Methods for predicting the entrainment from sieve plates are given in Section 11.13.5, Figure 11.27; a similar method for bubble-cap plates is given by Bolles (1963).

## 11.11. APPROXIMATE COLUMN SIZING

An approximate estimate of the overall column size can be made once the number of real stages required for the separation is known. This is often needed to make a rough estimate of the capital cost for project evaluation.

### *Plate spacing*

The overall height of the column will depend on the plate spacing. Plate spacings from 0.15 m (6 in.) to 1 m (36 in.) are normally used. The spacing chosen will depend on the column diameter and operating conditions. Close spacing is used with small-diameter columns, and where head room is restricted; as it will be when a column is installed in a building. For columns above 1 m diameter, plate spacings of 0.3 to 0.6 m will normally be used, and 0.5 m (18 in.) can be taken as an initial estimate. This would be revised, as necessary, when the detailed plate design is made.

A larger spacing will be needed between certain plates to accommodate feed and side-streams arrangements, and for manways.

### *Column diameter*

The principal factor that determines the column diameter is the vapour flow-rate. The vapour velocity must be below that which would cause excessive liquid entrainment or a high-pressure drop. The equation given below, which is based on the well-known Souders and Brown equation, Lowenstein (1961), can be used to estimate the maximum allowable superficial vapour velocity, and hence the column area and diameter,

$$\hat{u}_v = (-0.171 l_t^2 + 0.27 l_t - 0.047)\left[\frac{(\rho_L - \rho_v)}{\rho_v}\right]^{1/2} \tag{11.79}$$

where $\hat{u}_v$ = maximum allowable vapour velocity, based on the gross (total) column cross-sectional area, m/s,

$l_t$ = plate spacing, m, (range 0.5–1.5).

The column diameter, $D_c$, can then be calculated:

$$D_c = \sqrt{\frac{4\hat{V}_w}{\pi \rho_v \hat{u}_v}} \tag{11.80}$$

where $\hat{V}_w$ is the maximum vapour rate, kg/s.

This approximate estimate of the diameter would be revised when the detailed plate design is undertaken.

## 11.12. PLATE CONTACTORS

Cross-flow plates are the most common type of plate contactor used in distillation and absorption columns. In a cross-flow plate the liquid flows across the plate and the vapour

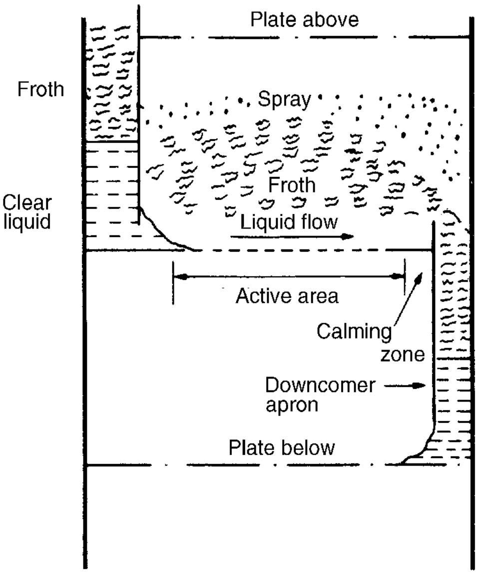


Figure 11.17. Typical cross-flow plate (sieve)

up through the plate. A typical layout is shown in Figure 11.17. The flowing liquid is transferred from plate to plate through vertical channels called “downcomers”. A pool of liquid is retained on the plate by an outlet weir.

Other types of plate are used which have no downcomers (non-cross-flow plates), the liquid showering down the column through large openings in the plates (sometimes called shower plates). These, and, other proprietary non-cross-flow plates, are used for special purposes, particularly when a low-pressure drop is required.

Three principal types of cross-flow tray are used, classified according to the method used to contact the vapour and liquid.

### 1. Sieve plate (perforated plate) (Figure 11.18)

This is the simplest type of cross-flow plate. The vapour passes up through perforations in the plate; and the liquid is retained on the plate by the vapour flow. There is no positive vapour liquid seal, and at low flow-rates liquid will “weep” through the holes, reducing the plate efficiency. The perforations are usually small holes, but larger holes and slots are used.

### 2. Bubble-cap plates (Figure 11.19)

In which the vapour passes up through short pipes, called risers, covered by a cap with a serrated edge, or slots. The bubble-cap plate is the traditional, oldest, type of cross-flow plate, and many different designs have been developed. Standard cap designs would now be specified for most applications.

The most significant feature of the bubble-cap plate is that the use of risers ensures that a level of liquid is maintained on the tray at all vapour flow-rates.

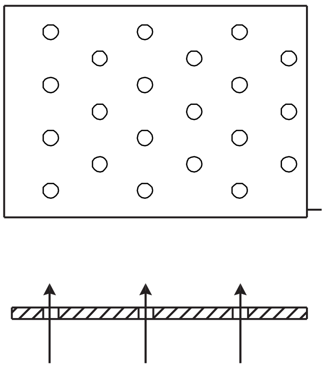


Figure 11.18. Sieve plate

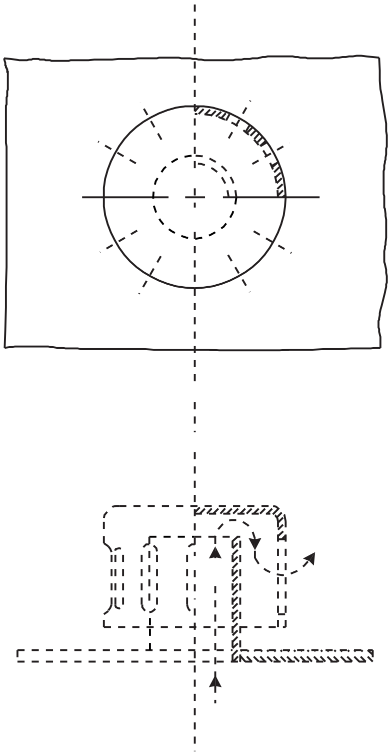


Figure 11.19. Bubble-cap

## *3. Valve plates (floating cap plates) (Figure 11.20)*

Valve plates are proprietary designs. They are essentially sieve plates with large-diameter holes covered by movable flaps, which lift as the vapour flow increases.

As the area for vapour flow varies with the flow-rate, valve plates can operate efficiently at lower flow-rates than sieve plates: the valves closing at low vapour rates.

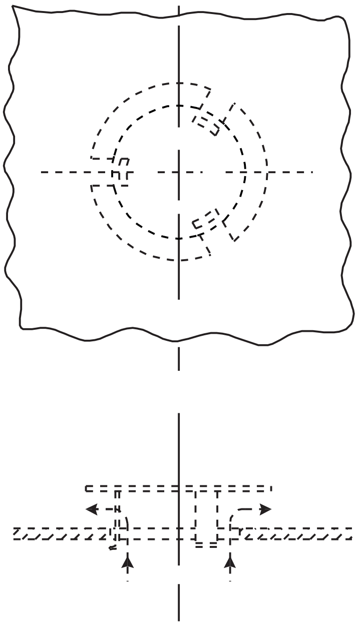


Figure 11.20. Simple valve

Some very elaborate valve designs have been developed, but the simple type shown in Figure 11.20 is satisfactory for most applications.

### *Liquid flow pattern*

Cross-flow trays are also classified according to the number of liquid passes on the plate. The design shown in Figure 11.21*a* is a single-pass plate. For low liquid flow rates reverse flow plates are used; Figure 11.21*b*. In this type the plate is divided by a low central partition, and inlet and outlet downcomers are on the same side of the plate. Multiple-pass plates, in which the liquid stream is sub-divided by using several downcomers, are used for high liquid flow-rates and large diameter columns. A double-pass plate is shown in Figure 11.21*c*.

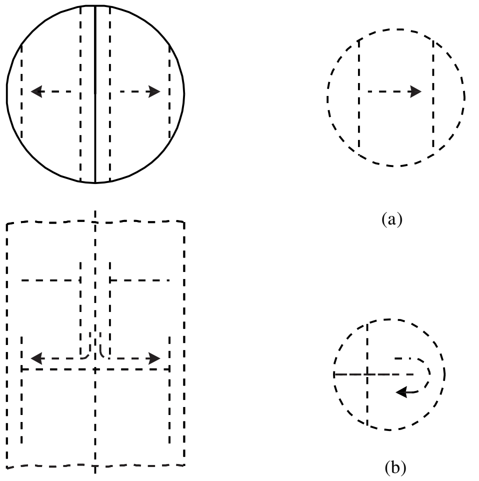
## 11.12.1. Selection of plate type

The principal factors to consider when comparing the performance of bubble-cap, sieve and valve plates are: cost, capacity, operating range, efficiency and pressure drop.

*Cost*. Bubble-cap plates are appreciably more expensive than sieve or valve plates. The relative cost will depend on the material of construction used; for mild steel the ratios, bubble-cap : valve : sieve, are approximately 3.0 : 1.5 : 1.0.

*Capacity*. There is little difference in the capacity rating of the three types (the diameter of the column required for a given flow-rate); the ranking is sieve, valve, bubble-cap.

