3 Overhead System Arrangements

3.1 INTRODUCTION

Having considered a particular approach to an overall strategy for controlling distillation columns, and having reviewed the fundamentals of distillation, at least for simple columns, let us now turn our attention to some practical aspects. The design of a satisfactory distillation control system involves far more than theory or mathematics. The engineer must have some idea of what constitutes effective equipment configurations and arrangements, as well as an appreciation of equipment performance limitations, and must be able to recognize when undesirable side effects are apt to interfere with an otherwise good control system. Typical equipment, control schemes, problems, and solutions are discussed in this section. The supporting mathematics and theory are covered in Part III.

The column overhead system is generally more complicated than either the feed system or the bottoms system. It usually must condense most of the vapor flow from the top tray, remove inerts, provide reflux flow back to the column, maintain column pressure in the right range, and satisfy part of the column material balance requirements.

Condensate is generally subcooled at least slightly, partly to minimize the likelihood of flashing and cavitation in valves and pumps, partly to control the amount of inerts in the system, and partly to control product losses through the vent. If subcooling is required for a pressure or vacuum column, the preferred method is to have the condensate-temperature controller manipulate the vent flow in some way. This arrangement avoids the instabilities and other control difficulties that often characterize condensate-temperature control systems based on manipulation of the condenser cooling water. In the case of vacuum columns, there may be problems associated with the control of the vacuum jets, and column turndown is usually limited, compared with that of atmospheric or pressurized columns.

Material balance control on the condensate may be accomplished in several ways:
—Flow control of reflux is cascaded, if possible, from column overhead composition, and distillate overflows from the vapor—liquid disengagement space beneath the condenser.
—Same as foregoing except that distillate flow is set by reflux drum level control.

If a smooth flow to the next step in the process is needed, a reflux drum, with averaging level control of distillate, should be employed. If the column top product is a vapor, takeoff should be by “averaging” pressure control. As an alternative, vapor may be taken off on flow control cascaded from top composition control while column pressure is controlled by heat input.

In this book we usually refer to the condensate receiver—the vessel that receives condensate from the condenser—by another name: reflux drum. Although it is less exact, this term is widely used in the petroleum industry.

### 3.2 TYPES OF CONDENSERS

In chemical and petroleum plants, we find at least five different kinds of condensers:

1. Horizontal shell-and-tube condenser with liquid coolant in the tubes and vapor on the shell side (Figure 3.1). This is probably the most popular type in petroleum refineries. By comparison with the vertical design discussed below, it is much better suited to partially “flooded” operation. In addition, at startup time, column inerts are usually vented more easily (i.e., with less pressure drop) through condensers of this design.

   The design illustrated in Figure 3.1 has two vents, each with a valve if the exchanger is operated flooded (see further discussion in Chapter 15). Some designs bring the vapor in at one end and vent uncondensables at the other. Sometimes condensate is taken out through two drawoffs instead of one. The cooling water valve is normally at the exchanger exit to make sure the tubes are filled at all times. Since the exit water is hot, the valve may need anticavitation trim.

2. Vertical shell-and-tube condenser with liquid coolant on the shell side and vapor entering the tubes at the top (Figure 3.2). This type is popular in the chemical industry because it minimizes condenser cost when highly corrosive process materials must be handled.

   With a longer condensing path, it is also better suited to applications in which it is desired to absorb the maximum amount of low boilers in the condensate. This condenser commonly has at its lower end a vapor—liquid disengaging pot, which also serves as a condensate receiver. Because all vapors must pass through the tubes, the speed of venting inerts at startup time is limited. For the same reason, this type of condenser cannot be operated partially “flooded.”

   Again, the cooling water valve is located at the exit to ensure that the shell is flooded, thereby minimizing corrosion, particularly if 316 SS tubes are used.
3. Internal, in-column head condenser (sometimes called "dephlegmator"). Here we have a number of different designs.

—Horizontal tube bundle with coolant in tubes (Figure 3.3). The vapor comes up from below and condensate drops into an annular space around the vapor nozzle. The latter has a "hat" over it to prevent condensate from dropping back down the column. Reflux may return internally via an overflow weir, or externally through a gravity flow line with a control valve.

—Vertical bundle with coolant on shell side. This design comes in two variations: "reflux" design, where the vapor goes up the tubes and is countercurrent to the condensate falling down, and a design with a chimney in the center such that the vapor rises in it, reverses direction, and comes down the tubes with the condensate.

—Air-cooled condensers (Figure 3.4)

—Spray condensers (Figure 3.5). Here condensate is recirculated through

FIGURE 3.1
Horizontal condenser, vapor in shell
a cooler and returned to a spray chamber. This type of condenser is most commonly used in vacuum service because of its low pressure drop.

3.3 ATMOSPHERIC COLUMNS

The preferred overhead system for atmospheric columns is shown in Figure 3.6. The condensed vapor falls into a reflux drum that should have 5–10 minutes' holdup (relative to condensate rate), and inerts are vented to a flare.
3.3 Atmospheric Columns

or cleanup system. At startup time total reflux may be achieved by using the reflux valve to control the level in the condensate receiver.

