Distillation

Processos de Separação

LEQB

2023/2024

McCabe Thiele Method

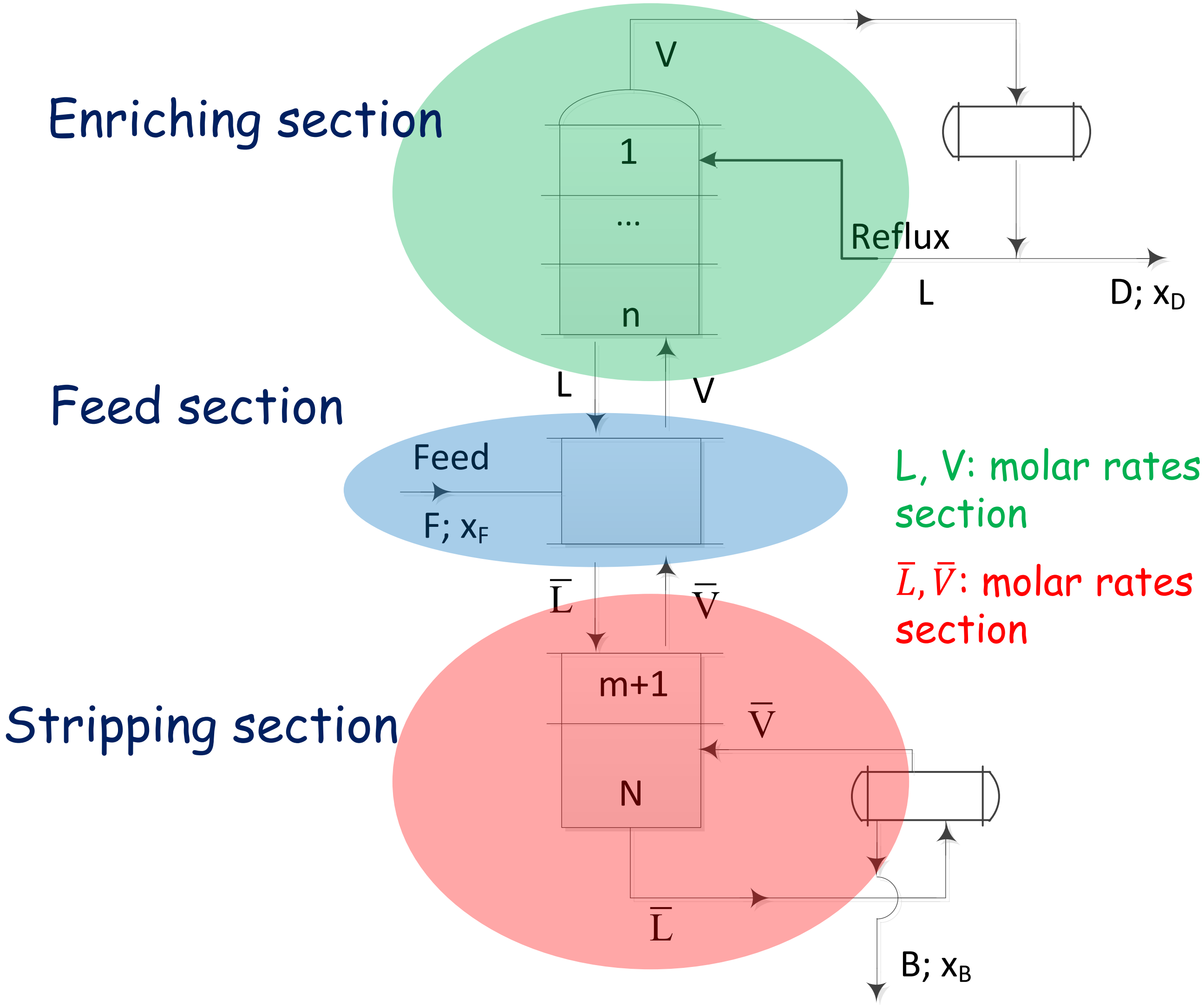
- Binary mixtures with ideal behavior
- Molar units

Molar latent heat of the mixture is **constant** and <u>independent of composition</u>

⇓

L and V flowrates are **constants**

McCabe Thiele Method



$$\begin{cases} F = B + D \\ Fx_F = Bx_B + Dx_D \end{cases}$$

$$V = L + D$$
$$\bar{L} = \bar{V} + B$$

L, V: molar rates in enriching section

$\bar{L}, \bar{V}$: molar rates in stripping section

$$R = L/D$$

Reflux rate

OL ≡ Operating Line

Enriching OL

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

Feed OL

$$y_i = \frac{i}{i-1} x_i - \frac{x_F}{i-1}$$

Stripping OL

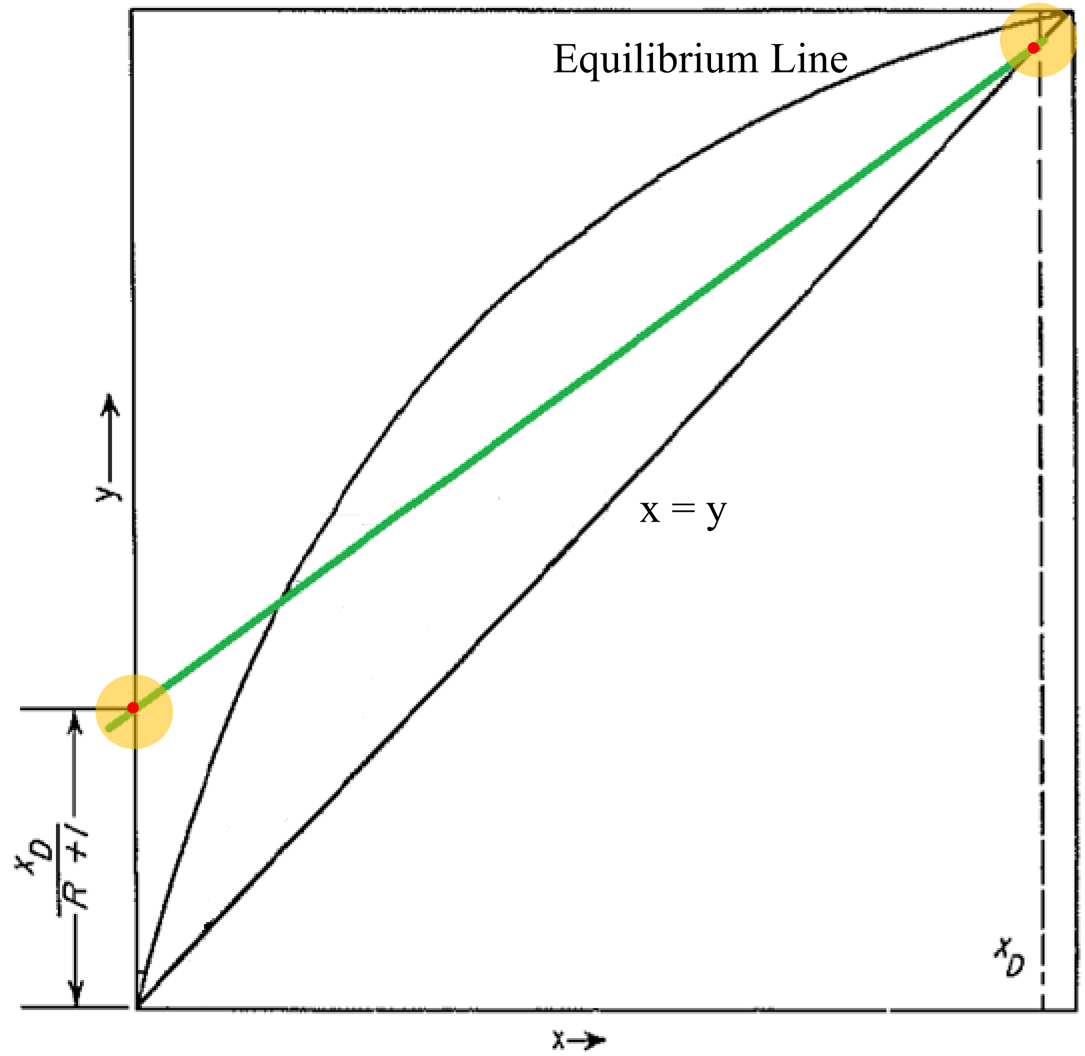
$$y_{m+1} = \frac{\overline{L}}{\overline{V}} x_m - \frac{B x_B}{\overline{V}}$$

McCabe Thiele Method – graphical resolution

Enriching OL

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

$$\begin{cases} \text{when } x_n = x_D \;\Rightarrow y_{n+1} = x_D \\ \text{when } x_n = 0 \;\Rightarrow y_{n+1} = \dfrac{x_D}{R+1} \end{cases}$$



