

GATEFLIX

MASS TRANSFER

**For
CHEMICAL ENGINEERING**

MASS TRANSFER

SYLLABUS

Fick's laws, molecular diffusion in fluids, mass transfer coefficients, film, penetration and surface renewal theories; momentum, heat and mass transfer analogies; stage-wise 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.

ANALYSIS OF GATE PAPERS

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2001	14
2002	11
2003	13
2004	15
2005	11
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1.1 INTRODUCTION

Transfer of mass from one point to another in a single phase or from one phase to another phase with the help of a driving force is known as mass transfer. The driving force is required for any transfer; in mass transfer concentration difference is driving force.

Types of mass transfer:

1. Molecular Diffusion: The transfer of mass or diffusion of species takes place in a stagnant medium.
2. Turbulent Diffusion: If the diffusion of species takes place in a turbulent medium, then the mechanism is known as turbulent or eddy diffusion.

Flux: The net rate at which a species in solution passes through unit area, which is normal to the direction of diffusion in unit time.

Molar Flux: The molar flux of species defined with reference to fixed spatial coordinates, N_A is

$$N_A = C_A V_A \dots\dots\dots (1.1)$$

This could be written in terms of diffusion velocity of A, (i.e. $V_A - V$) and molar average velocity of mixture, V as

$$N_A = C_A (V_A - V) + C_A V \dots\dots\dots (1.2)$$

By definition,

$$V = \frac{\sum C_i V_i}{C}$$

Therefore, equation (1.2) becomes

$$N_A = C_A (V_A - V) + C_A \frac{\sum C_i V_i}{C} \\ = C_A (V_A - V) + X_A \sum C_i V_i$$

For binary systems containing two components A and B,

$$N_A = C_A (V_A - V) + X_A (C_A V_A + C_B V_B) \\ = C_A (V_A - V) + X_A (N_A + N_B) \\ N_A = C_A (V_A - V) + X_A N \dots\dots\dots (1.3)$$

The first term on the right hand side of this equation is diffusional molar flux of A, and the second term is flux due to bulk motion.

Mass Flux: The mass flux of species defined with reference to fixed spatial coordinates, n_A is

$$n_A = \rho_A v_A \dots\dots\dots (1.4)$$

This could be written in terms of diffusion velocity of A, (i.e. $v_A - v$) and mass average velocity of mixture, v as

$$n_A = \rho_A (v_A - v) + \rho_A v \dots\dots\dots (1.5)$$

By definition,

$$v = \frac{\sum \rho_i v_i}{\rho}$$

Therefore, equation (1.5) becomes

$$n_A = \rho_A (v_A - v) + \rho_A \frac{\sum \rho_i v_i}{\rho} \\ = \rho_A (v_A - v) + Y_A \sum \rho_i v_i$$

1.2 FICK'S FIRST LAW:

The molar flux of a species with respect to observer moving with molar average velocity is directly proportional to the gradient of the concentration of that species.

$$J_A \propto \frac{dC_A}{dz}$$

If we remove the proportionality, then the constant of proportionality must be introduced, which is known as diffusivity or diffusion coefficient; denoted by D_{AB} for a binary mixture or D_{ij} for a multicomponent mixture. This coefficient tells us how easily species I diffuse in the solution or for a binary mixture how easily A diffuses into B. dC_A/dZ is the concentration gradient in the Z-direction.

$$J_A = -D_{AB} \frac{dC_A}{dz}$$

Where, minus sign represents the transfer of mass taking place from a region of higher concentration to a region of lower concentration.

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

Using this expression, Equation (1.3) could be written as,

$$N_A = -CD_{AB} \frac{dX_A}{dz} + X_A N \quad \dots\dots\dots (1.6)$$

1.3 RELATION AMONG MOLAR FLUXES:

For a binary system containing A and B, from Equation (1.6),

$$N_A = J_A + X_A N$$

Or, $J_A = N_A - X_A N \quad \dots\dots (1.7)$

Similarly, $J_B = N_B - X_B N \quad \dots\dots (1.8)$

Addition of equation (1.7) & (1.8) gives,

$$J_A + J_B = N_A + N_B - (X_A + X_B) N \quad \dots\dots (1.9)$$

By definition,

$$N = N_A + N_B \text{ and } X_A + X_B = 1$$

Therefore equation (1.9) becomes,

$$J_A + J_B = 0$$

$$J_A = -J_B$$

$$CD_{AB} \frac{dX_A}{dz} = -CD_{BA} \frac{dX_B}{dz} \quad \dots\dots (1.10)$$

From $X_A + X_B = 1$

$$dX_A = -dX_B$$

Therefore equation (1.10) becomes,

$$D_{AB} = -D_{BA} \quad \dots\dots\dots (1.11)$$

1.4 DIFFUSIVITY

Fick's law proportionality, D_{AB} , is known as mass diffusivity (simply as diffusivity) or as the diffusion coefficient. D_{AB} has the dimension of L^2/t , identical to the fundamental dimensions of the other

transport properties: Kinematic viscosity, $\nu = \frac{\mu}{\rho}$ in momentum transfer, and thermal diffusivity, $\alpha = \frac{K}{\rho C_p}$ in heat transfer.

Diffusivity is normally reported in cm^2/sec ; the SI unit being m^2/sec . Diffusivity depends on pressure, temperature, and composition of the system. Diffusivities of gases at low density are almost composition independent, increase with the temperature and vary inversely with pressure. Liquid and solid diffusivities are strongly concentration dependent and increase with temperature.

General range of values of diffusivity:

Gases: $5 \times 10^{-6} - 1 \times 10^{-5} \text{ m}^2/\text{sec}$

Liquids: $10^{-6} - 10^{-9} \text{ m}^2/\text{sec}$

Solids: $5 \times 10^{-14} - 1 \times 10^{-10} \text{ m}^2/\text{sec}$

1.4.1 DIFFUSIVITY IN GASES:

Pressure dependence of diffusivity is given by

$$D_{AB} \propto \frac{1}{P}$$

And temperature dependency is according to

$$D_{AB} \propto T^{3/2}$$

Diffusivity of a component in a mixture of components can be calculated using the diffusivities for the various binary pairs involved in the mixture. The relation given by Wilke is

$$D_{1-\text{mixture}} = \frac{1}{\frac{y_2'}{D_{1-2}} + \frac{y_3'}{D_{1-3}} + \dots + \frac{y_n'}{D_{1-n}}}$$

Where, $D_{1-\text{mixture}}$ is the diffusivity for component 1 in the gas mixture; D_{1-n} is the diffusivity for the binary pair, component 1 diffusing through component n; and y_n' is the mole fraction of component n in the gas mixture evaluated on a component -1 - free basis, that is

$$y_2' = \frac{y_2}{y_2 + y_3 + \dots + y_n}$$

1.4.2 DIFFUSIVITY IN LIQUIDS:

Temperature dependency is according to
 $D_{AB} \propto T$

1.5 STEADY STATE DIFFUSION

In this section, steady-state molecular mass transfer through simple systems in which the concentration and molar flux are functions of a single space coordinate will be considered.

In a binary system, containing A and B, this molar flux in the direction of z, as given by Eqn (1.6) is

$$N_A = -CD_{AB} \frac{dx_A}{dz} + X_A (N_A + N_B) \dots (1.11)$$

1.5.1 DIFFUSION OF A THROUGH NON-DIFFUSING B:

Liquid A is evaporating into gas B. Solubility of gas B in liquid A is negligible or B is non-diffusing. A stream of gaseous mixture A and B having concentration x_{A2} flows slowly over the top of the tube to maintain the mole fraction of A at x_{A2} . Entire system is kept at constant temperature and pressure. Gases A and B are assumed to be ideal.

$$N_A = J_A + X_A N$$

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

$$N_B = 0,$$

$$N_A = X_A N_A - CD_{AB} \frac{dx_A}{dz}$$

$$(1 - X_A) N_A = - CD_{AB} \frac{dx_A}{dz}$$

$$N_A \int_0^Z dz = - CD_{AB} \int_{X_{A1}}^{X_{A2}} \frac{dx_A}{(1 - X_A)}$$

$$N_A Z = CD_{AB} \ln \frac{1 - X_{A2}}{1 - X_{A1}}$$

$$N_A = \frac{CD_{AB}}{Z} \ln \frac{1 - X_{A2}}{1 - X_{A1}}$$

$$N_A = \frac{CD_{AB}}{Z} \ln \frac{X_{B2}}{X_{B1}}$$

$$N_A = \frac{CD_{AB}}{Z} \frac{X_{B2} - X_{B1}}{\ln \left(\frac{X_{B2}}{X_{B1}} \right)}$$

Where, $X_{BLM} = \frac{X_{B2} - X_{B1}}{\ln \left(\frac{X_{B2}}{X_{B1}} \right)}$ is called

logarithmic mean of B.

$$X_{A1} - X_{A2} = X_{B2} - X_{B1}$$

$$N_A = \frac{CD_{AB}}{Z} \frac{X_{A1} - X_{A2}}{X_{BLM}} \dots (1.12)$$

When the difference between Concentration X_{B2} & X_{B1} is very less then we take arithmetic mean not logarithmic mean.

Equation (1.12) can be written as in the form of logarithmic average concentration of B,

$$N_A = \frac{CD_{AB}}{Z} \frac{C_{A1} - C_{A2}}{C_{BLM}} \dots (1.13)$$

Where, $C_{BLM} = \frac{C_{B2} - C_{B1}}{\ln \left(\frac{C_{B2}}{C_{B1}} \right)}$ is called

logarithmic average concentration of B.

For an ideal gas, $C = \frac{P}{RT}$

Therefore, for an ideal gas mixture equation. (1.13) becomes

$$N_A = \frac{PD_{AB}}{RTZ} \frac{P_{A1} - P_{A2}}{P_{BLM}} \dots (1.14)$$

Example 1.1 Oxygen is diffusing in a mixture of oxygen-nitrogen at 1 std-atm, 25°C. Concentration of oxygen at planes 2 mm apart are 10 and 20 volume % respectively. Nitrogen is non-diffusing.

(a) Derive the appropriate expression to calculate the flux of oxygen. Define units of each term clearly.

(b) Calculate the flux of oxygen. Diffusivity of oxygen in nitrogen = $1.89 \times 10^{-5} \text{ m}^2/\text{s}$.

Solution: Let us denote oxygen as A and nitrogen as B. Flux of A (i.e.) N_A is made up of two components, namely that resulting from the bulk motion of A (i.e.), N_{A1} and that resulting from molecular diffusion J_A :

$$N_A = J_A + X_A N$$

From Fick's law of Diffusion,

$$J_A = -D_{AB} \frac{dC_A}{dz}$$

$$N_A = X_A N - D_{AB} \frac{dC_A}{dz} \quad \dots\dots\dots (1)$$

Since $N = N_A + N_B$ and $X_A = C_A/C$ equation (1) becomes

$$N_A = (N_A + N_B) \frac{C_A}{C} - D_{AB} \frac{dC_A}{dz} \quad \dots\dots (2)$$

Since B is non-diffusing $N_B = 0$. Also, the total concentration C remains constant. Therefore, equation (2) becomes,

$$\frac{\int_0^z dz}{C D_{AB}} = - \int_{C_{A1}}^{C_{A2}} \frac{dC}{(N_A C - N_A C_A)}$$

$$= \frac{1}{N_A} \ln \frac{C - C_{A2}}{C - C_{A1}}$$

$$N_A = \frac{C D_{AB}}{z} \ln \frac{C - C_{A2}}{C - C_{A1}} \quad \dots\dots\dots (3)$$

Replacing concentration in terms of pressures using Ideal gas law, equation (3) becomes

$$N_A = \frac{P_t D_{AB}}{RTz} \ln \frac{P_t - P_{A2}}{P_t - P_{A1}} \quad \dots\dots\dots (4)$$

Where,

D_{AB} = molecular diffusivity of A in B

P_t = total pressure of system

R = universal gas constant

T = temperature of system in absolute scale

z = distance between two planes across the direction of diffusion

P_{A1} = partial pressure of A at plane 1, and

P_{A2} = partial pressure of A at plane 2

Given:

$$D_{AB} = 1.89 \times 10^{-5} \text{ m}^2/\text{sec}$$

$$P_t = 1 \text{ atm} = 1.01325 \times 10^5 \text{ N/m}^2$$

$$T = 25^\circ\text{C} = 273 + 25 = 298 \text{ K}$$

$$z = 2 \text{ mm} = 0.002 \text{ m}$$

$$P_{A1} = 0.2 \times 1 = 0.2 \text{ atm} = 20265 \text{ N/m}^2 \text{ (From Ideal gas law and additive pressure rule)}$$

$$P_{A2} = 0.1 \times 1 = 0.1 \text{ atm} = 10132.5 \text{ N/m}^2$$

Substituting these in equation (4),

$$N_A = \frac{(1.89 \times 10^{-5})(1.01325 \times 10^5)}{(8314 \times 298 \times 0.002)} \ln \frac{(101325 - 10132.5)}{(101325 - 20265)}$$

$$N_A = 4.55 \times 10^{-5} \text{ kmol/m}^2 \cdot \text{s}$$

1.5.2 EQUIMOLAR COUNTER DIFFUSION:

A physical situation which is encountered in the distillation of two constituents whose molar latent heats of vaporization are essentially equal, stipulates that the flux of one gaseous component is equal to but acting in the opposite direction from the other gaseous component; that is, $N_A = -N_B$.

The molar flux N_A , for a binary system at constant temperature and pressure is described by,

$$N_A = (N_A + N_B) \frac{C_A}{C} - D_{AB} \frac{dC_A}{dz} \quad \dots\dots (1.15)$$

With the substitution of $N_A = -N_B$, Equation (1.15) becomes,

$$N_A = -D_{AB} \frac{dC_A}{dz} \dots\dots (1.16)$$

For steady state diffusion Equation (1.16) may be integrated, using the boundary conditions: at

$$z = z_1 \quad C_A = C_{A1}$$

$$\text{and } z = z_2 \quad C_A = C_{A2}$$

Giving,

$$N_A \int_{z_1}^{z_2} dz = -D_{AB} \int_{C_{A1}}^{C_{A2}} dC_A$$

$$N_A = \frac{D_{AB}}{(z_2 - z_1)} (C_{A2} - C_{A1}) \dots\dots\dots (1.17)$$

For an ideal gas, $C = \frac{P}{RT}$

Therefore, for an ideal gas mixture equation. (1.17) becomes

$$N_A = \frac{D_{AB}}{RT(z_2 - z_1)} (P_{A2} - P_{A1}) \dots\dots\dots (1.17)$$

This is the equation of molar flux for steady-state equimolar counter diffusion.

Concentration profile in this equimolar counter diffusion may be obtained from,

$$\frac{d}{dz} (N_A) = 0$$

(Since N_A is constant over the diffusion path)

And from equation (1.16)

$$N_A = -D_{AB} \frac{dC_A}{dz}$$

Therefore,

$$\frac{d}{dz} \left(-D_{AB} \frac{dC_A}{dz} \right) = 0$$

Or, $\frac{d^2 C_A}{dz^2} = 0 \dots\dots\dots (1.18)$

This equation may be solved using the boundary conditions to give,

$$\frac{C_A - C_{A1}}{C_A - C_{A2}} = \frac{z - z_1}{z_1 - z_2} \dots\dots\dots (1.19)$$

Equation, (1.19) indicates a linear concentration profile for equimolar counter diffusion.

Example 1.2 Methane diffuses at steady state through a tube containing helium. At point 1 the partial pressure of methane is $P_{A1} = 55$ kPa and at point 2, 0.03 m apart $P_{A2} = 15$ kPa. The total pressure is 101.32 kPa, and the temperature is 298 K. At this pressure and temperature, the value of diffusivity is $6.75 \times 10^{-5} \text{ m}^2/\text{sec}$.

- (i). Calculate the flux of CH_4 at steady state for equimolar counter diffusion.**
- (ii). Calculate the partial pressure at a point 0.02 m apart from point 1.**

Solution: For steady state equi-molar counter diffusion, molar flux is given by,

$$N_A = \frac{D_{AB}}{RT(z_2 - z_1)} (P_{A2} - P_{A1}) \dots\dots\dots (1)$$

Therefore,

$$N_A = \frac{(6.75 \times 10^{-5})(55 - 15)}{(8314 \times 298 \times 0.003)}$$

$$N_A = 3.633 \times 10^{-5} \frac{\text{kmol}}{\text{m}^2 \cdot \text{sec}}$$

And from (1), partial pressure at 0.02 m from point 1 is:

$$3.633 \times 10^{-5} = \frac{(6.75 \times 10^{-5})(55 - P_A)}{(8314 \times 298 \times 0.002)}$$

$$P_A = 28.33 \text{ kPa}$$

Example 1.3 For Equimolar counter diffusion from a sphere to a surrounding stationary infinite medium, the mass flux N_{Ai} of the diffusing component A at the interface is

given by $N_{Ai} = \frac{D_A}{R} (C_{Ai} - C_{Ab})$ where D_A is the diffusivity, R the radius of sphere and C_{Ai} and C_{Ab} the molar concentrations of A at the interface and at a point far away from the sphere. Show that the Sherwood number, based on the diameter of the sphere is equal to 2.

Solution: The mass flux N_{Ai} is given by

$$N_{Ai} = \frac{D_A}{R} (C_{Ai} - C_{Ab}) \dots\dots\dots (1)$$

The mass flux N_{Ai} of the diffusing component A at the interface is also given by,

$$N_{Ai} = K_c (C_{Ai} - C_{Ab}) \dots\dots\dots (2)$$

From the equations (1) and (2), we get

$$K_c = \frac{D_A}{R}$$

$$\frac{K_c R}{D_A} = 1$$

$$\frac{K_c D}{D_A} = 2$$

(Since, $R = \frac{d}{2}$ = diameter of sphere)

$$N_{Sh} = \frac{K_c D}{D_A} = 2$$

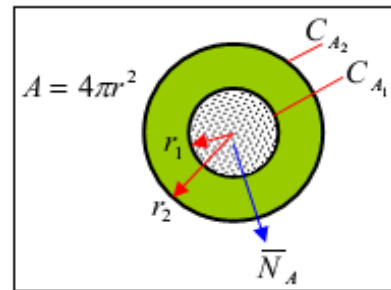
1.5.3 EVAPORATION OF SPHERICAL DROPLETS:

We shall consider the evaporation of spherical droplet such as a raindrop or sublimation of naphthalene ball. The vapor formed at the surface of the droplet is assumed to diffuse by

molecular motions into the large body of stagnant gas that surrounds the droplet.

Consider a naphthalene ball, as shown in figure. At any moment, when the radius of the ball is r_1 , the flux of naphthalene ball at any distance r from the center is given by,

$$N_A = X_A (N_A + N_B) - CD_{AB} \frac{dX_A}{dr}$$



Here $N_B = 0$ (since air is assumed to be stagnant) Therefore,

$$N_A = X_A N_A - CD_{AB} \frac{dX_A}{dr}$$

Rearranging,

$$N_A = - CD_{AB} \frac{dX_A}{(1-X_A) dr} \dots\dots\dots (1.20)$$

The flux N_A is not constant, because of the spherical geometry; decreases as the distance from the center of sphere increases. But the molar flow rate at r and $r + dr$ are the same.

$$AN_A|_r = AN_A|_{r+dr}$$

Where, A = Surface area of sphere at r and $r + dr$

Substituting $A = 4\pi r^2$

$$4\pi r^2 N_A|_r - 4\pi r^2 N_A|_{r+dr} = 0$$

$$\text{Or, } \lim_{dr \rightarrow 0} \frac{4\pi r^2 N_A|_{r+dr} - 4\pi r^2 N_A|_r}{dr} = 0$$

As $\frac{d}{dr}(4\pi r^2 N_A) = 0$

$$-N_A = \frac{\rho}{M} \frac{dr}{dt}$$

Integrating,

$$4\pi r^2 N_A = \text{constant} = W$$

Or, $N_A = \frac{W}{4\pi r^2}$

Put the value of N_A in Equation (1.20)

$$\frac{W}{4\pi r^2} = -CD_{AB} \frac{dX_A}{(1-X_A) dr}$$

$$W \int_{r_1}^{r_2} \frac{dr}{4\pi r^2} = -CD_{AB} \int_{X_{A1}}^{X_{A2}} \frac{dX_A}{(1-X_A)}$$

$$\frac{W}{4\pi} \left(\frac{1}{r_2} - \frac{1}{r_1} \right) = CD_{AB} \ln \frac{1-X_{A2}}{1-X_{A1}}$$

$\frac{1}{r_2} \cong 0$ ($r_2 = \text{radius of air infinity}$)

$$\frac{W}{4\pi r_1} = CD_{AB} \frac{X_{A1}-X_{A2}}{X_{B1M}}$$

$$\frac{W}{4\pi r_1^2} = \frac{CD_{AB}}{r_1} \frac{X_{A1}-X_{A2}}{X_{B1M}}$$

$$N_A|_{r=r_1} = \frac{CD_{AB}}{r_1} \frac{X_{A1}-X_{A2}}{X_{B1M}} \dots\dots\dots (1.21)$$

The radius of naphthalene ball decreases with time, but still we have taken it as steady state condition because it satisfies assumption of pseudo steady state diffusion i.e.