For those columns that must be protected from atmospheric oxygen or moisture, a vent system such as that shown in Figure 3.7 should be used. This is similar to the one recommended later for pressurized or vacuum columns. Note that inerts usually should be added after the condenser, to minimize product losses. Sometimes, however, it is necessary to add inerts ahead of the condenser, for pressure control. Figure 3.7 also shows a more commonly encountered tank arrangement where the reflux drum is common to both the top product system and the reflux system.

A potential and frequent source of trouble with both arrangements is the control of condensate temperature via cooling water. As shown by a study by B. D. Tyreus,11 for a constant subcooled temperature, process gain (°C/pph CW) and dominant time constant both decrease as total heat load increases. This compounds stability problems; we need an increasing controller gain and decreasing reset time as total heat load increases. Further, subcooling heat load must be a reasonable fraction of total heat load—say 5 percent—or the system will lack adequate sensitivity. Finally, many cooling water valves do not have adequate turndown; they are wide open in summer and almost closed in midwinter. A small and a large valve in parallel should often be used.

FIGURE 3.3
Alternative overhead system for pressure column
FIGURE 3.4
Air-cooled condenser
The suggested approaches to avoiding these difficulties are as follows:

1. Select the number of degrees of subcooling so that the sensible heat load will be at least 5 percent of the total heat load. This will have a secondary advantage of reducing the probability of cavitation in control valves and pumps.

2. If water-header pressure fluctuations are a problem, use a cascade temperature water-flow control system.

3. If summer–winter heat-load variations are sufficiently severe, use dual, split-range water valves. The smaller valve should open first and will provide adequate winter cooling. The ratio of cooling water rate for the maximum summer heat load to that for the minimum winter load is often two to three times as great as process turndown. (See also discussion in Chapter 11, Section 6.)

4. For the horizontal condenser, the temperature detector preferably should be located in the liquid line just beneath the condenser for maximum speed of response. For the vertical condenser, the temperature detector should be located in a trough at the lower end of a drip collector just below the tube bundle and above the reflux drum. (See Figure 3.8.)

![Diagram of Spray condenser](image)
FIGURE 3.6
Preferred overhead system for atmospheric column
5. The controller should have auto overrides (see Chapter 9), or perhaps adaptive gain and reset, to compensate for changes in condenser dynamics as condensate rate changes. An override from cooling-water exit temperature is also normally needed.

6. As an alternative to Item 5, one may use a recirculating coolant system ("tempered" coolant) with condensate temperature control of makeup coolant. This keeps the condenser dynamics constant and eliminates the problem of retuning the controller as the load changes (see Figure 3.9).

7. Another, completely different approach is to run the column at a slight pressure, say 3–5 psig, or under vacuum. Then the condenser cooling water may be manipulated by the pressure controller while subcooling is controlled by manipulating the vent (see Figure 3.10). This is discussed more fully in the next section. There is, however, a limitation to this technique: for protection

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**FIGURE 3.7**
Alternative overhead system for atmospheric column
FIGURE 3.8
Thermowell installation under vertical condenser
against fouling and corrosion, cooling water exit temperature should usually be limited to a maximum of 50–60°C (122–140°F), and sometimes lower. Increasingly, override controls are used to provide this protection.

Another alternative is to use exit-cooling-water temperature control, discussed in Section 3.4.

Finally, it is increasingly common to provide no condensate temperature control, but to run with full cooling at all times. This saves a control valve. Further, the quality of cooling water is sometimes so poor that a minimum velocity must be maintained in the exchanger to minimize fouling. For accurate control of internal reflux, an internal reflux computer is required (discussed in Section 11.1). As pointed out by Bolles, however, it is necessary to limit subcooling in some columns to avoid foaming on the top tray.

An additional problem with condensate temperature control, via cooling-water manipulation, relates to column safety. In an instance with which one of the authors is painfully familiar, an atmospheric column with such a control system was running at a very low feed rate. Condensate temperature became too low, so the controller closed the cooling-water valve located in the exit line from a vertical condenser. The water in the shell began to boil, the valve could not pass the required volume of steam, the cooling-water pump stalled, and product vapor issued in great quantities from the vent. Fortunately, an alert operator shut the column down before any damage occurred.

As a consequence, unaided condensate temperature control is not recommended. There should be an override from cooling-water exit temperature. Further, to minimize the hazard of winter freezeup, a limiter should be provided to prevent complete valve closure (see Chapter 9).

FIGURE 3.9
Tempered coolant system
3.4 VACUUM AND PRESSURE COLUMNS—LIQUID PRODUCT

The preferred arrangement for a vacuum or a pressure column with a large amount of inerts is shown in Figure 3.10. Here the inerts are pulled off or blown out through a vent line in which there is a throttle valve manipulated by the subcooled-condensate temperature controller. For a vacuum column, the low-pressure source is usually a steam jet. If the downstream pressure fluctuates too much, it may be necessary to use a cascade temperature-vent flow-control arrangement.

For a vacuum column with a small amount of inerts, the arrangement of Figure 3.10 may require an impractically small vent valve. In this event the arrangement of Figure 3.11, with a controlled bleed from the atmosphere (or source of inert gas), is better.

