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CHEMICAL ENGINEERING

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MASS TRANSFER

MASS TRANSFER

CHEMICAL: GATE & PSUS



CHEMICAL ENGINEERING

REVISED AS PER NEW GATE Syllabus

STUDY MATERIAL

MASS TRANSFER-MT

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Mass Transfer-MT : Marking Analysis in GATE (2000 to 2024)

Year	1 Mark	2 Marks	Total Marks
2024	1 × 3	2 × 5	13
2023	1 × 3	2 × 3	9
2022	1 × 4	2 × 3	10
2021	1 × 2	2 × 4	10
2020	1 × 2	2 × 6	14
2019	1 × 4	2 × 4	12
2018	1 × 3	2 × 5	13
2017	1 × 3	2 × 4	11
2016	1 × 3	2 × 3	9
2015	1 × 4	2 × 4	12
2014	1 × 4	2 × 3	10
2013	1 × 2	2 × 5	12
2012	1 × 2	2 × 4	10
2011	1 × 2	2 × 3	8
2010	1 × 1	2 × 4	9
2009	1 × 0	2 × 2	4
2008	1 × 2	2 × 10	21
2007	1 × 1	2 × 7	15
2006	1 × 1	2 × 9	19
2005	1 × 4	2 × 4	12
2004	1 × 5	2 × 7	19
2003	1 × 3	2 × 8	19
2002	1 × 2	2 × 2	6
2001	1 × 3	2 × 6	9
2000	1 × 4	2 × 2	8

List of Topics in GATE 2024 paper from Mass Transfer-MT













Diffusion, (VLE), Mass Transfer Equipments, Absorption, Diffusion of Species Through Stagnant Medium, Distillation column, Drying, Design of Plate column.

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CHAPTER-1**INTRODUCTION**

The process of mass transfer occurs due to concentration difference of mixture components. It occurs from a region of higher concentration to a region of lower concentration. Concentration difference is the pillar of mass transfer. Various separation techniques such as distillation, gas adsorption, liquid extraction, drying, crystallization, etc. are studied in Mass transfer, where operation may occur isothermally or non-isothermally. Mass transfer operation may occur simultaneously with heat transfer, for example; Drying, Humidification, Distillation, crystallization etc. Mass transfer operation may occur in one direction example, gas absorption. The contacting can be done in six ways namely, Gas-Gas, Gas-Liquid, Gas-solid, Liquid-Liquid and Liquid-Solid and Solid-Solid.

- (a) Liquid-Vapour → Distillation.
- (b) Liquid-gas → Gas absorption, stripping, Humidification and Dehumidification.
- (c) Liquid-Solid → Crystallization, Leaching, Adsorption.
- (d) Liquid- Liquid → Extraction.
- (e) Solid-Gas → Adsorption, Drying.

Examples :

Liquid –Gas : Separation of NH_3 from liquid gas ($\text{NH}_3 + \text{Air}$) mixture separation with water (C).
(A) (B)

Liquid-solid : Separation of colour from, ($\text{Colour} + \text{Water}$) mixture with activated carbon (C).
(A) (B)

Liquid-liquid : Separation of Benzene from (Reformed Naptha) using sulfonate (C) as solvent.

Solid gas : Separation of removal of smell from ($\text{Air} + \text{Smell}$) mixture using silica gel (C).
(B) (A)

In practical application as a chemical engineer we separate substance (A) from mixture of substance (A) and (B) using substance (C) with the help of mass transfer.

The equilibrium between phases is attained after sufficiently long time. Since Mass transfer occurs due to both molecular diffusion and turbulence, the detailed study of factors affecting mass transfer is studied. At the phase interface there is no resistance due to thermodynamic equilibrium (T, P, μ_i) at interface. Rate of mass transfer is measured by deviation from equilibrium i.e. higher the deviation, higher is the driving force.

1.1. Some Important Definitions:

1) Distillation:

Distillation is a vapour-liquid operation in which the mixture components are separated by use of thermal energy. When liquid mixture is heated, different components exert different vapour pressure, expressed in terms of relative volatility. This pressure difference results in separation of components in such a way that the top product contains higher amount of light component and bottom products contains higher amounts of heavier component, as shown in figure 1.1. A distillation example is separation of crude petroleum into gasoline, kerosene, etc.

