I.F. waiver to be done. No business is a charitable institution; profitability is the name of the game!

For export especially by sea, the packaging is much sturdier and normally the contractor requires the instrument and system supplier to adhere to its packing specification. Air shipments do not require the same strict requirements. However, if the goods are to be stored for any length of time at the recipient's end, then suitable precautions will have to be taken. Export packing is always charged for as an extra. In these instances, the delivery is usually made "free of charge" to the port of export and includes insurance and delivery to the port. Management costs are once again accounted for as an amount somewhere in the factors, though stated as either F.A.S. (free alongside ship) or F.O.B. (free on board), both referring to the delivery area of an ocean-going vessel or an aircraft. The actual terms are typically stated as F.O.B. London or F.O.B. New York, or any other port as the case may be. After the vendor delivers goods to the port, all charges incurred (i.e., freight, management etc.) from thereon and to the site are the contractor's responsibility, and must be borne by the contractor.

Shipping and insurance are areas of specialist knowledge; the project manager is well advised to seek this assistance as required, although a general overall knowledge is essential.

CLOSE OUT REPORT

Another objective in any employed position is to gain from experience and to enhance one's ability and usefulness to the employer, be that a corporation or one's self, and to apply the knowledge gained in future to the benefit of both self and employer. Accordingly, it is useful to produce a *close-out report* upon the completion of a project that will review the running of the project and compare the schedules defined at the project inception with the actual time required to complete the various tasks. The report must also record any serious problems encountered and the steps taken to solve them. Where the difficulties were technical, then input from the project engineer will also be advantageous. Every future project will benefit if the lessons learned on each project are diligently applied.

It is also necessary to produce a financial report that identifies the actual costs incurred over every aspect of the project and to draw comparisons with the original budget. This similarly important report will give the finance department of the organization data that can be used that will allow a more refined and profitable business operation in the future.

SOME TERMS FOUND IN CONTRACTUAL DOCUMENTS

The following list is not exhaustive, but covers only some of the more common terms used. Strictly speaking, the terms marked with an asterisk are not found on contractual documents, but they are given here as a means of clarifying some of the other definitions where used.

Bankers Draft—Equivalent to a check drawn by a bank upon itself. It offers a person or a company a document in payment of goods or services with the absolute authority and certainty of payment of the bank behind it. It is usually offered in payments in a foreign country. The bank should therefore be one of integrity and international repute.

Bill of Exchange—An unconditional order, in writing, addressed by one person or firm to another and signed by the person giving it. It requires the person or firm addressed to pay, on demand, or at some fixed determinable future date, a defined amount of money, to, or to the order of, a specified person, or to bearer.

Bill of Lading—Documentation that allows a consignment of goods to recipients so that they can take possession of the same. No shipping company will release the consignment unless these documents are presented to them because it represents the title to the goods.

Credit Note—A business document, usually printed in red to distinguish it from an invoice, made out by the seller and raised when one person or firm returns goods to another. Usually, only two copies are made. It should show (a) the names and addresses of both parties, (b) the exact description of the goods being returned, and (c) the unit price, number, and total value of the goods.

Debit Note—A document made out by the seller whenever the purchaser of goods or services has been undercharged on an invoice, or the seller wishes to make a charge on the purchaser, which increases the amount owing to the seller by the purchaser.

Discount Market*—In the United Kingdom a group of 11 member companies called the London Discount Market Association. They operate as "principals" whereby those with surplus money are prepared to "sell" to meet the needs of those prepared to "buy" its use. They borrow money themselves and re-lend it to others as a means of investment. In the United Kingdom, if the borrowing is from a bank, the borrowing rate is fixed at 1.625% below the minimum lending rate. They lend to the government, to banks, to commercial firms, and to financial houses. All transactions are made by word of mouth in order to keep the cost of borrowing down.

Exchange Control*—A system used by a government that rations available foreign currency. Such a system is operated by many countries; for example, in the United Kingdom some foreign suppliers will accept pounds Sterling in payment for goods or services, while others will demand payment in, say, U.S. dollars or sometimes the equivalent in gold.

F*orce majeur*—[French for "superior force"] An unexpected or uncontrollable event that upsets one's plans or releases one from obligations, especially legal obligations.

Import License—Authorization by the government to cover the importation of goods into the country. In the United Kingdom, all imported goods require this license; however, it is used mainly for statistical purposes. The importer makes application to the Department of Trade and Industry (DTI), which issues the document. An Open General License allows for unrestricted goods entry.

