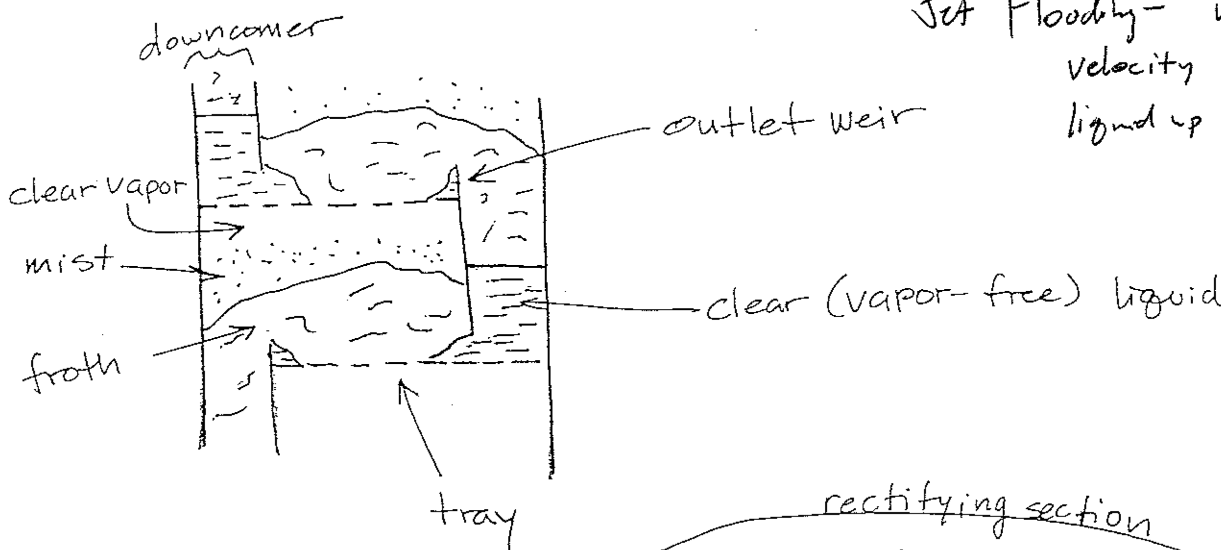
Distillation

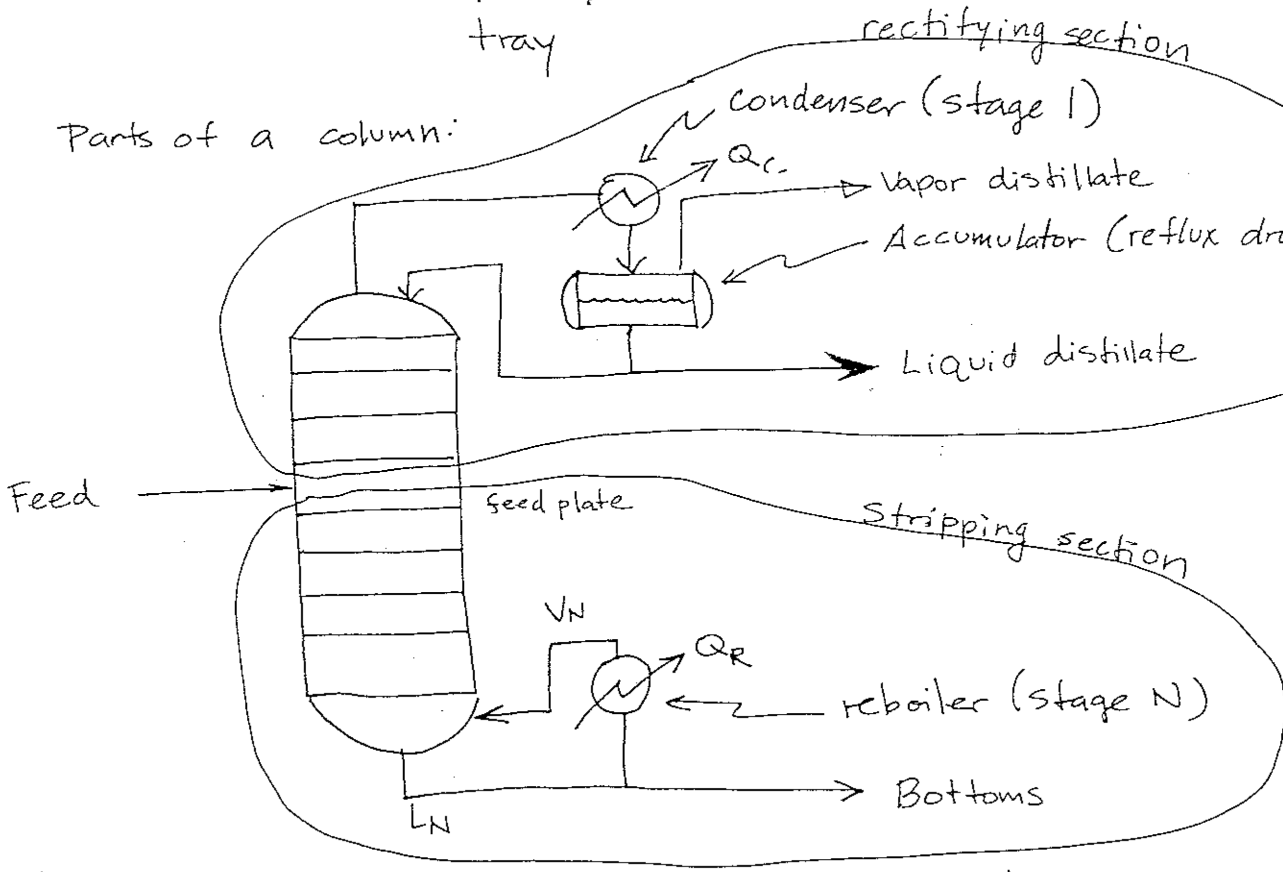
Vapor Velocity causes all flooding

- Distillation refers to the physical separation of a mixture into two or more liquids that have different boiling points.
- A distillation column consists of a space for contacting vapor and liquid for the purpose of