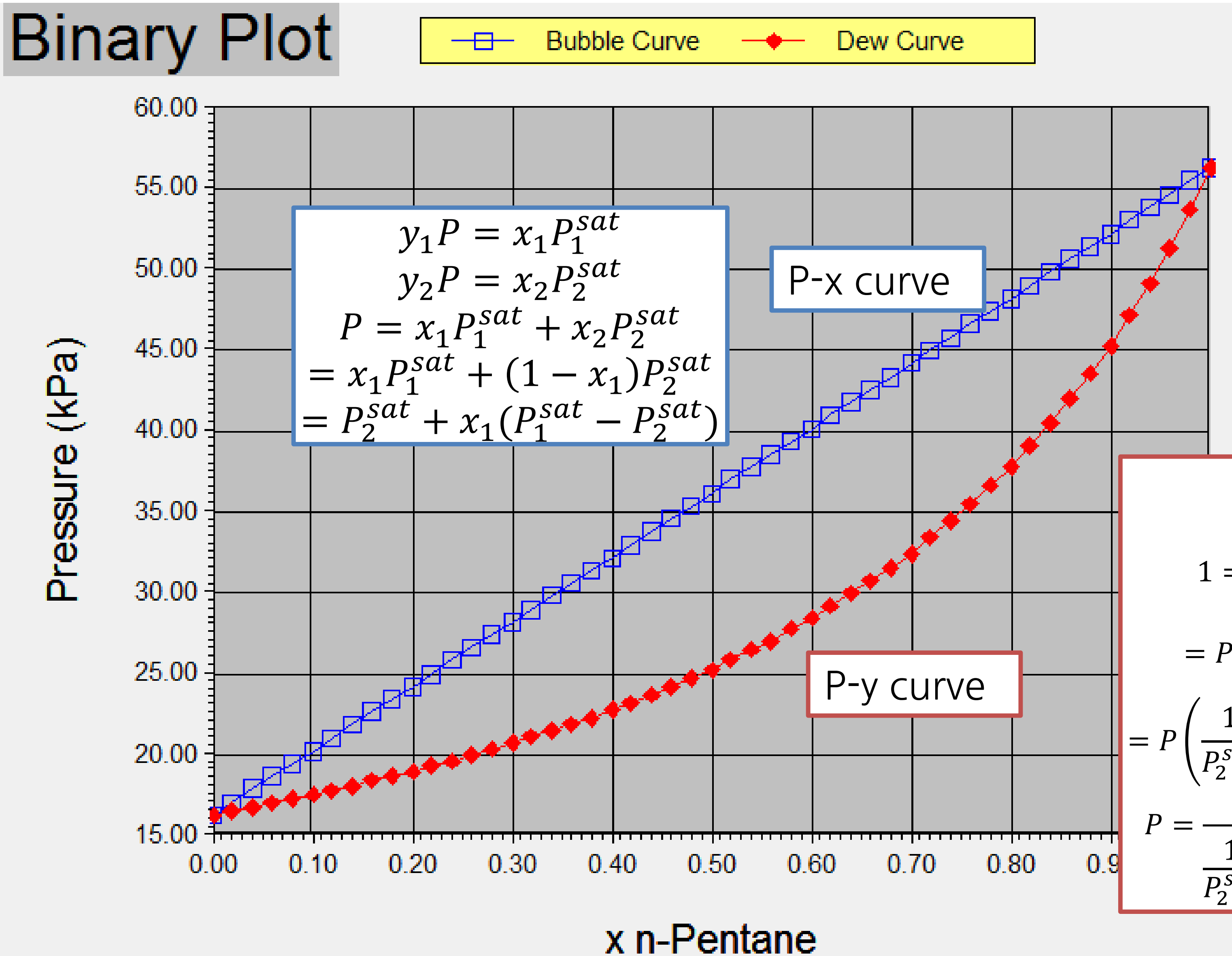
Distillation Column

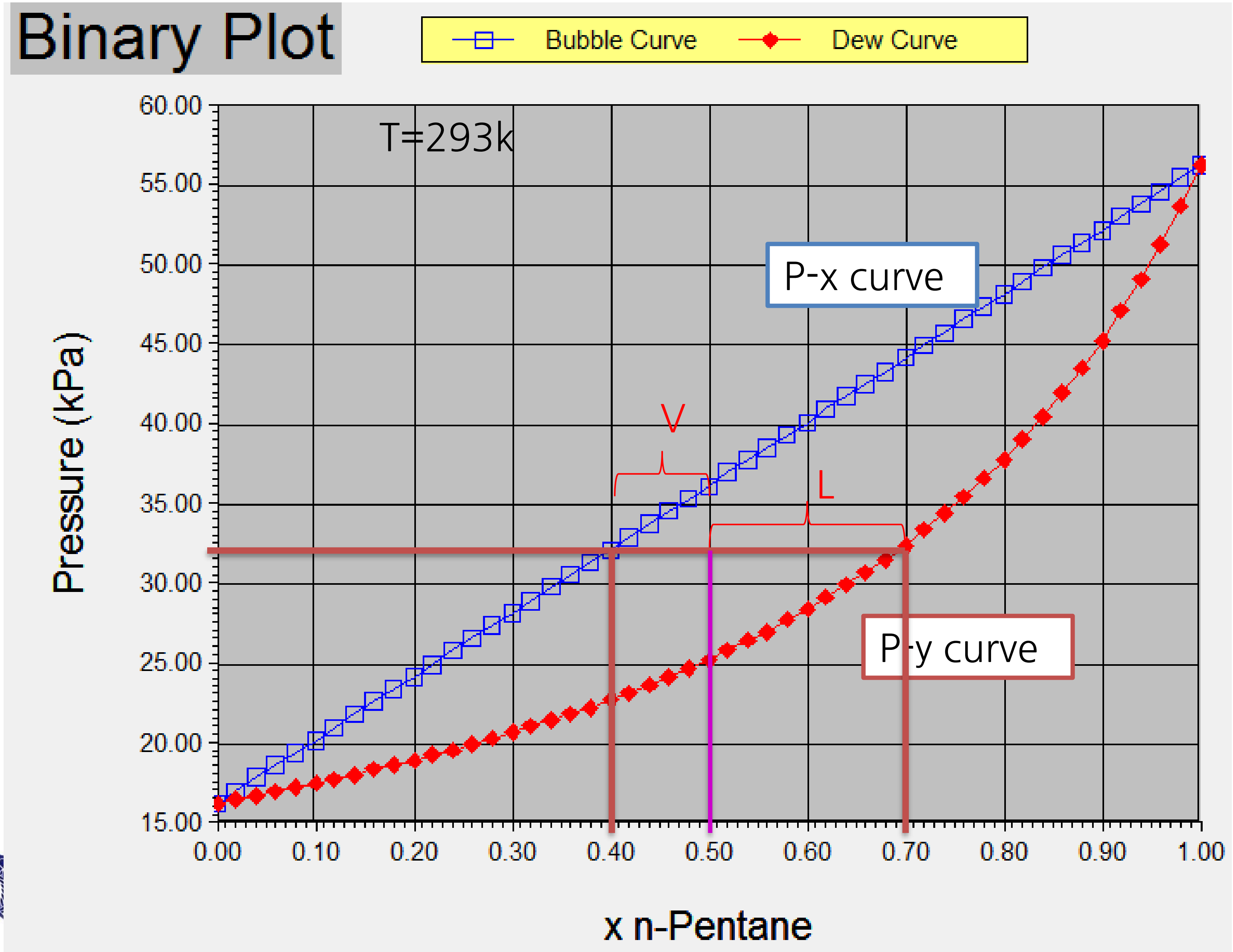
Pxy diagram



$$y_1 P = x_1 P_1^{sat}$$
$$y_2 P = x_2 P_2^{sat}$$
$$P = x_1 P_1^{sat} + x_2 P_2^{sat}$$
$$= x_1 P_1^{sat} + (1 - x_1) P_2^{sat}$$
$$= P_2^{sat} + x_1 (P_1^{sat} - P_2^{sat})$$

$$x_1 = y_1 P / P_1^{sat}$$
$$x_2 = y_2 P / P_2^{sat}$$
$$1 = P\left(\frac{y_1}{P_1^{sat}} + \frac{y_2}{P_2^{sat}}\right)$$
$$= P\left(\frac{y_1}{P_1^{sat}} + \frac{(1 - y_1)}{P_2^{sat}}\right)$$
$$= P\left(\frac{1}{P_2^{sat}} + y_1\left(\frac{1}{P_1^{sat}} - \frac{1}{P_2^{sat}}\right)\right)$$
$$P = \frac{1}{\frac{1}{P_2^{sat}} + y_1\left(\frac{1}{P_1^{sat}} - \frac{1}{P_2^{sat}}\right)}$$

Pxy diagram: lever rule



Lever rule

$$z_1 F = y_1 V + x_1 L$$

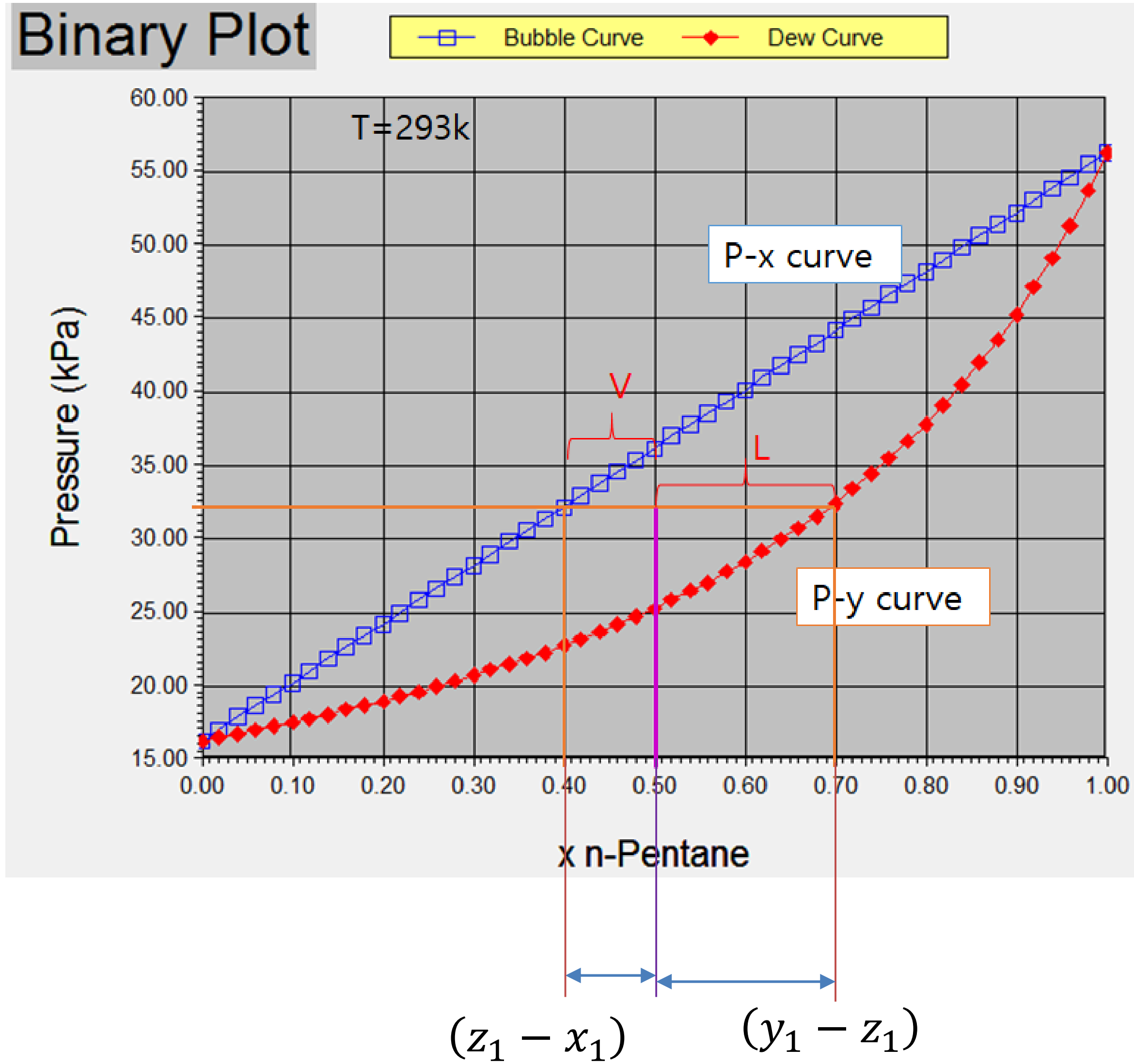
$$z_1 \frac{V+L}{L} = y_1 \frac{V}{L} + x_1$$

