

Example

For the problem specified in the Example above, estimate the number of ideal stages required below an acetone concentration of 0.04 (more volatile component), using the Robinson–Gilliland equation.

Solution:

5.6 Minimum number of stages (Fenske equation)

The Fenske equation (Fenske, 1932) can be used to estimate the minimum stages required at total reflux. The equation applies equally to multicomponent systems and can be written as:

$$\left(\frac{x_i}{x_r}\right)_d = \alpha^{N_m} \left[\frac{x_i}{x_r}\right]_b \quad (5.30)$$

where:

$\frac{x_i}{x_r}$ = the ratio of the concentration of any component i to the concentration of a reference component r , and the suffixes d and b denote the distillate (tops) (d) and the bottoms (b),

N_m = minimum number of stages at total reflux, including the reboiler,

α_i = average relative volatility of the component i with respect to the reference component.

Equation 5.30 can be written in terms of key component to estimate the number of stages:

$$N_m = \frac{\log\left[\frac{x_{LK}}{x_{HK}}\right]_d \left[\frac{x_{HK}}{x_{LK}}\right]_b}{\log \alpha_{LK}} \quad (5.31)$$

where α_{LK} is the average relative volatility of the light key with respect to the heavy key, and x_{LK} and x_{HK} are the light and heavy key concentrations.

Important Notes:

1- The relative volatility is taken as the geometric mean of the values at the column top and bottom temperatures. To calculate these temperatures initial estimates of the compositions must be made, so the calculation of the minimum number of stages by the Fenske equation is a trial-and-error procedure.

2- If there is a wide difference between the relative volatilities at the top and bottom of the column the use of the average value in the Fenske equation will underestimate the number of stages. In these circumstances, a better estimate can be made by calculating the number of stages in the rectifying and stripping sections separately;

taking the feed concentration as the base concentration for the rectifying section and as the top concentration for the stripping section, and estimating the average relative volatilities separately for each section. This procedure will also give an estimate of the feed point location.

Keep in mind...

When the number of stages is known, Equation 5.30 can be written in simple form as follows:

$$\frac{d_i}{b_i} = \alpha_i^{Nm} \left[\frac{d_i}{b_i} \right] \quad (5.32)$$

where d_i and b_i are the flow-rates of the component i in the tops and bottoms, d_r and b_r are the flow-rates of the reference component in the tops and bottoms.

Note:

Equation 5.32 can be used to estimate the split of components between the top and bottom of the column at total reflux.

From the material balance of each component:

$$f_i = d_i + b_i \quad (5.33)$$

where f_i is the flow rate of component i in the feed.

5.7 Minimum reflux ratio

Colburn (1941) and Underwood (1948) have derived equations for estimating the minimum reflux ratio for multicomponent distillations. As the Underwood equation is more widely used it is presented in this section. The equation can be stated in the form:

$$\sum \frac{\alpha_i x_{id}}{\alpha_i - \theta} = R_m + 1 \quad (5.34)$$

where:

α_i = description

R_m = the minimum reflux ratio,

$x_{i,d}$ = concentration of component i in the tops at minimum reflux

θ = is the root of the equation:

$$\sum \frac{\alpha_i x_{i,f}}{\alpha_i - \theta} = 1 - q \quad (5.35)$$

where $x_{i,f}$ is the concentration of component i in the feed, and q depends on the condition of the feed.

The value of θ must lie between the values of the relative volatility of the light and heavy keys, and is found by trial and error.

Note:

The values determined at total reflux, from the Fenske equation, can be used. A better estimate can be obtained by replacing the number of stages at total reflux by an estimate of the actual number; a value equal to $N_m/0.6$ is often used.

