

Chemical Engineering (GATE & PSUs)

Postal Correspondence

GATE & Public Sectors

MASS TRANSFER

GATE 2015 Top Results

Chemical Engineering



1st Rank
Archhit Trichal



2nd Rank
Keval Pareta

GATE 2015 Result

Name	ARCHHIT TRICHAL	 <i>Archhit Trichal</i>			
Registration Number	CH8804151135				
Gender	Male				
Examination Paper	Chemical Engineering (CH)				
Marks out of 100 [†]	65.67	All India Rank in this paper	1		
Qualifying Marks ^{‡‡}	27.52 (General)	24.77 (OBC (NCL))	18.34 (SC/ST/PwD)	GATE Score	947

Highest Result in GATE 2015

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GATE 2014 Topper

Chemical Engineering



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GATE 2015 Cut-off Marks

BRANCH	GENERAL	SC/ST/PD	OBC(Non-Creamy)	Total Appeared
Chemical Engineering	27.52	18.34	24.77	15874

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SYLLABUS : Mass Transfer: Fick's laws, molecular diffusion in fluids, mass transfer coefficients, film, penetration and surface renewal theories; momentum, heat and mass transfer analogies; stagewise and continuous contacting and stage efficiencies; HTU & NTU concepts design and operation of equipment for distillation, absorption, leaching, liquid-liquid extraction, drying, humidification, dehumidification and adsorption.

CHAPTER-1

INTRODUCTION

- The process of mass transfer occurs due to concentration difference of mixture component is called mass transfer.
- Mass transfer occurs from a region of higher concentration to a region of lower concentration.
- In mass transfer operation driving force is concentration difference (Pillar of mass transfer).
- In mass transfer operation we study about separation techniques such as distillation, gas adsorption, liquid extraction, drying, crystallization etc.
- Mass transfer operation may occur isothermally and non-isothermally.
- Mass transfer operation may occur in opposite direction example distillation.
- 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.
- During mass transfer operation at least two phases must be in contact to each other.
- During mass transfer operation a part of total flow of material must occur by molecular diffusion.
- During mass transfer operation material should flow from one phase to other phase.
- Phase contact can be in six way → Gas-Gas, Gas-Liquid, Gas-solid, Liquid-Liquid and Liquid – Solid and Solid-Solid.
 - (a) Liquid-Vapour (gas) → 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.
- After sufficient long time equilibrium between phases is attained.
- Mass transfer occurs due to molecular diffusion and turbulence.
- At the phase interface there is no resistance due to thermodynamic (T, P, η_i) equilibrium at interface.
- Rate of mass transfer measures by deviation from equilibrium.

SOME IMPORTANT DEFINITION

- 1) **Distillation**: Distillation is a gas liquid operation. It is also called fractional distillation.
In distillation liquid mixture component are separated by use of thermal energy. Distillation occur due to vapour pressure different between difference component. A distillation example is separation of crude petroleum into gasoline, kerosene etc.

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- 2) **Gas absorption:** Gas absorption is a gas liquid operation. In gas absorption method one or more constituents of a gas mixture separated by suitable solvent. Example of gas absorption methods is ammonia washing from ammonia-air mixture by means of water.
- 3) **Liquid Liquid extraction:** It is a liquid-liquid operation. It is also called solvent extraction. In this method liquid mixture constituent is separated by treating it with suitable solvent preferably dissolve one or more constituents of mixture.
- 4) **Crystallization:** It is liquid solid operation. In this operation solid particle. In the operation of solid particles will appear within a homogeneous liquid phase. In crystallization method we obtain uniform crystal of good purity.
- 5) **Drying:** Drying is gas- solid operation. In drying operation relatively small amount of water remove from solid material.

