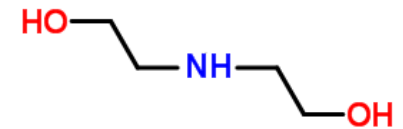


Gas Absorption-Desorption or Stripping

Gas Absorption is an operation in which a gas mixture is contacted with a liquid for the purposes of **preferentially dissolving one or more components** of the gas and to **provide a solution of them in the liquid**.

- Removal of acid gases (H_2S & CO_2) from Natural Gas by absorption into Alkanolamines (MEA, DEA, etc.).
- Removal of CO_2 from reformer gas in the production of Hydrogen
- Removal of NH_3 and Benzene & Toluene from coke oven gas



Absorption operations require mass transfer from **gas stream to liquid**.

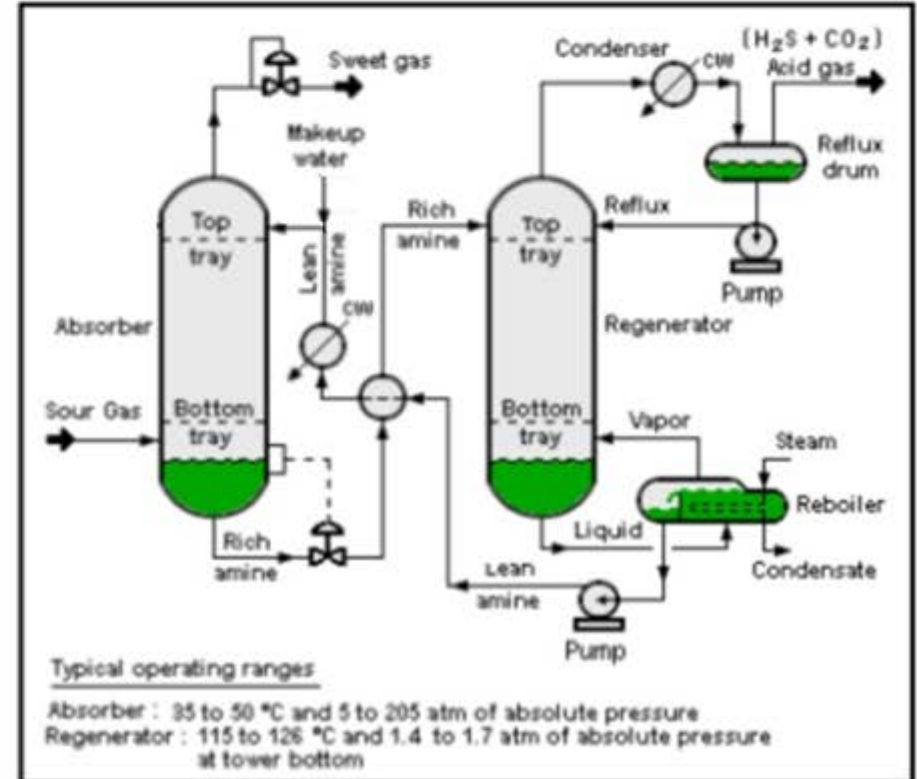
When the mass transfer occurs in the opposite direction, i.e., from **liquid to gas**, the operation is called **Desorption or Stripping**.

Removal of dissolved acid gases from rich alkanolamine solution by steam

Removal of benzene & toluene from rich hydrocarbon oil

Absorption-Desorption Operation

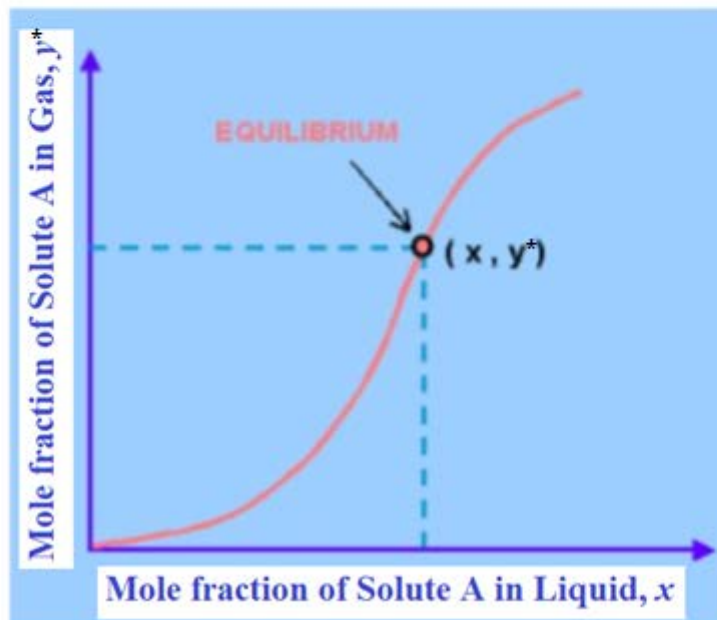
- In the **absorber**
 - H_2S is removed
 - contacting it with liquid amine DEA or MEA
 - **counter-current**
- The amine solution (inlet)
 - AKA lean amine
 - Enters the column at the top
- The gas outlet:
 - Sweet gas with the H_2S removed
- The amine solution (outlet)
 - Leaves the bottom of the column
 - Rich in absorbed H_2S
 - AKA rich amine
 - fed to the stripper/regenerator

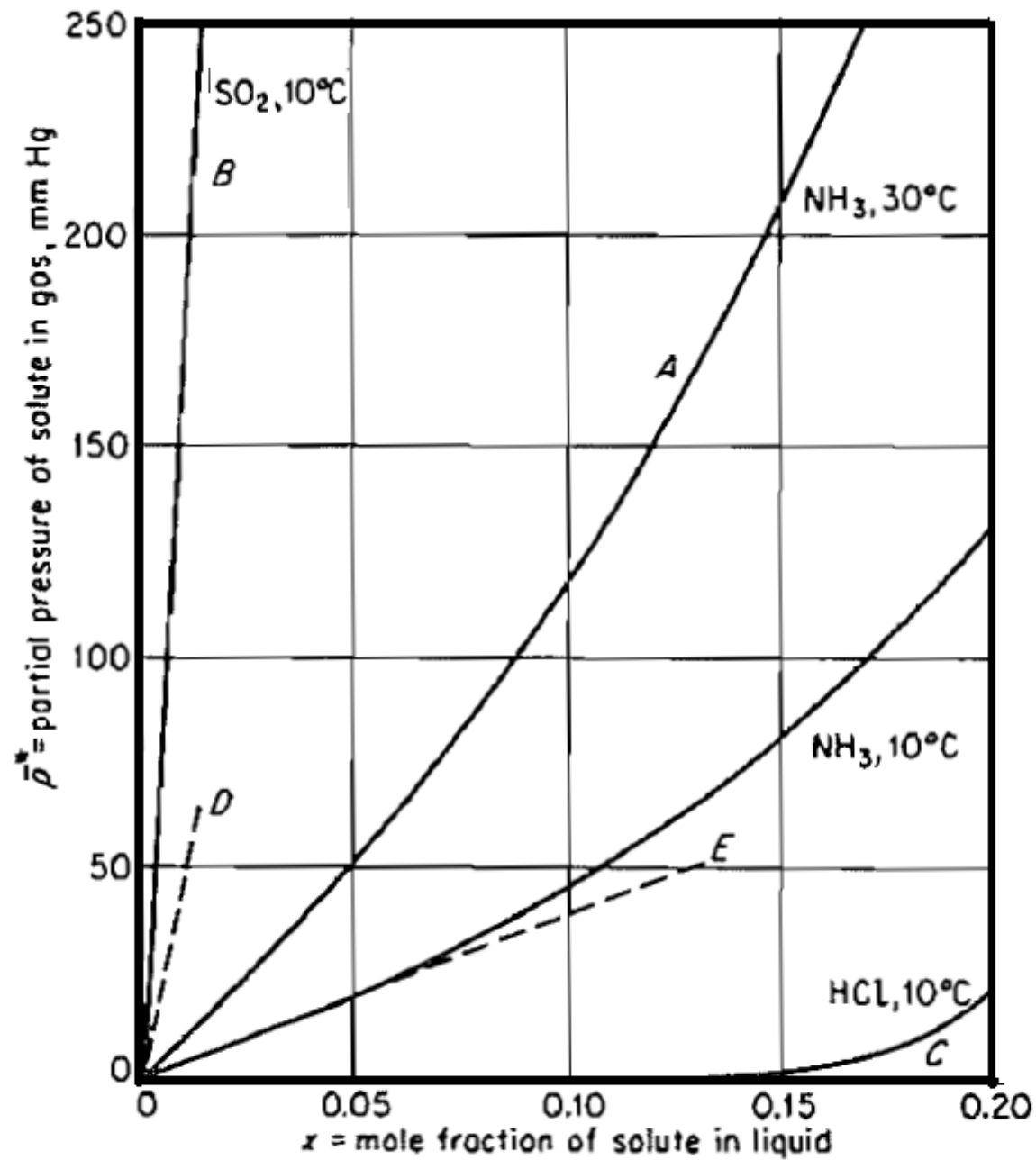


- In the **regenerator**
 - the opposite process takes place whereby
 - H_2S is removed from rich amine
 - Process is counter-current
- The “sour gases”
 - Leave due to non-condensation
 - Acid Gas
- The amine solution (outlet)
 - stripped of H_2S
 - leaves the bottom of the regenerator
 - sent back to the scrubber
 - Now “lean amine”
 - Recycled → more absorption

Equilibrium Distribution (Solubility) Curve

- The gas absorption process involves the re-distribution of solute between the gas phase and the liquid phase
- The two phases must come into close contact and achieve equilibrium condition.
- The equilibrium distribution curve is the relationship between solute concentration in the gas phase and in the liquid phase at constant temperature and pressure





Solubilities of Gases in Water

Henry's Law

- When the gas mixture in equilibrium with an ideal liquid solution follows the ideal gas behavior

$$p^* = P x$$

- When the solution is non-ideal, Raoult's law cannot be applied

- Most cases, it is more convenient to apply **Henry's law**

- Models for ideal solution, real gas
- Dilute solution
- "ideal-dilute" case

- Henry's law which states that:

- $p^* = H x$

- $y^* = p^*/P_T = m x$

where

- y^* = equilibrium mole fraction in gas phase
 - P_T = total system pressure
 - m = Henry's Law Constant
 - p^* = partial pressure of component in gas phase
- In many cases, the superscript '*' is dropped for convenience:

$$p_A = H x_A$$

$$y_A = m x_A$$

Solvent Selection

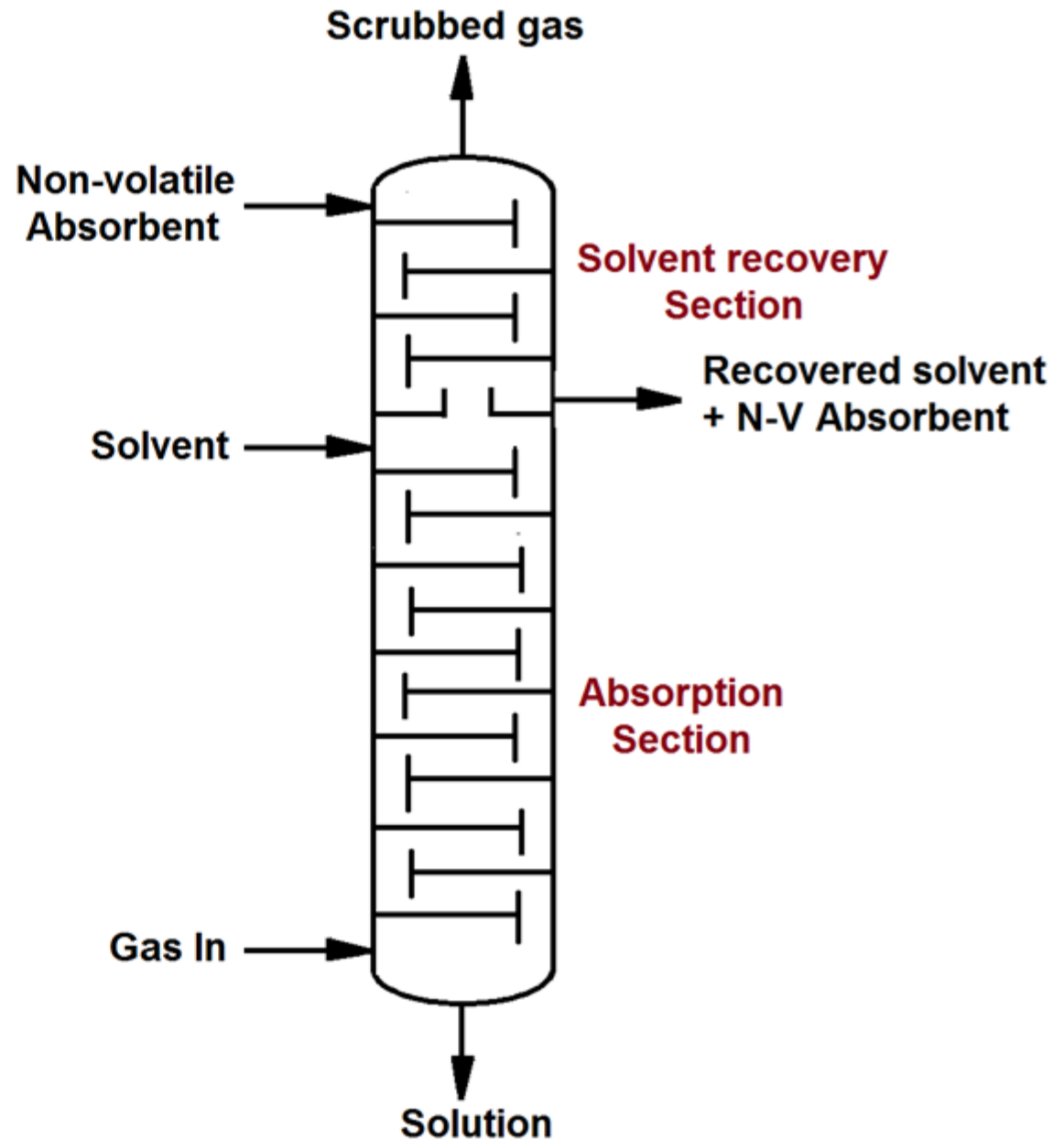
- If the principal purpose of the absorption operation is to produce a specific solution, as in the manufacture of hydrochloric acid, for example, the solvent is specified by the nature of the product, i.e. water is to be the solvent.
- If the principal purpose is to remove some components (e.g., impurities) from the gas, some choice is frequently possible.
 - Gas Solubility
 - Volatility
 - Corrosiveness
 - Cost
 - Viscosity
 - Miscellaneous