A more complicated but more flexible arrangement, such as that of Figure 3.12,* is well suited to either vacuum or pressure columns when the amount of inerts fluctuates over a wide range. It has worked well, for example, on a column in a semicontinuous process that is shut down and started up every day or so, and that must handle severe transients during the startup period. The vent line is connected to a pressure-dividing network with two control valves connected so that as one opens, the other closes. A split-range adjustment of the two positioners (see Chapter 11, Section 10) permits both valves nearly to close when the controller output signal is at its midrange value. Since the sum of the two acoustic resistances is always high, even though each valve is sized to handle a maximum flow equal to five to ten times the average, normal flow of air or gas through the two valves in series is economically small. When an expensive inert gas such as N₂ must be used, it is common to minimize or eliminate split-range overlap to reduce consumption even further. For large columns that must be started up and shut down frequently, an additional large vent valve is sometimes installed in parallel, and split-ranged with the small one. This facilitates getting the column online at startup.

For many columns the vent flow functions primarily as a purge and is small enough that moderate changes do not affect column operation. In such cases a manually set vent or bleed valve is often adequate and no direct control of condensate subcooling is necessary. For other cases, where column feed rate varies significantly, the vent or bleed valves may be tied to the pressure controller to work in parallel with the condenser cooling-water valve. An example is shown in Figure 3.13.

It should be acknowledged that many engineers today prefer to control condensate temperature by manipulation of condenser cooling water; pressure is then controlled by (1) throttling the vapor takeoff if there is a large amount of inerts, or (2) throttling an air or inert-gas bleed if there is only a small amount of inerts. The objections to, and difficulties with, condensate temperature control, via condenser cooling-water manipulation, were stated earlier. As far

* The symbolism “AO” means air-to-open; “AC” means air-to-close.
FIGURE 3.10
Overhead system for vacuum or pressure column—large amount of inerts
as we can tell, they are equally valid for pressure and vacuum columns as for atmospheric columns. If cooling water is adjusted manually, the flow is either insufficient or excessive.

So-called “water savers” are cooling-water exit-temperature controls. They have the advantage of minimizing cooling-water flow rate for any given heat load. Their use also minimizes subcooling—and there are instances where this is desirable—but at the expense of variable condensate temperature. This can cause variable internal reflux unless it is compensated for (see Chapter 11, Section 2). This kind of control is often implemented as shown in Figure 3.7; pressure is controlled by manipulation of makeup and vent valves.

FIGURE 3.11
Overhead system for vacuum column—small amount of inerts
For a large amount of inerts, it is certainly feasible to control pressure by throttling the vent flow; this procedure is recommended for columns with a vapor product (see next section) where condensate temperature is not controlled.

In designing controls for vacuum columns, the engineer should keep in mind that these columns have a narrow range of operation. The range in column pressure drop between flooding and tray instability for a perforated tray column in vacuum service may be no more than 10–15 percent.

One last consideration should be noted here—that of dynamics. We have previously indicated that pressure control, if used, should usually be of the "averaging" type, which provides slow, gradual correction. This fits in well

**FIGURE 3.12**
Alternative overhead system for pressure or vacuum column—small amount of inerts
with condenser cooling-water manipulation since condenser heat loads, like those of most heat exchangers, cannot be changed rapidly. Controlling condensate temperature via bleed manipulation should be comparatively rapid. On the other hand, controlling condensate temperature via cooling-water manipulation requires overcoming the condenser dynamics.

It should be acknowledged, however, that "tight" pressure control is required in some heat-recovery schemes. This is so because process-to-process heat exchangers are often designed for very small temperature differences; small changes in pressure can create relatively large changes in driving force.

3.5 PRESSURE COLUMNS—VAPOR PRODUCT

Pressure columns are sometimes operated so that the product comes off in the vapor phase. If the condenser is external to the column, the arrangement
of Figure 3.14 may be used. Here column pressure is controlled by manipulating the vapor vent valve. "Averaging" pressure control should be used, and when maximum smoothness of vapor flow is desired, pressure control should be cascaded to vapor flow control. A level controller on the reflux drum balances the rate of condensation against the reflux flow by manipulating condenser cooling water.

An alternative arrangement, used especially when the condenser is built into the head of the column, is that of Figure 3.15. Direct measurement and control of reflux are not possible since the flow is internal. Instead it must be controlled indirectly by manipulation of condenser cooling water, which, in turn, may be reset by a vapor-composition controller. This internal reflux arrangement works well if a heat-computation scheme is used for control. A scheme that we have used successfully is discussed in Chapter 11, Section 4.

If it becomes necessary, because of feed flow or composition fluctuations, or cooling-water-supply fluctuations, to provide reflux-to-feed ratio control, this may be done as follows. By measuring the cooling-water temperature rise
and flow rate, we can calculate the heat transferred, $q_c$. Knowing the latent heat of the reflux, we can calculate $w_R$, the reflux flow rate in pounds per hour. This calculated $w_R$ can then serve as the measured variable in a reflux flow control system that uses condenser cooling-water flow rate as the manipulated variable.