Indemnity*—A term used mainly in insurance. The meaning is the same as the everyday word "indemnify." For insurance purposes, it means that restoration will be as near as possible to the original condition. It is important to appreciate that indemnity never restores the insured to a better position than that which obtained before the occurrence.

Letter of Credit—A letter of credit is usually required in foreign dealings, for example, in the case of an overseas customer buying goods or services from a U.K.-based organization. The overseas customer is required to make available at a recognized London bank an irrevocable credit, which will enable the bank to "accept" the bill of exchange as the documents of title. The acceptance by the bank is very reliable and means that the bill will be discountable on the discount market. As soon as the authority to establish the credit is received, the London bank issues a Letter of Credit declaring its willingness to accept a Bill of Exchange against delivery of the shipping documents. In the event an overseas bank does not have a London branch, it makes the arrangements through a correspondent bank in the United Kingdom. However, the correspondent bank is under no obligation to accept the Bill of Exchange, thus making the method less reliable for anyone discounting it. To avoid the difficulty, the exporter should stipulate in his contract that the credit will be "confirmed" by a recognized U.K. bank.

Damages—A term encompassing some critical elements such as Liquidated and Consequential Loss, which require consideration of both legal and financial aspects. It is therefore important that the reader be aware of these requirements and seek professional advice regarding these aspects.

SUMMARY

1. A project, depending on its size and the involvement of personnel and expertise required, can be handled in two ways, broadly speaking. The first uses the knowledge and capability of a dedicated (assigned) project manager, whose sole task is to run the project efficiently within budget and to schedule. The second uses an experienced, capable technologist, who in addition to technical ability has the talent and competence to perform the tasks of project manager.
2. A project manager is one who by specific academic qualification in business administration and experience, in addition to technical qualifications, is allocated the task of project management. However, sometimes those who have the academic qualifications lack the important "people-managing" (interpersonal) skills and experience that are intrinsic to the job. Other project managers, though not possessing business administration qualifications, are enviable managers of the most demanding large-scale projects.
3. Good project managers (PMs) have multifaceted personalities. Duties involved in this demanding job primarily require a persona of openness to and approachability by others in technical and commercial matters. Since a PM is involved with people, he or she must be able to accept the foibles, haughtiness, and idiosyncrasies of individuals with grace, and yet in all dealings, be firm and fair. The PM's other important functions are to be sleuth, diplomat, and coach.
4. The PM has to be able to discern signs of serious trouble even in innocuous statements and must know how to listen to and heed advice given.
5. For most major projects at least three project managers may be involved, each with a different set of priorities, depending on their position within the overall project structure. The first project manager represents the end user and has the principal aim of completing the project within the defined schedule and fulfilling the design criteria. The second project manager represents the contractor and usually works from a fixed

price contract with the end user and a schedule that incorporates plant constructions other than those directly applicable to the control system. The third project manager representing the system supplier interacts directly with the main contractor and indirectly with the end user. This PM normally works from a fixed price contract that has been arrived at by bidding against the contractor's specification, and a delivery schedule agreed to prior to award of contract. The priorities are to complete the contract technically within the agreed time schedule and at minimum cost, thereby maximizing profit for the company.

6. Every project has a definite point of inception, and in projects dealing with control systems, experience has taught that the end user of the process has definite ideas on the way the process and various control systems should behave.
7. If the process involves a chemical plant, then a major plant construction company could be involved. This organization would be responsible for the whole plant and would be allowed to manage the work involved with the entire job. The chosen construction company (or contractor) has particular expertise in certain types of manufacturing processes and several specialist departments dealing with different aspects of the process.
8. In a "turnkey" project, the contractor is responsible for the entire project, from basic process design right through supply of the all plant-equipment and control systems. The contractor makes a profit based on his ability to produce the project within the bid price but at minimal cost to himself.
9. In a "cost-plus" project, the contractor, though still responsible for the design and providing the plant equipment and control systems, is also awarded an amount of money (by the end user) based on a fixed percentage of the overall contract value. In other words, the contractor is guaranteed a profit.
10. When the development of a process plant involves using currently existing vacant land on the site, or the acquiring of land adjacent to the plant to accommodate the process, the development is referred to as a greenfield development.
11. The development of a greenfield site in project discussions between the manufacturer and the construction company will have to be more elaborate. In the United Kingdom, government departments (the Department of the Environment, and Health and Safety to cite only two) would also be involved. Government is involved because the proposed plant will have to comply with government regulations. This intervention is unavoidable in most European countries and the United States. However, the rules that apply are not the same but vary from country to country.
12. Feasibility studies are conducted before implementing an expansion of a process plant. Such a study examines the case from the point of view of (a) the process and (b) the financial and legal involvement. Under the heading of the process, consideration is given to the projected market for the envisaged product, the interfacing of the new plant with the existing plant, the continuity of manufacture while additions are being constructed, and the effect of an eventual shutdown when the new addition is brought onstream. Under the heading of financial and legal involvement, considerations are given to raising the required finance, to the ROI (return on investment), to the legal implications of the addition, and to penalties for late or nondelivery.
13. Assessment of the financial risks involved is formalized into a study called the *risk*