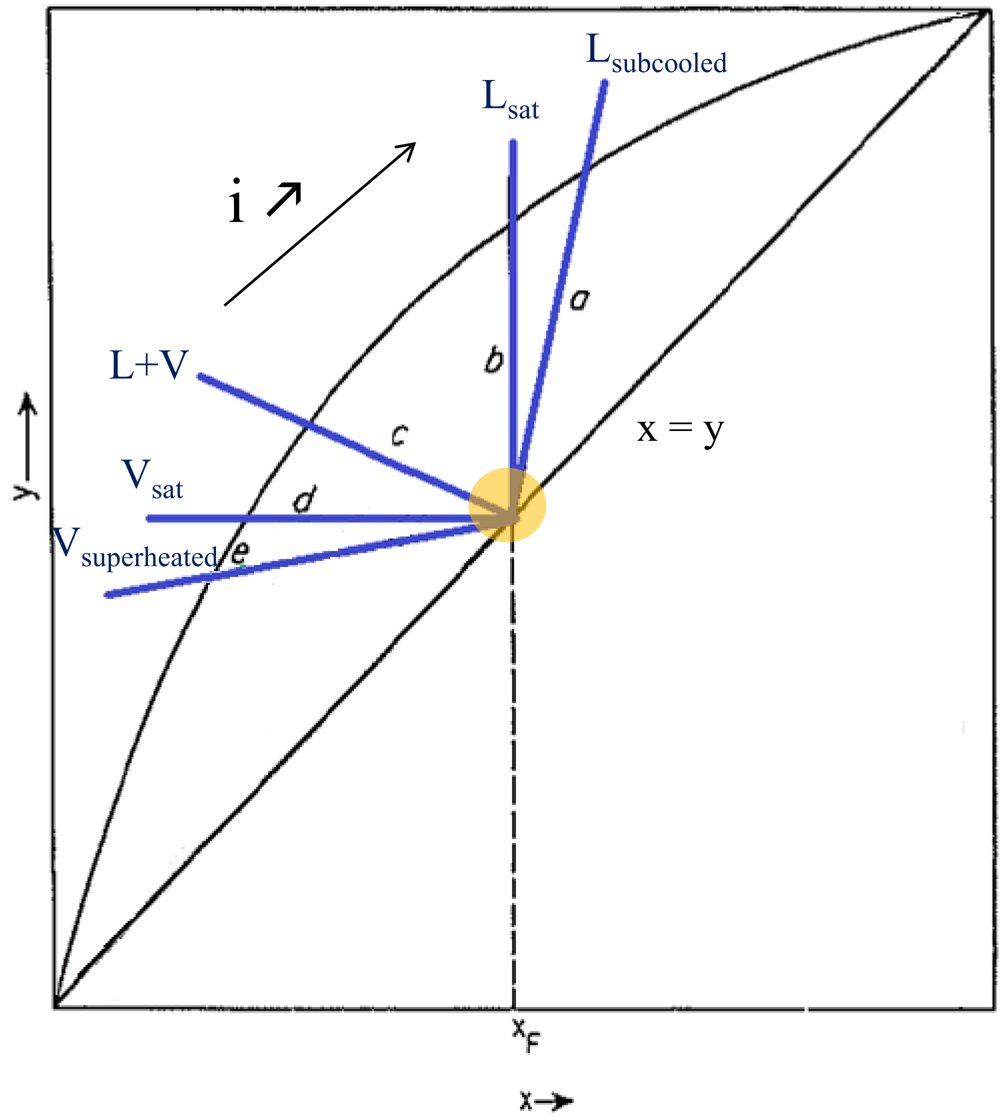
Feed OL

$$\text{i} = \frac{\text{moles of liquid flowing down}}{\text{moles of feed}} = \frac{\bar{L} - L}{F}$$

$$y_i = \frac{i}{i-1} x_i - \frac{x_F}{i-1}$$

when $x_i = x_F \Rightarrow y_i = x_F$

		$\overline{i-1}$
a) Subcooled liquid	i > 1	> 0
b) Saturated liquid	i = 1	∞
c) Saturated L+V	0 < i < 1	< 0
d) Saturated vapor	i = 0	0
e) Superheated vapor	i < 0	> 0



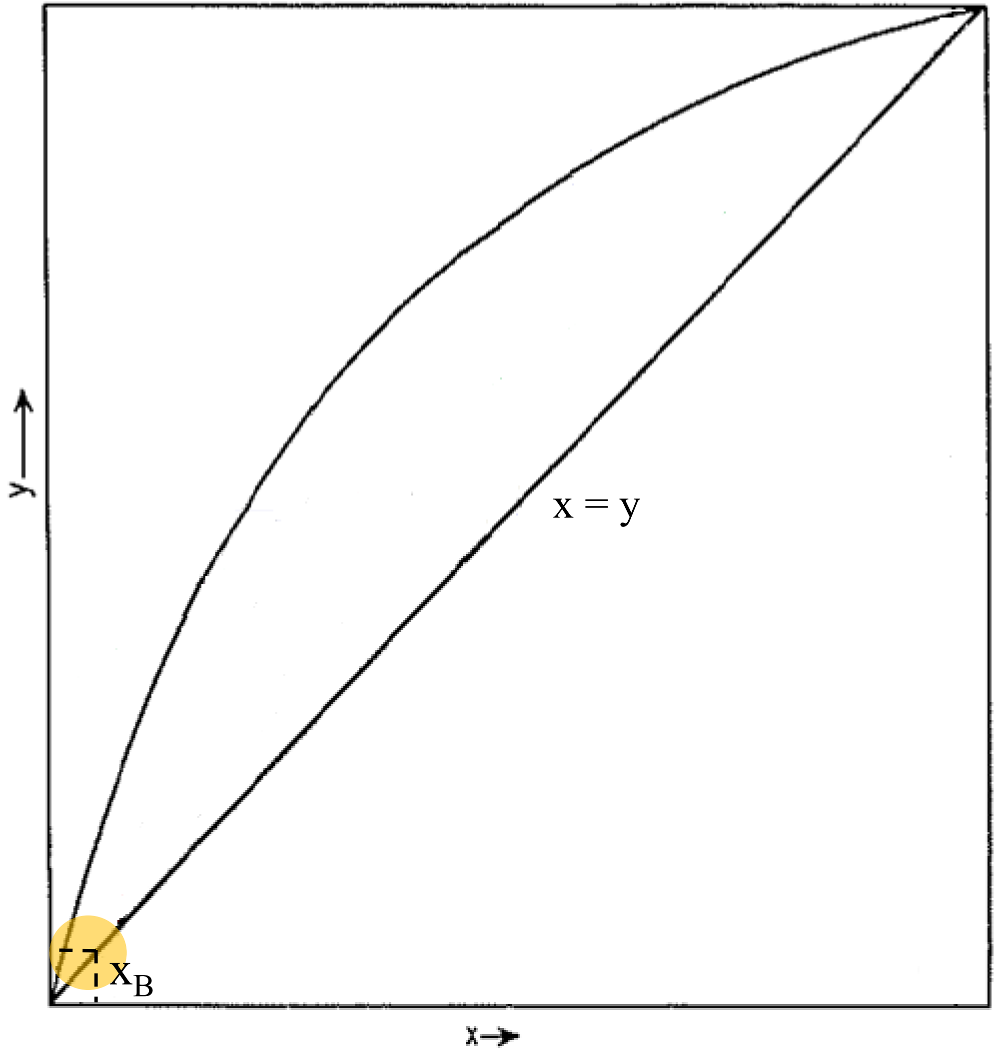
Stripping OL

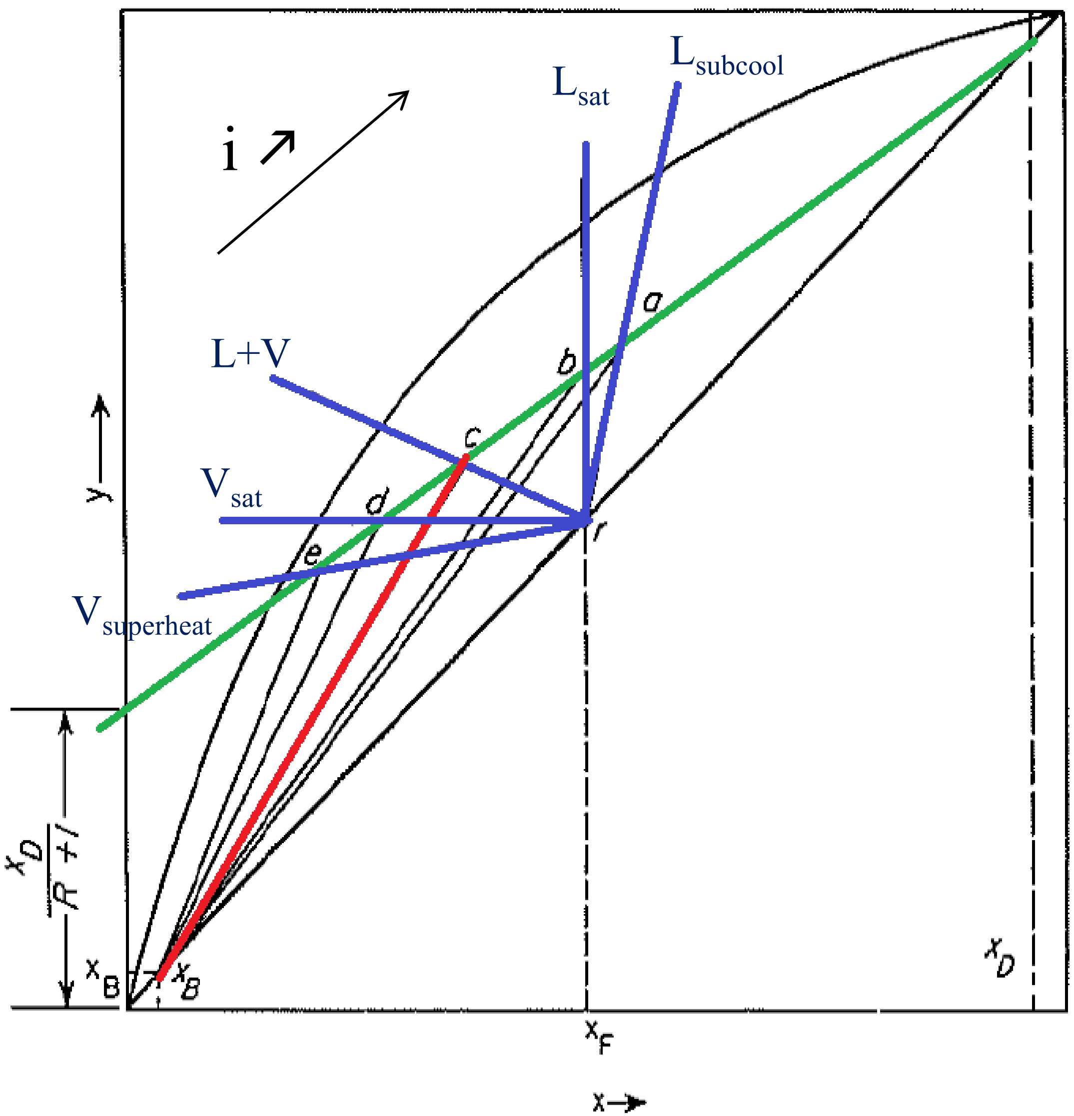
$$y_{m+1} = \frac{\bar{L}}{\bar{V}} x_m - \frac{B x_B}{\bar{V}}$$

$$\text{when } x_m = x_B \Rightarrow y_{m+1} = x_B$$

$$(\bar{L} = \bar{V} + B)$$

The stripping OL will be determined by knowing that the three OL's intersect in a single point