IMPORTANT NOTES:

- (i) Ideal gas law :

$$PV = nRT$$

Where P=KPa, V= Volume(m³)

n =Kmol T= Temperature (K)

$$R = 8.31451 \frac{m^2 KPa}{Kmol.K} = \text{gas constant}$$

- (ii) **Vapour Pressure:** The vapour pressure of a liquid is defined as the absolute pressure at which the liquid and its vapour are in equilibrium at given temperature.
- (iii) **Partial Pressure:** The partial pressure of a gas component that is present in a gases mixture is a pressure that would be exerted by that component. If it alone were present in the same volume and at the same pressure.
- (iv) **Dalton's law:** Dalton's law mathematically is given by –

$$p = p_A + p_B + p_C + \dots$$

Where P is the total pressure exerted by gaseous mixture. p_A , p_B and p_C are the partial pressure of component gases A, B, C.

- (v) **More Volatile Component:** More volatile component is lower boiling point component or with higher vapor pressure at a given temperature. (In a binary system). It is also called as the lighter component.
- (vi) **Less Volatile Component:** In a binary system, it is the component with higher boiling point or lower vapor pressure at a given temperature. It is also called as the heavier component.

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DIMENSIONLESS NUMBER:

(1) Sherwood number (Sh)

$$S_h = \frac{KL}{D_{AB}} = \frac{\text{convective mass transport}}{\text{molecular mass transport}}$$

Where L is the characteristics length

(2) Schmidt Number (Sc)

$$S_c = \frac{\mu}{D_{AB}} = \frac{\text{Momentum diffusivity}}{\text{Mass diffusivity}}$$

(3) Prandtl Number (Pr)

$$P_r = \frac{C_p \mu}{K} = \frac{\text{Momentum diffusivity}}{\text{Thermal diffusivity}}$$

(4) Lewis Number (Le)

$$L_e = \frac{S_c}{P_r} = \frac{K}{D_{AB} C_p}$$



.....:SAMPLE:.....: PART ONLY:.....

CHAPTER-2

CONCEPT OF DIFFUSION:

- (1) Diffusion is the movement of an individual component through a mixture from a region of higher concentration to lower concentration at fixed temperature and pressure with or without help of an external force.
- (2) Concentration gradient is cause for diffusion. As the mixture become uniform by diffusion then concentration gradient will zero.
- (3) Diffusion due to random movement of molecule is called molecular diffusion.
- (4) When movement of molecule occurs due to external force example convective movement of fluid is called turbulent diffusion. It is also called eddy diffusion.
- (5) Molecular diffusion is a slow process while turbulent diffusion is fast process.
- (6) In stationary fluid, mechanism of mass transfer is molecular diffusion. Molecular diffusion is mechanism in Laminar flow.
- (7) Eddy diffusion is mechanism in turbulent flow.
- (8) In all mass transfer operation diffusion takes place in one phase or in both phase.

.....:SAMPLE:.....: PART ONLY:.....

CHAPTER-3 MOLECULAR DIFFUSION

In molecular diffusion process species are diffuse in one another due to random motion of molecules.

Mass Concentration:

It is the mass of species A per unit of mixture (solution). It is equal to density (ρ) of solution. It is also denoted by ρ_A .

ρ_A

For Binary system have component A and B mass density (ρ) of solution is given by-

$$\rho_A + \rho_B = \rho$$

MOLAR CONCENTRATION:

Molar concentration is defined as the number of moles of species A per unit volume of the solution. Mathematically, It is given as

$$C_A = \frac{m_A}{M_A V}$$

Where

M_A = molecular weight of component A units of molar concentration in SI system are Kmol/m^3

For a binary system of A and B, the total molar concentration of the solution is given by

$$C = C_A + C_B$$

Mass Fraction:

The mass fraction x_A of species A may be defined as the ratio of the mass concentration of species A to the mass density of the solution.

Mathematically, It can be given as

$$x_A = \frac{\rho_A}{\rho}$$

MOLE FRACTION : The mole fraction (x_A) of species A can be defined as the ratio of molar concentration of A to the molar concentration of the solution.

