Flooded Condenser Controls: Principles and Troubleshooting

Flooded condensers are the prime tower pressure-control methods for total condensers that generate only liquid products, and although these control methods can be troublesome, a good understanding of their principles will help achieve improved, trouble-free operations

FIGURE 1. Distillation columns are crucial in many facilities, and pressure control within the tower is of the utmost importance in ensuring steady operations

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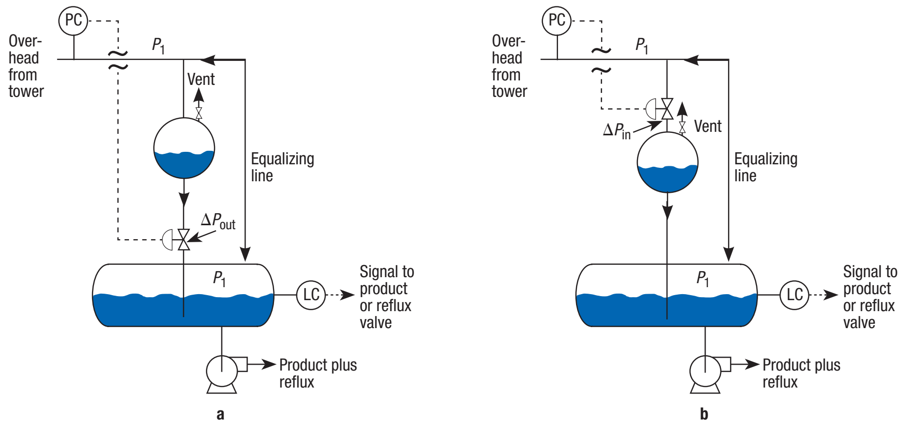
IN BRIEF

Pressure is the most important variable for controlling distillation columns (Figure 1) because pressure affects every aspect of a distillation system: vaporization, condensation, temperature, volatility and so on. An unsteady pressure typically results in an unsteady column.

There are several ways to control tower pressure, depending on how the tower is configured. If a tower has an overhead vapor product, manipulating the vapor flowrate usually controls pressure. If the tower has no vapor product (it has a total condenser and produces only liquid), tower pressure can be controlled by partially flooding the condenser and manipulating the liquid level in the condenser. Another alternative for either vapor or liquid products is to manipulate the coolant flowrate (or temperature) to control the tower pressure. Coolant manipulation is popular in refrigerated towers, but is usually avoided in cooling-water condensers, as it can cause accelerated fouling and corrosion.

Flooded condenser control is by far the preferred pressure-control method used with water-cooled total condensers (those generating liquid products only). It is also common with air-cooled total condensers. In this control method, the condenser area is partially flooded by condensate. The flooded tubes do not contact the vapor and perform little condensation. The column pressure is controlled by manipulating the flooded area.

FIGURE 2. These common flooded-condenser control arrangements show two different control-valve configurations. In Figure 2a, the control valve is located in the condensate liquid line, and in Figure 2b, the control valve is placed in the vapor line



Raising the liquid level in the condenser floods additional tubes, which reduces condensation area, thereby raising tower pressure. Conversely, lowering the liquid level in the condenser exposes more tubes, which increases the condensation area, and subsequently lowers the column pressure.

The principles of flooded condenser controls were described in literature more than 60 years ago. Chin's classic paper on distillation pressure-control describes many of the principles and good practices [*1*]. Yet, these methods continue to be among the most troublesome distillation controls. A good understanding of the principles, as well as learnings from past experiences, are key for avoiding many of the potential problems [*2*]. This article provides an updated and detailed description of the principles of flooded condenser control, and applies them to address many of the most common traps that can cause operational issues.

Common control arrangements

Although the flooded area performs little condensation, it serves the vital purpose of subcooling the condensate. Subcooling is beneficial when pumping volatile liquids [*3*]. Although the subcooling consumes some heat-transfer area, this area is not always added in the exchanger design. Some designers are comfortable to assume that the subcooling area can come from the overage included in the exchanger design [*3*]. Conversely, others prefer to oversize the condensers by as much as 25% to ensure subcooling, especially when the subcooling is critical, as in hot-vapor-bypass schemes [*4*].

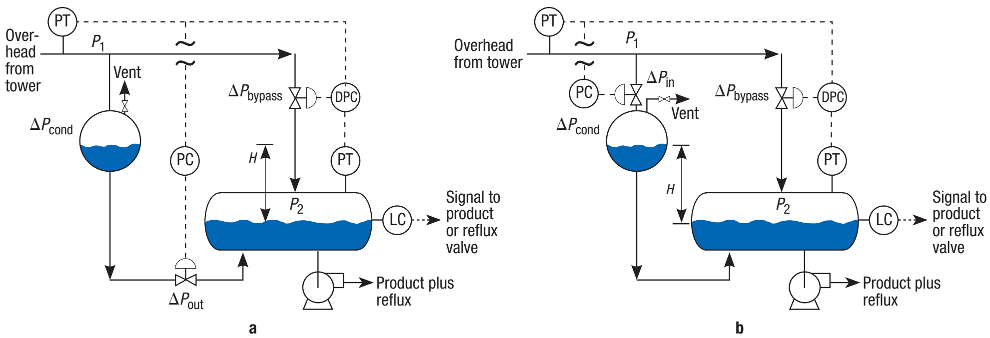
Figure 2 shows two common flooded-condenser control arrangements, both with the condenser mounted above the reflux drum. Figure 2a has the control valve in the condenser liquid outlet. The required control valve is small, and should be located as close to the reflux drum as possible to maximize static head when the condensate enters at the top of the drum [*1*]. For condensate entrance at the bottom of the reflux drum (as seen in Figure 3a), the valve should be located at the lowest horizontal leg. This method is simple and linear, and maintains the same pressure in the column and in the drum. It is therefore often favored [*1*, *5*].

This control method requires that a pressure-equalizing line is included [*1, 5, 6, 7*]. Without this line, the pressure in the reflux accumulator will be unsteady. A smaller equalizing line is required when the subcooled liquid is introduced near the bottom of the drum, as shown in Figure 2a.