a) Subcooled liquid $i > 1$

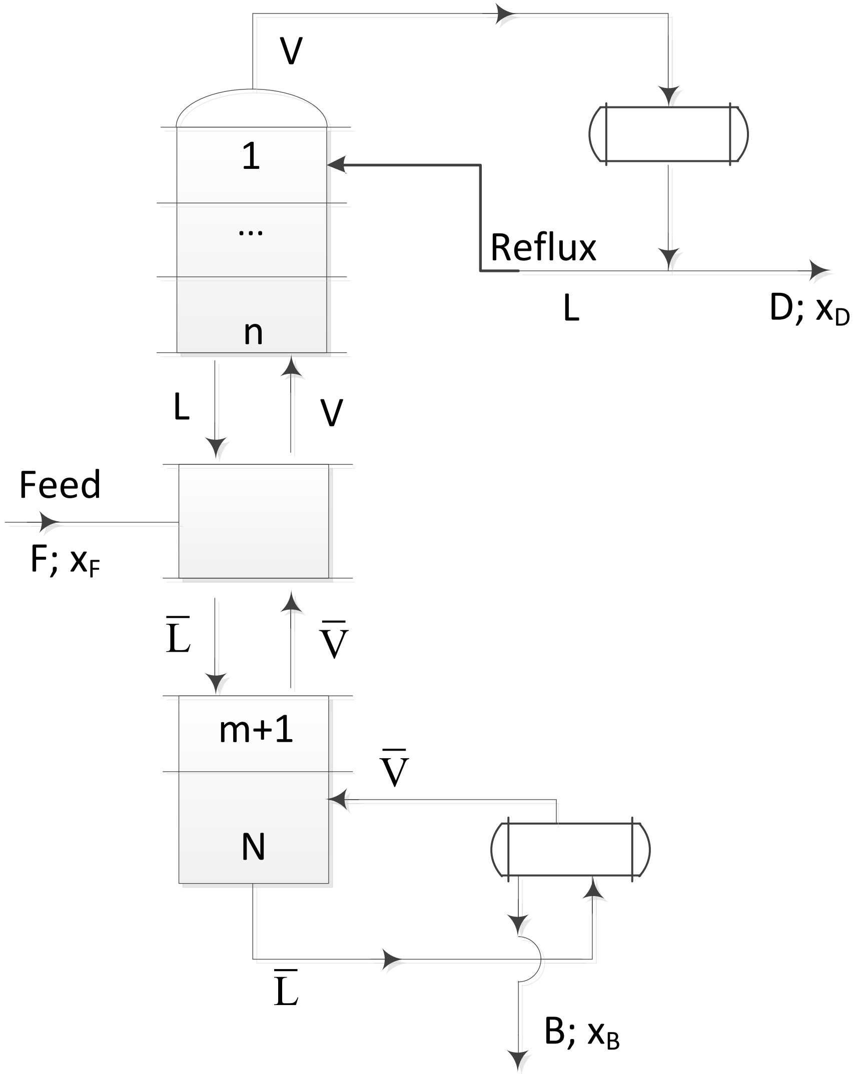
b) Saturated liquid $i = 1$

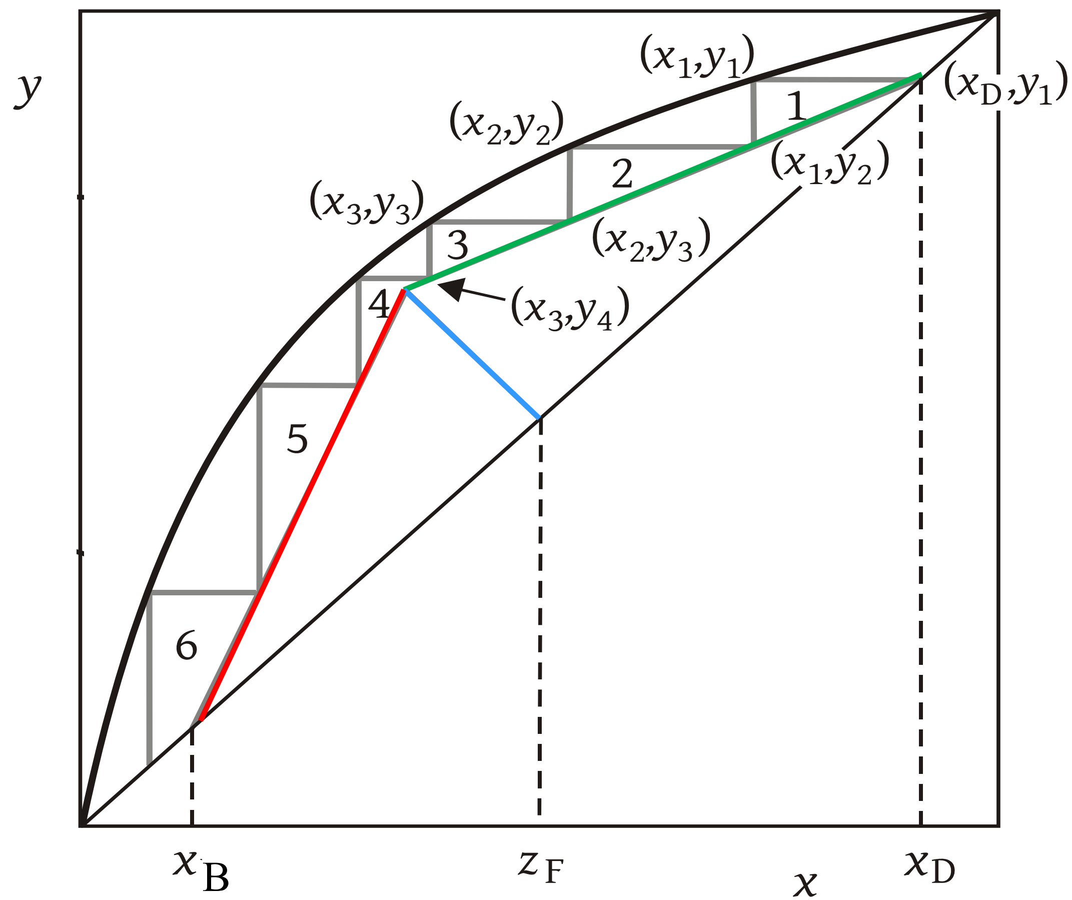
c) L+V saturated $0 < i < 1$

d) Saturated vapor $i = 0$

e) Superheated Vapor $i < 0$

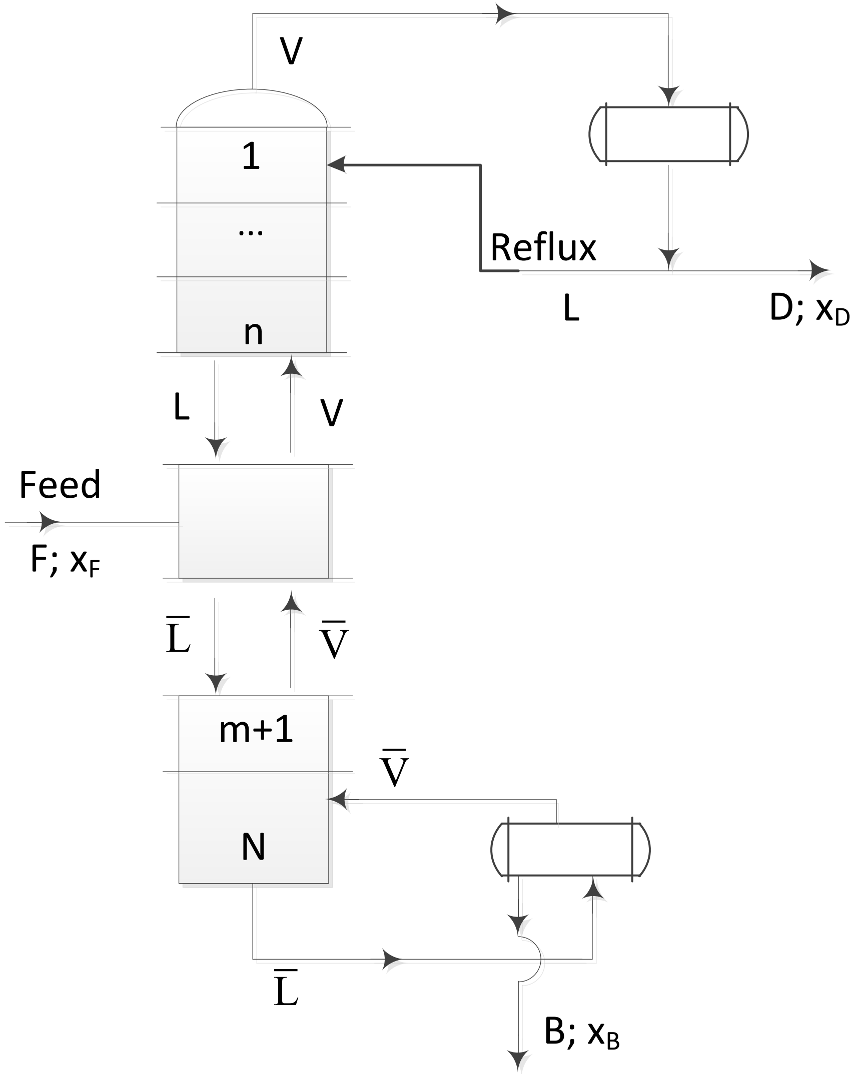
McCabe – Thiele Method

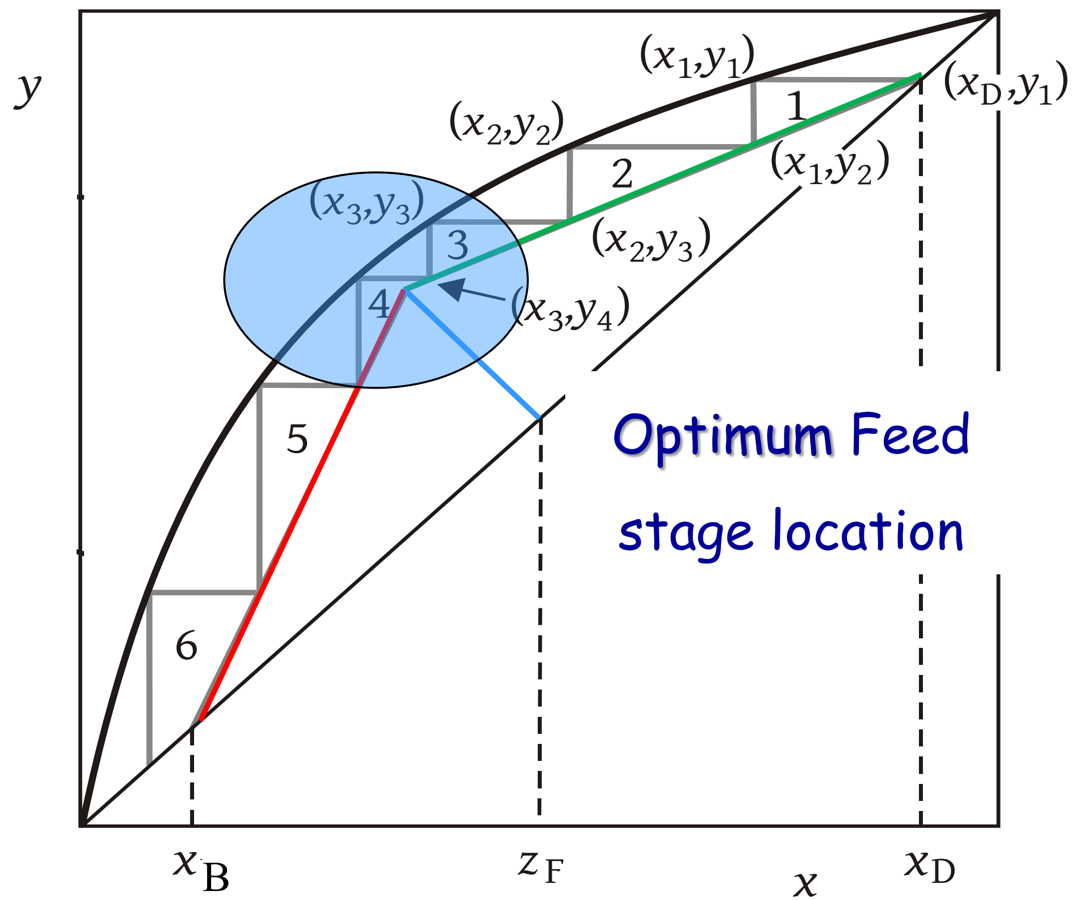




Example: Feed as saturated L+V

McCabe – Thiele Method





Example: Feed as saturated L+V

Equations needed

① Overall mass balance

$$F = B + D$$

$$F x_F = B x_B + D x_D$$

$$i = \frac{\bar{L} - L}{F}$$

$$R = L/D$$

$$V = L + D$$

$$\bar{L} = \bar{V} + B$$

② Enriching OL

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

$$\begin{cases} y_{n+1}\big|_{x_n = x_D} = x_D \\ y_{n+1}\big|_{x_n = 0} = \dfrac{x_D}{R+1} \end{cases}$$

③ Feed OL

$$y_i = \frac{i}{i-1} x_i - \frac{x_F}{i-1}$$

$$\begin{cases} y_i\big|_{x_i = x_F} = x_F \\ y_i\big|_{x_i = 0} = -\dfrac{x_F}{i-1} \end{cases}$$

④ Stripping OL

$$y_{m+1} = \frac{\bar{L}}{\bar{V}} x_m - \frac{B x_B}{\bar{V}}$$

$$y_{m+1}\big|_{x_m = x_B} = x_B$$

