15-9. Downcomer Dynamics

The problem of liquid capacity is the same for sieve trays as for bubble-cap trays. The tentative tray design evolved from flooding, weeping, and pressure-drop considerations must be checked for liquid-handling capacity. If this capacity is inadequate, operating difficulties with liquid gradient, downcomer backup, or flooding may be encountered. The reader will recognize that both sieve and bubble-cap trays employ the same downcomer design; hence the only real differences in liquid handling occur in the aerated zone.

As for bubble-cap trays, downcomer design involves the following considerations: (1) weir crest for liquid entering downcomer, (2) residence time of liquid in downcomer, (3) head loss of liquid leaving downcomer and flowing under downcomer apron, (4) total liquid backup as a criterion of approach to flooding. Items 1, 2, and 3 are covered specifically in Chap. 14, pages 486-488 and 496-498. Item 4, liquid backup, requires only minor adaptation to the ease of sieve trays.

Downcomer backup is obtained from a simple pressure balance (see Fig. 15-2) which results in the equation

$$h_{dc} = h_t + h_v + h_{wv} + \Delta + h_{in}$$

(15-24)

where $h_t$ is obtained from Eq. (15-18), $h_v$ is specified, $h_{wv}$ is obtained from Eqs. (14-22) to (14-28), $\Delta$ is obtained from Eq. 15-20, and $h_{in}$ is obtained from Eq. (14-42).

It should be noted that $h_{dc}$ in Eq. (15-24) is given in terms of clear liquid. Actually, the downcomer contains an aerated mass of height greater than $h_{dc}$. If this mass reaches the level of the tray above, flooding is approached. Usual practice is to assume a downcomer froth density (Eq. (14-44)) of 0.5 minimum. Accordingly, design should call for

$$h_t > 2h_{dc}$$

which has been found conservative in all but those cases involving systems of high foamability. Further downcomer dynamic considerations are given in Sec. 14-9.

15-10. Liquid Mixing

As noted earlier, the aerated mass does not always move across the tray in plug flow. The back-mixing which occurs may be considerable, especially at high vapor rates and liquid holdups (high weir and/or low liquid rates). This mixing is of concern in that it influences concentration driving forces for mass transfer. The various models for predicting liquid mixing and its effect on efficiency are discussed in Chap. 16.

TRAY DESIGN

15-11. General Considerations

The foregoing treatment on tray dynamics has, for convenience, included comments and recommendations for the process design of sieve trays. In the present sections supplementary material is given to assist the process designer with “hardware” aspects and to enable him to summarize his calculations in the form of a finished design job.

Several items must be specified by the process designer. These items are summarized in Table 15-1. Furthermore, the specifications must permit “satisfactory operation” in a zone bounded by liquid-vapor flow restrictions, as shown qualitatively in Fig. 15-9. The over-all optimum design of the sieve tray column embraces a great many considerations, and the important ones emerge only after the designer has a specific problem at hand.

As noted earlier, sieve trays and bubble-cap trays have many features in common. The reader should refer to Chap. 14 for details on selection of tray spacing, selection of tray type, and downcomer design. Material given here is selected for special emphasis or unique application regarding sieve trays.
Table 15-1. Process Design Specification Check List for a Sieve Tray Column

<table>
<thead>
<tr>
<th>Column design:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Diameter</td>
</tr>
<tr>
<td>2. Number of trays</td>
</tr>
<tr>
<td>3. Tray spacing</td>
</tr>
<tr>
<td>4. Flow and drawoff locations</td>
</tr>
<tr>
<td>5. Operating temperatures and pressures</td>
</tr>
<tr>
<td>6. Materials of construction</td>
</tr>
</tbody>
</table>

Tray design:
1. Liquid flow arrangement
2. Active area
3. Free (hole) area
4. Hole size, pitch, and pattern
5. Hole blanking
6. Tray baffles and calming zones
7. Downcomer area
8. Downcomer type and clearance
9. Tray inlet arrangement
10. Outlet weir type
11. Outlet weir dimensions
12. Tray thickness
13. Materials of construction
14. Tray and weir levelness

![Diagram](image)

**Fig. 15-9. Effect of liquid and vapor load on sieve tray performance.**

15-12. Area Terms

A number of different area designations are used in the design of sieve trays. Although these areas are defined where needed in the text and nomenclature, it is convenient to summarize them at this point.