*Operating range*. This is the most significant factor. By operating range is meant the range of vapour and liquid rates over which the plate will operate satisfactorily (the



(a)

(b)

(c)

Figure 11.21. Liquid flow patterns on cross-flow trays. (*a*) Single pass (*b*) Reverse flow (*c*) Double pass

stable operating range). Some flexibility will always be required in an operating plant to allow for changes in production rate, and to cover start-up and shut-down conditions. The ratio of the highest to the lowest flow rates is often referred to as the "turn-down" ratio. Bubble-cap plates have a positive liquid seal and can therefore operate efficiently at very low vapour rates.

Sieve plates rely on the flow of vapour through the holes to hold the liquid on the plate, and cannot operate at very low vapour rates. But, with good design, sieve plates can be designed to give a satisfactory operating range; typically, from 50 per cent to 120 per cent of design capacity.

Valve plates are intended to give greater flexibility than sieve plates at a lower cost than bubble-caps.

*Efficiency*. The Murphree efficiency of the three types of plate will be virtually the same when operating over their design flow range, and no real distinction can be made between them; see Zuiderweg *et al.* (1960).

*Pressure drop*. The pressure drop over the plates can be an important design consideration, particularly for vacuum columns. The plate pressure drop will depend on the detailed design of the plate but, in general, sieve plates give the lowest pressure drop, followed by valves, with bubble-caps giving the highest.

*Summary*. Sieve plates are the cheapest and are satisfactory for most applications. Valve plates should be considered if the specified turn-down ratio cannot be met with sieve plates. Bubble-caps should only be used where very low vapour (gas) rates have to be handled and a positive liquid seal is essential at all flow-rates.

## 11.12.2. Plate construction

The mechanical design features of sieve plates are described in this section. The same general construction is also used for bubble-cap and valve plates. Details of the various types of bubble-cap used, and the preferred dimensions of standard cap designs, can be found in the books by Smith (1963) and Ludwig (1997). The manufacturers' design manuals should be consulted for details of valve plate design; Glitsch (1970) and Koch (1960).

Two basically different types of plate construction are used. Large-diameter plates are normally constructed in sections, supported on beams. Small plates are installed in the column as a stack of pre-assembled plates.

## Sectional construction

A typical plate is shown in Figure 11.22. The plate sections are supported on a ring welded round the vessel wall, and on beams. The beams and ring are about 50 mm wide, with the beams set at around 0.6 m spacing. The beams are usually angle or channel sections, constructed from folded sheet. Special fasteners are used so the sections can be assembled from one side only. One section is designed to be removable to act as a manway. This reduces the number of manways needed on the vessel, which reduces the vessel cost.

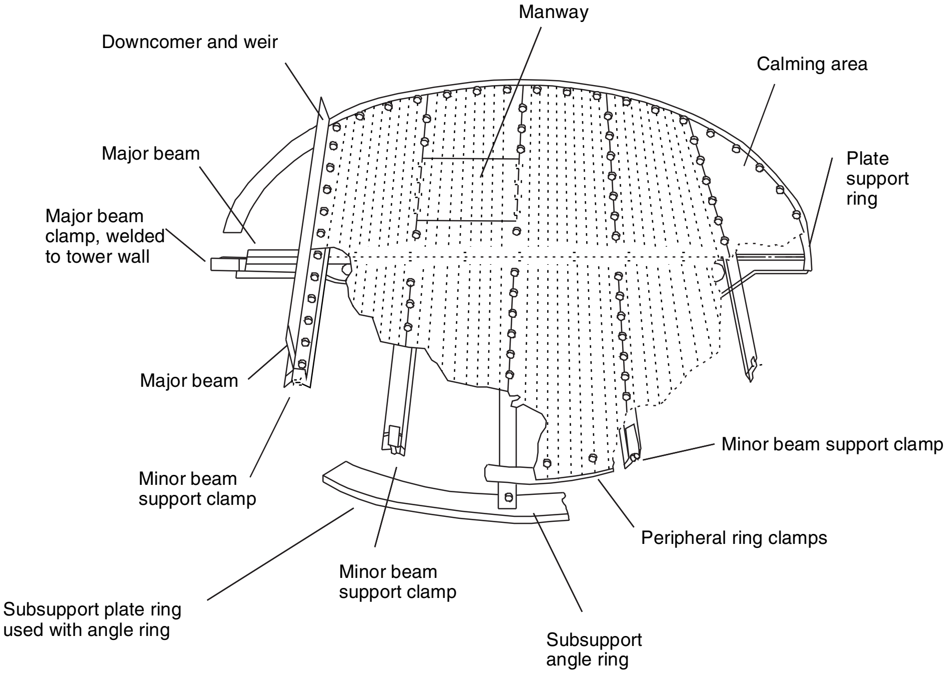


Figure 11.22. Typical sectional plate construction

Diagrams and photographs, of sectional plates, are given in Volume 2, Chapter 11.

## Stacked plates (cartridge plates)

The stacked type of construction is used where the column diameter is too small for a man to enter to assemble the plates, say less than 1.2 m (4 ft). Each plate is fabricated complete with the downcomer, and joined to the plate above and below using screwed rods (spacers); see Figure 11.23. The plates are installed in the column shell as an assembly (stack) of ten, or so, plates. Tall columns have to be divided into flanged sections so that plate assemblies can be easily installed and removed. The weir, and downcomer supports, are usually formed by turning up the edge of the plate.

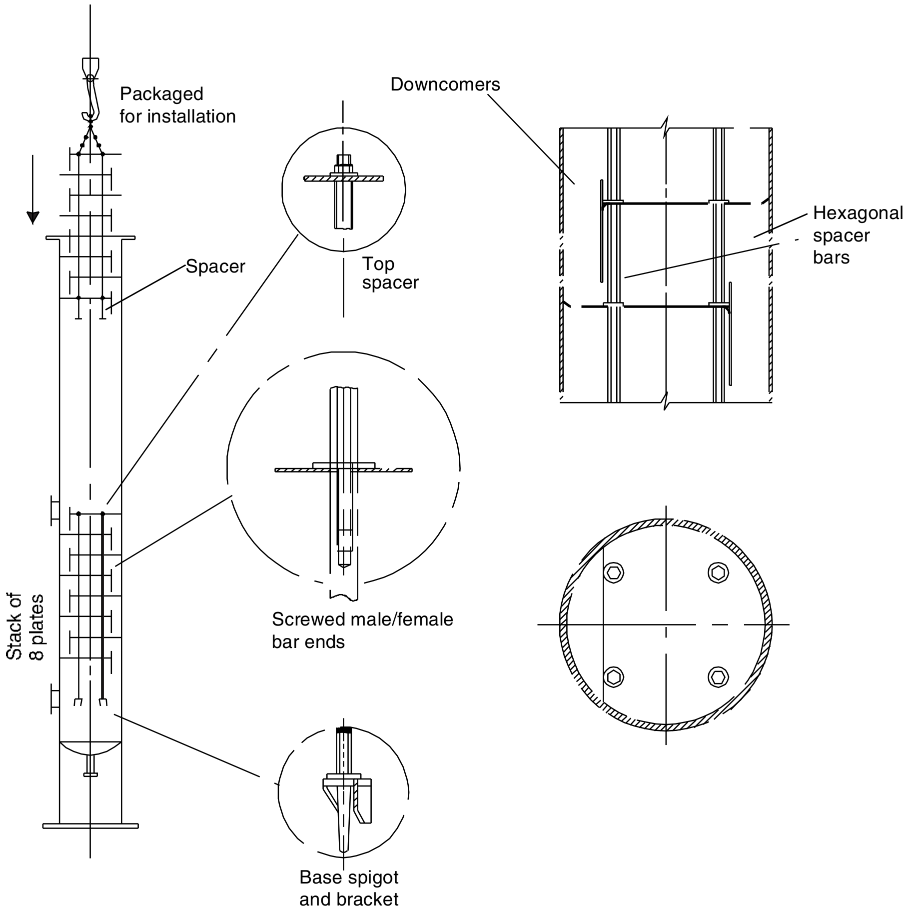


Figure 11.23. Typical stacked-plate construction

The plates are not fixed to the vessel wall, as they are with sectional plates, so there is no positive liquid seal at the edge of the plate, and a small amount of leakage will occur. In some designs the plate edges are turned up round the circumference to make better contact at the wall. This can make it difficult to remove the plates for cleaning and maintenance, without damage.

### *Downcomers*

The segmental, or chord downcomer, shown in Figure 11.24*a* is the simplest and cheapest form of construction and is satisfactory for most purposes. The downcomer channel is

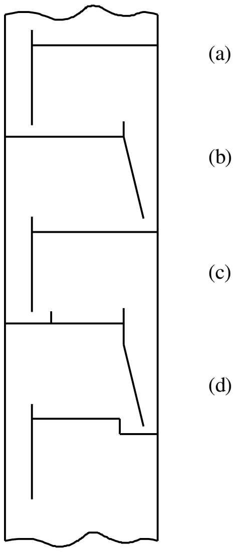


Figure 11.24. Segment (chord) downcomer designs. (*a*) Vertical apron (*b*) Inclined apron (*c*) Inlet weir (*d*) Recessed well

formed by a flat plate, called an apron, which extends down from the outlet weir. The apron is usually vertical, but may be sloped (Figure 11.24*b*) to increase the plate area available for perforation. If a more positive seal is required at the downcomer at the outlet, an inlet weir can be fitted (Figure 11.24*c*) or a recessed seal pan used (Figure 11.24*d*). Circular downcomers (pipes) are sometimes used for small liquid flow-rates.

