

5.3 Calculation of bubble point and dew point

Bubble point: a saturated liquid is at its bubble point (any rise in temperature will cause a bubble of vapour to form).

$$\text{Bubble point: } \sum y_i = \sum Kx_i \quad (5.6)$$

Dew point: a saturated vapour is at its dew point (any drop in temperature will cause a drop of liquid to form).

$$\text{Dew point: } \sum x_i = \sum y_i/K \quad (5.7)$$

5.4 Equilibrium Flash distillation

Where the feed stream is separated into liquid and vapors at equilibrium, the process can be called an equilibrium flash process.

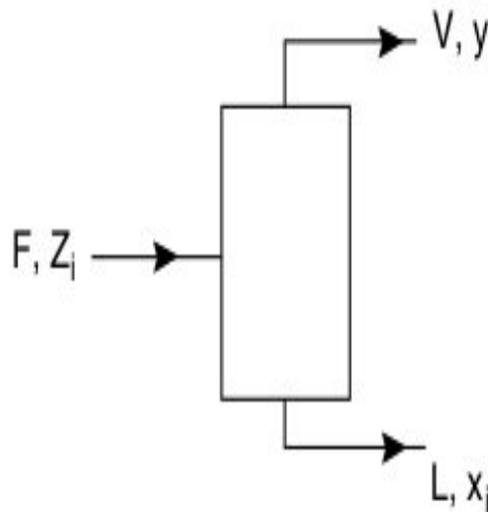


Figure 5.2: Flash distillation

Material balance, for any component, i :

$$Fz_i = Vy_i + Lx_i \quad (5.8)$$

$$Fz_i = VKx_i + Lx_i \quad (5.9)$$

Energy balance, total stream enthalpies:

$$Fh_f = VH + Lh \quad (5.10)$$

Equation 5.9 ca be written in a useful manner:

$$= Lx_i \left[\frac{V}{L} K_i + 1 \right] \quad (5.11)$$

From which:

$$L = \sum_i \frac{Fz_i}{\frac{VK_i}{L} + 1} \quad (5.12)$$

Similarly:

$$V = \sum_i \frac{Fz_i}{\frac{L}{VK_i} + 1} \quad (5.13)$$

Notes:

- The group L/VK_i is known as **the absorption factor** A_i . It is the ratio of the mols of any component in the liquid stream to the mols in the vapour stream.
- The group VK_i/L is called **the stripping factor** S_i , and is the reciprocal of the absorption factor.
- Flash calculations are often needed to determine the condition of the feed to a distillation column and, occasionally, to determine the flow of vapour from the reboiler, or condenser if a partial condenser is used.

Example:

A feed to a column has the composition given in the table below, and is at a pressure of 14 bar and a temperature of 60 °C. Calculate the flow and composition of the liquid and vapour phases.

Extra information taken from the appendix:

Feed	kmol/h	z_i
methan (C_2)	20	0.25
propane (C_3)	20	0.25
iso-butan (C_4)	20	0.25
npentan(C_5)	20	0.25

Feed	kmol/h	z_i	K_i
methan (C_2)	20	0.25	3.8
propane (C_3)	20	0.25	1.3
iso-butan (C_4)	20	0.25	0.43
npentan(C_5)	20	0.25	0.16

Solution:

5.5 Design methods for binary system

Figure 5.3 shows the flows and compositions in the top part of a column. Taking the system boundary to include the stage n and the condenser, gives the following equations: Material Balance:

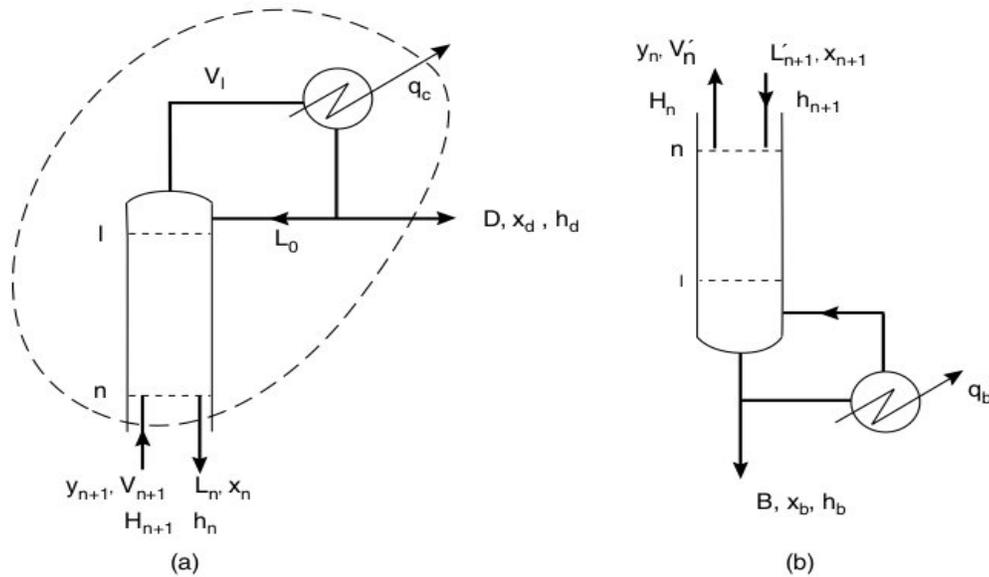


Figure 5.3: Column flows and compositions (a) Above feed (b) Below feed

$$\text{Total flows: } V_{n+1} = L_n + D \quad (5.14)$$

$$\text{For either component: } V_{n+1}y_{n+1} = L_nx_n + Dx_d \quad (5.15)$$

Energy balance:

$$\text{Total stream enthalpies: } V_{n+1}H_{n+1} = L_nh_n + Dh_d + q_c \quad (5.16)$$

where q_c is the heat removed in the condenser.

Combining equations 5.14 and 5.15 gives:

$$y_{n+1} = \frac{L_n}{L_n + D}x_n + \frac{D}{L_n + D}x_d \quad (5.17)$$

Combining equations 5.14 and 5.16 gives:

$$\text{Total stream enthalpies: } (L_n + D)H_{n+1} = L_n h_n + D h_d + q_c \quad (5.18)$$

Note:

At constant pressure, the stage temperatures will be functions of the vapour and liquid compositions only (dew and bubble points) and the specific enthalpies will therefore also be functions of composition.

$$H = f(y)$$

$$h = f(x)$$

The same equation can be written for the stripping section as shown in Figure 5.3b:

$$x_{n+1} = \frac{V'_n}{V'_n + B}y_n + \frac{D}{V'_n + B}x_b \quad (5.19)$$

The same equation for the energy balance:

$$L'_{n+1}h_{n+1} = (V'_n + B)h_{n+1} = V'_n H_n + B h_b - q_b \quad (5.20)$$

Lewis-Sorel method (equimolar overflow)

The molar liquid and vapour flow rates are taken as constant in the stripping and rectifying sections.

What is the equimolar overflow condition?

The molar vapour and liquid flows from each stage are constant. This will be true if:

- ◆ The component molar latent heats of vaporisation are the same.
- ◆ The specific heats, are constant over the range of temperature in the column.

- ◆ There is no significant heat of mixing.
- ◆ The heat losses are negligible.

These conditions are substantially true for practical systems when the components form near-ideal liquid mixtures.

Keep in mind!

The number of stages estimated by assuming equimolar overflow is usually small, when the latent heat are substantially different, but acceptable.

For equimolar overflow:

The material balance:

$$y_{n+1} = \frac{L}{L + D}x_n + \frac{D}{L + D}x_d \quad (5.21)$$

$$x_{n+1} = \frac{V'}{V' + B}y_n + \frac{B}{V' + B}x_b \quad (5.22)$$

where L is the constant liquid flow in the rectifying section D the reflux flow, L_0 , and V_0 is the constant vapour flow in the stripping section.