- **Tower area** $A_t$ is the total, or superficial, internal cross-sectional area of the tower.
- **Downcomer area** $A_d$ is the cross-sectional area at the top of the downcomer(s). For a segmental downcomer, it is the area of the segment formed by the overflow weir and the tower wall.
- **Net area** $A_n$ is the area for vapor flow above the tray. In the common single crossflow tray, $A_n = A_t - A_d$. If a splash baffle is located above the overflow weir (Fig. 15-2), $A_n = A_t - 2A_d$.
- **Active area** $A_a$ is the general area where aeration occurs. It is not limited entirely to the perforated zone, since turbulence effects carry aeration several inches past the perforations. For most design cases, $A_a$ is taken as the total area between inlet and outlet weirs, and when straight segmental downcomers are used with single crossflow, $A_a = A_t - 2A_d$.

- **Hole area** $A_h$ is the total area open to vapor flow. In a tray layout, $A_h$ is equal to the total opening in the perforated sheet metal used, minus blockage due to tray support members and special blanking strips.
- **Open area** is a ratio used only in identifying perforated sheet metal material. For a given section of material, open area refers to the ratio of hole area to total area and can be calculated from the following equations:

  - Equilateral triangular pitch:
    \[
    \text{Open area} = 0.905 \left( \frac{\text{hole diameter}}{\text{pitch}} \right)^2
    \]
  - Square pitch:
    \[
    \text{Open area} = 0.785 \left( \frac{\text{hole diameter}}{\text{pitch}} \right)^2
    \]


Perforated trays may be fabricated from a wide range of materials, depending upon both the nature of the process fluids and the availability of fabrication techniques. Most metals and commercial alloys can be perforated conveniently in the multiple punch presses employed by tray fabricators. In noncorrosive service, the use of stainless-steel perforated sheeting is recommended as a safeguard against hole enlargement by erosion and against rusting before initial startup or during shutdowns. Type 410 stainless steel is widely used and does not increase tray cost significantly because of the small metal thickness needed. Downcomers,
weirs, support beams, etc., may be specified of carbon steel if suitable for the materials handled.

Gasketing material, where employed, will also depend upon process conditions, with woven asbestos being generally satisfactory. Recent trends are toward elimination of gasketing in sectional trays except in cases where liquid flows are small. Where gasketing is not used, adequate bolting should be provided to achieve reasonably tight metal-to-metal contact.

**15-14. Tray Layout**

Hole diameters of \( \frac{1}{8} \) to \( \frac{1}{2} \) in. are commonly employed in sieve tray service, with larger hole sizes offering possible advantages in severe fouling applications. Small holes (\( \frac{1}{8} \) to \( \frac{1}{4} \) in. diameter) with the direction of punching oriented in the direction of vapor flow are often preferred. In usual practice, tray thickness of 12 or 14 U.S. Standard gauge is employed, except for carbon steel, where 10-gauge thickness has been used.

In the selection of small hole sizes, consideration should be given to minimum hole size limitations of punch dies, which depend on the thickness and type of material perforated. For small hole sizes and in the usual range of open area applying to sieve trays, a safe general rule is that the hole size should not be less than the sheet thickness in the case of carbon steel or not less than 1.25 times the sheet thickness when of stainless steel. Nickel, monel, and admiralty metal have hole-diameter limitations more nearly approaching those of carbon steel, while the requirements for Inconel are similar to those applying to stainless steel. With dies of advanced design, the limitations applying to hard materials are somewhat less stringent. For example, \( \frac{1}{16} \)-in. perforations can be provided in 14 U.S. Standard gauge (0.078 in.) stainless steel, and \( \frac{3}{16} \)-in. holes in 10 U.S. Standard gauge (0.141 in.) stainless steel. Thus, in cases where it is desirable to exceed the limitations expressed by the general rule given above, the matter should be referred to the tray fabricator.