⑤ The three OL's intersect in a single point

Problem 1

A distillation column is used to separate 100 mol/h of a mixture made of two compounds A and C. The feed mixture consists of equal parts of saturated vapor and liquid, with a molar composition of 35% A. It is intended to obtain a distillate with a molar composition of 93% A and a residue with a molar composition of 97.8% C. The reflux ratio is equal to 4.

a) How many equilibrium stages are needed in each section of the column?

b) What is the optimal plate for the feed inlet?

c) Determine the minimum reflux ratio (Rmin).

d) Determine the minimum number of theoretical plates required (Nmin).

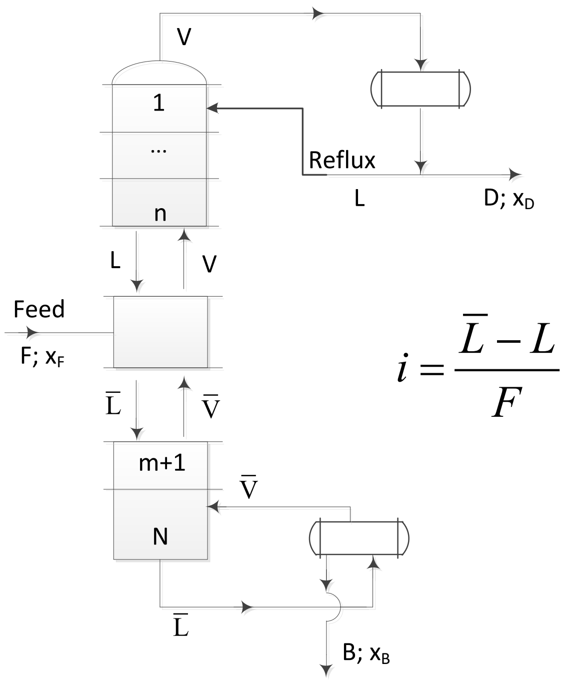
McCabe – Thiele Method

What is the effect in a distillation column when we change:

- ☞ the physical state of the feed
- ☞ the reflux ratio, R

NOTE: x_F, x_D and x_B constants

Physical state of Feed – *i*

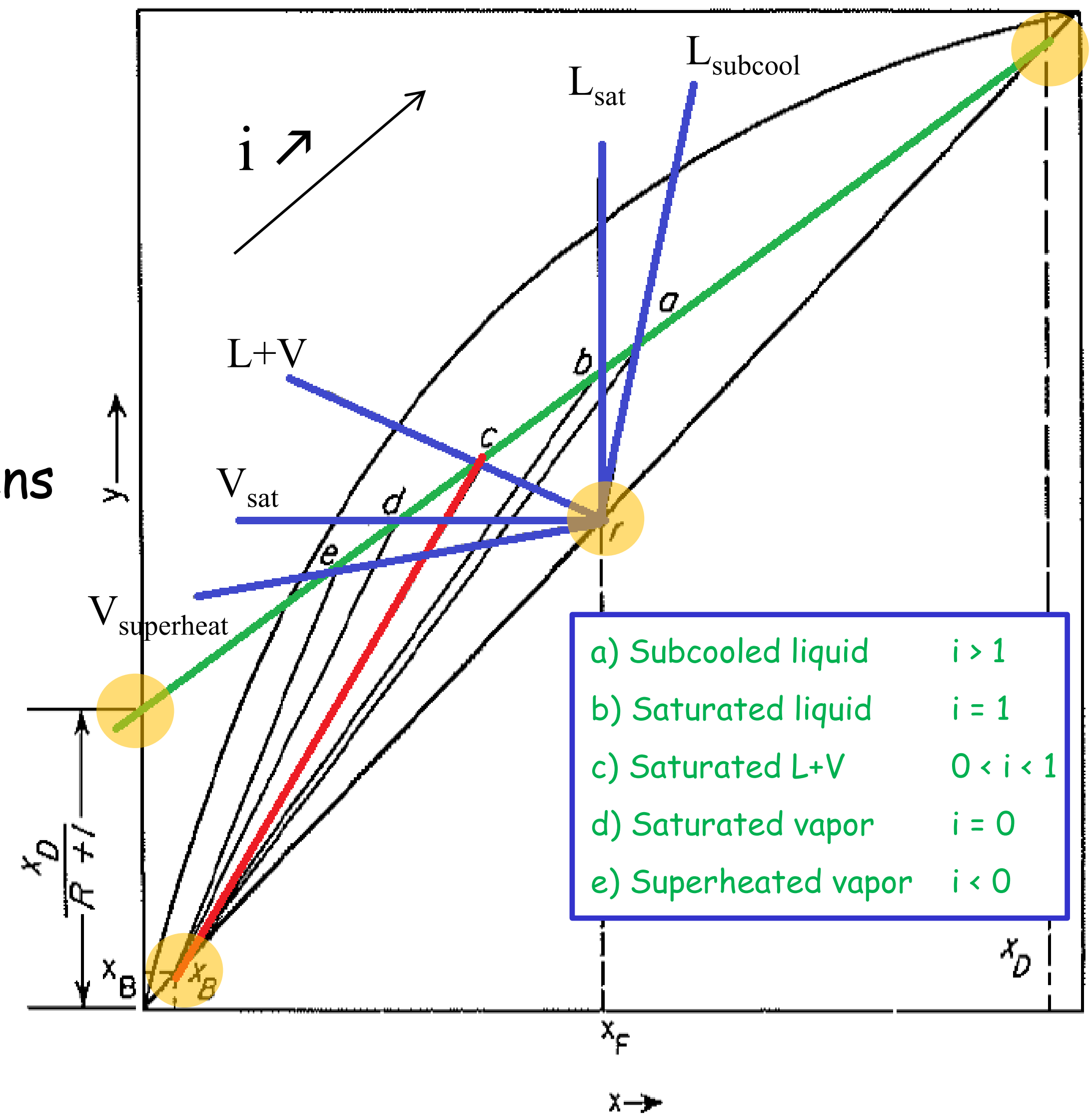


$$i = \frac{\bar{L} - L}{F}$$

If we fix x_F, x_D, x_B and R what happens when i increases?