Figure 2b shows a flooded condenser scheme similar to that in Figure 2a, but with the control valve located at the condenser vapor inlet. Similar to the method in Figure 2a, the condenser liquid outlet line must enter near the bottom of the reflux drum, and a pressure-equalizing line is required.

Placing the control valve in the vapor inlet (Figure 2b) renders the condensation pressure lower than when the valve is in the condensate outlet (Figure 2a), resulting in the requirement of additional condenser surface area. If no additional area is provided, tower pressure must be raised, which increases energy consumption. The required vapor-control valve is large and may be expensive with large overhead lines.

Figure 3 shows three additional flooded-condenser control schemes, all containing a control valve in the condenser vapor bypass. Figures 3a and 3b are analogous to Figures 2a and 2b; the only difference being the addition of the bypass control valve. This control valve helps overcome the pres-



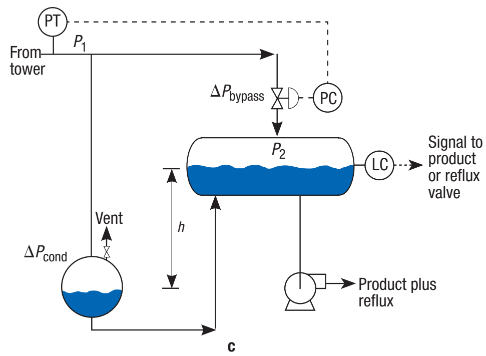


FIGURE 3. Three flooded-condenser control schemes with valves in the vapor bypass are shown: Figure 3a places the pressure-control valve in the condensate liquid line; Figure 3b places the pressure-control valve in the vapor line; and in Figure 3c, the pressure-control valve is in the hot-vapor bypass

sure drop in the condenser, especially when the liquid head is small.

Figure 3c shows the hot-vapor-bypass pressure-control method. Here, the location of the pressure-control valve is switched from the condenser route in Figures 2, 3a and 3b to the hot-vapor bypass. The condenser is at ground level, typically 10–20 ft below the reflux drum (which may be horizontal or vertical). The condensate must be subcooled so that the liquid surface in the drum is colder than in the condenser. While the pressure in the condenser is equal to the vapor pressure of the condensing vapor, the drum pressure is the vapor pressure of the cooler liquid surface in the drum. The difference in vapor pressures lifts condensate from the condenser into the drum. To reduce column pressure, the valve is throttled, reducing the hot vapor supply to the drum, and the drum's liquid surface cools. The colder surface has less vapor pressure. This increases the pressure difference between the condenser and the drum, which in turn sucks liquid from the condenser into the drum. This exposes additional tubes in the condenser, and increases the condensation rate, which lowers column pressure.

The hot-vapor-bypass arrangement permits the condensers to be mounted at ground level instead of on a platform above the reflux drum. Locating large cooling-water condensers at ground level eliminates the requirement for a massive condenser-support structure, and there is also no need to pipe cooling water to high elevations. This provides easy access for maintenance, the piping is simple, the control valve is small, and the response is fast [*3, 8*]. These advantages can translate into considerable savings in steelwork, platforms, trolleys and maintenance. These savings can be major in large installations, especially where a battery of condensers rather than a single exchanger is used. However, this method suffers from many potential issues, which are described in detail in Ref. 9.

Hydraulics of flooded condensers

Figure 3a shows a very common arrangement. The condenser is elevated above the drum, with the condensate descending into the drum due to gravity. The column pressure-control valve is in the condensate line from the condenser to the drum, which enters the drum below the liquid level. Up to this point, this scheme is the same as Figure 2a. The difference is that in Figure 3a, there is also a control valve in the condenser bypass. The presence of this control valve renders the pressure in the drum lower than at the condenser, which introduces a vapor-pressure effect. Assuming negligible line pressure losses, a pressure balance on the condenser gives Equation (1) below.

$$P_1 - P_2 = -H + \Delta P_{cond} + \Delta P_{out} \quad \textbf{(1)}$$

The variables in Equation (1) are defined as follows:

- P_1 is the pressure at the junction between the vapor line to the condenser and the condenser bypass in psia
- P_2 is the pressure at the vapor space inside the reflux drum in psia
- H is the head differential between the condenser liquid level and the reflux-drum liquid level in psi
- ΔP_{cond} is the condenser pressure drop in psi
- ΔP_{out} is the pressure drop across the condensate outlet control valve in psi

The density used to calculate the head differential H is the difference between the liquid and vapor densities, due to the presence of a static leg of vapor in the bypass line. The vapor density is based on the drum pressure and the drum vapor-space temperature. The liquid density is best approximated as the density of the subcooled liquid leaving the condenser. Without a control valve in the bypass (Figure 2a), then $P_1 = P_2$, and Equation (1) becomes Equation (2).

$$H = \Delta P_{cond} + \Delta P_{out} \quad (2)$$

Equation (2) states that for the Figure 2a configuration, the head required to drain the condenser must be high enough to overcome the condenser pressure drop plus the pressure drop of the condenser outlet valve. This condition may not be satisfied when the condenser pressure drop (ΔP_{cond}) is high, or the available liquid head H is low. Adding the valve in the bypass (converting the Figure 2a scheme to Figure 3a) changes the difference between P_1 and P_2 to ΔP_{bypass}, giving Equation (3).

$$P_1 - P_2 = \Delta P_{bypass} \quad (3)$$

Combining Equations (1) and (3) gives the scheme shown in Figure 3a, represented by Equation (4).

$$H + \Delta P_{bypass} = \Delta P_{cond} + \Delta P_{out} \quad (4)$$

Therefore, the pressure drop across the bypass valve helps the gravity head push the liquid from the condenser into the drum. For the arrangement in Figure 3b, the pressure drop at the condenser inlet ΔP_{in} (psi) replaces the pressure drop at the condenser outlet ΔP_{out}, and Equation (4) becomes Equation (5) below.

$$H + \Delta P_{bypass} = \Delta P_{cond} + \Delta P_{in} \quad (5)$$

For the arrangement in Figure 3c, there are no control valves at the condenser inlet or outlet, and the liquid head h (psi) is the difference between the reflux-drum liquid level and the liquid level in the condenser, meaning that $h = -H$. The value of H in Equation (4) is negative, as the liquid level in the reflux drum is at a higher elevation than that of the condenser. Equation (4) then becomes Equation (6).

$$\Delta P_{bypass} = \Delta P_{cond} + h \quad (6)$$

Vapor pressure differentials

As long as there is no hydraulic restriction in the condenser bypass line (Figure 2a), and the pressure drop of the condenser inlet line and at the condenser entry is low, the pressure is the same at the condenser as at the reflux drum. In this case, the vapor-pressure differential between the condenser surface and the drum's liquid surface is zero. In all other situations, the vapor-pressure differential plays a role, often a major one.