- 1) The diffusional rate should be very small.
- 2) The species which is diffusing should be very small in comparison to the species in which it is diffusing.

Time taken for the complete evaporation of a naphthalene ball:

Rate of Diffusion = Rate of evaporation

$$-4\pi r^2 N_A = \frac{d}{dt} \left(\frac{\rho}{M} \frac{4}{3} \pi r^3 \right)$$

From Equation (1.21),

$$N_A|_{r=r} = -\frac{CD_{AB}}{r} \frac{X_{A1}-X_{A2}}{X_{B1M}} = \frac{\rho}{M} \frac{dr}{dt}$$

$$-\int_{r_1}^0 r dr = \frac{MCD_{AB}}{\rho} \frac{X_{A1}-X_{A2}}{X_{B1M}} \int_0^{t_1} dt$$

$$t_1 = \frac{r_1^2 \rho}{2 M C D_{AB}} \frac{X_{B1M}}{X_{A1}-X_{A2}} \dots\dots\dots (1.22)$$

Example 1.4 A sphere of naphthalene having a radius of 2mm is suspended in a large volume of shell air at 318 K and 1 atm. The surface pressure of the naphthalene can be assumed to be at 318 K is 0.555 mmHg. The Diffusivity of naphthalene in air at 318 K is $6.92 \times 10^{-6} \text{ m}^2/\text{sec}$. Calculate the rate of evaporation of naphthalene from the surface.

Solution: Rate of evaporation of naphthalene is given by:

$$\frac{W}{4\pi r_1^2} = \frac{CD_{AB}}{r_1} \ln \frac{1-X_{A2}}{1-X_{A1}}$$

For gases,

$$C = \frac{P}{RT} \text{ and } X_A = \frac{C_A}{C} = \frac{P_A/RT}{P/RT} = \frac{P_A}{P}$$

Given: $D_{AB} = 6.92 \times 10^{-6}$

$$C = \frac{P}{RT} = \frac{101325}{8314 \times 318} = 0.03832$$

$$X_{A2} = 0 \text{ (Air is non-diffusing)}$$

$$X_{A1} = \frac{P_{A2}}{P} = \frac{0.555}{760} = 7.303 \times 10^{-4}$$

$$\frac{W}{4\pi(0.002)^2} = \frac{0.03832 * 6.92 * 10^{-6}}{0.002} \ln \frac{1-0}{1-(7.303 * 10^{-4})}$$

$$W = 4.863 * 10^{-12} \text{ kmol/sec}$$

$$N_A = \frac{CD_{AB} X_{A1} - X_{A2}}{Z X_{BLM}}$$

1.5.4 DIFFUSION IN LIQUIDS:

Case 1: For steady state diffusion of A through non diffusing B:

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

$$N_A = \frac{CD_{AB} X_{A1} - X_{A2}}{Z X_{BLM}}$$

Where, $C = \left(\frac{\rho}{M}\right)_{avg} = \frac{\left(\frac{\rho}{M}\right)_1 + \left(\frac{\rho}{M}\right)_2}{2}$

And $X_{BLM} = \frac{X_{B2} - X_{B1}}{\ln\left(\frac{X_{B2}}{X_{B1}}\right)}$

Case 2: For steady state equimolar counter diffusion:

$$N_A = -N_B$$

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

Where, $C = \left(\frac{\rho}{M}\right)_{avg} = \frac{\left(\frac{\rho}{M}\right)_1 + \left(\frac{\rho}{M}\right)_2}{2}$

Example 1.5 Calculate the rate of diffusion of butanol at 20°C under unidirectional steady state conditions through a 0.1 cm thick film of water when the concentrations of butanol at the opposite sides of the film are, respectively 10% and 4% butanol by weight. The diffusivity of butanol in water solution is $5.9 * 10^{-6} \text{ cm}^2/\text{sec}$. The densities of 10% and 4% butanol solutions at 20°C may be taken as 0.971 and 0.992 g/cc respectively. Molecular weight of butanol ($C_4 H_9OH$) is 74, and that of water 18.

Solution: For steady state unidirectional diffusion,

Conversion from weight fraction to Mole fraction:

$$X_{A1} = \frac{(0.1/74)}{(0.1/74 + 0.9/18)} = 0.026$$

$$X_{A2} = \frac{(0.04/74)}{(0.04/74 + 0.96/18)} = 0.010$$

Average molecular weight at 1 & 2:

$$M_1 = \frac{1}{(0.1/74 + 0.9/18)} = 19.47 \text{ kg/kmol}$$

$$M_2 = \frac{1}{(0.04/74 + 0.96/18)} = 18.56 \text{ kg/kmol}$$

$$C = \left(\frac{\rho}{M}\right)_{avg} = \frac{\left(\frac{\rho}{M}\right)_1 + \left(\frac{\rho}{M}\right)_2}{2}$$

$$= \frac{\left(\frac{0.971}{19.47}\right) + \left(\frac{0.992}{18.56}\right)}{2}$$

$$= 0.0517 \text{ gmol/cc}$$

$$= 51.7 \text{ kmol/m}^3$$

$$X_{BLM} = \frac{X_{B2} - X_{B1}}{\ln\left(\frac{X_{B2}}{X_{B1}}\right)} = \frac{(1 - X_{A2}) - (1 - X_{A1})}{\ln\left(\frac{1 - X_{A2}}{1 - X_{A1}}\right)}$$

$$i.e. X_{BLM} = \frac{(1 - 0.01) - (1 - 0.026)}{\ln\left(\frac{1 - 0.01}{1 - 0.026}\right)}$$

$$= \frac{0.016}{0.0163} = 0.982$$

Therefore,

$$N_A = \frac{CD_{AB} X_{A1} - X_{A2}}{Z X_{BLM}}$$

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

$$N_A = \frac{51.7 * 5.9 * 10^{-6} * 10^{-4}}{0.001} * \frac{(0.026 - 0.01)}{0.982}$$

$$= 4.97 * 10^{-7} \text{ kmol/m}^2 \text{ sec}$$

1.5.5 DIFFUSION IN SOLIDS:

Rates are slow in comparison to liquids and gases but it is important to us in many mass transfer operations. E.g. leaching of foods such as soya bean, crystallization, drying etc. Types of diffusion in solids:

There are two types.

- 1) Diffusion that can be considered to follow Fick's law and does not depend on the actual structure of solid. E.g. in leaching, the solid contains a large amount of water and solute is diffusing through this solution.
- 2) Diffusion in porous solid where actual structure and the voids are important.

$$N_A = \frac{\varepsilon}{\tau} D_{AB} \frac{dC_A}{dz}$$

Where, $\varepsilon =$

voidage (Fraction of voids in solid)

$\tau =$ *Tortuosity*

KNUDSEN DIFFUSION:

When mean free path is greater than pore diameter.

$$\text{i.e. } \lambda > d$$

It follows Knudsen law i.e.

$$J_A = -D_k \frac{dC_A}{dz}$$

Where, $D_k =$ Knudsen diffusivity $= \frac{2}{3} r_p V_T$

$r_p =$ radius of passage

$V_T =$ velocity of particle $= \left(\frac{8RT}{\pi M} \right)^{1/2}$

1.6 TRANSIENT DIFFUSION:

Transient processes, in which the concentration at a given point varies with time, are referred as unsteady state processes or time – dependent processes. This variation in concentration is associated with a variation in the mass flux.

In unsteady state processes there are three variables: concentration, time, and position.

One dimensional unsteady state mass transfer is defined by Fick's second law:

$$\frac{\delta^2 C_A}{\delta x^2} = \frac{1}{D_{AB}} \frac{\delta C_A}{\delta t}$$

2.1 INTRODUCTION

The rate of mass transfer is proportional to driving force and area.

$$W \propto \Delta C$$

If we remove the proportionality, then the constant of proportionality must be introduced, which is known as mass transfer coefficient and is denoted by K_c . Its unit is m/sec.

$$W = K_c \Delta C$$

$$N_A = \frac{W}{A} = K_c \Delta C$$

Like heat transfer, it is an experimental quantity and it can be calculated with the help of dimensionless numbers.

Case 1: Diffusion of A through non-diffusing B

For Gases:

$$N_A = \frac{CD_{AB}}{Z} \frac{C_{A1} - C_{A2}}{C_{BLM}}$$

$$N_A = K_c (C_{A1} - C_{A2})$$

Where,
$$K_c = \frac{CD_{AB}}{ZC_{BLM}}$$

$$N_A = \frac{CD_{AB}}{Z} \frac{y_{A1} - y_{A2}}{y_{BLM}}$$

$$N_A = K_y (y_{A1} - y_{A2})$$

Where,
$$K_y = \frac{CD_{AB}}{Zy_{BLM}}$$

$$N_A = \frac{PD_{AB}}{RTZ} \frac{P_{A1} - P_{A2}}{P_{BLM}}$$

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

Where,
$$K_G = \frac{PD_{AB}}{RTZP_{BLM}}$$

Relationship between K_c , K_y and K_G :

$$N_A = \frac{D_{AB}}{Z} \frac{C_{A1} - C_{A2}}{x_{BLM}}$$

$$N_A = K_c (C_{A1} - C_{A2})$$

Where,
$$K_c = \frac{D_{AB}}{Zx_{BLM}}$$

$$N_A = \frac{D_{AB}}{RTZ} \frac{P_{A1} - P_{A2}}{x_{BLM}}$$

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

Where,
$$K_G = \frac{D_{AB}}{RTZx_{BLM}}$$

$$N_A = \frac{CD_{AB}}{Z} \frac{y_{A1} - y_{A2}}{x_{BLM}}$$

$$N_A = K_y (y_{A1} - y_{A2})$$

Where,
$$K_y = \frac{CD_{AB}}{Zx_{BLM}}$$

$$K_G = \frac{K_y}{P} = \frac{K_c}{RT}$$

For Liquids:

$$N_A = \frac{C_{av}D_{AB}}{Z} \frac{x_{A1} - x_{A2}}{x_{BLM}}$$

$$N_A = K_x (x_{A1} - x_{A2})$$

Where,
$$K_x = \frac{C_{av}D_{AB}}{Zx_{BLM}}$$

$$N_A = \frac{D_{AB}}{Z} \frac{C_{A1} - C_{A2}}{x_{BLM}}$$

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

Where,
$$K_L = \frac{D_{AB}}{Zx_{BLM}}$$

$$K_x = \frac{K_L}{C_{av}}$$

Case 2: Equimolar counter diffusion:

For Gases:

$$N_A = \frac{CD_{AB}}{Z} (x_{A1} - x_{A2})$$

$$N_A = k'_y (x_{A1} - x_{A2})$$

Where,
$$k'_y = \frac{CD_{AB}}{Z}$$

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

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

Where, $k'_c = \frac{D_{AB}}{Z}$

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

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

Where, $k'_G = \frac{D_{AB}}{RTZ}$

$$k'_G = \frac{k'_y}{P} = \frac{k'_c}{RT}$$

For Liquids:

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

$$N_A = k'_x (x_{A1} - x_{A2})$$

Where, $k'_x = \frac{C_{av} D_{AB}}{Z}$

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

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

Where, $k'_x = \frac{D_{AB}}{Z}$

$$k'_x = \frac{k'_l}{C_{av}}$$

2.2 SIGNIFICANT PARAMETERS IN CONVECTIVE MASS TRANSFER:

Dimensionless parameters are often used to correlate convective transfer data. In momentum transfer Reynolds number and friction factor play a major role. In the correlation of convective heat transfer data, Prandtl and Nusselt numbers are important.

Nusselt Number: The ratio of convective heat flux to heat flux for conduction through a stagnant medium of thickness L for the same temperature difference.

$$Nu = \frac{h (\Delta T)}{\frac{k}{L} (\Delta T)} = \frac{hL}{k}$$

Analogy of nusselt number in mass transfer is Sherwood number.

Sherwood number: The ratio of convective mass flux to mass flux for diffusion through a stagnant medium of thickness L, under the driving force of difference.

$$Sh = \frac{K_G (\Delta P)}{\frac{P D_{AB}}{RTZ} \frac{P_{A1} - P_{A2}}{P_{BLM}}}$$

For dilute concentrations,

$$P_{BLM} = P$$

$$Sh = \frac{K_G (\Delta P)}{\frac{P D_{AB}}{RTZ} \frac{(\Delta P)}{P}}$$

$$Sh = \frac{K_G RTZ}{D_{AB}}$$

$$K_c = K_G RT$$

$$Sh = \frac{K_c Z}{D_{AB}}$$

Prandtl Number: It is defined as the ratio of momentum diffusivity to thermal diffusivity.

$$Pr = \frac{\gamma}{\alpha} = \frac{\mu/\rho}{k/\rho C_p} = \frac{\mu C_p}{k}$$

Analogy of Prandtl number in mass transfer is Schmidt number.

Schmidt Number: It is defined as the ratio of momentum diffusivity to mass diffusivity.

$$Sc = \frac{\gamma}{D_{AB}}$$

2.3 APPLICATION OF DIMENSIONLESS ANALYSIS IN MASS TRANSFER:

One of the methods of obtaining equations for predicting mass-transfer coefficients is the use of dimensionless analysis. Dimensional analysis predicts the various dimensionless parameters which are helpful in correlating experimental data. There are two important mass transfer processes, which we shall consider, the transfer of mass into a stream flowing under forced convection and the

transfer of mass into a phase which is moving as the result of natural convection associated with density gradients.

2.3.1 TRANSFER INTO A STREAM FLOWING UNDER FORCED CONVECTION:

Consider the transfer of mass from the walls of a circular conduit to a fluid flowing through the conduit. The mass transfer is due to the concentration driving force ($C_{As} - C_A$).

By the Buckingham method of grouping the variables, the number of dimensionless groups π is equal to the number of variables minus the number of fundamental dimensions. Hence the number of dimensionless group for this problem will be three. Therefore D_{AB} , ρ and D as the core variables, the three π groups to be formed are

$$\pi_1 = D_{AB}^a \rho^b k_c \quad \dots\dots (2.1)$$

$$\pi_2 = D_{AB}^d \rho^e D^f g \quad \dots\dots (2.2)$$

$$\pi_3 = D_{AB}^g \rho^h D^i \mu \quad \dots\dots (2.3)$$

Substituting the dimensions for π ,

$$\pi_1 = D_{AB}^a \rho^b k_c$$

$$1 = \left(\frac{L^2}{t}\right)^a \left(\frac{M}{L^3}\right)^b (L)^c \left(\frac{L}{t}\right)$$

Equating the exponents of fundamental dimensions on both sides of the equation, we have

$$L: \quad 0 = 2a - 3b + c + 1$$

$$t: \quad 0 = -a - 1$$

$$M: \quad 0 = b$$

Solving these equations,

$$a = -1, \quad b = 0, \quad c = 1$$

Thus

$$\pi_1 = \frac{K_c D}{D_{AB}} = Sh$$

which is termed as Sherwood number.

$$\pi_2 = \frac{Dv}{D_{AB}}$$

$$\text{And } \pi_3 = \frac{\mu}{\rho D_{AB}} = Sc$$

which is termed as Schmidt number.

Dividing π_2 by π_3 , we get

$$\frac{\pi_2}{\pi_3} = \frac{Dv}{D_{AB}} \bigg/ \frac{\mu}{\rho D_{AB}} = \frac{Dv\rho}{\mu} = Re$$

Which is the Reynolds number

The result of the dimensional analysis of mass transfer by forced convection:

$$Sh = \varphi(Re, Sc)$$

Which is analogous to the heat transfer correlation

$$Nu = \varphi(Re, Pr)$$

2.3.2 TRANSFER INTO A PHASE WHOSE MOTION IS DUE TO NATURAL CONVECTION:

Natural convection currents develop if there exists any variation in density within the fluid phase. The density variation may be due to temperature differences or to relatively large concentration differences.

According to Buckingham method of grouping the variables, there will be three dimensionless groups. Therefore D_{AB} , L and μ as the core variables, the three π groups to be formed are

$$\pi_1 = D_{AB}^a L^b \mu^c k_c \quad \dots\dots (2.4)$$

$$\pi_2 = D_{AB}^d L^e \mu^f \rho \quad \dots\dots (2.5)$$

$$\pi_3 = D_{AB}^g L^h \mu^i g \Delta\rho_A \quad \dots\dots (2.6)$$

Solving the dimensionless groups, we obtain,

$\pi_1 = \frac{K_c L}{D_{AB}} = Nu$ which is termed as Nusselt number.

$\pi_2 = \frac{\rho D_{AB}}{\mu} = \frac{1}{Sc}$, the reciprocal of Schmidt number.

$$\text{And } \pi_3 = \frac{l^3 g \Delta\rho_A}{\mu D_{AB}}$$

With the multiplication of π_2 and π_3 , we get

$$\pi_2 \pi_3 = \frac{\rho D_{AB} l^3 g \Delta\rho_A}{\mu \mu D_{AB}}$$

$$= \frac{l^3 \rho g \Delta\rho_A}{\mu^2} = Gr$$

Which is the Grashof number

The result of the dimensional analysis of mass transfer by natural convection:

$$Sh = \varphi(Gr, Sc)$$

Which is analogous to the heat transfer correlation

$$Nu = \varphi(Gr, Pr)$$

2.4 ANALYSIS AMONG MASS, HEAT AND MOMENTUM TRANSFER:

Diffusion in one dimension is described by the Fick's Law as

$$J_A = -D_{AB} \frac{dC_A}{dz} \quad \dots\dots (2.7)$$

Similarly, Heat conduction is described by Fourier's law as

$$q = -K \frac{dT}{dz} \quad \dots\dots\dots (2.8)$$

Where K is thermal conductivity

The similar equation describing momentum transfer as given by Newton's law

$$\tau = -\mu \frac{dv}{dz}$$

Where, τ is the momentum flux (or shear stress) and μ is the viscosity of fluid.

The similarity among the transfer phenomena and accordingly the existence of the analogies require that the following five conditions exist within the system

1. The physical properties are constant
2. There is no mass or energy produced within the system. This implies that there is no chemical reaction within the system
3. There is no emission or absorption of radiant energy.
4. There is no viscous dissipation of energy.
5. The velocity profile is not affected by the mass transfer. This implies there should be a low rate of mass transfer.

2.4.1 REYNOLDS ANALOGY:

Reynolds postulated that the mechanisms for transfer of momentum, energy and mass are identical. Accordingly,

$$\frac{f}{2} = \frac{h}{\rho v C_p} = \frac{K_c}{v}$$

Here, h is heat transfer coefficient

f is friction factor

v is free stream velocity

Reynolds analogy is valid when Prandtl number or Schmidt number equals to 1.

It is not valid for viscous sublayer, where the molecular diffusivities become important.

2.4.2 CHILTON COLBURN ANALOGY:

This analogy is valid for gases and liquids within the range of $0.6 < Sc < 2500$ and $0.6 < Pr < 100$.

It is valid for both turbulence and laminar.

$$\frac{f}{2} = \frac{h}{\rho v C_p} Pr^{2/3} = \frac{K_c}{v} Sc^{2/3}$$

$$\frac{f}{2} = J_H = J_D$$

Example 2.1 A stream of air at 100 kPa pressure and 300 K is flowing on the top surface of a thin flat sheet of solid naphthalene of length 0.2 m with a velocity of 20 m/sec. The other data are:

Mass diffusivity of naphthalene vapor in air = $6 \times 10^{-6} \text{ m}^2/\text{sec}$

Kinematic viscosity of air = $1.5 \times 10^{-5} \text{ m}^2.\text{sec}$

Concentration of naphthalene at the air-solid naphthalene interface = $1 \times 10^{-5} \text{ kmol} / \text{m}^3$

Calculate:

(a) The average mass transfer coefficient over the flat plate

(b) the rate of loss of naphthalene from the surface per unit width

Note: For heat transfer over a flat plate, convective heat transfer coefficient for laminar flow can be calculated by the equation.

$$Nu = 0.664 Re_L^{1/2} Pr_L^{1/3}$$

you may use analogy between mass and heat transfer.

