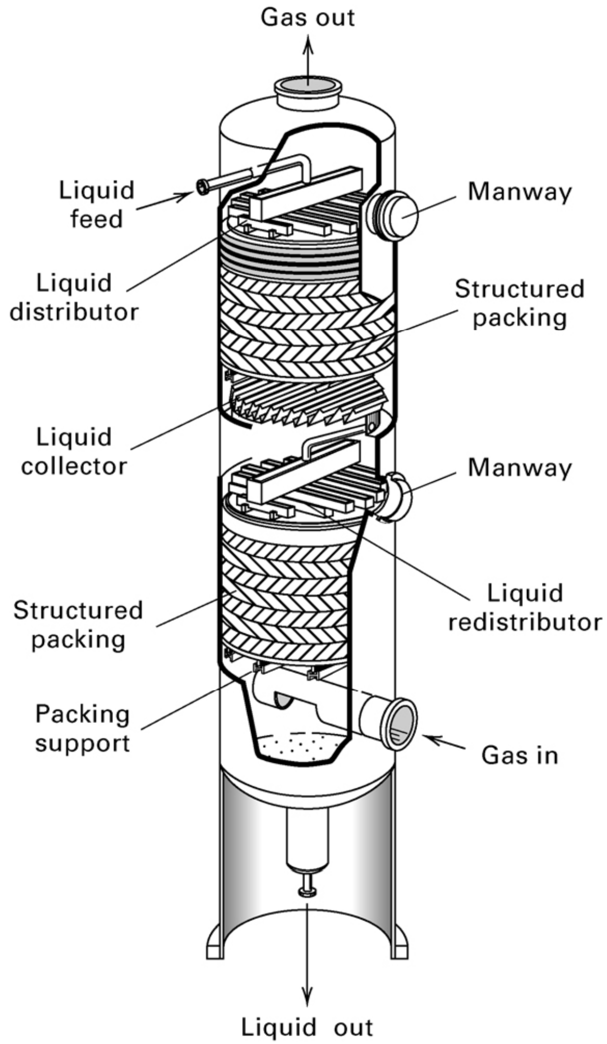
Lecture 10.
Absorption and Stripping (2)
[Ch. 6]

- Rate-Based Method for Packed Columns
  - Height equivalent to a theoretical plate (HETP)
  - Operating line based on material balance
  - Two-film theory
  - Determination of column packed height
  - Relation between NTU, HTU & N_t, HETP

Packed Columns

- Packed column : a vessel containing one or more sections of packing
  - Liquid flows downward as a film or as droplets between packing elements
  - Vapor flows upward through the wetted packing, contacting the liquid



- Packed columns are continuous, differential-contacting devices

  : do not have physically distinguishable, discrete stages

  ⇒ better analyzed by mass-transfer models than by equilibrium-stage concepts

Theoretical Plate

- In practice, packed-tower performance is often presented on the basis of equivalent equilibrium stages
- Height equivalent to a theoretical plate (HETP)

$$\text{HETP} = \frac{\text{packed height}}{\text{number of equivalent equilibrium stages}} = \frac{l_T}{N_t}$$

- HETP concept has no theoretical basis

  : HETP is difficult to generalize and is a function of the type of packing, the system being separated and the hydraulics of the column → Experimental or vendor-supplied values are used

▪ [Example] Bioethanol recovery from a CO_2-rich vapor

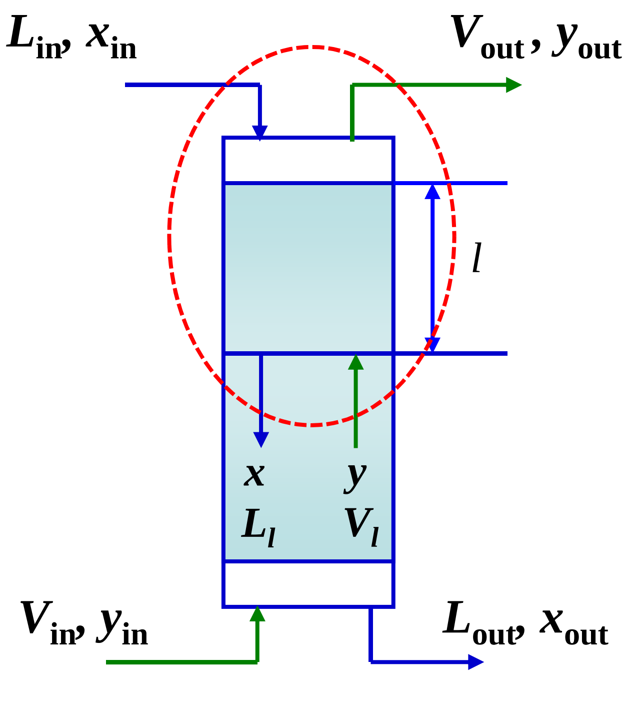
Number of equilibrium plate : 6.1 (from equilibrium-stage method)