The pressure differences between the condenser and the drum in Figures 3a, 3b and 3c introduce vapor-pressure effects. In Figures 3a and 3c, $P_1 - \Delta P_{cond}$ is the vapor pressure of the liquid surface in the condenser, assuming most of the condenser pressure drop is near the condenser inlet — usually a reasonable assumption for total condensers. In Figures 2b and 3b, the vapor pressure of the liquid surface in the condenser is $P_1 - \Delta P_{in} - \Delta P_{cond}$. In all the schemes in Figures 2 and 3, P_2 is the vapor pressure at the reflux-drum surface.

In the schemes in Figures 2 and 3, the hot vapor provided by the bypass condenses onto the drum liquid surface, which keeps the surface hot. At steady state, the hot bypass introduces sufficient vapor to maintain the temperature of the drum's liquid surface at the value corresponding to the desired vapor pressure P_2. Heat flows from the hot liquid surface to the subcooled liquid underneath, and there are also atmospheric heat losses from the vapor space of the drum. These heat flows must be matched by condensing the hot vapor from the bypass.

As long as the drum surface remains steady, most of the heat flow from the surface to the subcooled bulk liquid is by conduction. Since process liquids are good thermal insulators, the conduction heat transfer from the hot surface to the subcooled liquid is small. In reality, convection and some bulk movement raise the heat transfer from the surface to the subcooled bulk liquid, but even accounting for these, the bypass vapor flowrate can easily match the heat demand at the drum liquid surface.

Ref. 9 details the heat balance for the drum in relation to the scheme in Figure 3c. The heat-balance discussion presented there also fully applies to other flooded-condenser control schemes (Figures 2a, 2b, 3a and 3b).

The vapor-pressure effects become of utmost importance in the hot-vapor-bypass scheme with submerged condensers (Figure 3c). In this scheme, the vapor-pressure differences directly determine the flooded height in the condenser. In the elevated-condenser schemes (Figures 3a and 3b), the condenser inlet or outlet valve directly determines the flooded height, with the bypass mainly used to provide sufficient pressure drop, per Equations (4) and (5).

With the hot-vapor-bypass scheme (Figure 3c), the vapor-pressure difference provides the driving head that pumps the condensate liquid from the condenser into the reflux drum as described in Equation (6). Equation (3) can be combined with Equation (6) to give Equation (7):

$$P_1 - P_2 - \Delta P_{cond} = h \quad (7)$$

Equation (7) shows that the vapor-pressure difference is balanced by the liquid head lift. If higher pressure is required in the tower, there is a need to flood more area in the condenser. This requires reducing the liquid head lift h. To achieve this, the vapor-pressure differential $P_1 - P_2 - \Delta P_{cond}$ must be reduced. With P_1 and ΔP_{cond} constant, this is achieved by opening the hot-vapor bypass to raise P_2. Opening the hot-vapor bypass heats up the liquid surface in the drum, which raises the vapor pressure P_2. Conversely, to reduce column pressure, there is a need to lower the liquid level in the condenser, which raises the liquid head lift. This is achieved by closing the bypass valve. This cools the surface in the drum and lowers P_2. The larger $P_1 - P_2$ difference sucks liquid from the condenser into the drum, thus exposing more condenser area for condensation. These mechanisms are described in detail in Ref. 9.

OVERCOMING CHALLENGES

Correct configuration is mandatory for the success of all flooded condenser schemes, due to their challenging nature.

Vapor to vapor and liquid to liquid lines

Bypass vapor must enter the vapor space of the reflux drum. The bypass should be free of pockets where liquid can accumulate, and any horizontal runs should drain into the reflux drum. The author is familiar with cases where a pocket of liquid in the hot-vapor-bypass line in Figure 3c led to severe oscillations and column pressure swings. Most importantly, liquid from the condenser must enter the reflux drum near the bottom of the drum, well below the liquid surface. This is imperative with the Figure 3c configuration, and also highly recommended with the other schemes. The rule is "vapor to vapor, liquid to liquid."

If the liquid enters at the bottom of the drum with an upward momentum (as shown in Figures 3a, 3b and 3c), a horizontal baffle should be added above the inlet to spread the momentum of the incoming liquid jet. As reported in Refs. 9 and 10, liquid jets at velocities of a few feet per second can easily penetrate through several feet of drum liquid, bringing a variable amount of subcooled liquid to the drum liquid surface, disturbing the surface. In some cases, such disturbances have caused a massive amount of liquid to be suddenly sucked from the condenser into the drum [*9*, *10*].

Figure 4a depicts a case in which violation of this practice led to severe pressure fluctuations, an inability to maintain column pressure and a capacity bottleneck [*9*, *11*]. In this scheme, subcooled liquid mixed with vapor at its dewpoint, and vapor collapse occurred at the site of mixing. The rate of vapor collapse varied with changes in subcooling, overhead temperature and condensation rate. Variation of this collapse rate induced pressure fluctuations and hammering.

The green piping in Figure 4b shows the piping modification that eliminated the problem. The liquid and vapor lines were separated, and the vapor line was altered so that it introduced vapor into the top of the reflux drum. After these changes were made, the tower pressure no longer fluctuated, and the problem was completely solved.

This case is one example of a violation of the "vapor to vapor, liquid to liquid" rule described above, and is the most common cause of poor performance with hot-vapor-bypass schemes. A number of these cases have been reported in literature [*5*, *6*, *11*, *12*].

