Inside a Trayed Distillation Column
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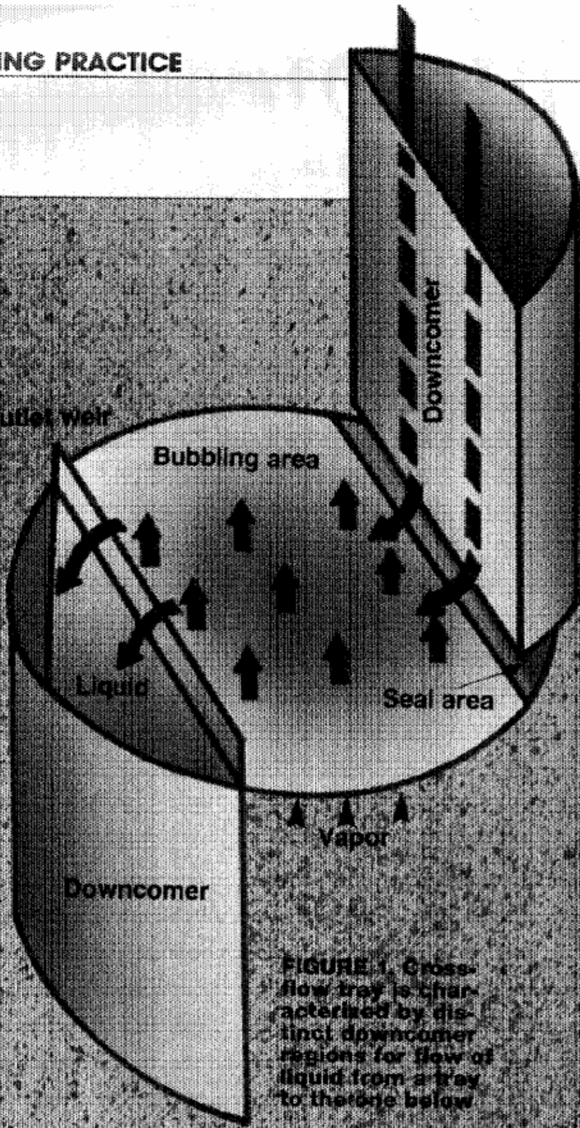

FIGURE 1. Crossflow tray is characterized by distinct downcomer regions for flow of liquid from a tray to the one below

INSIDE A TRAYED DISTILLATION COLUMN

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Tray-type distillation columns are complex devices. A key to selecting a column intelligently or operating it efficiently is to have a good understanding of how the liquid and vapor behave inside the vessel.

This behavior depends largely on the kind of tray. Accordingly, the tray type plays a major role in setting important operating parameters for the column such as its capacity, separation efficiency, pressure drop and turndown ratio.†

Distillation trays used in the chemical process industries can be broadly classified as crossflow trays with downcomers and dualflow trays without downcomers. It is convenient to discuss each of the two separately.‡

CROSSFLOW TRAYS

A crossflow tray consists of three areas, as seen in Figure 1. These are the bubbling area, the entrance to the downcomer that leads to the tray below, and the seal area for the downcomer from the tray above.

Liquid descending the downcomer from the tray above changes direction at the downcomer seal area and enters the bubbling area. Here the liquid comes in contact with vapor ascending through the tray. An outlet weir usually provided, on the downstream side of the bubbling area, maintains the liquid level on the tray.

The bubbling area can be fitted with numerous types of tray hardware. However, sieve, valve and bubble-cap trays account for the majority of installations.

In sieve trays, the bubbling action is due simply to perforations in the tray. In recent years, these trays have be-

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*Presently at Brown & Root Braun

†A good visual description of tray-column behavior is offered by Reference [1], a motion picture.

‡For information related more explicitly to solving problems in operating columns, see "Troubleshooting distillation columns; Part 3: Trayed columns," May 1989, pp. 126-138.

come especially widely used. They are simple to design, and can be employed with considerable confidence over most ranges of operation. Ease of fabrication makes them less expensive than other types. And they can accommodate large-diameter holes, which enables them to resist fouling.

Valve trays are basically sieve trays that have valves atop the perforations. They likewise have gained much popularity, and are available in various designs from several manufacturers. Because the valves can close at low vapor throughput and thus lessen liquid leakage to the tray below, valve trays enable a column to operate effectively at well below its design capacity; that is, they operate effectively at high turndown ratio (discussed later).

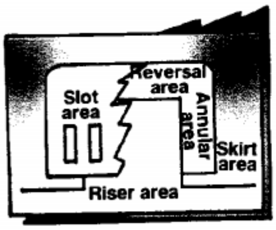


FIGURE 2. Bubble caps entail a rather convoluted pathway for the rising vapor

Bubble-cap trays are outfitted with numerous bubble caps (see Figure 2), each consisting of a hole in the tray floor, a chimneylike riser pipe over the hole, and an inverted cup over the riser. Clearance between the tray floor and the cap allows vapor passage. The caps may also be provided with slots or holes for the vapor traffic. These trays were long the favorite of the process industries and are still in frequent use. A properly designed bubble-cap tray can be operated down to near zero vapor rate without significant loss in separation efficiency.

Numerous other kinds of trays are on the market, most intended for specific uses. Reference [2] briefly surveys a large number of these devices, and includes a list of sources where further information about them can be found.

The performance diagram

The key determinant of tray performance is the relative amounts of liquid and vapor directed to the tray. These define a region of normal operation, as seen in Figure 3 for a sieve tray.

Assume that the tray represented by Figure 3 is initially operating at Point M, a low to moderate liquid rate and a vapor rate such that the tray is in the region of normal operation. As the liquid rate is held constant and the vapor rate is increased, more liquid is entrained in the vapor and carried over into the tray above. Above a certain vapor rate, Point E, entrainment becomes excessive and tray efficiency deteriorates to an unacceptable level. This defines the practical upper operating limit of the tray, even though the hydraulic stability may still be maintained at this vapor rate.

If the vapor rate is further increased, the entrainment will cause liquid to accumulate in the column (Point F). The tray goes into a condition known as hydraulic flood, meaning that it is no longer operable at all. This is known as entrainment flooding.