Gas Solubility

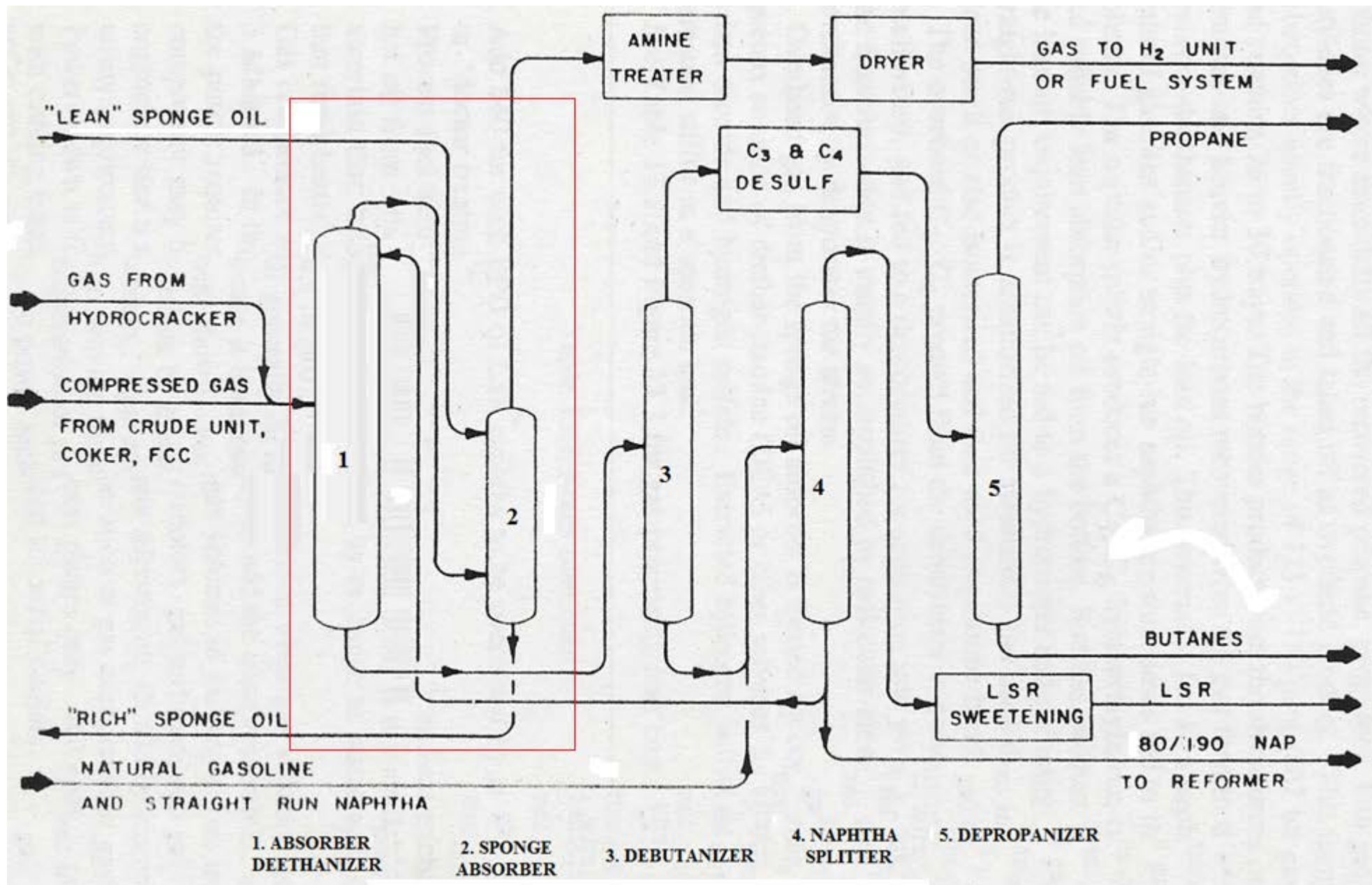
- The gas solubility should be high, thus increasing the rate of absorption and decreasing the quantity of solvent required.
- Absorbent should not dissolve carrier gas
- Generally solvent with a chemical nature similar to the solute to be absorbed will provide good solubility.
- A chemical reaction of the solvent with the solute will frequently result in very high gas solubility, but if the solvent is to be recovered for re-use, the reaction must be reversible.

Volatility

- The solvent should have
 - Low volatility
 - solvent loss with carrier gas is very small
 - Low vapour pressure
 - reduces loss of solvent
- If necessary, a second, less volatile liquid can be used to recover the evaporated portion of the first.



**Tray Absorber
with Volatile Solvent Recovery Section**



Refinery Gas Processing Unit

Corrosiveness

- The solvent should not be corrosive
 - Materials of construction required for the equipment should not be unusual or expensive.

Viscosity

- Low viscosity
 - Preferred for reasons of rapid absorption rates
 - Improved flooding characteristics in packed column
 - Low pressure drops on pumping
 - Good heat transfer characteristics.

Cost

- The solvent should be
 - inexpensive
 - losses are not costly
 - should be readily available.

Miscellaneous

- The solvent should be
 - Non-toxic
 - Non-flammable
 - Chemically stable
 - Should have low freezing point.

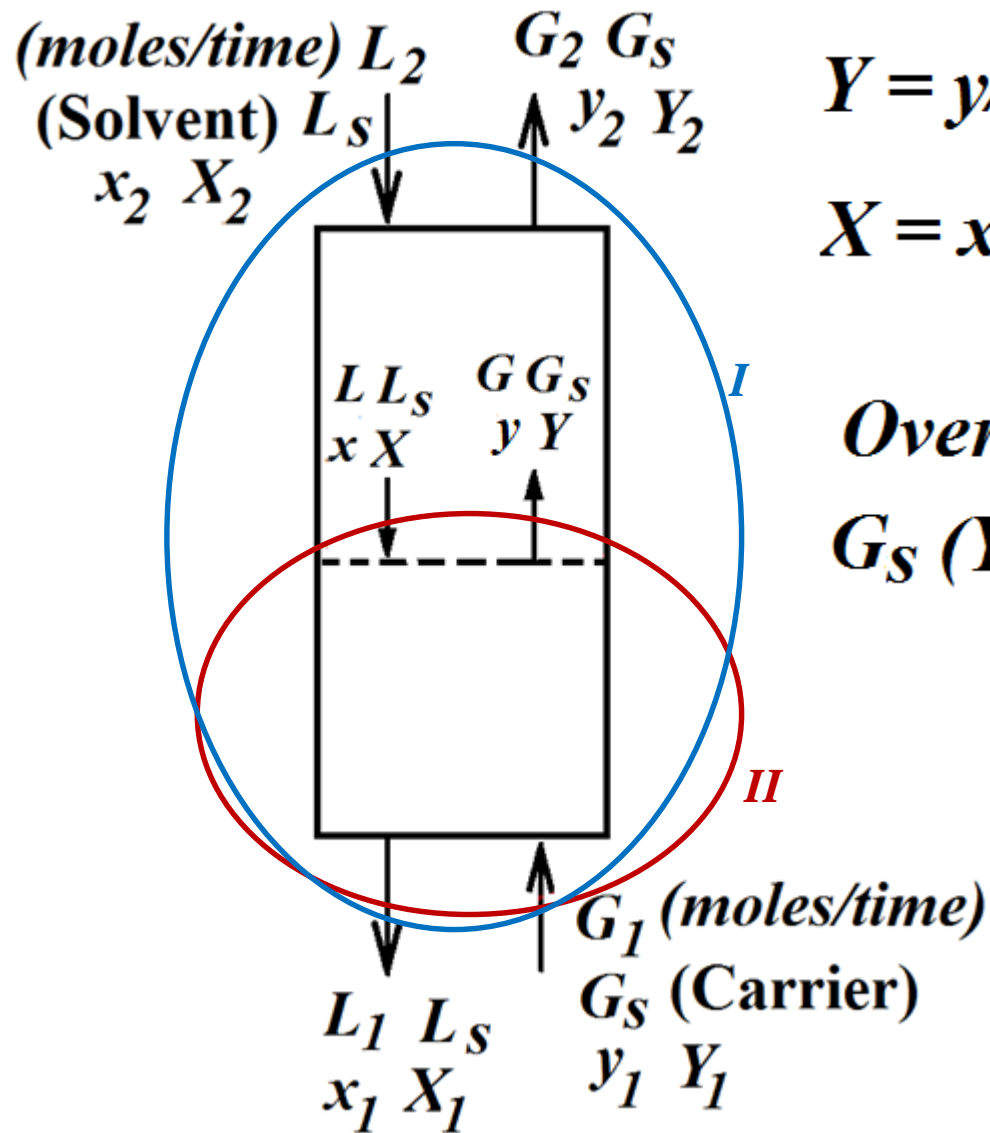
Design of Absorber/Stripper

Design Steps

1. Gas/Liquid → Flow rates, Compositions, Temperature & Pressure
2. Desired degree of recovery / purity
3. Absorbent Selection (Stripping Agent)
4. Operating Pressure/Temperature; Max. Pressure Drop
5. Min. Solvent Flow Rate; Actual Solvent Flow Rate as $x(L_{\min})$
6. Number of Equilibrium Stages; Stage Efficiency
7. Heating Effects / Duty
8. Type of Absorber Unit/Equipment
9. Height of Absorber
10. Diameter of Absorber

Design of Absorber/Stripper

Single Component Absorption: Material Balance



$$Y = y/(1-y) \quad G_S = G(1-y) = G/(1+Y)$$

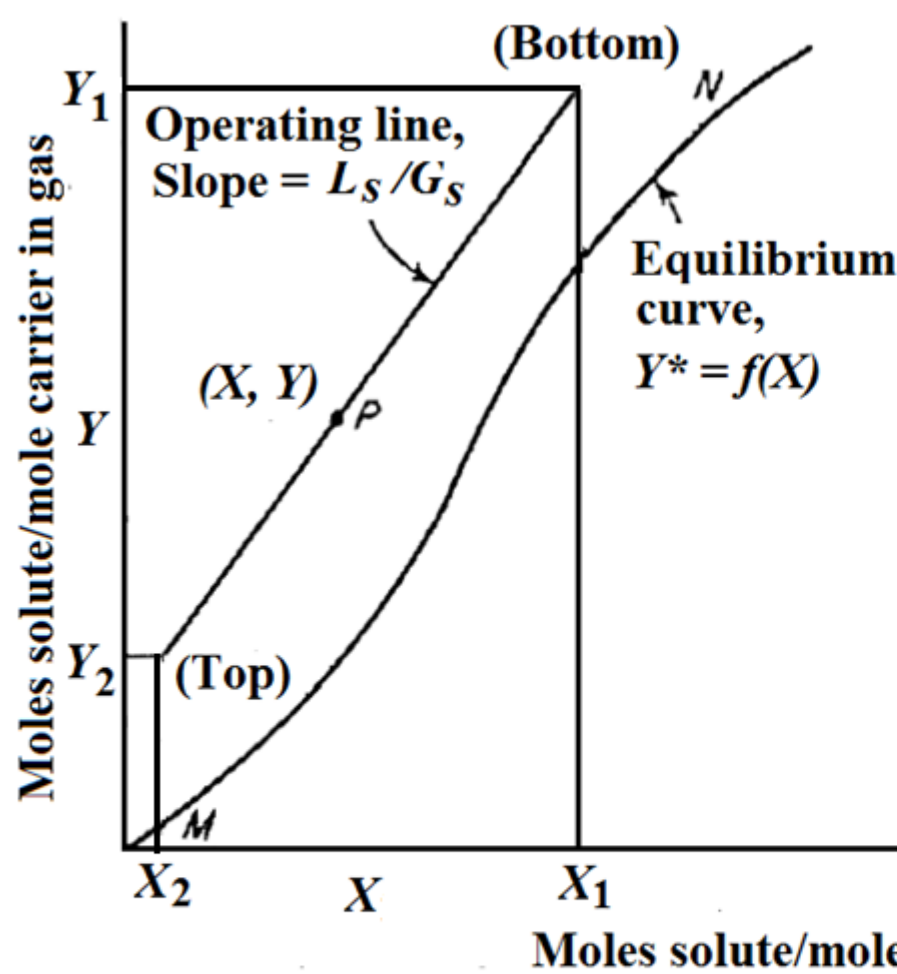
$$X = x/(1-x) \quad L_S = L(1-x) = L/(1+X)$$

Overall material (solute) balance:

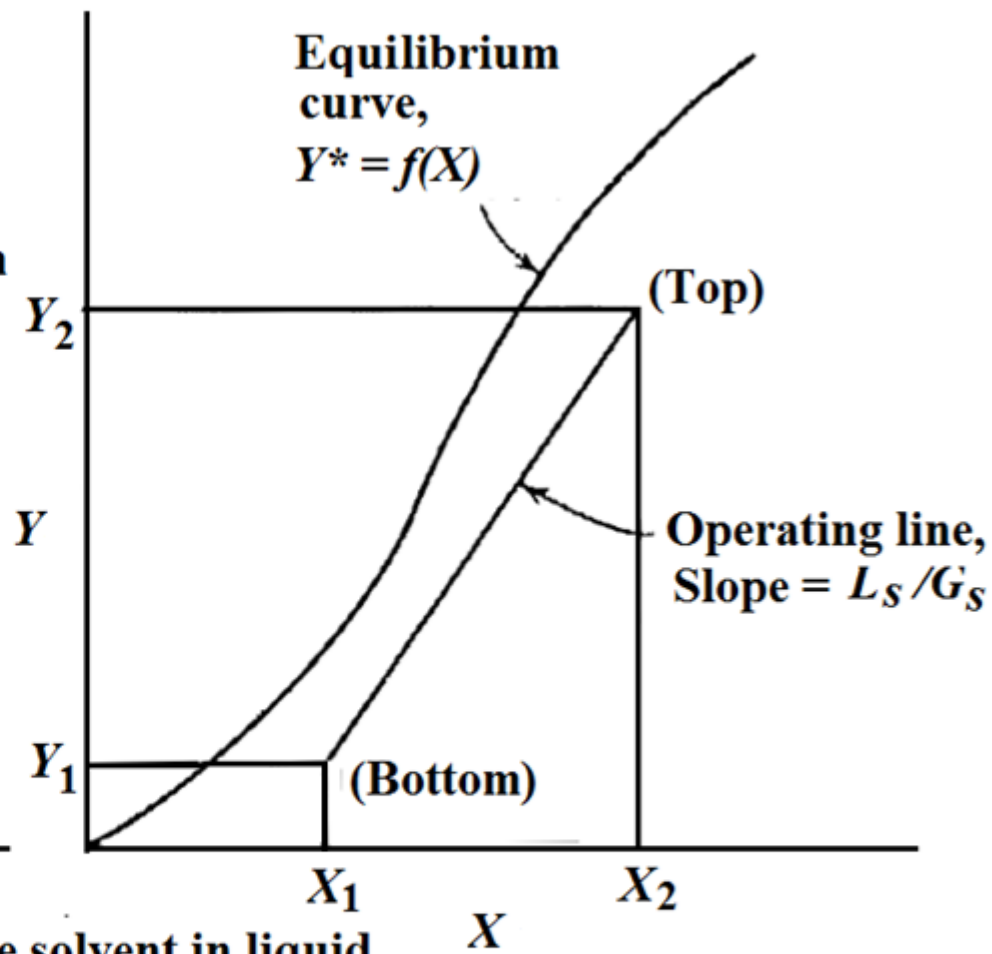
$$G_S (Y_1 - Y_2) = L_S (X_1 - X_2)$$

Material (solute) balance at the lower part:

$$G_S (Y_1 - Y) = L_S (X_1 - X)$$

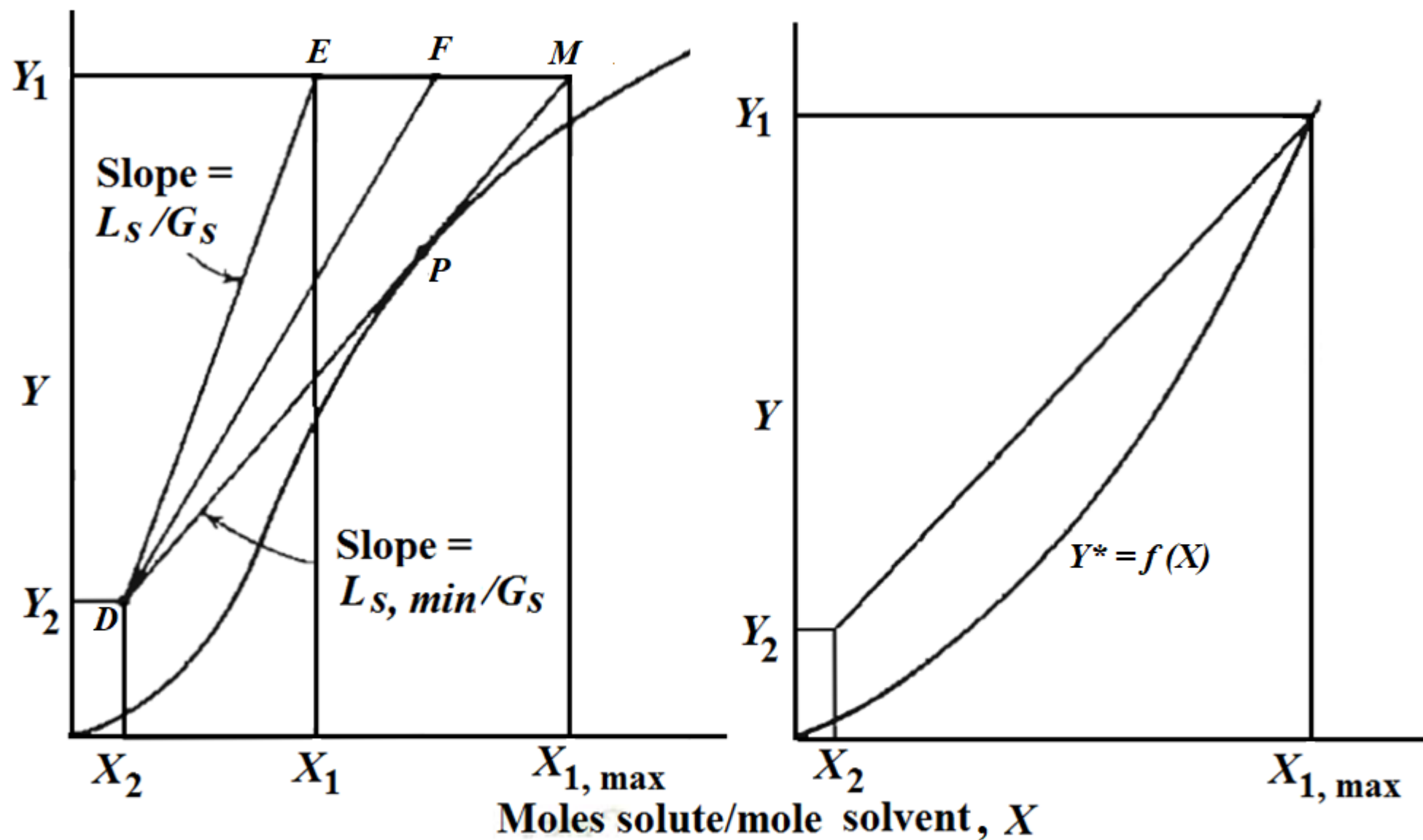


(a) Absorber

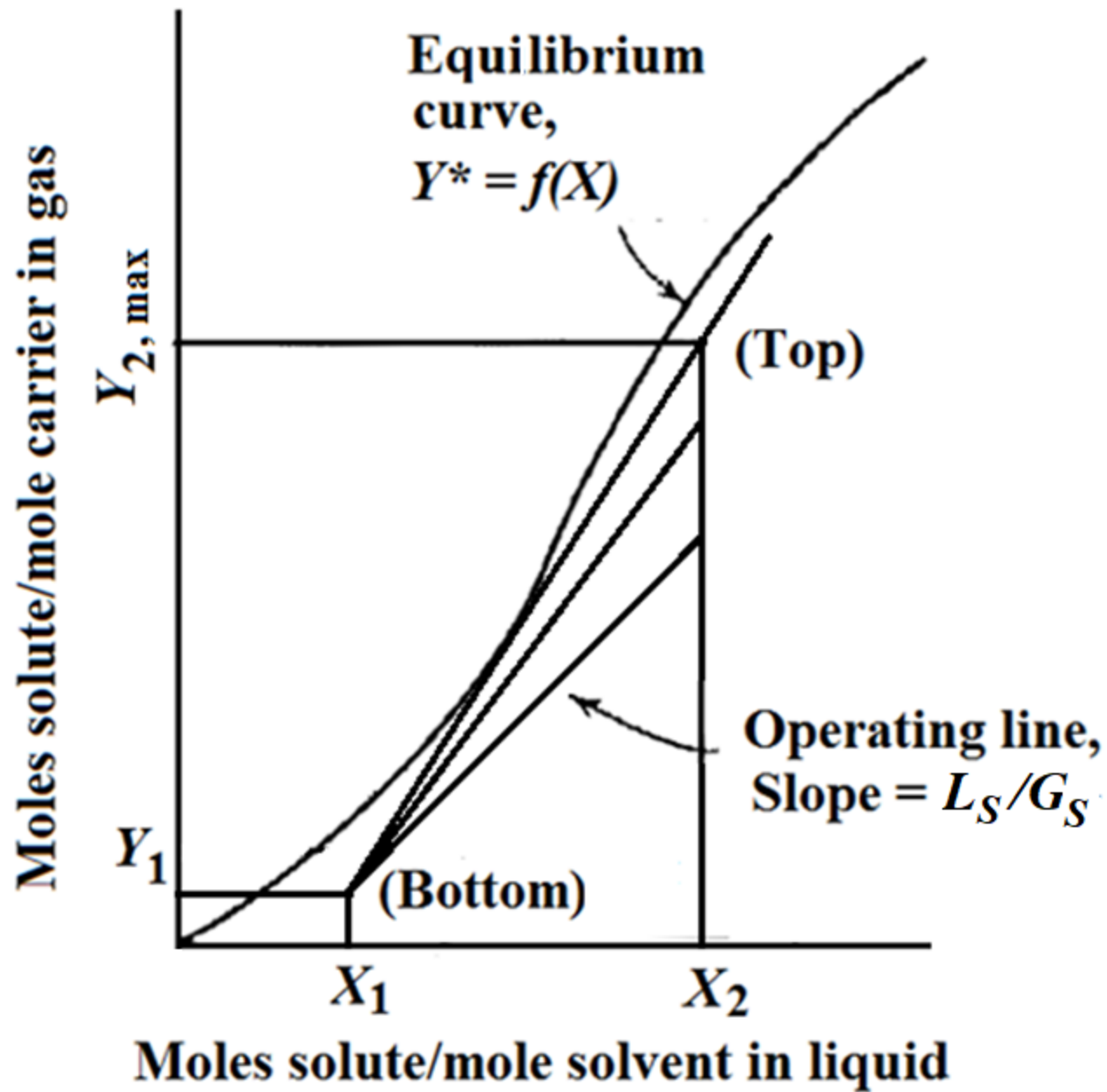


(b) Stripper

Operating Lines for Absorber and Stripper



Minimum Liquid/Gas Ratio for Absorption

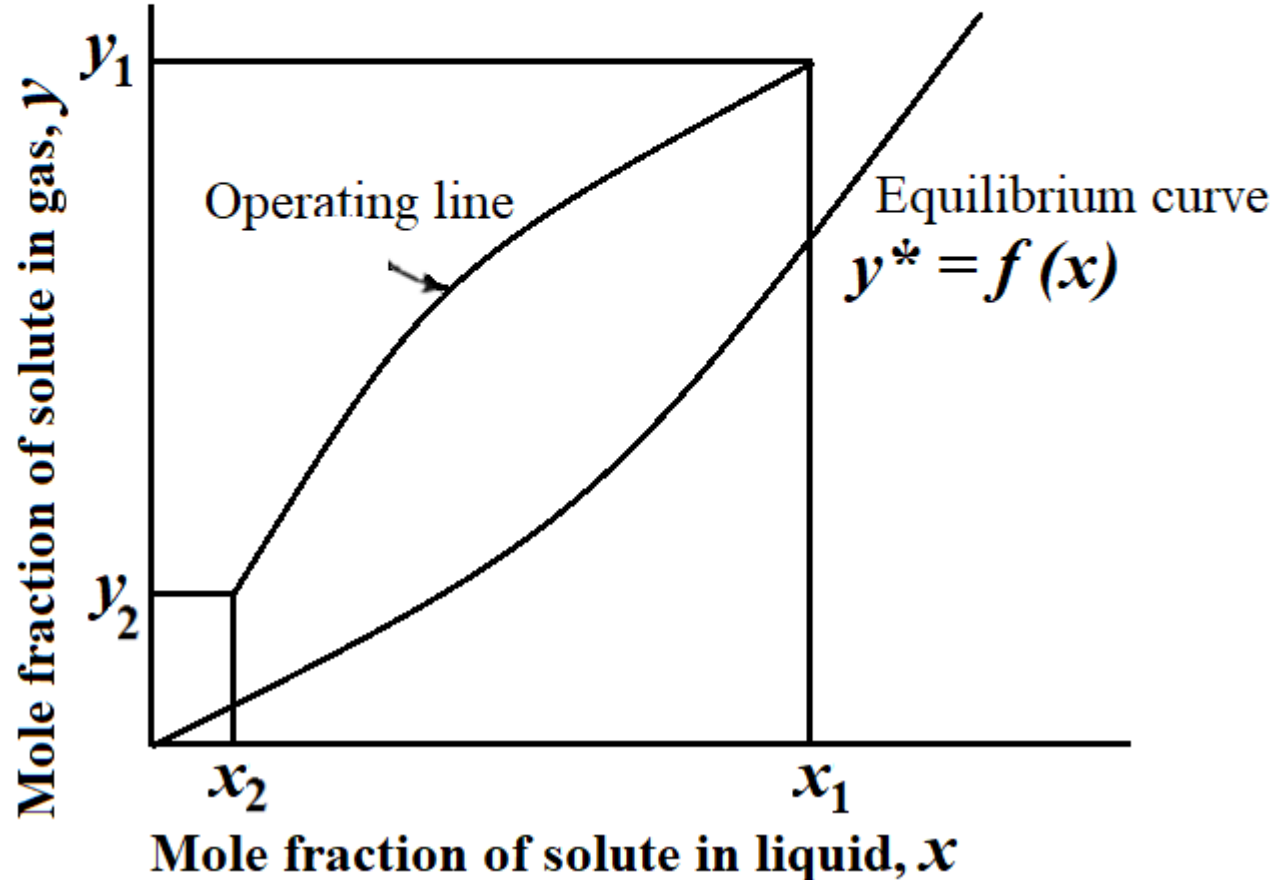


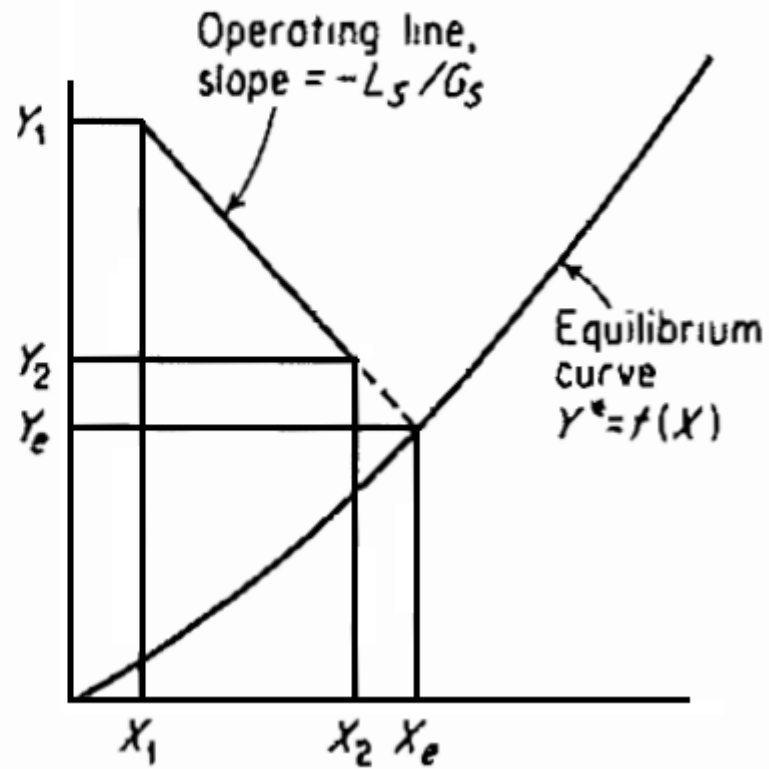
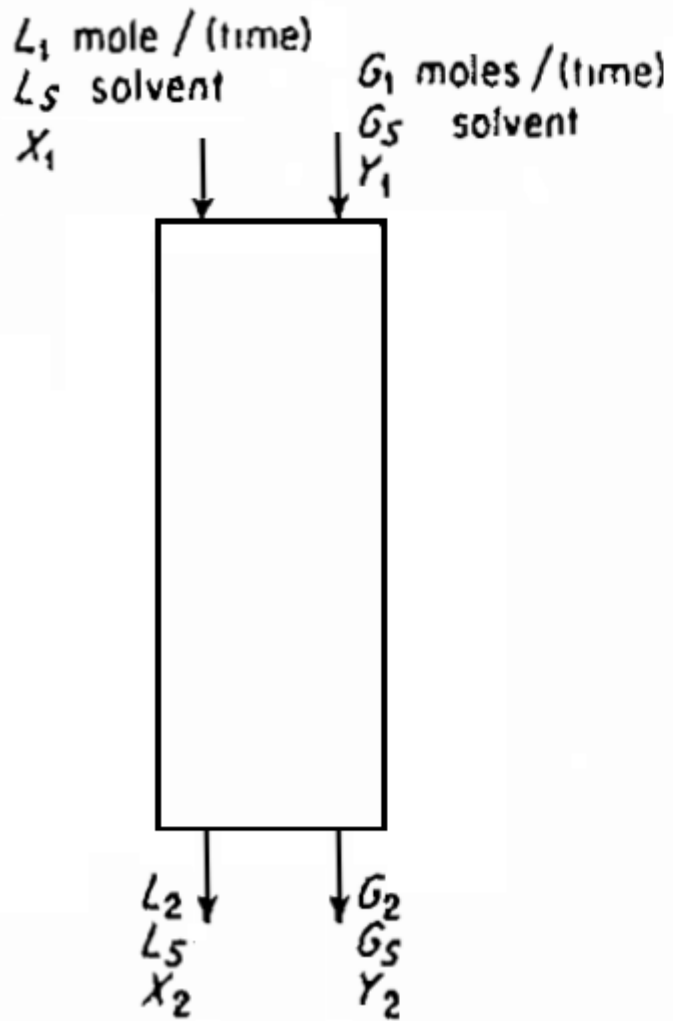
Minimum Gas Rate for Stripper

Operating line in mole fraction

$$G_S (Y_1 - Y) = L_S (X_1 - X)$$

$$G_S \left(\frac{y_1}{1-y_1} - \frac{y}{1-y} \right) = L_S \left(\frac{x_1}{1-x_1} - \frac{x}{1-x} \right)$$

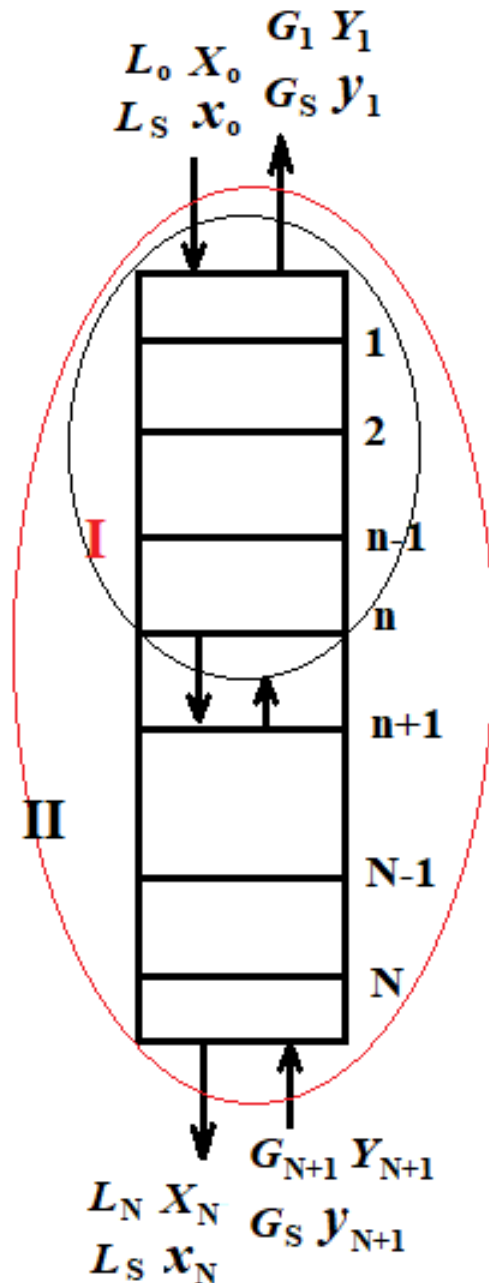




Co-current Absorber

Counter-current Multistage Gas Absorption

One Component Transferred



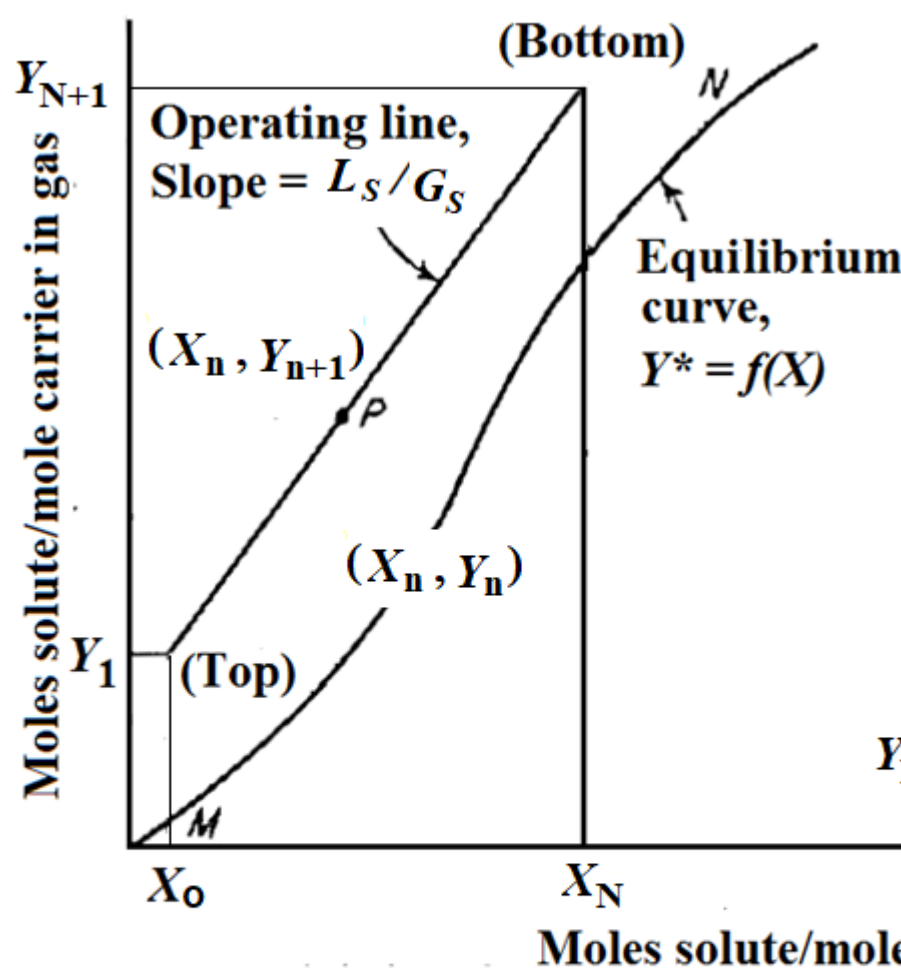
Material balance over Envelope I:

$$G_S (Y_{n+1} - Y_1) = L_S (X_n - X_o)$$

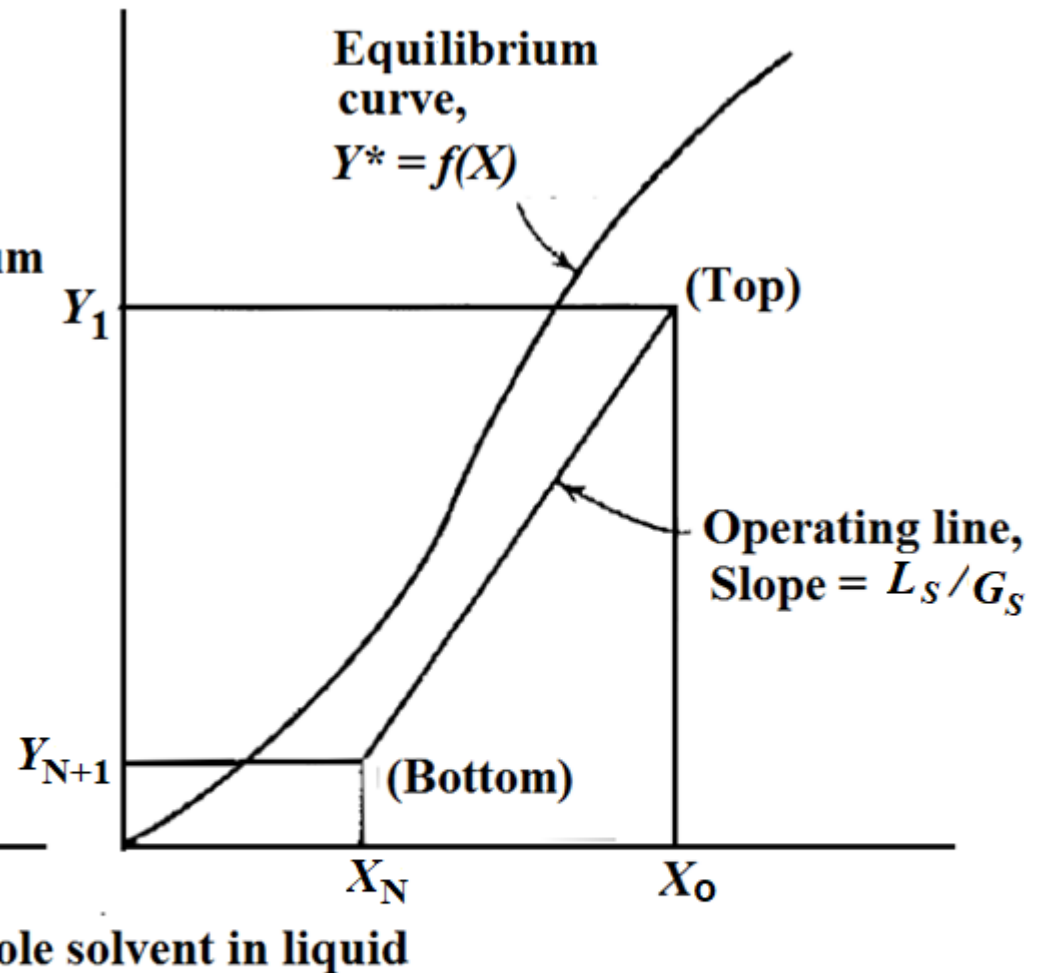
$$\Rightarrow (Y_{n+1} - Y_1) = \frac{L_S}{G_S} (X_n - X_o)$$

**Overall material balance
(over Envelope II):**

$$(Y_{N+1} - Y_1) = \frac{L_S}{G_S} (X_N - X_o)$$



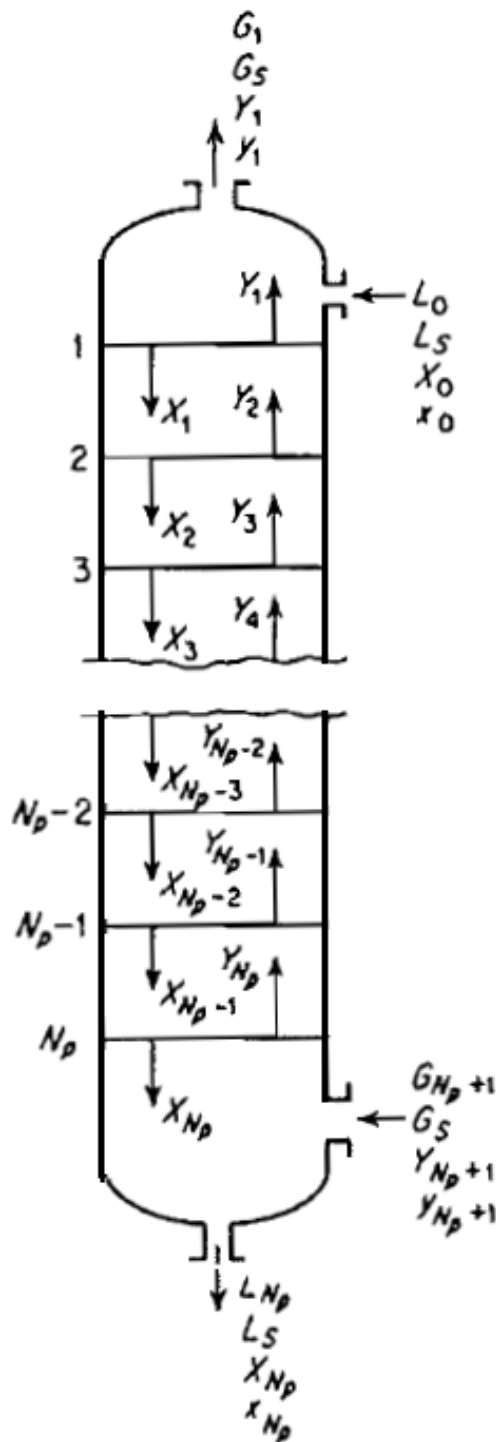
(a) Absorber



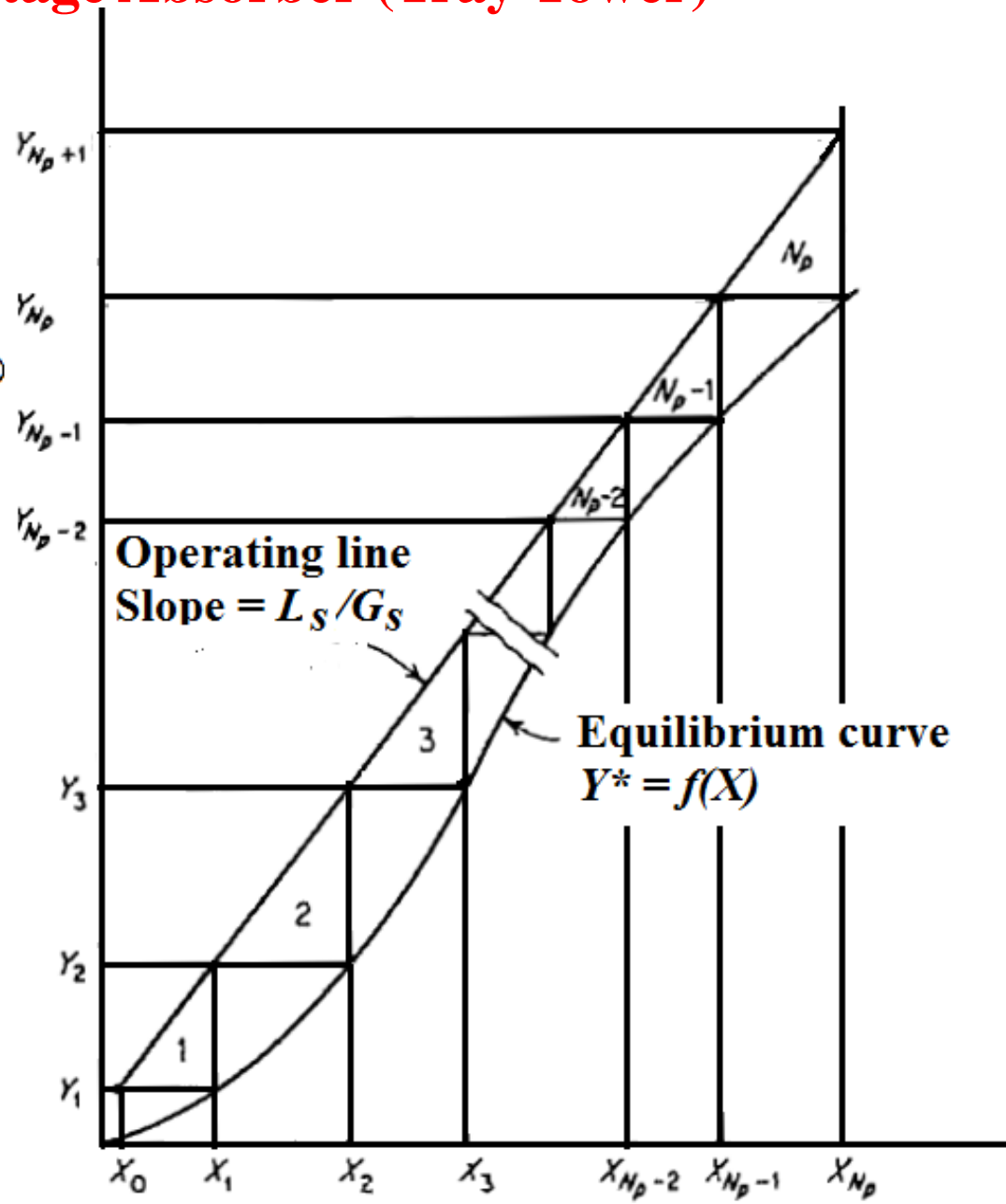
(b) Stripper

Operating Lines for Multistage Absorber and Stripper

Determination of Number of Stages in Counter-current Multistage Absorber (Tray Tower)



Y = moles solute/mole solvent gas



X = moles solute/mole solvent liquid

Theoretical Determination of Number of Ideal Stages for Straight Equilibrium Line

Kremser-Brown-Souders (or simply Kremser) Equations

Absorption

For $A \neq 1$ Absorption factor, $A = L_S/mG_S$ **For $A = 1$**

$$\frac{Y_{N+1} - Y_1}{Y_{N+1} - mX_0} = \frac{A^{N+1} - A}{A^{N+1} - 1}$$

$$\frac{Y_{N+1} - Y_1}{Y_{N+1} - mX_0} = \frac{N}{N+1}$$

$$N = \frac{\log \left[\frac{Y_{N+1} - mX_0}{Y_1 - mX_0} \left(1 - \frac{1}{A} \right) + \frac{1}{A} \right]}{\log A}$$

$$N = \frac{Y_{N+1} - Y_1}{Y_1 - mX_0}$$

Stripping

For $S \neq 1$ Stripping factor, $S = mG_S/L_S$ **For $S = 1$**

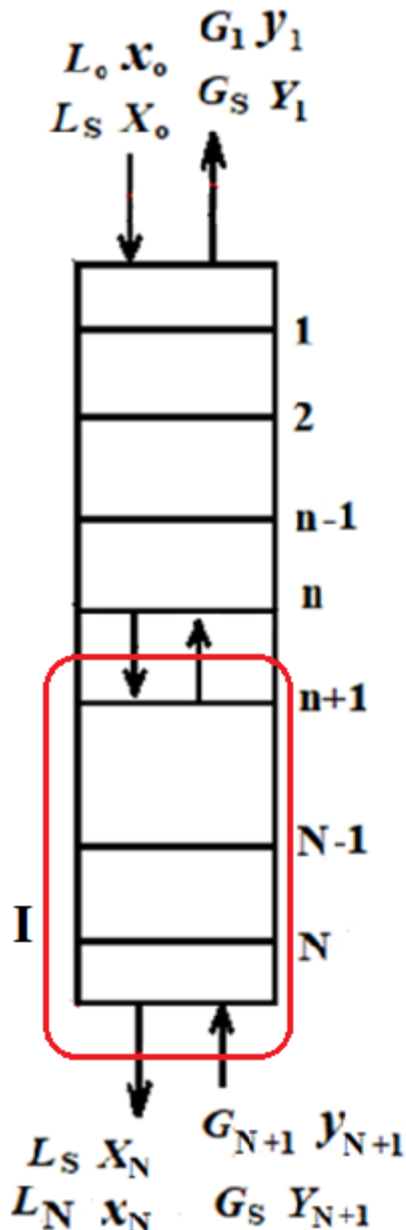
$$\frac{X_0 - X_N}{X_0 - Y_{N+1}/m} = \frac{S^{N+1} - S}{S^{N+1} - 1}$$

$$\frac{X_0 - X_N}{X_0 - Y_{N+1}/m} = \frac{N}{N+1}$$

$$N = \frac{\log \left[\frac{X_0 - Y_{N+1}/m}{X_N - Y_{N+1}/m} \left(1 - \frac{1}{S} \right) + \frac{1}{S} \right]}{\log S}$$

$$N = \frac{X_0 - X_N}{X_N - Y_{N+1}/m}$$

Theoretical Determination of Number of Ideal Stages for Straight Equilibrium Line



Equilibrium line is given as:

$$Y_n = m X_n$$

Material balance over Envelope I gives:

$$G_S(Y_{n+1} - Y_{N+1}) = L_S(X_n - X_N)$$

$$\Rightarrow Y_{n+1} - Y_{N+1} = \frac{L_S}{G_S} \left(\frac{Y_n}{m} - X_N \right)$$

$$= A Y_n - m A X_N$$

(where A = absorption factor = $L_S / m G_S$)

$$\Rightarrow Y_{n+1} - A Y_n = Y_{N+1} - A Y_N \quad \dots (1)$$

Equation (1) is a linear first-order finite difference equation, which can be solved in a similar way as ordinary differential equation.