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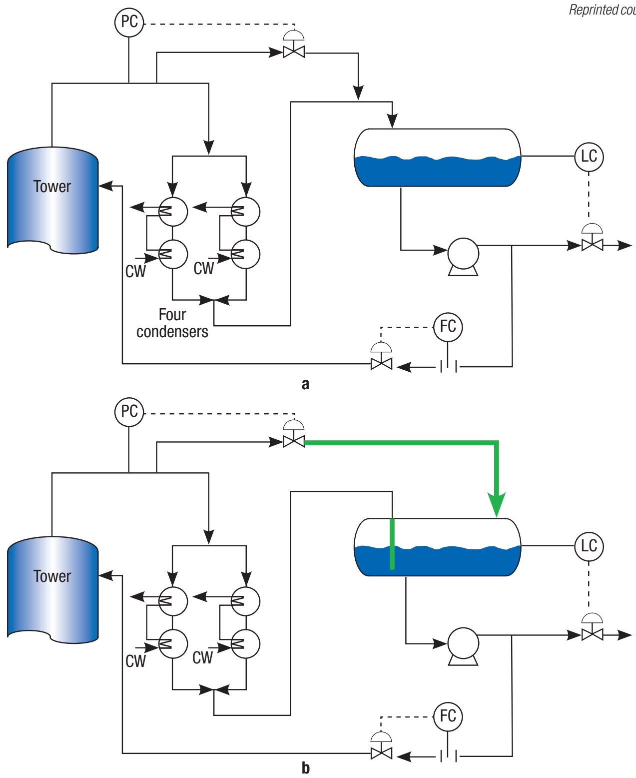


FIGURE 4. These diagrams show correct and incorrect hot-vapor-bypass hookups. Figure 4a illustrates a common mistake that leads to pressure fluctuations. Figure 4b shows modifications (in green) that correct the issues in Figure 4a, and provide sound pressure control [*9*]

Any subcooled liquid streams entering the drum must also enter at or near the bottom of the drum. In one case, subcooled liquid entered the drum vapor space (presumably due to unflooding of the liquid inlet) [*6*]. The vapor space was 100°F hotter, and rapid condensation sucked the liquid leg between the drum and condenser into the drum in seconds.

With the systems in Figures 2a, 3a and 3b, there is some debate in the literature whether the liquid should be introduced into the vapor space or into the liquid at (or at least near) the bottom of the drum. Ref. 1 recommends liquid entry above the liquid level so that drum level does not affect the condenser level.

The author and others strongly prefer that the subcooled liquid enters at the bottom of the drum [*8*, *13*]. Introducing subcooled liquid above the liquid level is likely to cause vapor collapse onto the cold liquid. This in turn may result in pressure fluctuations and possible hammering. Further, introducing the subcooled liquid onto the drum liquid surface drops the vapor pressure in the drum by a large amount, raising the demand of hot vapor from the bypass tremendously, and often overwhelming the capacity of the bypass. Unless a much larger bypass is available, the pressure inside the drum can decrease to as low as the vapor pressure of the liquid at the subcooled temperature. The author is familiar with situations where this pressure loss pulled vacuum inside the reflux drum. In other cases, drum pressure fluctuated, sometimes wildly. In some other situations where the bypass was large, the liquid almost entirely lost its subcooling, causing cavitation of the reflux pump. Splashing subcooled liquid onto the drum surface can also lead to the generation of static electricity. The higher the difference between the bubble point and the subcooled temperature, the more aggravated these issues become. Configurations where the liquid line enters the drum liquid also have the advantage of providing a better seal to the condenser and preventing vapor from blowing through the condenser [*3*].

A common design practice is to introduce the liquid from the top of the drum via a slotted or perforated pipe, so that most of the liquid is introduced below the drum liquid level, but some is splashed onto the liquid surface. This method is better than introducing all the liquid into the vapor space, but is not as good as introducing all the liquid near the bottom of the drum, and has been troublesome. The larger the opening that discharges liquid into the vapor space, the more troublesome this method is likely to be, especially in situations with a high degree of subcooling, such as during cold winter nights or low-rate operation. The issues are identical to those described in the previous paragraph. In the author's experience, severe hammering has occurred when highly subcooled liquid was introduced from the top of the drum with perforated or slotted dip pipes. The hammering ceased after the slots in the vapor space were blocked.

Surface agitation

Operation may be troublesome if the drum's liquid surface is agitated. Surface agitation is a particular concern with the hot-vapor-bypass scheme (Figure 3c), but the other schemes are not immune. Such agitation stirs up subcooled liquid and brings it to the hot liquid surface in the drum, causing fluctuations in the drum pressure. The source of agitation may be from impingement of a high-velocity hot vapor jet on the liquid surface, due to upward-directed subcooled liquid jets reaching the liquid surface, as well as other causes. Control instability has been reported when surface agitation occurred due to strong external vibrations on the reflux drum platform [*14*]. Agitation of the liquid surface can often be avoided by judicious baffling [*9*].

Inert padding

Instability due to surface disturbances or agitation may be alleviated, even mitigated, by padding the drum with non-condensable inert gases. A source of inerts, such as nitrogen or fuel gas, is connected to the vapor space of the drum. The drum pressure is controlled by adding or venting the inerts. The drum pressure is no longer the vapor pressure of the liquid, but now equals the sum of the vapor pressure (*VP*) of the drum liquid and the inerts partial pressure, as shown in Equation (8). The box on p. 44 presents a practical calculation example of the effects of inerts in a tower.

$$P_2 = VP_{\text{drum liquid}} + P_{\text{inerts}} \quad (8)$$

With total condensers, inert padding is usually implemented during operation as a temporary solution to alleviate instability, especially since the inerts can be quite expensive. The vented inerts contain vaporized product. In the calculation example on p. 44, assuming ideality and equilibrium, 10% (3.1 psia/30 psia) of the vent gas at 80°F on a molar basis will be hexane. On a weight basis, the hexane fraction of the vent gas is even higher due to the low molecular weight of the inerts — 26% hexane on a weight basis for nitrogen padding. This vented product is likely to be lost, and may increase flaring or emissions. The inerts, even nitrogen and fuel gas, can be absorbed into the product, and can later increase pressure in downstream equipment, resulting in more product loss and flaring downstream. To avoid inconsistent transitions from the inert-addition mode to the venting mode, there is often a pressure range in which inerts are added simultaneously with venting, which compounds the previously described issues [*15*]. In order to maximize product recovery and minimize emissions and flaring, some experts recommend against using inert padding with total condensers, other than as a temporary solution [*15*]. Diagnosing the cause of, and eliminating the surface instability, is usually a preferred longterm solution, especially with volatile products.