Stock perforated metal is listed in terms of open area. Equations given above can be used to estimate this area and for determining hole pitch and blanking required for specified hole areas. A preliminary hole pitch is calculated by considering as perforated area the difference between the active area and the area covered by tray supports, tray rings, etc. If the calculated pitch does not correspond to a commercial standard, the next smaller pitch is selected and the (net) perforated area is calculated to determine the amount of blanking required. Some tray fabricators prefer that the designer specify hole diameter and total hole area, with a tolerance of 1 per cent, preferably 5 per cent. This provides leeway for using die arrangements not corresponding to stock perforated metal.

In the event that the hole area requirements vary considerably within the tower, it may be desirable to employ more than one pitch and/or hole diameter in order to avoid excessive tray blanking. The blanking should not exceed about 25 per cent of the tray area, except when it is intentionally provided for temporary operation at reduced rates.

Blanking strips should be distributed uniformly over the active area, except when used for calming zones at the weirs. In order to avoid "dead spots" in the active area, it is suggested that the width of the blanking strips not exceed about 7 per cent of the tray diameter for small towers or about 5 per cent of the diameter for large towers.

Blanking strips should be fastened so that a fairly tight seal is provided, removal is easy, and the perforated sheet not be distorted or buckled. Fastening with machine screws or similar attachments is perhaps the simplest.

Perforated sheet metal, available from several manufacturers, comes in standard widths of 36 and 48 in. and in standard lengths of 96, 120, and 144 in. For special requirements, other widths and lengths can be provided. Tray support members can be spaced at 12, 16, 18, or 24 in. for minimum waste of metal. In some designs these members are formed from blank margins of perforated sheets and thus eliminate the need for separate supports. It should be kept in mind that the spacing and type of tray support members employed with sectional trays will be influenced by accessibility through manways.

**15-15. Summary of Effects of Tray Design Variables**

The process designer has several tray design variables that he must specify (Table 15-1). Not all these variables are independent, but each will be discussed separately for its general effect on performance.

**Liquid-flow Arrangement.** A long liquid-flow path contributes to high tray efficiency. However, the long path also contributes to hydraulic gradient and possible tray instability. Shortening the path by splitting the liquid into two parts (double-crossover tray) adds to the cost of tray construction.

**Active Area.** A large active area contributes to low vapor velocity and mass-transfer coefficients. Excessive vapor rates through a small active cross section cause entrainment, flooding, and low interfacial areas.

**Hole Area.** A high hole area contributes to weeping. A low hole area contributes to stable tray operation but increases pressure drop, and, below a given value, increases entrainment.

**Hole Size, Pitch, and Pattern.** Small hole size contributes to good gas dispersion, low pressure drop, low weeping, and low entrainment. Large holes are less easily fouled.
Hole pitch and pattern are associated with active area and hole areas as discussed above.

**Hole Blanking.** Blanking a portion of the perforations (i.e., covering with sheet metal) enables reduction of open area of perforated sheets to the desired value and provides flexibility for future increases in vapor throughput. However, if the blanked areas are localized and constitute a significant portion of the perforated area, excessive entrainment can result. Blanked area should normally not exceed about 25 per cent of the active area.

**Tray Baffles and Calming Zones.** Baffles for directing liquid movement on the tray are not required unless a reverse-flow tray is used. Calming zones at liquid entry and exit are not usually required.

**Downcomer Area.** A high downcomer area contributes to low liquid velocities and good froth collapse. A low downcomer area permits greater utilization of the tower area for vapor throughput.

**Downcomer Type and Clearance.** Sloped segmental downcomers are more expensive than straight segmental downcomers and consume tray area that might be used for perforations if the downcomer base has ample flow area. However, for foaming systems the increased inlet area of the sloped downcomer is helpful for vapor disengagement from liquid.