Solution: Given: Correlation for heat transfer

$$Nu = 0.664 Re_L^{1/2} Pr_L^{1/3}$$

The analogous relation for mass transfer is

$$Sh = 0.664 Re_L^{1/2} Sc_L^{1/3}$$

Where,

$$Sh = \frac{KL}{D_{AB}}$$

$$Sc = \frac{\gamma}{D_{AB}}$$

$$Re = \frac{Dv\rho}{\mu}$$

$$\frac{K(0.2)}{(6 \times 10^{-6})} = 0.664 * \left(\frac{(0.2 * 20)}{(1.5 \times 10^{-5})} \right)^{1/2} \left(\frac{(1.5 \times 10^{-5})}{(6 \times 10^{-6})} \right)^{1/3}$$

$$K = 0.014 \text{ m/sec}$$

Rate of loss of naphthalene

$$= k(C_{Ai} - C_{Ab})$$

$$= 0.014 * (1.0 * 10^{-5} - 0)$$

$$= 1.4024 * 10^{-7} \text{ kmol/m}^2 \text{ sec}$$

Rate of loss per meter width

$$= (1.4024 * 10^{-7}) * (0.2)$$

$$= 2.80 * 10^{-8} \text{ kmol/m sec}$$

2.5 CONVECTIVE MASS TRANSFER CORRELATIONS:

Extensive data have been obtained for the transfer of mass between a moving fluid and certain shapes, such as flat plates, spheres and cylinders.

2.5.1 FLAT PLATE:

From the experimental measurements of rate of evaporation from a liquid surface or from the sublimation rate of a volatile solid surface into a

controlled air-stream, several correlations are available. These correlation have been found to satisfy the equations obtained by theoretical analysis on boundary layers,

$$Sh = 0.664 Re_L^{1/2} Sc_L^{1/3}, \text{ for } Re_L < 3 * 10^5$$

$$Sh = 0.036 Re_L^{0.8} Sc_L^{1/3}, \text{ for } Re_L > 3 * 10^5$$

These equations may be used if the Schmidt number in the range $0.6 < Sc < 2500$.

Example 2.2 If the local Nusselt number for the laminar boundary layer that is formed over a flat plate is

$$Nu_x = 0.332 Re_x^{1/2} Pr_x^{1/3}$$

Obtain an expression for the average film-transfer coefficient \bar{k}_c , when the Reynolds number for the plate is

a) $Re_L = 100\ 000$

b) $Re_L = 1500\ 000$

The transition from laminar to turbulent flow occurs at $Re_x = 3 \times 10^5$.

Solution: By definition:

$$\bar{k}_c = \frac{\int_0^L k_c dx}{\int_0^L dx}$$

and

$$Nu_x = \frac{k_c x}{D_{AB}}$$

$$Sc_x = \frac{\gamma}{D_{AB}}$$

$$Re_x = \frac{xv\rho}{\mu}$$

For $Re_L = 100000$; (which is less than the Reynolds number corresponding to Transition value of $3 * 10^5$)

$$\bar{k}_c = \frac{\int_0^L 0.332 \left(\frac{xv\rho}{\mu} \right)^{1/2} Sc_x^{1/3} \frac{D_{AB}}{x} dx}{\int_0^L dx}$$

$$\bar{k}_c = \frac{0.332 \left(\frac{v\rho}{\mu} \right)^{1/2} Sc_x^{1/3}}{L} D_{AB} \int_0^L \frac{dx}{x^{1/2}}$$

i.e.

$$Sh_L = \frac{\bar{k}_c L}{D_{AB}} = 0.664 (Re_L)^{1/2} Sc_L^{1/3}$$

For $Re_L = 1500000 (> 3 \times 10^5)$;

$$\bar{k}_c = \frac{\left(\int_0^{L_t} 0.332(Re_x)^{\frac{1}{2}} Sc_x^{\frac{1}{3}} \frac{D_{AB}}{x} dx + \int_{L_t}^L 0.0292(Re_x)^{\frac{4}{5}} Sc_x^{\frac{1}{3}} \frac{D_{AB}}{x} dx \right)}{\int_0^L dx}$$

$$\bar{k}_c = D_{AB} \frac{\left(0.332 \left(\frac{v\rho}{\mu} \right)^{\frac{1}{2}} Sc_x^{\frac{1}{3}} \int_0^{L_t} \frac{dx}{x^{\frac{1}{2}}} + 0.0292 \left(\frac{v\rho}{\mu} \right)^{\frac{4}{5}} Sc_x^{\frac{1}{3}} \int_{L_t}^L \frac{dx}{x^{\frac{1}{5}}} \right)}{L}$$

$$Sh_L = \frac{\bar{k}_c L}{D_{AB}} = 0.664(Re_t)^{\frac{1}{2}} Sc_x^{\frac{1}{3}} + 0.0365 Sc_x^{\frac{1}{3}} ((Re_L)^{\frac{4}{5}} - (Re_t)^{\frac{4}{5}})$$

Where, $Re_t = 3 \times 10^5$

2.5.2 SINGLE SPHERE

Correlations for mass transfer from single spheres are represented as addition of terms representing transfer by purely molecular diffusion and transfer by forced convection, in the form

$$Sh = Sh_0 + C Re_L^m Sc_L^n$$

Where C, m and n are constants, the value of n is normally taken as 1/3.

For very low Reynolds number, the Sherwood number should approach a value of 2. Therefore the generalized equation becomes

$$Sh = 2 + C Re_L^m Sc_L^{\frac{1}{3}}$$

For mass transfer into liquid streams, the equation given by Brain and Hales

$$Sh = (4 + 1.21 Pe_{AB}^{\frac{1}{3}})^{\frac{1}{2}}$$

It is valid for when pecelet number Pe is less than 10,000. This pecelet number is equal to the product of Reynolds number and Schmidt number.

$$Pe_{AB} = Re Sc$$

For Peclet numbers greater than 10,000, the relation given by Levich,

$$Sh = 1.01 Pe_{AB}^{\frac{1}{3}}$$

This relation is given by Froessling,

$$Sh = 2 + 0.552 Re_L^{\frac{1}{2}} Sc_L^{\frac{1}{3}}$$

It is valid for at Reynolds number ranging from 2 to 800 and Schmidt number ranging 0.6 to 2.7.

For natural convection mass transfer, the relation given by Schutz

$$Sh = 2 + 0.59 (Gr_{AB} Sc)^{\frac{1}{4}}$$

It is useful over the range $2 \times 10^8 < Gr_{AB} Sc < 1.5 \times 10^{10}$.

Example 2.3 The mass flux from a 5 cm diameter naphthalene ball placed in stagnant air at 40° C and atmospheric pressure, is 1.47×10^{-3} mol/m². sec.

Assume the vapor pressure of naphthalene to be 0.15 atm at 40°C and negligible bulk concentration of naphthalene in air. If air starts blowing across the surface of naphthalene ball at 3 m/s by what factor will the mass transfer rate increase, all other conditions remaining the same? For spheres : $Sh = 2 + 0.6 Re_L^{\frac{1}{2}} Sc_L^{\frac{1}{3}}$

Where Sh is the Sherwood number and Sc is the Schmidt number. The viscosity and density of air are 1.8×10^{-5} kg/m.s and 1.123 kg/m³, respectively and the gas constant is 82.06 cm³.atm mol.K.

Solution: Given:

Mass Flux, $N_A = 1.47 \times 10^{-3}$ mol/m². sec.

$$N_A = K_G (\Delta P_A)$$

$$\text{Therefore, } K_G = \frac{K_C}{RT}$$

$$N_A = \frac{K_C}{RT} (\Delta P_A)$$

$$\frac{K_C}{RT} \left(\frac{0.15}{1} - 0 \right) = 1.47 \times 10^{-3} \times 10^{-4}$$

$$K_C = \frac{1.47 \times 10^{-7}}{0.15} * 82.06 * (273 + 40)$$

$$= 0.0252 \text{ cm/sec}$$

$$K_C = 2.517 \times 10^{-4} \text{ m/sec} \dots\dots (1)$$

Estimation of D_{AB} :

$$Sh_L = \frac{K_C L}{D_{AB}} = 2 \quad (\text{since } v = 0)$$

$$\frac{2.517 \times 10^{-4} * 5 \times 10^{-2}}{D_{AB}} = 2$$

$$D_{AB} = 6.2925 \times 10^{-6} \text{ m}^2 / \text{sec}$$

$$Sh = 2 + 0.6 Re_L^{1/2} Sc_L^{1/3}$$

$$\frac{k_c L}{D_{AB}} = 2 + 0.6 * \left(\frac{Lv\rho}{\mu} \right)^{0.5} \left(\frac{\gamma}{D_{AB}} \right)^{0.33}$$

$$\frac{K_c L}{D_{AB}} = 2 + 0.6 * \left(\frac{Lv\rho}{\mu} \right)^{0.5} \left(\frac{\gamma}{D_{AB}} \right)^{0.33}$$

$$\frac{K_c * 5 \times 10^{-2}}{6.2925 \times 10^{-6}} =$$

$$2 + 0.6 * \left(\frac{5 \times 10^{-2} * 3 * 1.123}{1.8 \times 10^{-5}} \right)^{0.5} \left(\frac{1.8 \times 10^{-5}}{1.123 * 6.2925 \times 10^{-6}} \right)^{0.33}$$

$$K_c = 0.0102 \text{ m/sec} \quad \dots (2)$$

Dividing equation (2) by (1), we get

$$\frac{N_{A2}}{N_{A1}} = \frac{0.0102}{2.517 \times 10^{-4}} = 40.5$$

2.5.3 SINGLE CYLINDER

Several investigators have studied the rate of sublimation from a solid cylinder into air flowing normal to its axis. Bedingfield and Drew correlated the available data in the form

$$\frac{k_G P Sc^{0.56}}{G_M} = 0.281 * (Re')^{-0.4}$$

Which is valid for $400 < Re < 25000$ and $0.6 < Sc < 2.6$

Where Re' the Reynolds number in terms of the diameter of the cylinder is G_M is the molar mass velocity of gas and P is the pressure.

2.5.4 FLOW THROUGH PIPES

Mass transfer from the inner wall of a tube to a moving fluid has been studied extensively. Gilliland and Sherwood, based on the study of rate of vaporization of nine different liquids into air given the correlation

$$Sh \frac{P_{BLM}}{P} = 0.023 Re_L^{0.83} Sc_L^{0.44}$$

Where, P_{BLM} is log mean composition of Carrier gas. This correlation is valid for over the range $2000 < Re < 35000$ and $0.6 < Sc < 2.5$.

Linton and Sherwood modified the above relation,

$$Sh = 0.023 Re_L^{0.83} Sc_L^{0.33}$$

and found to be valid for $2000 < Re < 70000$ and $1000 < Sc < 2260$.

Example 2.4 A solid disc of benzoic acid 3 cm in diameter is spinning at 20 rpm and 25° C. Calculate the rate of dissolution in a large volume of water. Diffusivity of benzoic acid in water is $1.0 \times 10^{-5} \text{ cm}^2 / \text{sec}$, and solubility is 0.003 g/cc. The following mass transfer correlation is applicable:

$$Sh = 0.6 Re_L^{1/2} Sc_L^{1/3}$$

Where, $Re = \frac{D^2 \omega \rho}{\mu}$ and ω is the angular speed in radians/time.

Solution:

$$\text{Diffusion rate} = N_A S \quad \dots (1)$$

Where, N_A = mass flux, and

S = surface area for mass transfer

$$N_A = K_c (C_{As} - C_{A\infty}) \quad \dots (2)$$

Where, C_{As} is the concentration of benzoic and at in water at the surface of the disc.

$C_{A\infty}$ is the concentration benzoic acid in wate for an from the surface of the disc.

Given:

$$Sh = 0.62 Re_L^{0.5} Sc_L^{0.33}$$

$$\frac{k_c D}{D_{AB}} = 0.62 \left(\frac{D^2 \omega \rho}{\mu} \right)^{0.5} \left(\frac{\gamma}{D_{AB}} \right)^{0.33} \quad \dots (3)$$

$$1 \text{ rotation} = 2 \pi \text{ radian}$$

$$\text{Therefore } 20 \text{ rotation per minute} = 20 * 2 \pi$$

$$\text{radian/min}$$

$$= 20/60 * 2 \pi \text{ radian/sec}$$

For water, $\rho = 1 \text{ g/cc}$, $\mu = 0.01 \text{ gm/cm.sec}$

From Equation (3),

$$k_c = 0.62 D_{AB} \left(\frac{\omega \rho}{\mu} \right)^{0.5} \left(\frac{\gamma}{D_{AB}} \right)^{0.33}$$

$$k_c = 0.62 * 1 * 10^{-5} * \left(\frac{(40\pi/60) * 1}{0.01} \right)^{0.5} \left(\frac{0.01}{1 * 10^{-5}} \right)^{0.33}$$

$$k_c = 8.973 * 10^{-4} \text{ cm/sec}$$

From Equation (2),

$$N_A = 8.973 * 10^{-4} * (0.003 - 0)$$

$$= 2.692 * 10^{-6} \text{ g/cm}^2.\text{sec}$$

From Equation (1),

$$N_A S = N_A * 2\pi r^2$$

$$= 2.692 * 10^{-6} * (2\pi * 1.5^2)$$

$$= 3.805 * 10^{-5} \text{ gm/sec}$$

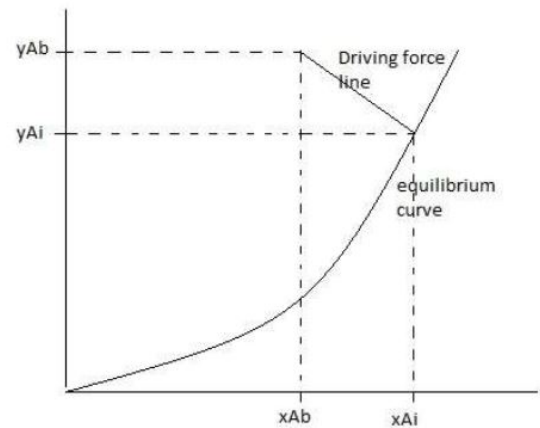
2.6 MASS TRANSFER BETWEEN PHASES:

In mass transfer from one phase to another phase, involved following sequential steps:

- 1) Solute A is transported from bulk of the gas phase to gas liquid interface because of driving force i.e. $(y_{Ab} - y_{Ai})$. Where, y_{Ab} = mole fraction of A in gas bulk phase and y_{Ai} = mole fraction of A in gas liquid interface on the gas side.
- 2) Solute A is absorbed by the liquid phase at the gas liquid interface such that the two concentrations are related by an equilibrium relationship $y_{Ai} = \phi(x_{Ai})$ or it is given by distribution coefficient $K = \frac{y_{Ai}}{x_{Ai}}$
- 3) The absorbed solute is transported from the gas liquid interface to the bulk of liquid

- 4) because of the same driving force i.e. $(x_{Ai} - x_{Ab})$. Where, x_{Ai} = mole fraction of A in gas liquid interface on the liquid side and x_{Ab} = mole fraction of A in the liquid bulk phase.

2.6.1 DETERMINATION OF INTERFACIAL CONCENTRATION:



For steady state, no accumulation and no generation, the mass transfer from one phase to another phase is given by,

$$N_A = K_y (y_{Ab} - y_{Ai}) \\ = K_x (x_{Ai} - x_{Ab}).$$

From graph, the slope of driving force line is,

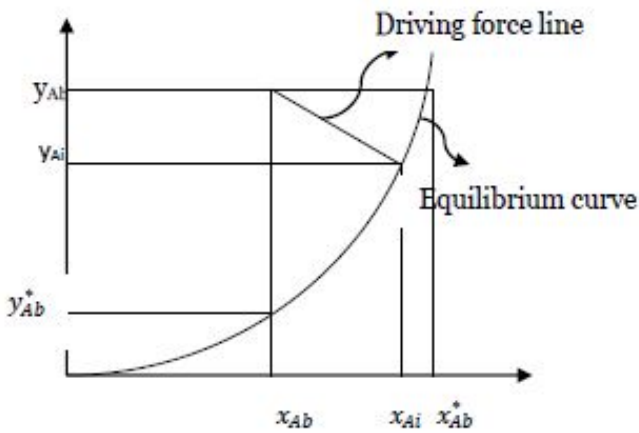
$$\frac{(y_{Ab} - y_{Ai})}{(x_{Ab} - x_{Ai})} = \frac{-K_x}{K_y}$$

Since the concept of interface is hypothetical. Determination of interfacial concentrations accurately is impossible to solve this problem; we introduce the concept of overall mass transfer coefficient.

Overall mass transfer coefficient is analogous to overall heat transfer coefficient and for that overall driving force may be defined as based on the liquid side or based on the gas side

$$N_A = K_Y(y_{Ab} - y_{Ab}^*)$$

$$= K_X(x_{Ab}^* - x_{Ab}).$$



From graph, the slope of driving force line is given by,

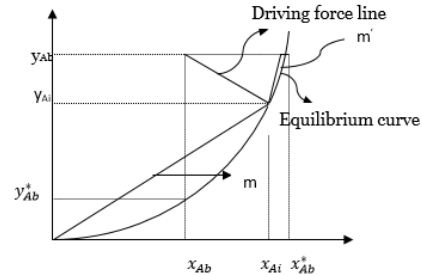
$$\frac{(y_{Ab} - y_{Ab}^*)}{(x_{Ab}^* - x_{Ab})} = \frac{-K_X}{K_Y}$$

Where, K_Y and K_X are Overall mass transfer coefficient based on the gas side or based on the liquid side.

y_{Ab}^* = Overall concentration in gas phase, which can remain in equilibrium with bulk liquid phase concentration x_{Ab} .

x_{Ab}^* = Overall concentration in liquid phase, which can remain in equilibrium with bulk gas phase concentration y_{Ab} .

2.6.2 DETERMINATION OF OVERALL MASS TRANSFER COEFFICIENT:



For gases:

$$(y_{Ab} - y_{Ab}^*) = (y_{Ab} - y_{Ai}) + (y_{Ai} - y_{Ab}^*)$$

$$\frac{N_A}{K_Y} = \frac{N_A}{K_Y} + m \frac{N_A}{K_X}$$

$$\frac{1}{K_Y} = \frac{1}{K_Y} + \frac{m}{K_X}$$

For liquids:

$$(x_{Ab}^* - x_{Ab}) = (x_{Ab}^* - x_{Ai}) + (x_{Ab} - x_{Ai})$$

$$\frac{N_A}{K_X} = \frac{N_A}{m'K_Y} + \frac{N_A}{K_X}$$

$$\frac{1}{K_X} = \frac{1}{m'K_Y} + \frac{1}{K_X}$$

2.7 THEORIES OF MASS TRANSFER:

2.7.1 FILM THEORY:

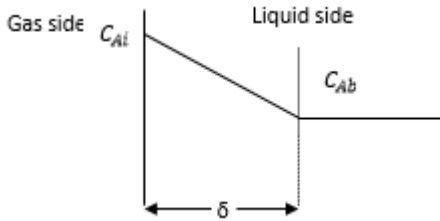
It is given by Whitman in 1923, and it considers mass transfer from a solid to flowing liquid.

Assumptions:

- 1) Mass transfer occurs purely by molecular diffusion at the phase boundary (wall).
- 2) The mass transfer through the film occurs at steady state.

- 3) Bulk flow term will be negligible at the phase boundary, hence it is neglected.

Beyond the film, the fluid is well mixed having concentration which is same as that of the bulk fluid concentration C_{Ab} .



$$N_A = K_m (C_{Ai} - C_{Ab})$$

$$N_A = \frac{D_{AB}}{\delta} (C_{Ai} - C_{Ab})$$

$$K_m = \frac{D_{AB}}{\delta}$$

2.7.2 PENETRATION THEORY:

It is given by HIGBIE, it tells us as the bubble rises, liquid elements from the bulk reach the top of the bubble move along its periphery, reach its bottom, then get detached from it and detached liquid elements eventually get mixed with the bulk of liquid.