effecting mass transfer between the two phases. volatility

Jet Flooding – Vapor velocity brings liquid up to next stage



Parts of a column:



ottom Stripping section: from feed tray down to reboiler

op rectifying section: condenser down to feed tray

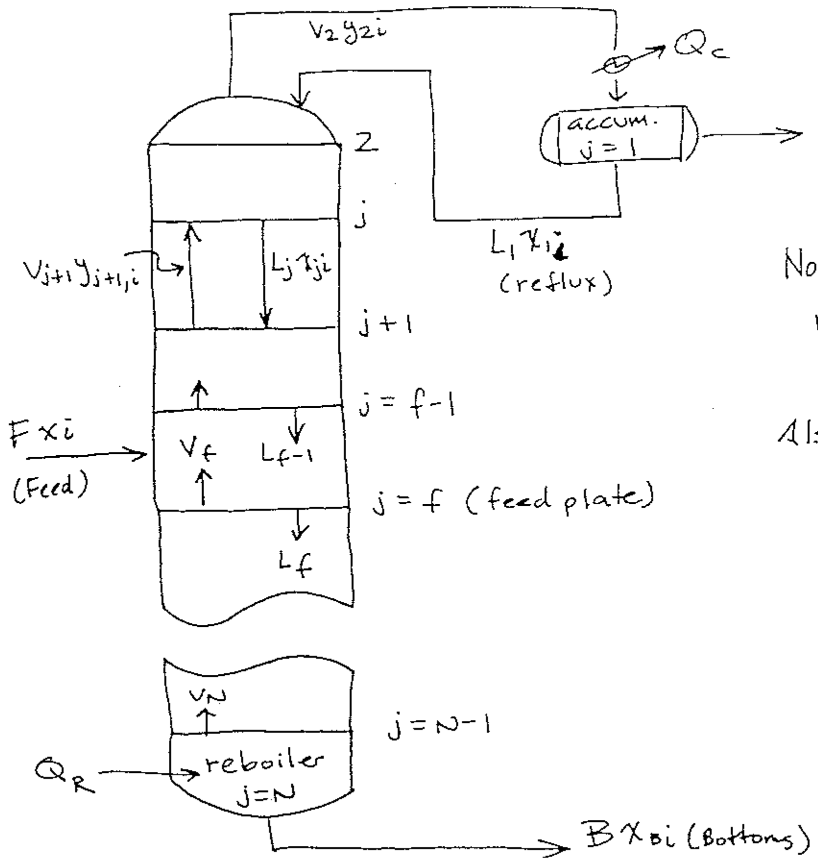
Distillation - Tray-by-Tray Calculations (Steady-State)

Feed:

tray with closest composition

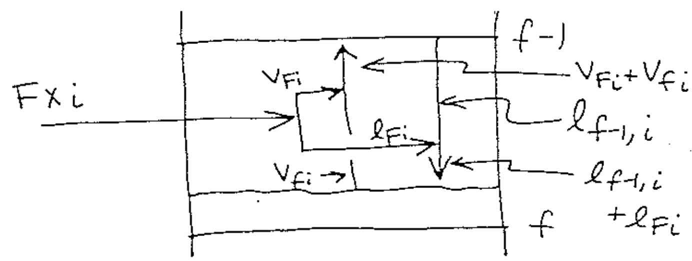
How to compute separation?

Model a distillation column as several flashes in series.

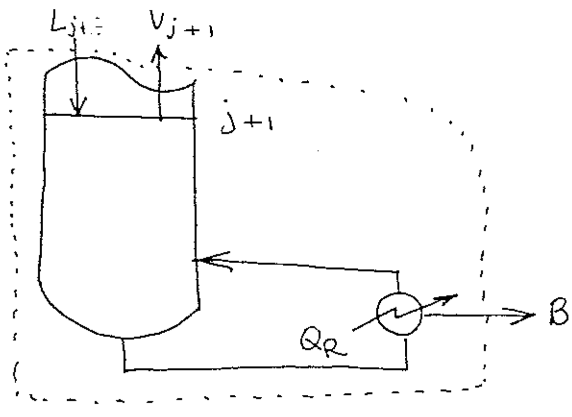


Note: V_j, L_j denote vapor or liquid rate leaving stage j.

Also, note flashing of the feed:



Balances are performed around the entire stripping or rectifying section up to a given tray. e.g. in the stripping section:



Component material balance:

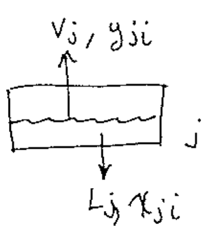
$$V_{j+1}\, y_{j+1,i} = L_j x_{ji} - B x_{Bi}$$

Enthalpy balance:

$$V_{j+1} H_{j+1} = L_j h_j - B h_B + Q_R$$

(H = vapor enthalpy, h = liquid enthalpy)

Also, the vapor and liquid leaving a tray are in equilibrium with each other:



$$y_{ji} = K_{ji} x_{ji} \qquad \left(K_{ji} = \frac{P_i^{sat}}{P}\right)$$

$$\sum_{i=1}^{c} y_{ji} = 1$$

$$\sum_{i=1}^{c} x_{ji} = 1$$

The equations needed to describe a distillation column are:

equilibrium relationships
$$\left\{\begin{array}{ll} y_{ji} = K_{ji} x_{ji} & j=1,2,\dots N \\ \sum_i^c y_{ji} = 1 & j=1,2,\dots N \\ \sum_i^c x_{ji} = 1 & j=1,2,\dots N \end{array}\right.$$

material balances
$$\left\{\begin{array}{ll} V_{j+1} y_{j+1,i} = L_j x_{ji} + D x_{Di} & j=1,2,\dots f-2 \text{ (rectifying)} \\ V_f y_{fi} + V_F y_{Fi} = L_{f-1} x_{f-1,i} + D x_{Di} & j = f-1 \text{ (one above feed)} \\ V_{j+1} y_{j+1,i} = L_j x_{ji} - B x_{Bi} & j = f, f+1, \dots N-1 \text{ (stripping)} \\ F x_i = D x_{Di} + B x_{Bi} & \text{overall} \end{array}\right.$$

enthalpy balances
$$\left\{\begin{array}{ll} V_{j+1} H_{j+1} = L_j h_j + D H_D + Q_c & j=1,2,\dots f-2 \\ V_f H_f + V_F H_F = L_{f-1} h_{f-1} + D H_D + Q_c & j=f-1 \\ V_{j+1} H_{j+1} = L_j h_j - B h_B + Q_R & j=f,f+1,\dots N-1 \\ F H_F = B h_B + D H_D + Q_c - Q_R & \text{overall} \end{array}\right.$$

$N(2c+3)$ eqns

Unknowns are:

Vapor and liquid mole fractions	$2cN$ (# components)
total flow rates	$2N$
temperatures	N
Reboiler & condenser duties	2
column pressure	1
	$N(2c+3)+3$ unk.