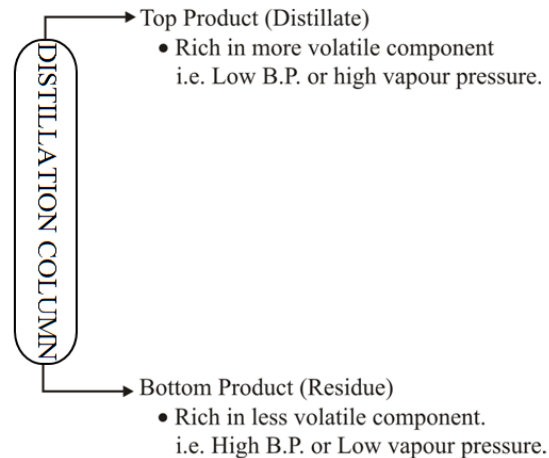


Fig. 1.1. Schematic diagram of a distillation column

2) Absorption and Stripping:

Gas absorption is a gas-liquid operation in which one or more constituents of a gas mixture are separated by using a suitable liquid solvent i.e. component moves from gas phase to liquid phase as shown in figure 1.2. Example of gas absorption methods is ammonia washing from ammonia-air mixture by means of water. Stripping is opposite of absorption i.e. a component moves from liquid phase to gas phase.

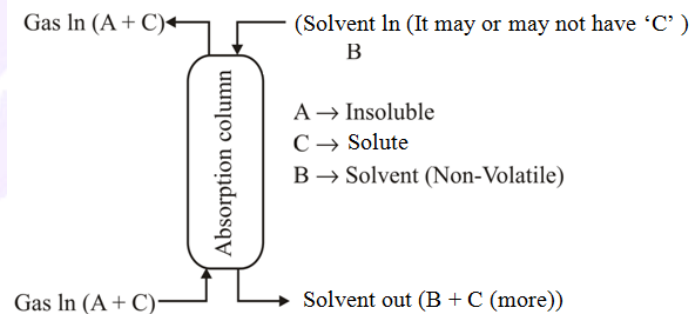


Fig. 1.2. Schematic diagram of an absorption column

3) Liquid-Liquid Extraction:

It is a liquid-liquid operation, also called as solvent extraction, in which components of a liquid mixture are separated by treating it with suitable solvent which dissolves one or more constituents of mixture more preferably. It is an efficient separation process in cases where separation is either not possible or not economical by using distillation eg. Separation of components of an azeotropic mixture.

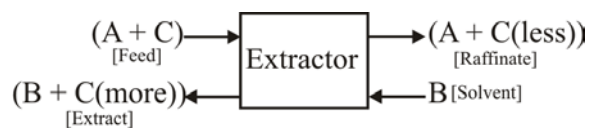


Fig. 1.3. Schematic diagram of a Liquid-Liquid Extractor

CHAPTER-2

DIFFUSION

The word diffusion is derived from the Latin word, “diffundere” which means “to spread out”. **Diffusion** is the movement of an individual component through a mixture from a region of higher concentration to lower concentration under the influence of a physical stimulus (such as concentration, activity, pressure and temperature gradients). Concentration and pressure gradients are the major driving forces. It may occur with or without the help of an external force. **Molecular diffusion** is a slow process, which occurs due to random movement of molecules (in stationary fluid and in laminar flowing fluid), while **Convective mass transfer** is a fast process, which occurs due to external force. Eddy diffusion is mechanism in turbulent flow. In all mass transfer operations, diffusion takes place in one or more phases. A distinguishing feature of diffusion is that it results in mixing or mass transport, without requiring bulk motion (bulk flow). Thus diffusion should not be confused with convection or advections, which are other transport phenomena that utilize bulk motion to move particles from one place to another. The driving force of molecular diffusion is concentration difference.

2.1. Molecular Diffusion

Fick's 1st law of diffusion (Adolf Fick – 1955)

Assumption: Constant (Temperature and Pressure)

Isobaric and Isothermal Binary system of component A and B.