Engineers need not look upon distillation columns as black boxes

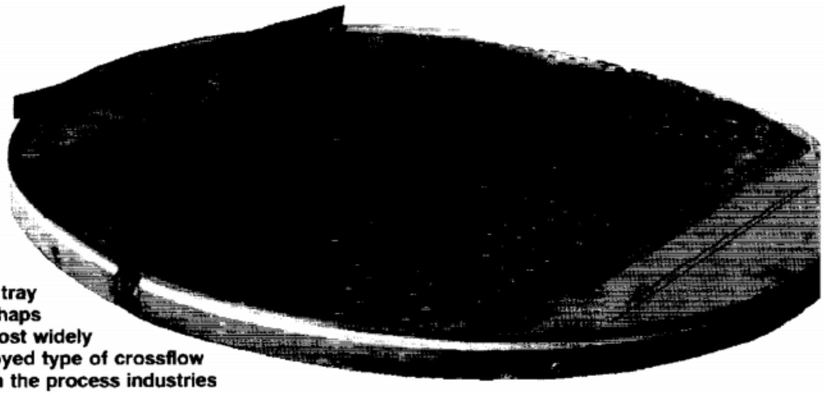
The situation is somewhat different if the liquid rate is relatively high, say at Point N. In this case, either a sizable increase in vapor rate or a rise in the liquid rate itself (even if vapor rate remains unchanged) will cause a hydraulic upset known as downcomer flooding.

Problems likewise arise if the vapor rate is lowered, either at a constant liquid rate or at a constant liquid-to-vapor (L/V) ratio. The upflowing vapor may not be able to counter the tendency of the liquid to leak through the tray holes, so the tray will begin to "weep," for instance at Point W. Weeping means that some liquid is bypassing the tray vapor-liquid contact zone, which adversely affects tray efficiency. However, a small amount of weeping will ordinarily lower the efficiency only marginally.

As the vapor rate is further lowered, the weep rate will increase and eventually cause the tray efficiency to deteriorate significantly. This (Point L) is the practical lower operating limit of the tray. At this condition, however, some portion of the liquid is still flowing over the weir and into the downcomer to reach the tray below.

If the vapor rate is yet further reduced, weeping will become so severe that none of the liquid on the tray will be going over the weir. This (Point D) defines the dump point of the tray. Dumping may cause the downcomer to become unsealed and cause hydraulic instability.

Flooding and weeping — and ways to avoid or minimize them — are dis-



Sieve tray is perhaps the most widely employed type of crossflow tray in the process industries

cussed in more detail later. At this point, it is again worth noting that the lower operating limits will occur at much lower vapor rates if the bubbling area is equipped with a properly designed valve or bubble-cap tray.

Flow regimes

As the liquid enters the bubbling area and comes in contact with vapor ascending through the tray, the result may be a violent spray action, a quiescent flow of emulsified two-phase mixture across the tray, or (most likely) something between those two extremes. Tray action within the normal operating range can thus be divided into a spray regime, a froth or mixed regime, and an emulsion regime (see Figure 4).

An in-depth description of these regimes is given elsewhere [2,8]. But their significant features for the designer or operator of a column are as follows.

Spray: This is most likely at low liquid rates and high vapor velocities. It typically occurs near or under vacuum conditions, where the vapor velocity is high because the vapor density is low relative to the liquid.

As the vapor passes through the tray, it erupts through the shallow liquid layer and propels droplets of the liquid up into the inter-tray space. Thus, in this regime the vapor is the continuous phase and the liquid the dispersed.

On sieve trays the vapor does not pass through all the holes evenly. At any given moment it is usually erupting through about 30% of the holes, in several clusters randomly located throughout the bubbling area. This is followed by another eruption through another random set of approximately 30% of the holes, and so on.*

As the vapor rate is increased, eventually the spray will try to rise higher than the tray above and thus cause a massive entrainment flood. This type of entrainment flood is often referred to as "blowing flood."

***Emulsion*:** This occurs at the opposite end of the operating spectrum of a column. It is most likely with high-pressure systems in which the liquid rate is high and the vapor velocity through the column is low due to the relatively high vapor density.

Vapor rising through the tray perforations at relatively slow speed is "sheared off" by the cross-flowing liquid and slowly rises through the liquid layer as the latter flows across the tray. This shearing action takes place over the entire bubbling area.

The liquid with the slowly rising vapor appears to be an emulsion. The liquid is the continuous phase while the rising vapor in the form of bubbles surrounded by liquid is the dispersed phase.

***Froth or mixed*:** This is a mixture of spray and emulsion. It is most likely to occur near atmospheric pressure, and with moderate flowrates for both vapor and liquid.

Eruption of vapor through the tray is not so violent as in the spray regime, due to damping of the spray-generation effect. This damping is attributed to both the higher liquid rate and the more-moderate vapor velocity.

Emulsion flow is not likely to develop because the liquid rate and clear-liquid height on the tray are too low and the vapor velocity through the tray too high to permit significant shearing of vapor bubbles at the holes. The surface of the fluid is not so quiescent as in the emulsion regime. Conversely, there are not so many droplets generated as in the spray regime.

FIGURE 3. Performance diagram for sieve tray depicts operational behavior as a function of the vapor and liquid rates

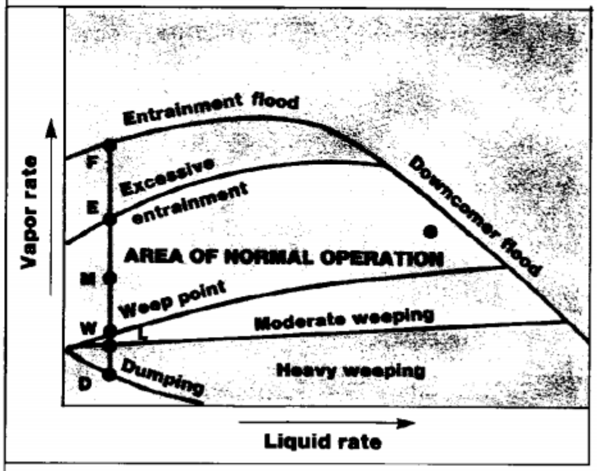
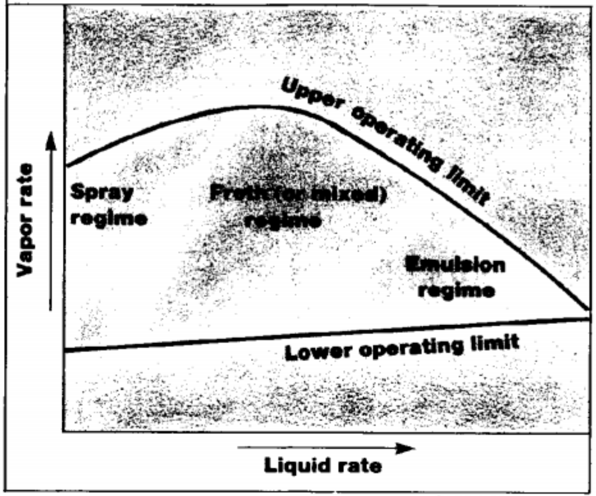