In small towers circular downcomers are cheaper than segmental downcomers but may represent wasted tray area for contacting.

A high clearance under the downflow baffle can allow vapor passage up the downcomer unless a seal is provided. A low clearance contributes toward undesirable backup of liquid in the downcomer.

**Tray Inlet Weir.** A tray inlet weir provides a positive seal against vapor flow up the downcomer and allows some distribution of liquid flowing to the tray. The disadvantages of the inlet weir are the additional expense, the possibility of plugging due to deposits of solids from the liquid, and the possibility of weeping due to impact of liquid on the tray.

**Tray OutletSplash Baffle.** A splash baffle blocks froth movement into the downcomer and increases liquid holdup on the tray. On the other hand, it increases pressure drop and entrainment and thus limits vapor-handling capacity.

**Outlet Weir Type.** A straight weir is cheap and readily adapted to a segmental downcomer. At very low weir crests, however, the notched weir is more likely to maintain uniform liquid overflow.

**Outlet Weir Height and Length.** Pressure drop, liquid holdup, and weeping tendency increase with weir height, but much less than in direct proportion. Higher weirs contribute to back-mixing of liquid and may be desirable for special holdup requirements (e.g., chemical reaction on tray).

---

**15-16. Operating Flexibility**

In general, sieve trays can be designed for a wide range of operating rates. Hole area can be chosen such that weeping occurs only at very low vapor rates. Entrainment characteristics are such that operation can be maintained very close to the flood point. Thus, operating ranges from 30 to 40 to 90 to 95 percent of flooding are often possible without sacrifice in tray efficiency.

For vacuum columns where pressure drop is critical, narrower operating ranges must be expected. Low hole area to prevent weeping creates excessive dry-tray pressure drop, and the required compromise may increase minimum operating rate to 50 percent of flooding or higher.

There frequently is some misinterpretation regarding the need for operating flexibility in tray columns. For distillation operations, loading can be maintained at low feed rates by effectively varying reflux and boilup ratios. For absorption operations the changed liquid/vapor ratio may be a help because of its effect on the absorption factor, although there is at the same time an effect on flood point. The reasoning for absorbers also applies to strippers where steam or other extraneous gas is used; for reboiled strippers, however, sensitivity to load changes may be quite great.

---

**15-17. Design Procedure and Example Calculation**

The example used for bubble-cap tray design will now be recalculated on the basis of using sieve trays. The reader may recall that the benzene-toluene system is involved, and he should refer to Chap. 14, page 527, for problem details. The numbered steps below constitute a procedure which is general for all new sieve tray designs. If the problem involves rerating an existing tower, adjustments in the procedure should be obvious.

1. Calculate flow parameter. From Eq. (15-1)

   \[
   F_{n} = \frac{200,000 (0.168)}{240,000 (43.3)} = 0.052
   \]

2. Choose tray and spacing. For initial design choose 3/16-in. holes, hole area/tower area = 0.10, 14 U.S. Standard gauge tray material (0.078 in.), 2-in. weir height, and 24-in. tray spacing. Although tower diameter will probably be large, attempt to use a single crossflow tray for minimum cost. Also use segmental downcomers, straight weirs, and weir length equaling 77 percent of tower diameter. For this case the downflow segment is 12 percent of tower area.

   This column will operate under nonfouling and noncorrosive conditions; thus, it may be desirable in later calculations to reduce the hole size to
1/4 in. In addition, the system handled is nonfoaming and no difficulties with excessive entrainment are anticipated.

3. Calculate tower diameter. From Fig. 15-3, \( C_n \) for flooding = 0.36. Since surface tension \( \sim 20 \) dynes/cm, no correction is needed. System also meets other requirements of Fig. 15-3.