Decanting water

If the reflux drum is used to decant small quantities of free water from condensed hydrocarbons or other water-insoluble organics, the entry point of the condensate liquid (and other subcooled liquid streams that may contain free water) should be located within the drum opposite to the end at which the liquid product and reflux are withdrawn. The water-removal boot should be just upstream of the point where the reflux and product streams are withdrawn [*16*], as illustrated in Figure 5 for the control system from Figure 2a. In many cases, a short standpipe (about 6 to 12 in. tall) or judicious baffling are used as additional measures to keep water out of the reflux and product draw [*16*], but these additional measures may lead to water accumulation in the drum. Also, corrosion is possible when the interface level controller in the boot malfunctions, and potentially acidic water is not adequately removed from the drum. Ref. 17 describes a related experience.

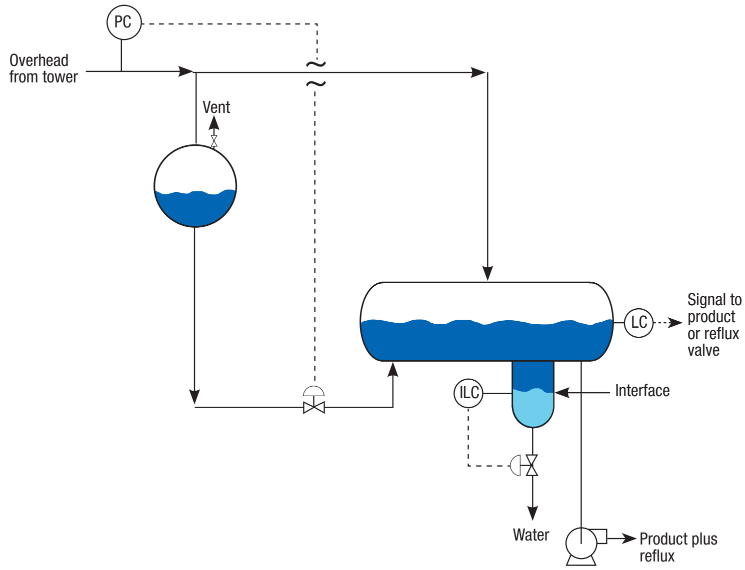


FIGURE 5. The flooded-condenser control scheme from Figure 2a is illustrated here with a water decanting configuration

Non-condensable gases

Flooded condenser schemes are suitable only for total condensers, although some less satisfactory variations are also available for partial condensers [*5*]. The schemes in Figures 2 and 3 can handle small amounts non-condensable gases, such as those introduced during startups or upstream upsets. To handle these non-condensables, vents are required on the condenser and the drum. The condenser vents can be directed to the vapor space of the drum, to an upstream unit or elsewhere. The drum vents should be board-operated, and if frequent venting is anticipated, the condenser vents should also be board-operated. In one case, a debutanizer flooded-condenser system experienced frequent high pressure, instability and flaring due to the breakthrough of non-condensables from an upstream tower that had control issues [*18*]. The problem

THE IMPACT OF INERT PADDING

Consider a tower making hexane top product at 35 psia and 210ºF. The overhead vapor is totally condensed, and is subcooled to 80ºF before entering the reflux accumulator at 30 psia. With no inerts, the drum liquid surface will be at about 200ºF to match the vapor pressure of hexane at 30 psia. A disturbance that lifts 5% of the subcooled liquid to the surface will cool the surface to 194ºF (0.05 × 80ºF + 0.95 × 200ºF), which will in turn drop the drum pressure by 3 psi — quite a large pressure swing. In contrast, with inerts filling the drum vapor space, the drum surface can be as cool as the subcooled temperature of 80ºF. At this temperature, the vapor pressure of hexane is 3.1 psia, with the partial pressure of the inerrts making up the remaining drum pressure. A 6ºF drop in surface temperature will lower the hexane vapor pressure to 2.7 psia, causing only a small change of 0.4 psia to the drum pressure. ❑

was mitigated by adding a manual board-operated condenser vent that was opened upon high pressure and vented to an upstream system.

Insufficient subcooling

Flooded-condenser control methods produce subcooled reflux and product. This subcooling is beneficial in avoiding net positive suction head (NPSH) issues in the pump or flashing problems in the reflux or product line. Such flashing can lead to instability, poor reflux distribution at the tower inlet, slug flow and even hammering [*19*]. The instability may be particularly severe with the flooded drum method (discussed below), due to its potential interaction with the column pressure control. However, other flooded condenser methods can also exhibit such issues.

Subcooling is diminished when the condenser nears its maximum capacity. This may be the natural maximum limit, or can be caused by fouling, non-condensable accumulation, condenser drainage or other issues. Subcooling is also diminished when liquid is splashed onto the surface of the drum, as discussed earlier. Finally, many advanced controls use pressure minimization strategies, such as Shinskey's floating pressure control [*19*, *20*]. These strategies reduce tower pressure during periods of favorable ambient temperatures to conserve energy, and in high-pressure towers (greater than 150 psia), can also maximize capacity. The pressure reduction brings the condenser closer to its limit, and by doing so, minimizes subcooling.

Issues with insufficient subcooling can be avoided, as long as the condenser is not near its capacity limit. The keys are to avoid splashing the condensate liquid onto the drum surface, minimize condenser fouling, properly vent non-condensables from the condenser and adequately monitor the subcooling. Some override control, or simply an operator advisory to limit the pressure minimization upon low subcooling, may also be beneficial.

Air condensers

Air condensers are elevated above the reflux drum, so the only compatible flooded condenser schemes are those for condensers mounted above the drum (as seen in Figures 2, 3a and 3b, as well as Figure 7, discussed further below). The hot-vapor-bypass scheme (Figure 3c) requires mounting the condenser below the drum, and is incompatible with air condensers. In one tower, overhead vapor was condensed in an elevated air condenser followed by a ground-level cooling water condenser. The Figure 3c scheme worked well when the liquid level was in the water condenser, but became unstable on cold days when the air condenser supplied the total condensation duty and the liquid level climbed into the air condenser. The solution was to reduce the air condenser duty by shutting off fans and closing louvers so the liquid level remained in the water condenser [*9*].