1.5-inch metal Pal rings are used for random packings : HETP = 2.25 ft

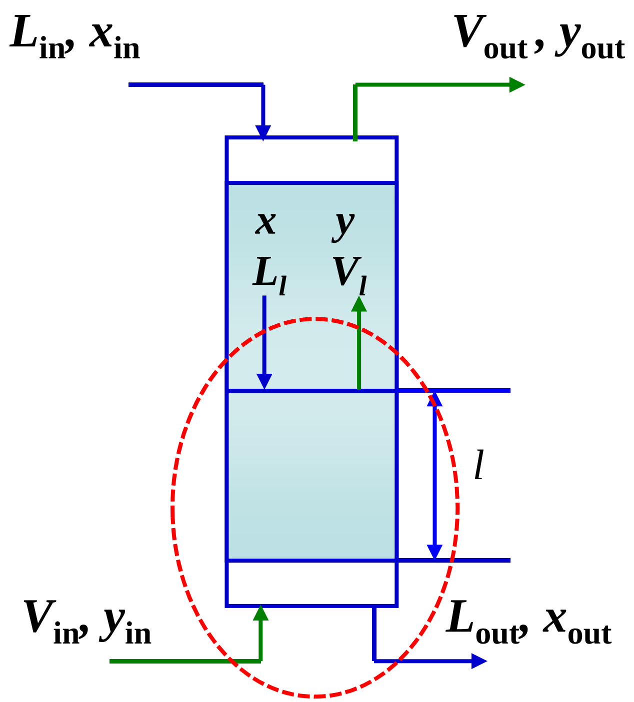
$$l_T = (\text{HETP}) \cdot N_t = 2.25 \times 6.1 = 13.7\,\text{ft}$$

Operating Line

Absorber



Stripper



Material balance

$$x_{in}L_{in} + yV_l = xL_l + y_{out}V_{out}$$

$$xL_l + y_{in}V_{in} = x_{out}L_{out} + yV_l$$

Assuming dilute solutions, $V_l = V_{in} = V_{out} = V$ and $L_l = L_{in} = L_{out} = L$

Operating line

$$y = x\left(\frac{L}{V}\right) + y_{out} - x_{in}\left(\frac{L}{V}\right)$$

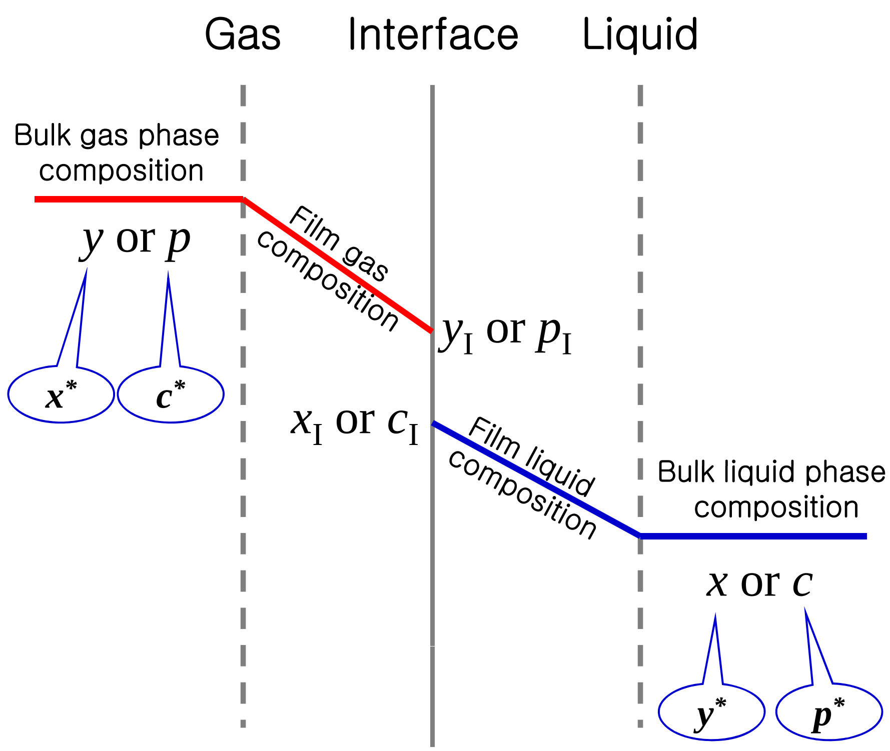
$$y = x\left(\frac{L}{V}\right) + y_{in} - x_{out}\left(\frac{L}{V}\right)$$