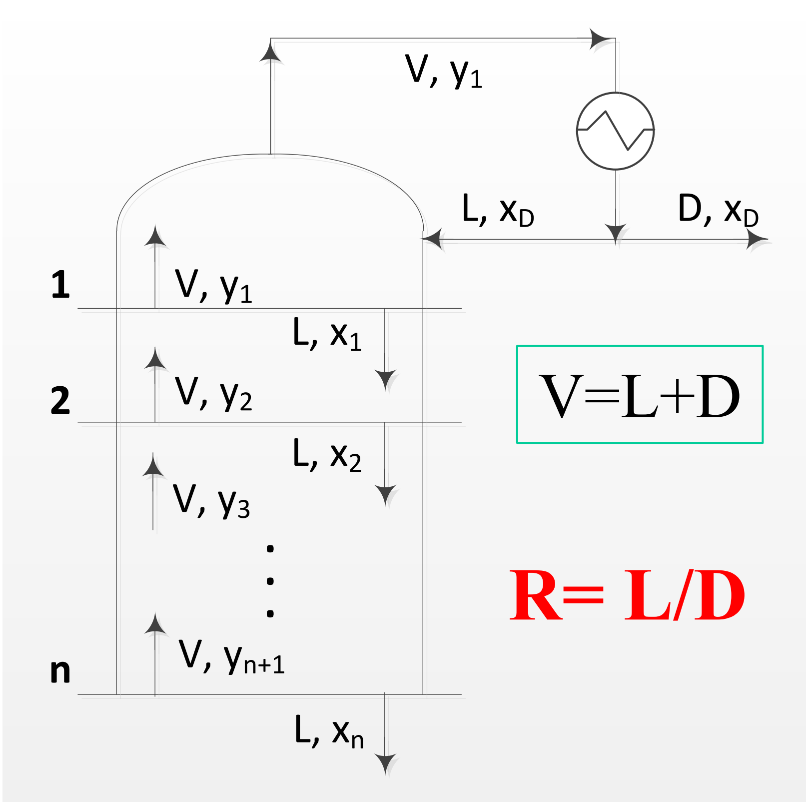
$\Downarrow$

- The enriching section decreases
- The stripping section increases



Reflux ratio, *R*

If we fix x_F, x_D, x_B and *i* what will happen when *R* increases?



$R \nearrow \Leftrightarrow L \nearrow$

What happens to the operating lines?

Reflux ratio, *R*

R= L/D

If we fix x_F, x_D, x_B and i what will happen when R increases?

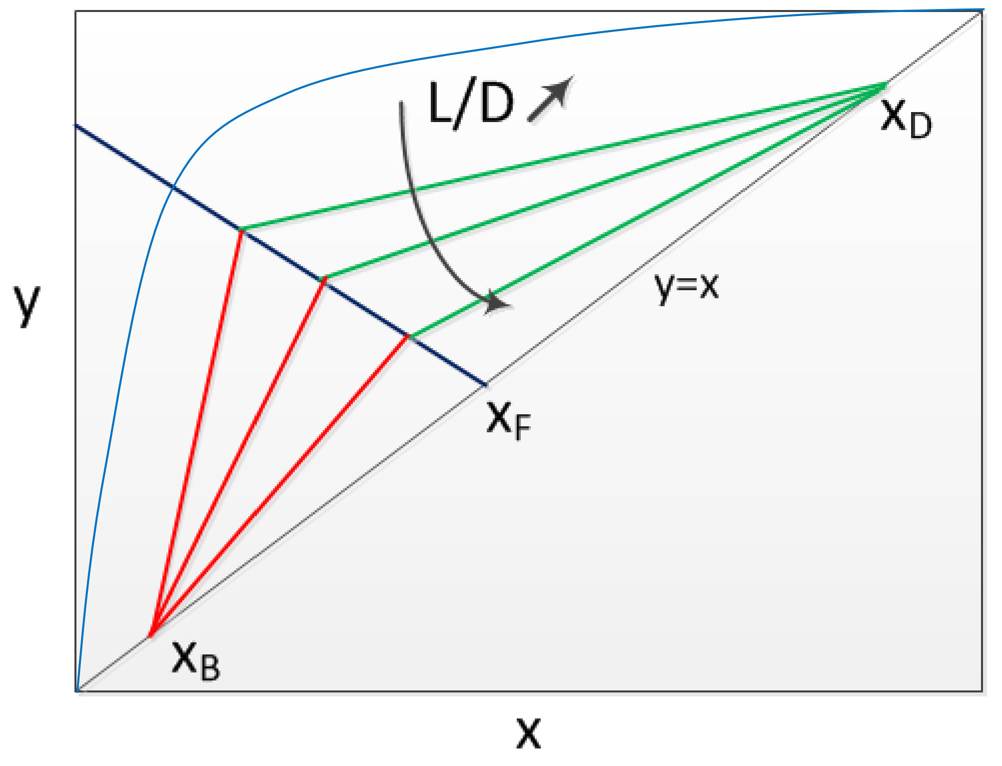
=> the slope of the enriching and stripping OLs are affected

Enriching OL

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

↗ ↘

If R ↗



Reflux ratio, *R*

R= L/D

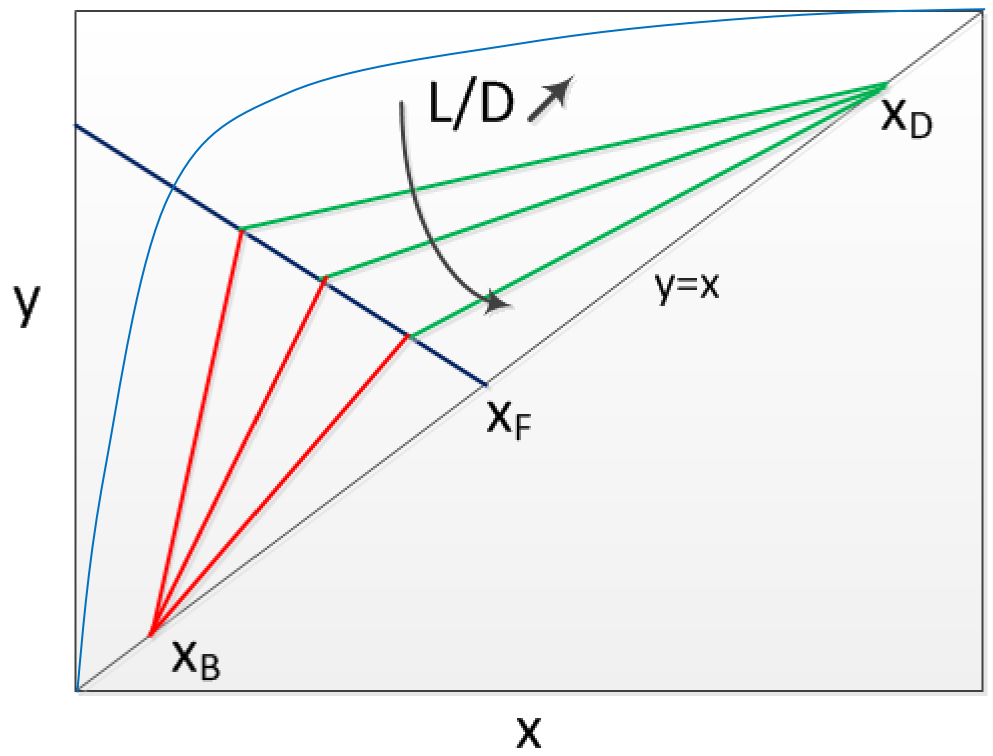
If we fix x_F, x_D, x_B and *i* what will happen when *R* increases?

=> the slope of the enriching and stripping OLs are affected

OL's move away from equilibrium line

=> Number of stages ↘

Reflux ↗ ⇔ N ↘

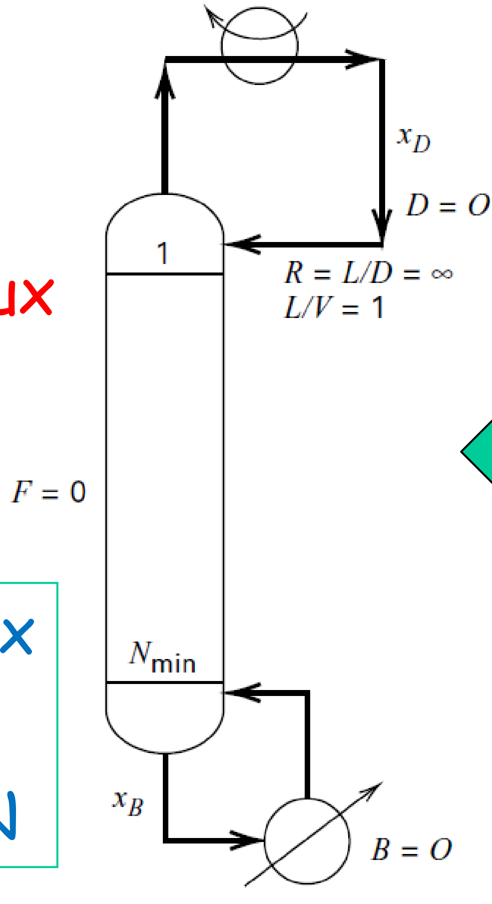


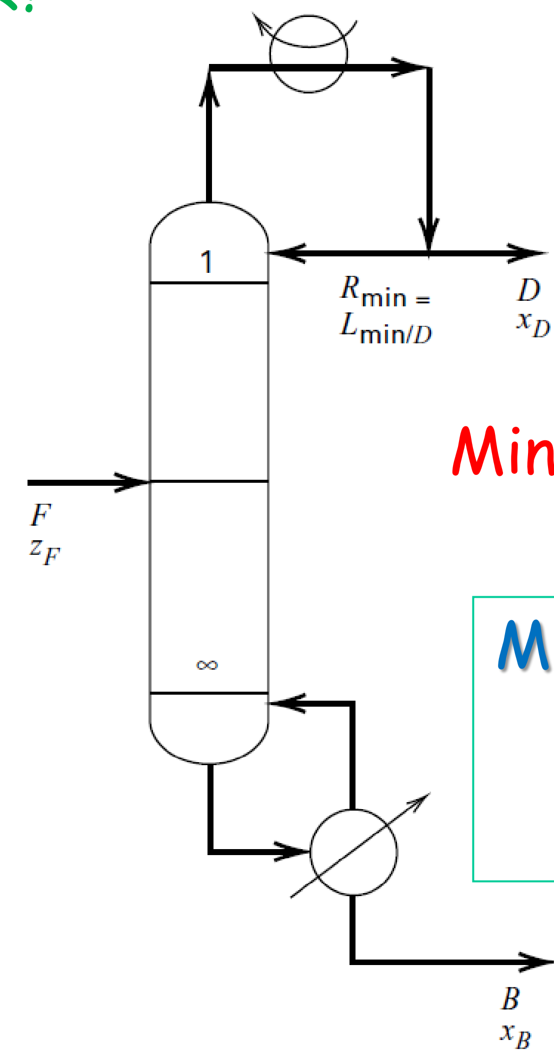
Reflux ratio, *R*

R= L/D

What are the limits of variation of R?

