Mass transfer

Lecture 06: *Enthalpy balances*

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Learning objectives

- **Establish and use enthalpy balance in analyzing the operation of fractionating columns.**
- **Understand the design variables affecting performance of a tray used in the column.**
- **Quantitatively assess factors influencing pressure drop across the plate.**
- **Distinguish and be able to calculate each type of efficiency used in operating the actual columns.**

Today’s outline

- **Introduction**

- **Enthalpy balances in the two sections**

- **Design of sieve-plate columns**
  - ✓ Typical values for each parameter
  - ✓ Design objectives
  - ✓ Pressure drop calculation
  - ✓ Weeping & Flooding

- **Plate efficiency**
  - ✓ Types of efficiency
  - ✓ Relationships between each pair

21.4 Introduction

- **Enthalpy balances can be used to calculate the actual variations in the vapor and liquid flow rate.**
  - ✓ The enthalpy data will be available in the form of the graph or data bank within the computer software.

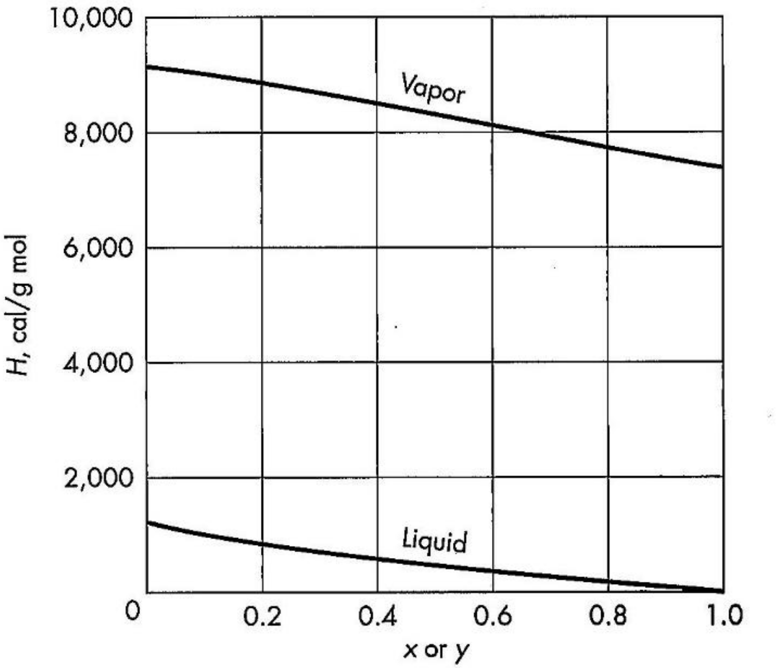


FIGURE 21.21
Enthalpy–concentration diagram for benzene-toluene at 1 atm.

- ✓ Liquid or vapor mixtures at the bubble or dew point, respectively.
- ✓ Is temperature the same across the lines?