Two-Film Theory (1)

- A concentration gradient exists in each film
- Physical equilibrium at the interface
- Volumetric mass transfer coefficient, ka is commonly used

$$ka = \frac{\text{kg mol}}{\text{s} \cdot \text{m}^3 \text{ packing} \cdot \text{mol fraction}}$$

a : mass transfer area per unit volume of packed bed

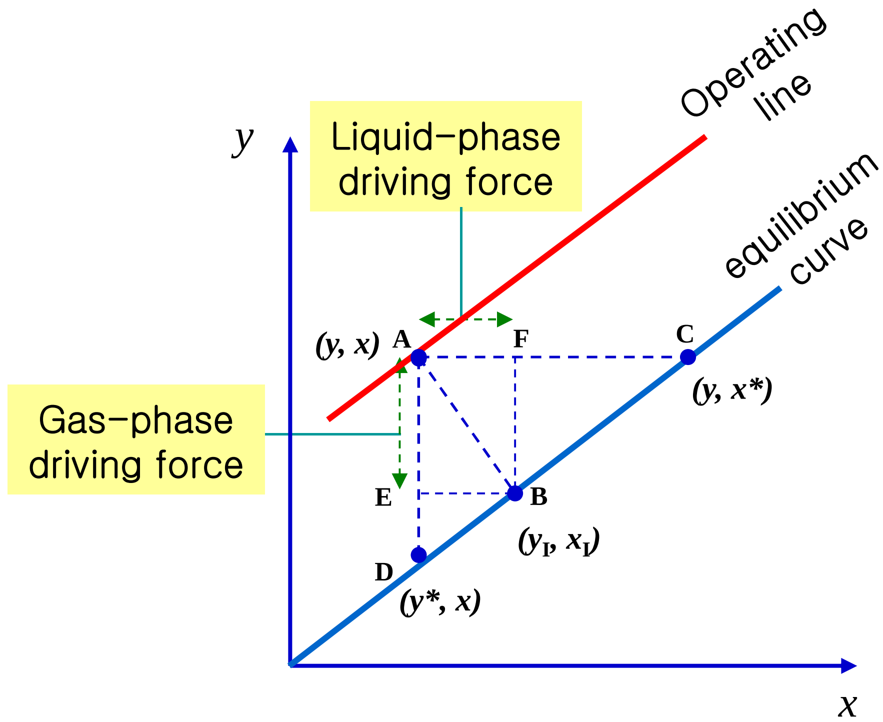


Two-Film Theory (2)

- At steady state absorption, without chemical reactions,
  (rate of solute mass transfer across gas film)
  = (rate of solute mass transfer across liquid film)

$$r = k_y a(y - y_I) = k_x a(x_I - x)$$

$$\frac{(y - y_I)}{(x - x_I)} = -\frac{k_x a}{k_y a}$$



- Mass transfer resistance in gas phase is very low → $y_I \approx y$
  : Liquid-film controlling process
- Mass transfer resistance in liquid phase is very low → $x_I \approx x$
  : Gas-film controlling process
- Rate of mass transfer can be increased by promoting turbulence and/or increasing dispersion

Two-Film Theory (3)

- Mass transfer in terms of overall driving force

$$r = K_y a(y - y^*) = K_x a(x^* - x)$$

y^* : fictitious vapor mole fraction in equilibrium with x in bulk liquid
x^* : fictitious liquid mole fraction in equilibrium with y in bulk vapor

$$\frac{1}{K_y a} = \frac{1}{k_y a} + \frac{1}{k_x a}\left(\frac{y_I - y^*}{x_I - x}\right)$$

$$\frac{1}{K_x a} = \frac{1}{k_x a} + \frac{1}{k_y a}\left(\frac{x^* - x_I}{y - y_I}\right)$$

$$\frac{y_I - y^*}{x_I - x} = \frac{\overline{ED}}{\overline{BE}} = K$$

$$\frac{x^* - x_I}{y - y_I} = \frac{\overline{CF}}{\overline{FB}} = \frac{1}{K}$$