### Side-stream and feed points

Where a side-stream is withdrawn from the column the plate design must be modified to provide a liquid seal at the take-off pipe. A typical design is shown in Figure 11.25*a*. When the feed stream is liquid it will be normally introduced into the downcomer leading to the feed plate, and the plate spacing increased at this point; Figure 11.25*b*.

### Structural design

The plate structure must be designed to support the hydraulic loads on the plate during operation, and the loads imposed during construction and maintenance. Typical design values used for these loads are:

Hydraulic load: 600 N/$m^2$ live load on the plate, plus 3000 N/$m^2$ over the downcomer seal area.
Erection and maintenance: 1500 N concentrated load on any structural member.

It is important to set close tolerances on the weir height, downcomer clearance, and plate flatness, to ensure an even flow of liquid across the plate. The tolerances specified will depend on the dimensions of the plate but will typically be about 3 mm.

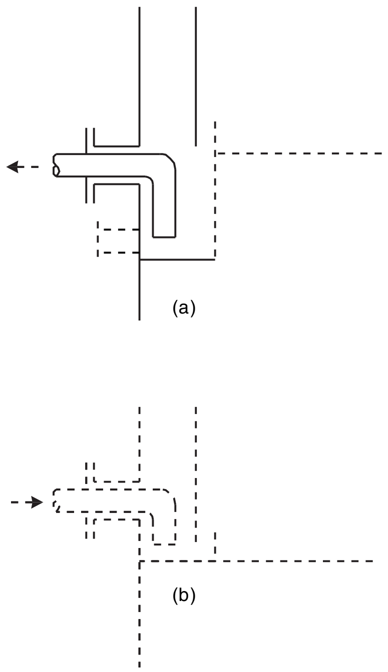


Figure 11.25. Feed and take-off nozzles

The plate deflection under load is also important, and will normally be specified as not greater than 3 mm under the operating conditions for plates greater than 2.5 m, and proportionally less for smaller diameters.

The mechanical specification of bubble-cap, sieve and valve plates is covered in a series of articles by Glitsch (1960), McClain (1960), Thrift (1960*a*, *b*) and Patton and Pritchard (1960).

## 11.13. PLATE HYDRAULIC DESIGN

The basic requirements of a plate contacting stage are that it should:

Provide good vapour-liquid contact.
Provide sufficient liquid hold-up for good mass transfer (high efficiency).
Have sufficient area and spacing to keep the entrainment and pressure drop within acceptable limits.
Have sufficient downcomer area for the liquid to flow freely from plate to plate.

Plate design, like most engineering design, is a combination theory and practice. The design methods use semi-empirical correlations derived from fundamental research work combined with practical experience obtained from the operation of commercial columns. Proven layouts are used, and the plate dimensions are kept within the range of values known to give satisfactory performance.

A short procedure for the hydraulic design of sieve plates is given in this section. Design methods for bubble-cap plates are given by Bolles (1963) and Ludwig (1997). Valve plates are proprietary designs and will be designed in consultation with the vendors. Design manuals are available from some vendors; Glistsch (1970) and Koch (1960).

A detailed discussion of the extensive literature on plate design and performance will not be given in this volume. Chase (1967) and Zuiderweg (1982) give critical reviews of the literature on sieve plates.

Several design methods have been published for sieve plates: Kister (1992), Barnicki and Davies (1989), Koch and Kuzniar (1966), Fair (1963), and Huang and Hodson (1958); see also the book by Lockett (1986).

### Operating range

Satisfactory operation will only be achieved over a limited range of vapour and liquid flow rates. A typical performance diagram for a sieve plate is shown in Figure 11.26.

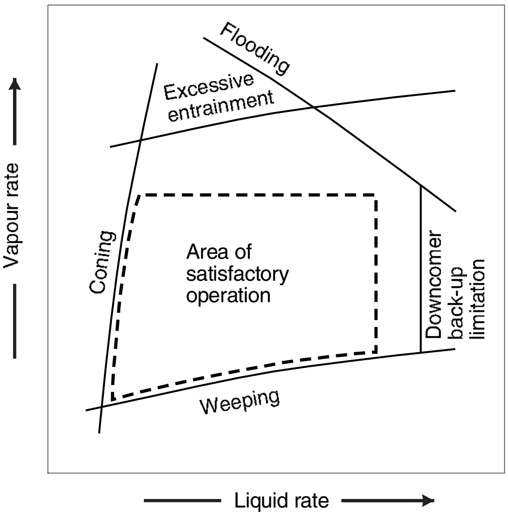


Figure 11.26. Sieve plate performance diagram

The upper limit to vapour flow is set by the condition of flooding. At flooding there is a sharp drop in plate efficiency and increase in pressure drop. Flooding is caused by either the excessive carry over of liquid to the next plate by entrainment, or by liquid backing-up in the downcomers.

The lower limit of the vapour flow is set by the condition of weeping. Weeping occurs when the vapour flow is insufficient to maintain a level of liquid on the plate. “Coning” occurs at low liquid rates, and is the term given to the condition where the vapour pushes the liquid back from the holes and jets upward, with poor liquid contact.

In the following sections gas can be taken as synonymous with vapour when applying the method to the design of plates for absorption columns.

### 11.13.1. Plate-design procedure

A trial-and-error approach is necessary in plate design: starting with a rough plate layout, checking key performance factors and revising the design, as necessary, until a satisfactory design is achieved. A typical design procedure is set out below and discussed in the following sections. The normal range of each design variable is given in the discussion, together with recommended values which can be used to start the design.

#### *Procedure*

1. Calculate the maximum and minimum vapour and liquid flow-rates, for the turn down ratio required.
2. Collect, or estimate, the system physical properties.
3. Select a trial plate spacing (Section 11.11).
4. Estimate the column diameter, based on flooding considerations (Section 11.13.3).
5. Decide the liquid flow arrangement (Section 11.13.4).
6. Make a trial plate layout: downcomer area, active area, hole area, hole size, weir height (Sections 11.13.8 to 11.13.10).
7. Check the weeping rate (Section 11.13.6), if unsatisfactory return to step 6.
8. Check the plate pressure drop (Section 11.13.14), if too high return to step 6.
9. Check downcomer back-up, if too high return to step 6 or 3 (Section 11.13.15).
10. Decide plate layout details: calming zones, unperforated areas. Check hole pitch, if unsatisfactory return to step 6 (Section 11.13.11).
11. Recalculate the percentage flooding based on chosen column diameter.
12. Check entrainment, if too high return to step 4 (Section 11.13.5).
13. Optimise design: repeat steps 3 to 12 to find smallest diameter and plate spacing acceptable (lowest cost).
14. Finalise design: draw up the plate specification and sketch the layout.

This procedure is illustrated in Example 11.11.

### 11.13.2. Plate areas

The following areas terms are used in the plate design procedure:

$A_c$ = total column cross-sectional area,
$A_d$ = cross-sectional area of downcomer,
$A_n$ = net area available for vapour-liquid disengagement, normally equal to $A_c - A_d$, for a single pass plate,
$A_a$ = active, or bubbling, area, equal to $A_c - 2A_d$ for single-pass plates,
$A_h$ = hole area, the total area of all the active holes,
$A_p$ = perforated area (including blanked areas),
$A_{ap}$ = the clearance area under the downcomer apron.

### 11.13.3. Diameter

The flooding condition fixes the upper limit of vapour velocity. A high vapour velocity is needed for high plate efficiencies, and the velocity will normally be between 70 to

90 per cent of that which would cause flooding. For design, a value of 80 to 85 per cent of the flooding velocity should be used.

The flooding velocity can be estimated from the correlation given by Fair (1961):

$$u_f = K_1\sqrt{\frac{\rho_L - \rho_v}{\rho_v}} \tag{11.81}$$

where $u_f$ = flooding vapour velocity, m/s, based on the net column cross-sectional area $A_n$ (see Section 11.13.2),

$K_1$ = a constant obtained from Figure 11.27.

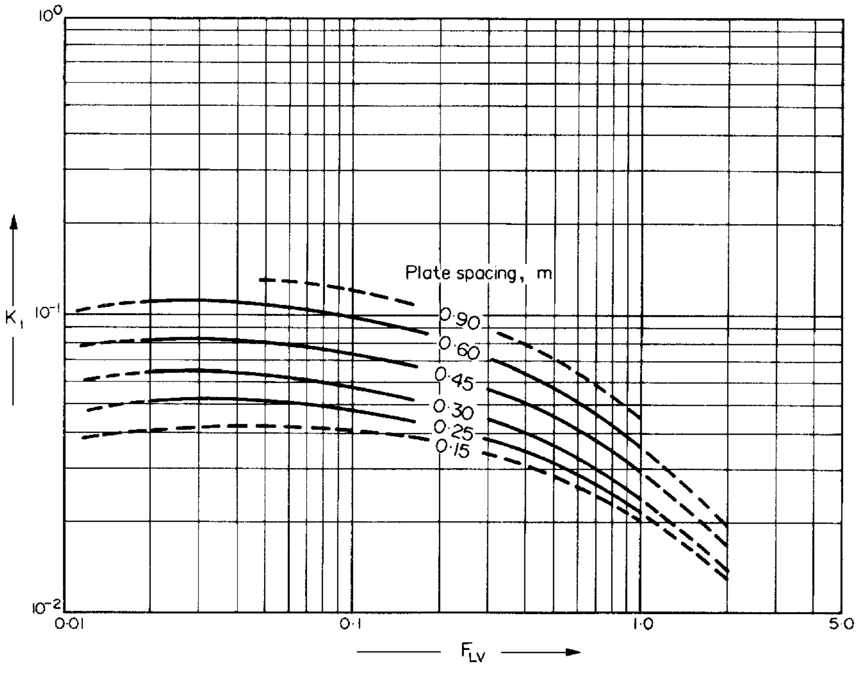


Figure 11.27. Flooding velocity, sieve plates

The liquid-vapour flow factor $F_{LV}$ in Figure 11.27 is given by:

$$F_{LV} = \frac{L_w}{V_w}\sqrt{\frac{\rho_v}{\rho_L}} \tag{11.82}$$

where $L_w$ = liquid mass flow-rate, kg/s,

$V_w$ = vapour mass flow-rate, kg/s.