An air condenser has a small ratio of height to width. Any change in liquid level, even as small as 1 in., may result in an entire tube row being covered or uncovered. Typically, an air condenser will have very few rows (well below 10), so covering or uncovering one results in a bump in heat transfer. It is common to slightly slope several bottom tube rows, or all rows, towards the outlet so that the movement of liquid level up or down the tubes is smoother [*4*].

Valve configurations

There are unique issues associated with the various valve configurations shown in Figures 2 and 3. The following sections detail these issues and provide some guidance for avoiding them.

Valve in the condenser vapor inlet line (Figure 2b and 3b). As mentioned earlier, this method places a backpressure valve in the overhead vapor line, thereby reducing condenser temperature difference and capacity.

To minimize pressure drop, the overhead valve is often designed for a small pressure drop when fully open. This often leads to valve oversizing. When oversized, the valve operates barely open during winter and cold spells. In this situation, very small valve movements cause large fluctuations in tower pressure. In one case, it was necessary to throttle a manual valve upstream in the line to force the control valve to operate close to its half-open position [16].

This method is prone to liquid hammering if the valve closes excessively. In one case, the valve closed fully under some startup conditions [21]. Vapor downstream of the valve rapidly condensed, causing liquid to be rapidly drawn from the reflux drum, which in turn generated a liquid hammer that shook the whole unit. The problem was solved by changing the valve so that it would not fully close [21].

Valves in both the condenser and bypass lines (Figures 3a and 3b). The addition of the second valve generates potential interaction between the loops controlling pressure and differential pressure. There is also the question of which variable should be used to control the bypass. Friedman's work in Ref. 22 specifically addresses these questions.

Friedman advocates controlling the bypass using a separate drum-pressure controller (Figure 6a), rather than the differential pressure controller in Figures 3a and 3b. Ref. 1 reports one successful case with the system shown in Figure 6a where the liquid head was small and the valve in the bypass line was needed.

The Figure 6a scheme is uncommon, but the author is familiar with troublesome interaction between the pressure controllers in this scheme. This interaction is discussed in Refs. 8 and 22. Ref. 22 states that in this interaction, the two control loops help each other. Both references also state that the key for success with this scheme is to tune the drum pressure fast and the column pressure slow, much like a level controller. However, as previously stated, tower pressure is the most important column-control variable. It therefore needs to be tuned fast so it does not wander. Unlike pressure, level does not affect many variables, and as long as it stays within limits, it can move slower and be allowed to drift. Therefore, the Figure 6a scheme is not recommended by the author.

Another issue with using a separate drum pressure controller is that every time the setpoint is changed on the tower pressure controller, the same change must be made on the reflux-drum pressure controller [8]. The reflux-drum pressure setpoint needs to be lower than the tower pressure setpoint, making the scheme prone to major upsets if operator error occurs. To overcome this issue, Ref. 8 proposes an advanced control that subtracts an appropriate bias from the tower setpoint to provide the setpoint for the reflux-drum pressure controller.

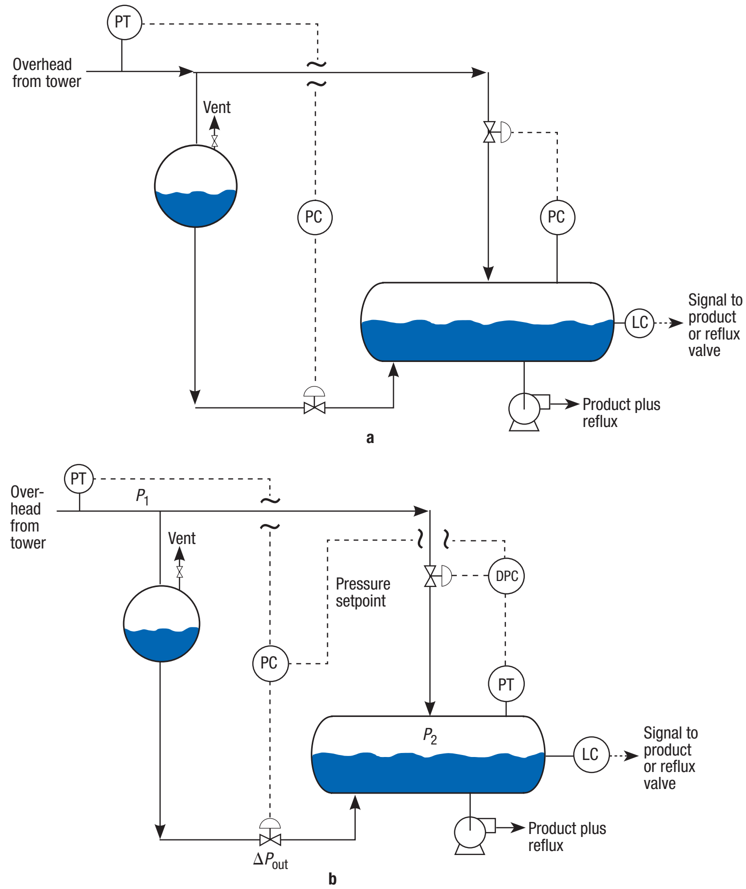


FIGURE 6. These schemes present alternatives to differential pressure control on the vapor bypass. Figure 6a shows a separate pressure controller on the reflux drum, which is not favored by the author. Figure 6b uses the pressure setpoint in the differential pressure controller, and alleviates concerns regarding negative controller interactions

A widely preferred alternative to the dual pressure-controller scheme in Figure 6a is the differential-pressure (dP) control scheme in Figure 3a and 3b. Friedman notes that with this scheme, the two controllers tend to fight each other. Upon an increase in column pressure, the condenser outlet valve (Figure 3a) opens, lowering the liquid level in the condenser, while the dP controller opens the bypass valve, which raises the liquid level in the condenser. While there is some debate in industry about the operability of this control scheme, it is accepted that if both controllers are tuned fast, there may be an unfavorable interaction.