“The molar flux of a species relative to an observer moving with molar average velocity is proportional to the concentration gradient of that species in that direction.”

$$J_{AZ} \propto \frac{dC_A}{dZ}$$

Where J_A molar flux of A with respect to an observer moving with bulk velocity in z direction.

c_A = concentration of A [kmol/m³]

$\frac{dc_A}{dz}$ = Concentration gradient in z direction

D_{AB} = proportionality constant known as molecule diffusivity or diffusion coefficient, (m²/sec)

z = Distance in the direction of diffusion, (m)

“-ve” sign shows that diffusion occur in the direction of decreasing concentration.

Diffusivity:

Diffusivity is defined as the ratio of the flux to the corresponding concentration gradient. It is denoted by ‘D’. Unit of diffusivity is m²/sec. It is a characteristic of the constituent and its environment (temperature, pressure, solution type i.e. whether gas, liquid or solid solution). It is a measure of its diffusive mobility. Let D_{AB} = Diffusive mobility of A in mixture of A and B.

Then, D_{BA} = Diffusive mobility of B in mixture of A and B.

Unit of diffusivity (m²/sec)

Significance: $(m \times m / sec) = (\text{Mean free path travelled by molecules} \times \text{Velocity})$

Hence if velocity increases or the mean free path travelled by molecules increases the diffusivity also increases.

2.2. Molecular Diffusion in Gases:

Flux for diffusion of A through non diffusing B.

Fundamental equation of mass transfer,

$$N_A = N_T x_A + J_A$$

Where, $(N_T = N_A + N_B)$

Flux for diffusion of A through non diffusing B.

Assumptions :

- (i) Steady state MT
- (ii) Isothermal and Isobaric condition
- (iii) Constant area of diffusion.
- (iv) No chemical reaction occurs

$$N_A \neq f(Z, r)$$

From general fundamental equation of Mass transfer,

$$N_A = N_T x_A + J_A$$

$$\int_{Z_1}^{Z_2} N_A D_Z = -D_{AB} C_T \int_{x_{A1}}^{x_{A2}} \frac{dx_A}{(1-x_A)}$$

$$N_A (Z_2 - Z_1) = -D_{AB} C_T \ln(1-x_A) \Big|_{x_{A1}}^{x_{A2}}$$

$$N_A (Z_2 - Z_1) = D_{AB} C_T \ln \left(\frac{1-x_{A2}}{1-x_{A1}} \right)$$

$$N_A = \frac{D_{AB} C_T}{(Z_2 - Z_1)} \ln \left(\frac{1-x_{A2}}{1-x_{A1}} \right)$$

Now, $(Z_2 - Z_1 = Z)$

→ **For Liquid Mole Fraction**

$$N_A = \frac{D_{AB} C_T}{Z} \ln \left(\frac{1-x_{A2}}{1-x_{A1}} \right)$$

→ **For Gaseous Mole Fraction,** $C_T = \frac{P_T}{R_T}$

$$N_A = \frac{D_{AB} P_T}{RTZ} \ln \left(\frac{1-y_{A2}}{1-y_{A1}} \right)$$

Summary Diffusion

Diffusion understanding by examples:

- Fragrance of bunch of roses and perfume reaches out to a person.
- A drop of ink released in water gradually spreads to make the water uniformly colored.
- The two modes of mass transfer are
 - Molecular diffusion.
 - Convective mass transfer.
- Fick's law of diffusion:

$$J_A = -CD_{AB} \frac{dx_A}{dz}$$

- For Binary mixture

$$N_A = \frac{N_A}{N_A + N_B} \frac{D_{AB}C}{z} \ln \frac{\frac{N_A}{(N_A + N_B)} - \frac{C_{A2}}{C}}{\frac{N_A}{(N_A + N_B)} - \frac{C_{A1}}{C}}$$

- For gases

$$N_A = \frac{N_A}{N_A + N_B} \frac{D_{AB}P_t}{RTz} \ln \frac{\frac{N_A}{(N_A + N_B)} - y_{A2}}{\frac{N_A}{(N_A + N_B)} - y_{A1}}$$