FIGURE 4. Relative amounts of vapor and liquid fed to tray determine the type of interaction between those two phases



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Upper limit

As noted earlier, flooding sets the maximum operating limit on a tray column. A flood point is defined as a condition where the combination of vapor and liquid traffic in the column is so great that any increase in either will make the column inoperable. This can be due to massive entrainment or to downcomer flooding in the column.

Entrainment flooding: This usually occurs in the low- to moderate-liquid-rate region or in the spray regime (or both). At low to moderate liquid rates, the spray height increases as the vapor rate is increased at the same time. Eventually the spray begins to reach the tray above and some of

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*This phenomenon has been photographed in several normal and high-speed motion pictures [1].

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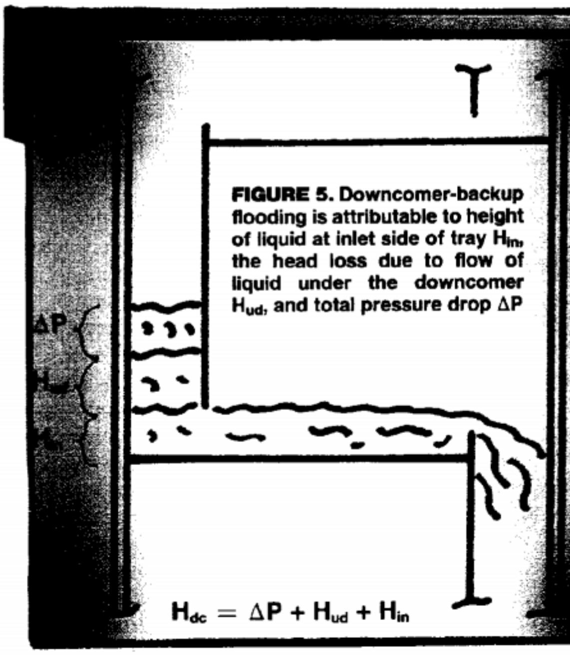

FIGURE 5. Downcomer-backup flooding is attributable to height of liquid at inlet side of tray H_{in}, the head loss due to flow of liquid under the downcomer H_{ud}, and total pressure drop ΔP

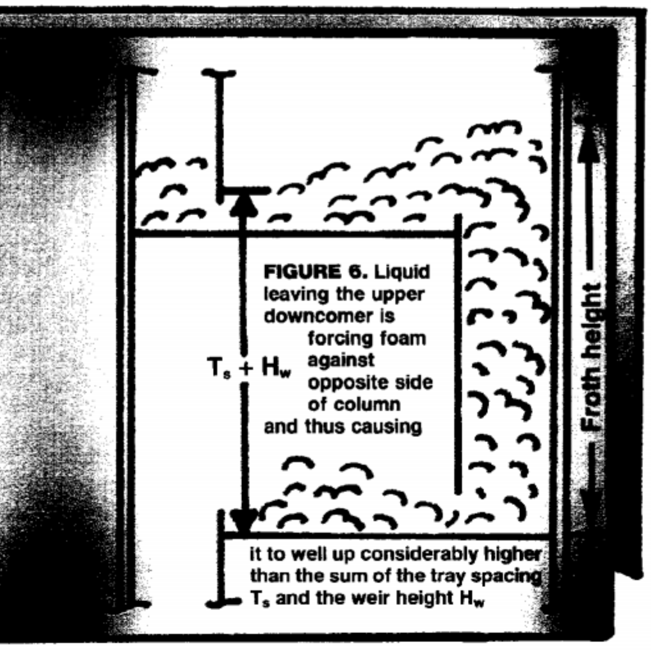

FIGURE 6. Liquid leaving the upper downcomer is forcing foam against opposite side of column and thus causing it to well up considerably higher than the sum of the tray spacing T_s and the weir height H_w

the liquid is aspirated onto that tray as entrainment. When the vapor rate is further increased, the average spray height increases beyond the tray spacing, and entrainment on a massive scale begins to take place, causing the trays and column to flood.

Some of the more discernible symptoms of an entrainment flood are as follows:

- Excessive entrained liquid leaves the top of the column through the overhead vapor system, sharply increasing the reflux rate and making it difficult to maintain column pressure control
- If the column is equipped with properly lighted viewing windows, it is possible to see that the intertray space is full of spray and that a large proportion of the spray generated on a given tray is hitting the bottom of the tray above
- The overall tray pressure drop increases sharply with an incremental increase in vapor rate
- The separation efficiency gradually deteriorates as the amount of entrainment increases. Indeed, very little separation will take place over the entire column if it is allowed to go into an extremely heavy flood

There are several ways to increase the capacity of a column affected by entrainment flood. With sieve trays, either the tray area occupied by holes can be increased or the hole diameter decreased. Another approach is to increase the tray portion devoted to bubbling area, provided that the downcomer area is not already restricting the design. Higher capacity may also be obtained by increasing the tray spacing.

Downcomer flooding: There are two versions, downcomer backup and downcomer choking. Each usually occurs at high liquid rates and is caused by a mechanism entirely different from that for entrainment flooding.

Downcomer backup flooding occurs because the downcomer cannot accommodate the vapor-liquid mixture entering it. The aerated frothy liquid fills the downcomer and finally backs up onto the tray above. Its height in the downcomer is a function of the clear-liquid height and the degree of frothiness.