The following restrictions apply to the use of Figure 11.27:

1. Hole size less than 6.5 mm. Entrainment may be greater with larger hole sizes.
2. Weir height less than 15 per cent of the plate spacing.

3. Non-foaming systems.
4. Hole: active area ratio greater than 0.10; for other ratios apply the following corrections:

| hole: active area | multiply $K_1$ by |
|---|---|
| 0.10 | 1.0 |
| 0.08 | 0.9 |
| 0.06 | 0.8 |

5. Liquid surface tension 0.02 N/m, for other surface tensions $\sigma$ multiply the value of $K_1$ by $[\sigma/0.02]^{0.2}$.

To calculate the column diameter an estimate of the net area $A_n$ is required. As a first trial take the downcomer area as 12 per cent of the total, and assume that the hole–active area is 10 per cent.

Where the vapour and liquid flow-rates, or physical properties, vary significantly throughout the column a plate design should be made for several points up the column. For distillation it will usually be sufficient to design for the conditions above and below the feed points. Changes in the vapour flow-rate will normally be accommodated by adjusting the hole area; often by blanking off some rows of holes. Different column diameters would only be used where there is a considerable change in flow-rate. Changes in liquid rate can be allowed for by adjusting the liquid downcomer areas.

### 11.13.4. Liquid-flow arrangement

The choice of plate type (reverse, single pass or multiple pass) will depend on the liquid flow-rate and column diameter. An initial selection can be made using Figure 11.28, which has been adapted from a similar figure given by Huang and Hodson (1958).

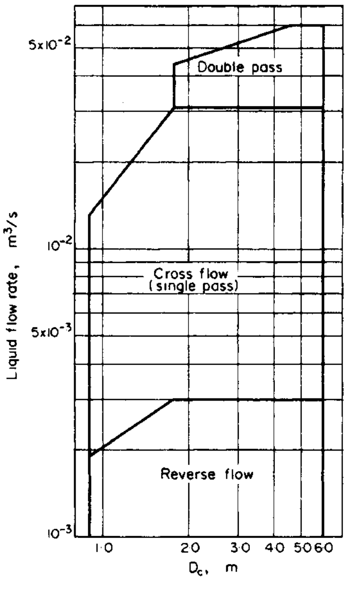


Figure 11.28. Selection of liquid-flow arrangement

### 11.13.5. Entrainment

Entrainment can be estimated from the correlation given by Fair (1961), Figure 11.29, which gives the fractional entrainment $\psi$ (kg/kg gross liquid flow) as a function of the liquid-vapour factor $F_{LV}$, with the percentage approach to flooding as a parameter.

The percentage flooding is given by:

$$\text{percentage flooding} = \frac{u_n \text{ actual velocity (based on net area)}}{u_f \text{ (from equation 11.81)}} \tag{11.83}$$

The effect of entrainment on plate efficiency can be estimated using equation 11.78.

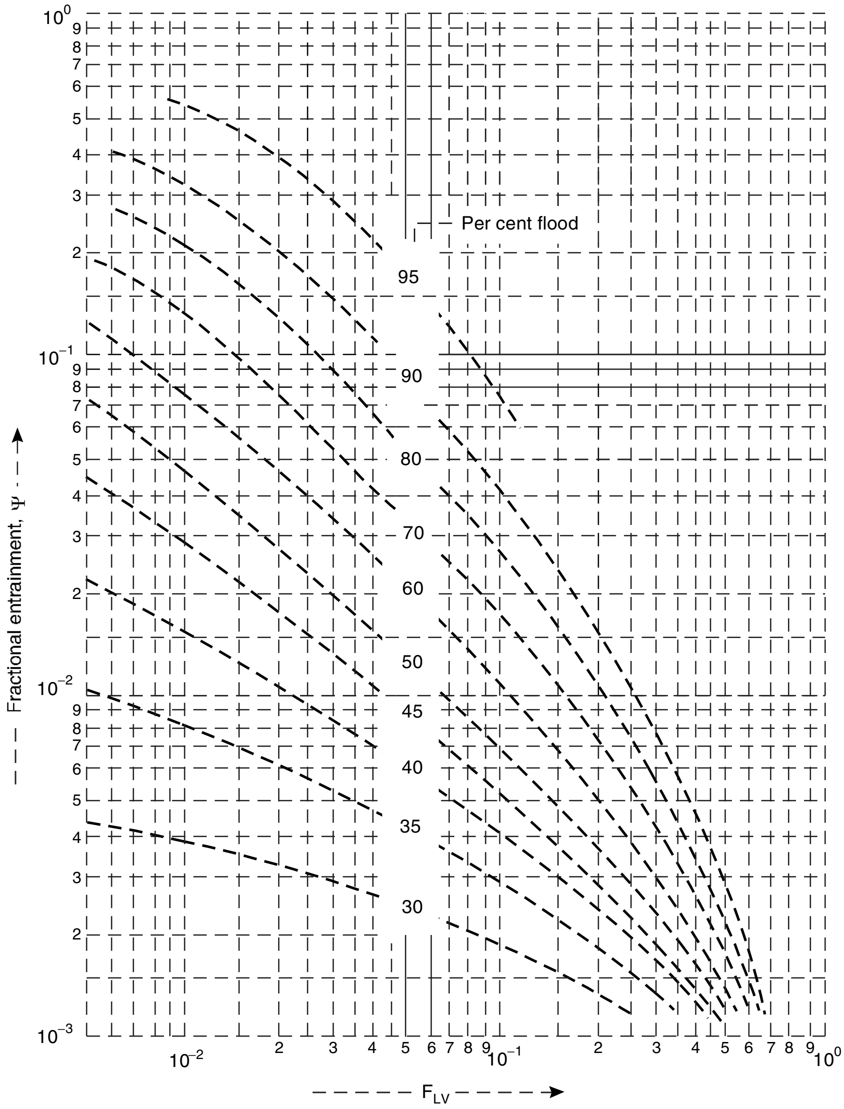


Figure 11.29. Entrainment correlation for sieve plates (Fair, 1961)

As a rough guide the upper limit of $\psi$ can be taken as 0.1; below this figure the effect on efficiency will be small. The optimum design value may be above this figure, see Fair (1963).

### 11.13.6. Weep point

The lower limit of the operating range occurs when liquid leakage through the plate holes becomes excessive. This is known as the weep point. The vapour velocity at the weep point is the minimum value for stable operation. The hole area must be chosen so that at the lowest operating rate the vapour flow velocity is still well above the weep point.

Several correlations have been proposed for predicting the vapour velocity at the weep point; see Chase (1967). That given by Eduljee (1959) is one of the simplest to use, and has been shown to be reliable.

The minimum design vapour velocity is given by:

$$\breve{u}_h = \frac{[K_2 - 0.90(25.4 - d_h)]}{(\rho_v)^{1/2}} \qquad (11.84)$$

where $\breve{u}_h$ = minimum vapour velocity through the holes(based on the hole area), m/s,

$d_h$ = hole diameter, mm,

$K_2$ = a constant, dependent on the depth of clear liquid on the plate, obtained from Figure 11.30.

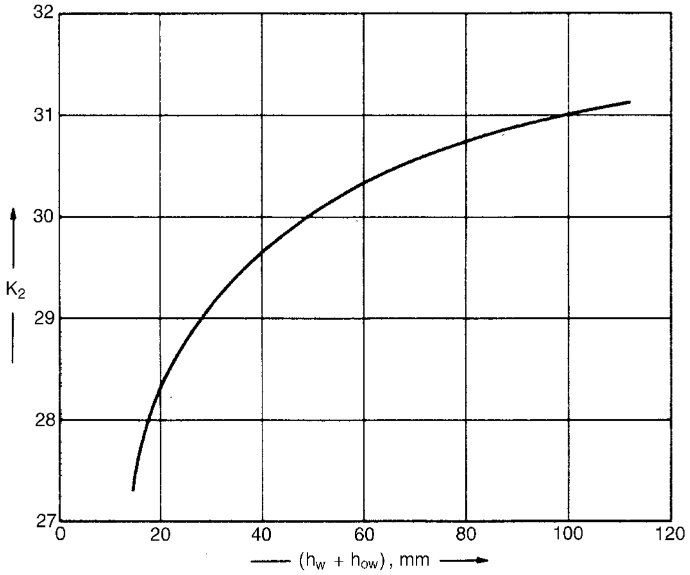


Figure 11.30. Weep-point correlation (Eduljee, 1959)

The clear liquid depth is equal to the height of the weir $h_w$ plus the depth of the crest of liquid over the weir $h_{ow}$; this is discussed in the next section.