$$z_1 \frac{V}{L} + z_1 = y_1 \frac{V}{L} + x_1$$

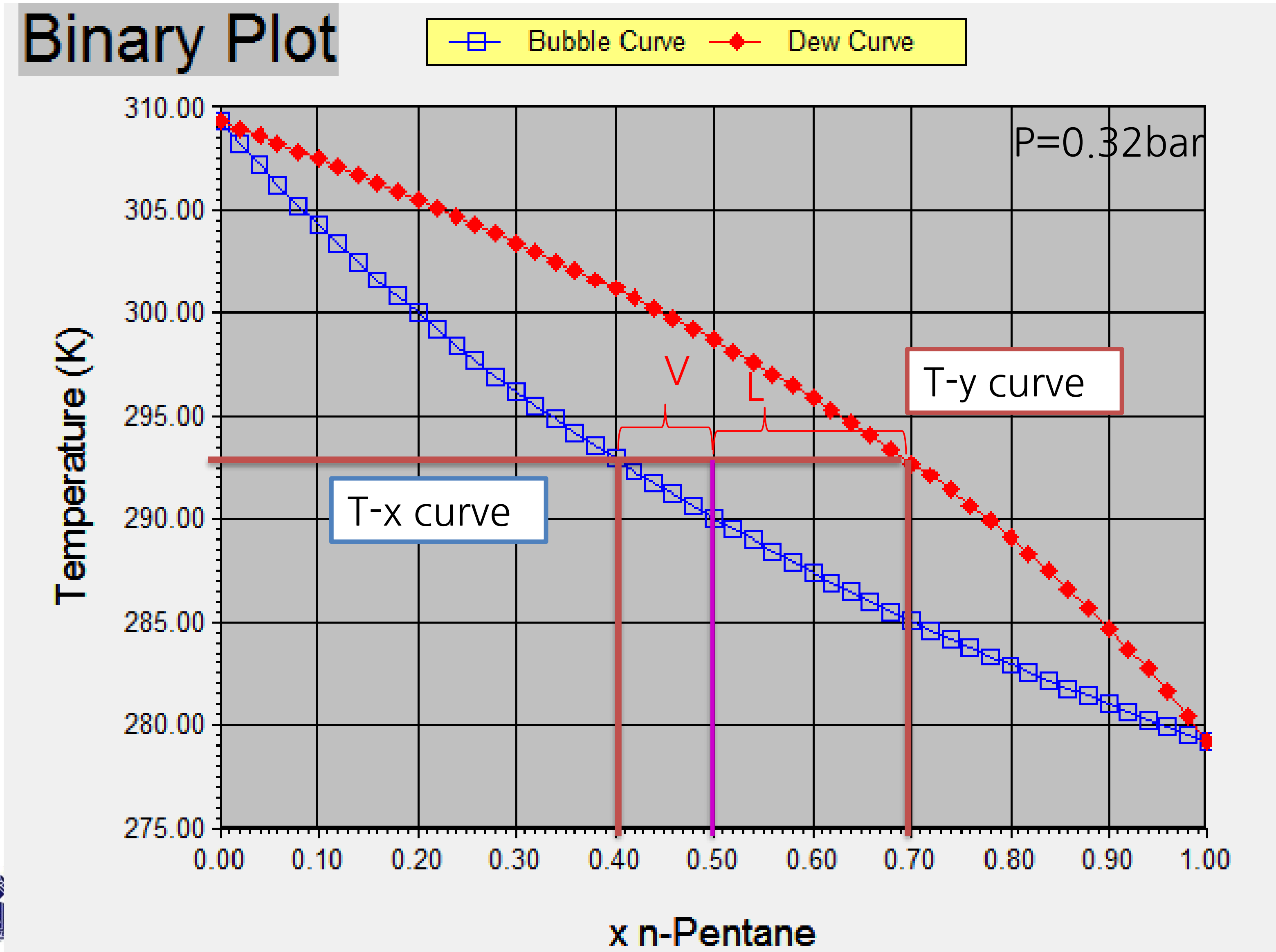
$$z_1 - x_1 = \frac{V}{L}(y_1 - z_1)$$

$$\frac{V}{L} = \frac{z_1 - x_1}{y_1 - z_1}$$

$$V:L = (z_1 - x_1):(y_1 - z_1)$$

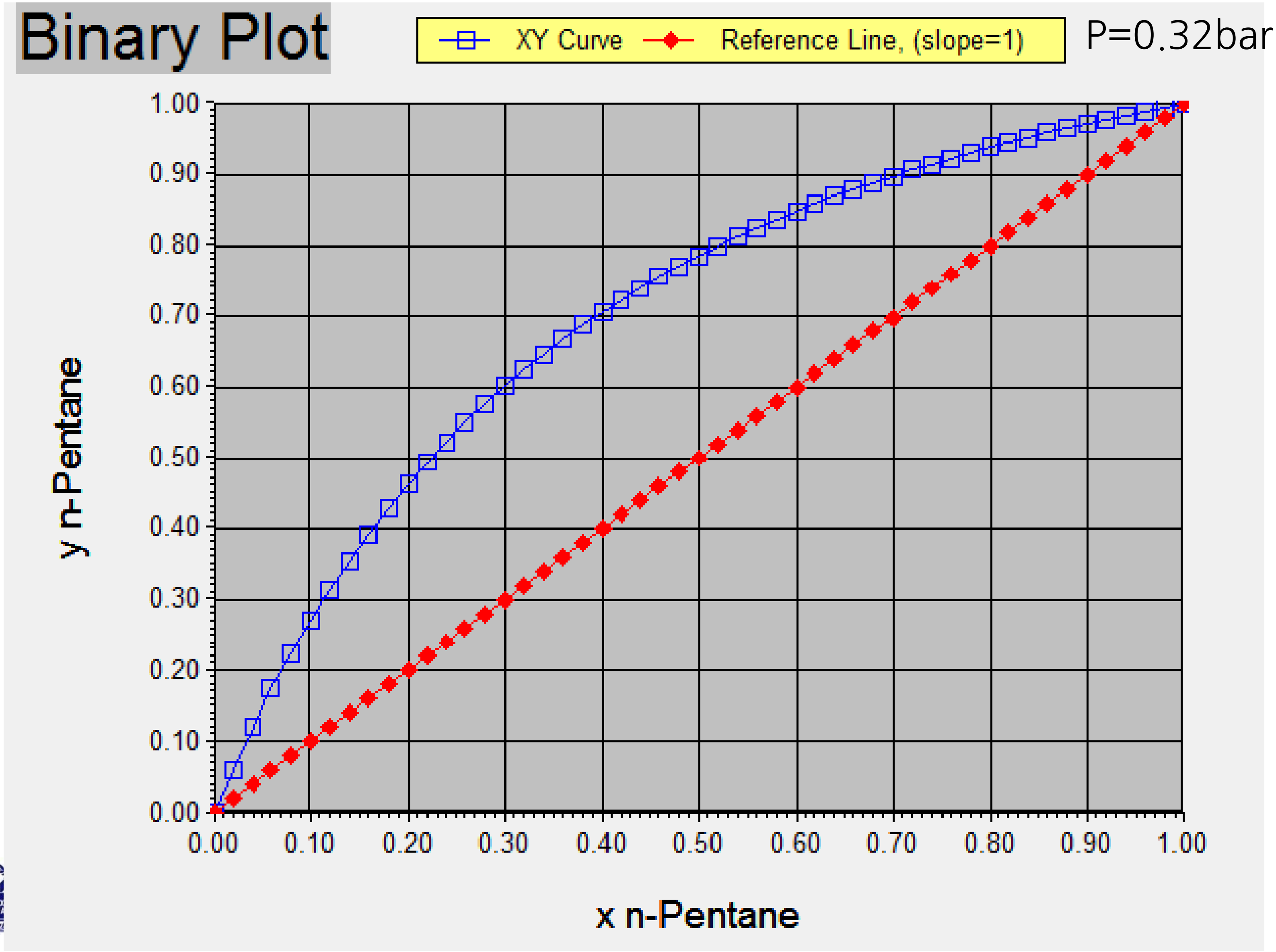


Txy diagram

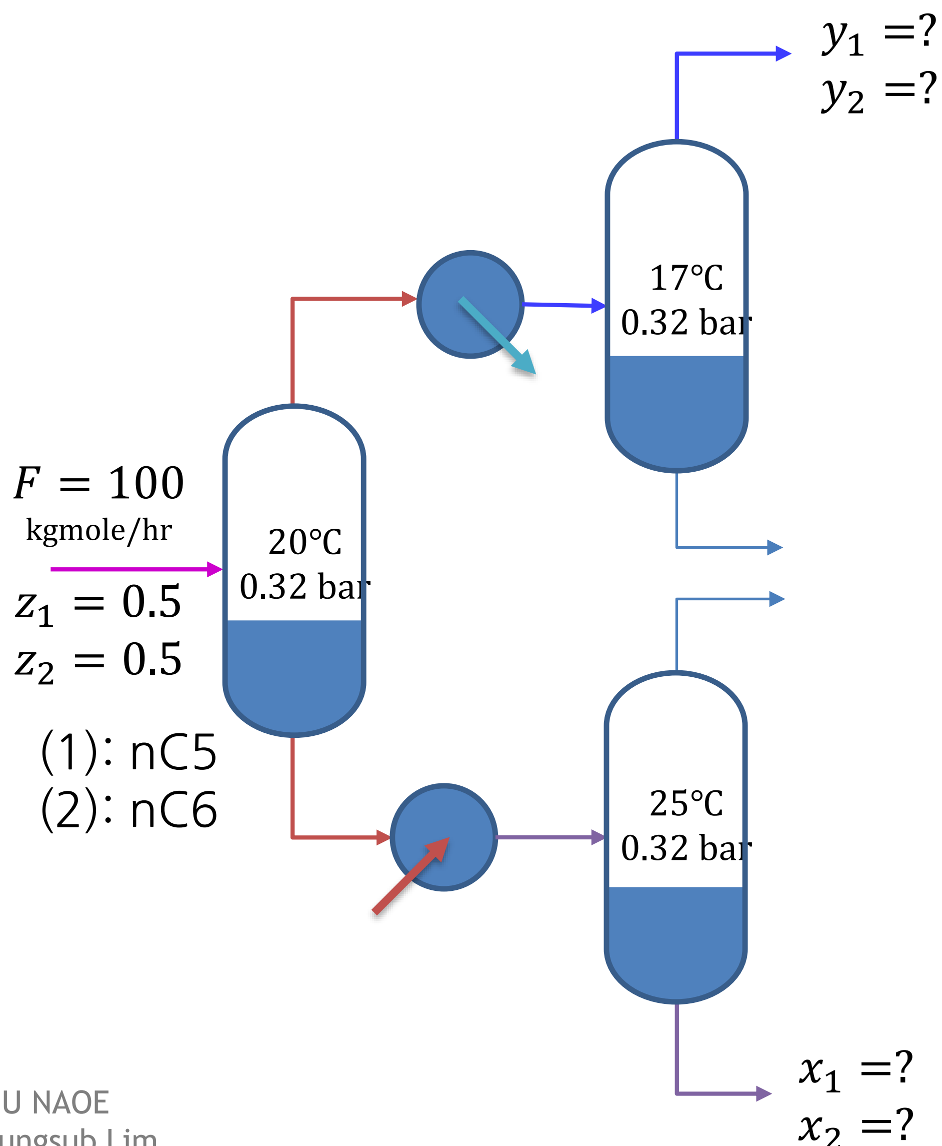


Binary Plot
Bubble Curve
Dew Curve
P=0.32bar
V
L
T-y curve
T-x curve
Temperature (K)
310.00
305.00
300.00
295.00
290.00
285.00
280.00
275.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
x n-Pentane