Flooding sets the upper operating limit for a column

In turn, the backup of clear liquid in the downcomer, H_{dc}, depends on three factors (see Figure 5):

1. The clear-liquid height at the inlet edge of the tray, H_{in}. This is a function of the weir height and the liquid rate
2. The total tray pressure drop, ΔP. This causes the liquid to back up because the vapor force necessary to overcome the tray pressure drop will also be pushing against the liquid leaving the downcomer. The tray pressure drop is a function of the vapor and liquid rates and the tray geometry
3. The head loss due to flow of liquid under the downcomer, H_{ud}. This is a function of the downcomer escape area, shape of the bottom edge of the downcomer and the liquid rate

Accordingly, the following relationship holds (with ΔP being expressed in terms of head):

$$H_{dc} = H_{in} + \Delta P + H_{ud}$$

The height of the frothy liquid, H_f, can be obtained from the equation

$$H_f = H_{dc}/\ \psi_f$$

where ψ_f is the downcomer aeration factor, which describes the degree of

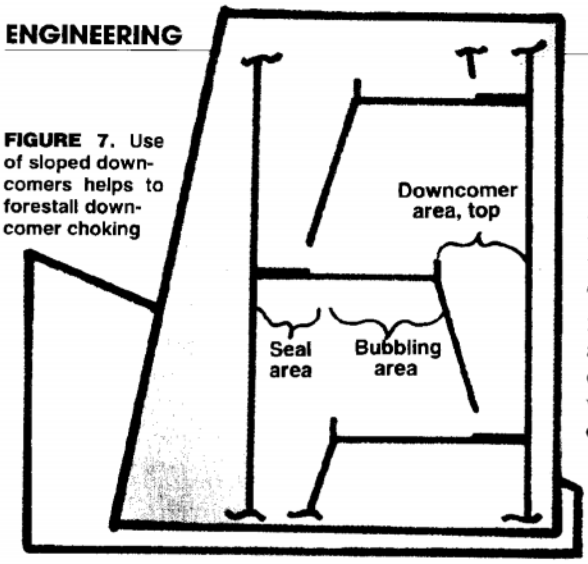

FIGURE 7. Use of sloped downcomers helps to forestall downcomer choking

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frothiness of the liquid in the downcomer.

The formal criterion for downcomer flooding, then, is the relationship

$$H_f \geq TS + H_w$$

where TS is the tray spacing and H_w the weir height.

In actual practice, however, the froth height over the downcomer can sometimes be considerably higher. This can happen when the horizontal component of the momentum of the liquid leaving the downcomer is sufficient to push the frothy liquid against the column wall and cause the froth to well up over the downcomer, as seen in Figure 6.

If the above calculations indicate that downcomer backup is excessive, the engineer should check the column for the previously mentioned factors that cause flooding. Also, there are three ways to increase the downcomer capacity by lowering the clear-liquid backup in the downcomer:

- The inlet clear-liquid height can be lowered by decreasing the weir height or by increasing the weir length
- The tray pressure drop can be lowered by installing a lower-pressure-drop device for vapor-liquid contact in the bubbling area or by lowering or lengthening the outlet weir
- The head loss under the downcomer can be lowered either by increasing the area under the downcomer or by shaping the outlet edge of the downcomer to produce a streamline flow for the exiting liquid.

If the level cannot be lowered by these means, another option is to split the flow. This can be done by increasing the number of downcomers per tray and therefore the number of flowpaths. Thus dividing the flowpath gives more area under the downcomers, longer outlet weir length and lower clean liquid height on the tray, all of which will contribute towards lessening the liquid height in the downcomers.

The other type of downcomer flooding, called choking, is due simply to the downcomer entrance area being inadequate for the amount of liquid entering. The answer is to provide a larger downcomer area at the top. Although this risks some loss in the bubbling area, that loss can be minimized if the downcomer is sloped from the top to the bottom, as shown in Figure 7.

Flooding factors

In practice, two key variables imposed upon the column by its role in the overall processing unit are its operating pressure and the liquid-to-vapor (L/V) ratio. Figure 8, taken from Kister [3], shows how these affect the flooding mechanism.

At low pressures (vacuum conditions) and low L/V ratios, the column is most likely to be operating in the spray regime. So the flooding is usually caused by the entrainment mechanism.

At high pressures, the difference between the vapor and liquid densities become smaller and separation of vapor from liquid on the tray and in the downcomer becomes difficult. Because of the stable emulsion-like behavior of the two-phase mixture, the downcomer aeration increases, causing the froth level in the downcomer to increase. The effect is intensified if the L/V ratio is high, because high liquid flowrates also increase tray pressure drop and tray liquid level, further promoting emulsion flow. Consequently, the mechanism of flooding is most likely to be of the downcomer-type in the region of high pressure and high liquid rate.

The region of moderate pressure and moderate L/V ratio is accordingly bounded by the spray-height (or entrainment) flooding mechanism on one end and the downcomer flooding mechanism on the other, and can best be analyzed in terms of the actual liquid and vapor flowrates, as presented in

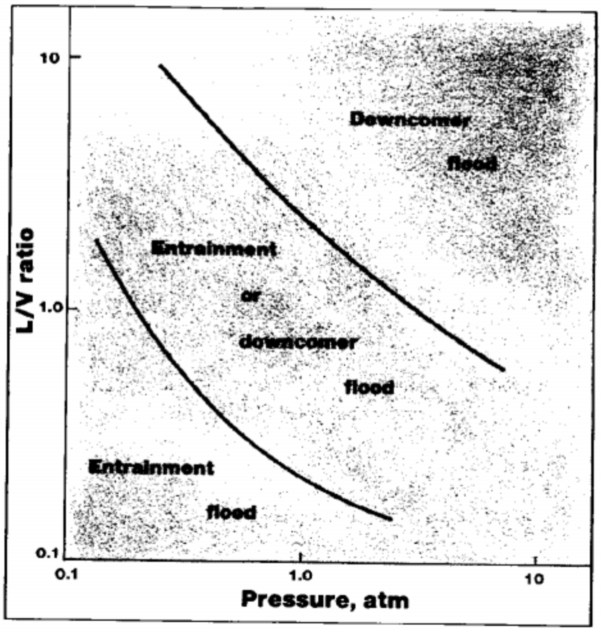

FIGURE 8. The nature of incipient flooding depends on the column operating pressure and liquid-to-vapor ratio

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Figure 3. Flooding encountered near the transition area between spray and froth regime would most likely resemble the entrainment flooding mechanism. On the other hand, flooding encountered near the transition area between the froth and emulsion regime would most likely resemble the downcomer flooding mechanism.