Use 85 per cent of flooding for design. Then, by Eqs. (15-3) and (15-4),

\[
U_a = \left( \frac{(0.39)(0.85)}{0.168/(43.5 - 0.17)} \right)^{0.4} = 4.90 \text{ fps}
\]

For \( Q = 397 \) efs and \( A_d = 0.12A_t \),

\[
A_t = \left( \frac{397}{0.88(4.90)} \right) = 92.1 \text{ ft}^2
\]

for which a tower diameter of 10.8 ft. is calculated. The usual practice is to round off to the next 1/2-ft size. Hence, tower diameter = 11.0 ft.

4. Tabulate areas:

\[
\begin{align*}
A_t &= 121(0.785) = 95.0 \text{ ft}^2 \\
A_d &= 0.12(95.0) = 11.4 \text{ ft}^2 \\
A_w &= 0.88(95.0) = 83.6 \text{ ft}^2 \\
A_s &= 0.76(95.0) = 72.2 \text{ ft}^2 \\
A_h &= 0.10(95.0) = 9.5 \text{ ft}^2
\end{align*}
\]

5. Adjust flow conditions:

\[
U_a = \frac{397}{83.6} = 4.75 \text{ ft/sec}
\]

Approach to flood: 4.75/4.90(85) = 82%

6. Calculate entrainment. From Fig. 15-4, for \( F_t = 0.052 \) and 82 per cent of flooding, \( \phi = 0.064 \). Total entrainment by Eq. (15-5) is

\[
c = 1 - 0.064 = 0.936
\]

Total moles/hr = 936 moles/hr (13,700 lb/hr)

7. Calculate pressure drop. For a hole/active-area ratio of

\[
\frac{9.5}{72.2} = 0.132
\]

and for a tray-thickness/hole-diameter ratio of 0.078/0.188 = 0.41, an orifice coefficient of 0.75 is read from Fig. 15-6. A hole velocity of 397/9.5 = 41.8 fps is then calculated. Finally, the dry-tray drop is obtained from Eq. (15-10):

\[
h_t = 0.186 \frac{0.168}{43.3} (41.8)^2 = 2.24 \text{ in. liquid}
\]

8. Calculate weep point. Pressure drop for bubble formation is obtained from Eq. (15-8):

\[
h_r = \frac{0.040(21)}{43.3(0.188)} = 0.10 \text{ in. liquid}
\]

Comparing \( h_t + h_r \) = 2.24 + 0.10 = 2.34 with

\[
0.77(132) = 102 \text{ in.}
\]

weir crest is calculated from the Francis equation for straight weirs [Eq. (14-22)]:

\[
h_{we} = 0.48 \left( \frac{\bar{V}}{n} \right)^{0.25} = 0.48 \left( \frac{577}{0.77(132)} \right)^{0.25} = 1.53 \text{ in. liquid}
\]

[The correction factor for tower wall constriction (Fig. 14-7) is not significant.]

The \( F \)-factor through the active area is

\[
F_{wa} = \frac{397}{72.2} (0.168)^{0.4} = 2.25
\]

From Fig. 15-7, the aeration factor \( \beta = 0.58 \). Hence, wet-tray drop is

\[
h_t = 0.58(2.0 + 1.53) = 2.05 \text{ in. liquid}
\]

and total tray pressure drop [Eq. (15-18)] is

\[
h_t = 2.24 + 2.05 = 4.29 \text{ in. liquid}
\]

9. Check liquid-handling capacity. Downcomer velocity, calculated on the basis of clear liquid and \( A_d = 11.4 \text{ ft}^2 \), is

\[
\frac{577}{(450)(11.4)} = 0.11 \text{ fps}
\]

which for a downcomer half full gives an indicated residence time of 1.0/0.11 = 9 sec. Although this is well above the minimum value of 3 sec (Chap. 14), the downcomer level must be checked.
Liquid gradient calculations require an approximate value of the froth height. This can be obtained from Eqs. (15-15) and (15-16):

\[ h_f = \frac{h_i}{2 \delta - 1} = \frac{2.05}{2(0.58) - 1} = 12.8 \text{ in.} \]

Equations (15-20) through (15-23) are then used to compute \( \Delta h_c \):

\[ U_f = \frac{(12)(1.28)(12)}{2.05(117)} = 0.77 \text{ fps} \]

where the width \( D_f \) is the arithmetic average of weir length (102 in.) and tower diameter (132 in.).

\[ R_w = \frac{(12.8)(117)}{2(12.8 + 117)12} = 0.87 \text{ ft} \]

\[ R_{to} = \frac{(0.87)(0.77)(43.3)}{(0.32)(6.72)(10^{-4})} = 1.35 \times 10^4 \]

A liquid viscosity of 0.32 centipoise is used in Eq. (15-23).

From Fig. 15-8, \( f \sim 0.02 \).

Since the weir-to-wall distance of a 12 per cent downflow segment is 18 per cent of the tower diameter, the net distance between weirs is 0.64(11.0) = 7.0 ft. Assuming this value of \( L_d = 7.0 \), \( \Delta \) is calculated from Eq. 15-20:

\[ \Delta = \frac{0.02(0.77)(7.0)(12)}{(32.2)(0.87)} = 0.036 \text{ in.} \]

This low value of \( \Delta \) shows that liquid gradient will not be a problem.

For downcomer backup estimation, the pressure drop for flow under the downcomer apron is required. Using 1.5-in. clearance, the area under the downflow apron is

\[ A_{dc} = \frac{1.5 \times 102}{144} = 1.06 \text{ ft}^2 \]

The downcomer apron pressure drop is [Eq. (14-42)]

\[ h_{dc} = 0.03 \left( \frac{Q}{100A_{dc}} \right)^2 = 0.03 \left( \frac{4577}{106} \right)^2 = 0.89 \text{ in.} \]

Finally, downcomer backup is calculated [Eq. (15-24)]:

\[ h_{dc} = h_i + h_w + h_{sw} + \Delta + h_{dc} \]

\[ = 4.3 + 2.0 + 1.5 + 0.04 + 0.9 \]

\[ = 8.7 \text{ in.} \]

This value of \( h_{dc} \) is safely below the recommended maximum of 12 in.

\( \text{Note half tray spacing). It may be concluded that the tray design contains ample liquid-handling capacity.} \]

10. Summarize process design of tray:

a. Single-pass tray with chord-type overflow weir. Tray material is type 410 stainless steel. Tray supports, downcomer baffle, and other auxiliaries are to be of carbon steel. No inlet weir is required. Downcomers are to be segmental, nonsloped, nonrecessed. No blanking is required.

b. Pertinent dimensions are:

<table>
<thead>
<tr>
<th>Tower diameter, ft</th>
<th>11.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tray spacing, in.</td>
<td>24</td>
</tr>
<tr>
<td>Active area, ft²</td>
<td>72.2</td>
</tr>
<tr>
<td>Hole area, ft²</td>
<td>9.5</td>
</tr>
<tr>
<td>Downflow area, ft²</td>
<td>11.4</td>
</tr>
<tr>
<td>Hole area/tower area</td>
<td>0.10</td>
</tr>
<tr>
<td>Hole area/active area</td>
<td>0.13</td>
</tr>
<tr>
<td>Hole size, in.</td>
<td>3/4</td>
</tr>
<tr>
<td>Weir length, in.</td>
<td>102</td>
</tr>
<tr>
<td>Weir height, in.</td>
<td>2</td>
</tr>
<tr>
<td>Downcomer clearance, in.</td>
<td>1.5</td>
</tr>
<tr>
<td>Tray thickness, U.S. Standard gauge</td>
<td>14</td>
</tr>
</tbody>
</table>

\[ \text{c. The hole pattern will probably be } 15 \frac{3}{4} \text{ in. triangular pitch, although this may require adjustment to match the mechanical design of the tray. The tray levelness tolerance should be set at } \pm \frac{1}{6} \text{ in.} \]

15-18. Crossflow Trays

The important proprietary perforated trays embodying froth crossflow are generally known as valve trays. The trays are similar to sieve trays with one important exception: The perforations are covered with liftable lids or "valves" which rise and fall with variations in vapor flow. The lids thus act as check valves to limit liquid weeping or dumping at low vapor rates. Accordingly, the chief advantage of valve trays is that high efficiency can be maintained over a wide range of operating throughputs. Design turndown ratios (page 547) can be as high as 10.