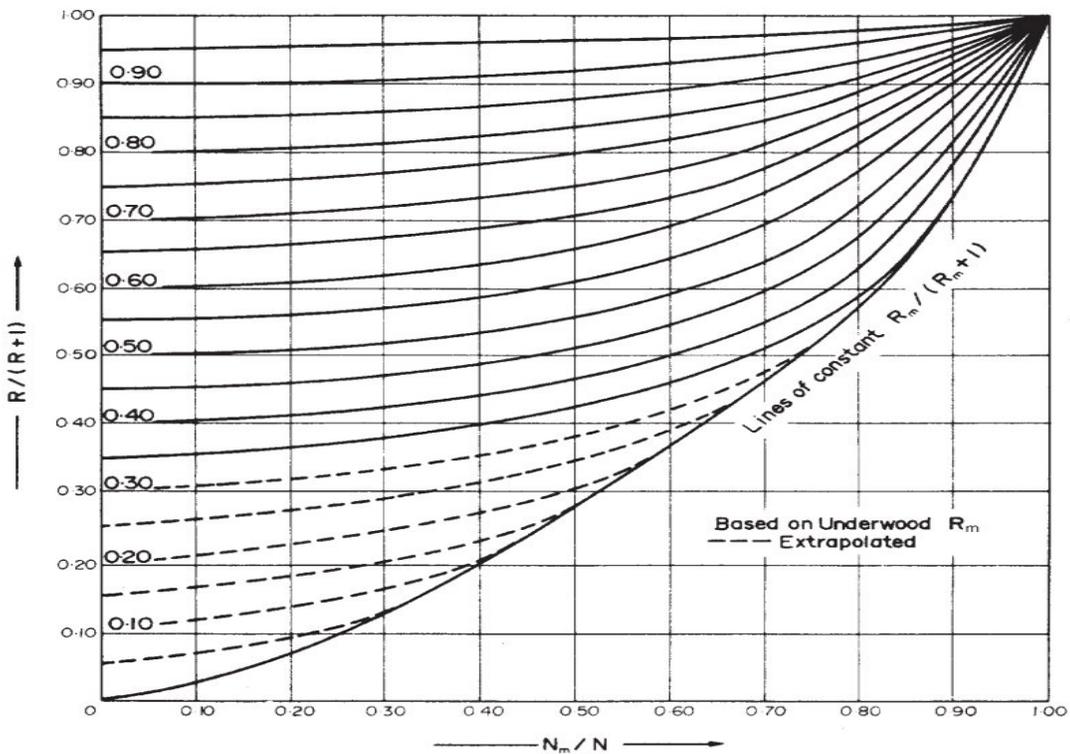


Figure 5.5: Erbar-Maddox correlation

5.8 Feed-point location

A limitation of the empirical methods, is that they do not give the feed-point location.

An alternative approach is to use the empirical equation given by Kirkbride (1944):

$$\log\left[\frac{N_r}{N_s}\right] = 0.206 \log\left[\left(\frac{B}{D}\right) \left(\frac{x_{f,HK}}{x_{f,LK}}\right) \left(\frac{x_{B,LK}}{x_{d,LK}}\right)^2\right] \quad (5.36)$$

where:

N_r number of stages above the feed, including any partial condenser,

N_s number of stages below the feed, including the reboiler,

B molar flow bottom product,

D molar flow top product,

$x_{f,HK}$ concentration of the heavy key in the feed,

$x_{f,LK}$ concentration of the light key in the feed,

$x_{d,HK}$ concentration of the heavy key in the top product,

$x_{b,LK}$ concentration of the light key if in the bottom product.

Example:

Estimate the number of ideal stages needed in the butane-pentane splitter defined by the compositions given in the table below. The column will operate at a pressure of 8.3 bar, with a reflux ratio of 2.5. The feed is at its boiling point. The data available in the Table below.

Equilibrium constants were taken from Table below. Relative volatilities:

	Feed (<i>f</i>)	Tops (<i>d</i>)	Bottoms (<i>b</i>)
Propane, C ₃	5	5	0
i-Butane, iC ₄	15	15	0
n-Butane, nC ₄	25	24	1
i-Pentane, iC ₅	20	1	19
n-Pentane, nC ₅	35	0	35
	100	45	55 kmol

	Top	Bottom	Average
Temp. °C	65	120	
C ₃	5.5	4.5	5.0
iC ₄	2.7	2.5	2.6
(LK) nC ₄	2.1	2.0	2.0
(HK) iC ₅	1.0	1.0	1.0
nC ₅	0.84	0.85	0.85

Solution:

5.9 Plate efficiency

The concept of a stage efficiency is used to link the performance of practical contacting stages to the theoretical equilibrium stage.

Three principal definitions of efficiency are used:

1- Murphree plate efficiency (Murphree, 1925), defined in terms of the vapour compositions by:

Definition: The Murphree plate efficiency is the ratio of the actual separation achieved to that which would be achieved in an equilibrium stage.

$$E_{mV} = \frac{y_n - y_{n-1}}{y_e - y_{n-1}} \quad (5.37)$$

where y_e is the composition of the vapour that would be in equilibrium with the liquid leaving the plate.

Definition: The Murphree plate efficiency is the ratio of the actual separation achieved to that which would be achieved in an equilibrium stage.

2- Point efficiency (Murphree point efficiency). If the vapour and liquid compositions are taken at a point on the plate, equation 5.37 gives the local or point efficiency, E_{mV} .

3- Overall column efficiency. This is sometimes confusingly referred to as the overall plate efficiency.

$$E_o = \frac{\text{number of ideal stages}}{\text{number of real stages}} \quad (5.38)$$

For the idealised situation where the operating and equilibrium lines are straight, the overall column efficiency and the Murphree plate efficiency are related by an equation derived by Lewis (1936):

$$E_o = \frac{\log[1 + E_{mV}(\frac{mV}{L} - 1)]}{\log(mV/L)} \quad (5.39)$$

where:

m = slope of the equilibrium line,

V = molar flow rate of the vapor

L = molar flow rate of the liquid

5.10 O'Connell's correlation

The overall column efficiency is correlated with the product of the relative volatility of the light key component (relative to the heavy key) and the molar average viscosity of the feed, estimated at the average column temperature.

$$E_o = 51 - 32.5 \log(\mu_a \alpha_a) \quad (5.40)$$

where:

μ_a = the molar average liquid viscosity, mNs/m²

α_a = average relative volatility of the light key.

Note:

On data obtained with hydrocarbon systems, but includes some values for chlorinated solvents and water-alcohol mixtures O'Connell's correlation was mainly based.

5.11 Approximate column sizing

5.11.1 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 column and where head room is restricted. 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.

When larger spacing between the plates are needed?

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

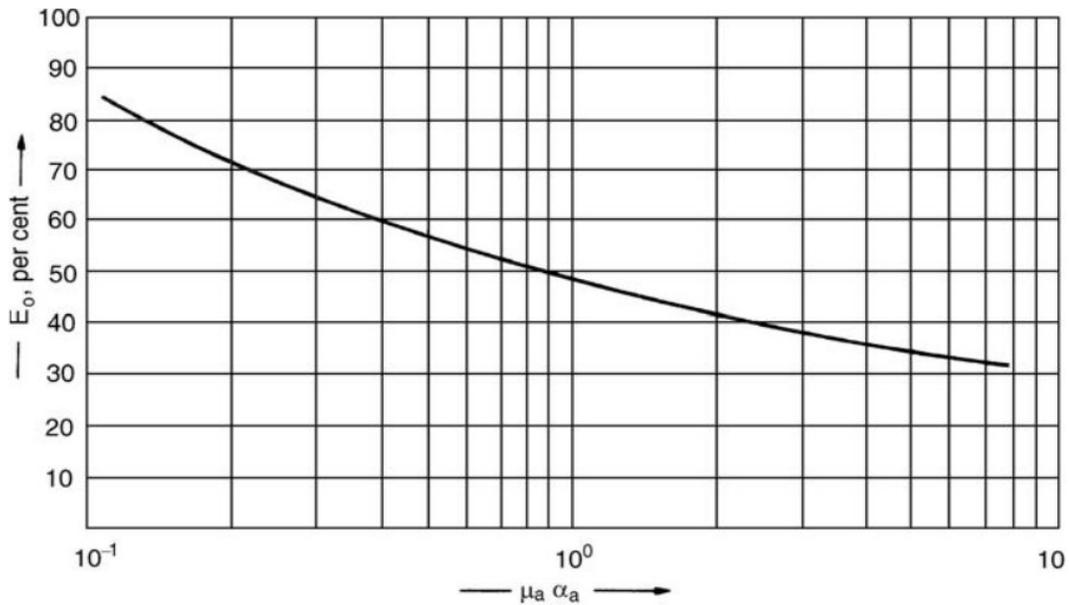


Figure 5.6: Distillation column efficiencies (bubble-caps) (after O’Connell, 1946)

5.11.2 Column diameter

- ✓ The vapor flow rate is the main factor to determine the column diameter
- ✓ This approximate estimate of the diameter would be revised when the detailed plate design is undertaken.

Why vapor flow rate is the main factor to determine the column diameter?

The vapour velocity must be below that which would cause excessive liquid entrainment or a high-pressure drop.

In order to estimate the maximum allowable superficial vapour velocity, and hence the column area and diameter, the following equation can be used:

$$u_v = (-0.171l^2 + 0.27l_t - 0.047) \left[\frac{(\rho_L - \rho_v)}{\rho_v} \right]^{\frac{1}{2}} \quad (5.41)$$

where:

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 can be estimated as follows:

$$D_c = \sqrt{\frac{4V_w}{\pi\rho_v u_v}} \quad (5.42)$$

V_w = the maximum vapour rate, kg/s.

5.12 Plate contactors

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

Describe the flowing of liquid in cross-flow plates and plot it?

A typical layout is shown in Figure 5.7. 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.

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

5.12.1 Sieve plate (perforated plate)

What are the characteristics of the sieve plate?

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

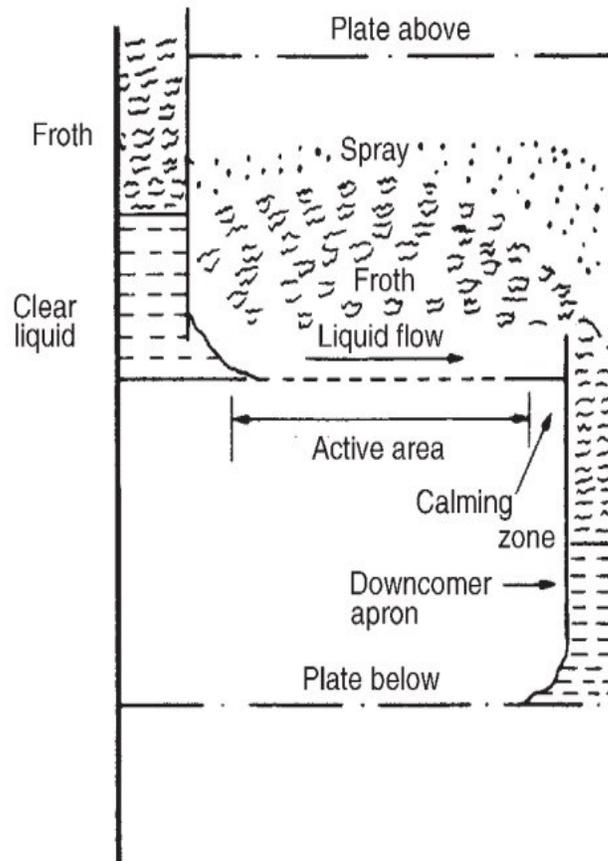


Figure 5.7: Typical cross-flow plate (sieve)

5.12.2 Bubble-cap plates

- 1- In which the vapour passes up through short pipes, called risers, covered by a cap with a serrated edge, or slots.
- 2- The bubble-cap plate is the traditional, oldest, type of cross-flow plate, and many different designs have been developed.
- 3- Standard cap designs would now be specified for most applications.
- 4- 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.

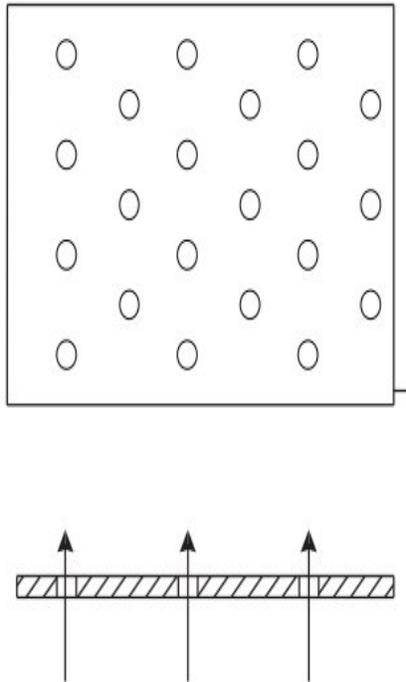


Figure 5.8: Sieve plate

5.12.3 Valve plates (floating cap plates)

- 1- Valve plates are proprietary designs.
- 2- They are essentially sieve plates with large-diameter holes covered by movable flaps, which lift as the vapour flow increases.
- 3- 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.

Note:- Some very elaborate valve designs have been developed, but the simple type shown in Figure 5.10 is satisfactory for most applications.

5.12.4 Liquid flow pattern

Classify the cross flow trays according to the number of liquid passes and sketch them?

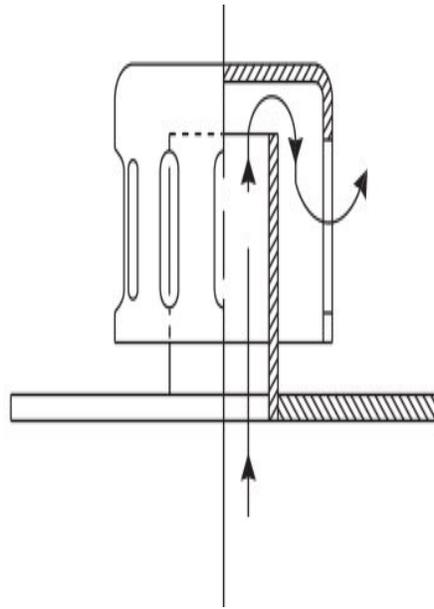


Figure 5.9: Bubble-cap

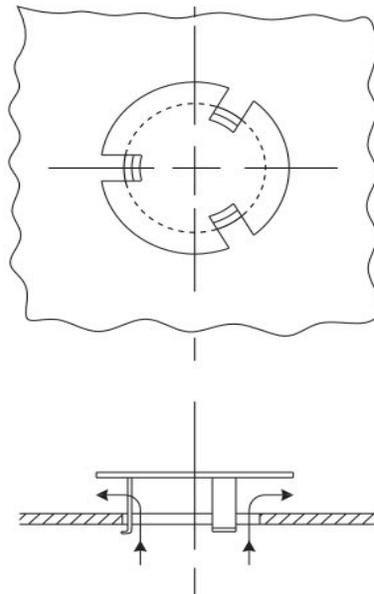


Figure 5.10: Simple valve

Cross-flow trays are also classified according to the number of liquid passes on the plate according to the following:-

Single pass plate: The design shown in Figure 5.11a

Reverse flow plates For low liquid flow rates as shown in Figure 5.11c. 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 plate: the liquid stream is sub-divided by using several downcomers, are used for high liquid flow-rates and large diameter columns.

Double pass plate: The design is shown in Figure 5.11c

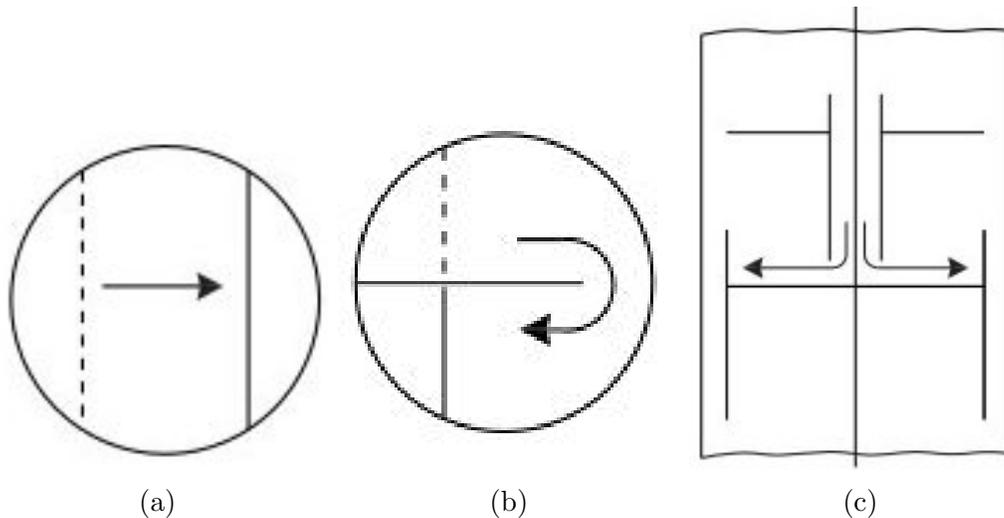


Figure 5.11: Liquid flow patterns on cross-flow trays. (a) Single pass (b) Reverse flow (c) Double pass

5.12.5 Selection of plate type

What are the factors that must be considered when we choose the plate?

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 stable operating range).

1- **Bubble-cap plates** have a positive liquid seal and can therefore operate efficiently at very low vapour rates.

2- **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 percent to 120 percent of design capacity.

3- **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.

Compare between the plates in 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.

5.13 Plate construction

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.