Unfortunately, pinning down the flooding mechanism at moderate pressure and moderate L/V is not really so simple, due to the fact that the cause-and-effect relationship becomes complicated near flood. As the flooding rate is neared, the entrainment generated from the tray and the froth in the downcomer both increase, and approach the value at which flooding would begin. Further increase in vapor rate may trigger flooding by either downcomer backup (due to increased pressure drop of the tray) or by massive entrainment (due to the high vapor velocity).

On the one hand, downcomer flood can increase the froth height on the tray and cause the entrainment to soar. On the other hand, the massive entrainment can increase the liquid traffic in the downcomer and trigger downcomer flooding.

Bear in mind that Figure 8 does not take into account the specific tray and downcomer design, the type of system, or operation conditions other than pressure and L/V. All of these can also influence the actual flooding mechanism.

Ultimate capacity

The preceding discussions of entrainment and downcomer flooding include methods for improving column capacity by modifying tray design or spacing. However, there are certain combinations of vapor and liquid rate beyond which further hardware improvements are of no avail. Beyond this ultimate capacity, "flooding by system limitation" will take place.

This can occur regardless of the operating pressure or the L/V ratio. It manifests itself as a substantial net upward flow of liquid relative to the total flow, and is a function of the velocity of the liquid drops populating the intertray spacing. The situation is like that of a sailor on a ship throwing a bucket of water against a strong wind and getting drenched.

Well-designed bubble-cap and valve trays may be operated down to near shut-off without impairing performance

Most trays must be operated above a certain throughput rate to obtain satisfactory performance. As noted earlier, this limitation is most binding with sieve trays. Well-designed bubble-cap and valve trays may be operated down to near shut-off without impairing performance.

The weep point of a sieve tray is a function of the tray geometry and the physical properties of the system. Sloshing and oscillation of the liquid on the tray causes the clear-liquid depth to vary simultaneously at random locations throughout the tray.

As the pressure drop across the tray is essentially the same at any of these, weeping occurs at those locations where the liquid head is temporarily high. The same condition applies even if the average head on the tray is less than that required to overcome the pressure difference across the tray.

Weeping liquid bypasses portions of two trays — not only the tray under observation but also the one below it, as the liquid is not descending through the downcomer. As weeping increases, therefore, the separation efficiency of the column will deteriorate. Experiments in commercial-scale columns have shown, however, that as much as 20% of the liquid can weep without onset of deterioration. This finding applies to all three types of trays.

Sieve-tray weeping may be reduced or eliminated by switching to a tray with lower hole area, or by installing blanking strips to reduce the hole area on the existing tray. However, either method will lower tray capacity.

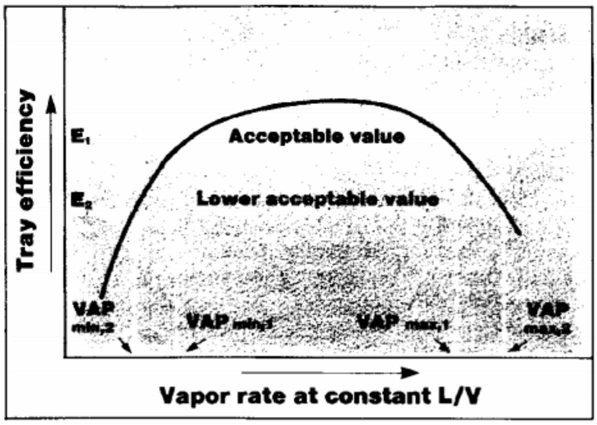

FIGURE 9. Turndown ratio depends on how high a tray efficiency is stipulated

Turndown ratio

The turndown ratio is a measure of the flexibility or the operating range of a given tray. It is defined as the ratio of two vapor rates: VAP_{max}, above which the tray efficiency drops below an acceptable value; and VAP_{min}, below which the tray efficiency is unacceptable:

$$\textit{Turndown ratio} = VAP_{max}/VAP_{min}$$

This ratio is not a rigorous number but instead depends on what the engineer considers to be an acceptable level of tray efficiency for a given situation. Consider Figure 9, which shows tray efficiency as a function of vapor rate

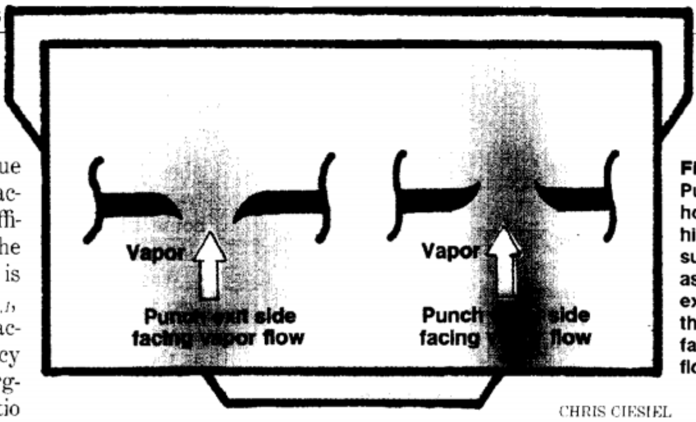

FIGURE 10. Punched holes incur a higher pressure drop if, as at left, the exit side of the punch faces the flow of vapor

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for a constant value of L/V. If the acceptable tray efficiency is E_1, the turndown ratio is $VAP_{max,1}/VAP_{min,1}$, whereas a lower acceptable efficiency of E_2 leads to a larger turndown ratio $VAP_{max,2}/VAP_{min,2}$ because of the shape of the efficiency profile. Note that VAP_{max} is taken as the practical upper operating limit of the tray, which is not necessarily the same as the flood point. The flood point is instead the upper operating limit of the tray from a hydraulic standpoint.

Sieve trays for vacuum service, with a relatively high percentage of hole area for low pressure drop, may have turndown ratios as low as 2 or less. On the other hand, ratios as large as 4 to 5 may be found with sieve trays designed for high-pressure services, having relatively low hole area.

Valve trays with properly designed valve units — ones that effectively prevent weeping when valves close at low vapor rates — extend the lower operating limit and increase the turndown ratio compared with sieve trays. However, on a valve tray that contains too many valves, or valves that are too light, the valves may open prematurely and induce weeping [4]. What's more, certain valve designs actually induce weeping because the legs on the valve units act like wicks. Switching to such designs would not increase the turndown significantly.