There are three major suppliers (proprietors) of valve trays (8, 12, 15), each having a variety of designs available. The perforations in the tray are large—typically 1.5 in. in diameter for circular perforations (8, 12) and 6 in. long for rectangular-slit perforations (15). The lids are larger than the perforations and either may move within spiders clamped to the tray deck or may be guided and stopped by integral legs which fit into the perforations. The lids are permitted a vertical movement of \( \frac{1}{2} \) to
1/2 in. and may have varying weights depending on system properties and desired operating flexibility.

Tray dynamics and design follow the same principles applying to sieve trays; however, test data covering performance are not generally available. Accordingly, detailed design and fabrication of valve trays are combined, and the tray cost includes a certain amount of engineering labor. It is usually necessary for the process designer to submit duty specifications to the proprietor; suggestions on this procedure have been presented by Thrift (19) and Winn (20).

In summary, valve trays provide more operating flexibility than sieve trays because of their variable-orifice characteristics. Since they are more complex mechanically, their fabrication is somewhat more expensive than sieve trays. Savings in engineering labor may be possible with valve trays, since the proprietor contributes to this function. On the other hand, he retains knowledge of design methods, and this may handicap the user in correlating plant performance data. Other features, such as entrainment, flooding, resistance to fouling, etc., are not likely to be greatly different between valve trays and sieve trays.

15-19. Counterflow Trays

In counterflow perforated trays, liquid and vapor compete for the same openings. The tray occupies the full tower cross section and has no weirs, baffles, or other attachments. Because of their simplicity, the trays are cheapest of the various perforated devices on a unit cross-section basis.

There are two major suppliers (proprietors) of counterflow trays, one (16) offering a flat tray perforated with rectangular slots and the other (18) offering a corrugated tray with small (1/4 to 1/4 in.) round perforations. There are obvious variations of these basic types, such as flat trays with large (1/2 to 1 in.) circular perforations and trays in which the openings represent spacings between parallel metal bars. In general the total hole area is 15 to 30 per cent of the total tower cross section.

The hydraulic characteristics of counterflow trays are somewhat similar to those of conventional packed columns. Liquid holdup and interfacial area are strong functions of vapor rate; hence, the operating range for high efficiency tends to be narrow. In operation, liquid dumps momentarily through one or more sections of the tray and the locations of liquid passage move about the tray in a random fashion. The corrugated trays have better control of liquid holdup and discharge and hence have a broader operating range. A unique advantage of counterflow trays is their self-cleaning ability, which has proved advantageous in fouling services.

As for crossflow trays, proprietors usually must be consulted for tray design. Use of the trays involves a fee which offsets the lower fabrication cost. At the same time, a certain amount of engineering is provided by the proprietor.

In summary, counterflow trays have a narrow operating range (turn-down ratio of 2 or less) and are sensitive to load changes. They occupy the full tower cross section and thus provide slight vapor-capacity advantages. In fouling services they operate more cleanly than the crossflow devices. Design methods are retained by the proprietor, and this may be a handicap to the user in analyzing plant performance of the trays. Cost, efficiency (at load), pressure drop, and entrainment are not greatly different from crossflow perforated trays.