### 11.13.7. Weir liquid crest

The height of the liquid crest over the weir can be estimated using the Francis weir formula (see Volume 1, Chapter 5). For a segmental downcomer this can be written as:

$$h_{ow} = 750 \left[ \frac{L_w}{\rho_L l_w} \right]^{2/3} \tag{11.85}$$

where $l_w$ = weir length, m,
$h_{ow}$ = weir crest, mm liquid,
$L_w$ = liquid flow-rate, kg/s.

With segmental downcomers the column wall constricts the liquid flow, and the weir crest will be higher than that predicted by the Francis formula for flow over an open weir. The constant in equation 11.85 has been increased to allow for this effect.

To ensure an even flow of liquid along the weir, the crest should be at least 10 mm at the lowest liquid rate. Serrated weirs are sometimes used for very low liquid rates.

### 11.13.8. Weir dimensions

#### *Weir height*

The height of the weir determines the volume of liquid on the plate and is an important factor in determining the plate efficiency (see Section 11.10.4). A high weir will increase the plate efficiency but at the expense of a higher plate pressure drop. For columns operating above atmospheric pressure the weir heights will normally be between 40 mm to 90 mm (1.5 to 3.5 in.); 40 to 50 mm is recommended. For vacuum operation lower weir heights are used to reduce the pressure drop; 6 to 12 mm $\left(\frac{1}{4} \text{ to } \frac{1}{2} \text{ in.}\right)$ is recommended.

#### *Inlet weirs*

Inlet weirs, or recessed pans, are sometimes used to improve the distribution of liquid across the plate; but are seldom needed with segmental downcomers.

#### *Weir length*

With segmental downcomers the length of the weir fixes the area of the downcomer. The chord length will normally be between 0.6 to 0.85 of the column diameter. A good initial value to use is 0.77, equivalent to a downcomer area of 12 per cent.

The relationship between weir length and downcomer area is given in Figure 11.31.

For double-pass plates the width of the central downcomer is normally 200–250 mm (8–10 in.).

### 11.13.9. Perforated area

The area available for perforation will be reduced by the obstruction caused by structural members (the support rings and beams), and by the use of calming zones.

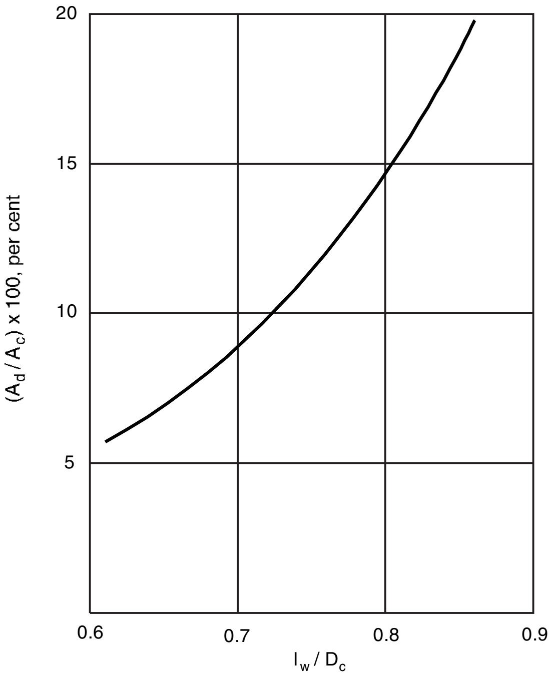


Figure 11.31. Relation between downcomer area and weir length

Calming zones are unperforated strips of plate at the inlet and outlet sides of the plate. The width of each zone is usually made the same; recommended values are: below 1.5 m diameter, 75 mm; above, 100 mm.

The width of the support ring for sectional plates will normally be 50 to 75 mm: the support ring should not extend into the downcomer area. A strip of unperforated plate will be left round the edge of cartridge-type trays to stiffen the plate.

The unperforated area can be calculated from the plate geometry. The relationship between the weir chord length, chord height and the angle subtended by the chord is given in Figure 11.32.

## 11.13.10. Hole size

The hole sizes used vary from 2.5 to 12 mm; 5 mm is the preferred size. Larger holes are occasionally used for fouling systems. The holes are drilled or punched. Punching is cheaper, but the minimum size of hole that can be punched will depend on the plate thickness. For carbon steel, hole sizes approximately equal to the plate thickness can be punched, but for stainless steel the minimum hole size that can be punched is about twice the plate thickness. Typical plate thicknesses used are: 5 mm (3/16 in.) for carbon steel, and 3 mm (12 gauge) for stainless steel.

When punched plates are used they should be installed with the direction of punching upward. Punching forms a slight nozzle, and reversing the plate will increase the pressure drop.

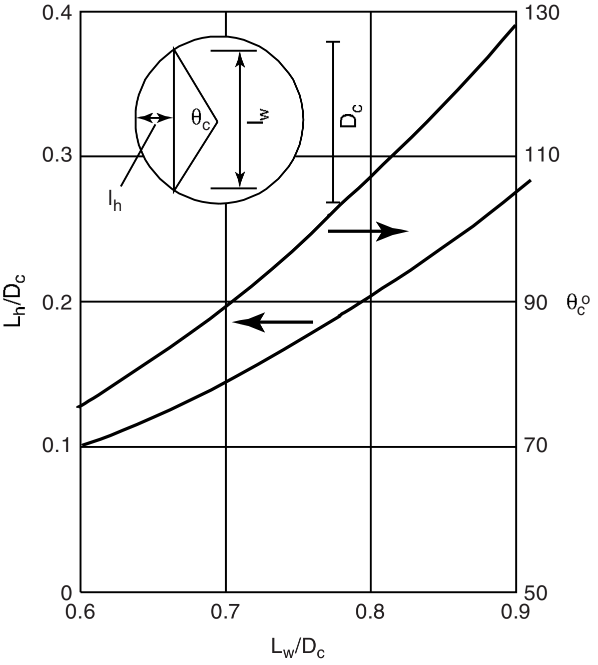


Figure 11.32. Relation between angle subtended by chord, chord height and chord length

### 11.13.11. Hole pitch

The hole pitch (distance between the hole centres) $l_p$ should not be less than 2.0 hole diameters, and the normal range will be 2.5 to 4.0 diameters. Within this range the pitch can be selected to give the number of active holes required for the total hole area specified.

Square and equilateral triangular patterns are used; triangular is preferred. The total hole area as a fraction of the perforated area $A_p$ is given by the following expression, for an equilateral triangular pitch:

$$\frac{A_h}{A_p} = 0.9\left[\frac{d_h}{l_p}\right]^2 \tag{11.86}$$

This equation is plotted in Figure 11.33.

### 11.13.12. Hydraulic gradient

The hydraulic gradient is the difference in liquid level needed to drive the liquid flow across the plate. On sieve plates, unlike bubble-cap plates, the resistance to liquid flow will be small, and the hydraulic gradient is usually ignored in sieve-plate design. It can be significant in vacuum operation, as with the low weir heights used the hydraulic gradient can be a significant fraction of the total liquid depth. Methods for estimating the hydraulic gradient are given by Fair (1963).

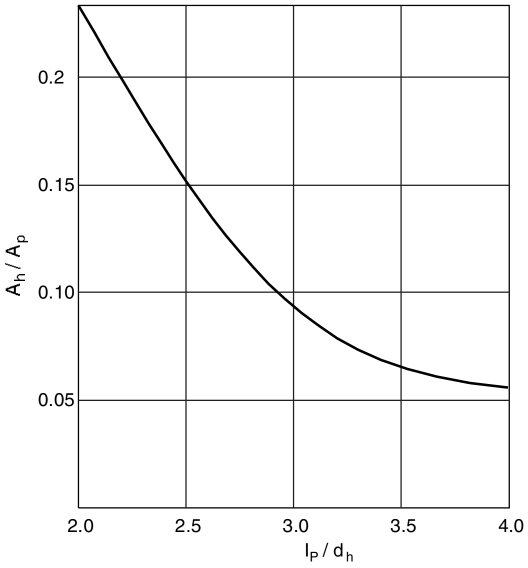


Figure 11.33. Relation between hole area and pitch

### 11.13.13. Liquid throw

The liquid throw is the horizontal distance travelled by the liquid stream flowing over the downcomer weir. It is only an important consideration in the design of multiple-pass plates. Bolles (1963) gives a method for estimating the liquid throw.

### 11.13.14. Plate pressure drop

The pressure drop over the plates is an important design consideration. There are two main sources of pressure loss: that due to vapour flow through the holes (an orifice loss), and that due to the static head of liquid on the plate.

A simple additive model is normally used to predict the total pressure drop. The total is taken as the sum of the pressure drop calculated for the flow of vapour through the dry plate (the dry plate drop $h_d$); the head of clear liquid on the plate ($h_w + h_{ow}$); and a term to account for other, minor, sources of pressure loss, the so-called residual loss $h_r$. The residual loss is the difference between the observed experimental pressure drop and the simple sum of the dry-plate drop and the clear-liquid height. It accounts for the two effects: the energy to form the vapour bubbles and the fact that on an operating plate the liquid head will not be clear liquid but a head of "aerated" liquid froth, and the froth density and height will be different from that of the clear liquid.

It is convenient to express the pressure drops in terms of millimetres of liquid. In pressure units:

$$\Delta P_t = 9.81 \times 10^{-3} h_t \rho_L \tag{11.87}$$

where $\Delta P_t$ = total plate pressure drop, Pa(N/m$^2$),
$h_t$ = total plate pressure drop, mm liquid.