For solution of the above non-homogeneous difference equation, first we have to find out the solution for the homogeneous part and then add it to the particular solution. The corresponding homogeneous equation is:

$$Y_{n+1} - A Y_n = 0 \quad \dots (2)$$

For this linear difference equation, we assume a solution of the form, $Y_n = B^n$, where B is a constant. Substituting in equation (2),

$$\begin{aligned} B^{n+1} - A B^n &= 0 \\ \Rightarrow B^n (B - A) &= 0 \Rightarrow B = A \end{aligned}$$

Therefore, the solution of the homogeneous equation is:

$$Y_n = C_1 A^n \quad \text{with } C_1 \text{ a constant.}$$

Let $Y_n = C_2$ be a particular solution. Then substituting in equation (1),

$$\begin{aligned} C_2 - A C_2 &= Y_{N+1} - A Y_N \\ \Rightarrow C_2 &= \frac{Y_{N+1} - A Y_N}{1 - A} \end{aligned}$$

The complete solution is, therefore,

$$Y_n = C_1 A^n + \frac{Y_{N+1} - A Y_N}{1 - A} \quad \dots (3)$$

Putting $n = 0$ in eqn. (3) we get,

$$Y_0 = C_1 + \frac{Y_{N+1} - AY_N}{1-A} \Rightarrow C_1 = Y_0 - \frac{Y_{N+1} - AY_N}{1-A}$$

Finally, the complete solution becomes

$$Y_n = \left(Y_0 - \frac{Y_{N+1} - AY_N}{1-A} \right) A^n + \frac{Y_{N+1} - AY_N}{1-A} \quad \dots (4)$$

Putting $n = N$ (for last stage), eqn. (4) takes the form

$$\begin{aligned} Y_N &= \left(Y_0 - \frac{Y_{N+1} - AY_N}{1-A} \right) A^N + \frac{Y_{N+1} - AY_N}{1-A} \\ \Rightarrow Y_N - \cancel{AY_N} &= A^N Y_0 - A^{N+1} Y_0 - A^N Y_{N+1} + A^{N+1} Y_N + Y_{N+1} - \cancel{AY_N} \\ \Rightarrow Y_N (A^{N+1} - 1) &= Y_{N+1} (A^N - 1) + A^N (A - 1) Y_0 \\ \Rightarrow Y_N &= \frac{(A^N - 1) Y_{N+1} - A^N (A - 1) Y_0}{A^{N+1} - 1} \quad \dots (5) \end{aligned}$$

A material balance over the entire absorber gives

$$\begin{aligned} G_S (Y_{N+1} - Y_1) &= L_S (X_N - X_0) \\ \Rightarrow Y_{N+1} - Y_1 &= A Y_N - A m X_0 \\ \Rightarrow Y_N &= \frac{Y_{N+1} - Y_1 + A m X_0}{A} \quad \dots (6) \end{aligned}$$

From eqns. (5) & (6) and putting $Y_0 = m X_0$, we get

$$\begin{aligned} \frac{Y_{N+1} - Y_1 + A m X_0}{A} &= \frac{(A^N - 1)Y_{N+1} - A^N(A - 1)mX_0}{A^{N+1} - 1} \\ \Rightarrow (A^{N+1} - 1)(Y_{N+1} - Y_1) + (A^{N+1} - 1)A m X_0 &= (A^{N+1} - A)Y_{N+1} + A^{N+1}(A - 1)mX_0 \\ \Rightarrow (A^{N+1} - 1)(Y_{N+1} - Y_1) &= (A^{N+1} - A)Y_{N+1} + (A^{N+1} - A)mX_0 \\ &= (A^{N+1} - A)(Y_{N+1} - mX_0) \\ \Rightarrow \frac{Y_{N+1} - Y_1}{Y_{N+1} - mX_0} &= \frac{A^{N+1} - A}{A^{N+1} - 1} \quad (\text{for } A \neq 1) \quad \dots (7) \end{aligned}$$

Eqn. (7) can be rearranged as follows

$$\begin{aligned} \cancel{A^{N+1}Y_{N+1}} - A^{N+1}Y_1 + \cancel{A^{N+2}mX_0} - Y_{N+1} + Y_1 - A m X_0 &= \cancel{A^{N+1}Y_{N+1}} - A Y_{N+1} + \cancel{A^{N+2}mX_0} - A^{N+1}mX_0 \\ \Rightarrow A^{N+1}(Y_1 - mX_0) = Y_{N+1}(A - 1) - mX_0(A - 1) + Y_1 - mX_0 &= (Y_{N+1} - mX_0)(A - 1) + Y_1 - mX_0 \\ \Rightarrow A^N = \frac{Y_{N+1} - mX_0}{Y_1 - mX_0} \left(1 - \frac{1}{A}\right) + \frac{1}{A} \\ \Rightarrow N = \frac{\log \left[\frac{Y_{N+1} - mX_0}{Y_1 - mX_0} \left(1 - \frac{1}{A}\right) + \frac{1}{A} \right]}{\log A} \quad (\text{for } A \neq 1) \quad \dots (8) \end{aligned}$$

For $A = 1$, eqn. (7) becomes

$$\frac{Y_{N+1} - Y_1}{Y_{N+1} - m X_0} = \frac{N}{N+1} \quad \dots (9)$$

$$\Rightarrow N = \frac{Y_{N+1} - Y_1}{Y_1 - m X_0} \quad \dots (10)$$

Similarly, for stripping, we can write

$$\frac{X_0 - X_N}{X_0 - Y_{N+1} / m} = \frac{S^{N+1} - S}{S^{N+1} - 1} \quad (\text{for } S \neq 1) \quad \dots (11)$$

and

$$N = \frac{\log \left[\frac{X_0 - Y_{N+1} / m}{X_N - Y_{N+1} / m} \left(1 - \frac{1}{S} \right) + \frac{1}{S} \right]}{\log S} \quad (\text{for } S \neq 1) \quad \dots (12)$$

For $S = 1$,

$$\frac{X_0 - X_N}{X_0 - Y_{N+1} / m} = \frac{N}{N+1} \quad \dots (13)$$

$$\text{and} \quad N = \frac{X_0 - X_N}{X_N - Y_{N+1} / m} \quad \dots (14)$$

These are known as ‘Kremser-Brown-Souders (or simply Kremser) Equations’

Dilute Gas Mixtures

$$L_0 = L_N = L_S = L \quad \text{and} \quad G_I = G_{N+I} = G_S = G, \text{ so that } A = L/mG$$

Absorption:

For $A \neq 1$

$$\frac{y_{N_P+1} - y_1}{y_{N_P+1} - m x_o} = \frac{A^{N_P+1} - A}{A^{N_P+1} - 1}$$
$$N_P = \frac{\log \left[\frac{y_{N_P+1} - m x_o}{y_1 - m x_o} \left(1 - \frac{1}{A}\right) + \frac{1}{A} \right]}{\log A}$$

For $A = 1$

$$\frac{y_{N_P+1} - y_1}{y_{N_P+1} - m x_o} = \frac{N_P}{N_P + 1}$$
$$N_P = \frac{y_{N_P+1} - y_1}{y_1 - m x_o}$$

Stripping:

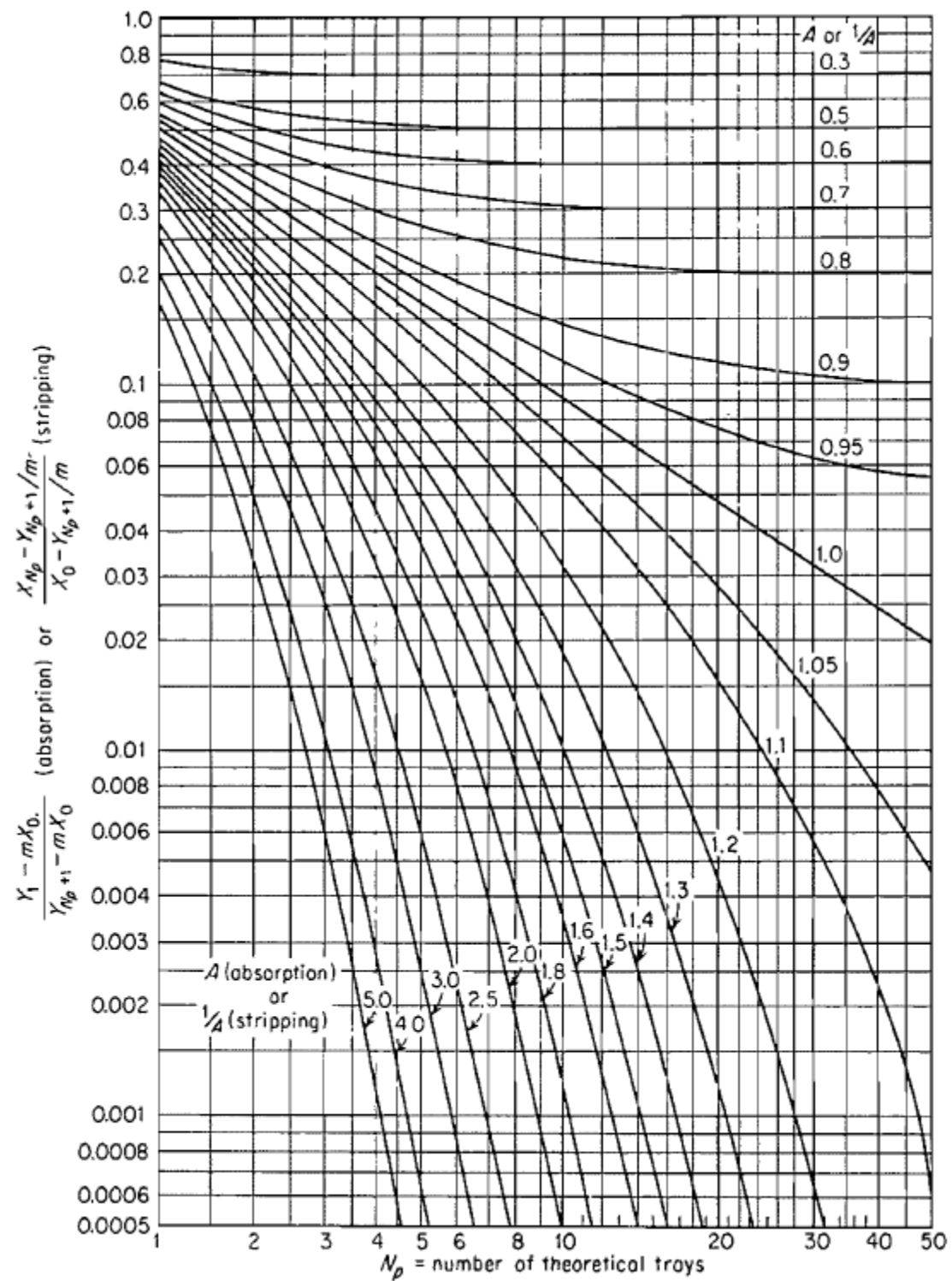
For $S \neq 1$

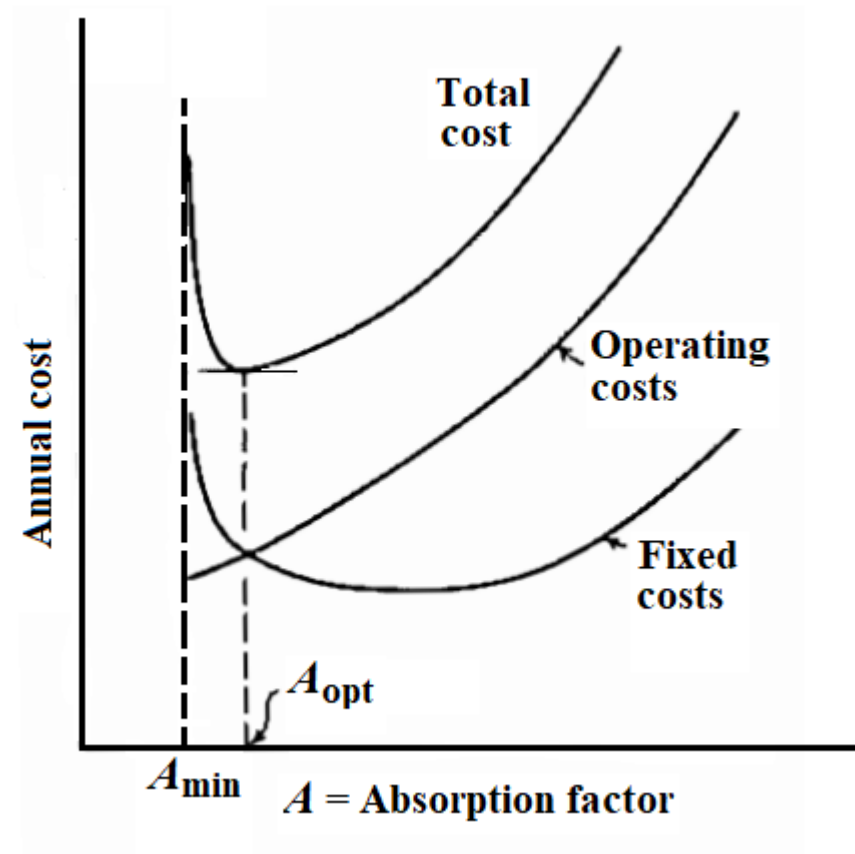
$$\frac{x_o - x_{N_P}}{x_o - y_{N_P+1} / m} = \frac{S^{N_P+1} - S}{S^{N_P+1} - 1}$$
$$N_P = \frac{\log \left[\frac{x_o - y_{N_P+1} / m}{x_{N_P} - y_{N_P+1} / m} \left(1 - \frac{1}{S}\right) + \frac{1}{S} \right]}{\log S}$$

For $S = 1$:

$$\frac{x_o - x_{N_P}}{x_o - y_{N_P+1} / m} = \frac{N_P}{N_P + 1}$$
$$N_P = \frac{x_o - x_{N_P}}{x_{N_P} - y_{N_P+1} / m}$$

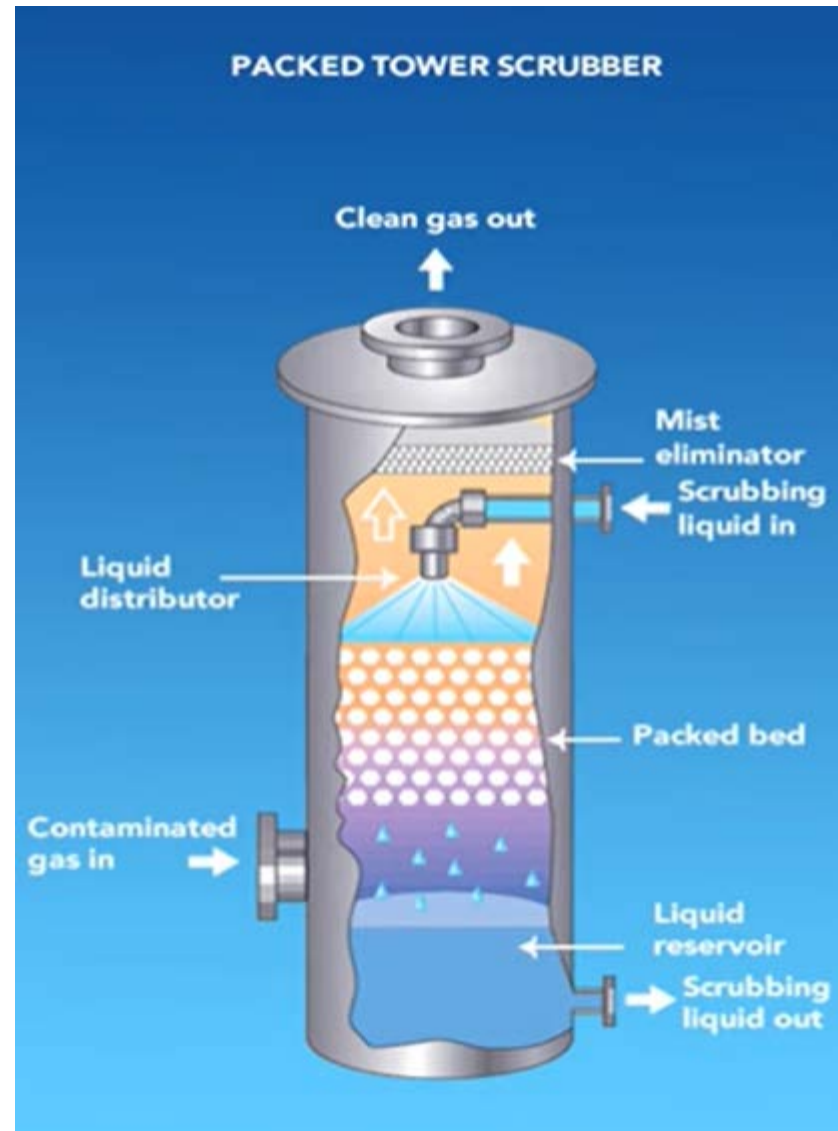
Kremser-Brown-Souders (or simply Kremser) Equations





**Determination of most economical (Optimum)
Absorption factor (A_{opt})**

Design of Continuous Contact Equipment (Packed Towers)



Counter-current contactors such as packed and spray towers operate in a different manner from the plate towers in that the fluids are in contact continuously in their path through the tower, rather than intermittently. Thus, in a packed tower the liquid and gas compositions change continuously with height of packing. Every point on an operating line, therefore, represents conditions found somewhere in the tower, whereas for tray towers, only the isolated points on the operating line corresponding to locations between two consecutive trays have real significance.