Questions and solutions

Q.1: In a binary gas-liquid system, $N_{A,EMD}$ is the molar flux of a gas A for equimolar counter diffusion with a liquid B. $N_{A,UMD}$ is the molar flux of A for steady one-component diffusion through stagnant B. Using the mole fraction of A in the bulk of the gas phase as 0.2 and that at the gas-liquid interface as 0.1 for both the modes of diffusion, the ratio of $N_{A,UMD}$ to $N_{A,EMD}$ is equal to _____ (rounded off to two decimal places). **GATE-2023: (2-Marks)**

Answer: 1.17

For S.S equimolar counter diffusion

$$N_{A,EMD} = \frac{D_{AB}S_m}{Z}(y_{A1} - y_{A2}) \quad \dots(1)$$

For S.S diffusion of A through stagnant B

$$N_{A,UMD} = \frac{D_{AB}S_m}{Zy_{B,m}}(y_{A1} - y_{A2}) \quad \dots(2)$$

$$\therefore \frac{N_{A,UMD}}{N_{A,EMD}} = \frac{1}{y_{B,m}} = \frac{\ln(y_{B1}/y_{B2})}{y_{B1} - y_{B2}}$$

Given, $y_{B1} = 1 - 0.2 = 0.8$

$y_{B2} = 1 - 0.1 = 0.9$

$$\therefore \frac{N_{A,UMB}}{N_{A,EMD}} = \frac{\ln(0.8/0.9)}{0.8-0.9} = 1.176$$

Q.2: Consider two stationary spherical pure water droplets of diameters d_1 and $2d_1$. CO_2 diffuses into the droplets from the surroundings. If the rate of diffusion of CO_2 into the smaller droplet is $W_1 \text{ mol s}^{-1}$, the rate of diffusion of CO_2 into the larger droplet is

- (A) W_1
 (B) $4W_1$
 (C) $0.5W_1$
 (D) $2W_1$

GATE-2022: (2-Marks)

Answer: B

Example:

Rate of diffusion for spherical droplets are given by

$$W_i \propto r_i^2 \text{ or } W_i \propto d_i^2$$

$$\frac{W_1}{W_2} = \left(\frac{d_1}{d_2}\right)^2 \Rightarrow \frac{W_1}{W_2} = \left(\frac{d_1}{2d_1}\right)^2$$

$$W_2 = 4W_1$$

Q.3: Consider steady-state diffusion in a binary A-B liquid at constant temperature and pressure. The mole-fraction of A at two different locations is 0.8 and 0.1. Let N_{A1} be the diffusive flux of A calculated assuming B to be non-diffusing, and N_{A2} be the diffusive flux of A calculated assuming equimolar counter-diffusion. The quantity $\frac{(N_{A1} - N_{A2})}{N_{A1}} \times 100$ is _____ (rounded off to one decimal place).

GATE-2022: (2-Marks)

Answer: 53.45

Example:

For unicomponent diffusion of component A

$$N_{A1} = \frac{D_{AB}P}{RT_z} \ln\left(\frac{1-x_{A2}}{1-x_{A1}}\right)$$

$$N_{A1} = \frac{D_{AB}P}{RT_z} \ln\left(\frac{1-0.1}{1-0.8}\right)$$

For equimolar counter diffusion

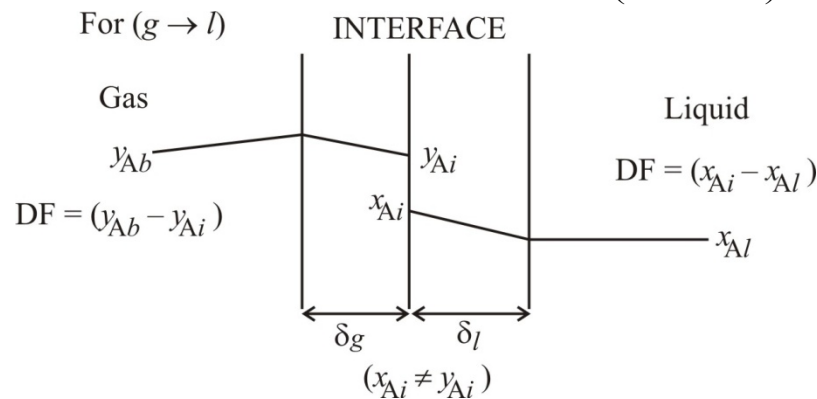
Chapter-3

INTER PHASE MASS TRANSFER

Inter Phase Mass Transfer (Two Film Theory)