### Dry plate drop

The pressure drop through the dry plate can be estimated using expressions derived for flow through orifices.

$$h_d = 51\left[\frac{u_h}{C_0}\right]^2 \frac{\rho_v}{\rho_L} \tag{11.88}$$

where the orifice coefficient $C_0$ is a function of the plate thickness, hole diameter, and the hole to perforated area ratio. $C_0$ can be obtained from Figure 11.34; which has been adapted from a similar figure by Liebson *et al.* (1957). $u_h$ is the velocity through the holes, m/s.

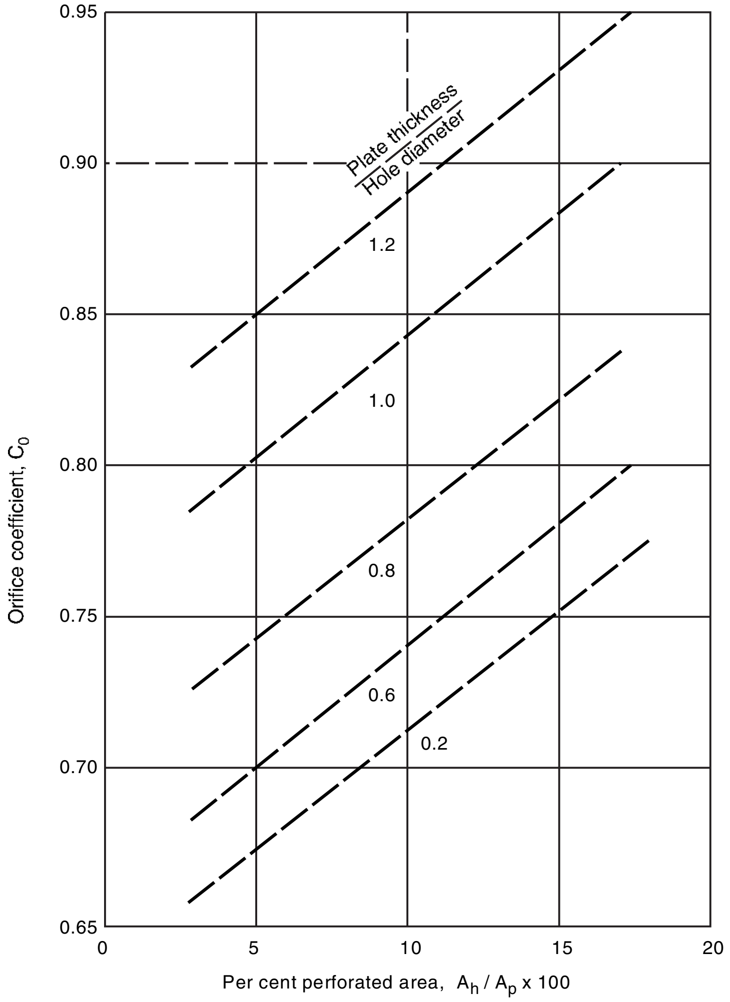


Figure 11.34. Discharge coefficient, sieve plates (Liebson *et al.*, 1957)

### Residual head

Methods have been proposed for estimating the residual head as a function of liquid surface tension, froth density and froth height. However, as this correction term is small the use of an elaborate method for its estimation is not justified, and the simple equation proposed by Hunt *et al.* (1955) can be used:

$$h_r = \frac{12.5 \times 10^3}{\rho_L} \tag{11.89}$$

Equation 11.89 is equivalent to taking the residual drop as a fixed value of 12.5 mm of water ($\frac{1}{2}$ in.).

### Total drop

The total plate drop is given by:

$$h_t = h_d + (h_w + h_{ow}) + h_r \tag{11.90}$$

If the hydraulic gradient is significant, half its value is added to the clear liquid height.

## 11.13.15. Downcomer design [back-up]

The downcomer area and plate spacing must be such that the level of the liquid and froth in the downcomer is well below the top of the outlet weir on the plate above. If the level rises above the outlet weir the column will flood.

The back-up of liquid in the downcomer is caused by the pressure drop over the plate (the downcomer in effect forms one leg of a U-tube) and the resistance to flow in the downcomer itself; see Figure 11.35.

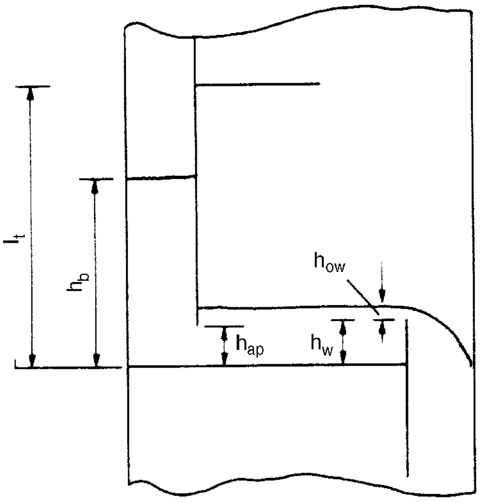


Figure 11.35. Downcomer back-up

In terms of clear liquid the downcomer back-up is given by:

$$h_b = (h_w + h_{ow}) + h_t + h_{dc} \tag{11.91}$$

where $h_b$ = downcomer back-up, measured from plate surface, mm,
$h_{dc}$ = head loss in the downcomer, mm.

The main resistance to flow will be caused by the constriction at the downcomer outlet, and the head loss in the downcomer can be estimated using the equation given by Cicalese *et al.* (1947)

$$h_{dc} = 166\left[\frac{L_{wd}}{\rho_L A_m}\right]^2 \tag{11.92}$$

where $L_{wd}$ = liquid flow rate in downcomer, kg/s,
$A_m$ = either the downcomer area $A_d$ or the clearance area under the downcomer $A_{ap}$; whichever is the smaller, $m^2$.

The clearance area under the downcomer is given by:

$$A_{ap} = h_{ap} l_w \tag{11.93}$$

where $h_{ap}$ is height of the bottom edge of the apron above the plate. This height is normally set at 5 to 10 mm $\left(\frac{1}{4} \text{ to } \frac{1}{2} \text{ in.}\right)$ below the outlet weir height:

$$h_{ap} = h_w - (5 \text{ to } 10 \text{ mm})$$

### Froth height

To predict the height of "aerated" liquid on the plate, and the height of froth in the downcomer, some means of estimating the froth density is required. The density of the "aerated" liquid will normally be between 0.4 to 0.7 times that of the clear liquid. A number of correlations have been proposed for estimating froth density as a function of the vapour flow-rate and the liquid physical properties; see Chase (1967); however, none is particularly reliable, and for design purposes it is usually satisfactory to assume an average value of 0.5 of the liquid density.

This value is also taken as the mean density of the fluid in the downcomer; which means that for safe design the clear liquid back-up, calculated from equation 11.91, should not exceed half the plate spacing $l_t$, to avoid flooding.

Allowing for the weir height:

$$h_b \not> \tfrac{1}{2}(l_t + h_w) \tag{11.94}$$

This criterion is, if anything, oversafe, and where close plate spacing is desired a better estimate of the froth density in the downcomer should be made. The method proposed by Thomas and Shah (1964) is recommended.

### Downcomer residence time

Sufficient residence time must be allowed in the downcomer for the entrained vapour to disengage from the liquid stream; to prevent heavily "aerated" liquid being carried under the downcomer.

A time of at least 3 seconds is recommended.

The downcomer residence time is given by:

$$t_r = \frac{A_d h_{bc} \rho_L}{L_{wd}} \tag{11.95}$$

where $t_r$ = residence time, s,
$h_{bc}$ = clear liquid back-up, m.

## Example 11.11

Design the plates for the column specified in Example 11.2. Take the minimum feed rate as 70 per cent of the maximum (maximum feed 10,000 kg/h). Use sieve plates.

## Solution

As the liquid and vapour flow-rates and compositions will vary up the column, plate designs should be made above and below the feed point. Only the bottom plate will be designed in detail in this example.

From McCabe-Thiele diagram, Example 11.2:

Number of stages = 16
Slope of the bottom operating line = 5.0
Slope of top operating line = 0.57
Top composition 94 per cent mol. 98 per cent w/w.
Bottom composition — essentially water.
Reflux ratio = 1.35

### *Flow-rates*

Mol. weight feed $= 0.033 \times 58 + (1 - 0.033)18 = 19.32$
Feed $= 13{,}000/19.32 = 672.9$ kmol/h
A mass balance on acetone gives:
Top product, $D = 672.9 \times 0.033/0.94 = 23.6$ kmol/h
Vapour rate, $V = D(1 + R) = 23.6(1 + 1.35) = 55.5$ kmol/h
An overall mass balance gives:
Bottom product, $B = 672.9 - 23.6 = 649.3$ kmol/h
Slope of the bottom operating line $L_m'/V_m' = 5.0$
and $V_m' = L_m' - B$, from which:
vapour flow below feed, $V_m' = 162.3$ kmol/h
liquid flow below feed, $L_m' = 811.6$ kmol/h

### *Physical properties*

Estimate base pressure, assume column efficiency of 60 per cent, take reboiler as equivalent to one stage.

$$\text{Number of real stages} = \frac{16 - 1}{0.6} = 25$$

Assume 100 mm water, pressure drop per plate.