Assumptions:

- 1) Unsteady state mass transfer occurs to liquid elements as long as it is contact with the bubble.
- 2) Equilibrium exists at the gas liquid interface.
- 3) Each of the liquid element stay in contact with the gas for same period of time.
- 4) The liquid element will be of infinite thickness.

$$\frac{\delta^2 C_A}{\delta x^2} = \frac{1}{D_{AB}} \frac{\delta C_A}{\delta t}$$

Boundary Conditions:

$$\text{At } t=0, \quad z \geq 0, \quad C_A = C_{Ab}$$

$$\text{At } t \geq 0, \quad z=0, \quad C_A = C_{Ai}$$

$$\text{At } t \geq 0, \quad z > 0, \quad C_A = C_{Ab}$$

$$K_m = \sqrt{\frac{4D_{AB}}{\pi t}}$$

2.7.3 SURFACE RENEWAL THEORY:

It is given by DANKWERT in 1951, the drawback of penetration theory is the assumption that the contact time is same for all the liquid elements. In turbulent medium some of the liquid elements are swept away and some continue to be in contact for long time. These will be a distribution of edge for the liquid elements present at the interface at any moment.

Assumptions:

- 1) Liquid elements at the interface are being randomly replaced by the fresh element from the bulk.
- 2) At any moment, each of the liquid elements at the surface has the same probability of being replaced.

$$K_m = \sqrt{D_{AB} \cdot S}$$

Where, S= fraction of surface area renewed in unit time

GATE QUESTIONS

Q.1 The surface renewal frequency in Danckwert's model of mass transfer is given by (k_L ; mass transfer coefficient, m/s)

[GATE -2001]

(A) $\sqrt{k_L^2 D_A}$ (B) $k_L^2 D_A$

(C) $\frac{k_L^2}{D_A}$ (D) $\frac{k_L}{D_A^2}$

Q.2 The Reynolds analogy for momentum heat and mass transfer is best applicable for

[GATE -2001]

- (a) gases in turbulent flow
- (b) gases in laminar flow
- (c) liquids in turbulent flow
- (d) liquids and gases in laminar flow

Q.3. The dimensionless group in mass transfer that is equivalent to prandtl number in heat transfer is

[GATE -2002]

- (a) nusselt number
- (b) Sherwood number
- (c) Schmidt number
- (d) Stanton number

Q.4 The diffusion coefficient, in m^2 / s . of Acetic acid in Benzene (liquid in liquid) is

[GATE -2003]

- (A) 2.09×10^2 (B) 2.09×10^{-5}
 (C) 2.09×10^{-9} (D) 2.09×10^{-12}

Q.5 Component A is diffusing in a medium B. The flux N_A relative to a stationary points equal to the flux due to molecular diffusion if

[GATE -2003]

- (a) Diffusion of A is in stagnant medium B
- (b) Mass transfer is accompanied by reaction
- (c) Molecular mean free path is high
- (d) There is equimolar counter-diffusion

Q.6 Experiments were conducted to determine the flux of a species A in a stagnant medium across a gas-liquid interface. The overall mass transfer coefficient based on the liquid side for dilute systems for the above was estimated to be $4 \times 10^{-3} \text{ kg.mol/m}^2 \text{ s}$. The equilibrium data for the system is given as $y = 2x$ the flux across the interface (in $\text{kg.mol/m}^2 \text{ s}$.) for bulk concentrations of A in gas phase and liquid phase as $y = 0.4$ and $x = 0.01$, respectively is

[GATE -2003]

- (A) 5.6×10^{-4} (B) 8.5×10^{-4}
 (C) 5.6×10^{-3} (D) 8.5×10^{-3}

Q.7 The Reynolds Number of the liquid was increased 100 fold for a laminar falling film used for gas-liquid contacting. Assuming penetration theory is applicable, the fold – increase in the mass transfer coefficient (k_e) for the same system is

[GATE -2003]

- (A) 100 (B) 10
 (C) 5 (D) 1

Q.8 A pure drug is administered as a sphere and as a cube. The amount of drug is the same in the two tablets. Assuming that the shape and size do not influence the mass transfer, the ratio of rate of dissolution in water at $t=0$ for the cubic to spherical tablet is

[GATE -2003]

- (A) 0.54 (B) 1.04
(C) 1.24 (D) 1.9

Common Data Question 9-10

Pure aniline is evaporating through a stagnant air film of 1 mm thickness at 300 K and a total pressure of 100 kPa. The vapor pressure of aniline at 300 K is 0.1 kPa. The total molar concentration under these conditions is 40.1 mol / m^3 . The diffusivity of aniline in air is $0.74 \times 10^{-5} \text{ m}^2 / \text{s}$.

[GATE -2004]

Q.9 The numerical value of the mass transfer coefficient is 7.4×10^{-3} . Its units are

- (A) m / s
(B) $\text{mol / (m}^2 \text{ s Pa)}$
(C) cm / s
(D) $\text{kmol / (m}^2 \text{ s Pa)}$

Q.10 The rate of evaporation of aniline is 2.97×10^{-4} . Its units are

- (A) mol / s (B) $\text{mol / (cm}^2 \text{ s)}$
(C) $\text{mol / (m}^2 \text{ s)}$ (D) $\text{kmol / (m}^2 \text{ s)}$

Common Data Question 11-12

The boiling points for pure water and pure toluene are 100°C and 110.6°C , respectively. Toluene and water are completely immiscible in each other. A

well-agitated equi-molar mixture of toluene and water is prepared. [GATE -2004]

Q.11 The temperature at which the above mixture will exert a pressure of one standard atm is

- (A) Less than 100°C
(B) 100°C
(C) Between 100 and 110°C
(D) 110.6°C

Q.12 At a total pressure of one standard atm exerted by the vapors of water and toluene, the mole fraction of water x_w in the vapor phase satisfies

[GATE -2004]

- (A) $0 < x_w < 0.5$ (B) $x_w = 0.5$
(C) $0.5 < x_w < 1.0$ (D) $x_w = 1.0$

Q.13 A long cylinder and a sphere both of 5 cm diameter are made from the same porous material. The flat ends of cylinder are sealed. Both the cylinder and sphere are saturated with the same solution of sodium chloride. Later, both the objects are immersed for a short and equal interval of time in a large tank of water, which is well agitated. The fractions of salt remaining in the cylinder and the sphere are X_c and X_s , respectively. Which of the following statements is correct?

[GATE -2004]

- (A) $X_c > X_s$ (B) $X_c = X_s$
(C) $X_c < X_s$ (D) X_c is greater/less than X_s depending on the length of the cylinder.

Q.14 The ratio of the diffusion coefficient in a gas to that in a liquid is of the order of

[GATE -2005]

- (A) 10^5 (B) 10^{-5}
 (C) 10^{-2} (D) 10^2

Q.15 Two solid discs of benzoic acid (molecular weight = 122) of equal dimensions are spinning separately in large volumes of water and air at 300 K. The mass transfer coefficients for benzoic acid in water and air are 0.9×10^{-5} and 0.47×10^{-2} m/s respectively. The solubility of benzoic acid in water is 3 kg/m³ and the equilibrium vapor pressure of benzoic acid in air is 0.04 kPa. Then the disc

[GATE -2005]

- (A) Dissolves faster in air than in water
 (B) Dissolves faster in water than in air
 (C) Dissolves at the same rate in both air and water
 (D) Does not dissolve either in water or in air.

Q.16 Match the variation of mass transfer coefficient given by the theory in Group I with the appropriate variation in Group II

[GATE -2005]

Group I

- (P) Film Theory
 (Q) Penetration theory
 (R) Boundary layer theory

Group II

- (1) $\propto D_{AB}$
 (2) $\propto D_{AB}^{2/3}$
 (3) $\propto D_{AB}^{1/2}$

(A) P - 1, Q - 2, R - 3

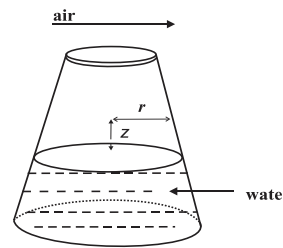
(B) P - 2, Q - 1, R - 3

(C) P - 1, Q - 3, R - 2

(D) P - 3, Q - 2, R - 1

Q.17 The following figure depicts steady one-dimensional diffusion of water vapor from the surface of water taken in a conical flask at room temperature. Derive the governing equation for determining the concentration profile of water vapor in the gas medium. Neglect change of level of water due to condensation. The temperatures of the gas and the liquid media are identical and constant.

[GATE -2007]



(A) $\frac{d}{dz} \left[r^2 \frac{CD_{wA}}{1-x_w} \frac{dx_w}{dz} \right] = 0$

(B) $\frac{d}{dz} \left[\frac{CD_{wA}}{1-x_w} \frac{dx_w}{dz} \right] = 0$

(C) $\frac{d}{dz} \left[r \frac{CD_{wA}}{1-x_w} \frac{dx_w}{dz} \right] = 0$

(D) $\frac{d}{dz} \left[rCD_{wA} \frac{dx_w}{dz} \right] = 0$

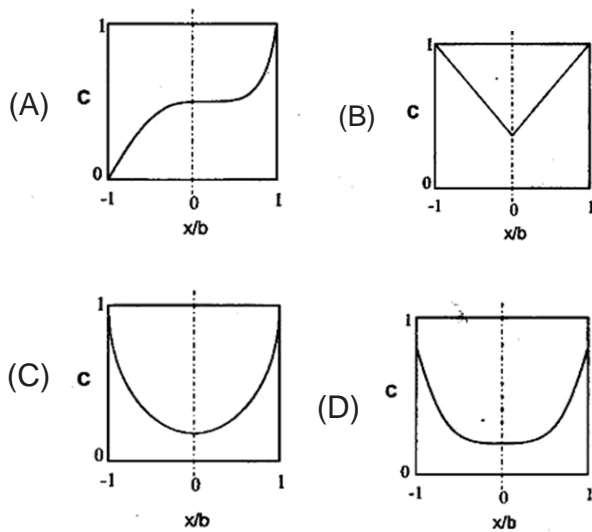
Q.18 A rectangular slab of thickness 2b along the x axis and extending to infinity along the other direction is initially at concentration C_{A0} . At time t=0, both surfaces of the slab(x=+b) have their concentrations increased to C_{AW} and maintained at that

value. Solute A diffuses into the solid. The dimensionless concentration C is defined as

$$C = \frac{c_A - c_{A0}}{c_{AW} - c_{A0}}$$

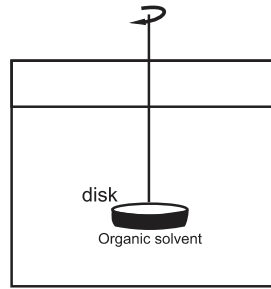
The diffusivity of A inside the solid is assumed constant. At a certain time instant, which **ONE** of the following is the correct representation of the concentration profile?

[GATE -2008]



Q.19 A sparingly soluble solute in the form of a circular disk is dissolved in an organic solvent s shown in the figure. The area available for mass transfer from the disk is A and the volume of the initially pure organic solvent is V . The disk is rotated along the horizontal plane at a fixed rpm to produce a uniform concentration of the dissolving solute in the liquid. The convective mass transfer coefficient under these conditions is k_c . The equilibrium concentration of the solute in the solvent is C^* . The time required for the concentration to reach 1% of the saturation value is given by

[GATE -2008]



(A) $\exp\left(\frac{-k_e A}{V} t\right) = 0.99$

(B) $\exp\left(\frac{-k_e A}{V} t\right) = 0.01$

(C) $\frac{V}{k_e A} \exp(-0.99) = t$

(D) $\frac{V}{k_e A} \exp(0.01) = t$

Q.20 According to the penetration theory of mass transfer, the mass transfer coefficient (k) varies with diffusion coefficient (D) of the diffusing species as

[GATE -2009]

- (A) D (B) $D^{-1/2}$
 (C) $D^{1/2}$ (D) $D^{3/2}$

Q.21 Species A is diffusing at steady state from the surface of a sphere (radius = 1 cm) into a stagnant fluid. If the diffusive flux at a distance $r = 3$ cm from the center of the sphere is $27 \text{ mol/cm}^2 \cdot \text{s}$, the diffusive flux (in $\text{mol/cm}^2 \cdot \text{s}$) at a distance $r = 9$ cm is

[GATE -2009]

- (A) 1 (B) 3
 (C) 9 (D) 27

Q.22 A liquid flows over a flat naphthalene plate of length L , at a Reynolds number ($Re_L = L\rho u_\infty / \mu$) of 1500, as shown in figure. The surface concentration of

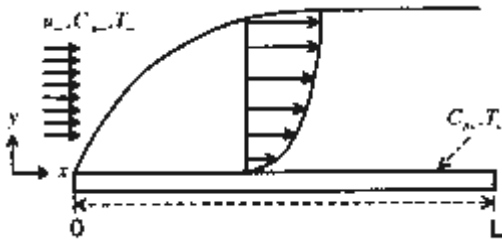
naphthalene is $C_{As} > C_{A\infty}$, and the surface temperature is $T_s > T_\infty$, Assume $Pr = Sc = 1$.

If at $x = L$, $\left. \frac{\partial C_A^*}{\partial y^*} \right|_{y^*=0} = 10$ where

$C_A^* = \frac{C_A - C_{As}}{C_{Ao} - C_{As}}$ and $y^* = \frac{y}{L}$, then the Nusselt

number and the friction coefficient at $x = L$, are

[GATE -2010]



(A) $10, \frac{1}{75}$ (B) 10, 10

(C) 20, 10 (D) $\frac{1}{75}$

Q.23 Ammonia (component 1) is evaporating from a partially filled bottle into surrounding air (component 2). The liquid level in the bottle and the concentration of ammonia at the top of the bottle are maintained constant. N_1 is the molar flux relative to a fixed location in space and J_1 , is the molar flux with respect to the average molar velocity of the constituent species in the gas phase. Assume that air in the bottle is stagnant. Which ONE of the following is CORRECT?

[GATE -2011]

- (A) $N_1 = \text{const}, N_2 = 0, J_1 + J_2 = 0$
- (B) $N_1 + N_2 = 0, J_1 + J_2 = 0$
- (C) $N_1 + N_2 = 0, J_1 = \text{const}, J_2 = 0$
- (D) $N_1 = \text{const}, N_2 = 0, J_1 = \text{const}, J_2 = 0$

Q.24 An equi-molar mixture of A and B (A being more volatile) is flash distilled continuously at a feed rate of 100 kmol / h, such that the liquid product contains 40 mol % of A if the relative volatility is 6, then the vapor product, in kmol / h, is

[GATE -2012]

- (A) 10 (B) 20
- (C) 25 (D) 45

Q.25 A study was conducted in which water was pumped through cylindrical pipes made of a sparingly soluble solid. For a given pipe and certain flow conditions, the mass transfer coefficient k_c has been calculated as 1 mm/s using the correlation $Sh = 0.025 Re^{0.6} Sc^{0.33}$

If the velocity of the fluid and the diameter of the pipe are both doubled, what is the new value of k_c in mm/s, up to 2 digits after the decimal point____. The vapor liquid equilibrium relation for an ideal binary system is given by

$$y_A^* = \frac{\alpha_{AB} x_A}{1 + (\alpha_{AB} - 1)x_A}$$

Here x_A and y_A^* are the mole fractions of species A in the liquid and vapor, respectively. The relative volatility (α_{AB}) is greater than unity.

[GATE -2013]

Q.26 A spherical storage vessel is quarter-filled with toluene. The diameter of the vent at the top of the vessel is 1/20th of the diameter of the vessel. Under the steady state condition, the diffusive flux of toluene is maximum at

[GATE -2014]

- (A) The surface of the liquid
- (B) The mid-plane of the vessel
- (C) The vent
- (D) A distance 20 times the diameter of the vent away from the vent

Q.27 Which ONE of the following statements is CORRECT for the surface renewal theory?

[GATE -2014]

- (A) Mass transfer takes place at steady state
- (B) Mass transfer takes place at unsteady state
- (C) Contact time is same for all the liquid elements
- (D) Mass transfer depends only on the film resistance

Q.28 A spherical ball of benzoic acid (diameter = 1.5 cm) is submerged in a pool of still water. The solubility and diffusivity of benzoic acid in water are 0.03 kmol/m^3 and $1.25 \times 10^{-9} \text{ m}^2/\text{s}$ respectively. Sherwood number is given as $Sh = 2.0 + 0.6 Re^{0.5} Sc^{0.33}$. The initial rate of dissolution (in kmol/s) of benzoic acid approximately is

[GATE -2014]

- (A) 3.54×10^{-11}
- (B) 3.54×10^{-12}
- (C) 3.54×10^{-13}
- (D) 3.54×10^{-14}

Q.29 A spherical naphthalene ball of 2mm diameter is subliming very slowly in stagnant air at 25°C . The change in the size of the ball during the sublimation can be neglected. The diffusivity of naphthalene in air at 25°C is $1.1 \times 10^{-6} \text{ m}^2/\text{s}$. The value of

mass transfer coefficient is $B \times 10^{-3} \text{ m/s}$, where B (up to one decimal place) is ____

[GATE -2015]

Q.30 For a binary mixture of components A and B, N_A and N_B denote the total molar fluxes of components A and B, respectively. J_A and J_B are the corresponding molar diffusive fluxes. Which of the following is true for equi - molar counter-diffusion in the binary mixture?

[GATE -2015]

- (A) $N_A + N_B = 0$ and $J_A + J_B \neq 0$
- (B) $N_A + N_B \neq 0$ and $J_A + J_B = 0$
- (C) $N_A + N_B \neq 0$ and $J_A + J_B \neq 0$
- (D) $N_A + N_B = 0$ and $J_A + J_B = 0$

Q.31 Consider a steady state mass transfer process between well-mixed liquid and vapour phases of a binary mixture comprising of components A and B. The mole fractions of component A in the bulk liquid (x_A) and bulk vapour (y_A) phases are 0.36 and 0.16, respectively. The mass transfer coefficients for component A in liquid and vapour phases are $0.1 \text{ mol}/(\text{m}^2.\text{s})$ and $0.05 \text{ mol}/(\text{m}^2.\text{s})$, respectively. The vapour-liquid equilibrium can be approximated as $y_A^* = 2x_A$ for x_A less than 0.4. The mole fraction of A in the liquid at the interface (up to two decimal places) is

[GATE -2015]

Q.32 Consider the following two cases for a binary mixture of ideal gases A and B under steady state conditions. In Case 1, the diffusion of A occurs through non-diffusing B. In Case 2, equimolar counter diffusion of

A and B occurs. In both the cases, the total pressure is 100 kPa and the partial pressures of A at two points separated by a distance of 10 mm are 10 kPa and 5 kPa. Assume that the Fick's first law of diffusion is applicable. What is the ratio of molar flux of A in Case 1 to that in Case 2?