→ It was first proposed by *Lewis and Whitman 1924*

For transfer of solute from ($g \rightarrow l$) phase known as absorption, $\begin{pmatrix} y_{Ab} > y_{Ai} \\ x_{Ai} > x_{Al} \end{pmatrix}$



y_{Ab} → Mole fraction of A in bulk gas

y_{Ai} → Mole fraction of A in interface (an gas side)

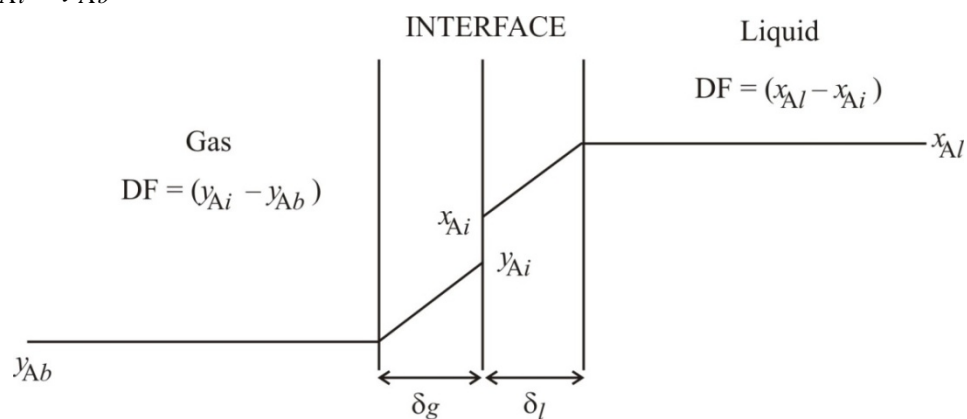
x_{Ai} → Mole fraction of A in interface (an liquid side)

x_{Al} → Mole fraction of A in bulk liquid

→ For transfer of solute from ($l \rightarrow g$) phase known as stripping

$$x_{Al} > x_{Ai}$$

$$y_{Ai} > y_{Ab}$$



Calculation of Flux:

→ Let's consider for absorption the same way may be used to write the formulas for stripping.

→ For Gas Side,

$$N_A = k_y (y_{Ab} - y_{Ai})$$

CASE – 2

If $(k_x \gg \gg k_y)$

Then $\left(\frac{1}{k_x} \ll \ll \frac{1}{k_y}\right)$

$$\frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x} \quad \left| \quad \frac{1}{K_x} = \frac{1}{k_x} + \frac{1}{m k_y} \right.$$

$$\frac{1}{K_y} = \frac{1}{k_y} \quad \left| \quad \frac{1}{K_x} = \frac{1}{m \cdot k_y} \right.$$

As, the overall resistance becomes equal to the gas resistance hence, gas side is controlling.

- Resistance is offered only by gas side and hence gas side controlling.
- Resistance offered by liquid side is negligible.
- Solute is highly soluble in liquid and also liquid has high solubility of solute.
- But gas side is not willing to transfer the solute to liquid.

CASE – 3

If $(m \ll \ll 1)$

- $m \rightarrow 0$
- Favourable condition for absorption

So, $\frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x} \quad \Rightarrow \quad \frac{1}{K_y} = \frac{1}{k_y} \quad \Rightarrow \quad \frac{1}{K_x} = \frac{1}{k_x} + \frac{1}{m k_y}$

As $m \rightarrow 0 \quad \Rightarrow \quad \frac{1}{m} \rightarrow \infty$

Hence, $\frac{1}{k_x}$ can be neglected as compared to $\frac{1}{m k_y}$

$$\frac{1}{k_x} = \frac{1}{m k_y}$$

- As overall resistance becomes equal to gas side resistance hence gas side controlling.

CASE – 4

If $(m \gg \gg 1)$

- $m \rightarrow \infty$
- Favourable condition for stripping.