Bubble-cap trays may have an infinite turndown ratio: they can be operated down to practically zero vapor rate if the risers, tray panels and outlet weirs have been carefully sealed. Indeed, this is one of the big reasons why bubble-cap designs are still very popular in certain services. However, failure to carefully seal the tray can negate any turndown benefits [5].

Crossflow-tray pressure drop

Pressure drop in the flow of vapor across (i.e., upwards through) an operating tray is caused by energy dissipation in the rising vapor as it passes successively through the tray deck and tray liquid. This is referred to as the wet-tray pressure drop. It is the sum of the dry-tray pressure drop, namely the drop across the tray hardware where there is no liquid present, and the pressure drop the vapor encounters as it flows through the liquid froth on the tray.

Pressure drop with sieve trays: This is mainly a function of the total hole area available for vapor flow. The hole area is often expressed as the percentage of the bubbling area. For a typical sieve tray, this ranges between 5 and 15%.

Generally, hole areas less than 5% lead to excess pressure drop, high entrainment or premature flooding, although they may lower the weep point. Hole areas greater than 15% may offer low pressure drop but lead to excessive weeping or premature dumping.

Two other parameters influence the dry-tray pressure drop. These are the ratio of hole diameter to tray thickness and the fabrication method of the holes.

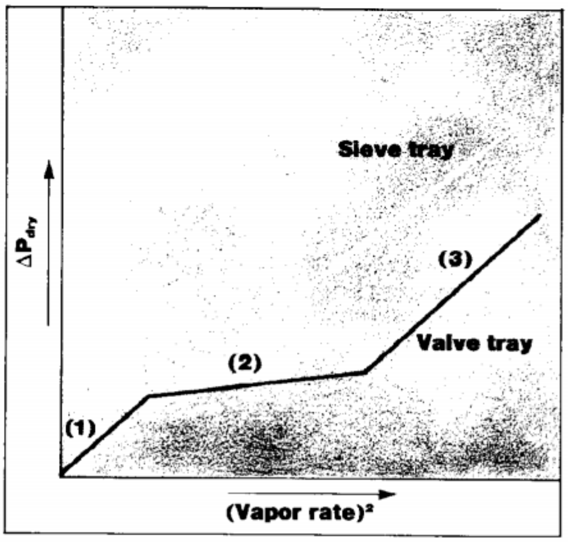
Because of contraction and expansion losses and vena-contracta effects, the dry-tray pressure drop increases with the ratio of the hole diameter to tray thickness, at realistic tray thicknesses and within the common hole-diameter range of 1/8 to 1 in. Furthermore, for a given hole-area tray, the dry-tray pressure drop will be smaller with smaller holes.

Sieve trays are fabricated by either punching out or drilling the holes. If the holes are punched, the punch-entry side is smooth and rounded and the exit side sharp and protruding, as shown in Figure 10, facing vapor flow.

If the sieve tray is installed in the column with the sharp side facing the vapor flow, the dry-tray drop can be considerably higher than if the smooth side faces it. A typical difference between the two is 10 to 15%.

With holes that are instead drilled, it is difficult to determine the entry side and exit side. The dry pressure drop is virtually the same regardless of which way the plates are installed, and is comparable to that of the punched plate with the punch exit side facing vapor flow.

FIGURE 11. Dry-tray pressure drop is a more complex function of vapor rate for valve trays than for sieve trays. See the accompanying text for the significance of the three numbers



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Pressure drop with valve trays: For purposes of analyzing pressure drop, the valve trays can be thought of as sieve trays with movable valves inserted in the holes. The vapor must provide additional force to lift the various valve units in the holes throughout the column.

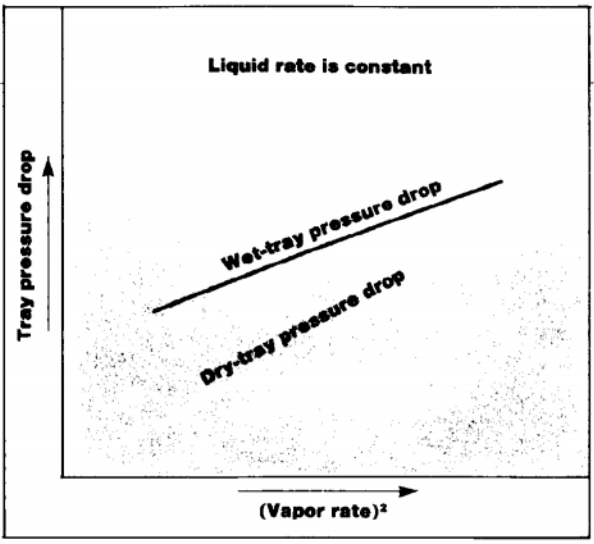


FIGURE 12. As vapor rate increases, wet-and dry-tray pressure drops tend to converge

The dry-tray pressure drop of valve trays can be analyzed in three stages: (1) at low vapor rates where the valves are initially all closed, (2) at moderate vapor rates where the valves are opening up, and (3) at higher vapor rates where the valves are fully open and the valve tray deck behaves as a fixed orifice plate. From that three-stage point of view, Figure 11 compares dry-pressure-drop profiles of a typical sieve tray and a typical valve tray. A detailed analysis is given by Bolles [4].

In some situations, the first stage may not extend over much of a range of vapor rates. This is especially true for high-turndown designs for clean services, in which the valve units tightly seal the tray at the closed position. For any of the vapor to go through the tray the valve units must be lifted, and thus the second stage becomes relevant at very low vapor rates.

More commonly, however, valve units are designed with small dimples on the valve to prevent the valves from sticking shut during service. Also, legs are often an integral part of the valve (as mentioned earlier, under the discussion of turndown ratio). Dimples or legs allow some vapor to flow when the valve is in the closed position [1].

***Pressure drop with bubble-cap trays*:** This is usually higher than that of the sieve trays at a comparable vapor rate. The reason is that the vapor must follow a more tortuous path.

The overall pressure drop is, in fact, the sum of eleven components, as can be seen by referring back to Figure 2. They are: contraction loss as the vapor enters the riser from the open space; pressure drop through riser; loss due to 90-deg change of direction from riser to reversal area; pressure drop through reversal area; loss due to 90-deg turn from the reversal to the annular area; pressure drop through annular area; loss due to 90-deg turn from annular to slot- and-skirt area; pressure drop through slot-and-skirt area; loss due to 90-deg turn from slot-and-skirt area to area between caps; pressure drop through area between caps; and, finally, expansion loss in going from the area between caps to the open space.