21.4 Overall enthalpy balance

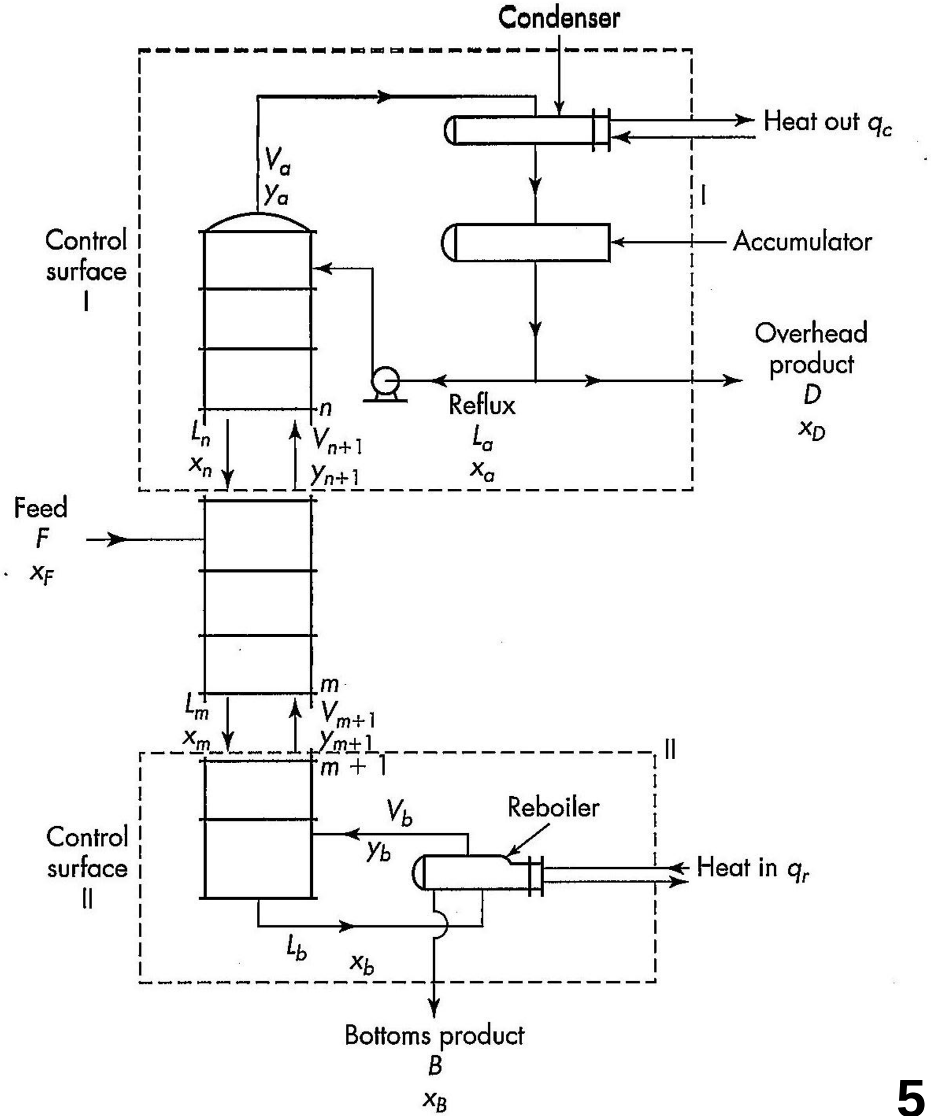
- **An overall enthalpy balance for the unit in below is**

$$F\ H_F + q_r = D\ H_D + B\ H_B + q_c$$

✓ If the feed is liquid at the boiling temperature, $F\ H_F \sim D\ H_D + B\ H_B$

✓ The degree of freedom in the above case is ???

✓ Different parameter is chosen first when designing vs operating the distillation column.



21.4 Enthalpy balance for the top

- **The enthalpy balance for the control surface I becomes**

$$V_{n+1}\,H_{y,n+1} = L_n\,H_{x,n} + D\,H_D + q_c$$

✓ q_c can be eliminated using the relation in below:

$$q_c = V_a\,H_{y,a} - R\,H_D - D\,H_D$$

where it is assumed that $H_R = H_D$

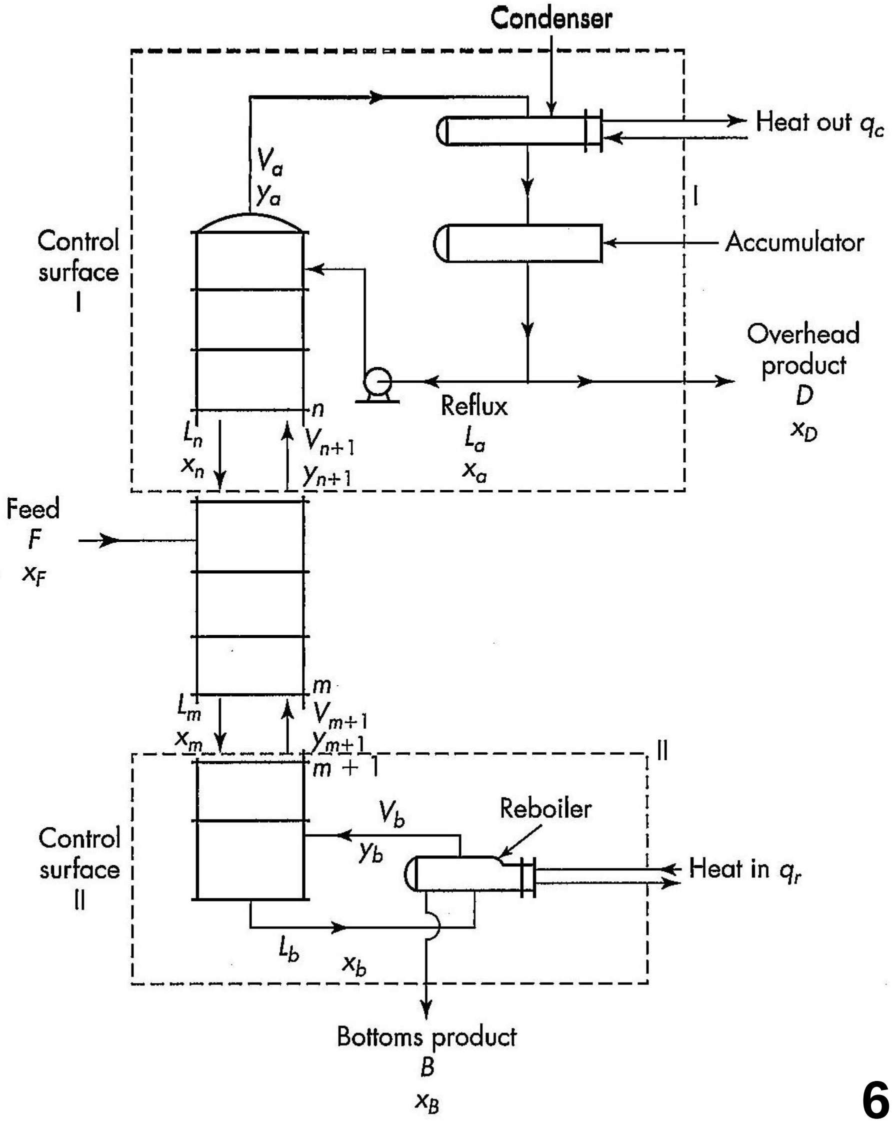
✓ The alternate form of MB becomes

$$V_{n+1}\,H_{y,n+1} = L_n\,H_{x,n} + V_a\,H_{y,a} - R\,H_D$$

✓ The exact value of V_{n+1} is obtained by trial-and-error involving the above and below equations:

$$y_{n+1} = \frac{L_n\,x_n}{V_{n+1}} + \frac{D\,x_D}{V_{n+1}}$$

$$V_{n+1} = L_n + D$$



21.4 Balance for the bottom

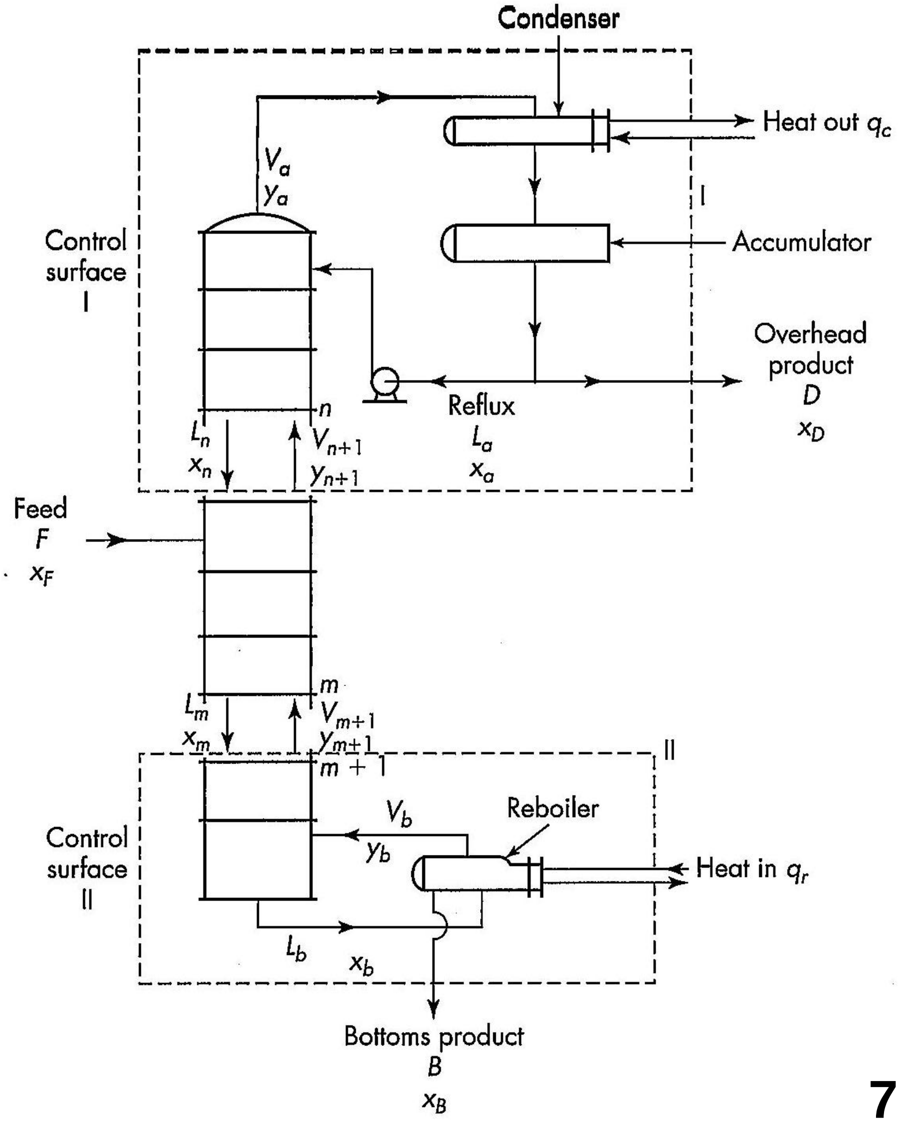
- **The enthalpy balance for the control surface II becomes**

$$V_{m+1}\,H_{y,m+1} = L_m\,H_{x,m} + q_r - B\,H_B$$

✓ The exact value of V_{n+1} is obtained by trial-and-error involving the above and below equations:

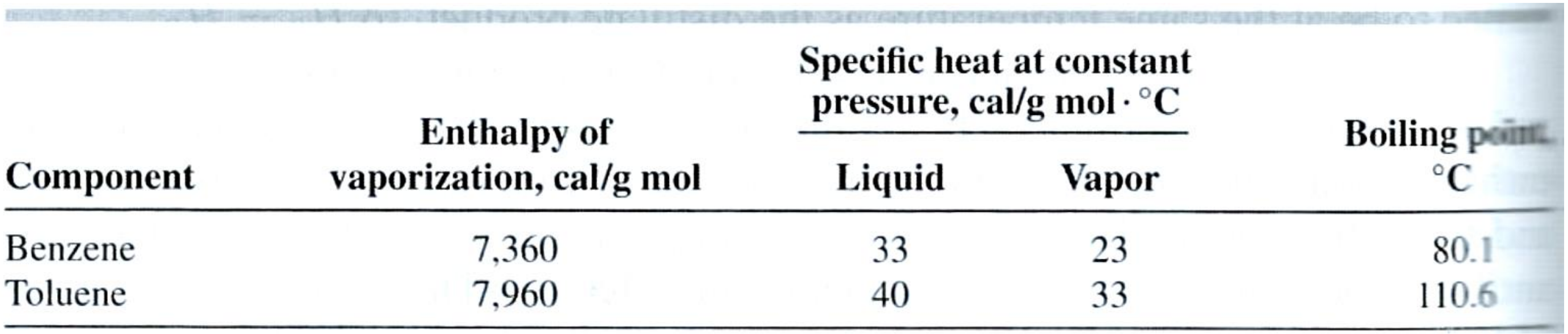
$$y_{m+1} =$$

$$V_{m+1} =$$



21.4 Impact of energy balance

Ex. 21.5. A mixture of 50 mol% benzene and toluene is to be separated by distillation at atmospheric pressure into 98% purity using a reflux ratio of 1.2 times the minimum value. The feed is liquid at the boiling point. Use enthalpy balances (Table in below) to calculate the flows of liquid and vapor at the top, middle, and bottom of the column, and compare these values with those based on constant molal overflow. Estimate the difference in the number of theoretical plates for the methods. (**In-class Homework**)