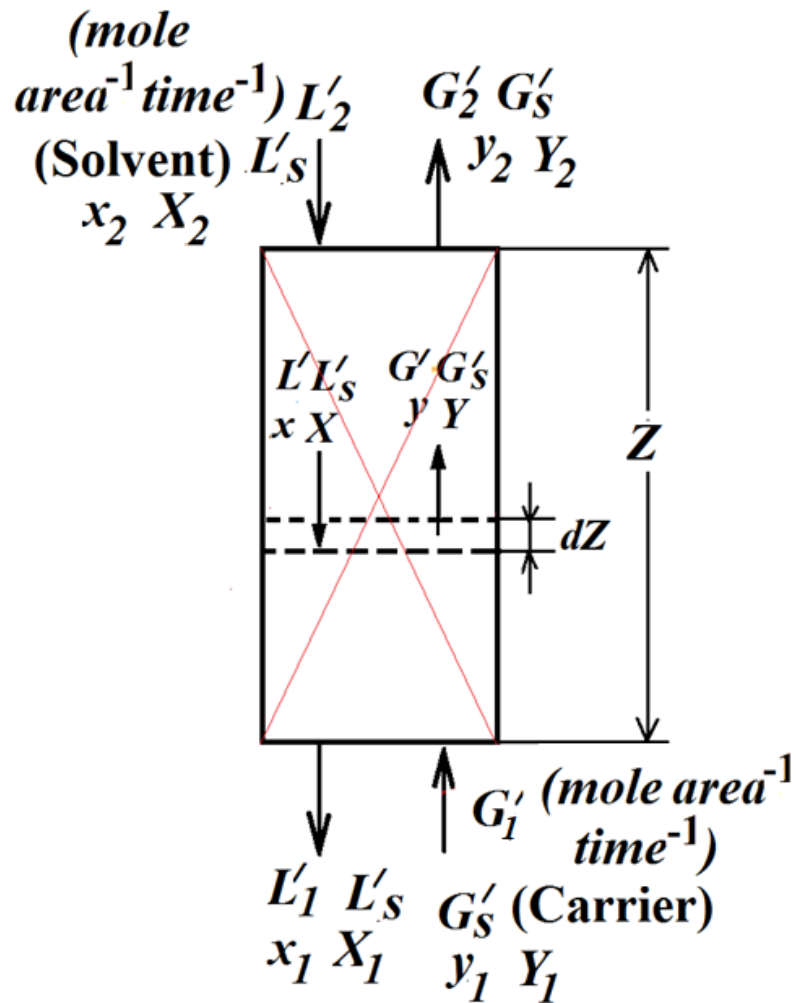
Height Equivalent to a Theoretical Plate/Tray (HETP)

The height equivalent to a theoretical tray or plate (HETP) is the required height of the packing to do the same mass transfer job as a theoretical plate.

The number of theoretical trays or plates required for a given change in concentration is computed by the methods followed for tray towers. This is then multiplied by the HETP.

HETP must be an experimentally determined quantity characteristic for each packing. Unfortunately, it is found that the HETP varies, not only with the type and size of the packing but also very strongly with flow rates of each fluid and for every system with concentration as well, so that an enormous amount of experimental data would have to be accumulated to permit utilization of the method. The difficulty lies in the failure to account for the fundamentally different action of tray and packed towers.

Design of Packed Tower for Single Component Absorption



$$S = a Z \quad \text{or, } dS = a dZ \quad \dots (1)$$

Material balance over differential section gives:

$$-d(G'y) = N_A dS = N_A a dZ \quad \dots (2)$$

$$\text{Again, } -d(G'y) = -G' dy - y dG' \quad \dots (3)$$

But $-dG'$ is the decrease in the total amount of gas, i.e., the amount of gas absorbed. Therefore,

$$-dG' = N_A a dZ \quad \dots (4)$$

The flux (N_A) can be expressed as:

$$N_A = k_y (y - y_i) \quad \dots (5)$$

From equations (2), (3), (4) and (5) we get,

$$-G' dy = y dG' + N_A a dZ = (1 - y) N_A a dZ$$

$$\Rightarrow -G' dy = k_y a (1 - y) (y - y_i) dZ \quad \dots (6)$$

Alternatively,

$$-d(G'y) = -d\left(\frac{G'_s y}{(1-y)}\right) = -\frac{G'_s dy}{(1-y)^2} = -\frac{G' dy}{1-y} \Rightarrow -\frac{G' dy}{1-y} = N_A a dZ = k_y a (y - y_i) dZ$$

Equation (6) on rearrangement and integration gives:

$$Z = \int_0^Z dZ = \int_{y_2}^{y_1} \frac{G' dy}{k_y a (1-y) (y - y_i)} \quad \dots (7)$$

Equation (7) can be used to calculate the height of the packing.

Design Procedure Based on “Transfer Unit”

We have got the expression for height of the packing as

$$Z = \int_{y_2}^{y_1} \frac{G' dy}{k_y a (1-y) (y - y_i)} \quad \dots (7)$$

It has been observed that the mass transfer coefficient is nearly proportional to $G^{0.8}$ in turbulent flow. From experimental data on a large number of columns, it has been found that the quantity $G'/k_y a (1-y)_{iM}$ remains fairly constant all through the tower. Then equation (7) can be expressed as

$$Z = \frac{G'}{k_y a (1-y)_{iM}} \times \int_{y_2}^{y_1} \frac{(1-y)_{iM} dy}{(1-y)(y - y_i)} \quad \dots (8)$$

$$\text{Where, } (1-y)_{iM} = y_{BM} = \frac{(1-y_i) - (1-y)}{\ln[(1-y_i)/(1-y)]} \quad \dots (9)$$

$$Z = H_{tG} \times N_{tG} \quad \dots (10)$$

$$H_{tG} = \frac{G'}{k_y a (1-y)_{iM}} = \frac{G'}{k_y a y_{BM}} \dots (11a) \quad N_{tG} = \int_{y_2}^{y_1} \frac{(1-y)_{iM} dy}{(1-y)(y-y_i)} \dots (11b)$$

Height of a transfer unit (H_{tG}) indicates inversely the relative ease with which a tower can accomplish mass transfer. Thus the more the mass transfer coefficient and specific interfacial area, the more effective is the tower for mass transfer and less is the height of a transfer unit.

Number of transfer unit (N_{tG}) indicates the difficulty involved with the degree of separation desired. The more is the degree of separation desired, the less will be the driving force available and higher will be the number of transfer units.

Similarly, liquid phase transfer units are expressed as:

$$H_{tL} = \frac{L'}{k_x a (1-x)_{iM}} = \frac{L'}{k_x a x_{BM}} \dots (12a) \quad N_{tL} = \int_{x_2}^{x_1} \frac{(1-x)_{iM} dx}{(1-x)(x_i-x)} \dots (12b)$$

For Strippers

$$H_{tG} = \frac{G'}{k_y a (1-y)_{iM}} = \frac{G'}{k_y a y_{BM}}$$

$$N_{tG} = \int_{y_1}^{y_2} \frac{(1-y)_{iM} dy}{(1-y)(y_i - y)}$$

$$H_{tL} = \frac{L'}{k_x a (1-x)_{iM}} = \frac{L'}{k_x a x_{BM}}$$

$$N_{tL} = \int_{x_1}^{x_2} \frac{(1-x)_{iM} dx}{(1-x)(x - x_i)}$$

Procedure for Determining Tower Height

$$H_{tG} = \frac{G'}{k_y a (1-y)_{iM}} = \frac{G'}{k_y a y_{BM}}$$

When the variation of gas flow rate over the column is considerably large, an average value of it may be used as:

$$G' = (G_1' + G_2')/2.$$

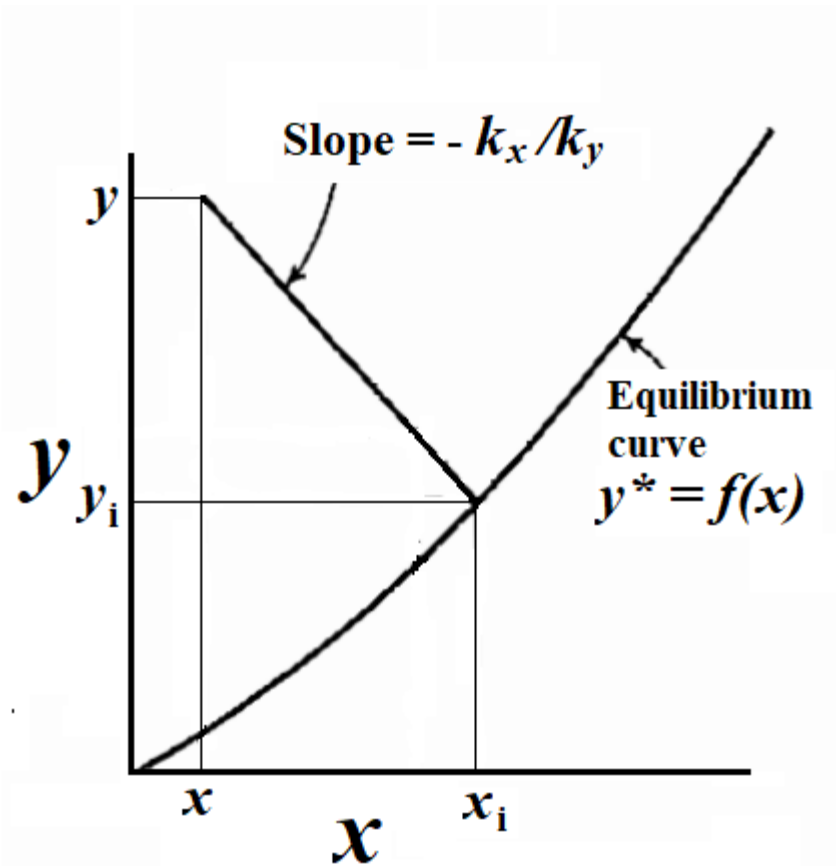
Similarly, as y_{BM} varies with height an average value is taken by calculating y_{BM} at the bottom and top and taking the arithmetic average as:

$$y_{BM} = [(y_{BM})_1 + (y_{BM})_2]/2.$$

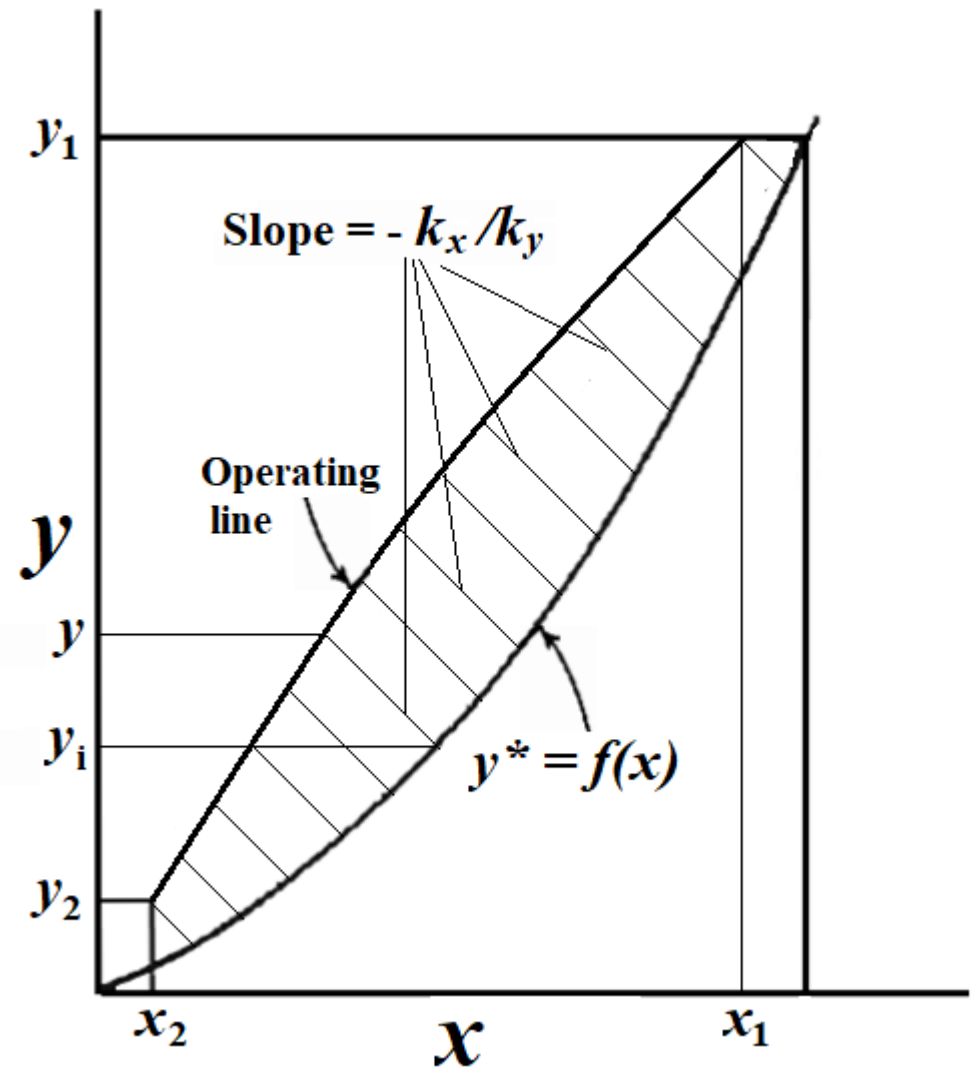
$$N_{tG} = \int_{y_2}^{y_1} \frac{(1-y)_{iM} dy}{(1-y)(y-y_i)}$$

$$N_A = k_y (y - y_i) = k_x (x_i - x)$$

$$\Rightarrow (y - y_i) = - \frac{k_x}{k_y} (x - x_i)$$



Determination of interfacial concentration



**Determination of interfacial concentrations
at different locations of the contactor**

Design Procedure Based on Overall Coefficients

$$N_A = K_G (p - p^*) = K_L (C^* - C) \quad \dots (13)$$

$$= K_y (y - y^*) = K_x (x^* - x) \quad \dots (14)$$

$$Z = \int_{y_2}^{y_1} \frac{G' dy}{P_t K_G a (1-y) (y - y^*)} = \int_{y_2}^{y_1} \frac{G' dy}{K_y a (1-y) (y - y^*)} \quad \dots (15)$$

Again, the above expression may be written as the product of two terms, one the height of transfer unit based on overall coefficient and the other the number of transfer unit based on overall driving force.

$$Z = \frac{G'}{K_y a (1-y)^*{}_M} \times \int_{y_2}^{y_1} \frac{(1-y)^*{}_M dy}{(1-y)(y - y^*)} \quad \dots (16)$$

$$\text{Where, } (1-y)^*{}_M = y_{BM}^* = \frac{(1-y^*) - (1-y)}{\ln[(1-y^*)/(1-y)]} \quad \dots (17)$$

$$Z = H_{tOG} \times N_{tOG} \quad \dots (18)$$

$$H_{tOG} = \frac{G'}{K_y a (1-y)^*{}_M} = \frac{G'}{K_y a y^*{}_{BM}} \quad \dots (19a)$$

For considerably large variation of gas flow rate over the column, an average value of it may be used as:

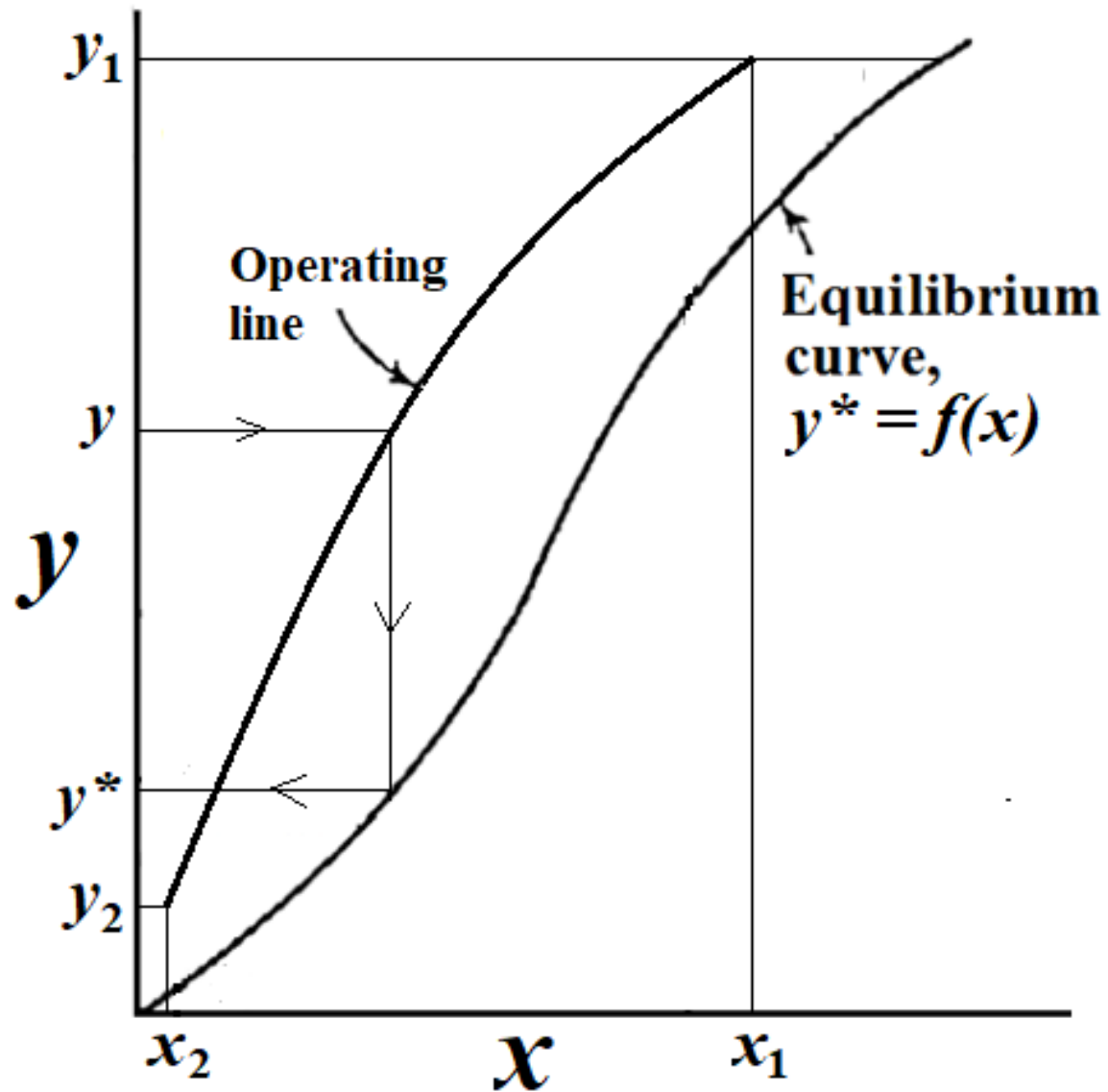
$$G' = (G_1' + G_2')/2.$$

Similarly, as $y^*{}_{BM}$ varies with height an average value is taken by calculating $y^*{}_{BM}$ at the bottom and top and taking the arithmetic average as: $y^*{}_{BM} = [(y^*{}_{BM})_1 + (y^*{}_{BM})_2]/2$.

$$N_{tOG} = \int_{y_2}^{y_1} \frac{(1-y)^*{}_M dy}{(1-y)(y-y^*)} \quad \dots (19b)$$

Similarly,

$$H_{tOL} = \frac{L'}{K_x a (1-x)^*{}_M} = \frac{L'}{K_x a x^*{}_{BM}} \quad \dots (19c) \quad N_{tOL} = \int_{x_2}^{x_1} \frac{(1-x)^*{}_M dx}{(1-x)(x^*-x)} \quad \dots (19d)$$



Determination of overall driving force

Simplified Design Procedure for Moderately Concentrated Gas

The expression for number of transfer unit on overall gas phase resistance basis is:


$$N_{tOG} = \int_{y_2}^{y_1} \frac{y^*_{BM} dy}{(1-y)(y-y^*)} \quad \dots (19b)$$

The above expression can be simplified by replacing log mean average with arithmetic average as:

$$(1-y)^*_M = y^*_{BM} = \frac{(1-y^*) + (1-y)}{2} = \frac{2(1-y) + (y-y^*)}{2}$$

Now, the expression for N_{tOG} becomes:

$$N_{tOG} = \frac{1}{2} \int_{y_2}^{y_1} \left[\frac{2(1-y)}{(1-y)(y-y^*)} + \frac{y-y^*}{(1-y)(y-y^*)} \right] dy = \int_{y_2}^{y_1} \frac{dy}{(y-y^*)} + \frac{1}{2} \int_{y_2}^{y_1} \frac{dy}{(1-y)}$$

 $N_{tOG} = \int_{y_2}^{y_1} \frac{dy}{(y-y^*)} + \frac{1}{2} \ln \left[\frac{(1-y_2)}{(1-y_1)} \right] \quad \dots (20a)$

The first integral has to be evaluated either graphically or numerically.

Similarly,

$$N_{tOL} = \int_{x_2}^{x_1} \frac{dx}{(x^*-x)} + \frac{1}{2} \ln \left[\frac{(1-x_2)}{(1-x_1)} \right] \quad \dots (20b)$$

Further Simplified Design Procedure for Lean Gas

In case of lean gas, it is easier to find out H_{tOG} .

In that case, $y^*_{BM} \simeq 1$ and the expression for H_{tOG} becomes

$$H_{tOG} = G'/K_y a.$$

Moreover, the gas flow rate is more or less constant throughout the tower for dilute gas so that $G' \simeq G_1' \simeq G_2' \simeq G_S'$.

Again, the expression for number of transfer unit can be further simplified as

$$N_{tOG} = \int_{y_2}^{y_1} \frac{dy}{y - y^*} \quad \dots (21)$$

If, however, the equilibrium line is linear (which very often occurs in low concentration range), then the expression for N_{tOG} becomes

$$N_{tOG} = \frac{y_1 - y_2}{(y - y^*)_M} \quad \dots (22)$$

$$\text{Where, } (y - y^*)_M = \frac{(y_1 - y_1^*) - (y_2 - y_2^*)}{\ln[(y_1 - y_1^*)/(y_2 - y_2^*)]} \quad \dots (23)$$

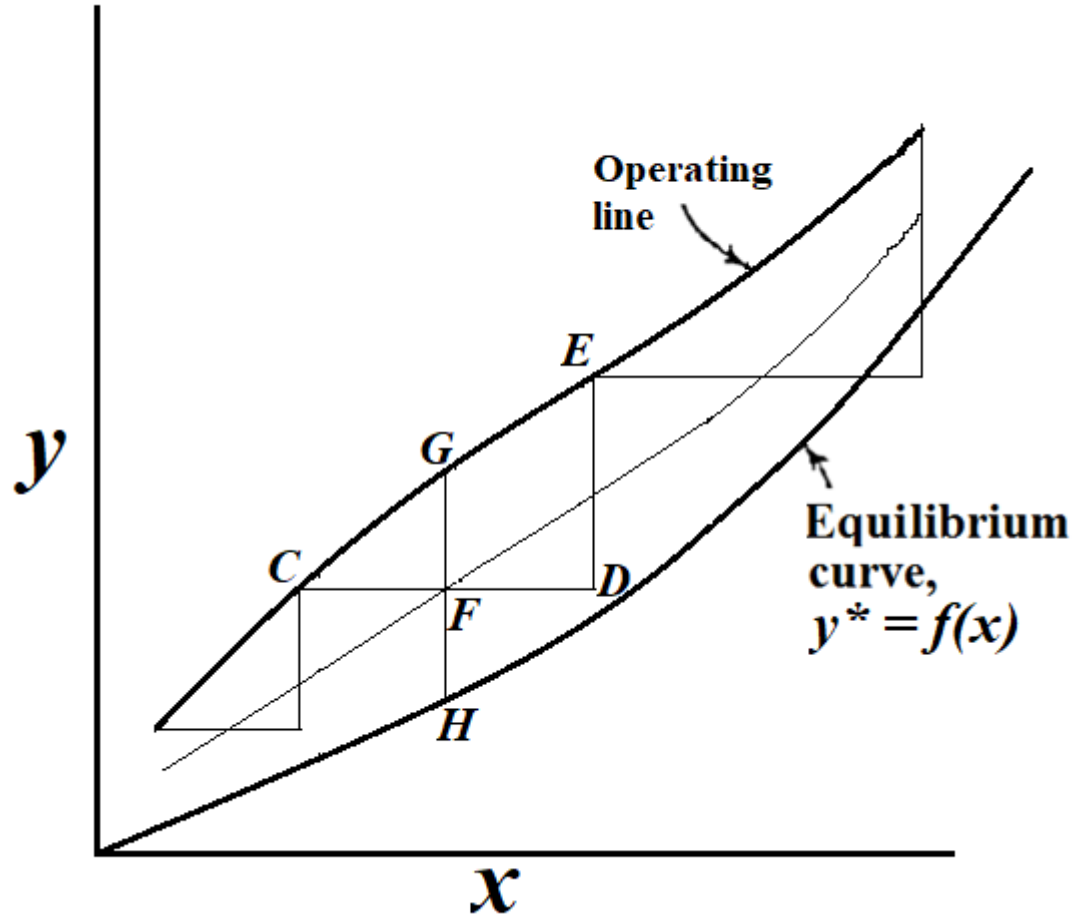
is the logarithmic average of the concentration differences at the ends of the tower.

Definition of Transfer Unit

$$N_{tOG} = \frac{y_1 - y_2}{(y - y^*)_M} \quad \dots (22)$$

A quantitative significance of N_{tOG} can be given from the above equation, applicable for dilute systems. In fact, this is considered as defining equation for transfer unit. In this equation, if we put $N_{tOG} = 1$, then $(y_1 - y_2) = (y - y^*)_M$, i.e., **Over a single transfer unit, the change in gas concentration is equal to the average driving force.**

Graphical Construction for Transfer Units

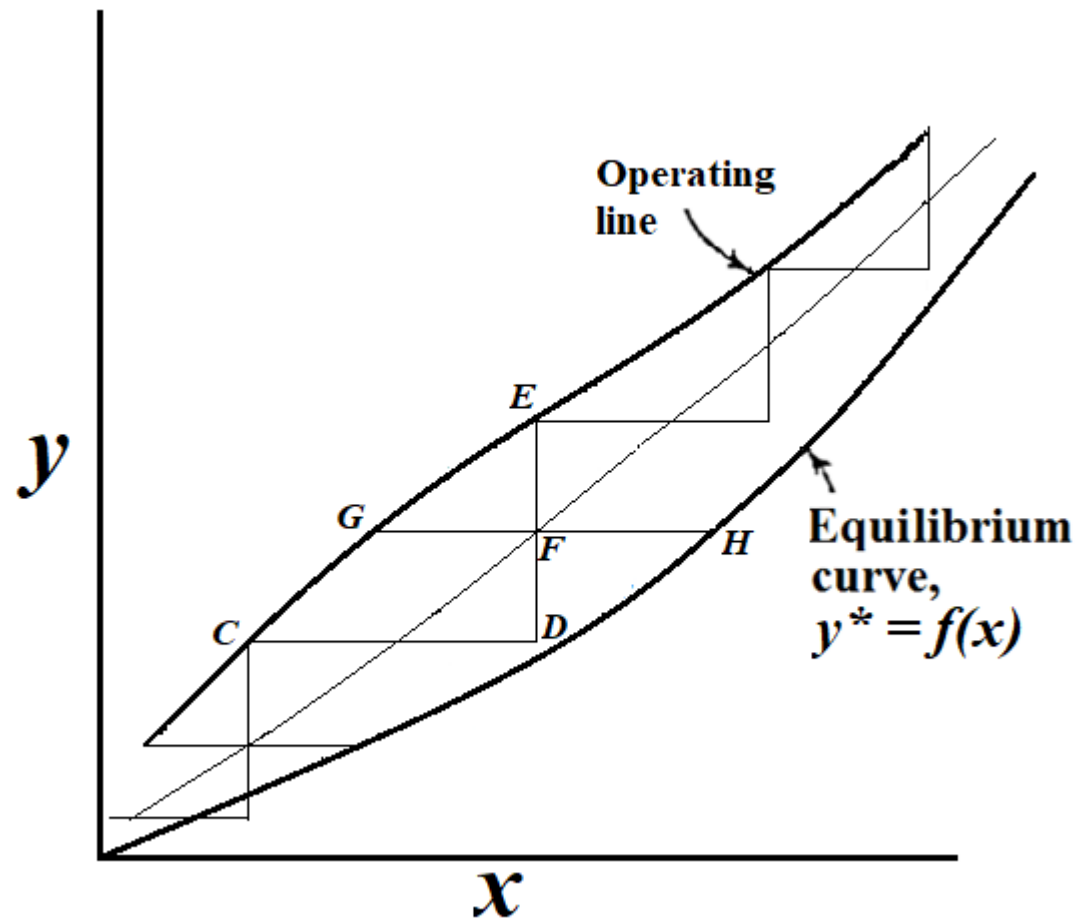


$$\triangle CFG \parallel \triangle CDE$$

$$ED/GF = CD/CF = 2$$

$$\Rightarrow ED = 2 GF = GH$$

Graphical determination of transfer units



$$\triangle CDE \parallel \triangle EFG$$

$$CD/GF = DE/EF = 2$$

$$\Rightarrow CD = 2 GF = GH$$

Graphical determination of N_{tOL}

Dilute Solutions

$$N_{tOG} = \int_{y_2}^{y_1} \frac{dy}{y - y^*} \quad \dots (21)$$

$$N_{tOG} = \int_{y_2}^{y_1} \frac{(1-y)^*_M dy}{(1-y)(y-y^*)} \quad \dots (19b)$$

If the equilibrium curve in terms of mole fractions is linear over the range of compositions x_1 to x_2 , then

$$y^* = mx + r. \quad \dots (24)$$

If the solutions are dilute, the operating lines can be considered as a straight line as well

$$y = \frac{L}{G}(x - x_2) + y_2 \quad \dots (25)$$

so that the driving force $(y - y^*)$ is linear in x

$$y - y^* = q x + s \quad \dots (26) \quad q = (L/G - m)$$

where q , r and s are constants.

$$s = y_2 - (L/G) x_2 - r$$

Therefore, equation (21) becomes

$$\begin{aligned} N_{tOG} &= \frac{L}{G} \int_{x_2}^{x_1} \frac{dx}{qx + s} = \frac{L}{Gq} \ln \frac{qx_1 + s}{qx_2 + s} = \left[\left(\frac{y_1 - y_2}{x_1 - x_2} \right) / \frac{(y_1 - y_2) - m(x_1 - x_2)}{(x_1 - x_2)} \right] \ln \left(\frac{y_1 - y_1^*}{y_2 - y_2^*} \right) \\ &= \frac{(y_1 - y_2)}{[y_1 - (mx_1 + r)] - [y_2 - (mx_2 + r)]} \ln \left(\frac{y_1 - y_1^*}{y_2 - y_2^*} \right) = \frac{y_1 - y_2}{(y_1 - y_1^*) - (y_2 - y_2^*) / \ln \left(\frac{y_1 - y_1^*}{y_2 - y_2^*} \right)} \\ \Rightarrow N_{tOG} &= \frac{y_1 - y_2}{(y - y^*)_M} \quad \dots (22) \end{aligned}$$

Dilute Solutions, Henry's Law

$$N_{tOG} = \int_{y_2}^{y_1} \frac{dy}{y - y^*} \quad \dots (21)$$

If Henry's law applies, then r in equation (24) is zero so that the equilibrium line becomes

$$y^* = m x \quad \dots (28)$$

The equation of the operating line is: $y = \frac{L}{G}(x - x_2) + y_2 \quad \dots (25)$

Eliminating x from equations (25) and (28) and substituting y^* in equation (21), we get

$$\begin{aligned} y &= \frac{L}{G} \left(\frac{y^*}{m} - x_2 \right) + y_2 \\ \Rightarrow y &= \frac{L}{mG} (y^* - m x_2) + y_2 = A(y^* - m x_2) + y_2 \\ \Rightarrow y^* &= \frac{1}{A} (y - y_2) + m x_2 \quad \dots (29) \end{aligned}$$

Where, $A = L/mG$ is the absorption factor, in case of absorber.