Three things about the column must therefore be specified.
eg. pressure, reflux rate (L_1), and distillate rate (D)

There are a number of methods for solving these. Most involve an (almost) diagonal matrix at some point.

- Theta Method (θ is a fudge factor used to drive to column to mass bal.)
- 2N Newton-Raphson (lots of fun)

Distillation- Use of the McCabe-Thiele Method

The McCabe-Thiele method represents mass balance equations as straight lines on an equilibrium curve.

First, we assume that, in each of the sections, the vapor and liquid rates leaving each tray are constant. i.e.

$$L_1 = L_2 = \dots = L_{f-1} = L$$
$$V_1 = V_2 = \dots = V_{f-1} = V$$
$$\bar{L}_f = \bar{L}_{f+1} = \dots \bar{L}_N = \bar{L}$$
$$\bar{V}_f = \bar{V}_{f+1} = \dots = \bar{V}_N = \bar{V}$$

← Bars denote stripping section.

$L_{st} = \phi$ all stages
$V_{st} = \phi$ all stgs

This assumption is known as <u>constant molar overflow</u>.

liq./vapor rates the same in two sections

In the rectifying section, for stage n, we have:

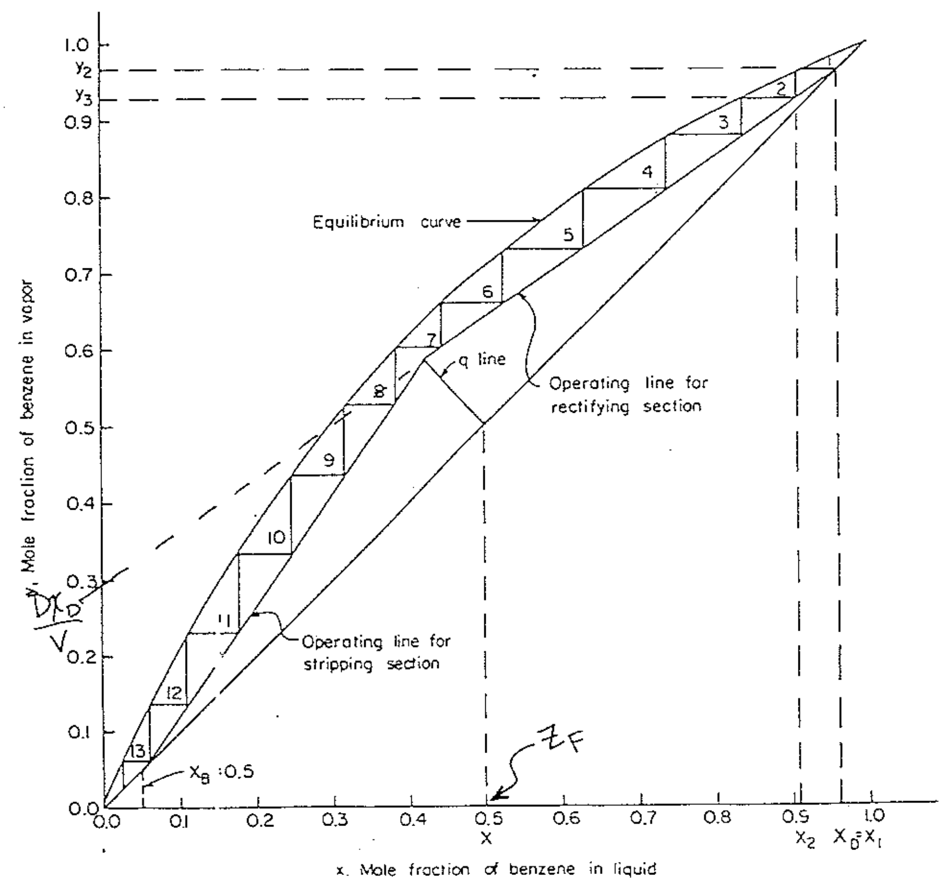
$$y_n = \frac{L}{V} x_{n+1} + \frac{D x_D}{V} \quad \left(\text{describes a line, slope} = \frac{L}{V},\ \text{int} = \frac{D x_D}{V}\right)$$