Equation 5.21 and Equation 5.22 can be written in an alternative way:

$$y_{n+1} = \frac{L}{V}x_n + \frac{D}{V}x_d \quad (5.23)$$

$$y_n = \frac{L'}{V'}x_{n+1} - \frac{B}{V'}x_b \quad (5.24)$$

where V is the constant vapour flow in the rectifying section ($V=L+D$); and \dot{L} is the constant liquid flow in the stripping section ($\dot{L}=\dot{V}+B$).

These equations are linear, with slopes L/V and \dot{L} / \dot{V} .

McCabe-Thiele method

Equation 5.23 and 5.24 and the equilibrium relationship can be solved by the graphical method developed by McCabe and Thiele.

The McCabe-Thiele method can be used for the design of columns with side streams and multiple feeds. The liquid and vapour flows in the sections between the feed and take-off points are calculated and operating lines drawn for each section.

Procedure:

- 1 Plot the vapour-liquid equilibrium curve from data available at the column operating pressure. In terms of relative volatility:

$$y = \frac{\alpha x}{(1 + (\alpha - 1)x)} \quad (5.25)$$

where α is the geometric average relative volatility of the lighter (more volatile) component with respect to the heavier component (less volatile).

- 2 Make a material balance over the column to determine the top and bottom compositions, x_d and x_b , from the data given.
- 3 The top and bottom operating lines intersect the diagonal at x_d and x_b respectively; mark these points on the diagram.
- 4 The point of intersection of the two operating lines is dependent on the phase condition of the feed. The line on which the intersection occurs is called the q line. The q line is found as follows:

1- Calculate the value of the ratio q given by:

$$q = \frac{\text{heat to vaporise 1 mole of feed}}{\text{molar latent heat of feed}} \quad (5.26)$$

2- Plot the q line, slope $(q/q - 1)$, intersecting the diagonal at z_f (the feed composition).

- 5 Select the reflux ratio and determine the point where the top operating line extended cuts the y axis:

$$\phi = \frac{x_d}{1 + R} \quad (5.27)$$

- 6 Draw in the top operating line, from x_d on the diagonal to ϕ .

- 7 Draw in the bottom operating line; from x_b on the diagonal to the point of intersection of the top operating line and the q line.
- 8 Starting at x_d or x_b , step off the number of stages.

Note:

The feed point should be located on the stage closest to the intersection of the operating lines.