So, $\frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x}$

As $m \rightarrow \infty$ hence we can neglect $\frac{1}{k_y}$ as compared to $\frac{m}{k_x}$.

$$\frac{1}{K_y} = \frac{m}{k_x}$$

$$\frac{1}{K_x} = \frac{1}{k_x} + \frac{1}{m k_y}$$

As $m \rightarrow \infty \Rightarrow \frac{1}{m} \rightarrow 0$, hence we can neglect $\frac{1}{m k_y}$ as compared to $\frac{1}{k_x}$.

$$\frac{1}{K_x} = \frac{1}{k_x}$$

As overall resistance becomes equal to liquid side hence, liquid side as controlling.

Question: Consider interphase mass transfer of a species S between two immiscible liquids A and B. The interfacial mass transfer coefficient of S in liquid A is twice of that in liquid B. The equilibrium distribution of S between the liquids is given by $y_S^A = 0.5y_S^B$, where y_S^A and y_S^B are the mole-fractions of S in A and B, respectively. The bulk phase mole-fraction of S in A and B is 0.10 and 0.02, respectively. If the steady-state flux of S is estimated to be $10 \text{ kmol h}^{-1} \text{ m}^{-2}$, the mass transfer coefficient of S in A is _____ $\text{kmol h}^{-1} \text{ m}^{-2}$ (rounded off to one decimal place).

Answer: 222.22

(GATE-2022: 2-Marks)

Example:

$$y_{S1}^A = 0.10$$

$$y_{S1}^B = 0.02$$

$$y_s^A = 0.5 y_s^B$$

$$k_{y_s}^A = 2k_{y_s}^B$$

$$N = 10 \text{ kmol/h}^{-1} \text{ m}^2$$

$$K_y = ?$$

$$\frac{1}{K_y} = \frac{1}{k_{y_s}^A} + \frac{m}{k_{y_s}^B}$$

$$\frac{1}{K_y} = \frac{1}{k_{y_s}^A} + \frac{0.5}{k_{y_s}^B} \quad \dots(1) \quad [m = 0.5]$$

And

$$N = K_y (y - y_s^A)$$

$$10 = K_y (0.10 - 0.01) \quad [y_s^A = 0.5 \times 0.02] = 0.01$$

$$\text{or, } 10 = K_y = 111.11 \quad \dots(2)$$

from (1) and (2)

$$\frac{1}{111.11} = \frac{1}{k_{y_s}^A} + \frac{0.5}{0.5k_{y_s}^A}$$

$$\frac{1}{111.11} = \frac{2}{k_{y_s}^A} \Rightarrow k_{y_s}^A = 222.22 \frac{\text{kmol}}{\text{hr.m}^2}$$

Chapter-4

Absorption and Stripping

Absorption is selective dissolution of one or more component (solute) of gas or vapour stream into a liquid (solvent). Stripping is exactly opposite of absorption. The transfer of a component from liquid phase, in which it is dissolved to a gas phase, also called desorption.

There are two methods for solutes desorption:

- (a.) Pressure reduction (b.) Temperature increase

4.1. CLASSIFICATION OF ABSORPTION:

Absorption is a process between a gaseous phase and liquid phase, which can be accompanied with or without chemical bonding. If the bonding between gaseous and liquid phase is simple van-der-walls force of attraction (i.e. the species are joined physically), then it is called physical absorption. Similarly, when the molecule of gases and liquid are attached by chemical bonds, it is called chemical absorption. In general the physical absorption is accompanied by release of a small of heat while, chemical absorption occurs with release of a comparatively large amount of heat.