Total Reflux





R ≠ 0!

Why?

Minimum Reflux

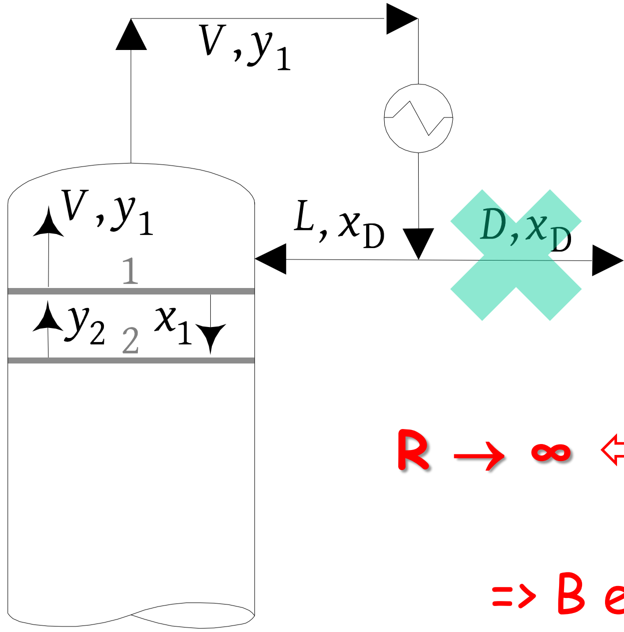
Total reflux
⇳
Minimum N

Minimum reflux
⇳
Infinite N

Reflux ratio, *R*

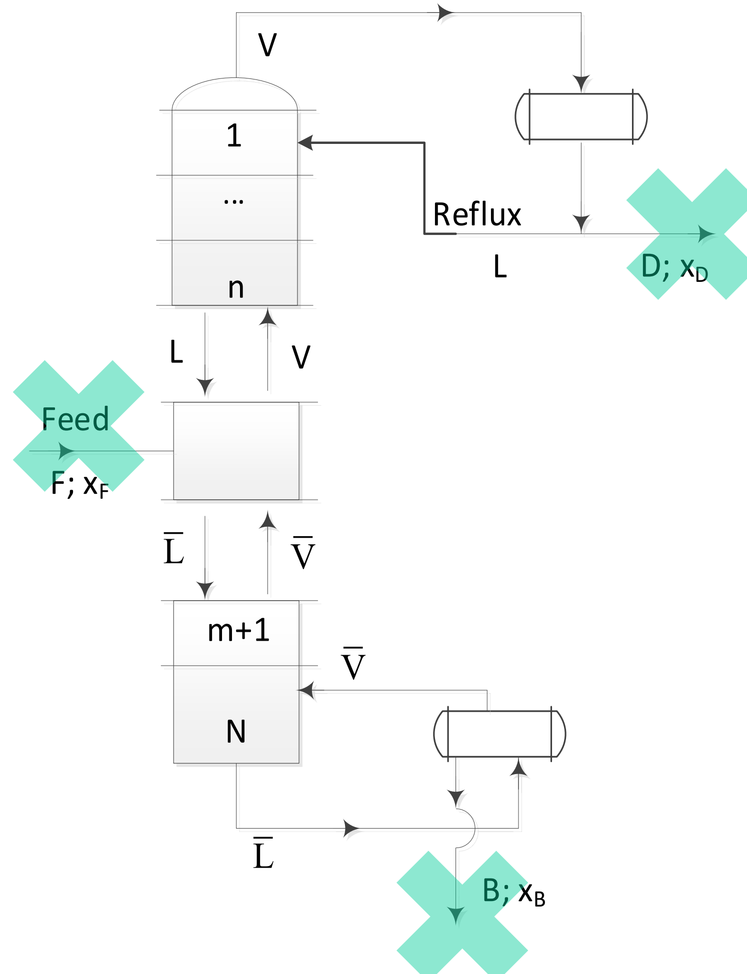
R= L/D

Total Reflux (infinite)



$R \to \infty \Leftrightarrow D \to 0 \Rightarrow L = V$

$\Rightarrow B$ e $F = 0$



Total Reflux, R → ∞

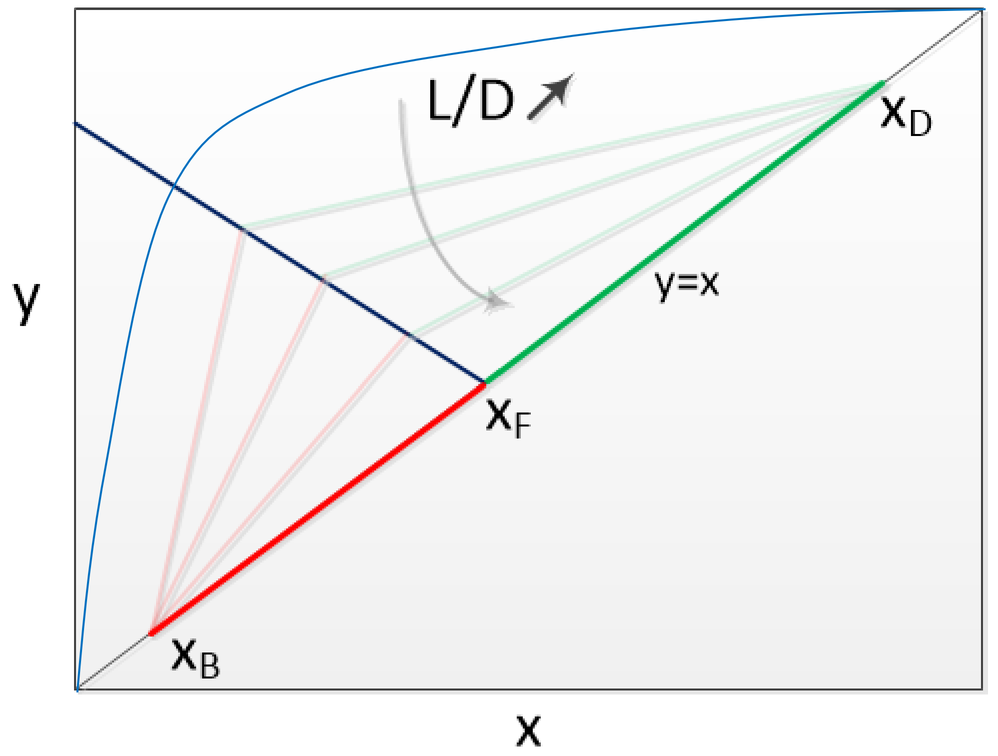
R= L/D

V= L+D

When $R \rightarrow \infty$

$D \rightarrow 0 \Rightarrow L = V$

$$\boxed{y_{n+1} = \cancelto{=1}{\frac{L}{V}} x_n + \cancelto{=0}{\frac{Dx_D}{V}}}$$



Total Reflux, R → ∞

R= L/D

V= L+D

When R → ∞

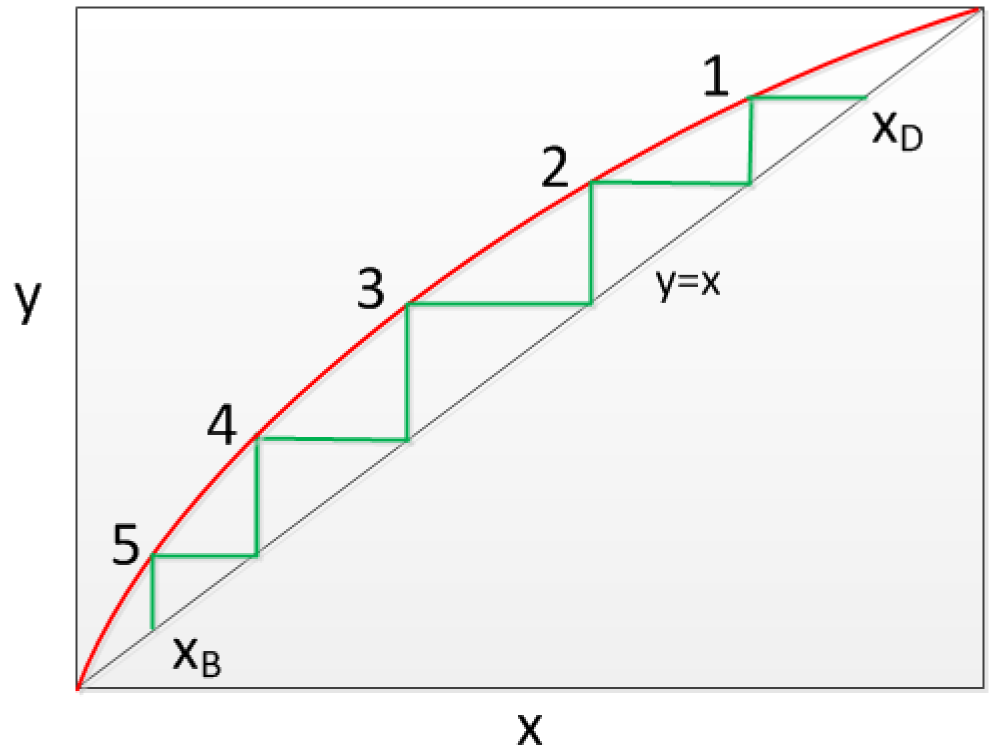
D → 0 => L = V

$$y_{n+1} = \underbrace{\cancel{\frac{L}{V}}}_{=1} x_n + \underbrace{\cancel{\frac{Dx_D}{V}}}_{=0}$$