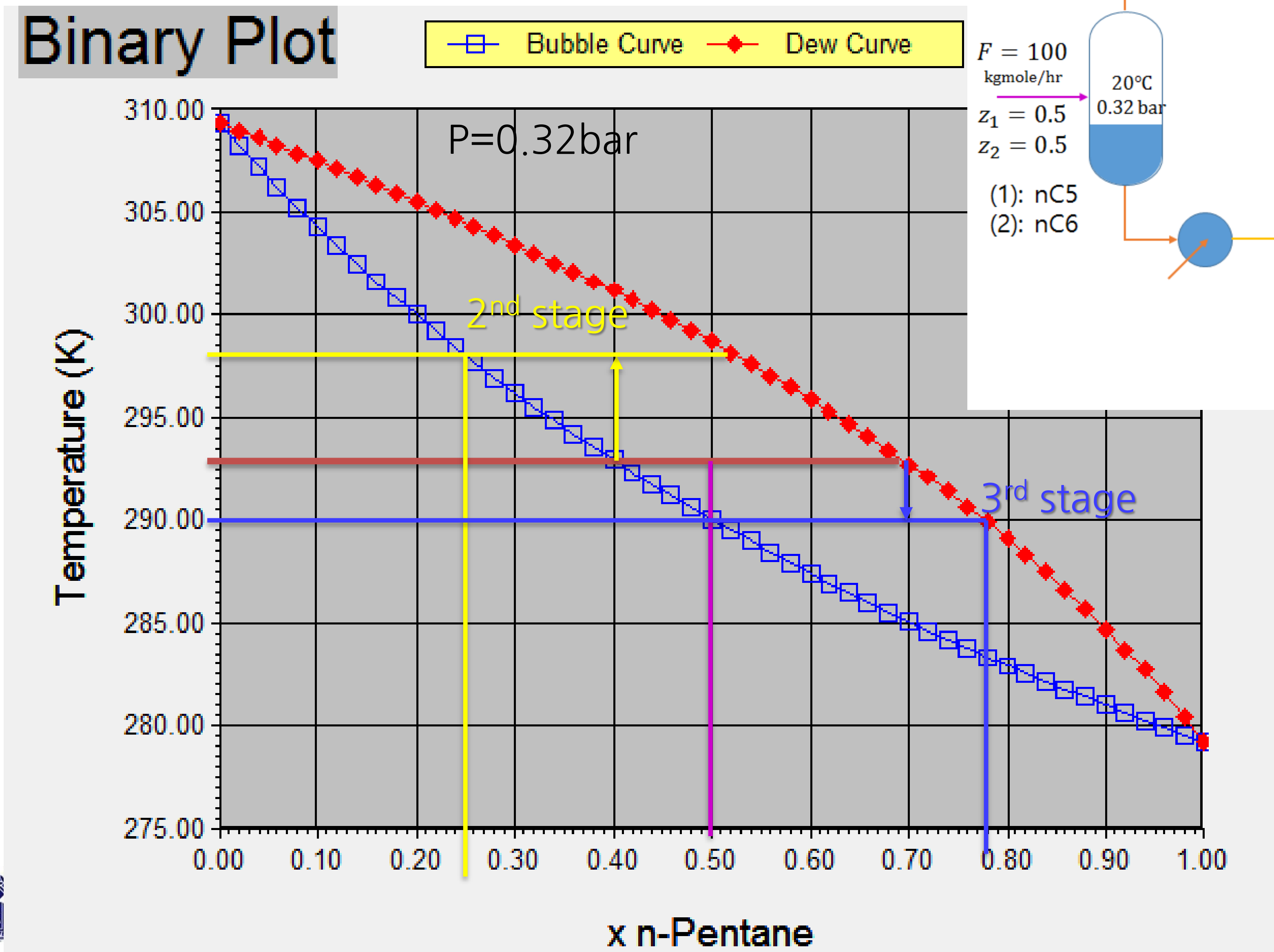
xy diagram


Binary Plot
XY Curve
Reference Line, (slope=1)
P=0.32bar
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
y n-Pentane
x n-Pentane

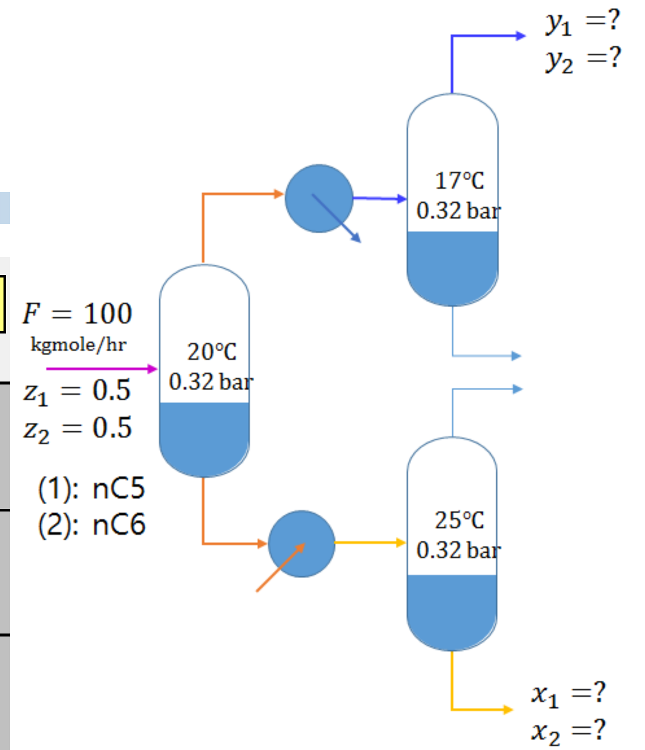
Multi-stage flash



Txy diagram

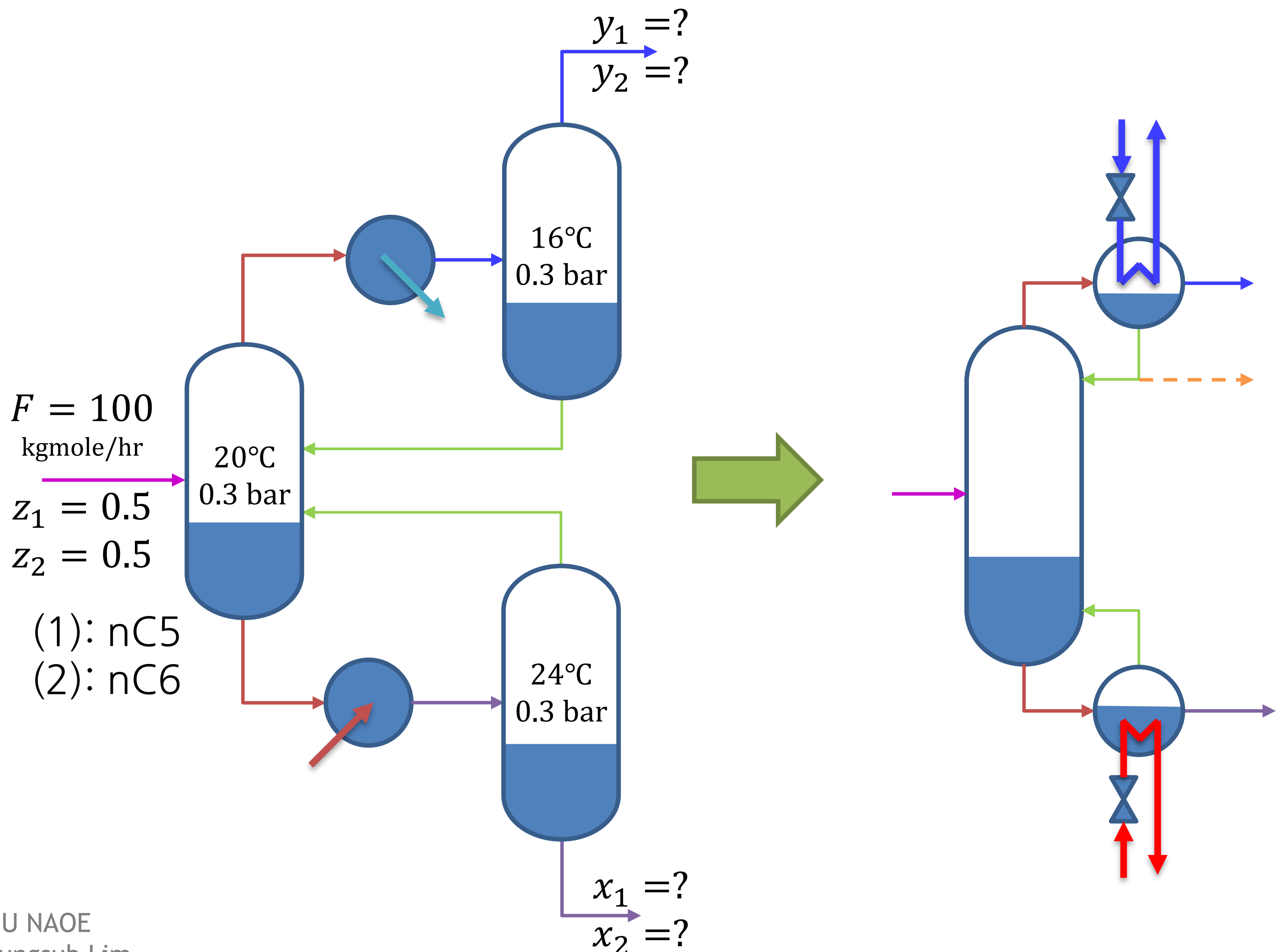


Binary Plot
Bubble Curve
Dew Curve
P=0.32bar
2nd stage
3rd stage
310.00
305.00
300.00
295.00
290.00
285.00
280.00
275.00
Temperature (K)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
x n-Pentane