In the stripping section:

$$y_n = \frac{\bar{L}}{\bar{V}} x_{n+1} - \frac{B x_B}{\bar{V}} \quad \left(\text{slope} = \frac{\bar{L}}{\bar{V}},\ \text{int} = \frac{-B x_B}{\bar{V}}\right)$$

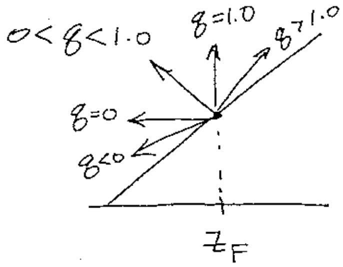
Also, the maximum possible separation,

$$y_n = x_{n+1} \quad \text{gives us the 45° line}$$



Steps for creating a McCabe-Thiele Diagram.

1. Construct x_1, y_1 plot.
2. Draw 45° line
3. Place feed location on x-axis
4. Draw q-line. Start from 45° line at $x = z_F$. The slope is determined by: $y = \frac{q}{q-1} x - \frac{z_F}{q-1}$



q is a stream property "quality" and is sort of like liquid fraction:

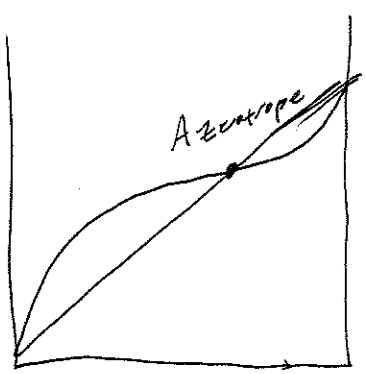
$q = 1.0$ sat. liquid
$q = 0$ sat. vapor
$q > 1$ subcooled liquid
$q < 0$ superheated vapor

q can be estimated as: $\dfrac{(\text{heat required to fully vaporize one mole of feed})}{(\text{molar heat of vaporization})}$

5. Pick x_D, distillate purity.
6. Draw rectifying section operating line. Start from x_D and 45° line and draw line through the y-axis at $\frac{x_D D}{V}$. Note that, due to the CMO assumption, the slope of this line is trivially related to the reflux ratio (RR).

$$\frac{L}{V} = \left(\frac{V}{L}\right)^{-1} = \left(\frac{V_2}{L_1}\right)^{-1} = \left(\frac{L_1 + D}{L_1}\right)^{-1} = \left(1 + \frac{1}{RR}\right)^{-1} = \frac{RR}{1+RR}$$

7. Pick x_B, bottoms purity.
8. The rectifying section op. line should cross the q-line somewhere between the eqbm line and 45° line (If not – pinch point!). From this intersection, draw a straight line to intersect the y-axis at $-x_B \frac{B}{\bar{V}}$. (or, you can stop at $x = y = x_B$.) This is the stripping section operating line.
9. Starting from x_D and 45° line, begin stepping down stages between the eqbm line and operating line. Continue until you cross $x = x_B$.
10. Take one horizontal step = 1 theoretical stage.



Other Uses of McCabe - Thiele Diagram

Minimum number of trays.

The operating line becomes the 45° line.

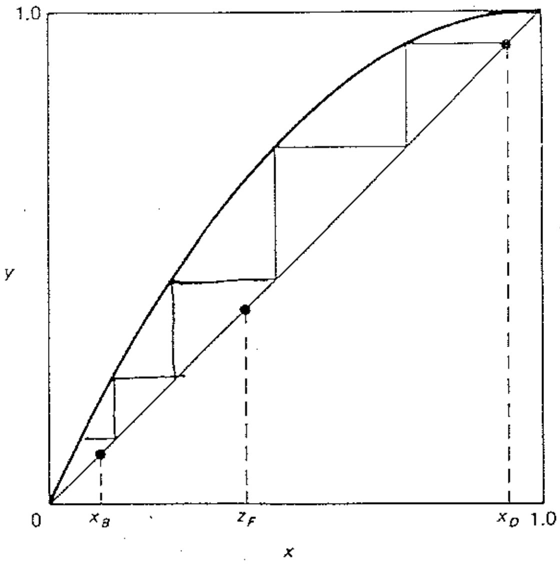


Figure 9-11 McCabe–Thiele construction for minimum trays

minimum reflux rate

~~[illegible]~~ An intercept of the operating line with the equilibrium line means an infinite number of trays will be required. The first place that this happens will give the minimum refluy ~~[illegible]~~ rate.