### 3.6 MISCELLANEOUS PRESSURE-CONTROL TECHNIQUES

**Hot-Vapor Bypass**

Another common method for pressure control of pressurized columns involves running with maximum cooling water and bypassing part of the hot gas around the condenser. Several configurations have been employed. In one system the condenser is at a lower level than the receiver by 10 to 15 feet. This means

![Diagram](image-url)  
**FIGURE 3.15**  
Alternative overhead system for pressure column—vapor product
that the condenser runs partially flooded. Common practice, as suggested by Hollander\(^2\) and shown in Figure 3.16A, is to bring the condensate into the bottom of the reflux drum (or at least under the liquid surface) and to bring the hot-gas bypass into the top of the drum. Dynamic problems with such a system can be severe. Suppose, for example, that the column pressure has risen, perhaps as a consequence of increased boilup. The pressure controller pinches the bypass valve to force more vapor into the condenser. This results in a temporary increase in pressure since it takes time for the condenser level to drop. Eventually, however, condenser contents drop to a new, lower level, which permits a higher rate of condensation and causes the pressure to be restored. The temporary “wrong-way” pressure response is commonly called “inverse response”; other examples will be discussed later.

Another technique sometimes encountered involves throttling the vapor to the condenser. This suffers from the drawback of requiring a large valve. It also lowers the operating pressure on the condensing side, which limits heat-transfer capabilities.

Another configuration, as shown in Figure 3.16B, has the condenser mounted above the reflux drum. As suggested by Chin\(^3\), the hot-gas line around the condenser has no valve in it. A valve on the liquid from the condenser floods the condenser to hold column pressure. The liquid in the reflux drum is subcooled, so there is condensation of vapor at the liquid–gas interface in the drum. A vertical reflux drum is recommended to reduce this interfacial area. The liquid line from the condenser should extend down into the liquid in the drum so that the cold liquid is introduced near the bottom of the drum.

These hot-vapor bypass systems are not recommended for systems with even small amounts of inerts.

**Flooded Condenser**

A pressure-control technique that is growing in popularity involves partial flooding of the condenser without a hot-gas bypass, as shown in Figure 3.17. If the pressure gets too high, the controller opens either the distillate or reflux valve, thereby dropping the liquid level and increasing the heat-transfer area available for condensation. Maximum cooling-water rate is normally used. A mathematical analysis is presented in Chapter 15.

There are some practical problems that must be taken into account. Consider, for example, the horizontal condenser of Figure 3.1. The vapor enters at the center and uncondensed gas exits at the two ends. At low heat-transfer loads, the liquid level will run high. If there is insufficient clearance between liquid level and the top of the shell, violent surging and hammering may ensue.\(^4\) This may be minimized by designing adequate clearance into the condenser, or by injecting inerts into the incoming vapor partially to blanket the tubes, thereby lowering the liquid level.

Another problem was observed by Mueller\(^5\) on a partial condenser. At low heat-transfer loads, the liquid inventory in the shell was high. Pressure drop of uncondensed vapor from inlet to the two exits caused a low liquid level in
FIGURE 3.16A
Column pressure control by hot gas bypass
FIGURE 3.16B
Column pressure control by hot gas bypass
the center of the shell and high levels at the two ends. These levels were so close to the exit nozzles that severe entrainment of liquid in the leaving vapor was observed. This particular problem was solved by installing a bypass line between vapor inlet and vapor outlet.

In designing a flooded condenser, one must take care to choose a tube pitch that will not cause large changes in exposed tube area per change in condensate level. In some cases it will be helpful to rotate the tube bundle about its axis just slightly. For troubleshooting, level taps and a level transmitter should be provided. To protect the exchanger from damage at high liquid levels, it will be desirable in some cases to provide an override that will open an inert gas valve connected to the vapor inlet.

3.7 GRAVITY-RETURN REFLUX VERSUS PUMPED-BACK REFLUX

Many arguments have taken place as to whether it is better to locate the condenser overhead and provide gravity return reflux, or to locate the condenser at ground level (or nearly so) and pump the reflux back to the column. With the condenser overhead, the vapor and reflux lines can be short, which favors good overhead composition control. On the other hand, a ground level condenser

![Diagram](image-url)

**FIGURE 3.17**
Column pressure control with flooded condenser
3.7 Gravity-Return Reflux Versus Pumped-Back Reflux

is often easier to maintain, which is especially important if fouling and corrosion are problems. If an overhead condenser is used, a more expensive column-supporting structure is required, particularly if the overhead surge drum is also located at the top of the column. The support problem can be minimized, however, by building the condenser into the top of the column. But one also needs a higher head cooling-water pump, and it is harder to remove the condenser tube bundle for maintenance. If, however, one uses the arrangement of direct return reflux and overflow distillate, then the reflux does not come from the overhead surge drum and this vessel can be located at ground level. Since this tank with its contents is often far heavier than the condenser, the condenser can be located overhead with only a modest increase in structural requirements over a ground-located condenser. Overall a properly designed gravity-flow reflux system is significantly cheaper than a pumped-back reflux system; it is also probably safer since there is no pump to fail. For all gravity-return reflux systems, one must be careful to design the vapor piping and condenser to have a low pressure drop compared with the difference in head between the point of reflux return to the column and the condensate receiver liquid level.

**Reflux Flow or Flow-Ratio Control**

When reflux is flow or flow-ratio controlled, piping and instrumentation can be very simple. Perhaps the most common arrangement is that of Figure 3.18. Here reflux drum level is controlled by throttling distillate flow. A disadvantage, unless the drum has a large cross section, is that variations in level will cause momentary changes in both reflux and distillate flows. The reflux flow or flow-ratio controller will usually be fast enough that this will not be a problem for reflux flow. The level controller, on the other hand, may have to be cascaded to distillate flow control.

To avoid this problem, one may design a distillate overflow system that provides constant head for reflux. Consider, for example, the scheme of Figure 3.19, which features a vapor–liquid disengagement space built into the lower section of a vertical-tube, coolant-in-shell condenser. For maximum effectiveness the liquid pool in the vapor–liquid disengagement space should have a large cross-sectional area, and the overflow weir should permit a wide range of overflows with only a small change in head. Then, with head across the reflux line fixed, flow will vary only when the valve position is changed. For this application a valve with linear trim will have a linear installed characteristic if line drop is negligible; that is, a plot of reflux flow versus valve stem position will be a straight line. If the individual valve is shop calibrated, then valve stem position can be accurately related to reflux flow.

Use of this technique leads to the arrangement of Figure 3.20. Since the surge tank needs a level controller, there is no savings in instrumentation, but the equipment that needs to be installed at a high elevation is minimized.

Another method of controlling gravity return reflux is shown in Figure 3.21. Here a reflux flow measurement is coupled through a controller to a distillate valve. When this valve is pinched, it backs liquid up into the receiver,
causing more reflux to overflow. An elegant way of doing this is to cause reflux to overflow through a Sutro weir, as shown in Figure 3.22. The Sutro weir has the advantage of being a linear weir.\(^6\)

**Distillate Flow or Flow-Ratio Control**

For those columns with gravity return reflux, a severe oscillation in overhead vapor flow to the condenser is sometimes encountered. This is commonly called "reflux cycle" and has a typical period of several minutes. It has been observed primarily in columns where reflux flow is the difference between rate of condensation and distillate flow rate; that is, where distillate is on automatic flow control or column-composition control. Reversing the controls—that is, employing automatic reflux flow or flow-ratio control and allowing distillate to be the difference flow—provides a positive cure.

![Figure 3.18: Gravity flow reflux (flow controlled) and distillate (level controlled)](image-url)
A mathematical study of this phenomenon has been published. It was found that the following measures are helpful in increasing stability and minimizing cycle amplitude:

— Provide a difference in head between the liquid level in the reflux drum (or reflux accumulator) and point of reflux return to the column at least ten times as large as the average pressure drop across the vapor piping and condenser.
— Select the flow-metering orifice to hold liquid head in the reflux line at \( Q_{\text{max}} \) at the bottom of the pot with the Sutro weir.
— Use a large-diameter vapor line to reduce acoustic resistance and to increase acoustic capacitance.
— Use a horizontal condenser with vapor and a generous free volume on the shell side, or use a short, vertical condenser with many tubes (vapor inside tubes).
— Keep condensate subcooling to a minimum. If subcooling is zero, there will be no reflux cycle.
— Use a condenser with a recirculating coolant.
— Increase column operating pressure. This increases vapor density and decreases \( \partial T_c/\partial P \), thereby further improving stability; \( T_c \) is the condensing temperature.

![Diagram](image)

**FIGURE 3.19**
Liquid–vapor disengagement space built into condenser
FIGURE 3.20
Gravity-flow reflux system with ground-located surge tank for distillate
FIGURE 3.21
Control of gravity reflux flow rate by throttling top product flow
FIGURE 3.22
Control of gravity reflux flow rate by overflowing through Sutro weir and by throttling distillate flow
3.7 Gravity-Return Reflux Versus Pumped-Back Reflux

Although the preceding are helpful, it is sometimes necessary to take stronger measures. The following list of overhead schemes is in order of preference, from best to least desirable, when reflux flow must be the difference flow between rate of condensation and distillate flow:

—Pumped-back reflux, proportional level control cascaded to reflux flow control, $\tau_H \geq 3-5$ minutes. $\tau_H$ is the level control time constant (see Section 3.10).

—Pumped-back reflux, proportional level control, $\Delta p_i \geq 10$ psi, $\tau_H \geq 3-5$ minutes.

—Gravity-flow reflux, proportional level control cascaded to reflux flow control, $\tau_H \geq 3-5$ minutes.

—Gravity-flow reflux, proportional level control, $\Delta p_r \geq 5$ psi, $\tau_H > 3-5$ minutes.

—Gravity-flow reflux, surge tank with Sutro weir, $\tau_T > 3-5$ minutes. Make sure the reflux line has a sufficiently high hydraulic resistance. Note that $\tau_T$ is the hydraulic time constant of the surge tank with Sutro weir:

$$Q_s(s) = \frac{1}{A} \frac{1}{\frac{\partial Q}{\partial H} s + 1}$$

$$= \frac{1}{\tau_T s + 1}$$

(3.1)

(3.2)

where

$\frac{\partial Q}{\partial H} =$ constant for a Sutro weir

$Q_o =$ outflow, ft$^3$/min. from Sutro weir

$Q_i =$ inflow from condenser, ft$^3$/min.