For dilute solutions when the equilibrium curve is a nearly straight line

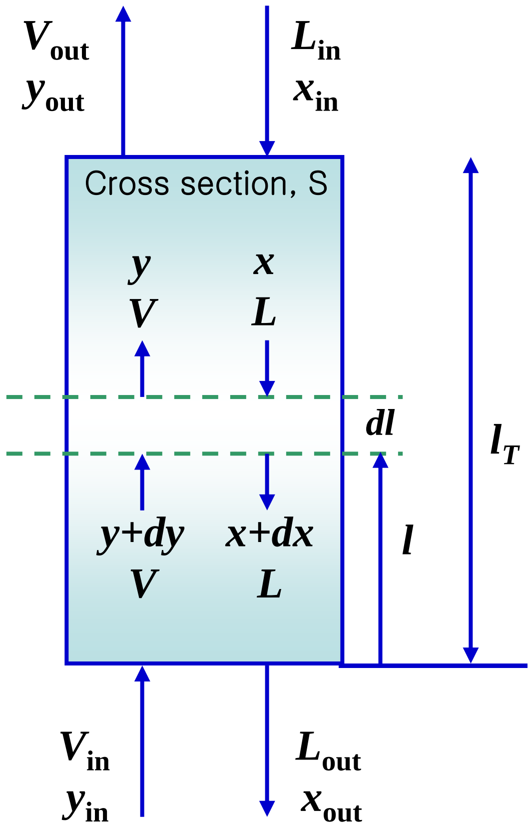
$$\frac{1}{K_y a} = \frac{1}{k_y a} + \frac{K}{k_x a}$$

$$\frac{1}{K_x a} = \frac{1}{k_x a} + \frac{1}{K k_y a}$$

Rate–Based Method (1)

- Determination of column packed height
  : commonly involves overall gas–phase coefficient, $K_y a$
  ∵ Liquid has a strong affinity for the solute
  (mass transfer resistance is mostly in the gas phase)

- Differential material balance for a solute



$$-Vdy = K_y a(y - y^*)Sdl$$

$$\frac{K_y aS}{V}\int_0^{l_T} dl = \frac{K_y aS l_T}{V} = \int_{y_{out}}^{y_{in}} \frac{dy}{y - y^*}$$

Packed height

$$l_T = \frac{V}{K_y aS}\int_{y_{out}}^{y_{in}} \frac{dy}{y - y^*}$$

Rate–Based Method (2)

- By Chilton and Colburn,

$$l_T = H_{OG} N_{OG}$$

$$H_{OG} = \frac{V}{K_y a S}$$

Overall height of a (gas) transfer unit, HTU

$$N_{OG} = \int_{y_{\text{out}}}^{y_{\text{in}}} \frac{dy}{y - y^*}$$

Overall number of (gas) transfer units, NTU

- Integration of NTU

$$\int_{y_{\text{out}}}^{y_{\text{in}}} \frac{dy}{y - y^*}$$

$$y^* = Kx$$

$$y = x\left(\frac{L}{V}\right) + y_{\text{out}} - x_{\text{in}}\left(\frac{L}{V}\right)$$

$$= \int_{y_{\text{out}}}^{y_{\text{in}}} \frac{dy}{(1 - KV/L)y + y_{\text{out}}(KV/L) - Kx_{\text{in}}}$$

$$L/(KV) = A$$

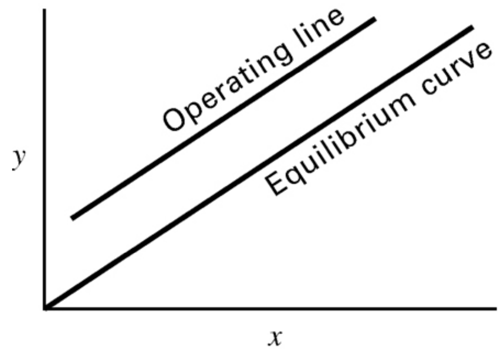
$$N_{OG} = \frac{\ln\{[(A-1)/A][(y_{\text{in}} - Kx_{\text{in}})/(y_{\text{out}} - Kx_{\text{in}})] + (1/A)\}}{(A-1)/A}$$

Relation between NTU, HTU & N_t, HETP

- When the operating and equilibrium lines are straight and parallel

$$\text{HETP} = H_{OG}$$

$$N_{OG} = N_t$$

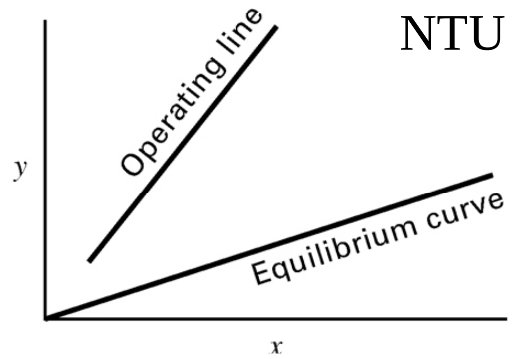


- When the operating and equilibrium lines are straight but not parallel

$$\text{HETP} = H_{OG} \frac{\ln(1/A)}{(1-A)/A}$$

$$N_{OG} = N_t \frac{\ln(1/A)}{(1-A)/A}$$

$\text{NTU} > N_t$



$\text{NTU} < N_t$