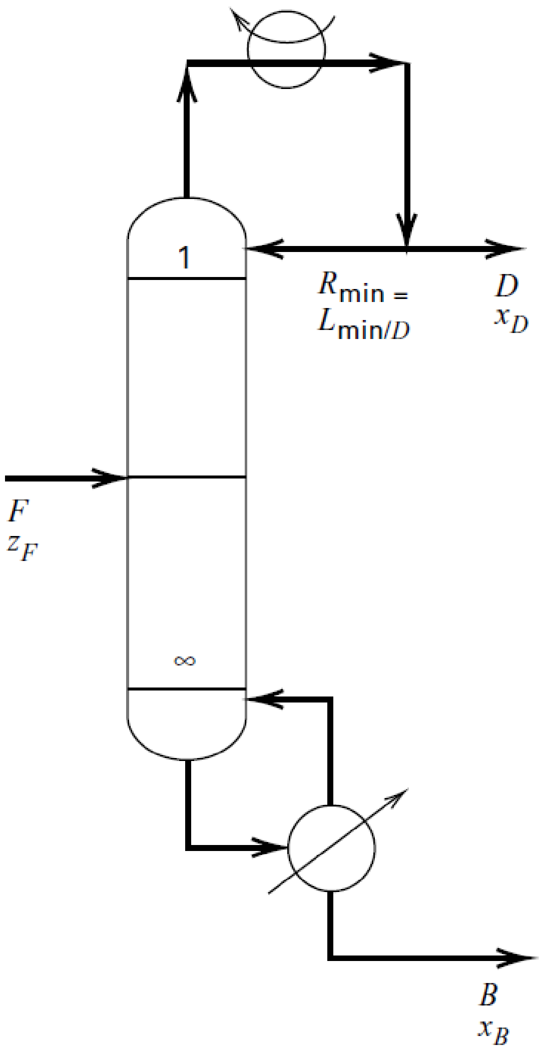
Total reflux

⇕

Minimum N



Minimum Reflux



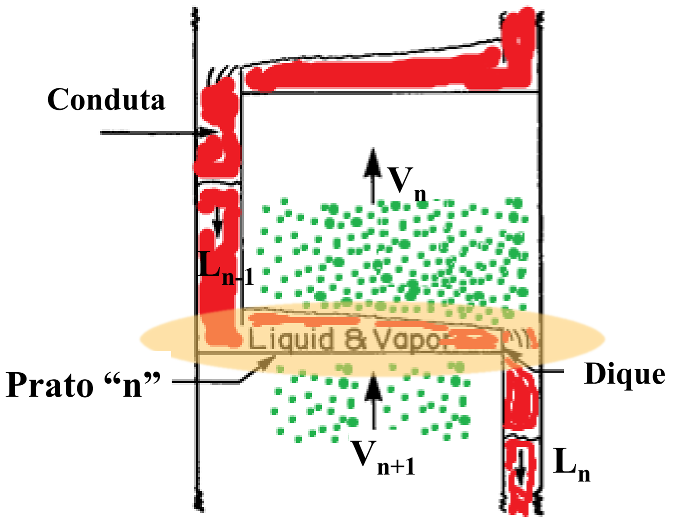
Minimum reflux

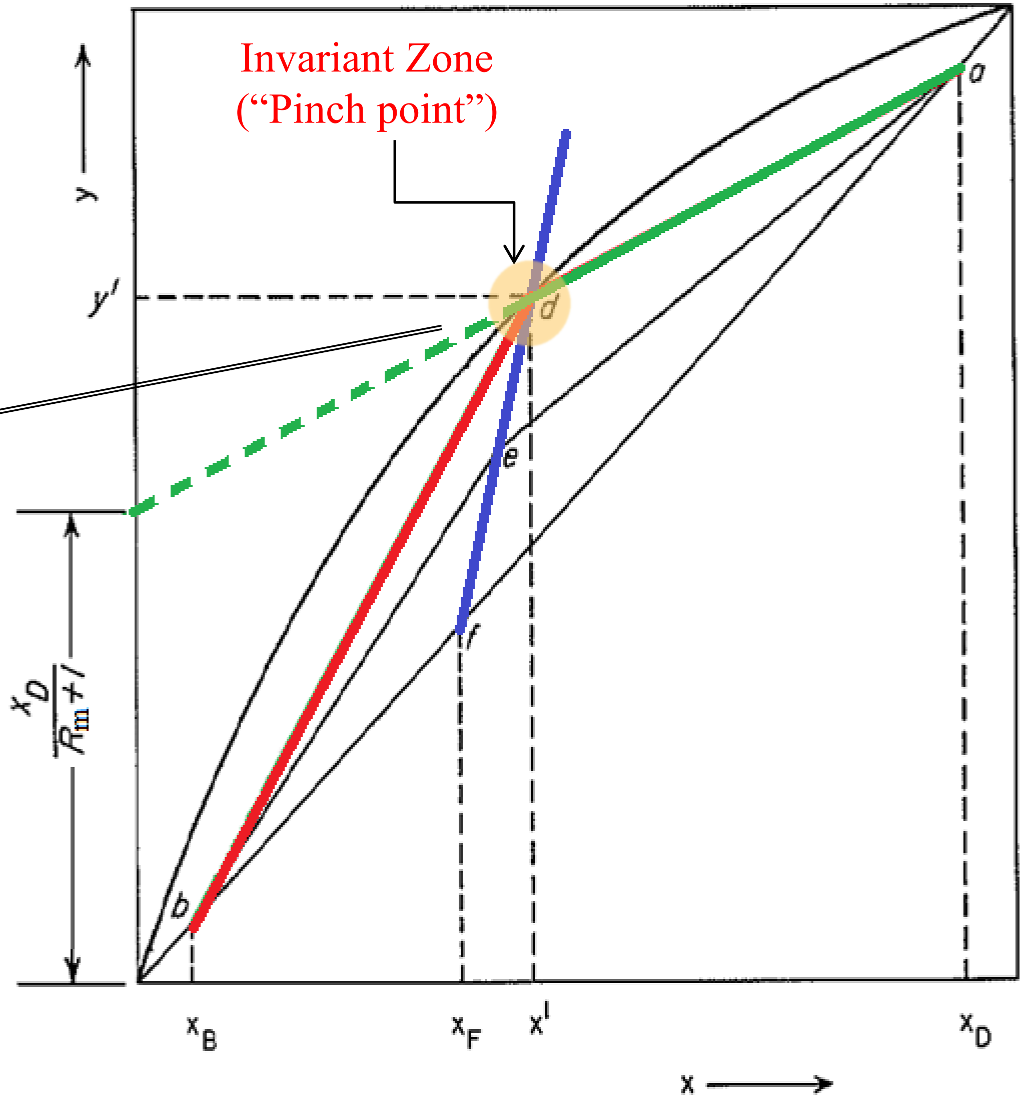
⇕

Infinite N

Minimum Reflux

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$





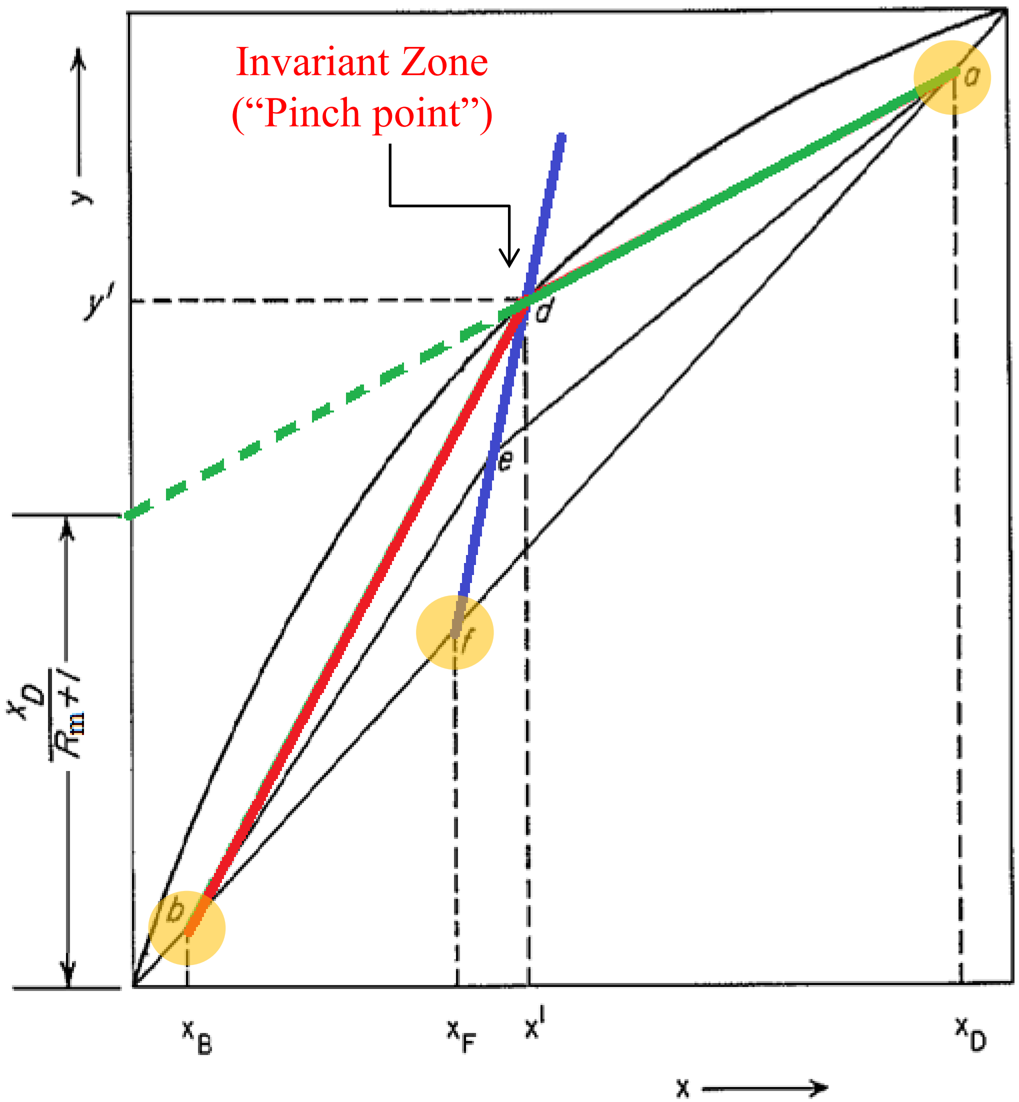
- V_n in equilibrium with L_n (Equilibrium line)
- V_n in equilibrium with L_{n-1} (Operating line)
- V_{n+1} in equilibrium with L_n (Operating line)