$A =$ cross-sectional area of vessel, ft$^2$ (vertical, cylindrical design assumed).

The last scheme is shown in Figure 3.23. Plant experience indicates that it does not completely eliminate the cycling, but reduces the amplitude by a factor of ten or more to an acceptable value. It is simple and inexpensive to fabricate and permits locating the condenser at a lower elevation than do any of the other techniques.

Another important point for gravity return reflux is the method of connecting the reflux piping to the column. Each of the two piping arrangements of Figure 3.24 has an undesirable upward loop just before entry into the column. Inerts sometimes accumulate in this pocket, thereby causing a reflux flow oscillation as a result of an intermittent siphon action. There have been cases where hot vapor was sucked back into this pocket and caused such severe hammer that the reflux line and column nozzle were ruptured.
FIGURE 3.23
Gravity-flow reflux, surge tank with Sutro weir, $\tau_T > 3-5$ minutes
This phenomenon is particularly troublesome with vacuum towers where some slight air leaks are unavoidable. The preferred arrangement of Figure 3.25 avoids this kind of flow instability; the piping may enter horizontally, or with a slight inclination as shown.

### 3.8 CONTROL TECHNIQUES WITH AIR-COOLED CONDENSERS

In recent years air-cooled heat exchangers have grown enormously popular. They have demonstrated, however, certain control problems. They are far more

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**FIGURE 3.24**

Undesirable piping arrangements for returning reflux to column

**FIGURE 3.25**

Preferred piping arrangement for returning reflux to column
sensitive to atmospheric changes such as rainstorms or even changes in wind velocity than are liquid-cooled exchangers. Various techniques have been devised to control the rate of heat transfer or to compensate for condensate temperature changes:

1. Use of induced-draft rather than forced-draft exchanger designs. Top-located fans provide much better protection against rainstorms (see Figure 3.4).
2. Partial bypass of hot liquid from upper section of the exchanger and mixture with cold liquid leaving at the bottom. This permits sensitive, rapid temperature control.
4. Adjustable louvers in the exchanger housing to control suction air flow.
5. Internal reflux computers (see Chapter 11).
6. Flooded operation.

### 3.9 "Tempered" Versus Once-Through Coolant

The term "tempered" has been applied to coolant systems that feature a high circulation rate through the condenser as shown by Figure 3.9. The temperature rise per pass is kept small, and the condenser must be designed for a small pressure drop on the coolant side to minimize pump horsepower requirements. A high-flow, low-head pump therefore is required. The two control valves may be replaced by a single three-way valve if the recirculating flow is not too much larger than the return flow.

Tempered coolant is employed for either or both of two reasons:

1. It eliminates problems with high-freezing-point condensate that might plug the condenser if once-through coolant were used. In extreme cases tempered coolant is taken from and returned to a supply tank that is temperature controlled.
2. Condenser dynamics are radically improved over those achieved with once-through coolant. Speed of response is greater and condenser dynamics do not change with load changes. Condensate-temperature and column-pressure control are easier.

### 3.10 Level Control of Condensate Receiver and Required Holdup

In this section, comments or suggestions regarding required holdup will be primarily from the standpoint of getting good, or at least adequate, control of the column with which the holdups are associated. Small holdups favor good composition control. But when the holdups are part of a feed system for another process step, requirements may be much greater. This is discussed in more detail in Chapter 5.
Level control in condensate receivers or reflux drums is commonly achieved by manipulating either top product flow or reflux flow. Less commonly, overhead level control is accomplished by adjusting boilup or by adjusting condenser cooling water. For the first two cases, a relatively simple control system can be used.

For maximum flow smoothing, it uses the cascade PI level-control to flow-control scheme of Figure 3.26. For this example level is maintained by throttling distillate flow. Note that the PI level controller must be enhanced with high- and low—overrides (called “auto overrides”) to keep level within the vessel. (With electronic analog or microprocessor controls, an alternate design with nonlinear gain and reset may be used—see reference 12.) Since, however, there are two outflows, one must also have overrides on reflux for the same reason. The quantitative design is discussed in Chapter 16. Note that the flow measurement must be linear (or linearized) for stability reasons. Cascade control is used to eliminate flow changes caused by control-valve upstream and downstream pressure variations.

For level control via reflux-flow manipulation, it is necessary to sacrifice flow smoothing in the interest of good composition control. If a PI controller
is used (usually without overrides), it should be tuned for tight control of level, not averaging level control. For this application it is probably more appropriate to use a proportional-only controller as shown in Figure 3.27.

As indicated, it uses a controller with gain 2 (50 percent PB). For pneumatics the bias is so set that the output is 9.0 psig when the input is 9.0 psig. This means that the control valve is closed at the 25 percent level and wide open at the 75 percent level. These numbers should be regarded as part of process design, and the bias adjustment therefore should be treated as a calibration adjustment rather than as a "tuning" adjustment. For pneumatic systems inexpensive fixed-gain relays are available for this application. Figure 3.27 also shows simple overrides that act on the distillate valve. If level gets too high, the distillate valve is opened; if level becomes too low, the distillate valve is closed. Chapter 9 discusses overrides further.