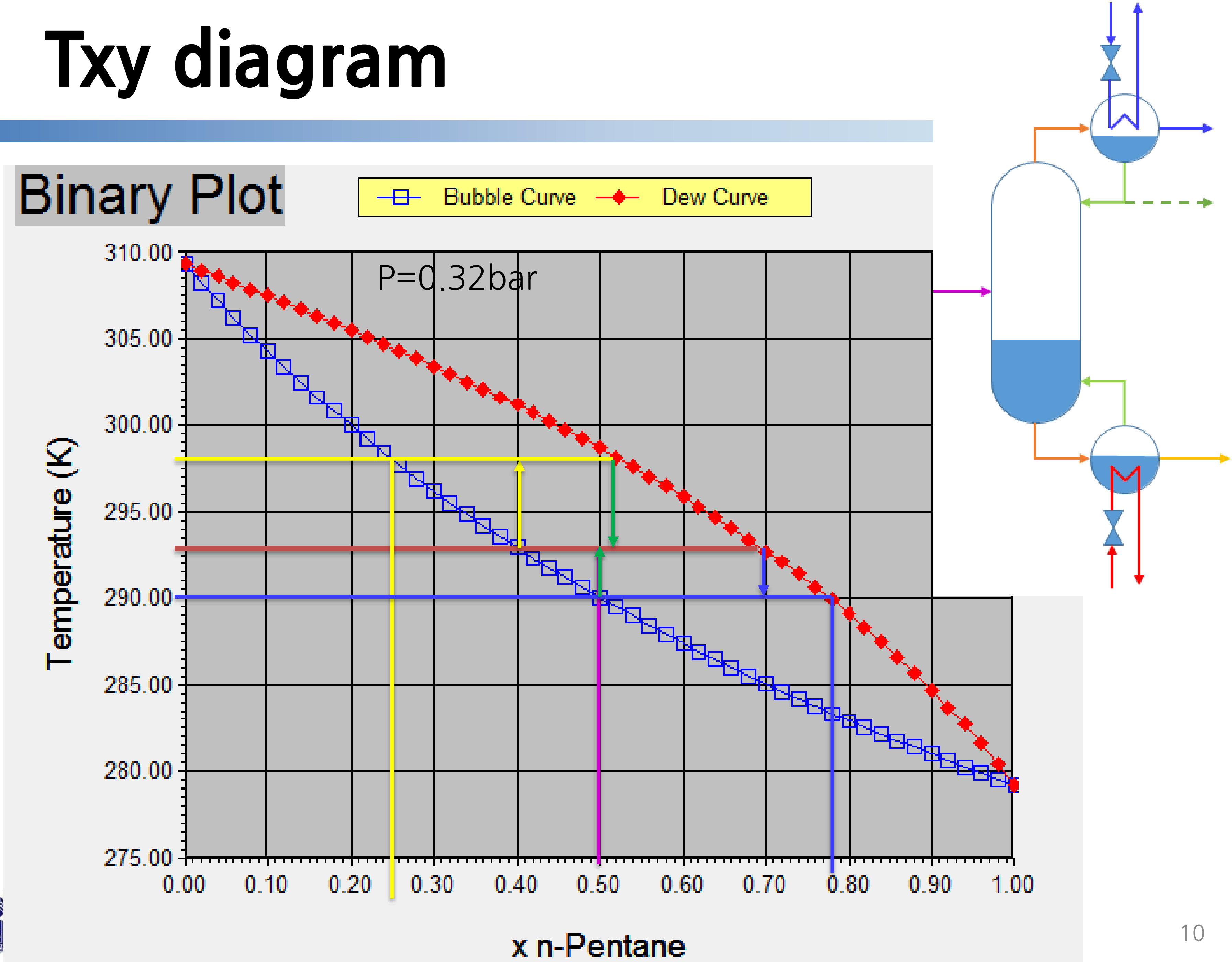


$y_1 = ?$
$y_2 = ?$
17°C
0.32 bar
$F = 100$
kgmole/hr
$z_1 = 0.5$
$z_2 = 0.5$
20°C
0.32 bar
(1): nC5
(2): nC6
25°C
0.32 bar
$x_1 = ?$
$x_2 = ?$

Multi-stage flash

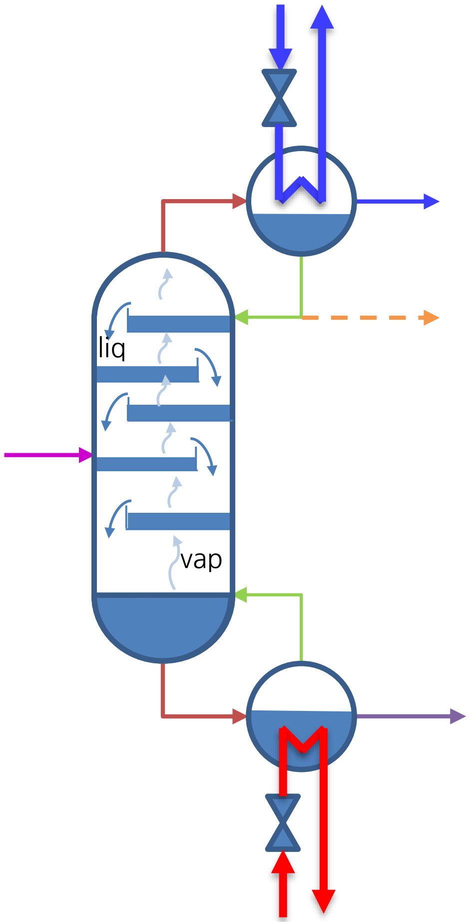


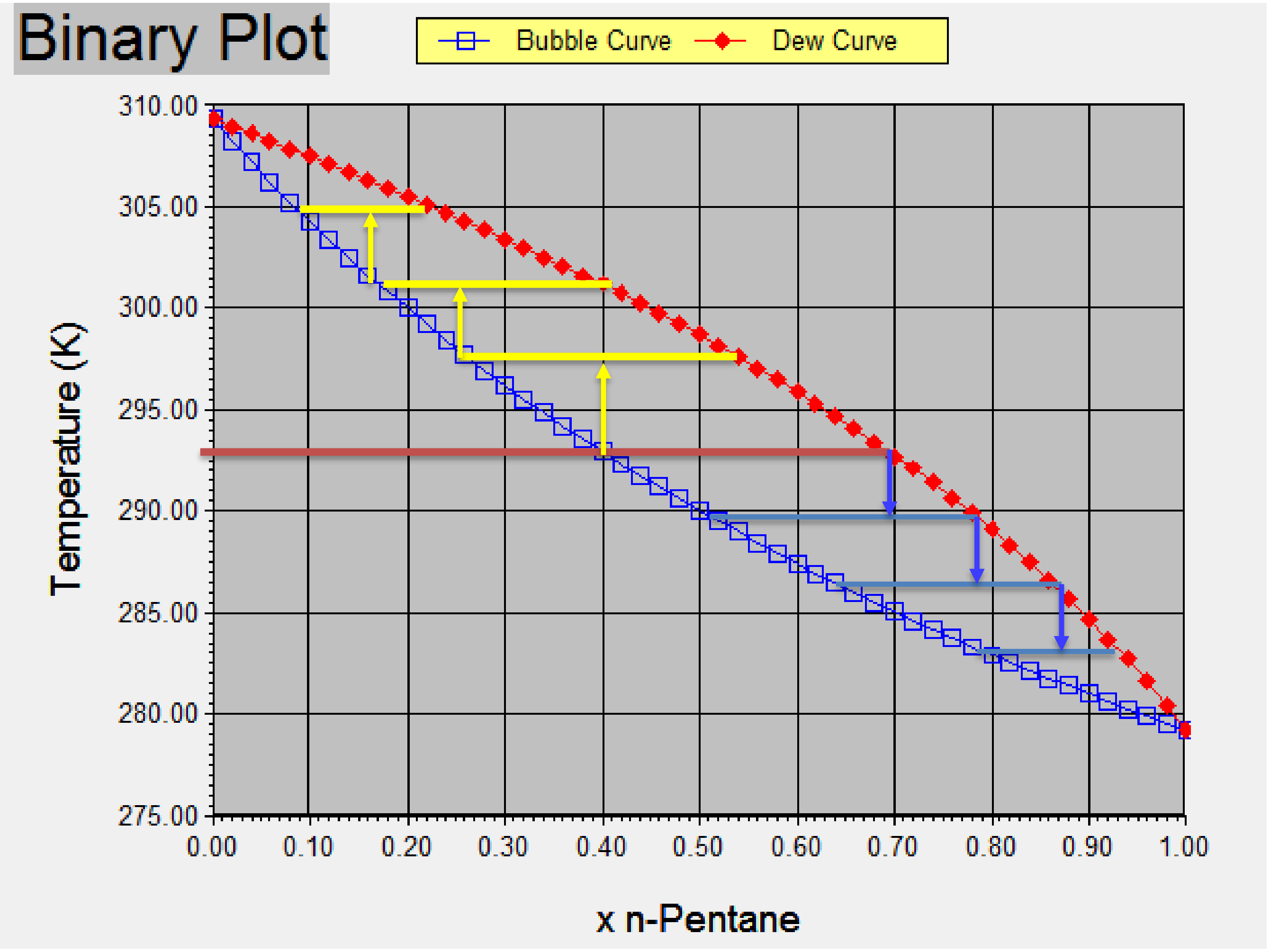
Txy diagram

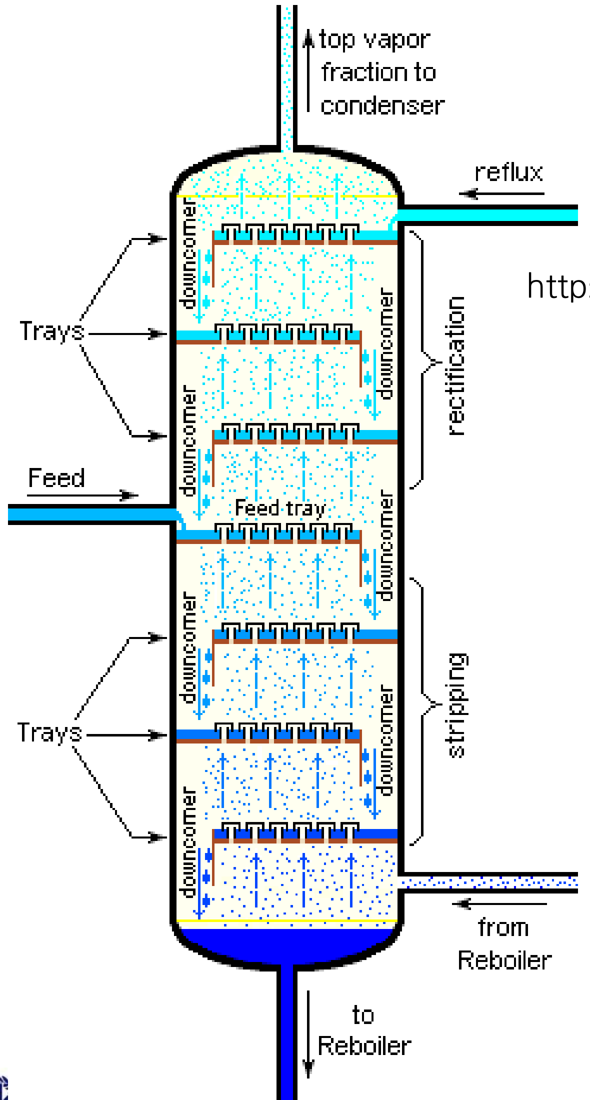


Binary Plot
Bubble Curve
Dew Curve
P=0.32bar
310.00
305.00
300.00
295.00
290.00
285.00
280.00
275.00
Temperature (K)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
x n-Pentane

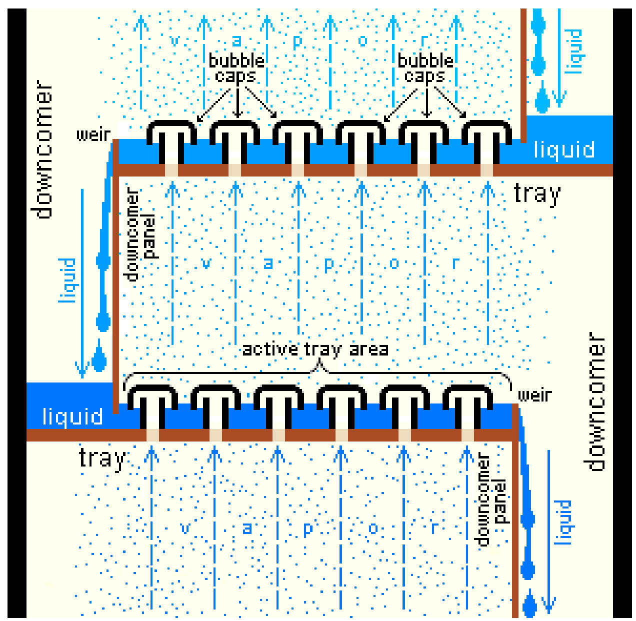
Distillation Column





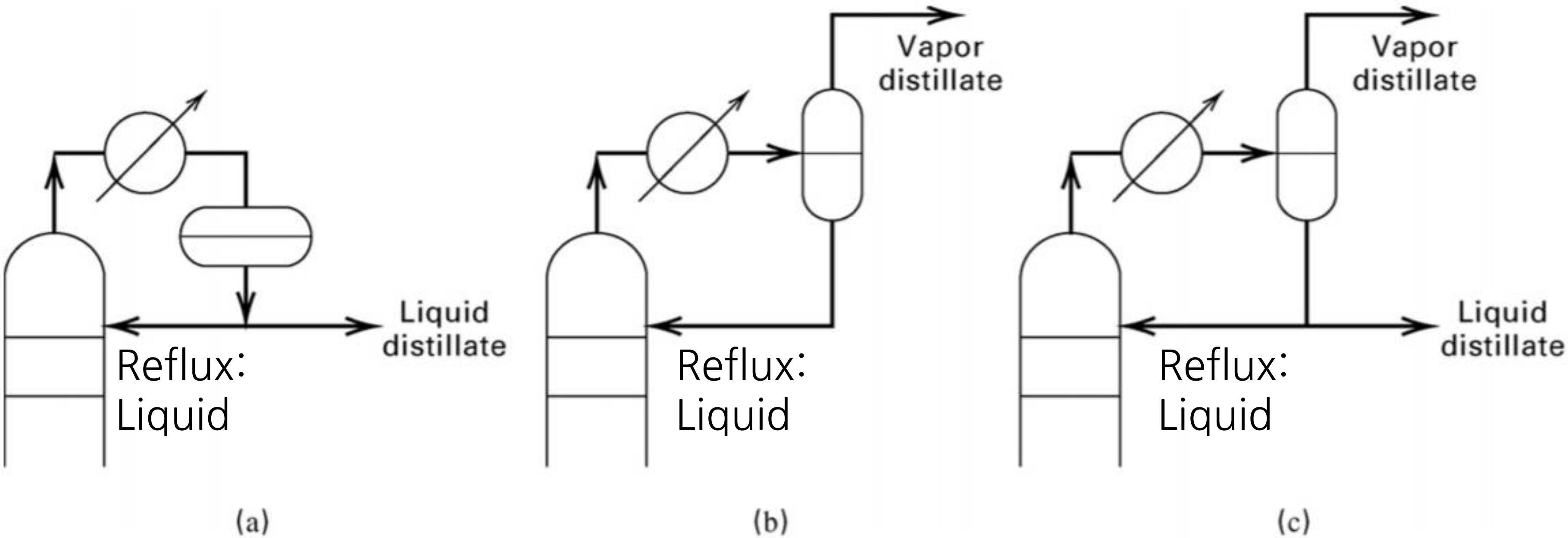


https://en.wikipedia.org/wiki/Fractionating_column



https://www.youtube.com/watch?v=vscX_zawdQw

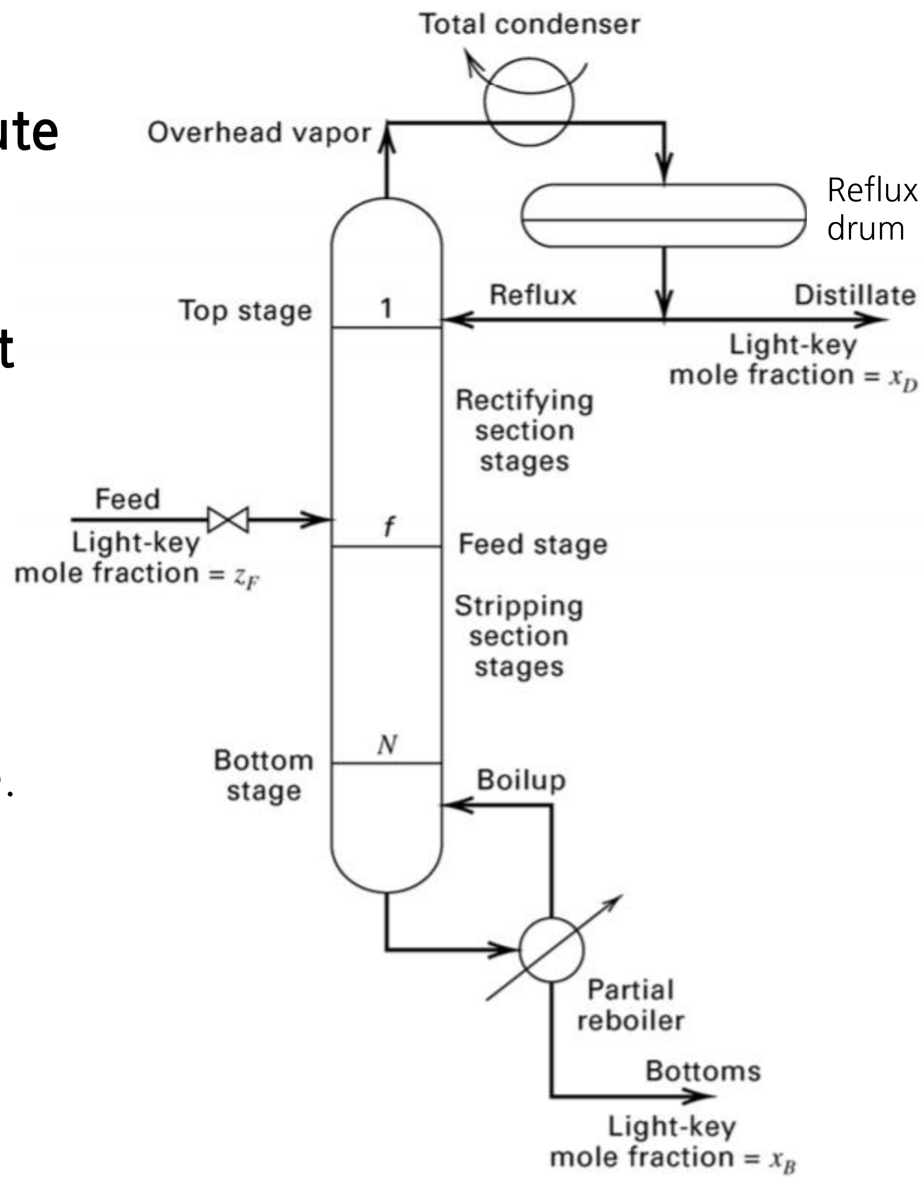
Condenser



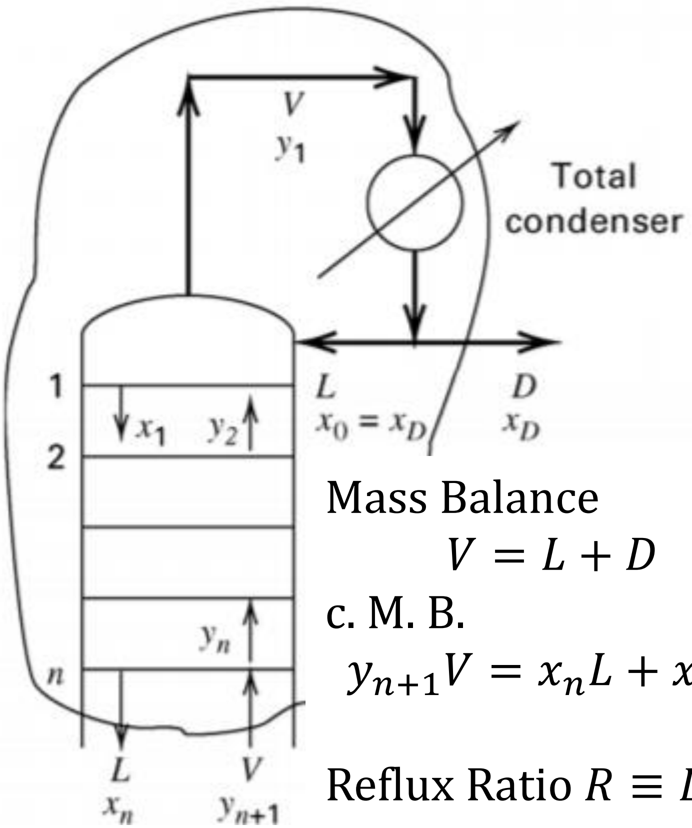
total condenser **partial condenser** **mixed condenser**

McCabe-Thiele Method

- **The McCabe-Thiele method was presented by two graduate students at Massachusetts Institute of Technology (MIT), Warren L. McCabe and Ernest W. Thiele in 1925.**
- **It can help you understand about distillation graphically.**
- **Assumptions**
  - It assumes binary system that considers separation of light key and heavy key only
  - The latent heat of two key substances is similar.
  - The mixing enthalpy is negligible.
  - Adiabatic
  - Constant pressure



Rectifying section



Mass Balance

$$V = L + D$$

c. M. B.

$$y_{n+1}V = x_n L + x_D D$$

Reflux Ratio $R \equiv L/D$

$$y_{n+1} = \frac{L}{V}x_n + \frac{D}{V}x_D$$

$$\frac{D}{V} = \frac{D}{L+D} = \frac{1}{R+1}$$

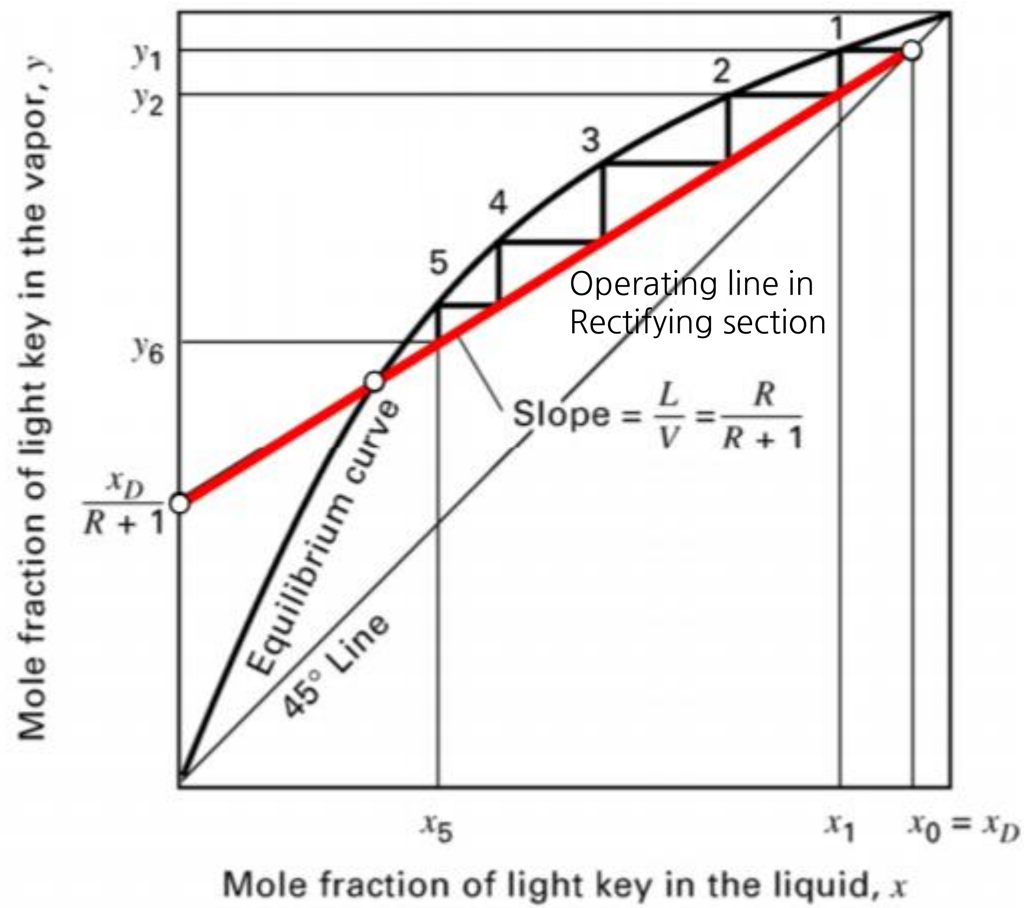
$$\frac{L}{V} = \frac{L}{L+D} = \frac{L/D}{L/D + D/D} = \frac{R}{R+1}$$

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

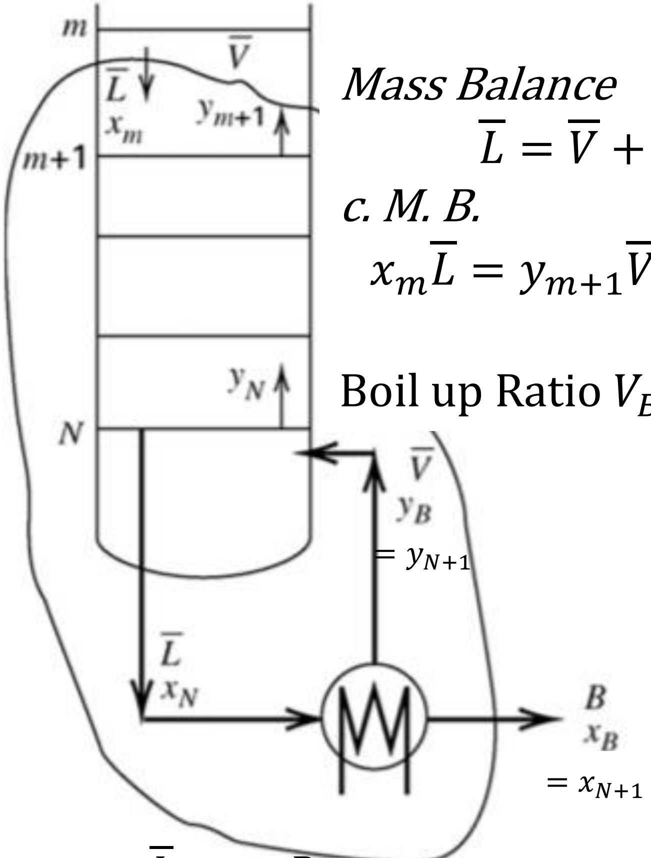
(Condenser)

$$n = 0 \rightarrow y_1 = \frac{R}{R+1}x_0 + \frac{1}{R+1}x_D = x_D$$

$$n = 1 \rightarrow y_2 = \frac{R}{R+1}x_1 + \frac{1}{R+1}x_D$$



Stripping section



Mass Balance

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

c. M. B.

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

Boil up Ratio $V_B \equiv \overline{V}/B$

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

$$\frac{\overline{L}}{\overline{V}} = \frac{\overline{V}+B}{\overline{V}} = \frac{V_B+1}{V_B}$$

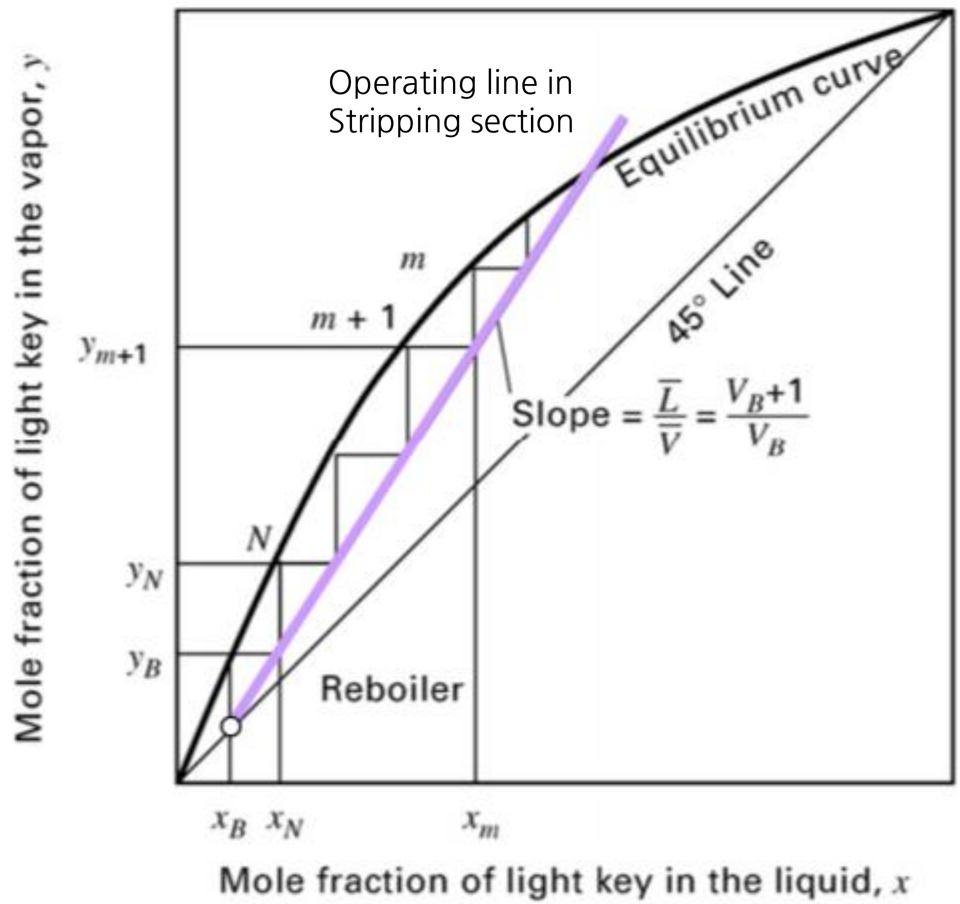
$$\frac{B}{\overline{V}} = \frac{1}{V_B}$$

$$y_{m+1} = \frac{V_B+1}{V_B}x_m - \frac{1}{V_B}x_B$$

(Reboiler)

$$m = N+1 \rightarrow y_{N+2} = \frac{V_B+1}{V_B}x_{N+1} - \frac{1}{V_B}x_B = x_B$$

$$m = N \rightarrow y_{N+1} = y_B = \frac{V_B+1}{V_B}x_N - \frac{1}{V_B}x_B$$



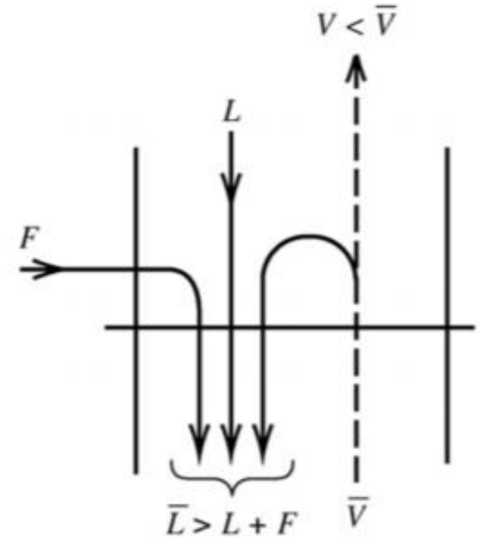
Feed stage configuration

(a) Subcooled liquid

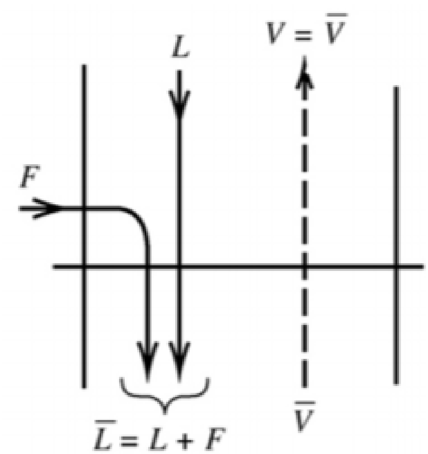
– Feed stream liquefies vapor ($\bar{V}$) partially

(b) bubble point liquid

– Feed stream is becomes liquid with L

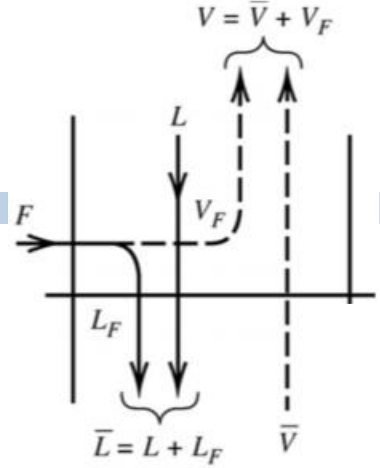


(a)



(b)

Feed stage

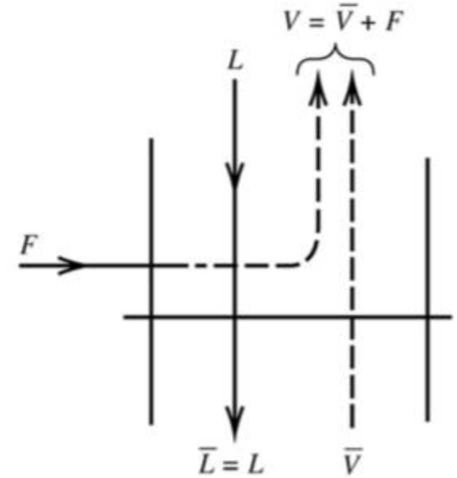


(c) Partially vaporized

- Vapor to vapor, liquid to

(d) Dew point vapor

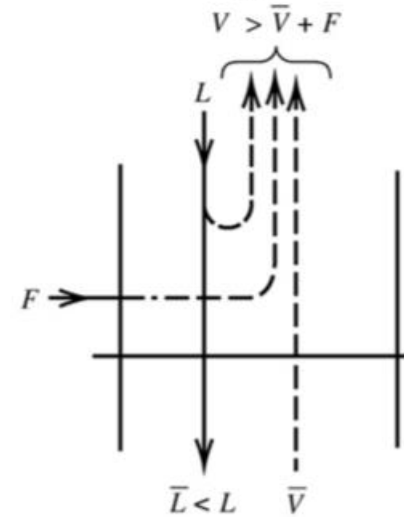
- Feed stream is becomes vapor with V



(d)

(e) Superheated vapor

- Feed stream vaporize the liquid L partially



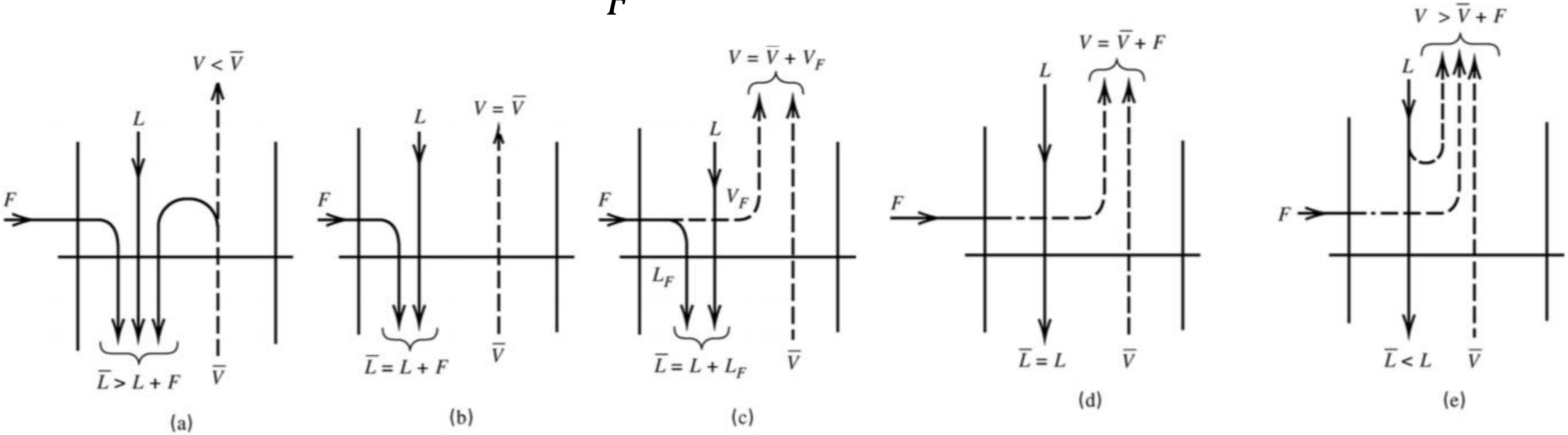
(e)

SNU NAOE
Youngsub Lim

The q-line

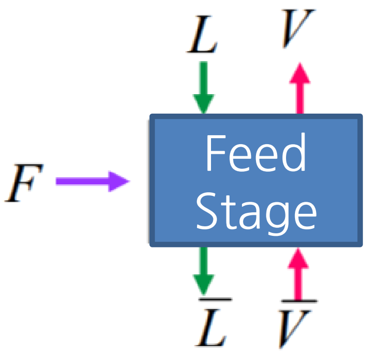
- q :ratio of the increase in molar flux rate across the feed stage

$$q = \frac{\overline{L} - L}{F}$$



$q > 1$ $\quad$ $q = 1$ $\quad$ $0 < q < 1$ $\quad$ $q = 0$ $\quad$ $q < 0$

The q-line



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

$$\bar{L} - L = \bar{V} - V + F$$

$$q = \frac{\bar{L} - L}{F} = \frac{\bar{V} - V + F}{F}$$
$$= 1 + \frac{\bar{V} - V}{F}$$

cmb in Rectifying section.

$$yV = Lx + Dx_D$$

Cmb in Stripping section.

$$y\bar{V} = x\bar{L} - x_B B$$

$$y(\bar{V} - V) = x(\bar{L} - L) - x_B B - x_D D \qquad (z_F F = x_D D + x_B B)$$

$$y(\bar{V} - V) = x(\bar{L} - L) - x_B B - x_D D = x(\bar{L} - L) - z_F F$$

$$y\frac{(\bar{V} - V)}{F} = x\frac{(\bar{L} - L)}{F} - z_F$$

$$y(q-1) = xq - z_F$$

$$y = \frac{q}{q-1}x - \frac{z_F}{q-1} \quad \text{(q-line)}$$

- **q-line must pass the point (z_F, z_F), because**

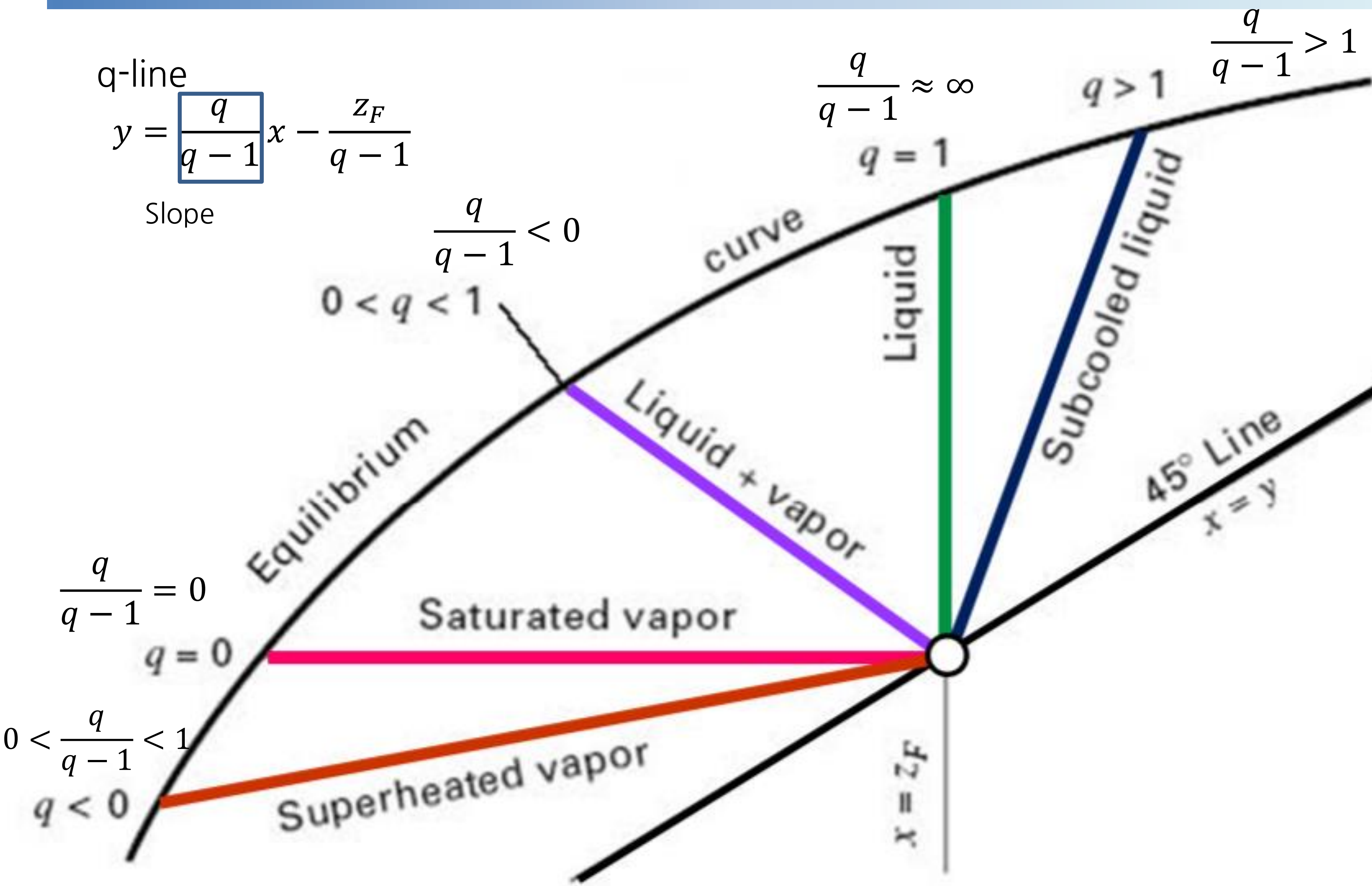
$$y = \frac{q}{q-1}z_F - \frac{z_F}{q-1} = z_F \; when \; x = z_F$$

The q-line

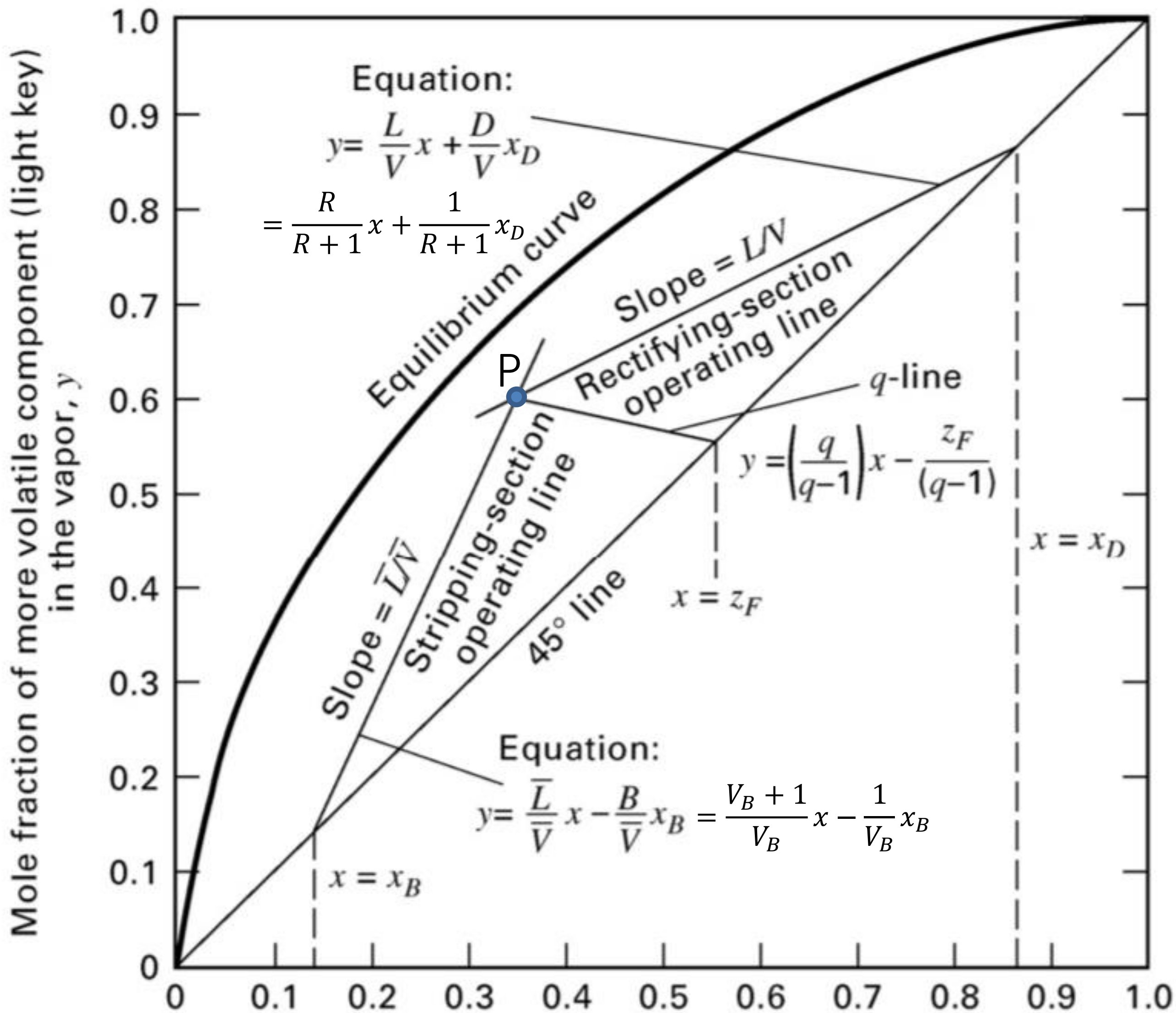
q-line

$$y = \boxed{\frac{q}{q-1}} x - \frac{z_F}{q-1}$$

Slope

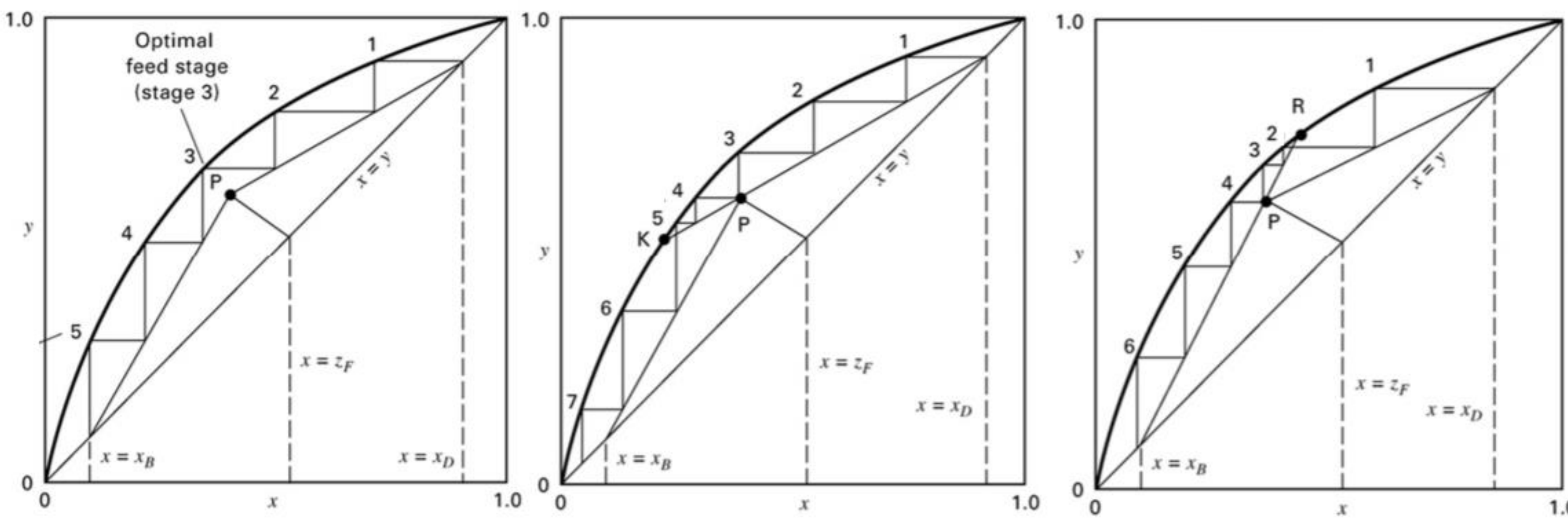


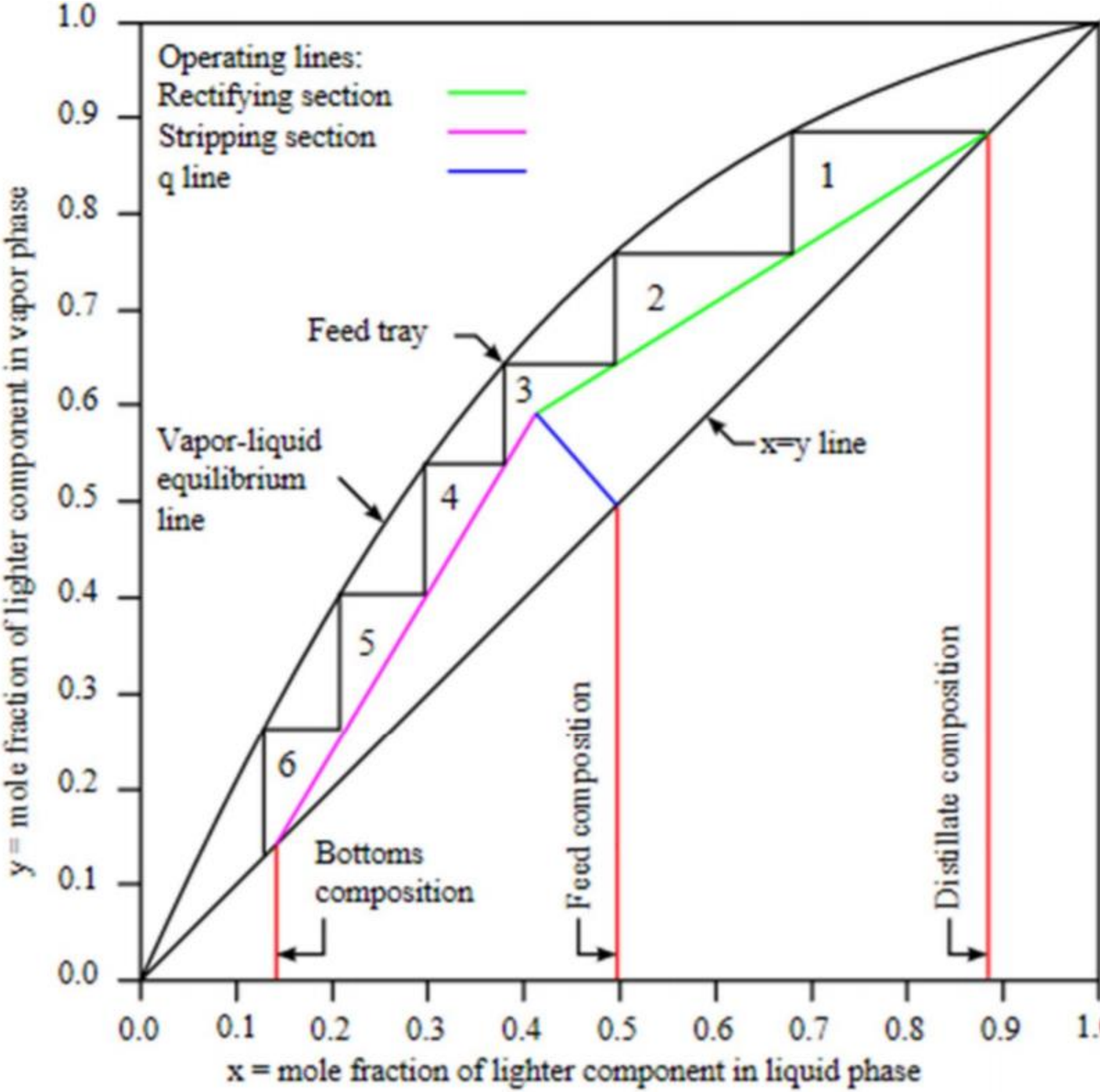
- To satisfy mass balance and phase equilibrium, the operation lines at rectifying and stripping section must meet with q line at one point.
- The point P can move with design variables (R, V_B, q). If the feed stream condition is fixed, the point P moves with R or V_B



Determination of stage number and feed stage

- For minimum number of stage, feed stage must be located nearby the extension of q-line



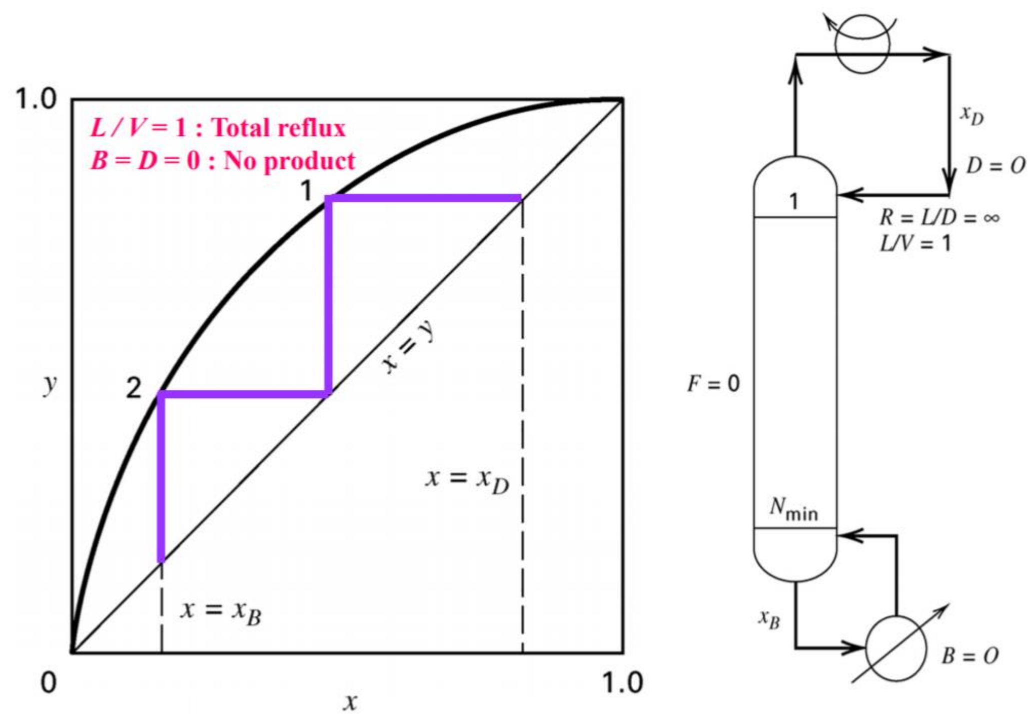


Operating lines:
Rectifying section
Stripping section
q line
1
2
3
4
5
6
Feed tray
Vapor-liquid equilibrium line
x=y line
Bottoms composition
Feed composition
Distillate composition
y = mole fraction of lighter component in vapor phase
x = mole fraction of lighter component in liquid phase
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Minimum number of Equilibrium Stage

$$y = \frac{R}{R+1}x + \frac{1}{R+1}x_D$$

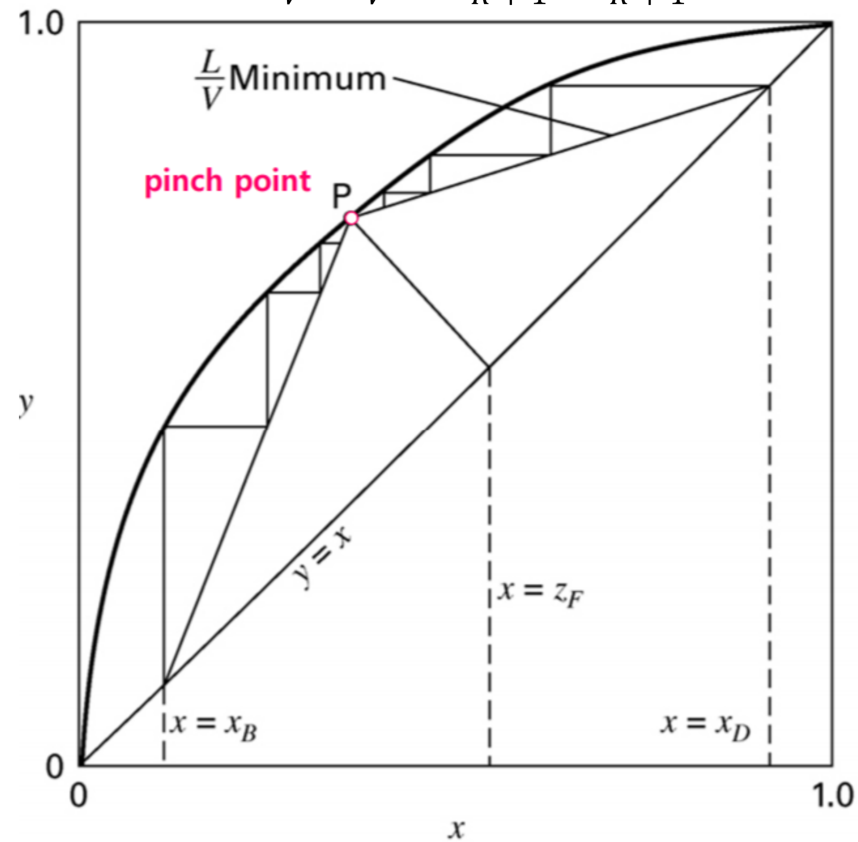
- If R increases, the slope of operating line in rectifying section converges to 1→it can reduce the number of stage
- If R converges to infinity, we can decide theoretically minimum number of stages.
- Generally the number of stages is decided as double of the minimum number of stages.



Minimum Reflux Ratio, R_{min}

- To minimize R, we need to decrease the slope of the operating line at rectifying section. However, if the feed condition is fixed, q-line is also fixed and then we cannot decrease the OP out of equilibrium line.

$$y = \frac{L}{V}x + \frac{D}{V}x_D = \frac{R}{R+1}x + \frac{1}{R+1}x_D$$



- When the OP meets the q-line at the equilibrium line, R value is minimized. (with infinite number of stages)
- From the slope R_{min} is decided.
- Generally design value of R has 1.1-1.5

$$(L/V)_{min} = \frac{R_{min}}{R_{min}+1}$$