$$\text{Column pressure drop} = 100 \times 10^{-3} \times 1000 \times 9.81 \times 25 = 24{,}525 \text{ Pa}$$

$$\text{Top pressure, 1 atm (14.7 lb/in}^2) = 101.4 \times 10^3 \text{ Pa}$$

$$\begin{aligned}\text{Estimated bottom pressure} &= 101.4 \times 10^3 + 24{,}525\\ &= 125{,}925 \text{ Pa} = \underline{\underline{1.26 \text{ bar}}}\end{aligned}$$

From steam tables, base temperature 106°C.

$$\rho_v = 0.72 \text{ kg/m}^3$$

$$\rho_L = 954 \text{ kg/m}^3$$

$$\text{Surface tension } 57 \times 10^{-3} \text{ N/m}$$

Top, 98% w/w acetone, top temperature 57°C

From PPDS (see Chapter 8);

$$\rho_v = 2.05 \text{ kg/m}^3,\ \rho_L = 753 \text{ kg/m}^3$$

Molecular weight 55.6

$$\text{Surface tension } 23 \times 10^{-3} \text{ N/m}$$

### Column diameter

$$F_{LV} \text{ bottom} = 5.0\sqrt{\frac{0.72}{954}} = 0.14 \tag{11.82}$$

$$F_{LV} \text{ top} = 0.57\sqrt{\frac{2.05}{753}} = 0.03$$

Take plate spacing as 0.5 m
From Figure 11.27

$$\text{base } K_1 = 7.5 \times 10^{-2}$$

$$\text{top } K_1 = 9.0 \times 10^{-2}$$

Correction for surface tensions

$$\text{base } K_1 = \left(\frac{57}{20}\right)^{0.2} \times 7.5 \times 10^{-2} = 9.3 \times 10^{-2}$$

$$\text{top } K_1 = \left(\frac{23}{20}\right)^{0.2} \times 9.0 \times 10^{-2} = 9.3 \times 10^{-2}$$

$$\text{base } u_f = 9.3 \times 10^{-2}\sqrt{\frac{954 - 0.72}{0.72}} = 3.38 \text{ m/s} \tag{11.81}$$

$$\text{top } u_f = 9.3 \times 10^{-2}\sqrt{\frac{753 - 2.05}{2.05}} = 1.78 \text{ m/s}$$

Design for 85 per cent flooding at maximum flow rate

$$\text{base } \hat{u}_v = 3.38 \times 0.85 = 2.87 \text{ m/s}$$

$$\text{top } \hat{u}_v = 1.78 \times 0.85 = 1.51 \text{ m/s}$$

Maximum volumetric flow-rate

$$\text{base} = \frac{162.3 \times 18}{0.72 \times 3600} = 1.13 \text{ m}^3/\text{s}$$

$$\text{top} = \frac{55.5 \times 55.6}{2.05 \times 3600} = 0.42 \text{ m}^3/\text{s}$$

Net area required

$$\text{bottom} = \frac{1.13}{2.87} = 0.40 \text{ m}^2$$

$$\text{top} = \frac{0.42}{1.51} = 0.28 \text{ m}^2$$

As first trial take downcomer area as 12 per cent of total.
Column cross-sectioned area

$$\text{base} = \frac{0.40}{0.88} = 0.46 \text{ m}^2$$

$$\text{top} = \frac{0.28}{0.88} = 0.32 \text{ m}^2$$

Column diameter

$$\text{base} = \sqrt{\frac{0.46 \times 4}{\pi}} = 0.77 \text{ m}$$

$$\text{top} = \sqrt{\frac{0.34 \times 4}{\pi}} = 0.64 \text{ m}$$

Use same diameter above and below feed, reducing the perforated area for plates above the feed.

Nearest standard pipe size (BS 1600); outside diameter 812.8 mm (32 in); standard wall thickness 9.52 mm; inside diameter 794 mm.

## Liquid flow pattern

$$\text{Maximum volumetric liquid rate} = \frac{811.6 \times 18}{3600 \times 954} = 4.3 \times 10^{-3} \text{ m}^3/\text{s}$$

The plate diameter is outside the range of Figure 11.28, but it is clear that a single pass plate can be used.

## Provisional plate design

$$\text{Column diameter } D_c = 0.79 \text{ m}$$

$$\text{Column area } A_c = 0.50 \text{ m}^2$$

$$\text{Downcomer area } A_d = 0.12 \times 0.50 = 0.06 \text{ m}^2, \text{ at 12 per cent}$$

$$\text{Net area } A_n = A_c - A_d = 0.50 - 0.06 = 0.44 \text{ m}^2$$

$$\text{Active area } A_a = A_c - 2A_d = 0.50 - 0.12 = 0.38 \text{ m}^2$$

$$\text{Hole area } A_h \text{ take 10 per cent } A_a \text{ as first trial} = 0.038 \text{ m}^2$$

Weir length (from Figure 11.31) = 0.76 × 0.79 = 0.60 m

| | |
|---|---|
| Take weir height | 50 mm |
| Hole diameter | 5 mm |
| Plate thickness | 5 mm |

### Check weeping

$$\text{Maximum liquid rate} = \left(\frac{811.6 \times 18}{3600}\right) = 4.06 \text{ kg/s}$$

Minimum liquid rate, at 70 per cent turn-down = 0.7 × 4.06 = 2.84 kg/s

$$\text{maximum } h_{ow} = 750\left(\frac{4.06}{954 \times 0.06}\right)^{2/3} = 27 \text{ mm liquid} \tag{11.85}$$

$$\text{minimum } h_{ow} = 750\left(\frac{2.85}{954 \times 0.60}\right)^{2/3} = 22 \text{ mm liquid}$$

$$\text{at minimum rate } h_w + h_{ow} = 50 + 22 = 72 \text{ mm}$$

From Figure 11.30, $K_2 = 30.6$

$$\breve{u}_h(\text{min}) = \frac{30.6 - 0.90(25.4 - 5)}{(0.72)^{1/2}} = 14 \text{ m/s} \tag{11.84}$$

$$\text{actual minimum vapour velocity} = \frac{\text{minimum vapour rate}}{A_h}$$

$$= \frac{0.7 \times 1.13}{0.038} = 20.8 \text{ m/s}$$

So minimum operating rate will be well above weep point.

### Plate pressure drop

Dry plate drop

Maximum vapour velocity through holes

$$\hat{u}_h = \frac{1.13}{0.038} = 29.7 \text{ m/s}$$

From Figure 11.34, for plate thickness/hole dia. = 1, and $A_h/A_p \simeq A_h/A_a = 0.1$, $C_0 = 0.84$

$$h_d = 51\left(\frac{29.7}{0.84}\right)^2 \frac{0.72}{954} = 48 \text{ mm liquid} \tag{11.88}$$

residual head

$$h_r = \frac{12.5 \times 10^3}{954} = 13.1 \text{ mm liquid} \tag{11.89}$$

total plate pressure drop

$$h_t = 48 + (50 + 27) + 13 = 138 \text{ mm liquid}$$

*Note*: 100 mm was assumed to calculate the base pressure. The calculation could be repeated with a revised estimate but the small change in physical properties will have little effect on the plate design. 138 mm per plate is considered acceptable.

### Downcomer liquid back-up

Downcomer pressure loss

Take $h_{ap} = h_w - 10 = 40$ mm.

Area under apron, $A_{ap} = 0.60 \times 40 \times 10^{-3} = 0.024 \text{ m}^2$.

As this is less than $A_d = 0.06 \text{ m}^2$ use $A_{ap}$ in equation 11.92

$$h_{dc} = 166 \left(\frac{4.06}{954 \times 0.024}\right)^2 = 5.2 \text{ mm} \tag{11.92}$$

say 6 mm.

Back-up in downcomer

$$h_b = (50 + 27) + 138 + 6 = 221 \text{ mm} \tag{11.91}$$

$$\underline{\underline{0.22 \text{ m}}}$$

$0.22 < \frac{1}{2}$(plate spacing + weir height)
so plate spacing is acceptable

Check residence time

$$t_r = \frac{0.06 \times 0.22 \times 954}{4.06} = 3.1 \text{ s} \tag{11.95}$$

$>3$ s, satisfactory.

### Check entrainment

$$u_v = \frac{1.13}{0.44} = 2.57 \text{ m/s}$$

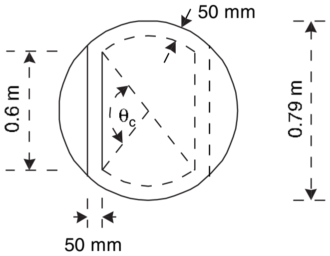
$$\text{per cent flooding} = \frac{2.57}{3.38} = 76$$

$$F_{LV} = \underline{\underline{0.14}}, \text{ from Figure 11.29, } \Psi = 0.018, \text{ well below } 0.1.$$

As the per cent flooding is well below the design figure of 85, the column diameter could be reduced, but this would increase the pressure drop.

### Trial layout

Use cartridge-type construction. Allow 50 mm unperforated strip round plate edge; 50 mm wide calming zones.