Component	Enthalpy of vaporization, cal/g mol	Specific heat at constant pressure, cal/g mol · °C		Boiling point °C
		Liquid	Vapor	
Benzene	7,360	33	23	80.1
Toluene	7,960	40	33	110.6

- ✓ ***Will you need more, less, or the same number of plates if the feed was liquid 10 degC below the bp?***

21.4 Design of sieve-plate

- **The actual column design requires specification of other process variables including the typical values in below:**
  - ✓ type of tray:
    sieve
  - ✓ size and pattern of holes:
    5~12 mm, triangular
  - ✓ tray spacing:
    0.15~2.00 m
  - ✓ weir height: 12~75 cm
  - ✓ pressure drop per tray:
    50~100 mm H_2O
  - ✓ column diameter:
    downcomers take 20~30% of the plate area; 0.3~9.0 m

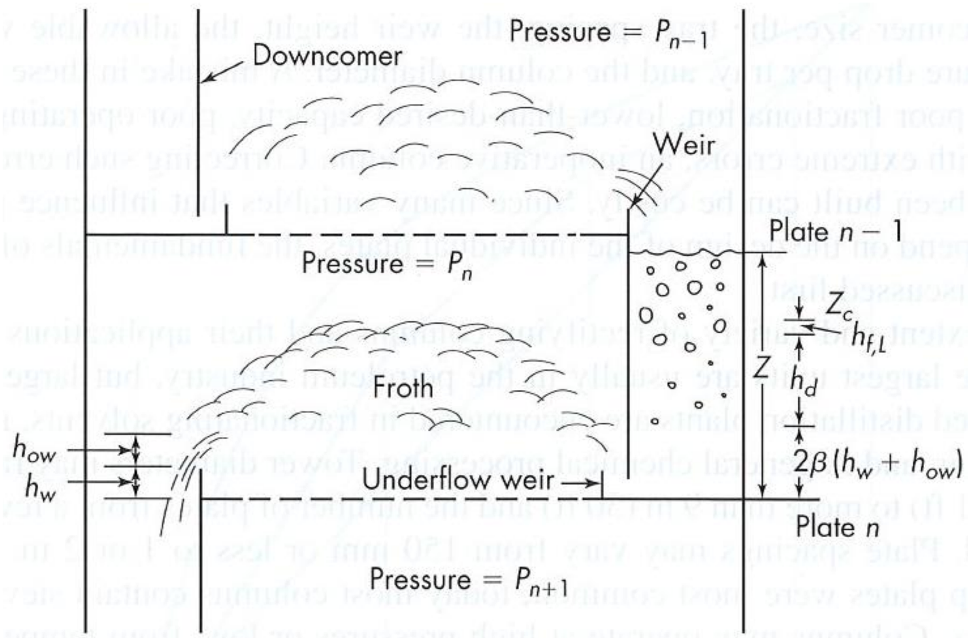


FIGURE 21.24
Normal operation of sieve plate.

21.4 Plate design objectives

- **The ultimate goal is to maximize plate efficiency, which will be due to the following characteristic phenomena:**
  - ✓ Enhance vapor-liquid mixing;
  - ✓ Maintain the optimal vapor flow;
  - ✓ Maintain the optimal liquid depth;
  - ✓ Minimize pressure drop;
  - ✓ Prevent fouling