Mathematically

$$x_A = \frac{C_A}{C}$$

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Note: For a binary system,

$$x_A' + x_B' = 1$$

$$x_A + x_B = 1$$

Note:

- (i) In gas phase concentration are expressed in terms of partial pressure.
- (ii) In case of ideal gas

$$p_A V = n_A RT$$

$$C_A = \frac{n_A}{V} = \frac{p_A}{RT}$$

Where p_A is the partial pressure of species A in mixture

n_A = number of moles of A

V = molar volume of mixture

T = temperature (absolute)

R = universal gas constant

- (iii) x_A in terms of p_A is given as:

$$x_A = \frac{C_A}{C} = \frac{p_A/RT}{p/RT} = \frac{p_A}{p}$$

Where p is the total pressure exerted by the gas mixture.

- (iv)

$$C = C_A + C_B = \frac{p_A}{RT} + \frac{p_B}{RT} = \frac{p}{RT}$$

Velocity

- (i) Different chemical species are moving at different velocity in a diffusing mixture. The bulk velocity of the mixture would be some sort of an average velocity.
- (ii) For a mixture of n species local mass average velocity u is defined as

$$u = \frac{\sum_{i=1}^n u_i}{\sum_{i=1}^n 1}$$

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Where u^i is velocity of i^{th} species

(iii) In case of binary system

$$u = \frac{A u_A + B u_B}{C}$$

(iv) Local molar average velocity U of mixture is given by

$$U = \frac{\sum_{i=1}^n C_i u_i}{\sum_{i=1}^n C_i}$$

(v) In a binary system

$$U = \frac{C_A u_A + C_B u_B}{C}$$

SOME IMPORTANT DEFINITION :

(I) **Mass flow rate:**

It is the quantity of flow material. Unit is mass per time.

MOLAR FLOW RATE : It is quantity of flow material. Units is molar per time.

FLUX: Flux is vector quantity. The amount of species (mass or molar units) that crosses a unit area per unit time is called mass transfer flux of a species.

MASS FLUX: The mass flux of species i is defined as the mass of species i that pass through a unit area per unit time.

(i) Mass flux relative to fixed coordinate is given by,

$$n_i = u_i u_i$$

(ii) Mass flux relative to the mass average velocity u is given by,

$$j_i = \dots_i (u_i - u)$$

Molar Flux:

Molar flux is defined as moles of species i that passes through a unit area per unit time.

(i) Molar flux relative to the stationary coordinate is given by,

$$N_i = C_i u_i$$

(ii) Molar flux relative to molar average velocity U is given by,

$$J_i = C_i (u_i - U)$$

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Note:

For a binary system A and B following relationships are useful:

(i) The mass flux of A and B relative to stationary coordinate are-

$$n_A = \rho_A u_A$$

$$n_B = \rho_B u_B$$

(ii) The mass flux of A and B relative to mass average velocity are-

$$j_A = \rho_A (u_A - u)$$

$$j_B = \rho_B (u_B - u)$$

(iii) The molar fluxes of A and B with respect to stationary coordinates are-

$$N_A = C_A u_A$$

$$N_B = C_B u_B$$

(iv) The molar fluxes of A and B relative to molar average velocity U are:

$$J_A = C_A (u_A - U)$$

$$J_B = C_B (u_B - U)$$

J_A and J_B are diffusion flux of components A and B.

(v)

$$n_A = \rho_A u + j_A$$

$$n_A = \rho_A \left(\sum n_i + j_A \right)$$

(vi) $N_A = C_A U + J_A$

$$N_A = C_A \left(\sum N_i \right) + J_A$$

Molecular Diffusion

Fick's Law of Diffusion (Steady state)

(i) The flux of diffusing component A (diffusion flux of A) in z direction in a binary mixture of A and B is proportional to the molar concentration gradient.

(ii) Mathematically Fick's law is given by :

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$$J_A = -D_{AB} \frac{dC_A}{dz} \quad (\text{For binary mixture})$$

Where J_A is the molar flux of A in z direction.

C_A = concentration of A [Kmol/m^3]

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

D_{AB} is the proportionality constant, known as molecule diffusivity, (m^2/sec)

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

(iii) (-)ve sign show that diffusion occur in the direction of decreasing concentration.

DIFFUSIVITY:

- (i) Diffusivity is defined as the ratio of the flux to the corresponding concentration gradient. Units of diffusivity is m^2/sec .
- (ii) Diffusivity of any component is a measure of its diffusive mobility.
- (iii) Mathematical expression

$$N_A = J_A + x_A (N_A + N_B)$$

Where J_A = contribution due to concentration gradient, diffusion flux

$x_A(N_A + N_B)$ = Bulk motion contribution flux due to bulk flow

MOLECULAR DIFFUSION IN GASES:

1. Steady state equimolar counter diffusion :

For steady state diffusion of two ideal gases. Flux for an equal number of gas moles are diffusing counter current to each other is given by following relation

$$N_A = \frac{D_{AB}}{RTz} (p_{A1} - p_{A2})$$

Where,

N_A = molar flux of A ($\text{Kmol/m}^2\text{sec}$)

D_{AB} = Diffusivity of A in B (m^2sec)

$Z = (Z_2 - Z_1)$ = Distance through which diffusion occur in m.

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p_{A1} and p_{A2} are the partial pressure of component A at the starting diffusion path and at the end diffusion path respectively.

2. Steady state diffusion of A through non diffusion/stagnant B :

- (i) For the steady state diffusion of an ideal gas A through a stagnant gas B, the flux is given by

$$N_A = \frac{D_{AB} p}{RTZ p_{B,M}} (p_{A1} - p_{A2})$$

Where $p_{B,M}$ logarithm mean concentration of stagnant gas.

- (ii) Physical meaning of this equation is that flux is proportional to the concentration difference expressed in terms of partial pressure of A and inversely proportional to the distance Z and stagnant gas concentration ($p_{B,M}$).

MOLECULAR DIFFUSION IN LIQUID :

- (1) Steady state equimolar counter diffusion:

- (i) In this case,

$$N_A = -N_B = \text{constant}$$

- (ii) Flux equation for steady state equimolar counter diffusion is given by

$$N_A = \frac{D_{AB}}{Z} (C_{A1} - C_{A2})$$

- (ii)
$$N_A = \frac{D_{AB}}{Z} \left(\frac{\dots}{M} \right)_{\text{avg}} (X_{A1} - X_{A2})$$

Where $(X_{A1} - X_{A2})$ is the concentration difference in of mole fraction.

(2) Steady state diffusion of A through Non-diffusion B

- (i) $N_A = \text{Constant}$ $N_B = 0$

- (ii) In this case flux is given by

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Where $(x_B)_{lm} = \frac{x_{B2} - x_{B1}}{\ln\left(\frac{x_{B2}}{x_{B1}}\right)}$ $N_A = \frac{D_{AB}}{Z \cdot (x_B)_{lm}} \left(\frac{\dots}{M}\right)_{avg} (x_{A1} - x_{A2})$

Diffusion in solid :

- (i) Example of diffusion in solids are leaching, drying etc.
- (ii) Fick's law for the steady state diffusion can be written as \rightarrow

$$N_A = -D_A \frac{dC_A}{dz}$$

Where N_A is the diffusion rate A per unit cross section of solid.

D_A = Diffusivity of A through the solid :

$\frac{dC_A}{dz}$ = concentration gradient.

Case(1) Diffusion through a flat plate.

$$N_A = D_A \frac{[C_{A1} - C_{A2}]}{Z}$$

Where $Z = Z_2 - Z_1$ = slab thickness.

C_{A1} and C_{A2} = Concentration of A at the opposite sides of slab.

Case (2) For the other solid shape rate of diffusion is given by

$$W = N_A A_{avg} = D_{Avg} \frac{[C_{A1} - C_{A2}]}{Z}$$

Where A_{avg} = average cross section available for diffusion.

- (i) In case of cylinder

$$A_{avg} = \frac{2f[r_2 - r_1]L}{\ln(r_2/r_1)} \text{ and } Z = (r_2 - r_1)$$

- (ii) In case of sphere

$$A_{avg} = 4 r_1 r_2 \text{ and } Z = (r_2 - r_1)$$

Steady state equimolar counter Diffusion

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(i) When two component diffuse at the same molar flow rate in the opposite direction in each other. Then this transfer process is called equimolar counter diffusion.

(ii) $J_A = -J_B$

Where J_A is the molar flux of component A in x direction due to molecular diffusion ($\text{Kmol A/m}^2\text{s}$)

(iii) Transfer rate of two species by molecular transport (diffusion) are always equal but in opposite direction.

Mass transfer Coefficient :

(i) Mass transfer coefficient is defined as the rate of mass transfer per unit area per unit concentration difference.

(ii) Mass transfer coefficient is needed to estimate the mass transfer rate in turbulent flow.

(iii) For steady state equimolar counter diffusion \rightarrow

$$N_A = k_g'(p_{A1} - p_{A2})$$

Where k_g' is mass transfer coefficient in the gas phase.

Where

(iv) For steady state diffusion of A through stationary B

$$N_A = K_G(p_{A1} - p_{A2})$$

(v) In case of liquid phase

$$N_A = K_L'(C_{A1} - C_{A2})$$

Where k_L' mass transfer coefficient for liquid.

(vi) Mass transfer coefficient may also be defined as the rate of mass transfer from bulk of one phase to an interface of unit area for unit driving force.

CASE (1) :

For equimolecular counter diffusion :

$$N_A = K_y'(Y_{A1} - Y_{A2}) \quad , \quad N_A = K_C'(C_{A1} - C_{A2})$$

(For Gas)

$$N_A = K_x'(X_{A1} - X_{A2}) \quad , \quad N_A = K_C'(C_{A1} - C_{A2})$$

(For liquids)

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CASE (2) :

Transfer of A through non-transferring B

$$N_A = K_y' (Y_{A1} - Y_{A2}) \quad , \quad N_A = K_C (C_{A1} - C_{A2}) \quad (\text{For Gas})$$

$$N_A = K_x (X_{A1} - X_{A2}) \quad , \quad N_A = K_L (C_{A1} - C_{A2}) \quad (\text{For liquids})$$

Overall Mass Transfer Coefficient :

$$(1) \quad \frac{1}{K_G} = \frac{1}{k_G} + \frac{m}{k_L} \quad \dots\dots(1)$$

Where K_G is overall gas phase mass transfer coefficient

$$(2) \quad \frac{1}{K_L} = \frac{1}{mk_G} + \frac{1}{K_L} \quad \dots\dots(2)$$

K_L is overall liquid phase mass transfer coefficient.

(3) If $m=0$ (highly soluble gas)

Then from equation

$$\boxed{K_G = k_G} \quad \dots\dots(1)$$

Such transfer process is called gas film controlling. Example is absorption of ammonia in water.

(4) m is very large ($m \gg 1$) [a insoluble gas] then from equation-2

$$\boxed{K_L = k_L}$$

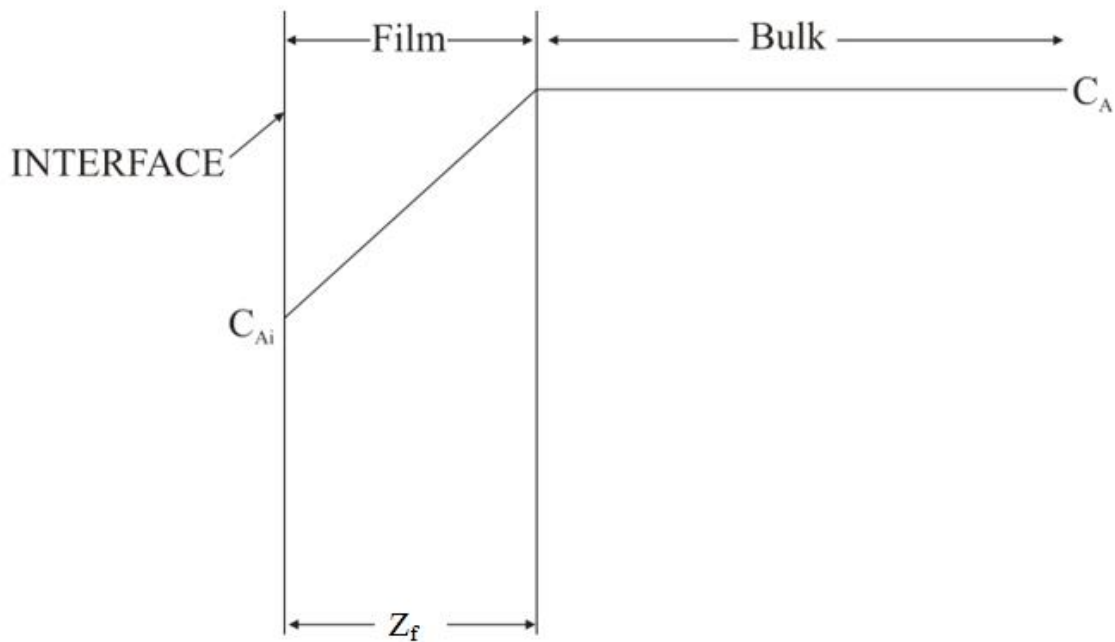
In such a case overall mass transfer coefficient based on liquid film coefficient example is absorption of SO_2 in water.

Mass Transfer Theories

There are several theories which have been proposed to explain and correlate interphase mass transfer. The most widely accepted theories are \rightarrow

1. Film theory
2. Penetration theory
3. Surface-Renewal theory

FILM THEORY :



- (1) In this theory assume that all resistance to mass transfer in turbulent flow is confined in a thin film adjacent to the phase boundary (as given in figure)
- (2) Within this film the mass transfer occur by steady state molecular diffusion alone and outside this film, turbulence level is so high that all concentration gradient destroy by turbulent eddy mixing.
- (3) The film thickness would be in range of 0.1-1mm for gas phase transport.
- (4) The film thickness would be in range of 0.01 – 0.1mm for liquid phase transport.
- (5) Most widely used model to describe mass transfer from a gas phase into liquid phase is two film theory.
- (6) For steady state molecular diffusion in Z direction

$$\frac{D_{AB} d^2 C_A}{dz^2} = 0$$

- (7) Solution of this equation :

$$N_{AZ} = \frac{D_{AB}}{RTZ_G} (p_A - p_{Ai}) = K_G (p_A - p_{Ai}) \quad (\text{Gas Phase})$$

- (8)
$$N_{AZ} = \frac{D_{AB}}{Z_L} (C_{Ai} - C_A) = K_L (C_{Ai} - C_A) \quad (\text{For liquid film})$$

In this equation subscript G,L and i indicate gas film, liquid film and interface respectively.

PENETRATION THEORY :

- (1) Mass transfer penetration theory describe the diffusion of sparingly soluble gases into liquid over short period.

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(2) In this theory assumption made that turbulence transfer fluid elements from the bulk fluid phase to the interface.

(3) The average mass transfer coefficient in this theory is defined by

$$\bar{K}_L = \frac{\bar{N}_{Az}}{(C_{Ai} - C_{A\infty})}$$
 is given by

$$\bar{K}_L = z \sqrt{\frac{D_{AB}}{te}}$$

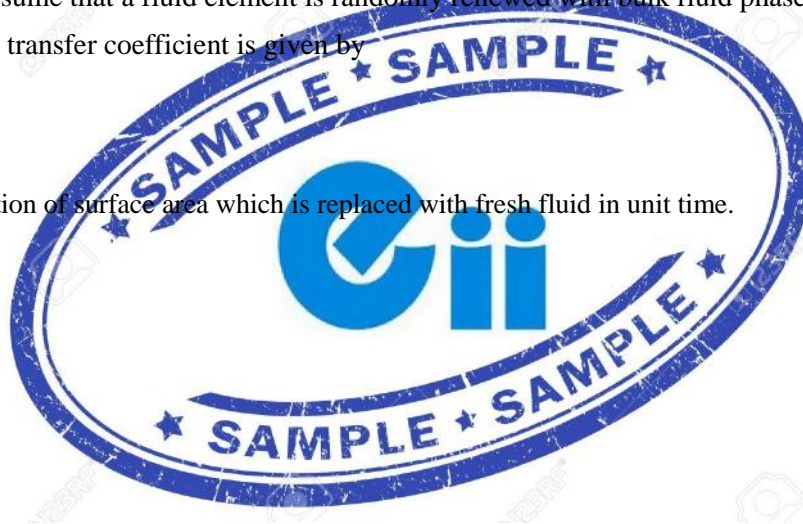
SURFACE RENEWAL THEORY :

According to this theory :

- (1) Fluid eddies at the surface are exposed to varying length of time.
- (2) This theory assume that a fluid element is randomly renewed with bulk fluid phase.
- (3) Average mass transfer coefficient is given by

$$\bar{K}_L = \sqrt{SD_{AB}}$$

Where S is the fraction of surface area which is replaced with fresh fluid in unit time.



IMPORTANT KEY TO REMEMBER

(1) Fick's law is given by

$$J_A = -D_{AB} \frac{dC_A}{dz} \text{ (for binary system)}$$

(2) Steady state equimolar counter diffusion is given by

$$N_A = \frac{D_{AB}}{RTz} (p_{A1} - p_{A2})$$

(3) Steady state diffusion of A through Non-diffusing B

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$$\frac{N_A = D_{AB} p (p_{A1} - p_{A2})}{RTZ p_{B,M}}$$

- (4) Stead state equimolar counter diffusion

$$N_A = -N_B = \text{constant}$$

- (5) Steady state diffusion of A through non-diffusing B

$$N_A = \text{constant}, N_B = 0$$

- (6) Overall mass transfer coefficient is given by

$$\frac{1}{K_G} = \frac{1}{k_G} + \frac{m}{k_L}$$

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{mk_G}$$

- (7) In penetration theory

$$\bar{K}_L = \sqrt{\frac{D_{AB}}{f t e}}$$

- (8) In surface Renewal theory

$$\bar{K}_L = \sqrt{S D_{AB}}$$



SOLVED NUMERICALS

1. Calculate the equilibrium composition of the liquid and vapour phase for a mixture of methyl alcohol and water at a temperature of 400k and under a pressure of 45KPa.

Assume that both liquid and vapour behave ideally

Data :

Vapour pressure of water at 400k = 15KPa

Vapour pressure of methanol at 400k = 60KPa

Solution:

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Let x_1 and y_1 be mole fraction of methyl alcohol in liquid and vapour respectively.

p_1 = partial pressure of methyl alcohol

$$p_1 = p_1^0 x_1 = 60x_1$$

p_2 = water partial pressure

$$p_2 = p_2^0 x_2 = 15(1-x_1)$$

and we know total pressure $P = p_1 + p_2$

$$\Rightarrow 45 = 60x_1 + 15(1-x_1)$$

$$\Rightarrow 45 - 15 = 60x_1 - 15x_1$$

$$\Rightarrow 30 = 45x_1$$

$$x_1 = 0.67$$

$$y_1 = \frac{P_1}{P} = \frac{P_1^0 x_1}{P} = \frac{60 \times 0.67}{45} = 0.89$$

Hence at equilibrium :

Liquid phase = 0.67 mole fraction of methyl alcohol

Vapour phase = 0.89 mole fraction of methyl alcohol.

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