If the manipulated valve has a linear installed flow characteristic (preferred), and if there is no level self-regulation (if $\Delta \rho_p$ does not change appreciably with change in level),* then the dynamic response of the proportional-only† level control system may be defined by a first-order time constant:

$$\tau_H = \frac{A}{K_{mb}K_c \frac{dQ_e}{d\theta_e}} (3.3)$$

where

- $\tau_H$ is in minutes
- $A = \text{cross-sectional area, ft}^2, \text{of seal pot (vertical, cylindrical design assumed)}$
- $K_{mb} = \text{level transmitter gain}$
  
  \[ = \Delta \theta_{mb} \Delta H_T \text{; } \Delta H_T \text{ is the level transmitter span corresponding to the output signal span } \Delta \theta_{mb} \text{ (psi for pneumatics)} \]
- $K_c = \text{controller gain, dimensionless}$
- $\frac{dQ_e}{d\theta_e} = \text{valve gain, ft}^3/\text{min} \text{ psi}$
  
  \[ = k_v(Q_{FS}/\Delta \theta_e) \text{ for valve with linear installed flow characteristics; } \Delta \theta_e \text{ is input span of valve positioner corresponding to full valve travel} \]
- $Q_{FS} = \text{flow-sheet value of manipulated flow, ft}^3/\text{min}$

* If there is significant level self-regulation, one should use cascade level-flow control.
† As will be seen in Chapter 16, $\tau_H$ is also important in the design of PI level controls. It is expressed a little differently, however, for cascade controls.
FIGURE 3.27
Proportional-only condenser seal pot level control via reflux flow
During the early stages of a design project, the level nozzle spacing usually must be determined before control valves are sized. Typically, however, valve-sizing procedures lead to:

\[
(Q_o)_{max} = k_v Q_{FS}
\]  \hspace{1cm} (3.4)

where \(k_v\) is a multiplying factor typically in the range of 2–6. (See discussion on valve sizing in Chapter 11.)

Then, from equation (3.3), for a linear installed valve characteristic, for \(k_v = 4\), \(K_c = 2\), and \(\Delta \theta_{mh} = \Delta \theta_v \):

\[
\Delta H_T = \frac{K_c \cdot k_v Q_{FS}}{A} \tau_H
\]  \hspace{1cm} (3.5)

\[
= \frac{2 \times 4 Q_{FS}}{A} \tau_H = \frac{8 Q_{FS}}{A} \tau_H
\]  \hspace{1cm} (3.6)

In the discussion that follows, the various control schemes usually will require a \(\tau_H \geq 2\) minutes. For any given scheme, however, one should make sure that override time constants are at least 1 minute, that is, \([\tau_H]_{OR} \geq 1\) minute. This may require a \(\tau_H\) much greater than 2 minutes.

If pneumatic instruments are involved, the preceding is adequate for two-pipe designs with up to a 1200-foot one-way distance for 1/4-inch OD plastic tubing or a 2000-foot one-way distance for 3/8-inch OD plastic tubing. For electronic-analog or microprocessor controls, the limiting factor will be the speed of response of the valve-positioner valve-actuator combination.

If, for process reasons, the available holdup must be very small, it is sometimes possible, by the use of special techniques, to design for \(\tau_H\) or \([\tau_H]_{OR}\) less than 1 minute. High-performance valve positioners probably will be required, and for pneumatic instruments various methods are available for minimizing lags and improving speed of response. Experimental data for long pneumatic tubing runs are given in reference 10. System performance then should be checked by frequency-response methods or computer simulation. As noted earlier, if additional volume is required for smoothing out feed to the next process step, it should be preferably in a separate vessel outside of the reflux path.

Process engineers often think of "holdup time" rather than a time constant, \(\tau\). Holdup time is usually considered to be equal to volume divided by throughput. If we think in terms of the volume corresponding to the level transmitter span,

\[
\text{Holdup time} = \frac{A H_T}{Q_{FS}} = \tau_H = \tau_{HU} = \tau_H \times K_c \times k_v
\]

\[
\tau_H = \frac{A \Delta H_T}{\Delta \theta_m \times K_c \times \frac{k_v Q_{FS}}{\Delta \theta_v}}
\]

and
3.10  Level Control of Condensate Receiver and Required Holdup

\[ \Delta \theta_m = \Delta \theta_c, \quad K_c = 2, \quad k_v = 4 \]

\[ \tau_H = \frac{A \Delta H_T}{8 Q_{fs}} \]

Therefore, if \( \tau_H \geq 2 \) minutes,

\[ \tau_{H_U} \geq 2 \text{ minutes} \times 2 \times 4 \]
\[ \geq 16 \text{ minutes} \]

For proportional-reset controllers, we will usually use \( K_c = 0.25 \). Then:

\[ \tau_{H_U} \geq 2 \text{ minutes} \times 0.25 \times 4 \]
\[ \geq 2 \text{ minutes} \]

This illustrates an advantage of PI controllers in averaging level-control service. For the same \( \tau_{H} \), only one eighth the volume is required.

There is some disagreement about optimum reflux drum holdup. Small holdups of liquid are desirable from the standpoint of reducing time constants in the overhead composition control loop. This permits faster and tighter composition control.

