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Introduction to McCabe-Thiele Design Method: Binary Distillation

#PART I ✱

✱ PART II

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Ref: P. C. Wankat, Separation *Process Engineering, Prentice Hall*, 4th ed, 2017

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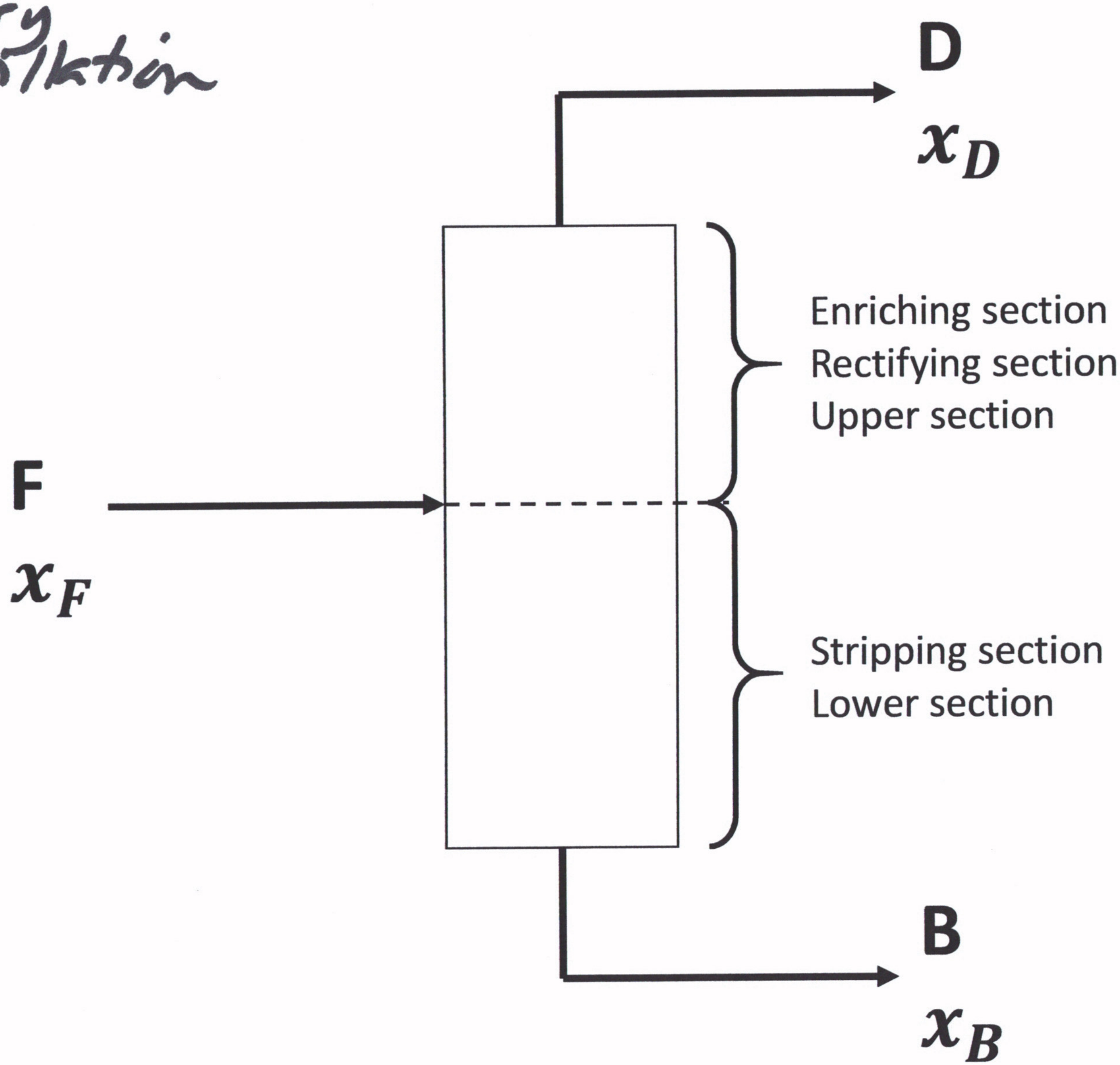
McCabe-Thiele Method

Binary Distillation



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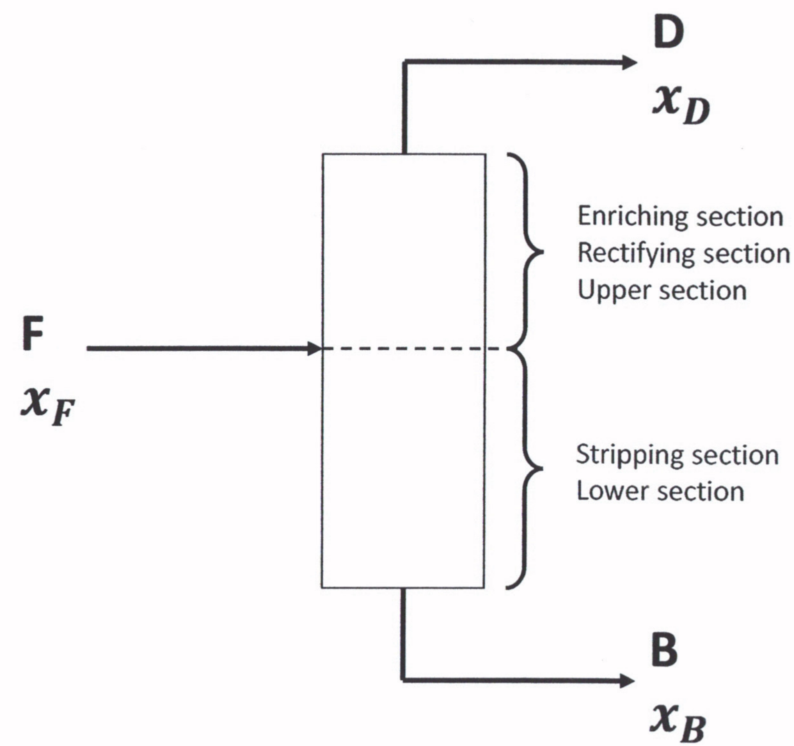
The McCabe-Thiele method assumes

Constant Molar Overflow (CMO)

<u>Enriching section</u>
Liquid molar flow rates $= L$
Vapor molar flow rates $= V$

<u>Stripping section</u>
Liquid molar flow rates $= \bar{L}$
Vapor molar flow rates $= \bar{V}$



Four conditions:
1. $\Delta\widehat{H}_{vap}$ independent of mixture concentration
2. Latent heat dominates
3. Adiabatic column, $\dot{Q} = 0$
4. Saturated liquid and vapor lines on $\widehat{H} - x_A$ diagram are parallel

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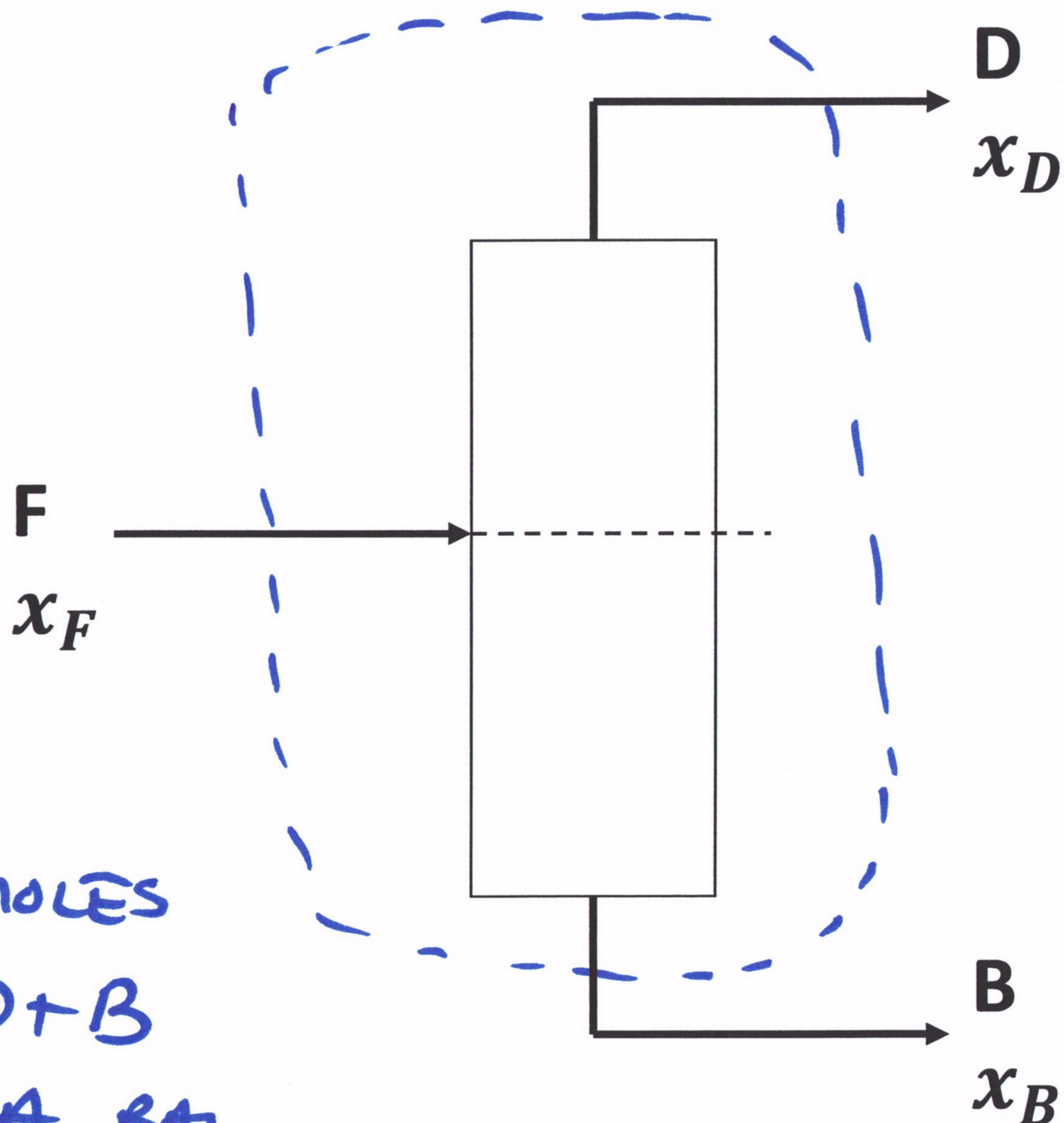
Overall mole balance



TOTAL MOLES

$$F = D + B$$

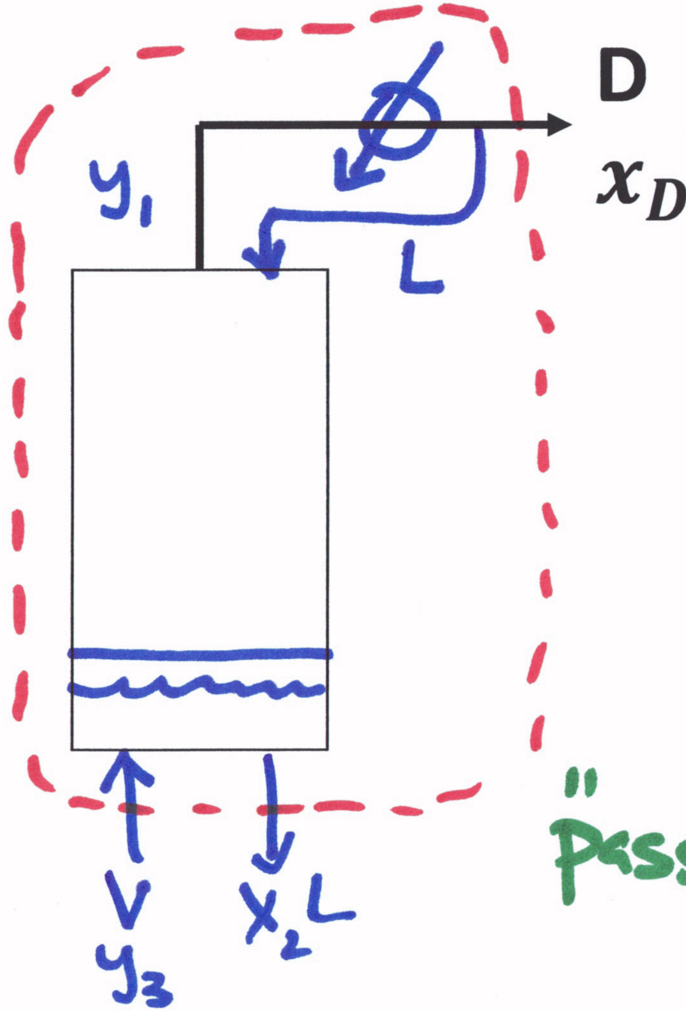
MOLES A BAL

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

* Mass balance (molar basis) Enriching Section

total condenser

1



$y_1 = x_D$

stage 2

"passing streams"

total moles bal

$V = L + D$

moles A bal

\# $y_3 V = x_2 L + x_D D$

$$y_3 = \left(\frac{L}{V}\right) x_2 + \frac{\overset{=V-L}{D}}{V} x_D$$

$$y_3 = \left(\frac{L}{V}\right) x_2 + \left(\frac{V-L}{V}\right) x_D$$

$$\boxed{y = \underbrace{\left(\frac{L}{V}\right)}_{\text{slope}} x + \left(1 - \frac{L}{V}\right) x_D}$$

operating line (enriching section)

To find a point on the line

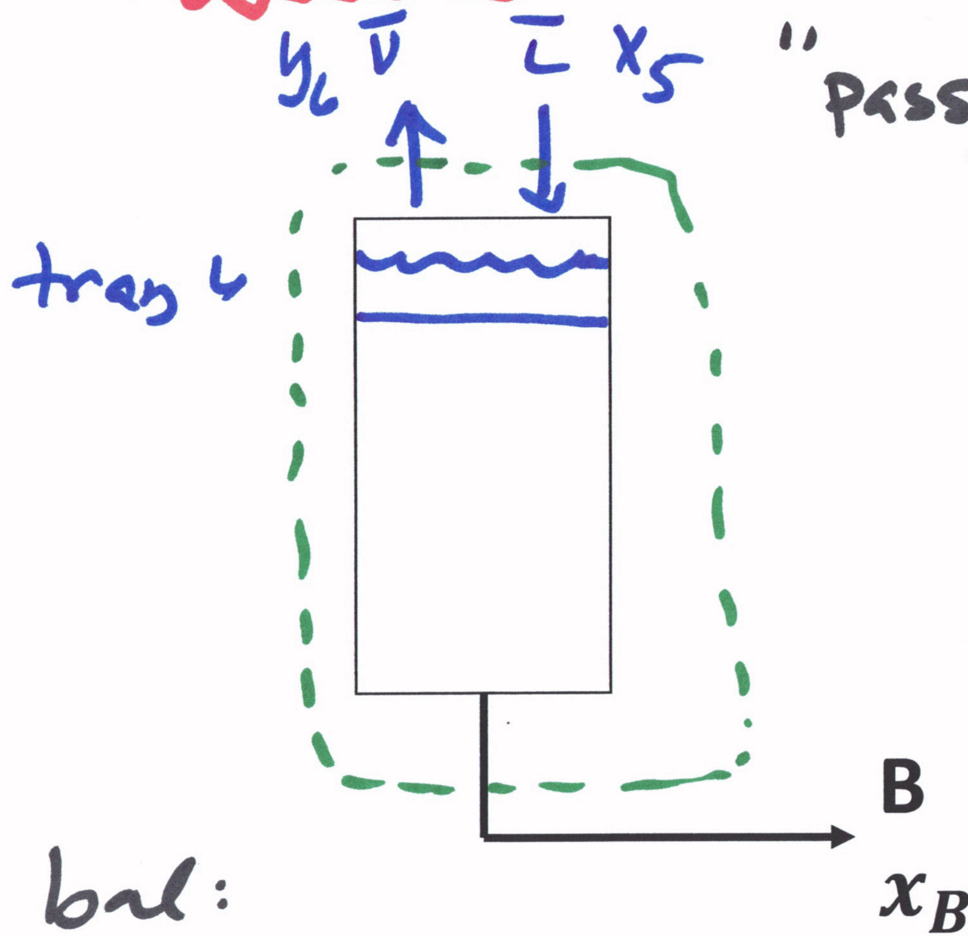
let $x = x_D$

$$y = \frac{L}{V} x_D + \left(1 - \frac{L}{V}\right) x_D$$

$$= \cancel{\frac{L}{V} x_D} + x_D \cancel{- \left(\frac{L}{V}\right)} x_D$$

$$\boxed{y = x_D}$$

Mass balance (molar basis) Stripping Section



"passing streams"

total mol bal:

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

moles A bal:

$$x_5 \bar{L} = y_6 \bar{V} + x_B B$$

$$y_L \bar{V} = x_S \bar{L} - x_B B$$

$$y_L = \left(\frac{\bar{L}}{\bar{V}}\right) x_S - \left(\frac{\overset{\bar{L}-\bar{V}}{B}}{\bar{V}}\right) x_B$$

$$y_L = \left(\frac{\bar{L}}{\bar{V}}\right) x_S - \left(\frac{\bar{L}-\bar{V}}{\bar{V}}\right) x_B$$

$$\boxed{\bar{y} = \left(\frac{\bar{L}}{\bar{V}}\right) \bar{x} - \left(\frac{\bar{L}}{\bar{V}} - 1\right) x_B}$$

operating line
(stripping section

To find a point on the line

let $\bar{x} = x_B$

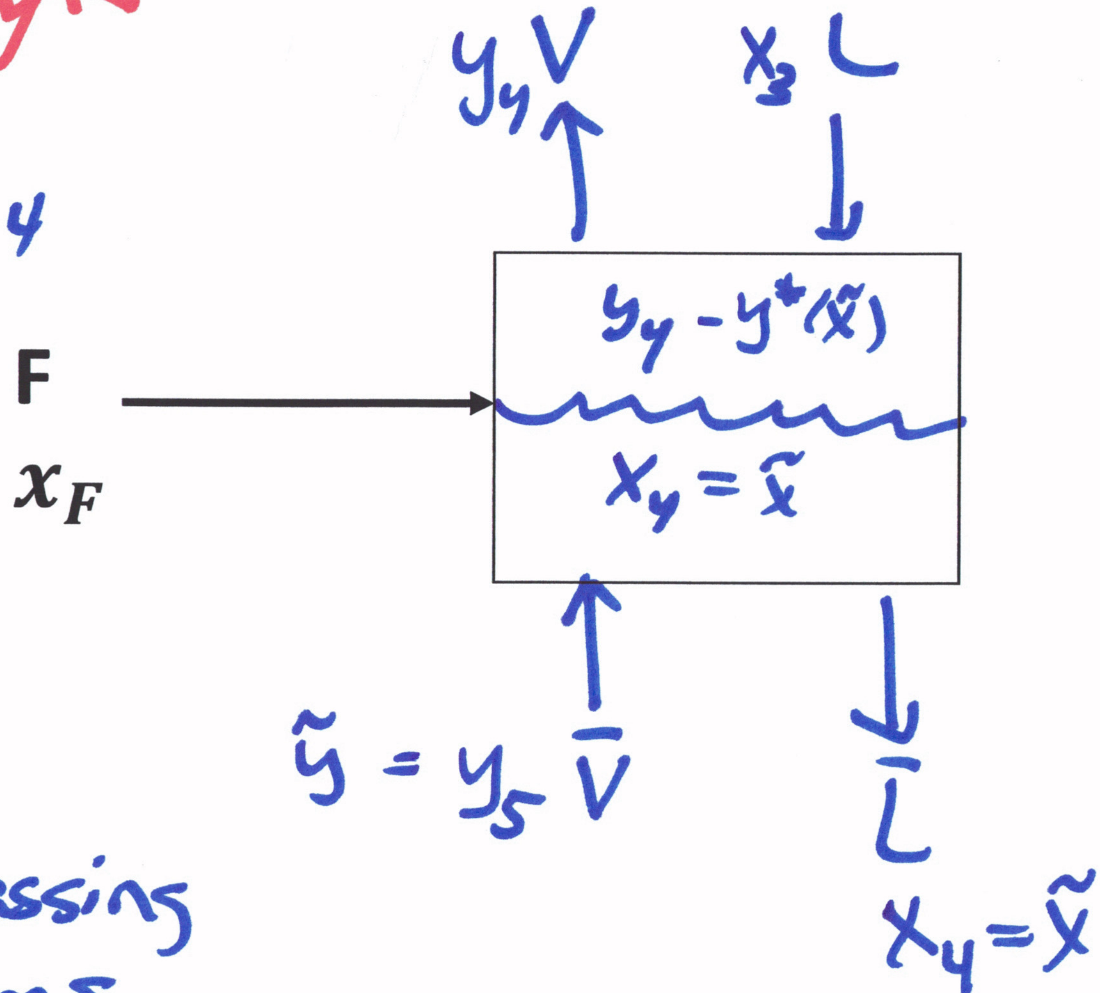
$$\bar{y} = \left(\frac{\bar{L}}{\bar{V}}\right) x_B - \left(\frac{\bar{L}}{\bar{V}} - 1\right) x_B$$

$$= \cancel{\left(\frac{\bar{L}}{\bar{V}}\right) x_B} - \cancel{\left(\frac{\bar{L}}{\bar{V}} x_B\right)} + x_B$$

$$\boxed{\bar{y} = x_B}$$

Feed Tray

stage 4



$\tilde{x}$ & $\tilde{y}$ are passing streams (top + bottom)

AT FEED

1. $\tilde{y}\,\bar{V} = \tilde{x}\,\bar{L} - x_B B$ stripping

2. $\tilde{y}\,V = \tilde{x}\,L + x_D D$ enriching

subtract 2 − 1

$$\tilde{y}(V-\bar{V}) = \tilde{x}(L-\bar{L}) + \overbrace{x_D D + x_B B}^{x_F F}$$

$$\boxed{\tilde{y} = \left(\frac{L-\bar{L}}{V-\bar{V}}\right)\tilde{x} + \frac{x_F F}{V-\bar{V}}}$$

"passing streams"
(at feed tray)

To find a point on the feed line

let $\tilde{x} = x_F$

$$\tilde{y} = \left(\frac{L-\bar{L}}{V-\bar{V}}\right) x_F + \frac{x_F F}{V-\bar{V}}$$

(return to this after quality discussion)

Returning (see p11)

$$\tilde{y} = \left(\frac{-q\cancel{F}}{(1-q)\cancel{F}}\right) x_F + \frac{x_F \cancel{F}}{(1-q)\cancel{F}}$$

$$\tilde{y} = \left(\frac{-q}{1-q}\right) x_F + \left(\frac{1}{1-q}\right) x_f$$

$$\tilde{y} = \frac{\cancel{(1-g)}\, x_F}{\cancel{(1-g)}}$$

$$\boxed{\tilde{y} = x_F}$$

(the third time we found a point on the 45° line)

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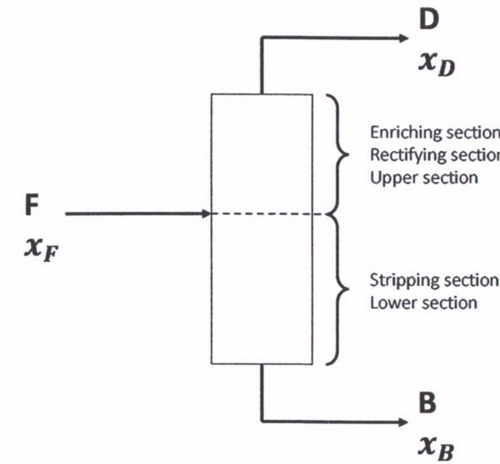
McCabe-Thiele Method



Goal: Determine the number of stages of a distillation column that can achieve the desired separation

Constraints

1. Overall mass conservation (mole balances)
2. Equilibrium stages $y^*(x^*)$
3. All stages above the feed satisfy the same mole balances drawn through D
4. All stages below the feed satisfy the same mole balances drawn through B
5. Upper and lower operating lines intersect at the feed tray
6. The quality q of the feed and mole balances on each phase at the feed tray close the calculation

NOW

Summary of Constraints (thus far)

1. Overall mass conservation (mole balances)

$$V = L + D$$

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

1. Equilibrium stages: data $y^* = f(x^*)$
2. Above the feed mole balances constrain passing streams $y(x)$ (operating line):

$$y = \left(\frac{L}{V}\right)x + \left(1 - \frac{L}{V}\right)x_D$$

3. Below the feed passing streams $\bar{y}(\bar{x})$ (operating line)

$$\bar{y} = \left(\frac{\bar{L}}{\bar{V}}\right)\bar{x} - \left(\frac{\bar{L}}{\bar{V}} - 1\right)x_B$$

5. Upper and lower intersect at feed tray, $\tilde{y}(\tilde{x})$

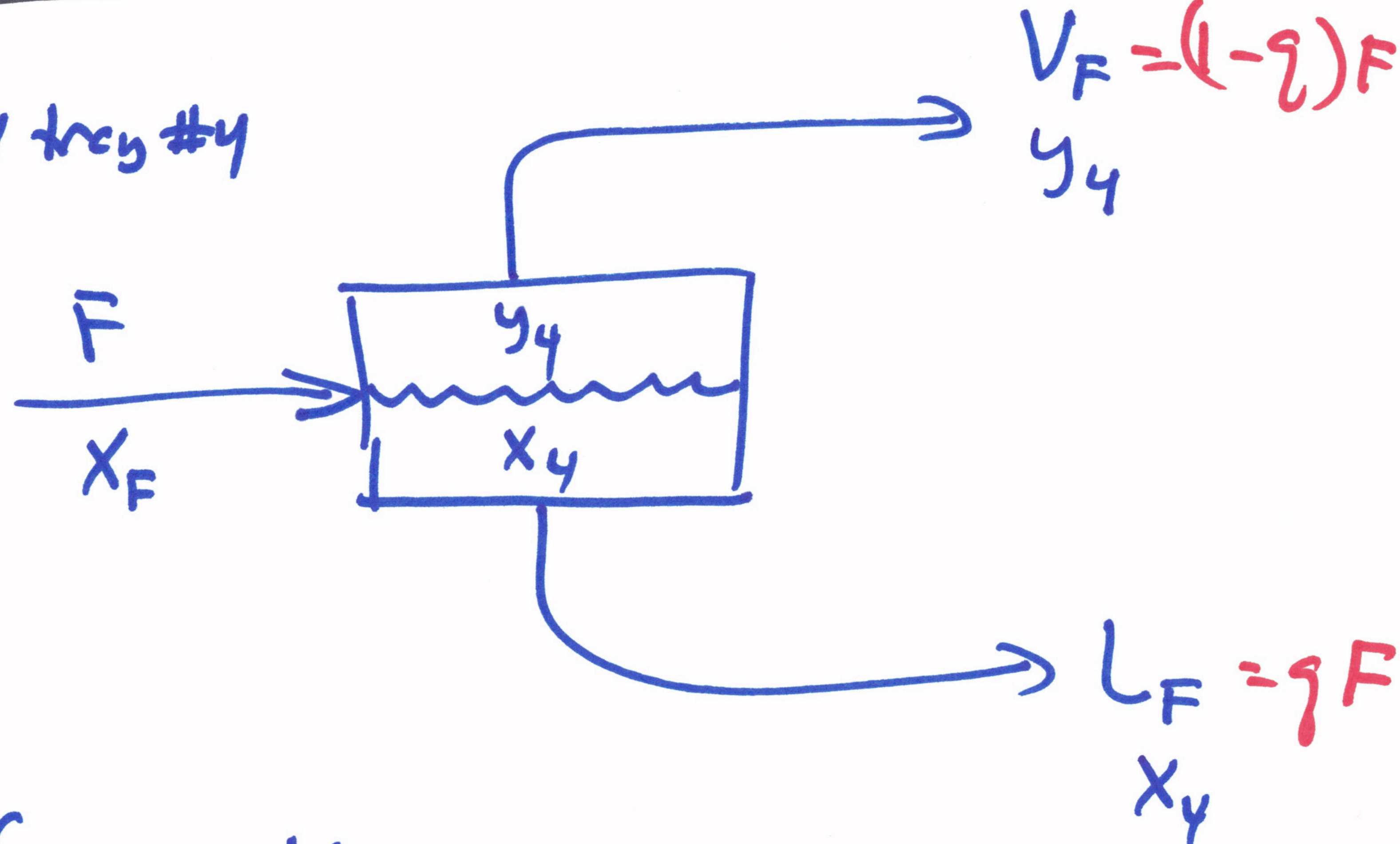
$$\tilde{y} = \left(\frac{L - \bar{L}}{V - \bar{V}}\right)\tilde{x} + \frac{x_F F}{V - \bar{V}}$$

4. The quality q of the feed and mole balances on each phase at the feed tray close the calculation

$-qF = L - \bar{L}$; $(1-q)F = V - \bar{V}$; $\tilde{y} = \left(\frac{q}{q-1}\right)\tilde{x} + \frac{x_F}{1-q}$

Quality of feed

feed tray #4

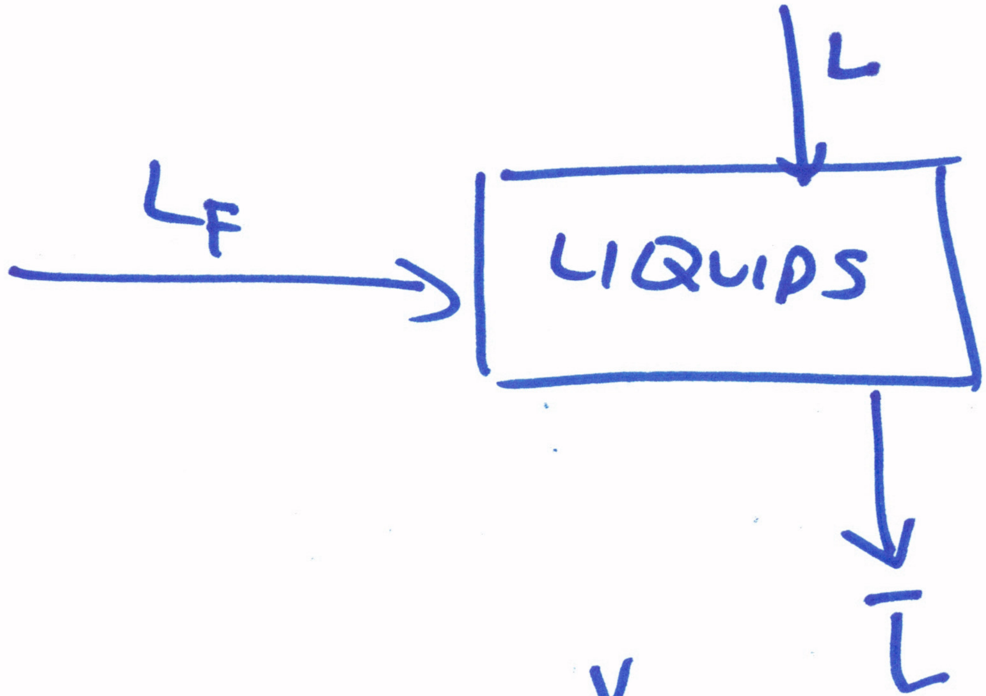


define quality:

$$q = \frac{L_F}{F}$$

$$1-q = \frac{F - L_F}{F} = \frac{V_F}{F}$$

V

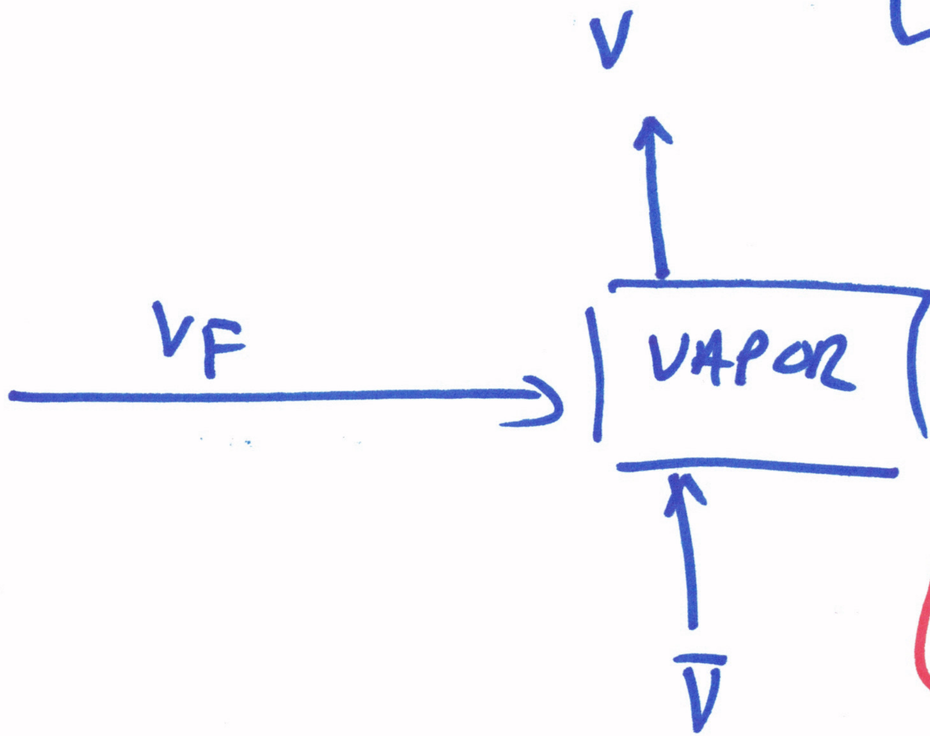


$$L_F + L = \bar{L}$$

$$L_F = \bar{L} - L$$

$$-L_F = L - \bar{L}$$

$$\boxed{-qF = L - \bar{L}}$$



$$V_F + \bar{V} = V$$

$$V_F = V - \bar{V}$$

$$\boxed{(1-q)F = V - \bar{V}}$$

Returning to the feed tray:
(passing streams)

$$\tilde{y} = \left(\frac{\overbrace{L-\bar{L}}^{-q\cancel{F}}}{\underbrace{V-\bar{V}}_{(1-q)\cancel{F}}}\right)\tilde{x} + \frac{x_F \cancel{F}}{\underbrace{V-\bar{V}}_{(1-q)\cancel{F}}}$$

$$\tilde{y} = \left(\frac{-q}{1-q}\right)\tilde{x} + \left(\frac{x_F}{1-q}\right)$$

$$\boxed{\tilde{y} = \underbrace{\left(\frac{q}{q-1}\right)}_{\text{slope}}\tilde{x} + \frac{x_F}{1-q}}$$

q-line (feed)

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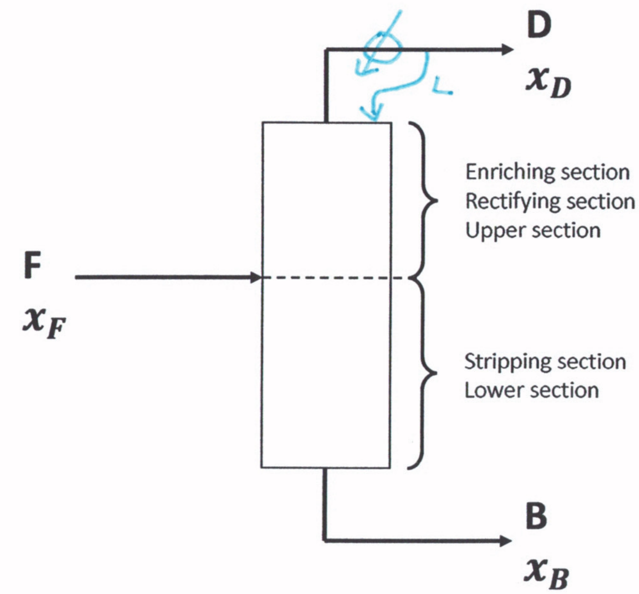
McCabe-Thiele Design Calculation—Binary Distillation



Find:

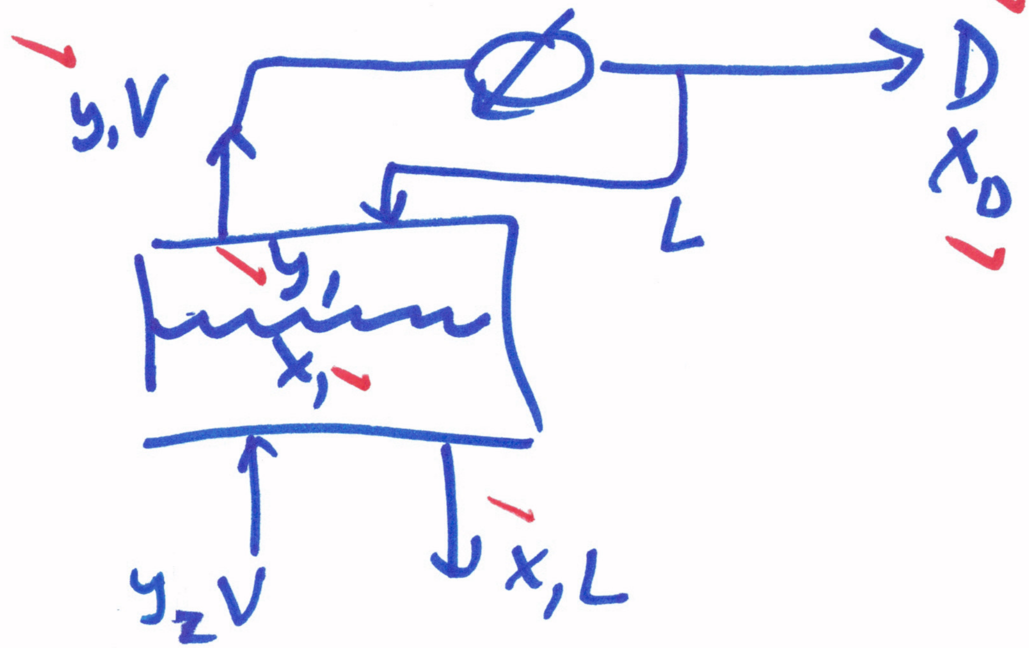
1. Number of equilibrium stages
2. Optimum location of the feed

Given:

1. F, x_F, x_D, x_B
2. Column pressure (sets $y^*(x^*)$)
3. $q = 0.5$ slope -1
4. Reflux ratio, $r = \frac{L}{V} = 0.625$

walk thru column...