[GATE -2016]

- (A) 0.58 (B) 1.08
(C) 1.58 (D) 2.18

Q.33 Consider steady state mass transfer of a solute A from a gas phase to a liquid phase. The gas phase bulk and interface mole fractions are $y_{A,o}$ and $y_{A,i}$ respectively. The liquid phase bulk and interface mole fraction are $x_{A,L}$ and $x_{A,i}$, respectively. The

ratio $\frac{(x_{A,i} - x_{A,L})}{(y_{A,G} - y_{A,i})}$ is very close to zero. The implies that mass transfer resistance is

[GATE -2017]

- (a) Negligible in the gas phase only
(b) Negligible in the liquid phase only
(c) Negligible in both the phase
(d) Considerable in both the phase

Q.34 The sherwood number (Sh_L) correlation for laminar flow over a flat plate of length L is given by

$$Sh_L = 0.664 Re_L^{0.5} Sc^{1/3}$$

Where Re_L and Sc represent Reynolds number and Schmidt number, respectively. This correlation, expressed in the form of Chilton – Colburn j_D factor is

[GATE -2017]

- (A) $j_D = 0.664$ (B) $j_D = 0.664 Re_L^{-0.5}$
(C) $j_D = 0.664 Re_L$ (D) $j_D = 0.664 Re_L^{0.5} Sc^{2/3}$

Q.35 According to the surface renewal theory, the unit of fractional rate of surface renewal is

[GATE -2018]

- (A) $m^2 s^{-2}$ (B) $m^2 s^{-1}$
(B) $m s^{-1}$ (D) s^{-1}

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(C)	(A)	(C)	(C)	(D)	(B)	(B)	(C)	(A)	(D)	(A)	(C)	(C)	(A)
15	16	17	18	19	20	21	22	23	24	25	26	27	28
(B)	(C)	(A)	(C)	(A)	(C)	(B)	(A)	(A)	(A)	(D)	(C)	(B)	(B)
29	30	31	32	33	34	35							
(1.1)	(D)	(0.106)	(B)	(B)	(B)	(D)							

EXPLANATIONS

Q.1. (C)

Danckwerts model

$$S = \frac{K_L^2}{D_{AB}}$$

Where, D_{AB} - Diffusivity

K_L - Mass transfer coefficient

S - Surface renewal frequency

Q.2. (A)

Reynolds analogy \Rightarrow to relate turbulent momentum and heat transfer

$$\frac{f}{2} = \frac{h}{C_p G} = \frac{K_c'}{V_{\text{average}}}$$

For gas \Rightarrow if Schmidt and Prandtl number are near 1.0 and only skin friction is present in flow past a flat plate or inside a pipe, experimental data are near to the above equation for liquid or form drag analogy is invalid

Q.3. (C)

$$P_t = \frac{C_p \mu}{k} = \frac{\mu}{\frac{\rho}{k}} = \frac{\text{momentum diffusivity}}{\text{Thermal diffusivity}}$$

$$S_c = \frac{\mu}{\rho D_{AB}} = \frac{\left(\frac{\mu}{\rho}\right)}{D_{AB}} = \frac{\text{Momentum diffusivity}}{\text{mass diffusivity}}$$

Q.4 (C)

Liquid in liquid diffusion coefficient order

$$\Rightarrow 10^{-9} \frac{\text{m}^2}{\text{sec}}$$

(gas in gas) diffusion coefficient order

$$\Rightarrow 10^{-5} \text{ m}^2/\text{sec.}$$

Diffusion coefficient is a physical constant which depends on temperature, pressure, molecular size and some other properties of diffusing substance

Q.5. (D)

$$N_A = J_A^* + \frac{C_A}{C} (N_A + N_B)$$

Given flux $N_A = J_A^*$

\therefore From equation $N_A + N_B = 0$

$$N_A = -N_B$$

Therefore equimolar counter diffusion

Q.6. (B)

Flux across the interface (gas - liquid)

$$N_A = k_x \frac{(X_{AG} - X_{AL})}{(1 - X_A)_{LM}}$$

Given ; $y = 2x$

$$\therefore y_{AG} = 0.4$$

$$\therefore X_{AG} = \frac{0.4}{2} = 0.2$$

$$\text{and } X_{AL} = 0.01 \text{ (given)}$$

$$\begin{aligned} \text{Now } (1 - X_A)_{LM} &= \frac{(1 - X_{AL}) - (1 - X_{AG})}{\ln \frac{1 - X_{AL}}{1 - X_{AG}}} \\ &= \frac{(1 - 0.01) - (1 - 0.2)}{\ln \left(\frac{1 - 0.01}{1 - 0.2} \right)} = 0.891 \end{aligned}$$

$$k_x = 4 \times 10^{-3} \text{ kg mol/m}^2 \cdot \text{s} \text{ \{given\}}$$

$$\begin{aligned} N_A &= k_x \times \frac{X_{AG} - X_{AL}}{(1 - X_A)_{LM}} = 4 \times 10^{-3} \times \frac{(0.2 - 0.01)}{0.891} \\ &= 8.51 \times 10^{-4} \text{ kmol/m}^2 \cdot \text{s} \end{aligned}$$

Q.7 (B)

From penetration theory

$$k_c = 2 \sqrt{\frac{D_{AB}}{\pi t}}$$

$$\therefore k_c = 2 \sqrt{\frac{D_{AB} \times u}{\pi L}} \quad \therefore t = \frac{L}{u}$$

$$k_c \propto \sqrt{u}$$

$$\therefore \frac{k_{c_2}}{k_{c_1}} = \sqrt{\frac{u_2}{u_1}} = \sqrt{\frac{\rho u_2 d}{\mu} \times \frac{\mu}{\rho u_1 d}}$$

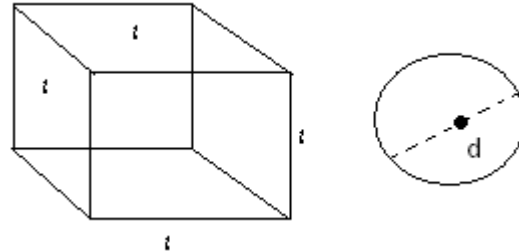
$$\therefore Re_c = \frac{\rho u d}{\mu} \quad \therefore \frac{k_{c_2}}{k_{c_1}} = \sqrt{\frac{Re_2}{Re_1}}$$

$$\therefore \frac{Re_2}{Re_1} = 100 \text{ (given)} \quad \therefore \frac{k_{c_2}}{k_{c_1}} = \sqrt{100}$$

$$\frac{k_{c_2}}{k_{c_1}} = 10$$

Q.8 (C)

$$\frac{\text{Rate of dissolution of cube}}{\text{Rate of dissolution of sphere}} = \frac{\text{surface area of cube}}{\text{surface area of sphere}}$$



Volume of cube = volume of sphere

$$\therefore l^3 = \frac{4}{3} \pi r^3$$

$$l^3 = \frac{4}{3} \pi \left(\frac{d}{2} \right)^3$$

$$\frac{l}{d} = \left(\frac{\pi}{6} \right)^{1/3}$$

$$\begin{aligned} &\frac{(\text{rate of dissolution})_{\text{cube}}}{(\text{rate of dissolution})_{\text{sphere}}} \\ &= \frac{6l^2}{4\pi r^2} = \frac{6l^2}{4\pi \left(\frac{d}{2} \right)^2} = \frac{6}{\pi} \left(\frac{l}{d} \right)^2 \end{aligned}$$

$$= \frac{6}{\pi} \left(\frac{\pi}{6} \right)^{2/3} = 1.24$$

Q.9 (A)

Numerical value of mass transfer coefficient.

According to film theory

$$k_c = \frac{D_{AB}}{\delta} = \frac{00.74 \times 10^{-5} \text{ m}^2 / \text{sec}}{01 \times 10^{-3} \text{ m}} = 7.4 \times 10^{-3} \text{ m/sec}$$

Q.10 (D)

Rate of evaporation of aniline is 2.97×10^{-4}

$$\text{Rate of evaporation} = K_c (C_A - 0)$$

$$= 7.4 \times 10^{-3} \frac{\text{m}}{\text{sec}} \times \left(40.1 \frac{\text{mol}}{\text{m}^3} \right)$$

$$= 2.97 \times 10^{-4} \frac{\text{kmol}}{\text{m}^2 \cdot \text{sec}}$$

Its unit is $\text{kmol} / \text{m}^2 \text{ sec}$.

Q.11 (A)

The boiling point of a mixture of two immiscible liquids is always less than the boiling point of each individual component. i.e. the b.p of a mixture of water and toluene will be always less than 100°C (See the concept of steam distillation)

Q.12 (C)

As water has a lower bp than toluene at 1 std atm pressure (and for all temperatures) water has a higher vapor pressure than toluene. So the vapor phase will always be richer in water (but can never be equal to one if it is a mixture of toluene and water) $X_w > 0.5$ but less than 1.0 $0.5 < X_w < 1.0$

Q.13 (C)

Diffusion area of cylinder = πDL

$$\text{Diffusion area of sphere} = 4 \times \frac{\pi D^2}{4} = \pi D^2$$

Since in question long cylinder is given i.e $L \gg D$

$$\pi DL \gg \pi D^2$$

Hence more NaCl will diffuse,

i.e less fraction of salt would remain

in the cylinders compared to the sphere

Hence (C) is the correct answer.

Q.14 (A)

Q.15 (B)

We have

$$N_{\text{water}} = 0.9 \times 10^{-5} \frac{\text{m}}{\text{s}} \times \left(3.0 \frac{\text{kg}}{\text{m}^3} - 0 \right) = 2.7 \times 10^{-5} \frac{\text{kg}}{\text{m}^2 \cdot \text{s}}$$

$$\Rightarrow K_c (C_s - 0)$$

$$N_{\text{air}} = 0.47 \times 10^{-2} \frac{\text{m}}{\text{s}} \left[0.04 \text{ kPa} \times \frac{1 \text{ k mol}}{8.314 \text{ kPa} \cdot \text{m}^3} \times \frac{1}{300\text{k}} - 0 \right]$$

$$\Rightarrow k_p \left(\frac{P_m}{Rt} - 0 \right)$$

$$= 7.537 \times 10^{-8} \frac{\text{k mol}}{\text{m}^3 \cdot \text{s}}$$

$$= 7.537 \times 10^{-8} \frac{\text{kmol}}{\text{m}^3} \times 122 \frac{\text{kg}}{\text{k mol}} = 9.19 \times 10^{-6}$$

Q.16 (C)

Film theory $\rightarrow K \propto D_{AB}$

Penetration Theory $\rightarrow K \propto (D_{AB})^{2/3}$

Hence (C) is the correct answer.

Q.17 (A)

Q.18 (C)

Q.19 (A)

Q.20 (C)

According to penetration theory

$$(N_A)_{\text{avg}} = 2 (C_{Ai} - C_{Ao}) \sqrt{\frac{D_{AB}}{\pi \theta}}$$

$$(N_A)_{\text{avg}} = (k_L)_{\text{avg}} (C_{Ai} - C_{Ao})$$

$$(k_L)_{\text{avg}} = \sqrt{D_{AB}}$$

Q.21 (B)

$$J_{\text{flux}} \propto \frac{1}{A}$$

$$\therefore \frac{J_1}{J_2} = \frac{A_2}{A_1} = \frac{r_2^2}{r_1^2} \quad \text{or} \quad \frac{27}{J_2} = \frac{81}{9}$$

or $J_2 = 3 \text{ mol} / \text{cm}^2 \cdot \text{s}$

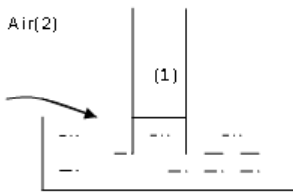
Hence, (B) is the correct answer.

Q.22 (A)

Q.23 (A)

We have Diffusion of component 1

Non- diffusing component is 2



$$N_1 = \frac{D_{12} P}{RTz p_{2,m}} (p_1 - p_{1,B}) \text{Liq level Constant}$$

Partial pressure of 1 at surface partial pressure of 1 in bulk

$N_1 = \text{constant}$

$N_2 = 0$

We know

$$N_1 = \underline{J_1} + X_A (N_1 + \cancel{N_2})^0 \quad J_1 = D_{12} \frac{\partial c_1}{\partial x},$$

Diffusive Flux

Under flux due to $J_2 = -D_{21} \frac{\partial c_2}{\partial x}$

$N_2 = J_2 + X_B N_1$

$0 = J_2 + X_B N_1$

or $N_1 = (J_1 + J_2) + N_1(X_A + \cancel{X_B}^{x=1}) = (J_1 + J_2) + N_1$

or $J_1 + J_2 = 0$, $N_1 = \text{constant}$, $N_2 = 0$

Hence (A) is the correct answer

Q.24 (A)

In flash distillation, vapor and liquid is in equilibrium

$x_F = 0.5$ and $x_B = 0.4$ $\alpha = 6$

$$y_D = \frac{\alpha x_B}{1 + (\alpha - 1)x_B} = 0.8$$

take balance

$D + B = 100 \dots \dots \dots (1)$

$0.8D + 0.4B = 50 \dots \dots \dots (2)$

By solving equations, we get $D = 25$

Hence Answer is (C)

Q.25 (1.148)

We know that

Schmidt No. $\Rightarrow N_{Sc} = \frac{\mu}{\rho D}$

Sherwood No. $\Rightarrow N_{Sh} = \frac{k_c L_c}{D}$

Reynolds No. $\Rightarrow N_{Re} = \frac{\rho v L_c}{\mu}$

Given that $N_{Sh} = 0.025 N_{Re}^{0.6} N_{Sc}^{0.33}$

Thus $\frac{k_c L_c}{D} = 0.025 \left(\frac{\rho v L_c}{\mu} \right)^{0.6} \left(\frac{\mu}{\rho D} \right)^{0.33}$

$\Rightarrow k_c \propto v^{0.6} D^{-0.4}$

$$\frac{k_{c1}}{k_{c2}} = \left(\frac{v_1}{v_2} \right)^{0.6} \left(\frac{D_2}{D_1} \right)^{0.4}$$

Given: $v_2 = 2v_1$ and $D_2 = 2D_1$

$\Rightarrow \frac{k_{c1}}{k_{c2}} = \left(\frac{v_1}{2v_1} \right)^{0.6} \left(\frac{2D_1}{D_1} \right)^{0.4}$

$$\Rightarrow \frac{k_{c1}}{k_{c2}} = \left(\frac{1}{2}\right)^{0.6} \left(\frac{2}{1}\right)^{0.4}$$

$$\Rightarrow \frac{k_{c1}}{k_{c2}} = 0.87055$$

$$\Rightarrow k_{c2} = 1.1487k_{c1}$$

The range is between 1.14 – 1.16.

Q.26 (C)

Q.27 (B)

Q.28 (B)

Given that

$$Sh = 2 + 0.6Re^{0.5} Sc^{0.33}$$

$$\text{Diameter} = 1.5 \text{ cm}$$

$$\text{solubility} = 0.03 \text{ kmol/m}^3$$

$$\text{Diffusivity} = 1.25 \times 10^{-9} \text{ m}^2/\text{s}$$

$$\text{Given } Sh = 2 + 0.6(Re)^{0.5}(Sc)^{0.33}$$

Initially Sh: 2

$$\frac{K_c d}{D_{AB}} = 2, K_c = \text{Mass transfer coefficient (m/s)}$$

$$\Rightarrow K_c = \frac{2 \times 1.25 \times 10^{-9}}{1.5 \times 10^{-2}} = 1.67 \times 10^{-7} \text{ m/sec}$$

$$\begin{aligned} \text{Initial rate of dissolution} &= K_c A(C_s - 0) = K_c AC_s \\ &= 1.67 \times 10^{-7} \times \pi \times (1.5 \times 10^{-2})^2 \times 0.03 = 3.54 \times 10^{-12} \text{ kmol/sec} \end{aligned}$$

Q.29 1.1

We know that

For spherical ball Dimensionless Sherwood number = 2

$$\frac{k_c L}{D_{AB}} = 2$$

When L = characteristic length = diameter of Spherical ball = d = 2 mm = 2 x 10⁻³ m

$$K_c = \frac{2 \times D_{AB}}{d} = \frac{2 \times 1.1 \times 10^{-3} \text{ m}}{2 \times 10^{-3}}$$

$$K_c = 1.1 \times 10^{-3} \text{ m/s}$$

$$\text{So, } B = 1.1$$

Q.30 (D)

Q.31 0.22

We have

$$\text{Given } x_A = 0.36$$

$$Y_A = 0.16$$

$$K_L = 0.1 \text{ mol/m}^2 \text{ sec}$$

$$K_s = 0.05 \text{ mol/m}^2 \text{ s}$$

$$y_A^* = 2x_A \quad \text{for } x_A < 0.4$$

$$\text{So } y_{Ai} = 2x_{Ai} \quad (i)$$

At steady state mass flux is constant

$$\begin{aligned} k_L(x_A - x_{Ai}) &= k_s(y_{Ai} - y_A) \\ 0.1(0.36 - x_{Ai}) &= 0.05(2x_{Ai} - 0.16) \end{aligned}$$

$$\frac{0.1}{0.05}(0.36 - x_{Ai}) = 2x_{Ai} - 0.16$$

$$0.72 - 2x_{Ai} = 2x_{Ai} - 0.16$$

$$x_{Ai} = 0.22$$

Q.32 (B)

We know that

$$\frac{NA_1}{NA_2} = \frac{1}{Y_{BLM}} = \frac{P}{P_{BLM}} = 1.08$$

Q.33 (B)

$$\text{Here } \frac{(x_{A,i} - x_{A,L})}{(y_{A,G} - y_{A,i})} = 0$$

$$\text{Or } x_{A,i} - x_{A,L} = 0$$

$$x_{A,i} = x_{A,L}$$

Mole fraction of liquid phase interface is equal to mole fraction of liquid phase bulk it means resistance in the liquid phase is negligible

Q.34 (B)

$$Sh_L = 0.664 Re_L^{0.5} Sc^{\frac{1}{3}} \rightarrow$$

$$\text{Chilton-Coburn factor } j_D = \frac{Sh_L}{Re_L Sc^{\frac{1}{3}}}$$

$$Sh_L = j_D \cdot Re_L Sc^{\frac{1}{3}}$$

From equation

$$j_D Re_L Sc^{\frac{1}{3}} = 0.664 Re_L^{0.5} Sc^{\frac{1}{3}}$$

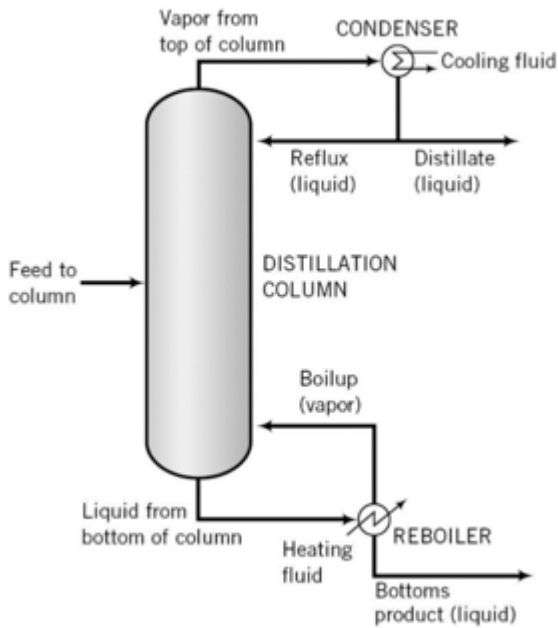
$$j_D = 0.664 Re_L^{-0.5}$$

Q.35 (D)

According to surface renewal theory the unit of surface renewal frequency is s^{-1}

3.1 INTRODUCTION

Distillation is a technique of separation of more volatile component from the lesser volatile ones in a feed solution. The separation is based on **relative volatility** of components. The mixer is always in Vapor-Liquid Equilibrium (VLE) in the distillation column.

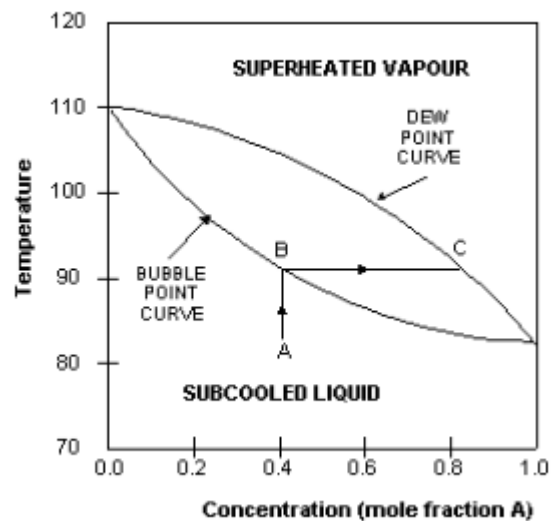


3.2 T-XY DIAGRAM

The boiling point diagram is a plot of temperature v/s compositions of liquid and vapor phases. This diagram is used to show how the equilibrium vapor and liquid phase compositions vary with temperature.