Larger reflux drum holdups (10–30 minutes in terms of total condensate rate) are favored by some designers because they provide more liquid-surge capacity. This enables the column to ride through larger disturbances without losing reflux flow, and consequently internal liquid flows (which take some time to reestablish). In the experience of one of the authors, larger reflux drum holdups have proved particularly desirable for columns that occasionally experience slugs of light ends or inertcs in the feed. The condenser is essentially blanketed during the period it takes to vent these noncondensibles off. Without several minutes of reflux holdup, liquid flows would be lost and the time for the column to recover from this upset would be appreciably lengthened. This problem, however, may be minimized by appropriate use of overrides.

**Level Control Via Top Product (Distillate)**

If level goes high, indicating that the sum of the distillate and reflux flows is less than condensate rate, we want to increase the reflux flow. As shown in Figure 3.26, this is accomplished by a relay with a gain of 4 and a high selector (HS). On the other hand, if level goes too low, we want to pinch reflux flow. This is accomplished by another gain 4 relay and a low selector (LS). (See Chapter 9 for further discussion.) Let us now see what effect the difference between top product flow and reflux flow has on \( \tau_H \) and \( [\tau_H]_{OR} \). Let us suppose that \( Q_R = 5 Q_D \), where \( Q_R \) is reflux flow and \( Q_D \) is top-product flow. Then:

\[ \tau_H = \frac{A \Delta H_T \times 12}{K_c \times 12 Q_{mfd}} \]  

(3.7)
and

\[
[\tau_H]_{OR} = \frac{A \Delta H_T \times 12}{K_K K_{OR} \times 12 Q_{mfr}}
\]  

(3.8)

where

\[ Q_{mFD} = \text{distillate flow-meter span, ft}^3/\text{min} \]
\[ Q_{mFR} = \text{reflux flow-meter span, ft}^3/\text{min} \]

and \( K_{OR} \) is the override relay gain and \( K_K \) is the subcooling factor discussed in the next section. Here it is assumed that both the distillate- and reflux-flow control loops are fast compared with the level control loop. If \( K_K = 0.25 \), \( K_K = 2 \), and \( K_{OR} = 4 \):

\[
\tau_H = \frac{A \Delta H_T \times 12}{0.25 Q_{mFD} \times 12}
\]  

(3.9)

and

\[
[\tau_H]_{OR} = \frac{A \Delta H_T \times 12}{4 \times 2 \times Q_{mFR} \times 12}
\]  

(3.10)

Therefore,

\[
\frac{\tau_H}{[\tau_H]_{OR}} = 32 \frac{Q_{mFR}}{Q_{mFD}}
\]  

(3.11)

If the flow-meter spans are in the same ratio as the average flows (5:1), then:

\[
\frac{[\tau_H]}{[\tau_H]_{OR}} = 32 \times 5 = 160
\]  

(3.12)

This indicates that override action may be extremely rapid compared with that of normal level control. This is not usually desirable; it may upset the process. For this reason we mostly choose \( K_{OR} = 2 \) if possible.

**Level Control Via Reflux Flow**

For the system of Figure 3.27, this is very similar to the previous case except that the controller must have a gain of \(-2\) for an AC reflux valve and a level above 75 percent must open the distillate valve, while a level below 25 percent must close it. For gravity flow reflux, level control via reflux should be avoided, if possible, since such designs are often plagued by a “reflux cycle” as mentioned in Section 3.7. If this design cannot be avoided, the entire condenser–reflux system should be designed according to the recommendation in Section 3.7.

For level control via reflux, the characteristic time constant is defined a little differently:

\[
\tau_H = \frac{A \Delta H_T}{K_K K_K (Q_R)_{fs} k_p}
\]  

(3.13)
where

\[ K_w = \frac{\text{subcooling constant}}{\text{lbm internal reflux flow}} \times \frac{\text{lbm external reflux flow}}{\text{lbm external reflux flow}} 
= 1 + \frac{c_p}{\lambda} (T_O - T_R) \]  

(3.14)

where

\[ c_p = \text{reflux specific heat, pcu/lbm } ^\circ\text{C} \]
\[ \lambda = \text{vapor latent heat, pcu/lbm} \]
\[ T_O = \text{vapor temperature, } ^\circ\text{C} \]
\[ T_R = \text{external reflux temperature, } ^\circ\text{C} \]

To allow for condenser dynamics, \( \tau_H \) should be at least 5 minutes and \([\tau_H]_{OR}\) at least 2 minutes. Note that reflux valves should be sized to handle the maximum rate for total reflux operation.

For columns with simple controls, level control via reflux has the advantage that external reflux temperature changes do not change internal reflux.

**Level Control with Small Seal Pot Volume**

If satisfactory flow smoothing cannot be achieved with a gain 2, proportional-only level controller (usually because available holdup is very small), one should use a proportional reset level controller. The proper design is discussed in Chapter 16.

**Level Control Via Boilup**

For overhead level control via boilup, a dynamic analysis should be made to determine proper holdup and controller type. If level is cascaded to flow control, the flow transmitter should have a linear output with flow. If an orifice \( AP \) transmitter is used, this should be followed by a square root extractor.

**REFERENCES**