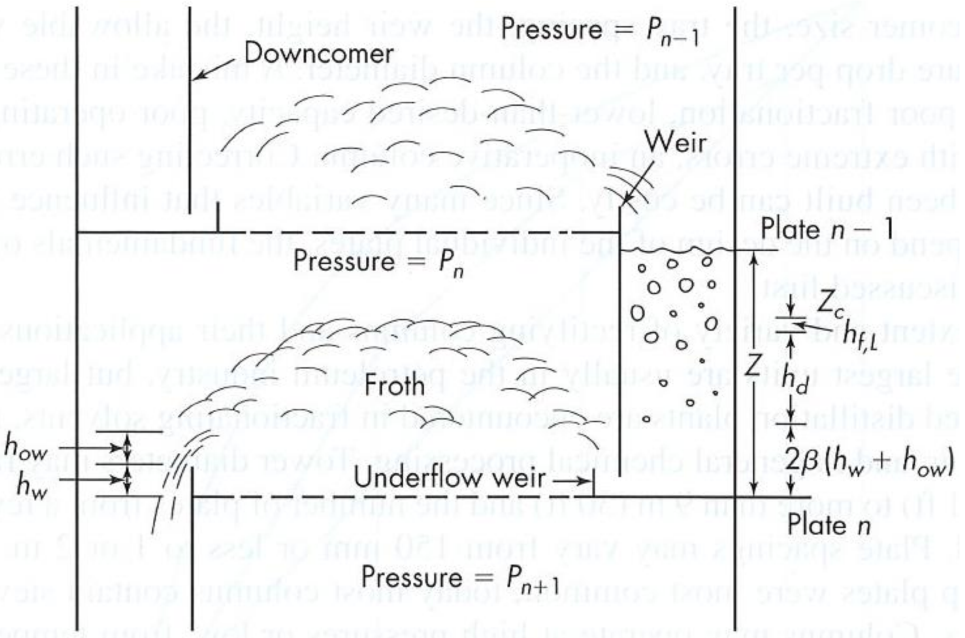


FIGURE 21.24
Normal operation of sieve plate.

21.4 Pressure drop per plate

- **Difference in vapor pressure drives vapor flow through the holes and liquid on the plate:**
  - ✓ Is the vapor pressure higher or lower at the top?
  - ✓ Why do we want to minimize the vapor pressure drop across plate?
  - ✓ It can be calculated as in below:

$$h_t = h_d + h_l$$

where h_t, h_d, and h_l are total pressure drop, friction loss in dry plate, and equivalent head of liquid, respectively.

$$h_d = 51.0\left(\frac{u_0^2}{C_0^2}\right)\left(\frac{\rho_V}{\rho_L}\right)$$

where u_0, C_0, are vapor velocity (m/s) and orifice coefficient.

$$h_l = \beta(h_d + h_{ow})$$

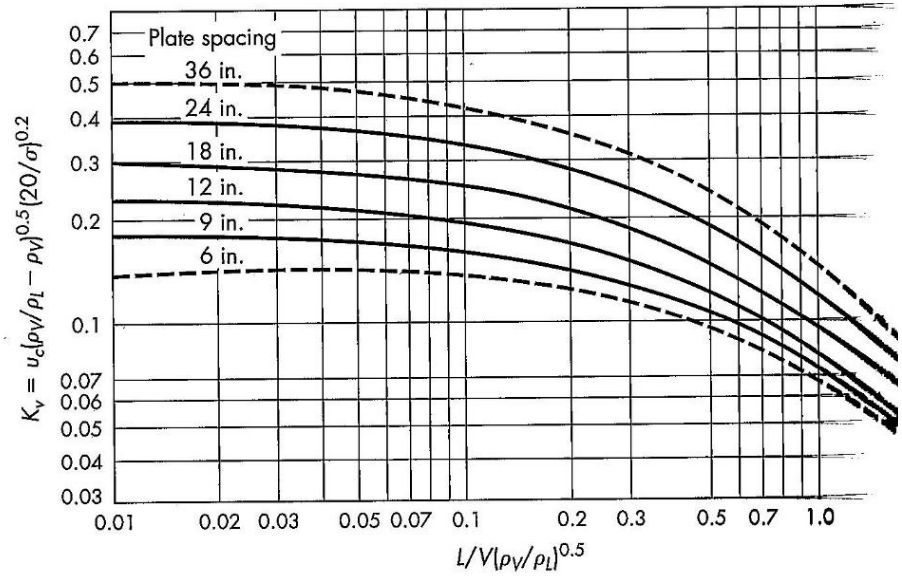
where β, h_d, h_{ow} are empirical correlation factor, height of weir and clear liquid above the weir, respectively.

21.4 Weeping and flooding

- **Weeping is the liquid flowing down through the holes due to insufficient pressure drop across the plate.**
  - ✓ Will this increase/decrease plate efficiency?
  - ✓ There is an optimal vapor flow velocity that maximizes efficiency; too high velocity will result in large pressure drop, and flooding.

$$u_c = K_v\sqrt{\frac{\rho_L-\rho_V}{\rho_V}}\left(\frac{\sigma}{20}\right)^{0.2}$$

where u_c, σ, are max. allowable velocity and liquid surface tension.