The dry pressure drop of a bubble-cap tray can be calculated analytically by summing up all these components. For the more-popular bubble caps, however, pressure-drop coefficients are often made available by the manufacturer. Further details and a method of estimating the pressure-drop coefficient are given by Bolles [6].

***Pressure drop due to liquid*:** In general, this is based upon the sum of the outlet weir height plus the crest over the weir as calculated by the Francis weir formula,* plus half of the hydraulic gradient. In sieve and valve trays, the hydraulic gradient is usually small and is neglected in the calculation, but it should not be neglected on bubble cap trays. Further details are presented by Bolles [6] and Fair [7].

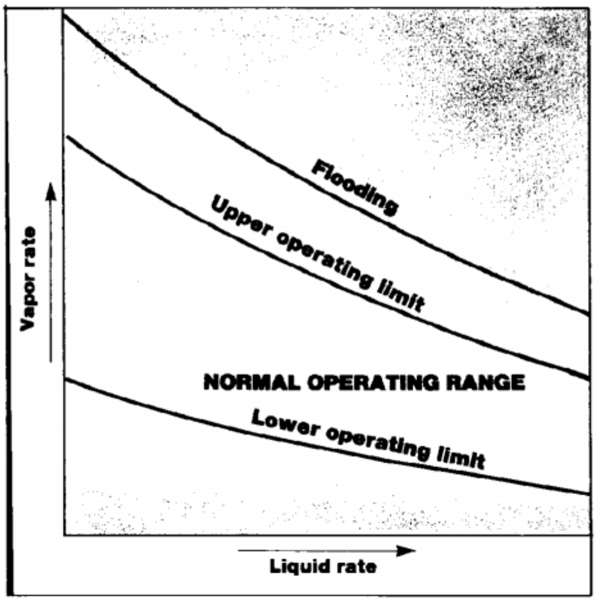
The effect of the aerated liquid decreases as the vapor rate is increased. For a constant liquid rate, the dry- and wet-tray pressure drops converge, as shown in Figure 12.

DUALFLOW TRAYS

In a dualflow tray, the entire tray consists of the bubbling area. There is no downcomer nor downcomer seal area as in the cross-flowing trays, and both the descending liquid and the ascending vapor pass through the holes. The fractional hole area of a dualflow tray is usually higher than that of the crossflow sieve tray at comparable operating conditions.

Dualflow trays offer several attractions. They can be designed for a lower pressure drop than can crossflow trays. Versions having large hole diameter are well suited for use in fouling services. Dualflow trays are relatively inexpensive, in terms of both material

FIGURE 13. Liquid-vapor interaction for dualflow trays is relatively simple to depict



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*This formula is discussed in "Perry's Chemical Engineers' Handbook," 6th Ed., p. 5-19.

cost and installation cost. They can readily be used for debottlenecking columns that suffer capacity limitations.

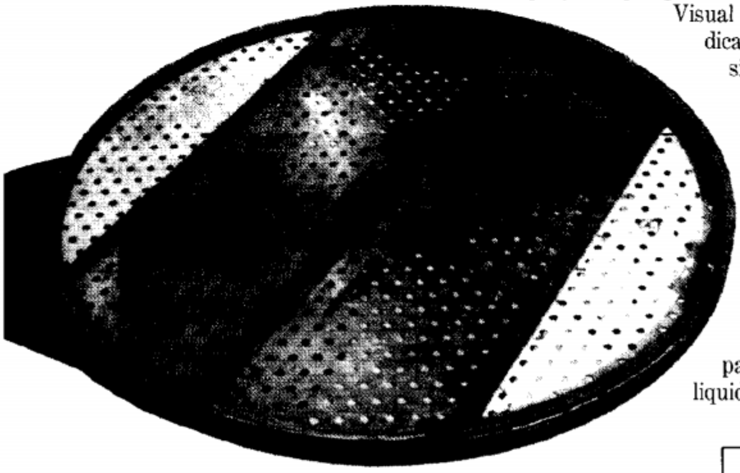
On the other hand, they exhibit lower efficiencies than crossflow trays. And they have a relatively narrow operating range; their turndown ratio tends to be low.

The performance diagram for a typical dualflow tray (see Figure 13) is simpler than that for a crossflow tray. Consider in turn the effect of insufficient or excessive vapor.

From a hydraulic standpoint, the lower operating limit of a dualflow tray may be described as the condition where the rising vapor applies just enough of a resistance to the falling liquid so that the latter will not merely rain through the perforations but be partially held up at each tray level. When the vapor rate drops below this limit, the raining down of liquid through the holes causes insufficient vapor-liquid contacting and therefore poor efficiency. Column behavior in this case resembles the operation of cooling towers having splash-grid packing.

Conversely, as the vapor rate is raised, spray will begin to form. As vapor rate rises further and exceeds the normal operating range, the spray height will reach the tray spacing. The spray will start impinging on the tray above and be aspirated onto it as entrainment, causing the tray efficiency to deteriorate.

If the vapor rate is further increased, the entrainment will exceed the downward flowing liquid, causing liquid to accumulate in the inter-tray space and eventually push the column into hydraulic flood. If the column is provided with viewing ports, such filling of the inter-tray space can be noted visually. Other, indirect symptoms are excessive column pressure drop, excessive entrainment into the column overhead, or deterioration of the tray efficiency to the extent that the desired separation is no longer achieved.



Dualflow tray is characterized by a lack of downcomers; the liquid descends through the holes

Inside the column

In columns equipped with dualflow trays and operating under vacuum, the liquid rate is typically relatively low whereas the vapor velocity is high due to low vapor density. The sprays generated by the vapor erupting through the liquid bed consists of discrete, small-diameter droplets. The liquid descending through the holes forms rivulets that break up into larger drops and are readily distinguishable from the sprays erupting from the tray floor.

Visual observations indicate that any given single hole of a dualflow tray does not pass liquid and vapor simultaneously. Each is either passing vapor upwards, passing liquid downwards, or passing neither liquid nor vapor.

The splashing, wavelike liquid on the tray undulates over the entire bubbling area at a certain frequency, in synchronization with the action of the holes. Wherever the waves form crests, liquid momentarily surges through clusters of holes beneath. This drains the crests and transforms them into troughs.