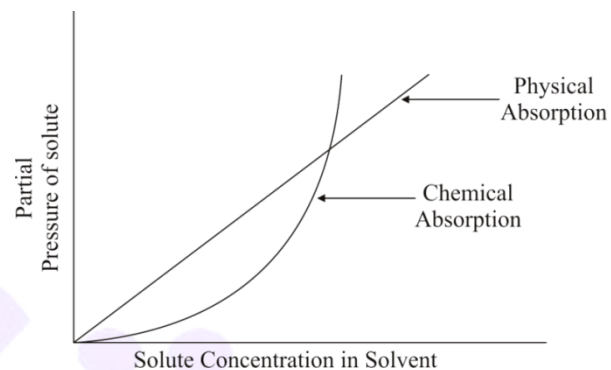


Fig.5.1. Effect of partial pressure of solute on absorption

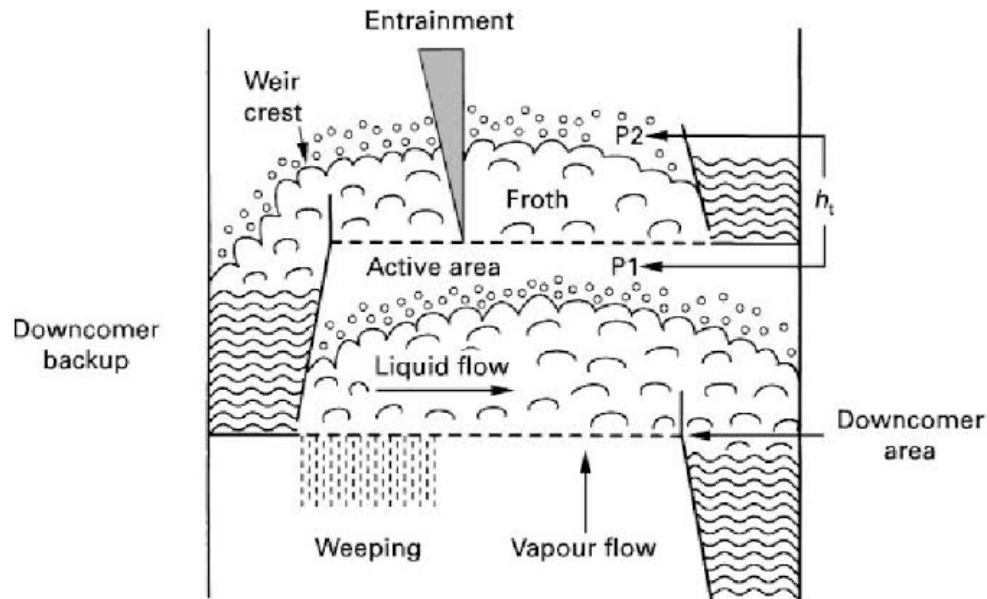
When the partial pressure of the component to be separated is high, physical absorption process are advantageous, while the case when solute have lower partial pressure, chemical absorption is advantageous as shown in fig. 5.1.

Difference between Physical and Chemical Absorption:

Physical absorption is characterized by the solvent and solute interaction which is linear over a range of partial pressure and concentration due to exothermic nature of absorption. It usually results in heating of solution. Thermal effects are usually order of 20 kcal/kmol. **Chemical absorption** is characterized by non-linear interaction and that weaken at higher concentration as that system become saturated. Chemical absorption systems often releases heat up to about 1000 kcal/kmol.

Absorption Processes are Desirable when

1. A small amount of high boiling component must be remove from vapour stream.
2. In case a feed stream cooled compressed or both cooled and compressed before its bubble point reached.
3. When a small amount of a component removed by an irreversible reaction with a solvent



- For liquid-gas combinations which tend to foam excessively, high gas velocity may lead to a condition of **priming**, is an inoperative situation.
- If liquid rates are too low the gas rising through the openings of the tray may push the liquid away **coning** and contact of the gas and liquid is poor.
- If the gas rate is too low, much of the liquid may rain down through the openings of tray **weeping** thus failing to obtain the benefit of complete flow over the trays, and at very low gas rates, none of liquid reaches the down spouts (**dumping**).

Summary

- Gas absorption is a mass transfer operation in which one or more species is removed from a gaseous stream by dissolution in a liquid.
- The reverse of absorption is stripping or desorption.
- The insoluble components present in the gas which is not absorbed is called carrier gas.
- Tray towers are vertical cylinders in which the liquid and gas are contacted in step wise fashion on tray or plates.
- Problems associated with tray towers are **Entrainment, High pressure drops, Priming, Flooding, Weeping / Dumping, Foaming, and Coning.**
- Packed height in packed tower is :