NOMENCLATURE

\[ A_1 = \text{active, or "bubbling," area of tray (generally } A_1 = 2.4 A_2, \text{ ft}^2. \]
\[ A_2 = \text{downcomer area, cross-sectional area for total liquid downflow, ft}^2. \]
\[ A_{1a} = \text{minimum area under downflow apron, ft}^2. \]
\[ A_d = \text{net perforated area of tray, ft}^2. \]
\[ A_s = \text{net cross-sectional area for vapor flow above the tray (generally } A_1 - A_d, \text{ ft}^2. \]
\[ A_{1a} = \text{total tower cross-sectional area, ft}^2. \]
\[ C_w = \text{vapor capacity parameter, as defined in Eq. (15-2), fps.} \]
\[ C_v = \text{vapor discharge coefficient for dry tray.} \]
\[ D_p = \text{diameter of perforation, in.} \]
\[ D_{fl} = \text{total flow width across tray normal to flow, ft.} \]
\[ D_t = \text{tower diameter (ID), ft.} \]
\[ e = \text{liquid entrainment, lb moles/hr.} \]
\[ e = \text{entrainment ratio, lb liquid/lb dry vapor.} \]
\[ E_w = \text{local wet (with entrainment) efficiency, fractional.} \]
\[ E_{av} = \text{local dry (Murphree) vapor plate efficiency, fractional.} \]
\[ F_k = \text{f} = \text{friction factor for froth crossflow, Eq. (15-20).} \]
\[ F_{v} = \text{liquid-vapor flow parameter, defined by Eq. (15-1), dimensionless.} \]
\[ F_{av} = \text{vapor flow parameter based on active area, defined by Eq. (15-17).} \]
\[ F_w = \text{weir constriction correction factor, fractional.} \]
\[ g = \text{acceleration of gravity, 32.2 ft/sec}^2. \]
\[ h_{lo} = \text{head loss due to liquid flow under downflow apron, in. liquid.} \]
\[ h_{c} = \text{height of clear liquid in downcomer, in.} \]
\[ h_f = \text{height of froth (aerated mass) on tray, in.} \]
\[ h_{f} = \text{height of froth (aerated mass) in downcomer, in.} \]
\[ h_{lo} = \text{head loss due to vapor flow through perforations, in. liquid.} \]
\[ h_e = \text{equivalent height of clear liquid on tray, in.} \]
\[ h_{cl} = \text{height of clear liquid at inlet side of tray, in.} \]
\[ h_{oc} = \text{height of clear liquid at overflow weir, in.} \]
\[ h_{oc} = \text{height of liquid crest over weir, measured from top of weir (straight or circular} \]
\[ h_{w} = \text{weir} \]
\[ h_w = \text{weir length, in.} \]
TRAY HYDRAULICS

\[ L \] = liquid flow rate, lb mole/hr.
\[ L_f \] = length of flow path, ft.
\[ L_n \] = weir length, ft.
\[ M_L \] = molecular weight of liquid.
\[ M_v \] = molecular weight of vapor.
\[ q \] = liquid flow rate, cfs.
\[ q_f \] = liquid flow rate, gpm.
\[ Q \] = vapor flow rate, cfs.
\[ R_h \] = hydraulic radius for froth crossflow, ft.
\[ u_L \] = liquid velocity based on active area \( A_n \), fps.
\[ U_L \] = vapor velocity based on active area \( A_n \), fps.
\[ U_f \] = velocity of froth crossflow, fps.
\[ U_v \] = vapor velocity through perforations, fps.
\[ U_s \] = vapor velocity based on net area \( A_n \), fps.
\[ U_t \] = superficial vapor velocity based on total area \( A_n \), fps.
\[ V \] = vapor flow rate, lb mole/hr.
\[ w \] = liquid flow rate, lb/hr.
\[ W \] = vapor flow rate, lb/hr.
\[ X \] = parameter for two-phase flow, dimensionless.

Greek Symbols
\[ \alpha \] = aeration factor, dimensionless.
\[ \Delta \] = liquid gradient for tray or tray section, in.
\[ \mu \] = viscosity of liquid, lb/ft·sec.
\[ \rho_L \] = average froth density, lb/ft³.
\[ \rho_s \] = density of clear liquid, lb/ft³.
\[ \rho_v \] = vapor density, lb/ft³.
\[ \sigma \] = liquid surface tension, dynes/cm.
\[ \sigma_w \] = surface tension of water, dynes/cm.
\[ \rho_f \] = relative froth density, ratio of froth density to clear liquid density.
\[ \phi \] = liquid entrainment ratio, lb/lb (or mole/mole) gross liquid downflow.

REFERENCES