A simple solution, practiced by many of those that reported the scheme to be troublesome, is to tune the dP valve slow or to place the dP valve in manual mode. These solutions have been implemented successfully to overcome the controller interactions. It is important to keep in mind that the main objective of the dP valve is to provide a restriction that will overcome the pressure drops on the righthand sides of Equations (4) and (5), so there is no need for tight control of the bypass pressure drop. One must simply ensure that adequate resistance is present.

In Figure 6b, Friedman presents a more elegant, albeit less widely practiced, solution. Instead of controlling the actual dP, the dP is set as the difference between the setpoint on the pressure controller and the drum actual pressure. This scheme has the strength of Figure 3a, which maintains a set dP, without getting into the negative interactions. Also, this configuration permits fast tuning of the pressure controller, which is essential. As in the Figures 3a and 3b schemes, the pressure should be tuned fast and the dP slower. Remember that the dP's only purpose is to provide sufficient pressure drop across the condensate valve.

- There is a potential for interaction between the drum and the condenser liquid levels [*5*, 9, *10*, *20*, *24*, *25*]. To mitigate the interaction, the pressure controller should be tuned much tighter than the drum level controller [*20*, *24*]. This can be an issue if the reflux drum is small, and the level controller needs to be tuned fast to avoid overflow or loss of level. Although this scenario is quite uncommon, the author has experienced it, and Ref. 26 reports an additional case where this occurred
- Because of the liquid leg between the condenser and the drum, non-condensables accumulate in the condenser and need venting from their accumulation points. If a vent line is absent, instability and capacity bottlenecks may result [*27*]

To mitigate potential interactions between the drum and the condenser liquid levels, the pressure controller should be tuned much tighter than the drum level controller

Hot-vapor-bypass controls (Figure 3c). In the hot-vapor-bypass configuration with submerged condensers, there are numerous issues, which are covered in great detail in Ref. 9. The following are the key issues to keep in mind with this scheme:

- Correct piping is mandatory for the success of the hot-vapor-bypass control method. As described earlier, the bypass vapor must enter the vapor space of the reflux drum (Figure 3c or Figure 4b). The bypass should be free of pockets where liquid can accumulate, and any horizontal runs should drain into the reflux drum. Most importantly, liquid from the condenser, as well as any other subcooled liquid streams, such as the reflux-pump minimum-flow recycle stream, must enter near the bottom of the reflux drum. Many experiences have been reported in which incorrect piping led to instability, poor control and hammering [*4–6*, *11*, *12*, *23*]
- As previously described, operation may be troublesome and unstable if the drum's liquid surface is agitated [*1*, *6*, *9*, *10*]
- A sudden reduction in drum pressure can rapidly suck the liquid out of the condenser, causing a major upset [*9*,*10*]. There is also the possibility of U-tube oscillations [*5*, *24*, *25*]. Both issues can be mitigated by adding a throttling valve in the liquid leg between the condenser and the drum
- Leakage of vapor through the bypass valve at the closed position can substantially reduce condenser capacity. In one case, closing a manual valve in the hot-vapor bypass increased condenser capacity by 50% [*28*]
- Undersizing the bypass control valve may lead to an inability to maintain the tower pressure during cold winter days when the drum is not insulated. In one situation, poor pressure control due to undersizing was improved by installing a throttling valve in the liquid line from the condenser to the drum [*29*]
- In some cases, the hot-vapor-bypass control valve is manipulated by the drum pressure instead of the tower pressure [*29*]. Dynamically, this control scheme is inferior because the vapor volume in the drum is much smaller than in the tower and more variable in response to ambient changes
- The reflux-drum vapor space may require insulation to minimize interference from rain and snow [*1*, *5*, *6*, *9*]. This issue is reported to be more pronounced with narrow boiling-range mixtures [*1*, *6*], and at high pressure [*6*], where small temperature changes have a large effect on the split of overhead flow between the condenser and the bypass. At the

other extreme, the incidence of Rayleigh fractionation with wide-boiling mixtures (where heavy components condense out without combining with the remaining mixture), can also interfere with this control system [3]
- The amount of subcooling and vapor bypass rates can only be determined empirically. Simplified sizing procedures are available [6, 30], but these are based on heating all of the subcooled liquid to its bubble point, and therefore are grossly conservative. More reasonable sizing criteria can be inferred from the principles discussed in Ref. 9

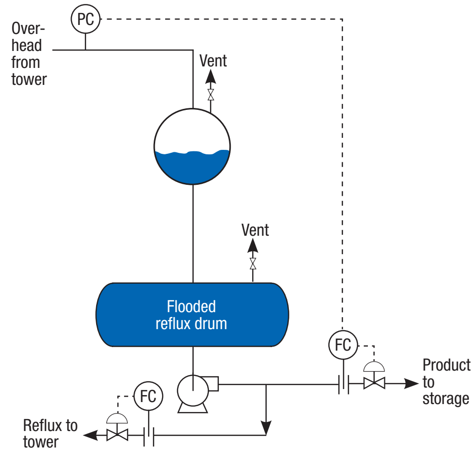


FIGURE 7. The flooded-drum control method can offer cost savings in some applications, but also introduces some unique issues

Flooded drum scheme

Figure 7 illustrates the flooded reflux-drum method. Here, the drum runs full of liquid, and the level control of the reflux drum is eliminated. Sometimes, especially in gravity systems that have no reflux pump, the reflux drum itself can be omitted. The pressure controller directly controls distillate flow. Due to the absence of vapor space, the flooded drum is smaller than a drum with a vapor space, the piping is simpler, and together with the elimination of the level control, this method can offer significant capital-cost savings.

Due to the tight pressure control that is usually required, distillate flowrate controlled by this method is likely to fluctuate. These fluctuations may destabilize downstream units. This method should therefore only be used when the product goes to storage [1, 5, 20, 24], and should be avoided when the product goes directly to another unit.