$$Z = H_{toG} \times N_{toG}$$

$$H_{toG} = \frac{G}{K_y a} (1-y)_M^*$$

$$N_{toG} = \int_{y_2}^{y_1} \frac{(1-y)_M^* dy}{(1-y)(y-y^*)}$$

For dilute gases

$$N_{toG} = \int_{y_1}^{y_2} \frac{dy}{y-y^*} = \frac{(y_1-y_2)}{(y-y^*)_m}$$

Questions and Solutions

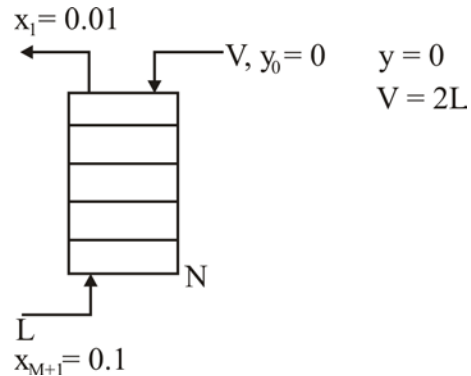
Question-1: A liquid L containing a dissolved gas S is stripped in a countercurrent operation using a pure carrier gas V. The liquid phase inlet and outlet mole fractions of S are 0.1 and 0.01, respectively. The equilibrium distribution of S between V and L is governed by $y_e = x_e$, where y_e and x_e are the mole fractions of S in V and L, respectively. The molar feed rate of the carrier gas stream is twice as that of the liquid stream. Under dilute solution conditions, the minimum number of ideal stages required is _____ (in integer). **(GATE-2023: 2-Marks)**

Answer: 3

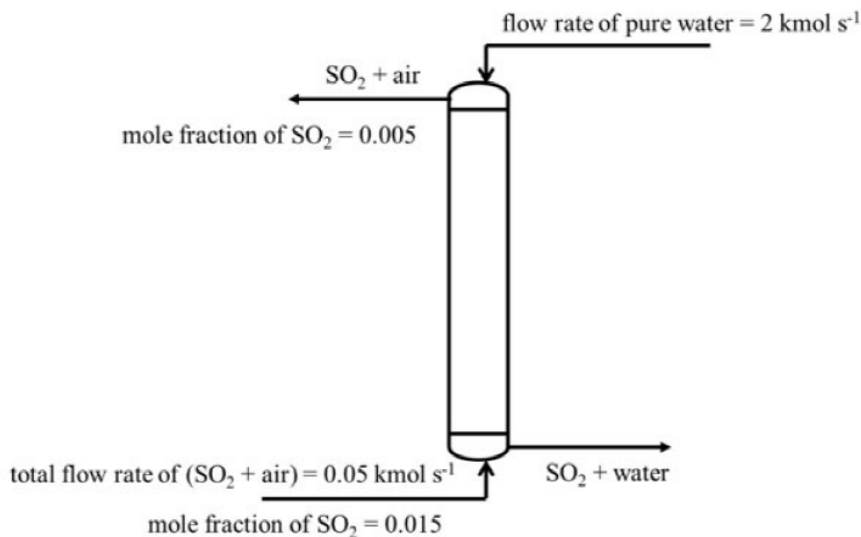
$$NTP = \frac{\ln \left[\left(\frac{x_{n+1} - \frac{y_0}{m}}{x_1 - \frac{y_0}{m}} \right) \left(1 - \frac{1}{S} \right) + \frac{1}{S} \right]}{\ln S}$$

Where $S = \frac{1}{A} = \frac{mV}{L} = \frac{1 \times 2L}{L} = 2$

$$NTP = \frac{\ln \left[\left(\frac{0.1 - 0}{0.01 - 0} \right) \left(1 - \frac{1}{2} \right) + \frac{1}{2} \right]}{\ln 2} = 2.4594 = 3.0$$



Question-2: SO₂ from air is absorbed by pure water in a counter current packed column operating at constant pressure. The composition and the flow rates of the streams are shown in the figure. **(GATE-2020 2-Marks)**



In addition, use the following data assumption

- Column operates under isothermal conditions
- At the operating temperature of the column, $y^* = 40x$, where y^* is the mole fraction of SO₂ in the gas that is in equilibrium with water containing SO₂ at a mole fraction of x



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TETALA MANI
SANDEEP REDDY

GATE 2021
7 Rank in Top 10



1
Rank

DHRUVAL KUMAR
THAKKAR

GATE 2020
10 Rank in Top 10



1
Rank

SACHIN

GATE 2019
9 Rank in Top 10



1
Rank

SHASHWAT
RAGHUVANSHI

GATE 2018
8 Rank in Top 10



1
Rank

PRASHANT
VARSHNEY

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