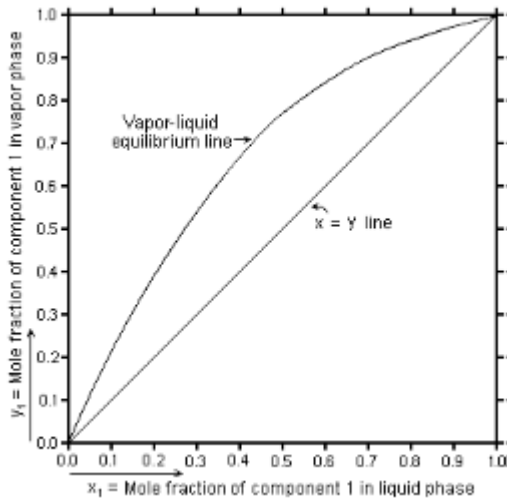
In the given figure, A is sub-cooled liquid mixture of two components. As the temperature of the system is increased, the

temperature of mixture increases till B (bubble point curve) without any change in the composition. At B, first vapor is formed with composition C and as the temperature increases the liquid composition follows **bubble point curve** and vapor composition follows **dew point curve**.



The line BC is known as **Tie Line** and represents the plate of distillation column. The top-most tie line is the last plate of column while the bottom-most tie line is the first plate of distillation column.

Since the vapor is richer in the more volatile substance, the curve lies above the 45° diagonal line, which has been drawn in for comparison.



3.3 RELATIVE VOLATILITY;

Relative volatility shows the ease of separation of more volatile component (A) from the lesser one (B). It is the ratio of A to B in the vapor phase to the same ratio in the liquid phase.

$$\alpha = \frac{y^A / y^B}{x^A / x^B}$$

NOTE: α is a function of temperature.

3.4 RAULT'S LAW

For an ideal solution, the equilibrium partial pressure P^* of a constituent at a fixed temperature equals the product of its vapor pressure P when pure at this temperature and its mole fraction x in liquid, this is Raoult's Law.

$$P_A^* = P_A x; \quad P_B^* = P_B (1-x)$$

If the vapor phase is also ideal,

$$P_t = P_A^* + P_B^* = P_A x + P_B (1-x)$$

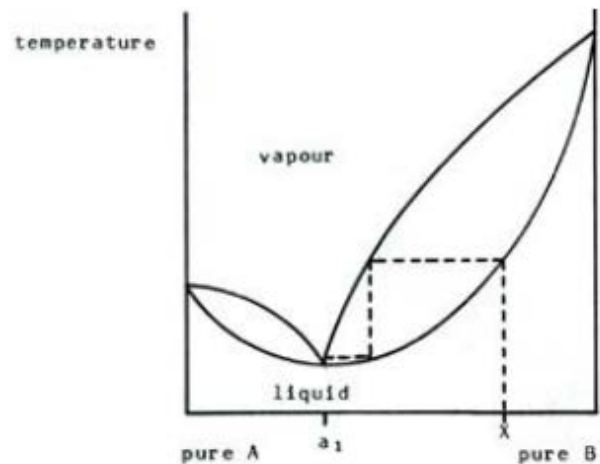
3.5 CONSTANT BOILING MIXTURES

An azeotrope is a mixture in which composition of the liquid does not change as it is converted into vapor. The dew point and the bubble point are identical at the azeotropic composition and thus the azeotropes are called **constant boiling mixtures**.

An azeotrope exhibits a maximum or a minimum boiling point relative to boiling points of the pure liquids and thus is classified as maximum boiling and minimum boiling azeotropes.

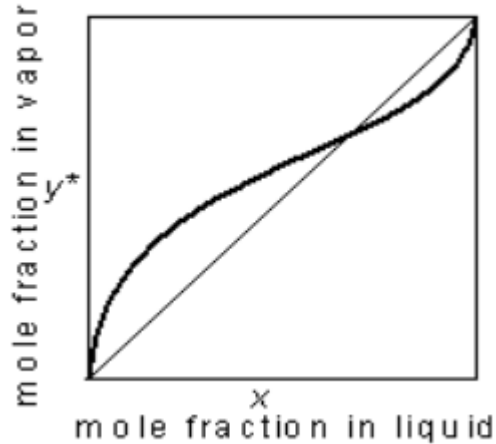
3.5.1 MINIMUM BOILING MIXTURES

Minimum boiling mixtures are also called **positive** azeotropes or **pressure maximum** azeotropes.



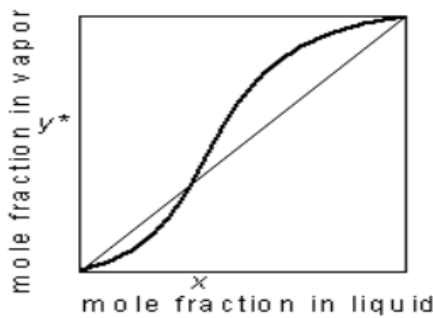
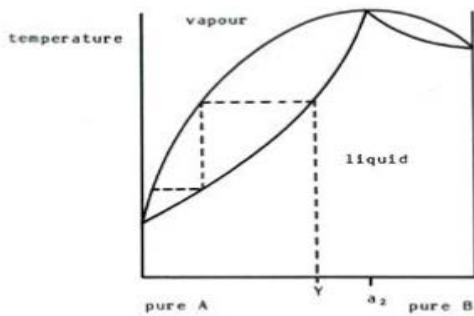
The intersecting point shows the composition at which concentrations at liquid and vapor phases become same and the separation cannot be done by using simple distillation column.

A graph between vapor and liquid phase compositions for more volatile component (A) can be shown as:



3.5.2 MAXIMUM BOILING MIXTURES

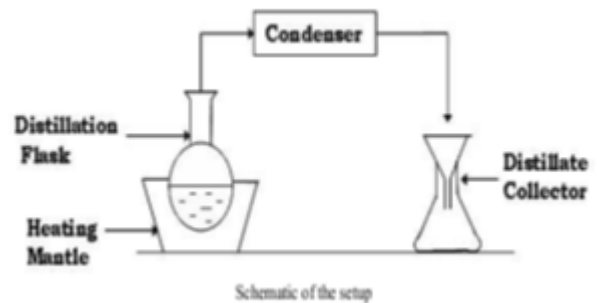
Maximum boiling mixtures are also called **negative azeotropes** or **pressure minimum azeotropes**.



3.6 DIFFERENTIAL DISTILLATION

In the case of a differential distillation, the vapor at any time is in equilibrium with the liquid from which it rises but changes continuously in the composition.

Thus, the mathematical approach used must be differential. Assume that L mol of liquid in the still of composition x mol fraction A and that an amount dD mol of distillate is vaporized, of mol fraction y^* in equilibrium with the liquid.



Rate of depletion of liquid is equal to the rate of distillate output, so the instantaneous rate of depletion of component in the liquid is therefore;

$$\text{In} - \text{Out} = \text{Accumulation}$$

$$0 - dD = dL$$

More volatile component;

$$0 - y^*dD = d(Lx)$$

$$-y^*dD = x dL + L dx$$

$$Y^*dL = x dL + L dx$$

$$\int_W^F \frac{dL}{L} = \int_{x_W}^{x_F} \frac{dx}{y^* - x}$$

$$\ln \frac{F}{W} = \int_{x_W}^{x_F} \frac{dx}{y^* - x}$$

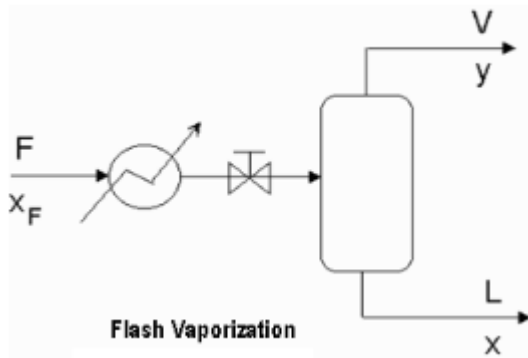
where, F = moles of feed with composition of more volatile component (A) as x_F , W = moles of residual liquid with composition of A as x_W .

The equation is called as **Rayleigh's equation**. In terms of relative volatility,

$$y^* = \frac{\alpha x}{1 + (\alpha - 1)x}$$

3.7 FLASH VAPORIZATION

Flash vaporization or also known as equilibrium distillation, is a single stage operation wherein a liquid mixture is partially vaporized, the vapor allowed to come to equilibrium with the residual liquid, and the resulting vapor and liquid phases are separated and removed from the vessel.



Material and enthalpy balances;

$$F = D + W$$

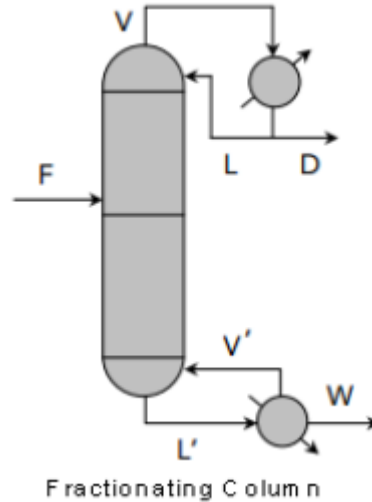
Component Balance

$$F z_F = D y_D + W x_W$$

Energy Balance

$$F H_F + Q = D H_D + W H_W$$

3.8 FRACTIONATION



Overall balance;

$$F = D + W$$

Component balance;

$$F x_F = D x_D + W x_W$$

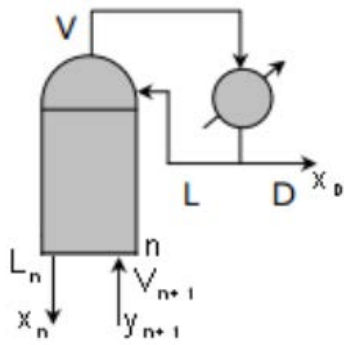
Rearrangement;

$$\frac{D}{F} = \frac{x_F - x_W}{x_D - x_W}$$

$$\frac{W}{F} = \frac{x_D - x_F}{x_D - x_W}$$

3.8.1 RECTIFYING SECTION

The above portion of the feed plate is called rectifying section and it is the vapor enriching part of the column.

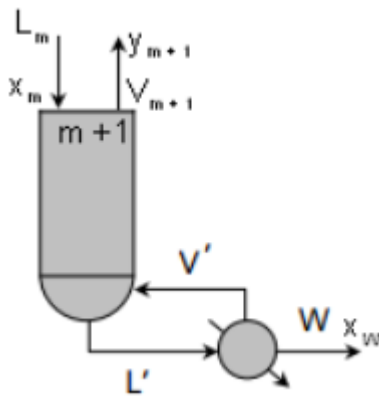


Reflux Ratio: $R = \frac{L}{D}$

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

3.8.2 STRIPPING SECTION

The below portion of the feed plate is called stripping section and it is the liquid enriching part of the column.

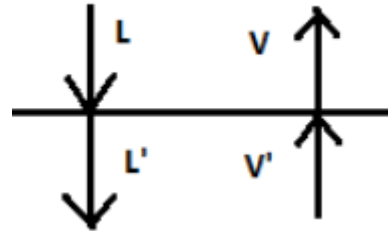


Boil-up Ratio: $R' = \frac{V'}{W}$

$$y_{m+1} = \frac{R'+1}{R'} x_m + \frac{x_W}{R'}$$

3.8.3 FEED PLATE

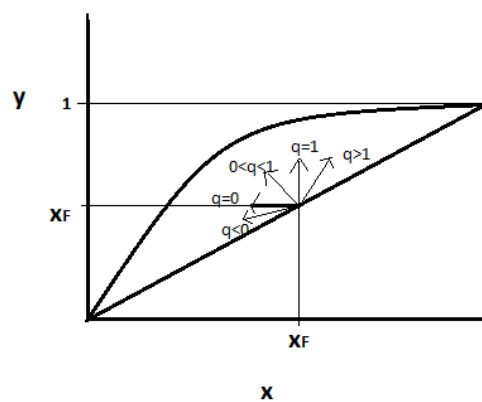
'q' is the fraction of liquid in the feed.



$$V = V' + (1 - q) F$$

$$L' = L + q F$$

$$y = \frac{-q}{1 - q} x + \frac{x_F}{1 - q}$$



Types of feed:

Saturated liquid - $q = 1$

Partial liquid - $0 < q < 1$

Saturated vapor - $q = 0$

Cold liquid - $q > 1$

Superheated vapor - $q < 0$

Definition of 'q' :-

$$q = \frac{\text{heat required to change one mole of feed to saturated vapor}}{\text{molar latent heat of vaporization}}$$

3.9 NUMBER OF PLATES ANALYSIS

There are various methods available to predict the number of plates of the distillation column, but the most suitable and appropriate methods are as follows:

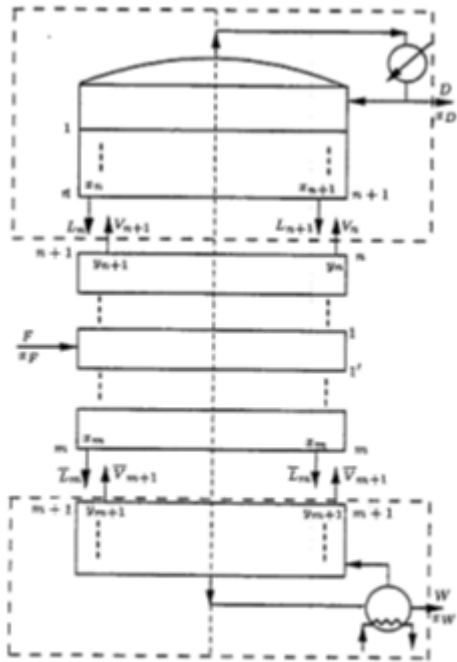


Figure 1. Material-balance diagrams of continuous fractionating column for McCabe-Thiele method (the left-side notations) and the revised method (the right-side notations).

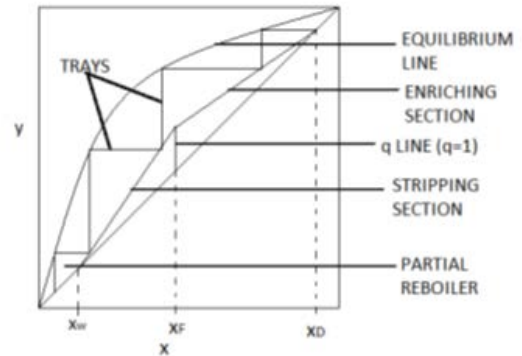
3.9.1 THE METHOD OF MCCABE AND THIELE

This method is used as a fundamental and simple technique to calculate the number of theoretical stages in a distillation column.

Assumptions :-

- i) Constant molar heat of vaporisation (no. of moles of vapor condensed is equal to no. of moles of liquid vaporised in the reboiler).

- ii) Constant molar overflow ($V_1 = V_2 = \dots = V_{n-1} = V_n$)
($L_1 = L_2 = \dots = L_{n-1} = L_n$)
- iii) No heat loss or gain are there (hence no energy balance required)
- iv) Column is adiabatic, at steady state and the pressure is constant throughout the column.



Partial reboiler/partial condenser acts as a tray because the separation of A and B takes place during heat up/cooling.

It also acts as a pressure filler as it converts liquid into vapor and increases the pressure.

McCabe-Thiele diagram calculates all the stages where separation takes place.

If N is the no. of stages,

CASE 1: Total Reboiler And Total Condenser

$$\text{no. of trays} = N$$

CASE 2: Partial Reboiler And Total Condenser

$$\text{no. of trays} = N - 1$$

CASE 3: Total Reboiler And Partial Condenser

$$\text{no. of trays} = N - 1$$

CASE 4 :Partial Reboiler And Partial Condensor

$$\text{no. of trays} = N-2$$

Example 3.1 A mixture of water and ethyl alcohol containing 0.16 mole fraction alcohol is continuously distilled in a plate fractionating column to give a product containing 0.77 mole fraction alcohol and a waste of 0.02 mole fraction alcohol. It is proposed to withdraw 25 per cent of the alcohol in the entering stream as a side stream containing 0.50 mole fraction of alcohol. Determine the number of theoretical plates required and the plate from which the side stream should be withdrawn if the feed is liquor at its boiling point and a reflux ratio of 2 is used.

Solution: Taking 100 kmol of feed to the column as a basis, 16 kmol of alcohol enter, and 25 percent, that is 4 kmol, are to be removed in the side stream. As the side-stream composition is to be 0.5, that stream contains 8 kmol.

Overall mass balance:

$$F = D + W + S$$

$$100 = D + W + 8 \quad \text{or} \quad 92 = D + W$$

Alcohol balance:

$$(100 \times 0.16) = 0.77 D + 0.02 W + 4$$

$$12 = 0.77 D + 0.02 W$$

$$D = 13.55 \quad \text{and} \quad W = 78.45$$

Top section :

$$R = 2 \quad \text{so, } L_n = 2 \times 13.55 = 27.1$$

$$V_n = L_n + D = 27.1 + 13.55 = 40.65$$

Between feed and side stream:

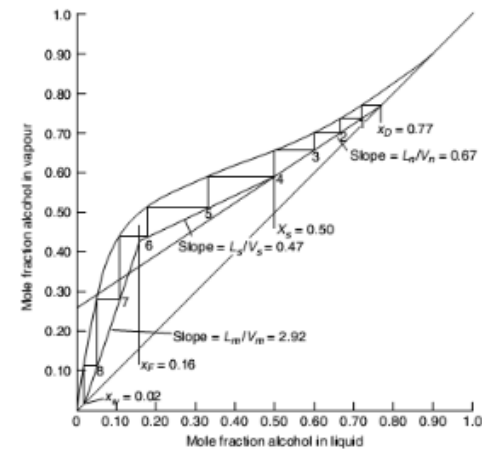
$$V_s = V_n = 40.65,$$

$$L_s = L_n - S = 27.1 - 8 = 19.10$$

Bottom:

$$L_m = L_s + F = 19.1 + 100 = 119.1$$

$$V_m = L_m - W = 119.1 - 78.45 = 40.65$$



Graphical construction for Problem

The steps corresponding to the theoretical plates may be drawn in as shown and 8 plates are required with the side stream being withdrawn from the fourth plate from the top.

3.9.2 TOATL REFLUX RATIO (R_∞)

This is the condition where there is no incoming and no outgoing.

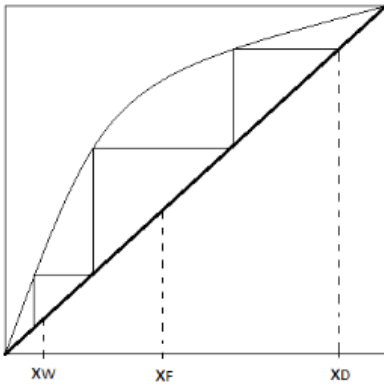
$$F = D = W = 0$$

Thus R and R' tends to ∞ .

$$\text{Slope of enriching section, } \frac{R}{R+1} \approx 1$$

$$\text{Slope of stripping section, } \frac{R'+1}{R'} \approx 1$$

This means all the lines merges with the diagonal,



Total no. of trays required in this condition is minimum and therefore, fixed cost decreases but the duty of reboiler and condenser increases and thus operating cost increases.

Total reflux condition is used at the start-up of the plant to achieve the desired purity or to achieve the equilibrium condition in the column.

FENSKE'S EQUATION

It is used to calculate the minimum no. of ideal trays required at total reflux condition.

$$N = \frac{\ln\left(\frac{x_D}{x_W} \frac{(1-x_W)}{(1-x_D)}\right)}{\ln \alpha}$$

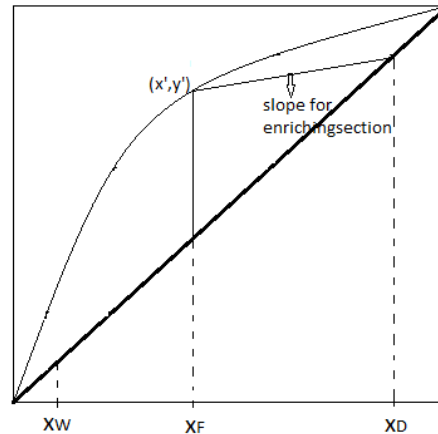
Where α is the relative volatility.

3.9.3 MINIMUM REFLUX RATIO (R_{min})

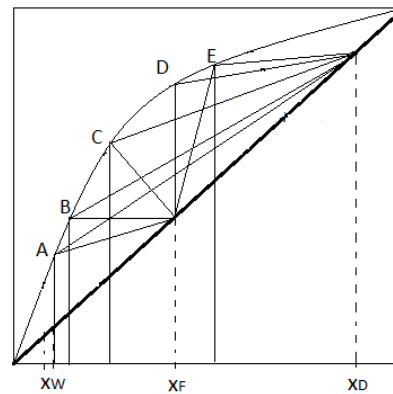
This is the condition where reflux ratio is minimum and the no of trays required is maximum, thus, the fixed cost increases and the operating cost decreases.