analysis. The risk analysis evaluates the effect of technical, scheduling, financial, and business decisions on the running of the project to a successful conclusion. It also documents any necessary mitigating actions.

14. After the contract has been awarded to the instrument and system manufacturer, the first or kickoff meeting is called at which the other team members will be established. It is assumed that the project engineer and administrator have already been involved and will therefore continue in these positions. The project manager will, under normal circumstances be the only point of contact between the two organizations (i.e., the contractor and the instrument manufacturer), and all communications and instructions will be made through this link.
15. No individual instrument manufacturer can ever meet the needs of an entire process plant from his range of products. Hence, other suppliers of the required instruments lying outside their product range will be involved. These other suppliers are usually referred to as third party, and equipment supplied is known as bought-out items.
16. The *critical path* is so named because any failure in meeting the defined targets will almost certainly mean a man-hour overrun, which, combined with the attendant cost overrun that is inevitable, as well as departure from scheduled delivery, will spell disaster for the project.
17. The target dates are usually referred to as milestones, and for obvious reasons the project manager and the project assistant keep a very close watch on these dates.
18. The most important, and perhaps sometimes the most overlooked, aspect of project management is the management of system changes. This has a direct impact on the cost and delivery of the system. It is essential that any changes be identified immediately after they occur, and it is imperative that a system be established with the contractor as to how to handle these modifications. In the case of major changes, it may be necessary to halt the contract and to agree to a revised (extended) delivery date, based on obtaining approval of the changes both technically and commercially prior to resuming work.
19. The supply of missing data by the contractor can also have a direct effect on the project schedule and hence the costs. It is therefore vital that missing data be identified as early as possible within the project schedule, and the implications of any delay passed on to the contractor as soon as possible.
20. A close-out report on the completion of a project reviews the running of the project and compares the schedules defined at project inception with the actual time required to complete the various tasks. The report must also record any serious problems encountered and the steps that were taken to solve them. Where the difficulties were technical, then inputs from the project engineer will also be advantageous. Every future project will benefit if the lessons learned on each project are diligently applied.

Bibliography

Atkins, P.W. & Beran, J.A. *General Chemistry.* 2nd ed. Scientific American Books, 1996.

Austin, George T. *Shreve's Chemical Process Industries.* 5th ed. New York: McGraw Hill, 1986.

deSá, D.O.J. *Instrumentation Fundamentals for Process Control.* New York: Taylor & Francis, 2001.

Foxboro. *Intelligent Automation Integrated Control Software Reference Manual.*

Foxboro. *99SC micro-Blendtrol II Controller Implementation* MI 019–606.

Lavigne, John R. *Instrumentation Applications for the Pulp and Paper Industry.* San Francisco: Miller Freeman Publications, 1979.

Lewis Michael J., & Young, Tom W.*Brewing.*London: Chapman & Hall, 1995.

Libby, C.Earl —ed. *Pulp & Paper Science and Technology.* Vols 1 & 2. New York: McGraw Hill, 1962**.**

Noltingk, B.E. *Instrumentation Reference Book.* London: Butterworth & Co. Ltd., 1988.

Notes on Fan Engineering Ref. No. SF337. Belfast, N. Ireland: Davidson & Co., Ltd.

Perrys Chemical Engineers Handbook. New York: McGraw Hill, 1984.

Proudlove, R.K. *The Science and Technology of Food.* 4th ed. London: Forbes Publication, Abbot House, 2001.

Ramsden, E.N. *A-Level Chemistry.* 4th ed. Cheltenham UK: Stanley Thornes (Publishers) Ltd., 2000.

Shinskey, F.G. *Distillation Control for Productivity and Energy Conservation.* New York: McGraw Hill, 1976.

Shinskey, F.G. *Energy Conservation through Control.* New York: Academic Press Inc, 1978.

Shinskey, F.G. *Process Control Systems.* 3rd ed. New York: McGraw Hill, 1988.

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