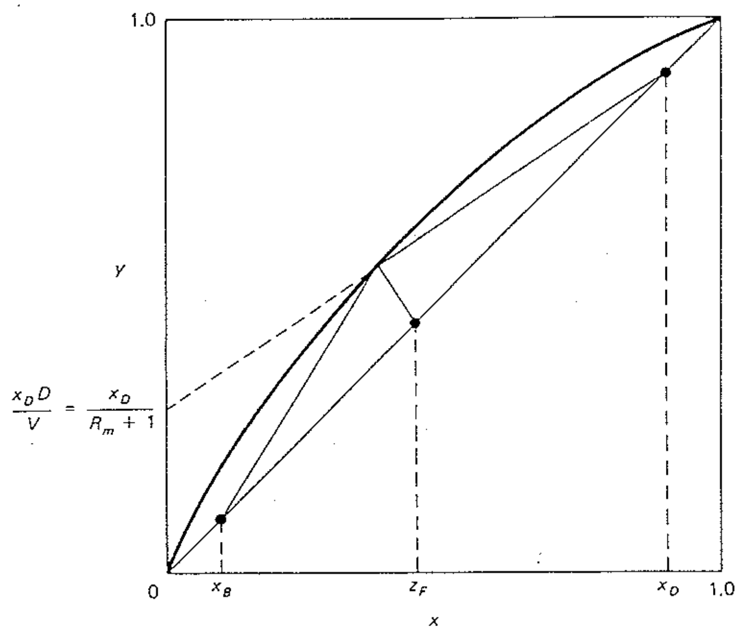


Figure 9-13 Determination of minimum reflux rate on a McCabe–Thiele

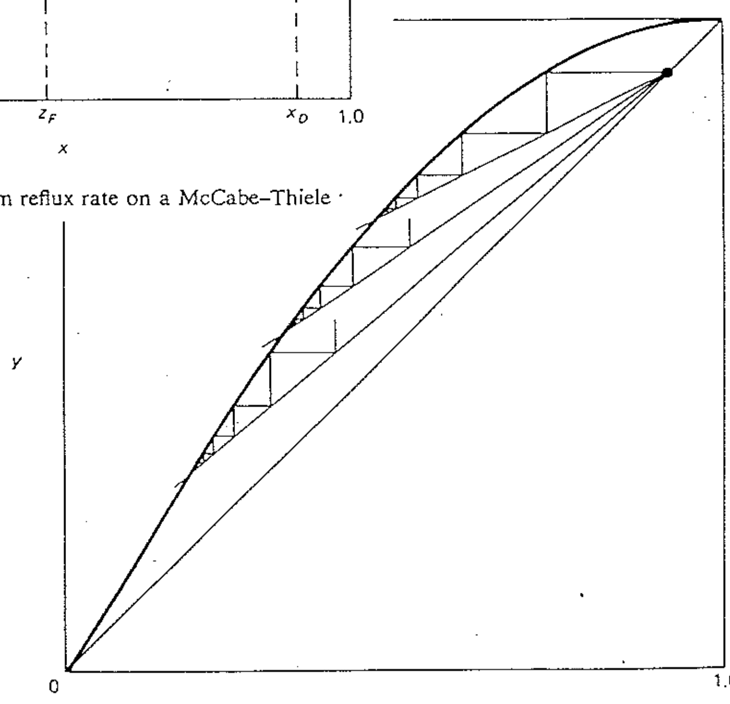


Figure 9-12 McCabe–Thiele construction showing infinite plates

Final Word

While McCabe-Thiele may only be valid for binary distillation, reasonable back-of-envelope estimates can be made by separating a mixture into heavy key and light key, and making a McCabe-Thiele plot to separate between them.