R_{min} is calculated to find the optimum reflux ratio

$$R_{opt} = (1.1 \text{ to } 1.4) R_{min}$$



CALCULATION : $R_{min} = \frac{x_D - y'}{y' - x'}$



- A : $q < 0$
- B : $q = 0 ; y' = x_F$
- C : $0 < q < 1 ; x' < x_F$
- D : $q = 1 ; x' = x_F$
- E : $q > 1 ; x' < x_D$

$$(R_{min})_{q>1} < (R_{min})_{q=1} < (R_{min})_{0<q<1} < (R_{min})_{q=0} < (R_{min})_{q<0}$$

Example 3.2 A continuous fractionating column is required to separate a mixture containing 0.695 mole fraction n-heptane (C_7H_{16}) and 0.305 mole fraction n-octane (C_8H_{18}) into products of 99 mole per cent

purity. The column is to operate at 101.3kN/m^2 with a vapor velocity of 0.6 m/s . The feed is all liquid at its boiling-point, and this is supplied to the column at 1.25 kg/s . The boiling-point at the top of the column may be taken as 372 K , and the equilibrium data are:

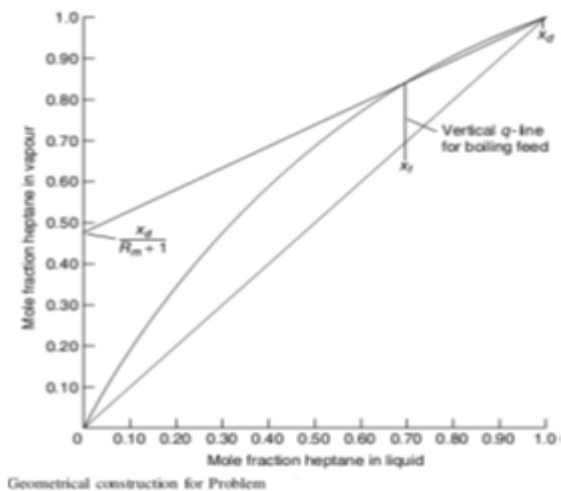
mole fraction of heptane in vapour	0.96	0.91	0.83	0.74
mole fraction of heptane in liquid	0.92	0.82	0.69	0.57

mole fraction of heptane in vapour	0.65	0.50	0.37	0.24
mole fraction of heptane in liquid	0.46	0.32	0.22	0.13

- Minimum reflux ratio?
- Column diameter, if required reflux is twice the minimum reflux ratio?

Solution:

The equilibrium curve is plotted in Figure given below. As the feed is at its boiling-point, the q -line is vertical and the minimum reflux ratio may be found by joining the point (x_D, x_D) with the intersection of the q -line and the equilibrium curve.



This line when produced to the y -axis gives an intercept of 0.475 .

$$x_D / (R_{\min} + 1) = 0.475 ; R_{\min} = 1.08$$

$$R_{\text{opt}} = 2 \times 1.08 = 2.16$$

$$\text{If } F = 100 ; 100 = D + W$$

$$100 \times 0.695 = 0.99 D + 0.01 W$$

As 99% n - octane is required

$$D = 69.9 ; W = 30.1$$

$$L_n = 2.16 \times D = 151 ; V_n = L_n + D = 221$$

Mean molecular mass feed

$$0.695 \times 100 + 0.305 \times 114 = 104.3\text{ kg/kmol}$$

$$\text{Feed rate} = 1.25 / 104.3 = 0.012\text{ kmol/s}$$

Vapor flow at top of column

$$221 / 100 \times 0.012 = 0.0265\text{ kmol/s}$$

Vapor density at the top

$$1 / 22.4 \times 273 / 372 = 0.0328\text{ kmol/m}^3$$

Volumetric flowrate =

$$0.0265 / 0.0328 = 0.808\text{ m}^3/\text{s}$$

Vapor velocity = 0.6 m/s

$$\text{Area required} = 0.808 / 0.6 = 1.35\text{ m}^2$$

$$\text{Column diameter} = [(4 \times 1.35) / \pi]^{0.5} = 1.31\text{ m}$$

UNDERWOOD FENSKE'S EQUATION

These are used to calculate min reflux ratio

$$q = 0 \quad R_{\min} = \frac{1}{\alpha - 1} \left[\alpha \frac{x_D}{x_F} - \frac{(1-x_D)}{(1-x_F)} \right] - 1$$

$$q = 1 \quad R_{\min} = \frac{1}{\alpha - 1} \left[\frac{x_D}{x_F} - \alpha \frac{(1-x_D)}{(1-x_F)} \right]$$

Example 3.3 A liquid containing four components, A, B, C and D, with 0.3 mole fraction each of A, B and C, is to be continuously fractionated to give a top product of 0.9 mole fraction A and 0.1 mole fraction B. The bottoms are to contain no more than 0.5 mole fractions A. Estimate the minimum reflux ratio required for this separation, if the relative volatility of A to B is 2.0

Solution: The given data may be tabulated as follows:

The Underwood and Fenske's equations:

$$\alpha = 2; x_D = .9; x_F = .3$$

$$R_m = \frac{1}{\alpha - 1} \left[\frac{x_D}{x_F} - \frac{\alpha(1 - x_D)}{(1 - x_F)} \right]$$

$$R_m = \frac{1}{2 - 1} \left[\frac{0.9}{0.3} - 2 \frac{(1 - 0.9)}{(1 - 0.3)} \right]$$

$$R_{\min} = 2.71$$

3.10 TYPES OF REBOILERS

- i) Kettle Reboiler – total
- ii) Thermosyphon Reboiler – partial
- iii) Fired Reboiler – partial
- iv) Forced Circulation Reboiler – total

3.11 IMPORTANT TERMS

3.11.1 ENTRAINMENT

In this condition, liquid is carried by vapor upto the tray above. It is caused by high vapour flow rate.

- i) It will contaminate the high purity product.
- ii) Excessive entrainment leads to flooding.

3.11.2 FLOODING

In this condition, liquid is entrained in the vapor up the column and is not allowed to come down either from downcomer or holes. Ultimately, the distillation process stops. It is indicated by a sharp increase in pressure drop.

CALCULATION OF COLUMN DIAMETER

$$\text{Molar flow rate} = (\delta/M) * A * V$$

Where, δ is the mixture's density, M is molecular weight, A is the area of plate and V is operating flooding velocity

$$A = (\pi/4)d^2 - \text{downcomer area}$$

d is diameter of column

3.11.3 WEEPING

It is caused by low vapor flow rate. Pressure exerted by vapor is insufficient to hold up the liquid and thus liquid starts exiting from holes. It is indicated by sharp decrease in pressure drop.

3.12 TRAY EFFICIENCY

- i. Overall efficiency =

$$\frac{\text{ideal no. of plates required}}{\text{actual no. of plates required}}$$

- ii. Murphree plate efficiency =

$$\frac{\text{actual mass transfer}}{\text{ideal mass transfer}}$$

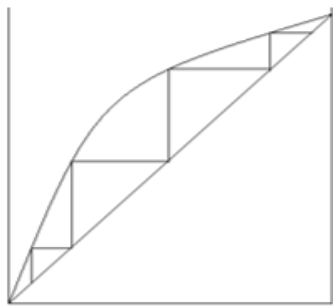
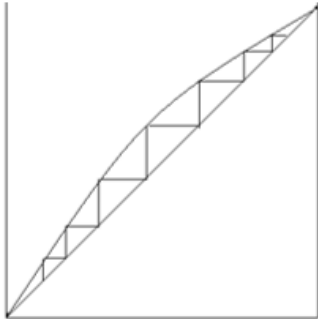
May exceed 100% efficiency as actual mass transfer also includes the transfer in space between the two plates.

- iii. Point efficiency =

$$\frac{\text{actual mass transfer at that point}}{\text{ideal mass transfer at the same point}}$$

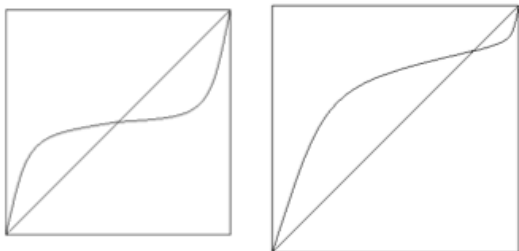
3.13 EFFECT OF PRESSURE

1. As pressure increases, the T-xy diagram shifts upwards and becomes narrower.
2. as pressure decreases, the equilibrium curve shifts upwards. Therefore, required no. of trays decreases.



3. Azeotropes can be avoided by decreasing the pressure.

Thus, distillation columns are always operated at low pressure and high temperature.



Example 3.4 An Equimolar mixture of benzene and toluene is contained in a piston / cylinder arrangement at a temperature T. what is the maximum pressure below which this mixture will exist as a vapor phase alone?

At the given T, the vapor pressure of benzene and toluene are 1530 and 640 mmHg, respectively. Assume that Raoult's law is valid.

Solution: Let the maximum pressure below which the mixture will exist as a vapor phase alone = P mmHg

At pressure P, the mole fraction of benzene in the vapor phase = 0.50

Let the mole fraction of benzene in the liquid phase at pressure P = x

$$P = 1530x + 640(1 - x)$$

$$P = 890x + 640$$

From Raoult's law

$$0.5P = 1530x$$

From equation (a) and (b), we get

$$P = 902.5 \text{ mmHg}$$

Example 3.5 A liquid mixture of benzene and toluene is in equilibrium with its vapor at 101 kPa 373 K. The vapor pressure of benzene and toluene at 373 K respectively are 156 and 63 kPa respectively. Assuming that the system obeys Raoult's law, the mole fraction of benzene in the liquid phase is

Solution: Let the mole fraction of benzene in the liquid phase is x ,

Since, the liquid and vapor phase are in equilibrium

Hence the vapor pressure and partial pressure of benzene will be same

$$P = P^{\text{V}}_{\text{BENZENE}} + P^{\text{V}}_{\text{TOLUENE}}$$

$$101 = 156x + 63 (1 - x)$$

$$x = 0.41$$

GATE QUESTIONS

Q.1 According to the Fenske equation, what will be the minimum number of plates required in a distillation column to separate an equimolar binary of components A and B into an overhead fraction containing 99 mole % A a bottoms fractions containing 98 mole % B ?[assume that the relative volatility ($\alpha_{AB} = 2$) does not change appreciably in the column

[GATE-2002]

- (a) 5 (b) 9
(c) 12 (d) 28

Q.2 Minimum reflux ratio in a distillation column results in

[GATE-2003]

- (a) Optimum number of trays
(b) Minimum reboiler size
(c) Maximum condenser size
(d) Minimum number of trays

Q.3 In distillation column sizing calculations by short cut methods, match the following

[GATE-2003]

P. Underwood's Equation	1. Number of real trays
Q. Fenske's Equation	2. Column diameter
R. Gilliland's Equation	3. Minimum number of ideal trays
S. Vapour velocity at flooding	4. Actual number of ideal trays
	5. Minimum reflux ratio
	6. Tray efficiency

- (A) P-1, Q-3, R-4, S-6
(B) P-2, Q-5, R-1, S-3
(C) P-5, Q-3, R-6, S-2
(D) P-5, Q-3, R-4, S-2

Q.4 In a distillation operation, what is the effect of the temperature of the reflux stream (given below) on the condenser and reboiler loads?

Reflux conditions:

- (ii) Reflux stream is completely liquid and is at its bubble point
(i) Reflux stream is below its bubble point. condenser and reboiler loads are the same in both the cases,

[GATE-2004]

- (A) reboiler load is the same in both the cases but condenser load is higher in case (i)
- (B) condenser load is the same in both the cases but reboiler load is higher in case (ii) both
- (C) condenser and reboiler loads are higher in case (ii) as compared to case (i)
- (D) both condenser and reboiler loads are higher in case (ii) as compared to case (i)

Q.5 A distillation column with N plates is being operated under normal conditions. At some point in time, the operation is shifted to total reflux condition (i.e., no product and residue are being withdrawn and feed to the column is stopped). At the new steady state,

[GATE-2004]

- (A) Composition of vapors and that of liquid do not vary throughout the column
- (B) Reboiler load and condenser load are minimum
- (C) The top and bottom compositions are unchanged with and without total reflux
- (D) The top and bottom compositions correspond to the maximum enrichment achievable.

Q.6 An aqueous solution of methanol is to be distilled in a tray column. High-pressure steam is available as a source of heat. For a given reflux ratio and overhead composition, two options are being explored: (i) a reboiler

is used, and (ii) no reboiler is used but steam is fed directly to the bottom of the column. As compared to option (i), in option (ii).

[GATE-2004]

- (A) Less number of trays are required,
- (B) Composition of the residue remains unchanged
- (C) More number of trays are required but the residue composition remains unchanged
- (D) More number of trays are required and the residue composition is more dilute in methanol

Q.7 A distillation column at a pilot plant is scaled up by 3 times for industrial use at steady state. After scaling up

[GATE-2005]

- (A) The number of theoretical trays increases by 3 times
- (B) The minimum reflux ratio is increased by three times
- (C) The feed flow rate and product flow rates are increased by three times
- (D) The feed composition and product compositions are increased by three times

Q.8 In a tray column, separating a binary mixture, with non-ideal stages, ONE of the following statements is TRUE,

[GATE-2005]

- (A) Point efficiency can exceed 100%
 (B) Murphree efficiency cannot exceed 100%
 (C) Murphree efficiency can exceed 100%
 (D) Both Murphree and point efficiencies can exceed 100%

Q.9 For a two-phase feed, where 80% of the feed is vaporized under column conditions, the feed line slope in the McCabe-Thiele method for distillation column design, is

[GATE-2005]

- (A) $-1/4$ (B) $+1/4$
 (C) $+4$ (D) -4

Q.10 A liquid mixture of benzene and toluene is in equilibrium with its vapor at 101 kPa and 373 K. The vapor pressures of benzene and toluene at 373 K respectively are 156 and 63 kPa respectively. Assuming that the system obeys Raoult's law, the mole fraction of benzene in the liquid phase is

[GATE-2005]

- (A) 0.65 (B) 0.41
 (C) 0.065 (D) 0.04

Q.11 separation column for vapor-liquid contact processes 200 kmol/hr of vapor. The flooding velocity is 3 m/s. If the column operates at 85% of flooding velocity and the down comer area is 10% of the total cross sectional area, what is the diameter of the column? Average density of vapor = 2 kg/m³ and its molecular weight = 44.

[GATE-2005]

- (A) 0.82 m (B) 0.72 m
 (C) 0.78 m (D) 1 m

Q.12 100 moles of a binary mixture F containing 60 mol% A (more volatile) and 40 mol% B is treated in a batch distillation still. After 1 hour, 70 moles of the distillate D is collected leaving behind the residue W. Relative volatility α is 2. The governing equation is

$$\log \frac{F x_f}{W x_w} = \alpha \log \frac{F(1-x_f)}{W(1-x_w)}$$

The average mole fraction of A in the distillate is

[GATE-2006]

- (A) 0.43 (B) 0.61
 (C) 0.69 (D) 0.73

Q.13 A saturated vapor is fed to a distillation column at 180 kmol/hr. Both the rectifying and stripping sections of the column operate at 60% of their respective flooding velocities. The flooding velocity of the rectifying section is twice that of the stripping section. The assumptions of constant molar overflow and constant molar vapor density throughout the column are valid. If the boil-up rate is 60 kmol/hr, then the relationship between the diameters of the rectifying section (d_r) and the stripping section (d_s) is

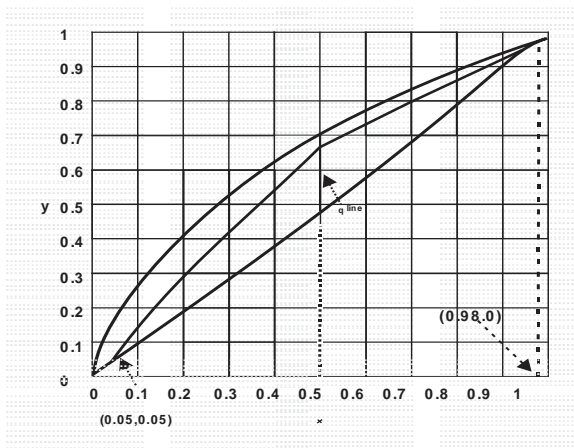
[GATE-2006]

- (A) $d_r = \sqrt{2} d_s$ (B) $d_r = \sqrt{3} d_s$
 (C) $d_r = 2 d_s$ (D) $d_r = 3 d_s$

Common Data Questions 14,15 & 16

A binary distillation column separates 100 mol/hr of a feed mixture into distillate D and residue W. The McCabe-Thiele diagram for this process is given below. The relative volatility for the binary system is constant at 2.4.

[GATE-2006]



Q.14 The distillate and residue flow rates (in mol/hr) are

[GATE-2006]

- (A) $D = 48.4, W = 51.6$
- (B) $D = 51.6, W = 48.4$
- (C) $D = 54.7, W = 45.3$
- (D) $D = 45.3, W = 54.7$

Q.15 The ratio of liquid to vapor molar flow rates in the rectifying section is

[GATE-2006]

- (A) 0.64
- (B) 1.00
- (C) 1.55
- (D) 1.80

Q.16 The minimum number of theoretical stages (inclusive of reboiler) for this process is

[GATE-2006]

- (A) 5.2
- (B) 6.1
- (C) 7.8
- (D) Infinite

Q.17. In a distillation operation, it is desired to have a very high purity bottom product. Initially, a kettle-type reboiler is used at the bottom of the column and the following analytical equation is used to obtain the equilibrium trays in the exhausting section of the column

$$N_p - m + 1 = \frac{\log \left[\frac{x_m - x_w/\alpha}{x_w - x_w/\alpha} (1 - \bar{A}) + \bar{A} \right]}{\log \left(\frac{1}{\bar{A}} \right)}$$

where x_m is the composition of the liquid leaving tray m . Tray m is the last equilibrium tray obtained by a McCabe Thiele graph of the exhausting section. If the kettle-type reboiler is replaced by a thermo-syphon reboiler, the analytical equation, for the exhausting section will be

[GATE-2007]

$$(A) N_p - m + 1 = \frac{\log \left[\frac{x_m - x_w/\alpha}{x_w - x_w/\alpha} (1 - \bar{A}) + \bar{A} \right]}{\log \left(\frac{1}{\bar{A}} \right)}$$

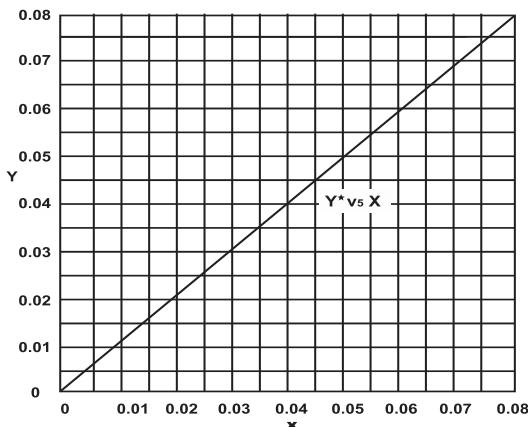
$$(B) N_p + 1 = \frac{\log \left[\frac{x_m - x_w/\alpha}{x_w - x_w/\alpha} (1 - \bar{A}) + \bar{A} \right]}{\log \left(\frac{1}{\bar{A}} \right)}$$

$$(C) N_p - m = \frac{\log \left[\frac{x_m - x_w/\alpha}{x_w - x_w/\alpha} (1 - \bar{A}) + \bar{A} \right]}{\log \left(\frac{1}{\bar{A}} \right)}$$

$$(D) \quad N_p - m + 2 = \frac{\log \left[\frac{x_m - x_w / \alpha (1 - \bar{A}) + \bar{A}}{x_w - x_w / \alpha} \right]}{\log \left(\frac{1}{\bar{A}} \right)}$$

Q.18 Benzene in an air-benzene mixture is to be reduced from 5.2 mol% in the feed to 0.5 mol% by contacting with wash oil in a multistage countercurrent gas absorber. The inlet flow-rate of air benzene mixture is 10 mol/s while benzene free wash oil comes in at 9.5 mol/s. If the equilibrium curve is given as $Y^* = X$, where Y^* and X are equilibrium mole ratios of benzene in air and benzene in oil, the number of equilibrium stages required to achieve the above separation is

[GATE-2007]



- (A) 12 (B) 10
(C) 8 (D) 6

Q.19 In a binary mixture containing components A and B, the relative volatility of A with respect to B is 2.5 when mole fractions are used. The molecular weights of A and B are 78 and 92 respectively. If the compositions are however expressed in mass fractions the relative volatility will then be

[GATE-2008]

- (A) 1.18 (B) 2.12
(C) 2.5 (D) 2.95

Q.20 An ideal flash vaporization is carried out with a binary mixture at constant temperature and pressure. A process upset leads to an increase in the mole fraction of the heavy component in the feed. The flash vessel continues to operate at the previous temperature and pressure and still produces liquid and vapor. After steady state is re-established,

[GATE-2008]

- (A) The amount of vapor produced will increase
(B) The amount of liquid produced will decrease
(C) The new equilibrium compositions of the vapor and liquid products will be different,
(D) The new equilibrium compositions of the vapor and liquid products will remain as they were before the upset occurred.