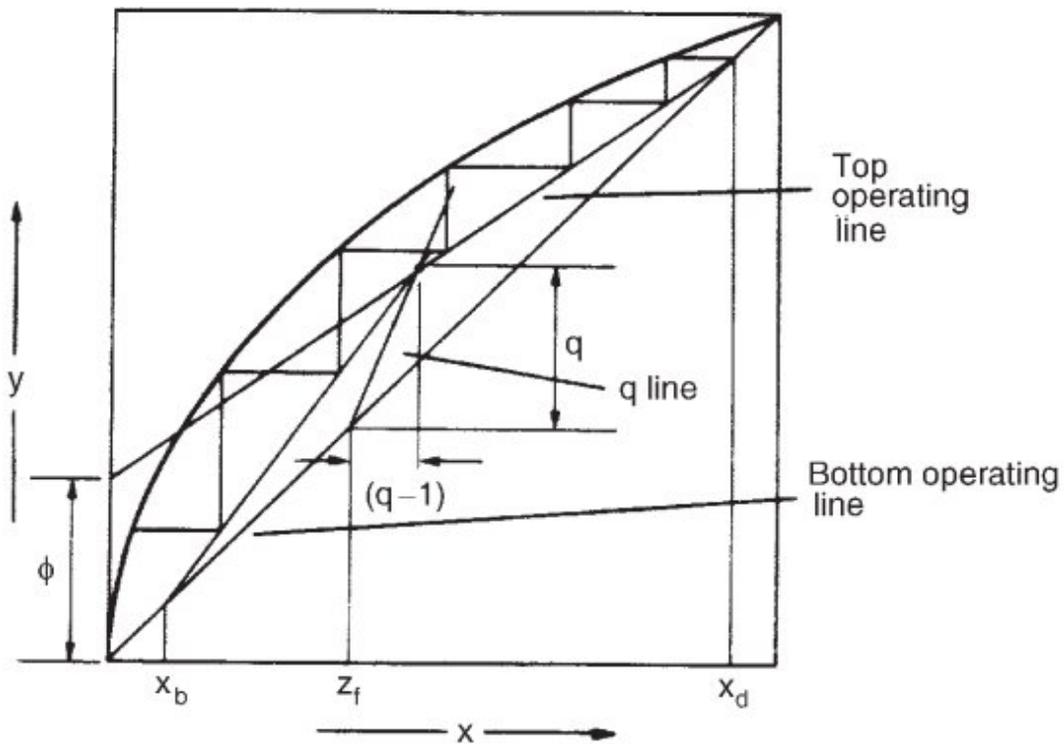


Figure 5.4: McCabe-Thiele diagram

The McCabe-Thiele method can be used when the condition of equimolar overflow cannot be assumed, but the operating lines will not then be straight. They can be drawn by making energy balances at a sufficient number of points to determine the approximate slope of the lines.

Low products concentration:

When concentrations of the more volatile component of either product is very low the steps on the McCabe-Thiele diagram become very small and difficult to plot.

This problem can be overcome by replotting the top or bottom sections to a larger scale, or on log-log paper.

Note:

The number of stages required can be calculated using the equations given by Robinson and Gilliland (1950) when the concentration is too small.

For the stripping section:

$$N_s^* = \frac{\left[\frac{(\frac{K'}{s'} - 1)(\frac{x'_r}{x_b} - 1)}{\frac{1}{s'}(K' - 1)} + 1 \right]}{\log \frac{K'}{s'}} + 1 \quad (5.28)$$

where:

N_s^* = number of ideal stages required from x_b to some reference point x_r

x_b = mol fraction of the more volatile component in the bottom product

x'_r = mol fraction of more volatile component at the reference point

s' = slope of the bottom operating line,

K' = equilibrium constant for the more volatile component.

For the rectifying section:

$$N_r^* = \frac{\log \left[\frac{(1-s) + x_r/x_d(s-k)}{1-K} \right]}{\log \left(\frac{s}{K} \right)} - 1 \quad (5.29)$$

where:

N_r^* = number of stages required from some reference point x_r to the x_d

x_d = mol fraction of the least volatile component in the top product,

x_r = mol fraction of least volatile component at reference point,

K = equilibrium constant for the least volatile component,

s = slope of top operating line.

Note: at low concentrations $K = \alpha$

Example:

Acetone is to be recovered from an aqueous waste stream by continuous distillation. The feed will contain 10 per cent w/w acetone. Acetone of at least 98 per cent purity is wanted, and the aqueous effluent must not contain more than 50 ppm acetone. The feed will be at 20 °C. Estimate the number of ideal stages required.

The equilibrium data available for the acetone-water system are presented in Table below:

Mol fraction x , liquid	0.00	0.05	0.10	0.15	0.20	0.25	0.30
Acetone y , vapour	0.00	0.6381	0.7301	0.7716	0.7916	0.8034	0.8124
bubble point °C	100.0	74.80	68.53	65.26	63.59	62.60	61.87

x	0.35	0.40	0.45	0.50	0.55	0.60	0.65
y	0.8201	0.8269	0.8376	0.8387	0.8455	0.8532	0.8615
°C	61.26	60.75	60.35	59.95	59.54	59.12	58.71

x	0.70	0.75	0.80	0.85	0.90	0.95
y	0.8712	0.8817	0.8950	0.9118	0.9335	0.9627
°C	58.29	57.90	57.49	57.08	56.68	56.30

Solution: