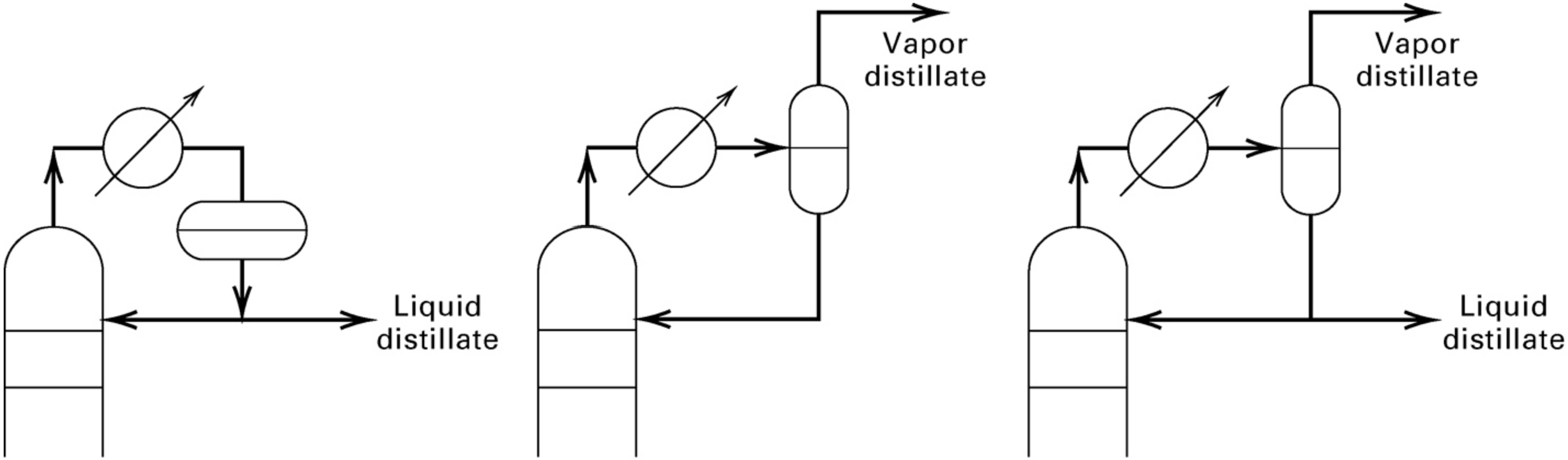
Lecture 12.
Binary Distillation (2)
[Ch. 7]

- Condenser Type
- Subcooled Reflux
- Reboiler Type
- Condenser and Reboiler Duties
- Feed Preheat
- Optimal Reflux Ratio
- Use of Murphree Efficiency
- Multiple Feeds, Side Streams, and Open Steam

Condenser Type

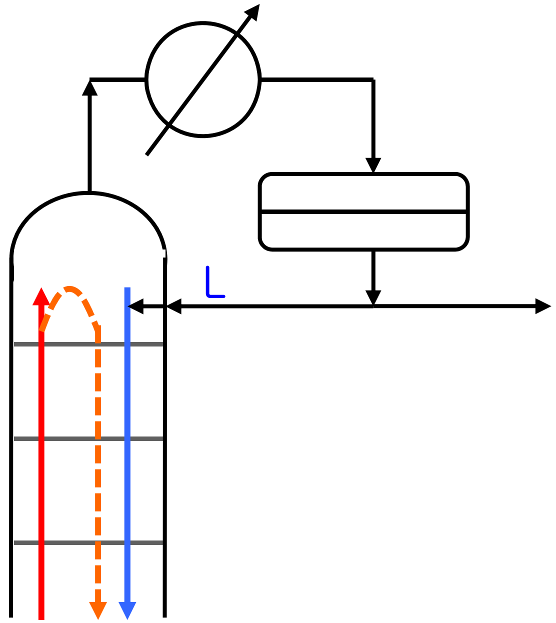
Total condenser | Partial condenser | Mixed condenser



- Partial condenser: liquid reflux and vapor distillate are at equilibrium in the reflux drum → In the McCabe-Thiele method, the partial condenser becomes the first equilibrium stage
- Mixed condenser: can provide both vapor and liquid distillates

Subcooled Reflux

- If the condenser outlet pressure is lower than the top tray pressure of the column, the reflux is subcooled
- When subcooled reflux enters the top tray, its temperature rises and causes vapor entering the tray to condense
- The latent enthalpy of condensation of the vapor provides the sensible enthalpy to heat the subcooled reflux to the bubble point



$$R'\Delta H^{\text{vap}} = RC_{P_L}\Delta T_{\text{subcooling}}$$

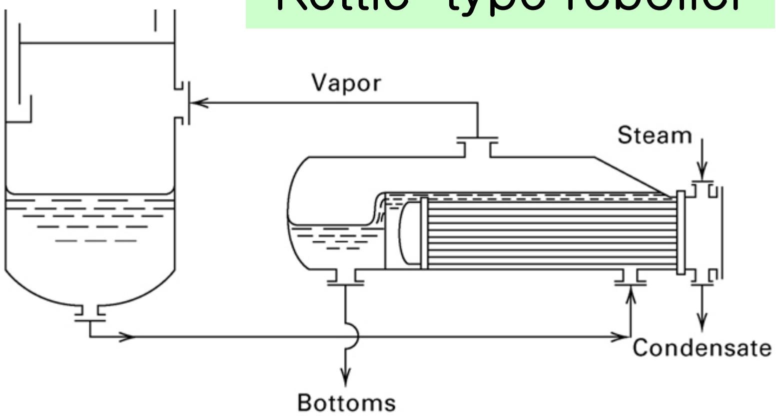
$$R_{\text{interanl}} = R + R'$$

$$R_{\text{internal}} = R\left(1 + \frac{C_{P_L}\Delta T_{\text{subcooling}}}{\Delta H^{\text{vap}}}\right)$$

The McCabe-Thiele construction should be based on the internal reflux ratio

Reboiler Type

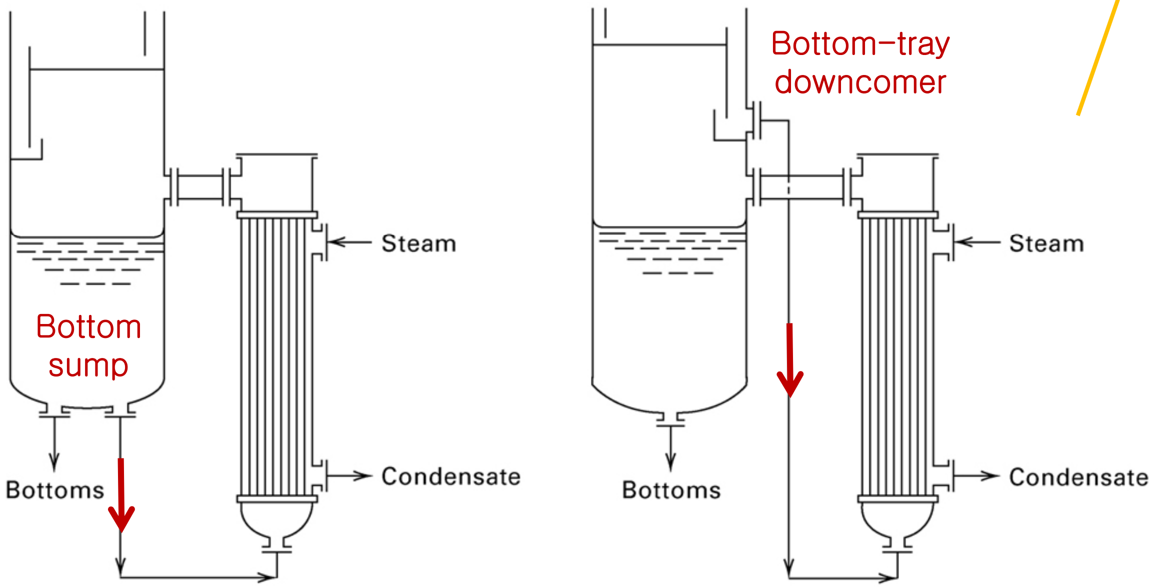
Kettle-type reboiler



Kettle reboilers are common

Equivalent to one equilibrium stage

Vertical thermosyphon-type reboiler



Thermosyphon reboilers are favored for

(1) Thermally sensitive bottom product compounds

(2) High bottom pressure

(3) Only small ΔT available for heat transfer

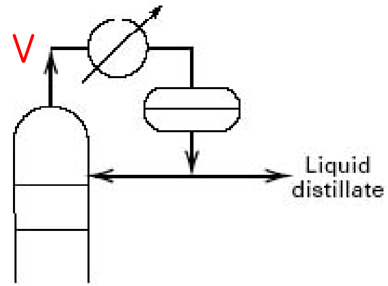
(4) Heavy fouling

Condenser and Reboiler Duties (1)

- Energy balance for the entire distillation column

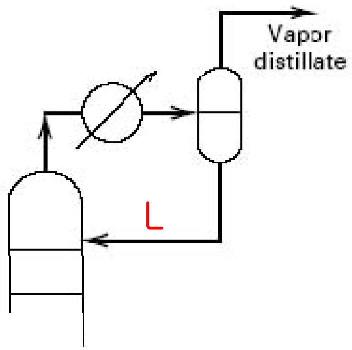
$$Fh_F + Q_R = Dh_D + Bh_B + Q_C + Q_{loss}$$

- Total condenser



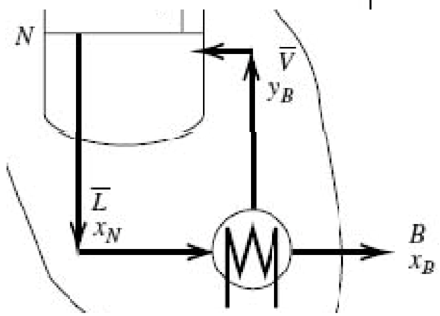
$$Q_C = V\Delta H^{vap} = (L+D)\Delta H^{vap} = D(R+1)\Delta H^{vap}$$

- Partial condenser



$$Q_C = L\Delta H^{vap} = DR\Delta H^{vap}$$

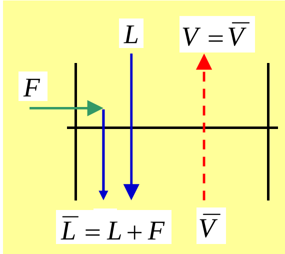
- Partial reboiler



$$Q_R = \overline{V}\Delta H^{vap} = BV_B\Delta H^{vap}$$

Condenser and Reboiler Duties (2)

- For bubble-point liquid feed and total condenser



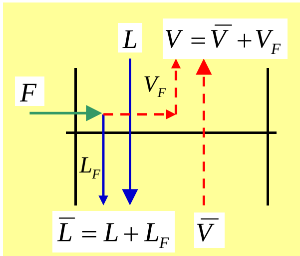
$$BV_B = L + D = D(R+1)$$

$$Q_R = Q_C$$

$$Q_C = D(R+1)\Delta H^{vap}$$

$$Q_R = BV_B \Delta H^{vap}$$

- For partially vaporized feed and total condenser



$$Q_R = Q_C\left[1 - \frac{V_F}{D(R+1)}\right]$$

$$Q_C = V \Delta H^{vap}$$

$$Q_R = \bar{V}\Delta H^{vap} = (V - V_F)\Delta H^{vap}$$

- Saturated steam rate for the reboiler

$$m_s = M_s Q_R / \Delta H_s^{vap}$$

- Cooling water rate for the condenser

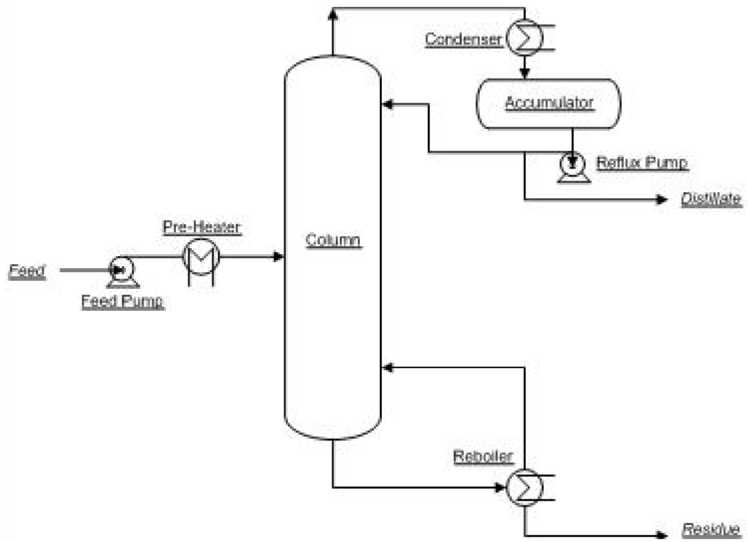
$$m_{cw} = Q_C / C_{P_{H_2O}}(T_{out} - T_{in})$$

Feed Preheat

- (Feed pressure) > (pressure in the column at the feed-tray)
- Deviation of feed temperature from column temperature at the feed location: second-law efficiency ↓
- It is usually best to avoid a subcooled liquid or superheated vapor feed
- The cost of reboiler steam is usually an order of magnitude higher than the cost of cooling water

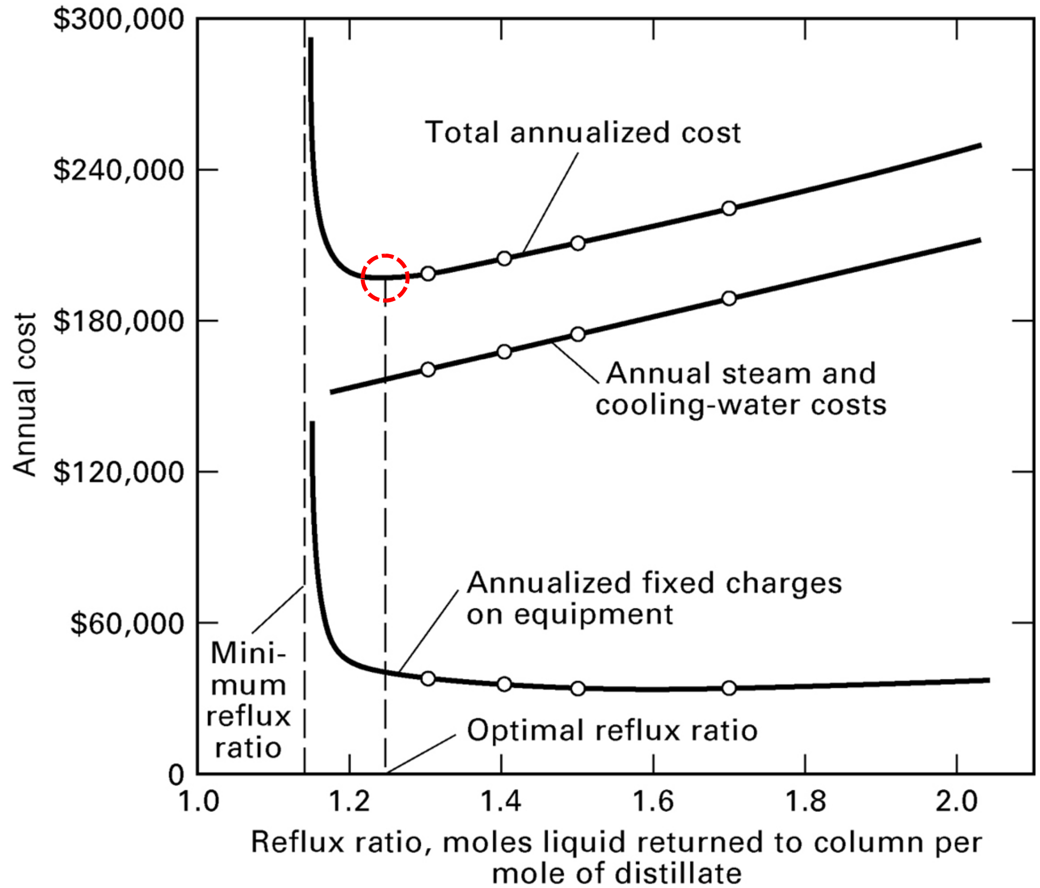
→ The feed is preheated and partially vaporized to reduce Q_R in comparison to Q_C

$$Q_R = Q_C\left[1 - \frac{V_F}{D(R+1)}\right]$$



Optimal Reflux Ratio

- (minimum reflux) < (reflux in industrial distillation) < (total reflux)
- When reflux ratio is increased from minimum value
  - Number of plates
  - Column diameter
  - Requirement of reboiler steam and condenser cooling water



- The total annual cost is dominated by the steam cost except at the minimum reflux condition

Use of Murphree Efficiency

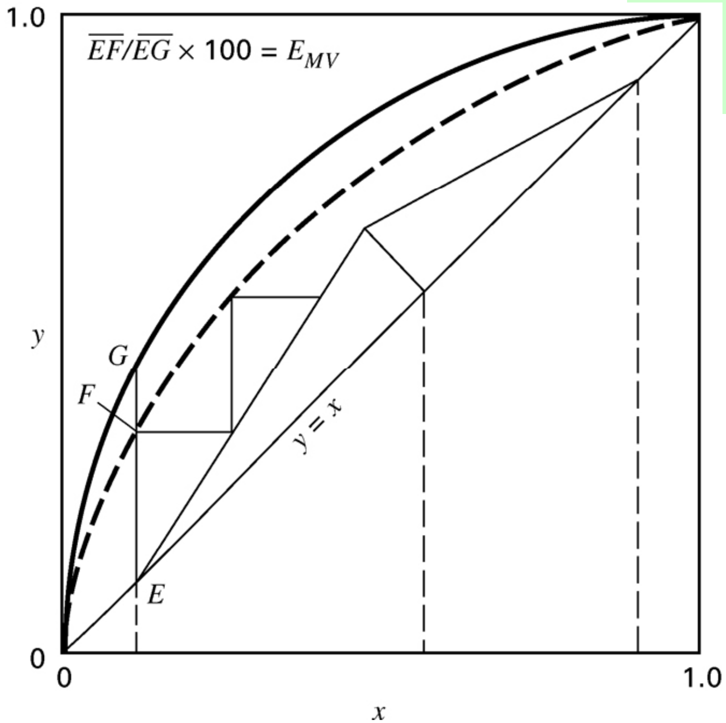
- Concentration changes for a given stage are usually less than predicted by equilibrium
- Murphree efficiency: (the change in actual composition in the phase) / (the change predicted by equilibrium)

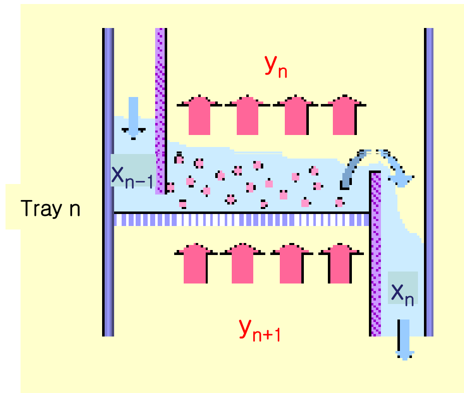
$$E_{MV} = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}}$$

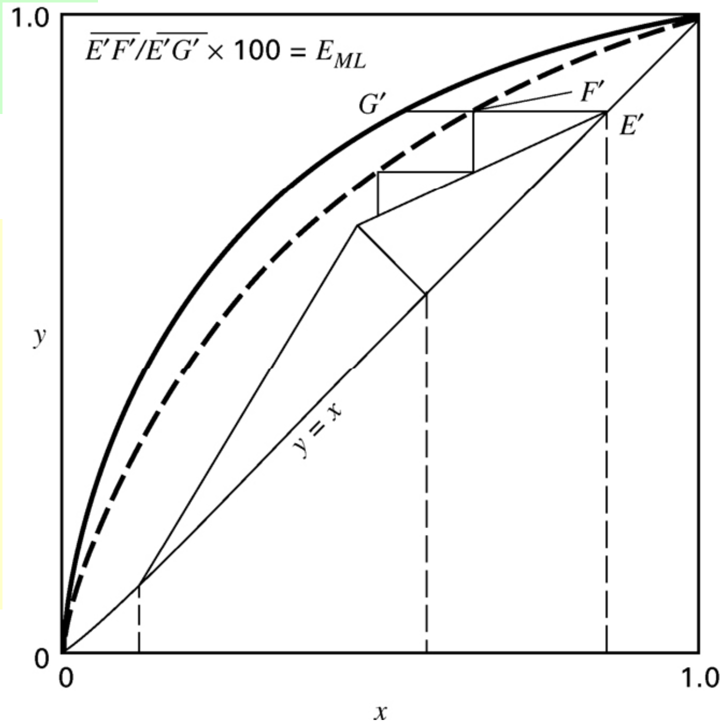
Efficiency based on vapor phase

Efficiency based on liquid phase

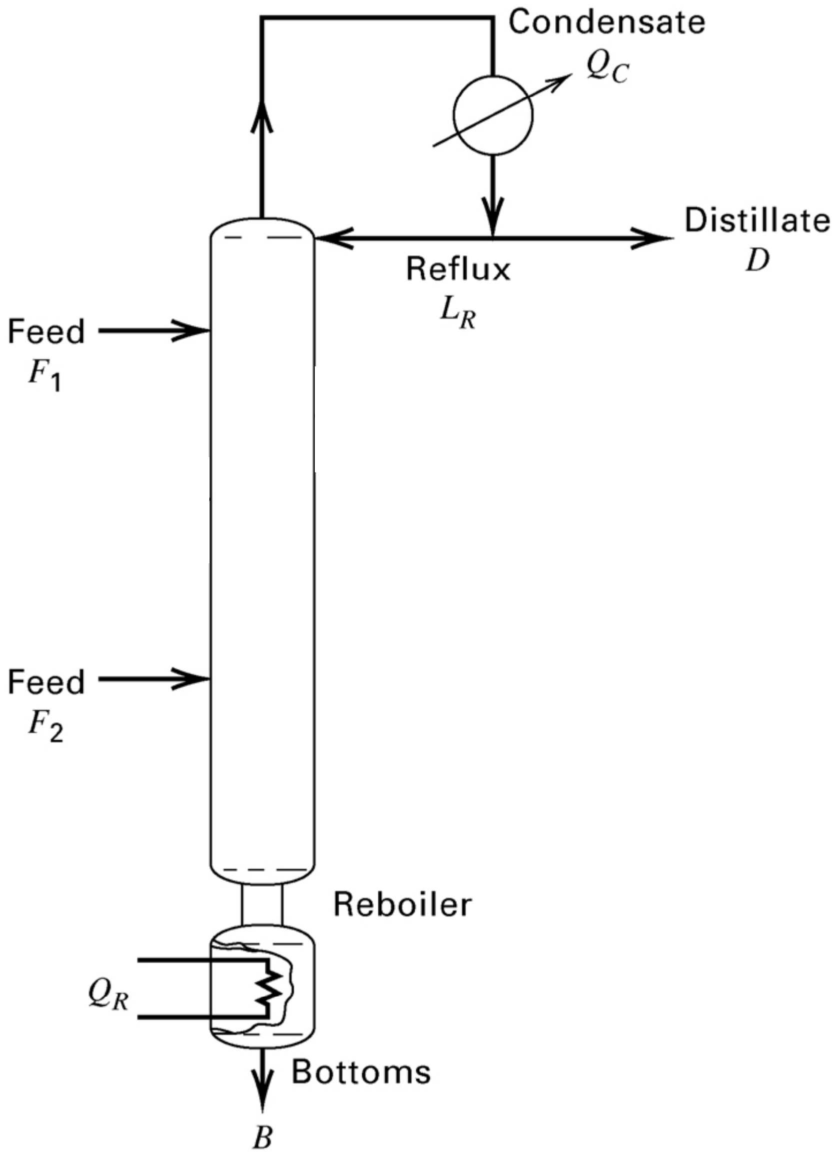
$$E_{ML} = \frac{x_n - x_{n-1}}{x_n^* - x_{n-1}}$$



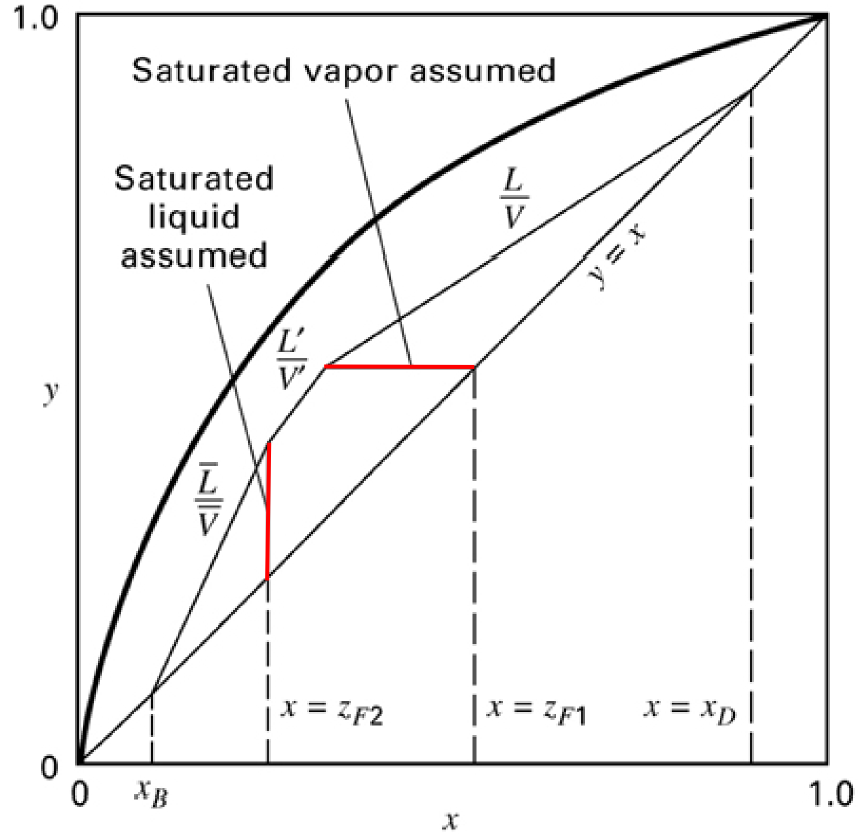




Multiple Feeds, Side Streams, and Open Steam (1)



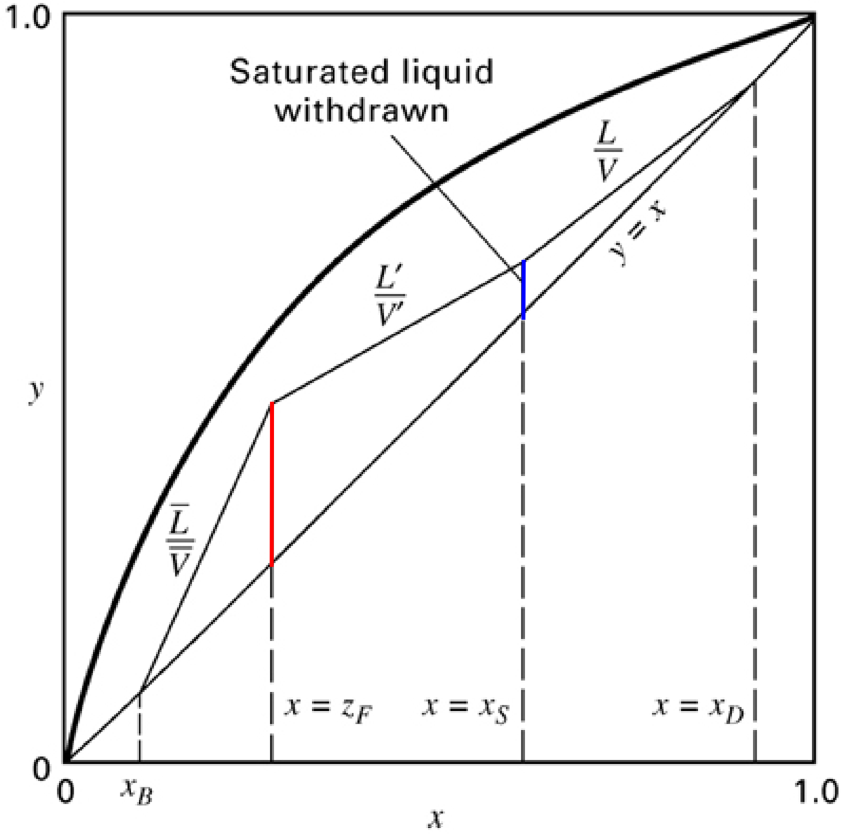
- Two feeds
  (saturated liquid & saturated vapor)



$$V' = V - F_1 \qquad \bar{L} = L' + F_2 = L + F_2$$

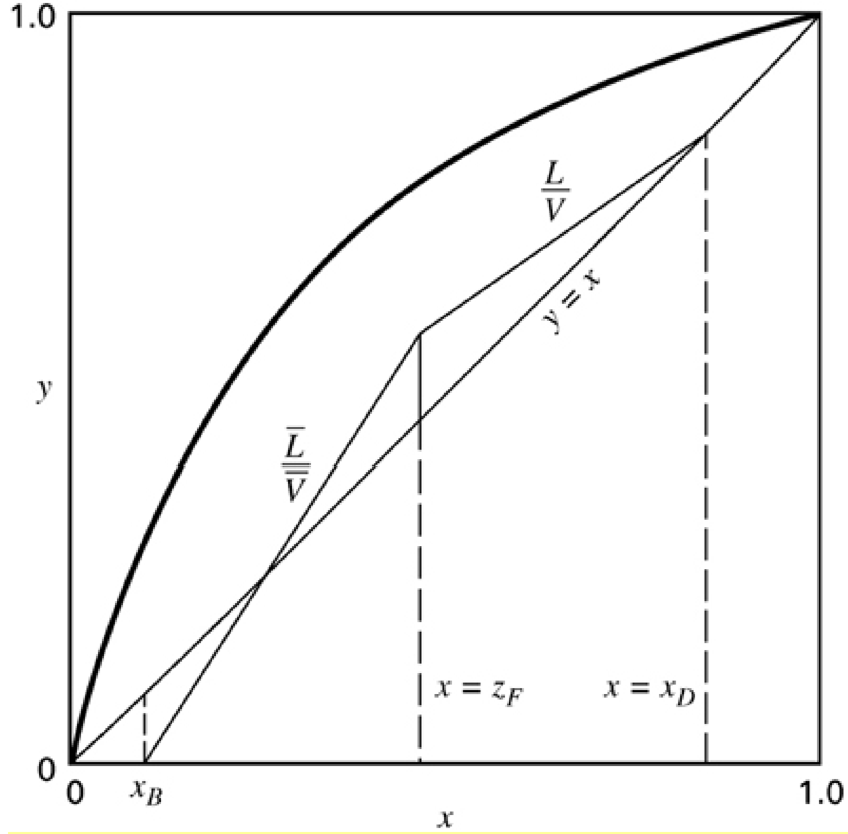
Multiple Feeds, Side Streams, and Open Steam (2)

- One feed, one side stream
  (saturated liquid)



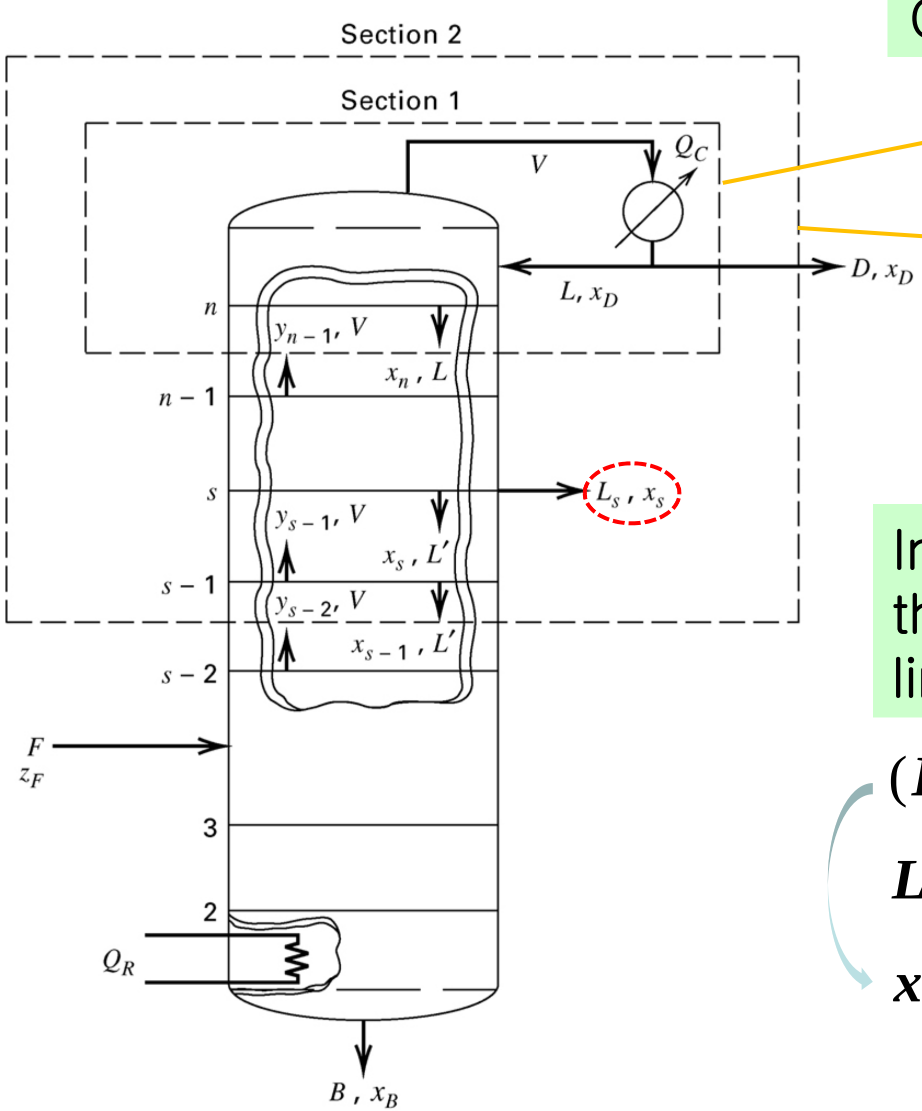
$$V' = V \qquad L' = L - L_S$$

- Use of open steam
  (rather than a reboiler)



Open steam can be used if one of the components is water, or if water can form a second liquid phase

[Example] One Feed, One Side Stream (Saturated Liquid)



Operating lines in the rectifying section

$$V_{n-1}y_{n-1} = L_n x_x + Dx_D$$

$$V_{s-2}y_{s-2} = L'_{s-1}x_{s-1} + L_s x_s + Dx_D$$

$$y = \frac{L}{V}x + \frac{D}{V}x_D \qquad y = \frac{L'}{V}x + \frac{L_s x_s + Dx_D}{V}$$

Intersection of the operating lines

$$(L - L')x = L_s x_s$$

$$L - L' = L_s$$

$$x = x_s$$