∴ Infinite number of stages

Minimum Reflux

x_F, x_D, x_B and *i* constants

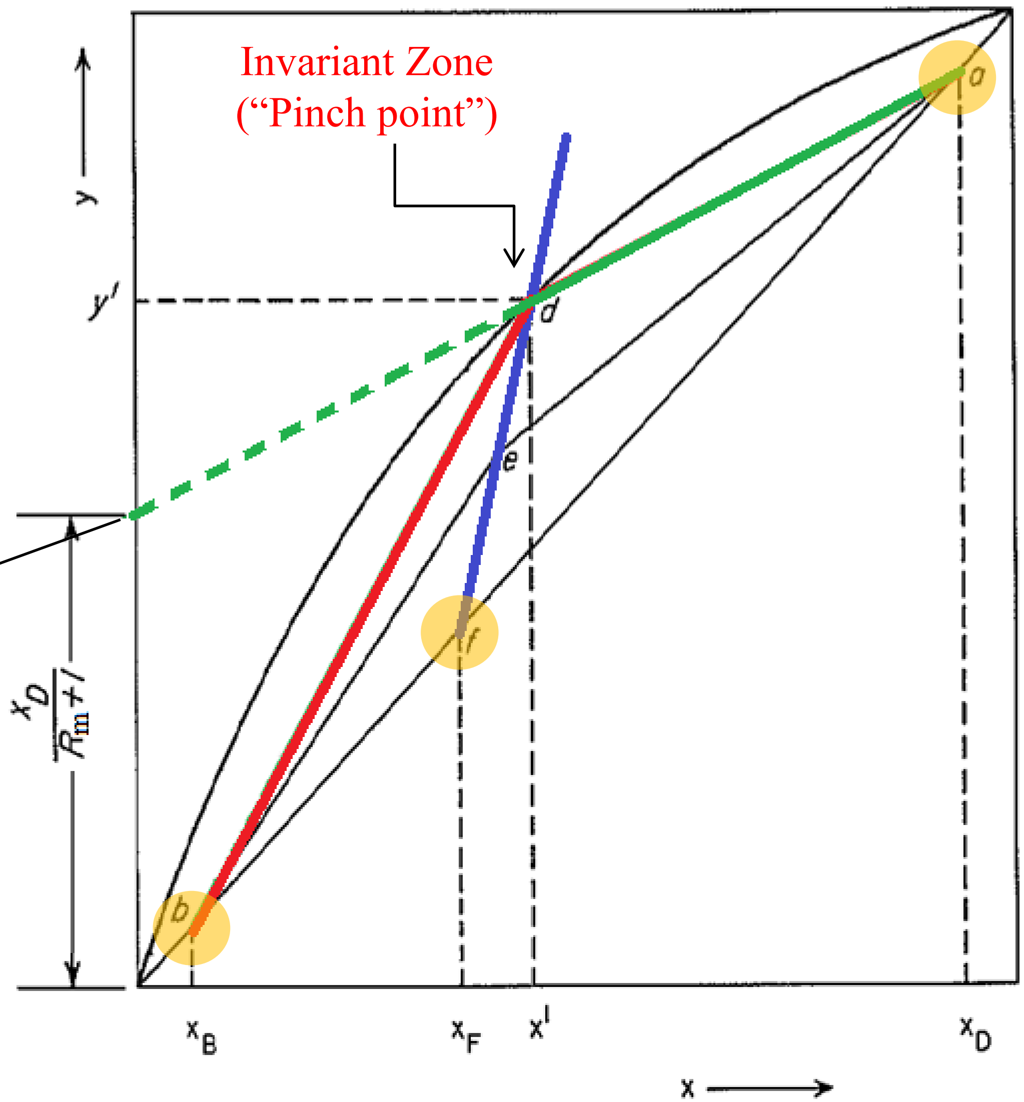
$$y_{n+1} = \frac{R_{\min}}{R_{\min}+1} x_n + \frac{x_D}{R_{\min}+1}$$



Minimum Reflux

x_F, x_D, x_B and i constants

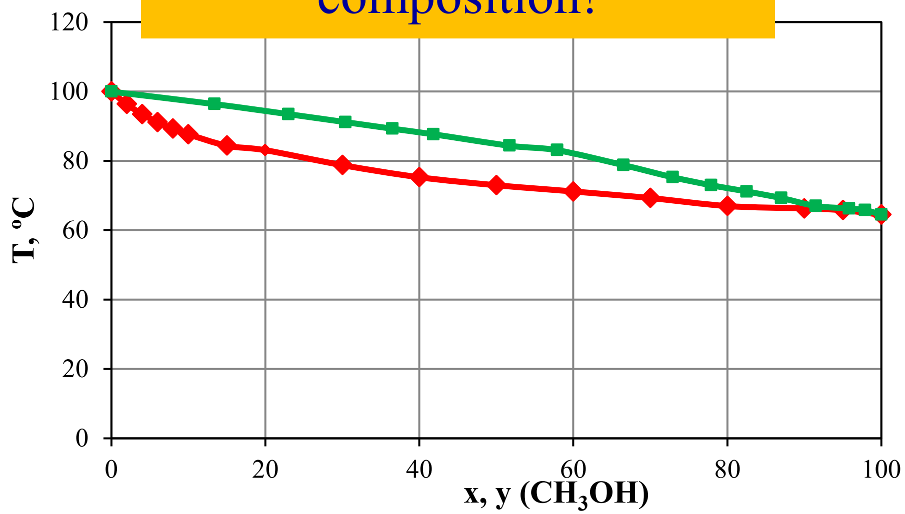
$$y_{n+1} = \frac{R_{\min}}{R_{\min}+1}x_n + \boxed{\frac{x_D}{R_{\min}+1}}$$

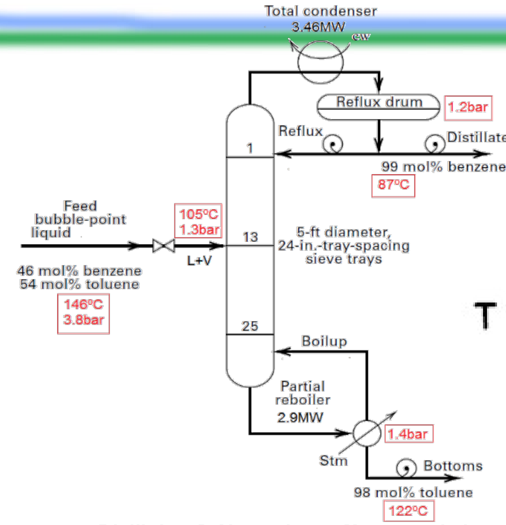


Problem 1

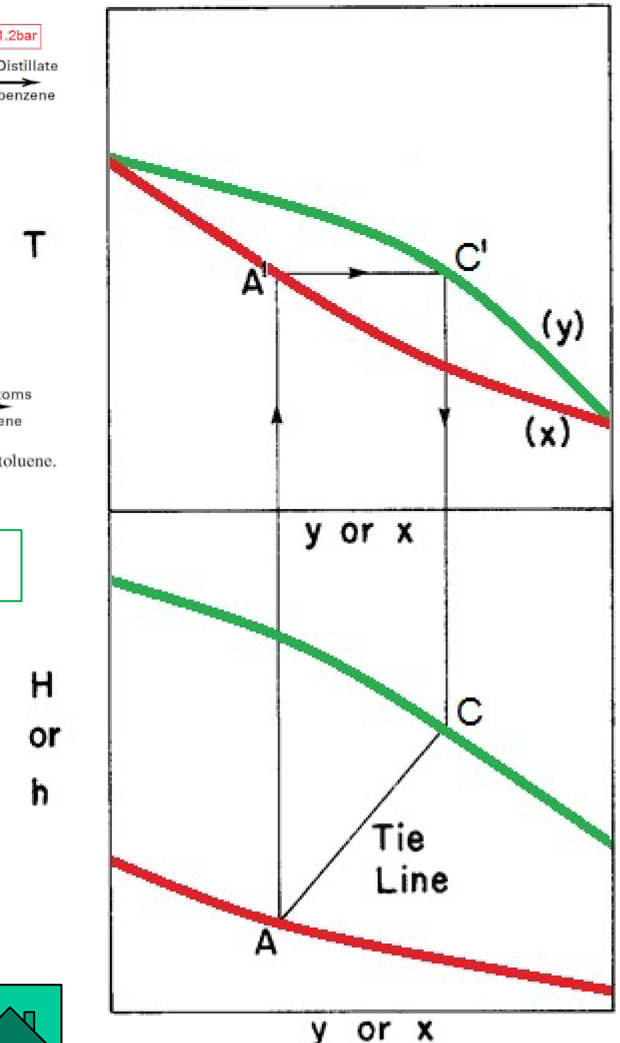
En… on diagram: Methanol + Water

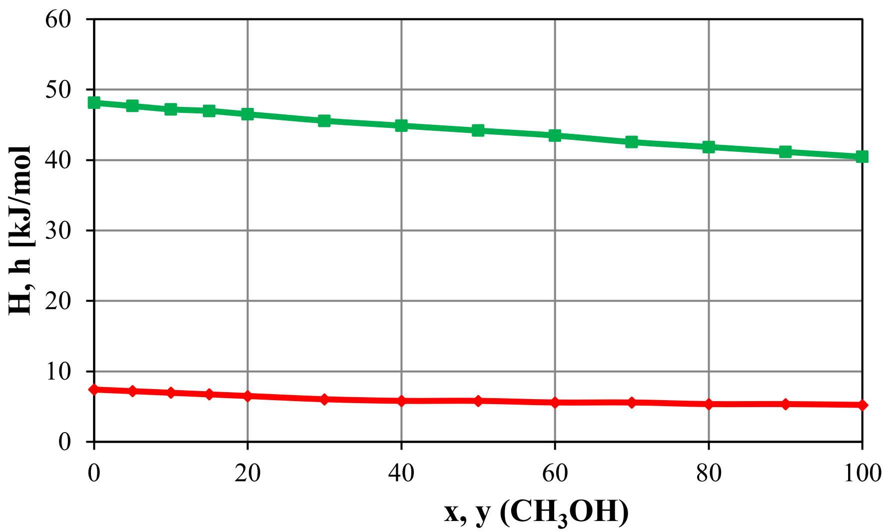
☛ For this system AH_{vap} is reasonably independent of composition!





Distillation of a binary mixture of benzene and toluene.





$\Delta H_{vap} = H_{vapor} - h_{líquid}$