21.4 Plate efficiency

- **Plate efficiency is used to translate ideal plates to actual plates needed.**

- **Three types of efficiency**
  - ✓ Overall efficiency, η_o: ratio of the number of ideal plates to the number of actual needed
  - ✓ Murphree efficiency, η_M: ratio of the actual versus ideal change in vapor phase concentration across the plate

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

where y_n* is the concentration in equilibrium with x_n.

  - ✓ local efficiency, η': the Murphree efficiency at a specific location

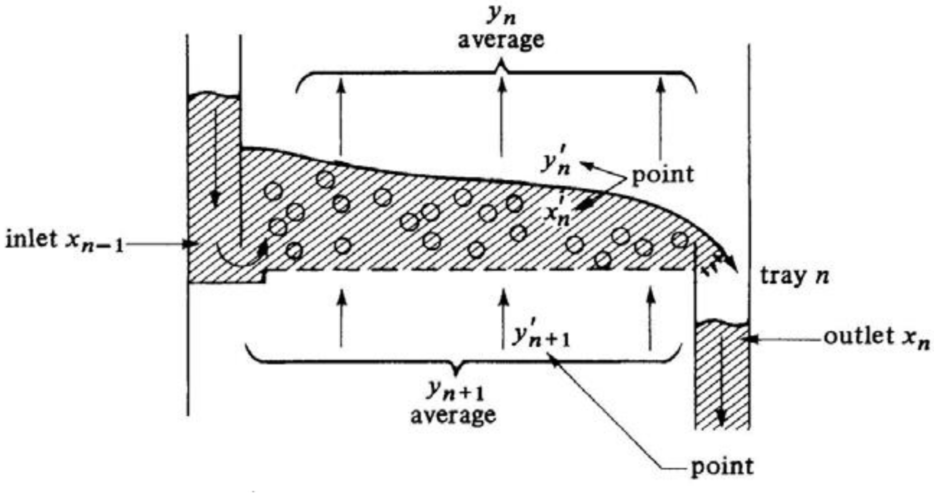
$$\eta' = \frac{y'_n - y'_{n+1}}{y'_{eq} - y'_{n+1}}$$

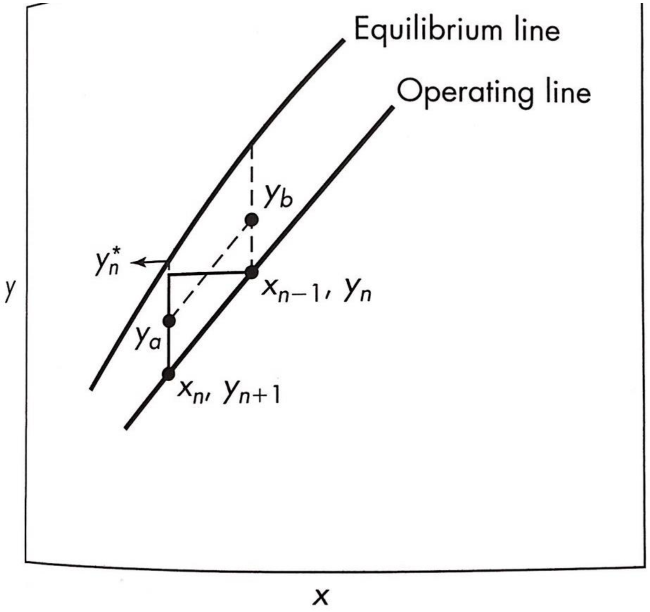
where ’ denotes local values.

21.4 η_M and η'

- **The two efficiencies are the same for small columns.**

- **In large fractionating columns, there is concentration gradient in the liquid phase from x_n to x_{n-1}.**
  - ✓ η' can be larger or smaller than η_M
  - ✓ Vapor mixing prior to going to the next plate has relatively lower impact on the relationship between the two efficiencies.