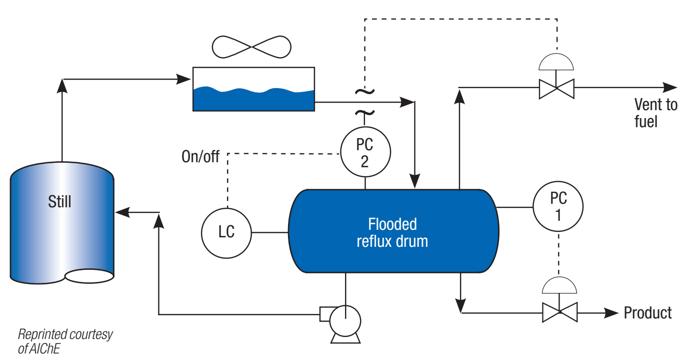
This method has sometimes been used to control reflux flow, but this practice is not recommended [5]. Here, reflux flow, rather than product flow, is likely to fluctuate, and this can destabilize the tower.

Besides the condenser venting issue above, the flooded-drum method has an additional venting issue. Accumulation of non-condensables in the drum may unflood the drum and interrupt the control action. These non-condensables must be vented from near the top of a liquid-full drum, so they need to be vented to a facility that can handle liquids, such as a knock-out drum. If accumulation of non-condensables is infrequent, manual venting from the top of the drum is often sufficient to maintain satisfactory operation. If non-condensables accumulate frequently, or the column is run unattended, automatic venting is required.

Figure 8 illustrates an automatic vent system that has worked well in practice [5, 12, 31]. A second pressure controller (PC 2), a level controller and a control valve in the vent line are added. The setpoint of PC 2 is lower than that of the normal pressure controller (PC 1). When the drum is full, the level controller keeps PC 2 tripped off, and the vent valve is closed. Drum unflooding (due to non-condensable accumulation) is sensed by a drop in drum level. The lower level activates PC 2. Since the setpoint of PC 2 is lower than PC 1, it opens the vent valve. As the drum pressure falls, PC 1 closes, helping to build up the drum level. As soon as the drum refills, the level controller trips PC 2, and the vent valve closes.

Since the venting required above is from a liquid-full drum, leaks from the vent line are likely to be liquid, giving a product loss much greater than a leaking vapor valve. Flashing of liquid across the valve can chill the vent line, sometimes resulting in icing or "weeping" on the outside of the pipe due to atmospheric moisture condensation, with possible overchilling or corrosion of the vent pipe. Ref. 16 describes one case of icing due to such a leak from a flooded drum in a debutanizer unit.

FIGURE 8. This flooded-drum automatic-vent system with dual pressure control has operated well in practice [31]



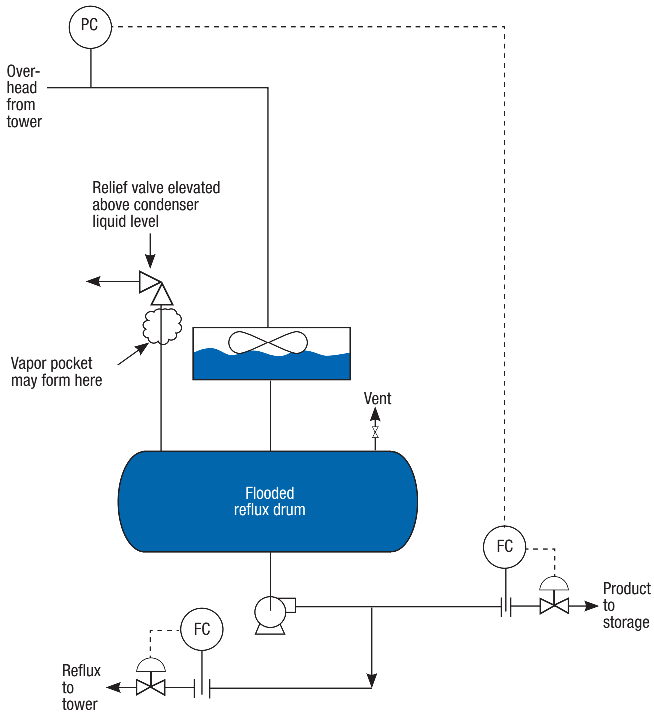


FIGURE 9. This configuration illustrates a relief valve mounted on a flooded drum

Unless the product is subcooled and at a significantly higher pressure than the storage facility, it is best to take the product to storage from downstream of the reflux pump (as shown in Figure 7). If the product is taken directly from the drum, flashing may occur downstream of the control valve, or it may be difficult to get the product into storage when the storage pressure is high. Either may cause instability or back excessive liquid into the condenser, thereby reducing its capacity and possibly leading to a relief situation. In one depropanizer process, pressure variations in elevated propane storage bullets downstream induced intermittent flashing and slug flow in the product line even though the product was pumped [*19*]. Collapse of vapor due to elevation and pressure changes is believed to have caused transient shockwaves and hammering, as well as chattering of the relief valves, in the pump-discharge circuit. The chattering was eliminated by adding a backpressure controller that prevented the flashing.

With the flooded drum method, a failure of the reflux pump often produces a relief situation. The condensate has nowhere to go, and quickly floods the condenser, ceasing condensation, causing the tower pressure to rise until the relief valve lifts. In other flooded condenser schemes (for instance, Figure 2a) where the reflux drum is not flooded, the vapor space in the drum provides operators with a few minutes to take action before the liquid fills the condenser. The author is familiar with one plant that replaced a flooded drum with a new non-flooded drum that was over twice the volume (to accommodate a vapor space) just to prevent recurrence of such a relief scenario.

Any relief valve mounted on the flooded drum (Figure 9) is most likely to discharge liquid, which may not provide adequate relief and may cause problems in the flare system. Furthermore, when the drum relief valve is elevated above the liquid level in the condenser, a vapor pocket may form in the valve inlet line during warm weather. Upon cooling (for instance, at night), the vapor pressure of the liquid in the small pocket falls. The vapor pocket may collapse, forcing a liquid rush that will hit the relief valve and cause chattering, as reported in two cases in Ref. 19. The need for a relief valve on the drum should be critically reviewed, as the relief valve on the tower should usually be able to relieve the drum.

Final remarks

Despite their importance in tower pressure control, flooded condenser controls have been some of the most challenging distillation-control techniques. However, operating experience indicates that they can be quite trouble-free when correctly designed and applied. It is hoped that the principles and experiences described in this article will pave the way for flooded-condenser controls' successful application for tower pressure control. ■

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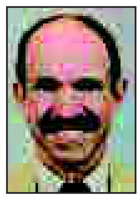

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