Vapor then erupts through the same clusters of holes, and the liquid at the bottom of the trough is projected upwards to form a spray in the inter tray space. To complete the "cycle," liquid rushes towards the bottom of the troughs, reforming the crests. The locations where the clusters of holes pass liquid through the tray, erupt vapor through the tray or pause in transit appear to move about the tray randomly.

If the column instead operates under relatively high pressure, the liquid flowrate is likewise relatively high, whereas the vapor rate is low due to high vapor density. The undulating liquid action on the tray is not so pronounced as in the low- to moderate-pressure systems.

Contact between vapor and liquid is much more subdued, and very little spray is generated by vapor rising through the liquid. The density difference between the liquid and the vapor is relatively low, and the liquid passing through the holes actually appears to lazily float down the intertray space in the column.

The capacity of a column equipped with dualflow trays can be increased

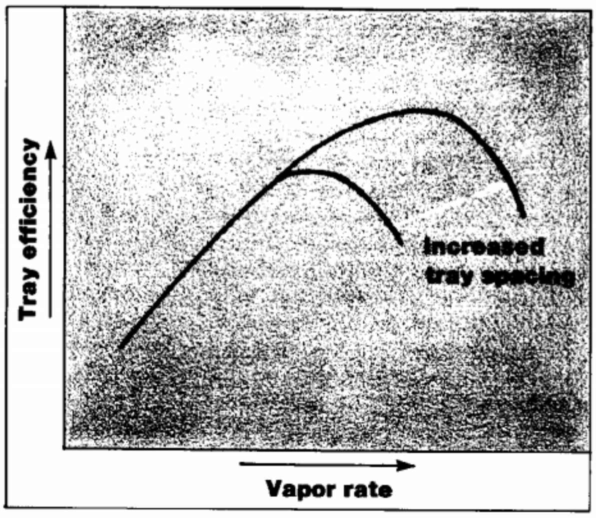


FIGURE 14. An increase in tray spacing may boost not only the capacity but also the peak efficiency

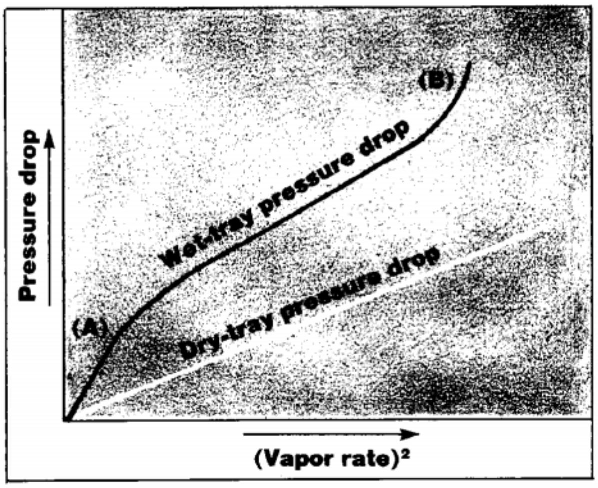


FIGURE 15. For dualflow trays, wet-tray pressure drop as a function of vapor rate exhibits three stages of behavior, as explained in text

by increasing the tray spacing. Frequently, increased tray spacing also results in increased peak efficiency (see Figure 14).

Increasing the hole area of a dualflow tray will increase the capacity of the tray. But this is a clearcut improvement only up to about 25% hole area. Beyond that level, the further increase in capacity would be accompanied by a decrease in separation efficiency, and this tradeoff should be examined carefully before implementation.

Increase in capacity can also be obtained by reducing hole diameter. The hole diameters of dualflow trays range between 1/4 and 1 in. However, small hole diameter may increase the plugging tendency of a tray in fouling service.

As discussed earlier in connection with crossflow trays, there is a limiting or terminal capacity for any dualflow-tray system that cannot be exceeded by improving tray design or increasing tray spacing. This limitation is associated with the vapor and liquid densities and the surface tension of the system.

Dualflow trays must be operated above a certain rate to obtain satisfactory performance. Weeping, of course, cannot be used as an indicator, since passing liquid through the holes (i.e., weeping) is a normal operating characteristic for dualflow trays. Instead, the criterion is the aforementioned ability of the tray to hold up an adequate liquid level.

As the vapor rate is increased at very low vapor rates, liquid holdup increases. At a sufficiently high vapor rate, a pulsating liquid seal is established. Once the seal is established, the tray efficiency will increase with each incremental increase in vapor rate until the maximum efficiency point is reached at approximately 90% of the flooding rate.

Tray efficiency typically acceptable as the lower operating limit is most likely to exist at above the vapor or liquid rate where the pulsating liquid seal is first established. This acceptable lower limit is typically about 40 to 70% of the flooding vapor rate.

Dualflow-tray pressure drop

As already discussed, dualflow trays are characterized by intermittent flow of vapor and liquid through various portions of the tray. Accordingly, pressure drop across an individual tray fluctuates slightly. However, each tray acts relatively independently of other trays in the column, and the fluctuations tend to cancel each other out. As a result, pressure-drop fluctuations across a group of several trays is negligible.

The dry-tray pressure drop for a dualflow tray is mainly a function of the total hole area on the tray, the hole size, the tray thickness, and the direction in which the holes are punched. These relationships are described in the discussion of sieve trays.

The wet-tray pressure drop and the liquid holdup are complex functions of the vapor and liquid flowrates and densities and the dry-tray pressure drop. Pressure drop rises and falls with time due to the fluctuations described earlier. A rigorous expression fully describing this phenomenon must include time and position on the tray as parameters. For simplicity, however, both parameters are usually neglected, and average values of pressure drop and liquid holdup are used.

Figure 15 shows a plot of a typical dualflow tray pressure drop at constant L/V against the square of the vapor rate. Also shown for comparison is the dry-tray pressure drop.

The straight steep line from the origin to Point A represents the pressure drops at vapor rates below which the pulsating seal is established on the tray. The line is steep because the descending liquid occupies the same holes as the vapor, thus lessening the effective hole area on the tray as the vapor and liquid rates are raised.

The pressure drop between Points A and B represents the effect of the increase in liquid holdup as the liquid and vapor rates are increased. The fact that the slope of the line between those points is greater than the dry-tray pressure-drop line also indicates an increase in liquid holdup with increase in liquid and vapor rates. The departure from the straight line of the pressure drop values beyond Point B shows the effect of entrainment and indicates that flooding is approached.

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