Now, substituting y^* in equation (21)

$$\begin{aligned}
 N_{tOG} &= \int_{y_2}^{y_1} \frac{dy}{y - \frac{1}{A}(y - y_2) - m x_2} = \int_{y_2}^{y_1} \frac{dy}{(1 - \frac{1}{A})y + (\frac{y_2}{A} - m x_2)} \\
 &= \frac{1}{1 - \frac{1}{A}} \ln \left[\frac{(1 - \frac{1}{A})y_1 + (\frac{y_2}{A} - m x_2)}{(1 - \frac{1}{A})y_2 + (\frac{y_2}{A} - m x_2)} \right] \\
 &= \frac{1}{1 - \frac{1}{A}} \ln \frac{(y_1 - m x_2) - \frac{1}{A}(y_1 - m x_2) + \frac{1}{A}(y_2 - m x_2)}{y_2 - m x_2} \\
 &= \frac{1}{1 - \frac{1}{A}} \ln \left[\frac{y_1 - m x_2}{y_2 - m x_2} (1 - \frac{1}{A}) + \frac{1}{A} \right] \\
 \Rightarrow N_{tOG} &= \frac{A}{A - 1} \ln \left[\frac{y_1 - m x_2}{y_2 - m x_2} (1 - \frac{1}{A}) + \frac{1}{A} \right] \quad \dots (30)
 \end{aligned}$$

For strippers, the corresponding expression for N_{tOL} is similar.

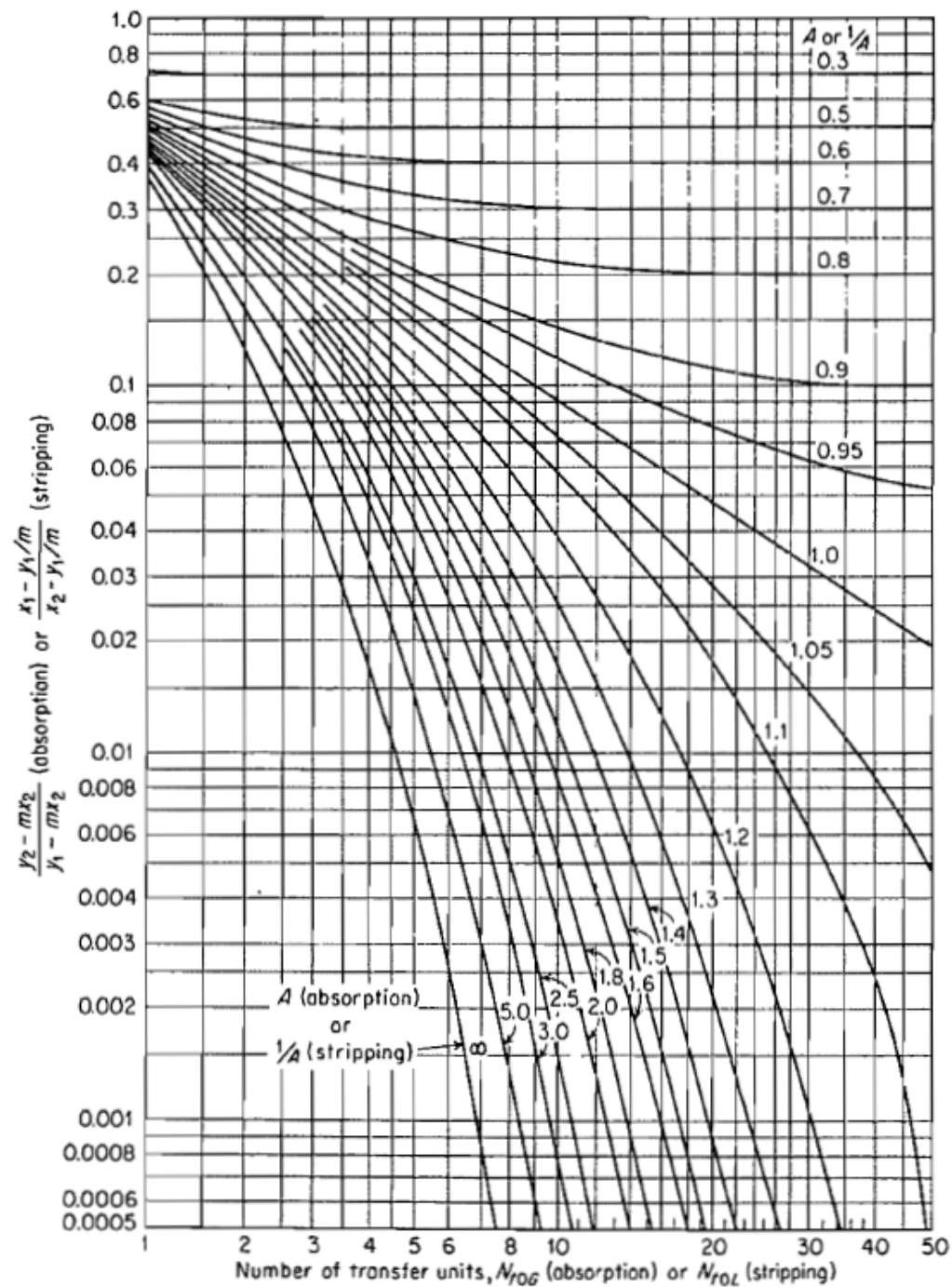
$$N_{tOL} = \frac{S}{S-1} \ln \left[\frac{x_2 - y_1 / m}{x_1 - y_1 / m} \left(1 - \frac{1}{S}\right) + \frac{1}{S} \right] \dots (31a)$$

$$N_{tOL} = \frac{1}{1-A} \ln \left[\frac{x_2 - y_1 / m}{x_1 - y_1 / m} (1-A) + A \right] \dots (31b)$$

For solutions and cases where Henry's law applies, prove that the number of overall liquid phase transfer units for counter-current desorption in packed towers is given by

$$N_{tOL} = \frac{1}{1-A} \ln \left[\frac{x_2 - y_1 / m}{x_1 - y_1 / m} (1-A) + A \right]$$

where the notations have their usual meanings.



Number of transfer units for absorbers or strippers with constant absorption or stripping factor

Overall Heights of Transfer Units

When overall number of transfer units are appropriate, the overall heights of transfer units can be synthesized from those for the individual phases through the relationship between overall transfer coefficients and individual transfer coefficients as follows:

$$H_{tOG} = \frac{G'}{K_y a y_{BM}^*} = \frac{G'}{y_{BM}^*} \left[\frac{1}{k_y a} + \frac{m}{k_x a} \right] = \frac{G'}{k_y a y_{BM} y_{BM}^*} + \frac{mG'}{L'} \frac{L'}{k_x a x_{BM} y_{BM}^*}$$

$$\Rightarrow H_{tOG} = H_{tG} \frac{y_{BM}}{y_{BM}^*} + \frac{mG'}{L'} H_{tL} \frac{x_{BM}}{y_{BM}^*} \quad \dots (32)$$

And,

$$\frac{1}{N_{tOG}} = \frac{1}{N_{tG}} \frac{y_{BM}}{y_{BM}^*} + \frac{mG'}{L'} \frac{1}{N_{tL}} \frac{x_{BM}}{y_{BM}^*} \quad \dots (33)$$

If the mass transfer resistance is essentially all in the gas, $y_i \approx y^*$, and

$$H_{tOG} = H_{tG} + \frac{mG'}{L'} H_{tL} \frac{x_{BM}}{y_{BM}^*} \quad \dots (34)$$

and, for dilute solutions, the concentration ratio of the last equation can be dropped so as to yield

$$H_{tOG} = H_{tG} + \frac{mG'}{L'} H_{tL} \quad \dots (35)$$

and

$$\frac{1}{N_{tOG}} = \frac{1}{N_{tG}} + \frac{mG'}{L'} \frac{1}{N_{tL}} \quad \dots (36)$$

In similar fashion, use of liquid phase overall coefficient yields

$$H_{tOL} = H_{tL} \frac{x_{BM}}{x_{BM}^*} + \frac{L'}{mG'} H_{tG} \frac{y_{BM}}{x_{BM}^*} \quad \dots (37)$$

and

$$\frac{1}{N_{tOL}} = \frac{1}{N_{tL}} \frac{y_{BM}}{y_{BM}^*} + \frac{mG'}{L'} \frac{1}{N_{tG}} \frac{x_{BM}}{y_{BM}^*} \quad \dots (38)$$

If the mass transfer resistance is essentially all in the liquid, $x_i \approx x^*$, and

$$H_{tOL} = H_{tL} + \frac{L'}{mG'} H_{tG} \frac{y_{BM}}{x_{BM}^*} \quad \dots (39)$$

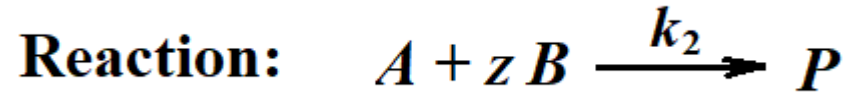
The concentration ratio of the last can be dropped for dilute solutions so that

$$H_{tOL} = H_{tL} + \frac{L'}{mG'} H_{tG} \quad \dots (40)$$

and

$$\frac{1}{N_{tOL}} = \frac{1}{N_{tL}} + \frac{L'}{mG'} \frac{1}{N_{tG}} \quad \dots (41)$$

Absorption with Chemical Reaction



Regime – 1: Very Slow Reaction

Regime – 2: Slow Reaction

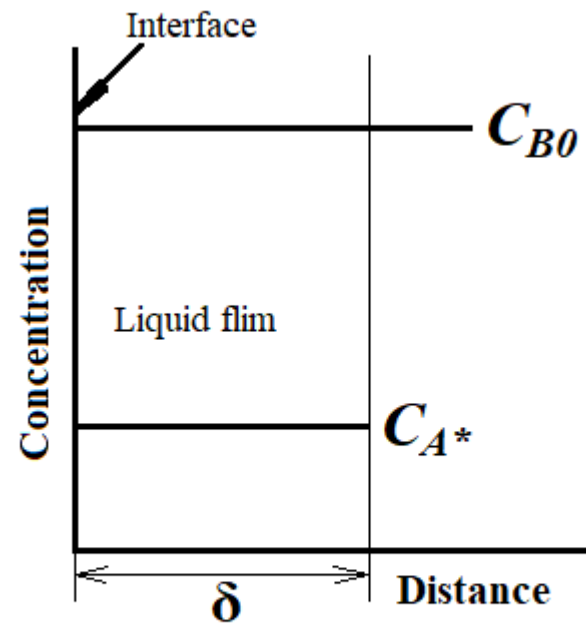
Regime – 3: Fast Reaction

Regime – 4: Instantaneous Reaction

Regime – 1: Very Slow Reaction

Rate of Absorption: $R_A a = l k_2 C_{B0} C_{A^*}$

Condition: $k_L a \gg l k_2 C_{B0}$



Concentration profiles in the liquid

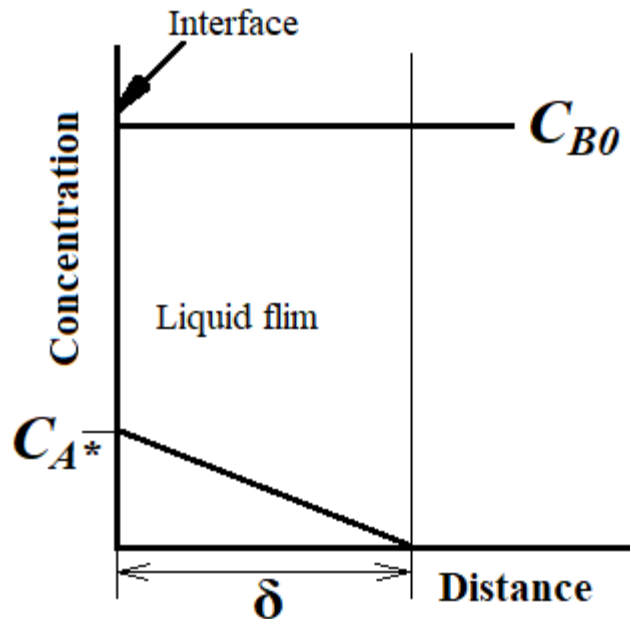
Regime – 2: Slow Reaction

Rate of Absorption: $R_A a = k_L a C_{A^*}$

Condition: $k_L a \ll l k_2 C_{B0}$

For no reaction within the film : $\sqrt{M} = \frac{\sqrt{D_A k_2 C_{B0}}}{k_L} \ll 1$

Hatta No.: $Ha = \frac{\sqrt{D_A k_2 C_{B0}}}{k_L}$

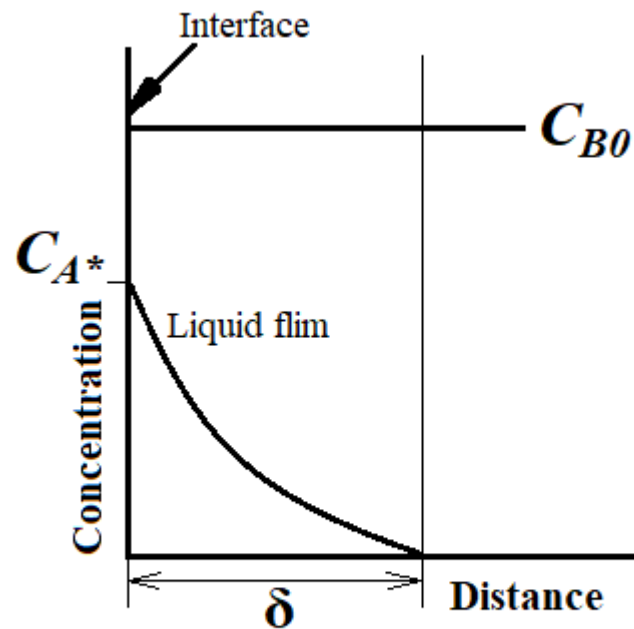


Concentration profiles in the liquid

Regime – 3: Fast Reaction

Rate of Absorption: $R_A a = k_L a C_{A^*} \frac{\sqrt{M}}{\tanh \sqrt{M}}$

Condition: $\sqrt{M} > 3$

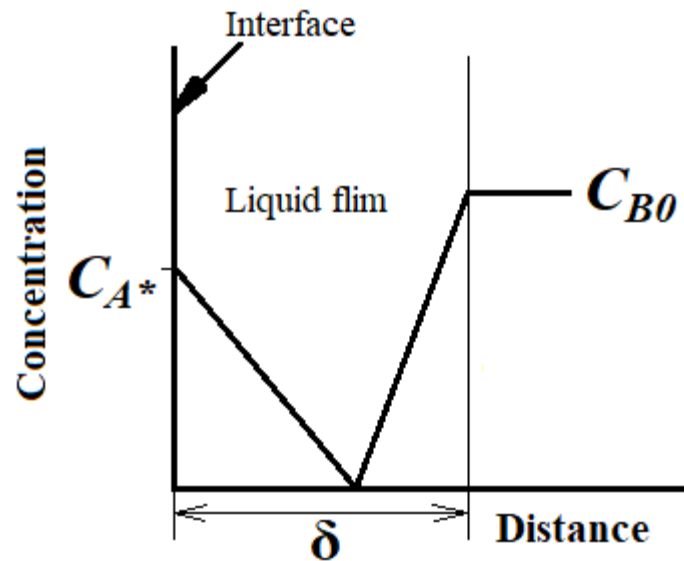


Concentration profiles in the liquid

Regime – 4: Instantaneous Reaction

Rate of Absorption: $R_A a = k_L a C_{A^*} \left[1 + \frac{D_B C_{B0}}{z D_A C_{A^*}} \right]$

Condition: $\sqrt{M} \gg \underbrace{\left[1 + \frac{D_B C_{B0}}{z D_A C_{A^*}} \right]}_q$



Concentration profiles in the liquid

Heterogeneous Reactions (Vol. II)

- L K Doraiswamy & M M Sharma

Gas- Liquid Reactions – P V Danckwerts

Thank you!