21.4 Use of η_M

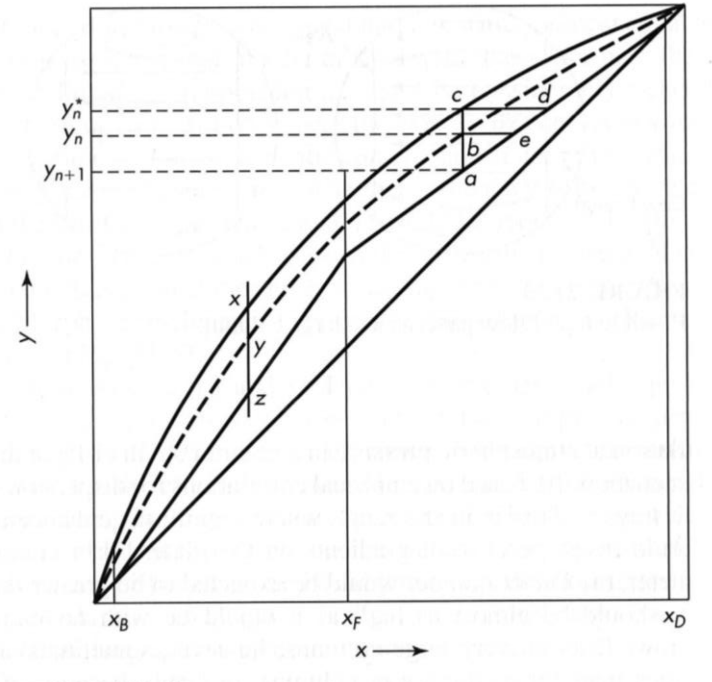
- **η_M can be used in the McCabe-Thiele method.**
  - ✓ We can plot the actual, less-than-equilibrium curve instead of the equilibrium curve as follows:

$$y'_e = y + \eta_M(y^* - y)$$

where y, y'_e , y^* are the n+1 stage vapor concentration, the actual vapor concentration of the nth stage, and the vapor concentration in equilibrium with liquid concentration (x) in the nth stage.

  - ✓ From the graph,

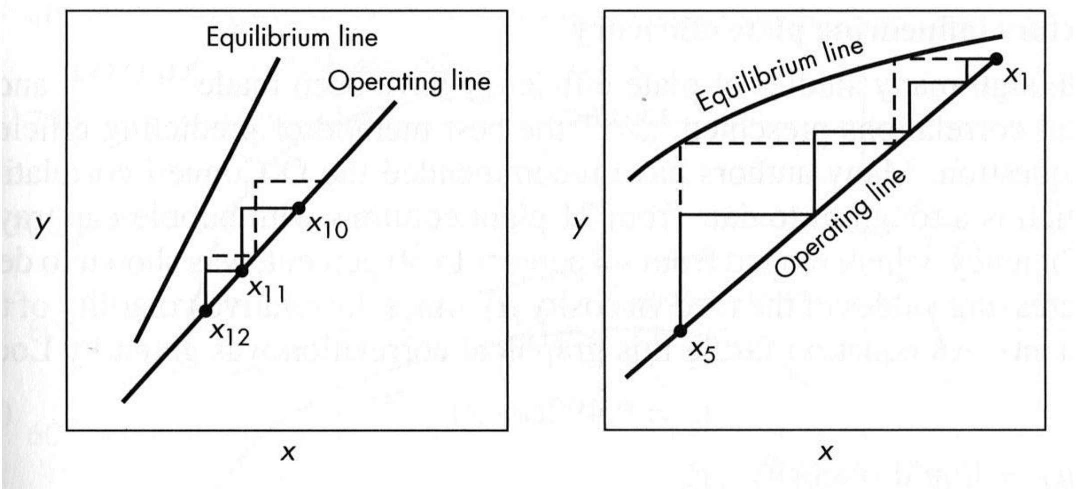
η_M = ?



21.4 η_M and η_O

- **The two efficiencies are not the same for small columns; it is also not an average of all η_M.**

- **The relationship between the two depends on slope of both the equilibrium and operating line.**
  - ✓ Is (a) usually top or bottom?
  - ✓ Is (b) usually top or bottom?
  - ✓ Is $\eta_M > \eta_O$ in (a) and (b)?



- ✓ When the lines are straight, $\eta_O = \dfrac{\ln[1+\eta_M(m\frac{V}{L}-1)]}{\ln(m\,V/L)}$