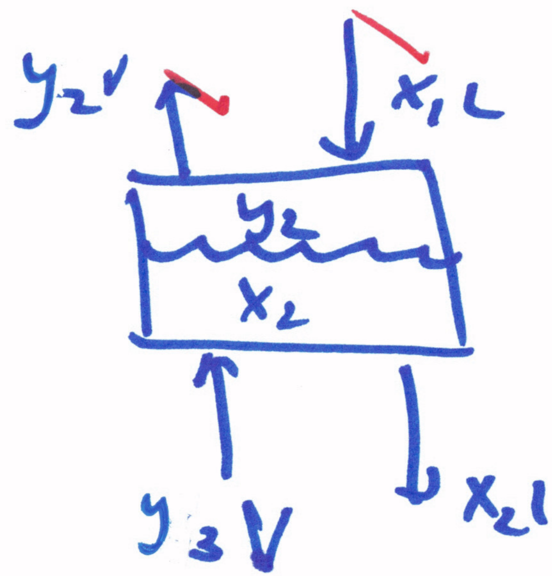
stage 1



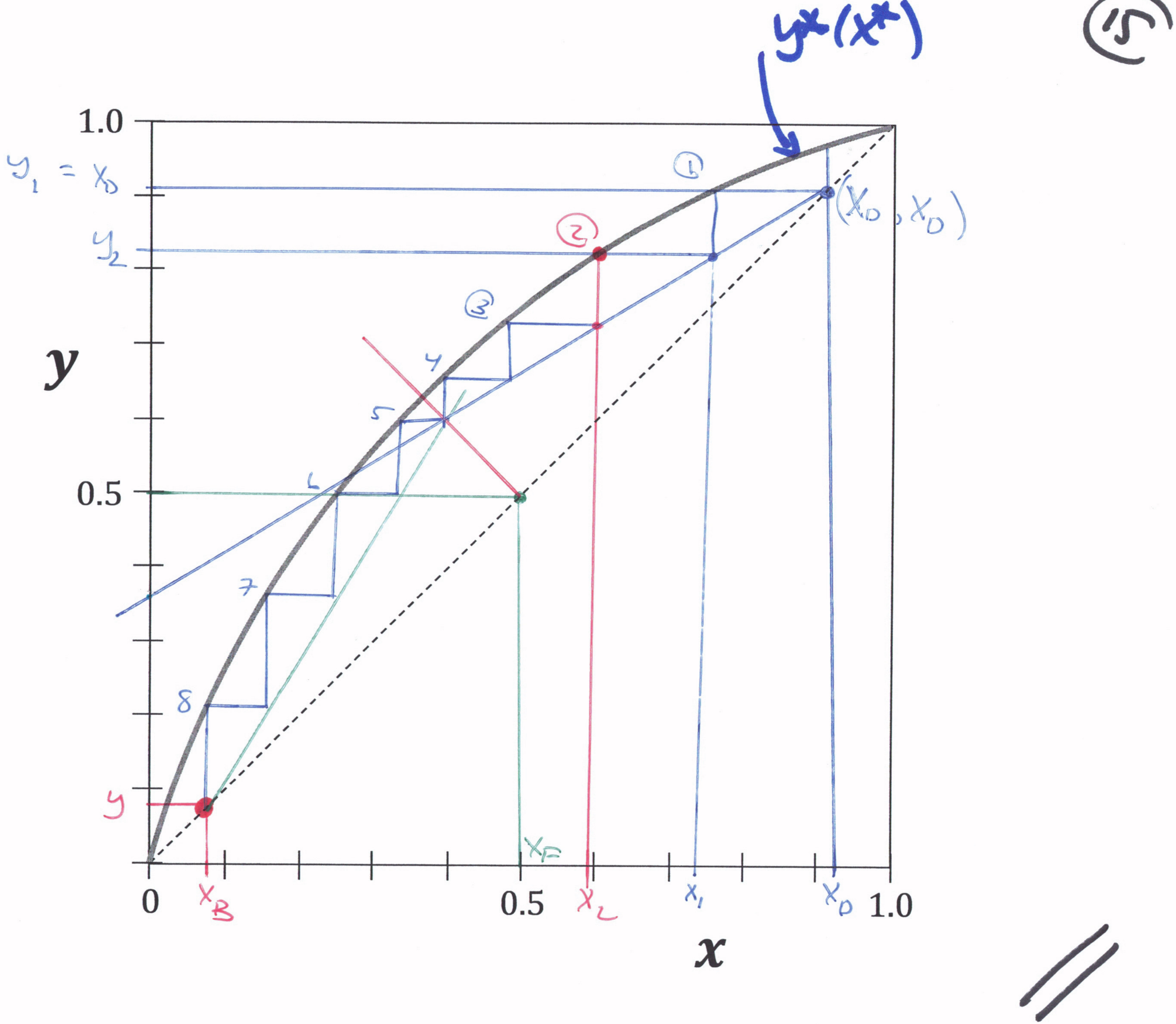
$\frac{L}{V} = 0.625$

(reflux ratio)

stage 2



etc.



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$y^*(x^*)$
1.0
$y_1 = x_D$
y_2
(x_D, x_D)
1
2
3
4
5
6
7
8
y
0.5
y
x_F
0
x_B
0.5
x_2
x_1
x_D
1.0
x