### Perforated area

From Figure 11.32, at $l_w/D_c = 0.6/0.79 = 0.76$

$$\theta_c = 99^\circ$$

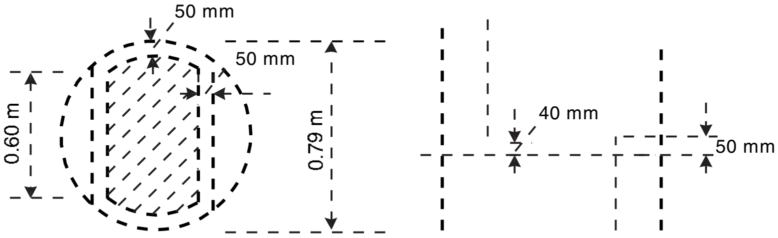
angle subtended by the edge of the plate = $180 - 99 = 81^\circ$
mean length, unperforated edge strips = $(0.79 - 50 \times 10^{-3})\pi \times 81/180 = 1.05$ m
area of unperforated edge strips = $50 \times 10^{-3} \times 1.05 = 0.053$ m$^2$
mean length of calming zone, approx. = weir length + width of unperforated strip
$= 0.6 + 50 \times 10^{-3} = 0.65$ m
area of calming zones = $2(0.65 \times 50 \times 10^{-3}) = 0.065$ m$^2$
total area for perforations, $A_p = 0.38 - 0.053 - 0.065 = 0.262$ m$^2$
$A_h/A_p = 0.038/0.262 = 0.145$
From Figure 11.33, $l_p/d_h = 2.6$; satisfactory, within 2.5 to 4.0.

### Number of holes

$$\text{Area of one hole} = 1.964 \times 10^{-5}\ \text{m}^2$$

$$\text{Number of holes} = \frac{0.038}{1.964 \times 10^{-5}} = 1935$$

### Plate specification



| | | | |
|---|---|---|---|
| Plate No. | 1 | Turn-down | 70 per cent max rate |
| Plate I.D. | 0.79 m | Plate material | Mild steel |
| Hole size | 5 mm | Downcomer | material Mild steel |
| Hole pitch | 12.5 mm Δ | Plate spacing | 0.5 m |
| Total no. holes | — | Plate thickness | 5 mm |
| Active holes | 1935 | Plate pressure drop | 140 mm liquid = 1.3 kPa |
| Blanking area | — | | |

## Example 11.12

For the plate design in Example 11.11, estimate the plate efficiency for the plate on which the concentration of acetone is 5 mol per cent. Use the AIChE method.

## Solution

Plate will be in the stripping section (see Figure 11.7).

Plate dimensions:
active area = 0.38 $m^2$,
length between downcomers (Figure 11.32) (liquid path, $Z_L$) = $0.79 - 2 \times 0.134 = 0.52$ m,
weir height = 50 mm.

Flow rates, check efficiency at minimum rates, at column base:

$$\text{vapour} = 0.7\frac{162.3}{3600} = 0.032 \text{ kmol/s}$$

$$\text{liquid} = 0.7\frac{811.6}{3600} = 0.158 \text{ kmol/s}$$

from the MaCable-Thiele diagram (Figure 11.7) at $x = 0.05$, assuming 60 per cent plate efficiency, $y \approx 0.4$. The liquid composition, $x = 0.05$, will occur on around the ninth plate from the bottom, the seventh from the top of the column. The pressure on this plate will be approximately:

$$9 \times 138 \times 10^{-3} \times 1000 \times 982 + 101.4 \times 10^3 = 113.6 \text{ kPa}$$

$$\text{say, } 1.14 \text{ bar}$$

At this pressure the plate temperature will be 79°C, and the liquid and vapour physical properties, from PPDS:

*liquid*

$$\text{mol. weight} = 20.02,\ \rho_L = 925 \text{ kg/m}^3,\ \mu_L = 9.34 \times 10^{-3} \text{ Nm}^{-2} \text{ s},$$

$$\sigma = 60 \times 10^{-3} \text{ N/m}$$

*vapour*

$$\text{mol. weight} = 34.04,\ \rho_v = 1.35 \text{ kg/m}^3,\ \mu_v = 10.0 \times 10^{-6} \text{ Nm}^{-2} \text{ s},$$

$D_L = 4.64 \times 10^{-9}$ $m^2/s$ (estimated using Wilke-Chang equation, Chapter 8)

$D_v = 18.6 \times 10^{-6}$ $m^2/s$ (estimated using Fuller equation, Chapter 8)

$$\text{Vapour, volumetric flow-rate} = \frac{0.032 \times 34.04}{1.35} = 0.81 \text{ m}^3/\text{s}$$

$$\text{Liquid, volumetric flow-rate} = \frac{0.158 \times 20.02}{925} = 3.42 \times 10^{-3} \text{ m}^3/\text{s}$$

$$u_a = \frac{0.81}{0.38} = 2.13 \text{ m/s}$$

$$F_v = u_a\sqrt{\rho_v} = \sqrt{2.13} \text{ m/s}$$

Average width over active surface $= 0.38/0.52 = 0.73$ m

$$L = \frac{3.42 \times 10^{-3}}{0.73} = 4.69 \times 10^{-3} \text{ m}^2/\text{s}$$

$$\mathrm{N}_G = \frac{(0.776 + 4.57 \times 10^{-3} \times 50 - 0.24 \times 2.48 + 105 \times 4.69 \times 10^{-3})}{\left(\dfrac{10.0 \times 10^{-6}}{1.35 \times 18.8 \times 10^{-6}}\right)^{1/2}}$$

$$= 1.44 \qquad (11.71)$$

$$Z_c = 0.006 + 0.73 \times 10^{-3} \times 50 - 0.24 \times 10^{-3} \times 2.48 \times 50 + 1.22 \times 4.69 \times 10^{-3} = 18.5 \times 10^{-3} \text{ m}^3/\text{m}^2 \qquad (11.75)$$

$$t_L = \frac{18.5 \times 10^{-3} \times 0.52}{4.69 \times 10^{-3}} = 2.05 \text{ s} \qquad (11.73)$$

$$\mathrm{N}_L = (4.13 \times 10^8 \times 4.64 \times 10^{-9})^{0.5} \times (0.21 \times 2.48 + 0.15) \times 2.05 = 1.9 \qquad (11.72)$$

$$D_e = (0.0038 + 0.017 \times 2.13 + 3.86 \times 4.69 \times 10^{-3} + 0.18 \times 10^{-3} \times 50)^2 = 0.0045 \text{ m}^2/\text{s} \qquad (11.77)$$

$$P_e = \frac{0.52^2}{0.0045 \times 2.05} = 29.3 \qquad (11.76)$$

From the McCabe-Thiele diagram, at $x = 0.05$, the slope of the equilibrium line $= 1.0$.

$$V/L = 0.032/0.158 = 0.20$$

$$\text{so, } \frac{mV}{L} = 1.0 \times 0.20 = 0.20$$

$$\frac{\left(\dfrac{mV}{L}\right)}{\mathrm{N}_L} = \frac{0.20}{1.9} = 0.11$$

From Figure 11.15 $E_{mv} = 0.70$

$$\frac{mV}{L} \cdot E_{mv} = 0.2 \times 0.58 = 0.12$$

From Figure 11.16 $E_{mV}/E_{mv} = 1.02$

$$E_{mV} = 0.70 \times 1.02 = 0.714$$

So plate efficiency $= \underline{\underline{71}}$ per cent.

*Note*: The slope of the equilibrium line is difficult to determine at $x = 0.05$, but any error will not greatly affect the value of $E_{mV}$.

### Example 11.13

Calculate the plate efficiency for the plate design considered in Examples 11.11 and 11.12, using Van Winkle's correlation.

### Solution

From Examples 11.12 and 11.11:

$$\begin{aligned}
\rho_L &= 925\ \text{kg/m}^3,\\
\rho_v &= 1.35\ \text{kg/m}^3,\\
\mu_L &= 0.34 \times 10^{-3}\ \text{Ns/m}^2,\\
\mu_v &= 10.0 \times 10^{-6}\ \text{Ns/m}^2,\\
D_{LK} &= D_L = 4.64 \times 10^{-9}\ \text{m}^2/\text{s},\\
h_w &= 50\ \text{mm},\\
FA\ \text{(fractional area)} &= A_h/A_c = \frac{0.038}{0.50} = 0.076,\\
u_v &= \text{superficial vapour velocity} = \frac{0.81}{0.50} = 1.62\ \text{m/s},\\
\sigma_L &= 60 \times 10^{-3}\ \text{N/m}\\
\text{Dg} &= \left(\frac{60 \times 10^{-3}}{0.34 \times 10^{-3} \times 1.62}\right) = 109\\
\text{Sc} &= \left(\frac{0.34 \times 10^{-3}}{925 \times 4.64 \times 10^{-9}}\right) = 79,\\
\text{Re} &= \left(\frac{50 \times 10^{-3} \times 1.62 \times 1.35}{0.34 \times 10^{-3} \times 0.076}\right) = 4232\\
E_{mV} &= 0.07(109)^{0.14}(79)^{0.25}(4232)^{0.08} \qquad (11.69)\\
&= \underline{\underline{0.79}}\ \text{(79 per cent)}
\end{aligned}$$

## 11.14. PACKED COLUMNS

Packed columns are used for distillation, gas absorption, and liquid-liquid extraction; only distillation and absorption will be considered in this section. Stripping (desorption) is the reverse of absorption and the same design methods will apply.

The gas liquid contact in a packed bed column is continuous, not stage-wise, as in a plate column. The liquid flows down the column over the packing surface and the gas or vapour, counter-currently, up the column. In some gas-absorption columns co-current flow is used. The performance of a packed column is very dependent on the maintenance of good liquid and gas distribution throughout the packed bed, and this is an important consideration in packed-column design.