Q.21 A batch distillation operation is carried out to separate a feed containing 100 moles of a binary mixture of A and B. The mole fraction of A in the feed is 0.7. The distillation progresses until the mole fraction of A in the residue decreases to 0.6. The equilibrium curve in this composition range may be linearized to $y^* = 0.7353x + 0.3088$. Here x and y are the mole fractions of the more volatile component A in the liquid and vapor phases respectively. The number of moles of residue is

[GATE-2008]

- (A) 73.53 (B) 48.02
(C) 40 (D) 30.24

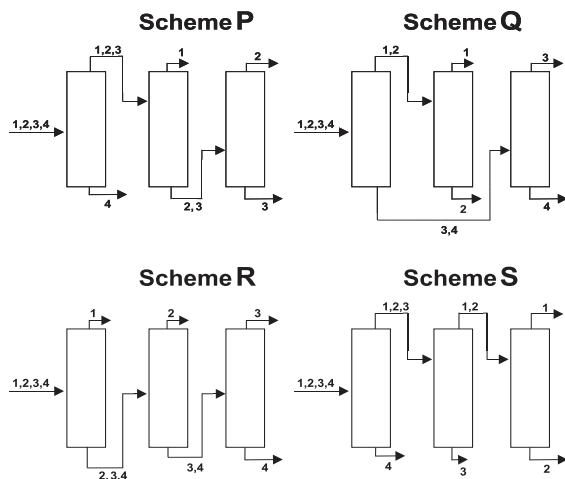
Q.22 The feed to a binary distillation column has 40 mol % vapor and 60 mol % liquid. Then, the slope of the q-line in the McCabe-Thiele plot is

[GATE-2009]

- (A) -1.5 (B) -0.6
(C) 0.6 (D) 1.5

Q.23 An equi-molar mixture of four hydrocarbons (1, 2, 3, 4) is to be separated into high purity individual components using a sequence of simple distillation columns (one overhead and one bottom stream). Four possible schemes are shown below.

[GATE-2009]



Component

- 1
2
3
4

K_i

- 6
3
2.5
1.1

Using the $K_i (= y_i^*/x_i)$ values given above, the optimal scheme is

- (A) P (B) Q
(C) R (D) S

Q.24 The flooding velocity in a plate column, operating at 1 atm pressure, is 3 m/s. If the column is operated at 2 atm pressure, under otherwise identical conditions, the flooding velocity will be

[GATE-2010]

- (A) $3/\sqrt{2}$ (B) $3/2$
(C) 1 (D) $3/4$

Common Data Questions 25 and 26

A binary feed mixture containing equimolar quantities of components S and T is to be distilled in a fractionating tower at atmospheric pressure. The distillate contains 96 mol % S. The q-line (feed line) intersects the equilibrium line at $x = 0.46$ and $y = 0.66$, where x and y are mole fractions. Assume that the McCabe - Thiele method is applicable and the relative volatility is constant.

[GATE-2011]

Q.25 The MINIMUM reflux ratio is

- (A) 1.6 (B) 1.5
(C) 0.66 (D) 0.6

Q.26 The feed is

- (A) At dew point
(B) At bubble point
(C) Superheated vapor
(D) Partially vapor

Q.27 In the McCabe Thiele diagram, if the x coordinate of the point of intersection of the q -line and the vapor-liquid equilibrium curve is greater than the x -coordinate of the feed point then the quality of the feed is

[GATE-2012]

- (A) Super heated vapor
- (B) Liquid below bubble point
- (C) Saturated vapor
- (D) Saturated liquid

Q.28 The vapor-liquid equilibrium curve of a binary mixture A-B, may be approximated by a linear equation over a narrow range of liquid mole fractions ($0.2 < x_A < 0.3$) as follows

$$y_A^* = 1.325 x_A + 0.121$$

Here y_A^* is the mole fraction of A in the vapor. 100 moles of a feed ($x_{A,F} = 0.28$) is batch distilled to a final residue ($x_{A,W} = 0.2$). Using the Rayleigh equation, the number of moles of the residue left behind in the distillation unit, up to 2 digits after the decimal point, is _____

[GATE-2013]

Q.29 The liquid mole fraction x_A at which the maximum difference between the equilibrium vapor mole fraction and liquid mole fraction occurs is

- (A) $\frac{1}{(1 + \sqrt{\alpha_{AB}})}$
- (B) $\frac{0.75}{(1 + \sqrt{\alpha_{AB}})}$
- (C) $\frac{0.5}{(\sqrt{\alpha_{AB}} + 1)}$
- (D) $\frac{0.75}{(\sqrt{\alpha_{AB}} + 1)}$

Q.30 A liquid having the composition found in the first part of the linked answer question is flash distilled at a steady state to a final liquid mole fraction of 0.25. If α_{AB} is 2.5, the fraction of the feed vaporized is

[GATE-2013]

- (A) 0.08
- (B) 0.20
- (C) 0.67
- (D) 0.74

Q.31 A binary distillation column is operating with a mixed feed containing 20 mol% vapour. If the feed quality is changed to 80 mol% vapour, the change in the slope of the q -line is _____

[GATE-2014]

Q.32 Identify the WRONG statement amongst the following:

[GATE-2015]

- (A) Steam distillation is used for mixtures that re immiscible with water.
- (B) Vacuum distillation is used for mixtures that are miscible with water.
- (C) Steam distillation is used for mixtures that are miscible with water.
- (D) Vacuum distillation columns have larger diameters as compared to atmospheric columns for the same throughput.

Q.33 A binary feed consisting of 25 mol% liquid and 75 mol% vapour is separated in a staged distillation column. The mole fraction of the more volatile component in the distillate product is 0.95. The molar flow rate of distillate is 50% of the feed

flow rate and McCabe-Thiele method can be used to analyze the column. The q-line intersects the operating line of the enriching section at (0.35, 0.5) on the x-y diagram. The slope of the stripping section operating line (up to one decimal place) is ____.

[GATE-2015]

Q.34 A binary distillation column is to be designed using McCabe Thiele method. The distillate contains 90 mol% of the more volatile component. The point of intersection of the q-line with the equilibrium curve is (0.5, 0.7). The minimum reflux ratio (rounded off to the first decimal place) for this operation is _____

[GATE-2016]

Q.35 The composition of vapour entering a tray in a distillation column is 0.47. The average composition of the vapour leaving the tray is 0.53. The equilibrium composition of the vapour corresponding to the liquid leaving this tray is 0.52. All the composition are expressed in mole fraction of the more volatile component

The Murphree efficiency based on the vapour phase, rounded to the nearest integer, is ____%

[GATE-2017]

Q.36 The vapor phase composition and relative volatilities (with respect to n-propane) on an ideal tray of a distillation column are

Component	Methane	Ethane	n-Propane
Mole fraction in vapour	0.12	0.28	0.60
Relative volatility	10	4	1

The mole fraction of n-Propane in the liquid phase, rounded to 2 decimal places, is.

[GATE-2017]

Q.37 An azeotropic mixture of ethanol and water is to be separated in a distillation column using benzene as an entrainer. At the column operating conditions, two liquid phases are formed on a tray. The degree(s) of freedom of the system for the choice of intensive properties at equilibrium is (are) ____

[GATE-2018]

Q.38 A binary distillation column is designed by McCabe-Thiele method to get a distillate mole fraction of 0.9. The enriching section operating line has an intercept with y-axis at 0.3 mole fraction. The ratio of liquid to vapour molar flow rate in the enriching section is __ (rounded off to third decimal place)

[GATE-2018]

ANSWER KEY:

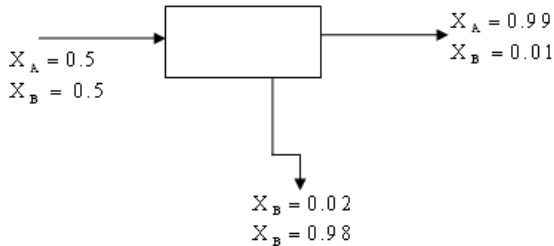
1	2	3	4	5	6	7	8	9	10	11	12	13	14
(C)	(B)	(D)	(C)	(D)	(D)	(C)	(C)	(A)	(B)	(A)	(C)	(A)	(A)
15	16	17	18	19	20	21	22	23	24	25	26	27	28
(A)	(C)	(B)	(A)	(C)	(B)	(B)	(A)	(C)	(A)	(B)	(D)	(B)	(66-67)
29	30	31	32	33	34	35	36	37	38				
(A)	(A)	(3.75)	(C)	(1.4)	(1)	(120)	(0.88)	(2)	(0.667)				

EXPLANATIONS

Q.1 (C)

Given $\alpha = 2$

Fenske equation



$$N_m = \frac{\log \left(\frac{x_D}{1-x_D} \cdot \frac{(1-x_w)}{x_w} \right)}{\log \alpha_{\text{average}}} = \frac{\log \left(\frac{0.99}{1-0.99} \times \frac{-0.02}{0.02} \right)}{\log 2} = 12.24$$

Required plate = 13 = 12 + 1 (due to total condenser)

Q.2 (B)

Minimum reflux ratio in distillation column results in minimum reboiler size

Q.3 (D)

Underwood's equation - minimum reflux ratio fenske's equation

$$N = \frac{\log \frac{x_d}{x_b} \cdot \frac{1-x_b}{x_d}}{\log \alpha_{\text{avg}}}$$

N = min no. of theoretical plate required
gilliland's equation : actual number of ideal trays

$$\frac{N - N_{\min}}{N + 1} = f \left(\frac{R_D - R_{Dm}}{R_D + 1} \right)$$

R_{Dm} is calculated by Underwood equation

N_{\min} is calculated by forsythe equation

Vapour velocity at flooding: column diameter

Q.4 (C)

Since in condition (i) the reflux is liquid at its bubble point and in condition (ii) the reflux is liquid below its bubble point hence the more condenser load is required in condition II. Now, when reflux is liquid below its bubble point, hence temperature of the tower reduces causing more reboiler load. Both condenser and reboiler loads are more in condition (ii) compared to condition (i)

Q.5 (D)

Q.6 (D)

When reboiler is not used then one extra tray is required to compensate for that, therefore more number of trays are used
Secondly steam is injected indirectly which increase the rate of heat transfer which in turn changes increases mass transfer.

Therefore residue will be much dilute in methanol
Hence (D) is the correct answer.

Q.7 (C)

Q.8 (C)

Q.9 (A)

Equation of feed line

$$Y = \frac{q}{(q-1)}x - \frac{x_f}{(q-1)}$$

Where q is fraction of feed that is in liquid

$$\text{Slope} = \frac{q}{q-1} = \frac{0.2}{(1-0.2)} = \frac{0.2}{0.8} = \frac{1}{4}$$

Hence (A) is the correct answer.

Q.10 (B)

Given: $p = 101 \text{ kPa}$, $P_b = 156 \text{ kPa}$,

$P_t = 63 \text{ kPa}$ For non-volatile

solution, x is the mole fraction of benzene

$$P = P_b \cdot x + P_t(1-x)$$

$$\therefore 101 = 156x + 63(1-x)$$

Now Solving for x, we get $x = 0.41$

Q.11 (A)

We have

$$200 \frac{\text{k mol}}{\text{h}} \times 44 \frac{\text{kg}}{\text{k mol}} \times \frac{1 \text{ m}^3}{2 \text{ kg}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 1.222 \text{ m}^3/\text{s}$$

Vapor velocity = 85% of flooding velocity

$$= 0.85 \times 3 \text{ m/s} = 2.55 \text{ m/s}$$

Cross sectional area of the plate available

$$\text{for vapor flow} = 1.222 \frac{\text{m}^3}{\text{s}} \times \frac{1 \text{ s}}{2.55 \text{ m}} = 0.479 \text{ m}^2$$

Down comer area = 10 % of total area of the plat

\therefore Area Available for vapor flow = 90 % plate area

$$\therefore \text{Plate C.S area} = 0.479 \text{ m}^2 \times \frac{1}{0.9} = 0.532 \text{ m}^2$$

$$\pi \frac{D^2}{4} = 0.532 \text{ m}^2 \Rightarrow D = 0.823 \text{ m}$$

Hence, (A) is the Correct answer.

Q.12 (C)

By using the formula given in question

$$\text{Ln} \left[\frac{100 \times .6}{30 \times x_w} \right] = 2 \text{ Ln} \left[\frac{100(1-.6)}{30(1-x_w)} \right]$$

$$x_w = 2.48, 0.402$$

Not possible

$$\text{Now } x_D = \frac{F X_f - W X_w}{D} = 0.6848 ; 0.64$$

Q.13 (A)

From graph,

$$x_D = 0.98 \quad x_f = 0.5 \quad x_w = 0.05$$

Given, $F = 100 \text{ mol/hr}$ $\alpha = 2.4$

We know, overall material balance,

$$F = D + W$$

$$\therefore 100 = D + W \quad (I)$$

$$\text{And } x_f \quad F_{x_f} = D x_D + W x_w$$

$$\therefore 100 \times 0.5 = D(0.98) + W(0.05)$$

$$\Rightarrow 50 = 0.98D + 0.05W$$

$$\text{from (i), } 50 = 0.98D + 0.05(100 - D)$$

$$\Rightarrow 45 = 0.93 D$$

$$\Rightarrow D = 48.4$$

$$\therefore W = 51.6$$

Hence (A) is the correct answer.

Q.14 (A)

From graph,

$$x_D = 0.98 \quad x_f = 0.5 \quad x_w = 0.05$$

Given, $F = 100 \text{ mol/hr}$ $\alpha = 2.4$

We know, overall material balance,

$$F = D + W$$

$$\therefore 100 = D + W \quad (I)$$

And $x_f \quad F_{x_f} = Dx_D + wx_w$

$$\therefore 100 \times 0.5 = D(0.98) + W(0.05)$$

$$\Rightarrow 50 = 0.98D + 0.05W$$

$$\text{from (i), } 50 = 0.98D + 0.05(100 - D)$$

$$\Rightarrow 45 = 0.93D$$

$$\Rightarrow D = 48.4$$

$$\therefore W = 51.6$$

Hence (A) is the correct answer.

Q.15 (A)

Slope of operating line can be calculate

$$\text{form graph } \frac{0.98 - 0.68}{0.98 - 0.5}$$

Ratio of liquid to vapor flow rate = 0.625

Flow rate

Q.16 (C)

We know that

$$\text{Number of plates} = \ln \left[\frac{(1-x_w) \left(\frac{x_D}{1-x_D} \right)}{x_w \left(\frac{x_f}{1-x_f} \right)} \right] \ln \alpha_{\text{avg}}$$

$$\frac{\ln \left[\frac{(1-0.05) \left(\frac{0.98}{1-0.98} \right)}{0.05 \left(\frac{0.5}{1-0.5} \right)} \right]}{\ln(2.4)}$$

$$[Q \ x_w = 0.05, x_D = 0.98] \begin{pmatrix} a_{11} & K & a_{1n} \\ M & O & M \\ a_{m1} & L & a_{mn} \end{pmatrix}$$

$$= \frac{\ln \left[\frac{0.95}{0.05} \times \frac{0.98}{0.02} \right]}{\ln(2.4)} = 7.8$$

Q.17 (B)

$$A_1 F_{12} = A_2 F_{21}$$

$$F_{21} = \frac{A_1 F_{12}}{A_2} = \frac{\pi r^2 \times 1}{2\pi r^2} = \frac{1}{2}$$

Q.18 (A)

Eqm data $y^* = X$ (for $y^* = mx$, $m = 1$)

Kremser - Brown squders eqm for

$$\frac{L}{mv} = \frac{9.5}{1 \times 9.48}$$

$$v = 10 \times (1 - 0.052) = 9.48$$

$$N = \frac{Y_{N+1} - Y_1}{Y_1 - mX_0} = \frac{0.052 - 0.005}{0.005 - 1 \times 0} = 9.4$$

\therefore No. of stages = 10

Q.19 (C)

$$\begin{aligned} \text{(relative volatility)} &= \frac{Y_A / X_A}{Y_B / X_B} \\ &= \frac{Y_A}{X_A} \cdot \frac{X_B}{Y_B} = \frac{Y_A (1 - X_A)}{X_A (1 - Y_A)} \end{aligned}$$

If we express by α^1

$$\alpha^1 = \left(\frac{Y_A N_A}{X_A m_A} \right) \left(\frac{X_B m_B}{Y_B m_B} \right) = \alpha$$

$\therefore \alpha$ will relatively same whatever, we express

In terms of mol fraction or mean fraction = 2.5

Hence (C) is the correct answer.

Q.20 (C)

Because relative volatility will constant, so y and x relation will be same
Hence (D) is the correct answer.

Q.21 (B)

According to Rayleigh equation

$$\ln \frac{F}{W} = \int_{x_w}^{x_f} \frac{dx}{y^* - x}$$

Where $y^* = 0.7353 x + 0.3088$

$X_f = 0.7, x_w = 0.6, f = 100$

$W = 48.02 \text{ kg}$

Hence, (B)

is the correct answer.

Q.22 (A)

In this case, a definite fraction of liquid is vaporized in such a way that the evolved

vapor and residual liquid are in equilibrium with each other

$$\begin{aligned} Y_A &= -\frac{(1-F)}{F} X_{A+} + \frac{X_F F}{F} \\ \text{Slope} &= -\frac{(1-f)}{f} \end{aligned}$$

Where, f = molar fraction of feed vaporized

$$\therefore \text{Slope} = -\frac{(1-0.4)}{0.4} = -1.5$$

Hence, (A) is the correct answer.

Q.23 (C)

Direct sequence distillation sequencing
Hence, (C) is the correct answer.

Q.24 (A)

Flooding velocity

$$\mu_f = K_c \sqrt{\frac{\rho_L - \rho_V}{\rho_V}}$$

Assuming $\rho_L \gg \rho_V$

$$\mu_f \propto \sqrt{\frac{\rho_L}{\rho_V}}$$

Now, $\rho_V = \frac{P}{RT}$

$$\therefore \mu_f = K_L \sqrt{\frac{\rho_L}{P/RT}}$$

$$\Rightarrow \mu_f \propto \frac{1}{\sqrt{P}}$$

$$\frac{\mu_f}{\mu_{f_1}} = \sqrt{\frac{1 \text{ atm}}{2 \text{ atm}}}$$

$$\Rightarrow \mu_{f_2} = \frac{3}{\sqrt{2}} \text{ m/s}$$

Hence, (A) is the correct answer.

Q.25 (B)

At minimum reflux, the point of contact of the operating and equilibrium line is at the intersection of feed line with equilibrium curve.

$$\text{slope} = \frac{0.96 - 0.66}{0.96 - 0.46} = 0.6$$

$$\therefore \frac{R_{\min}}{R_{\min} + 1} = 0.6 \Rightarrow R_{\min} = 1.5$$

(B) is the correct answer.

Q.26 (D)

we have

$$\text{slope of } q \text{ line} = \frac{0.66 - 0.5}{0.46 - 0.5} = -4$$

$$\therefore \frac{q}{q-1} = -4 \Rightarrow q = 0.8$$

Q $0 < q < 1$ thus, feed is partially vapor.

(D) is the correct answer.

Q.27 17.14

The x co-ordinate of intersection of q line and equilibrium curve $x' > x_F$

This indicate slope of q line is positive for $q > 1$

The feed is cold liquid.

Hence, Answer is (B)

Q.28 3.9

We know the Rayleigh Equation is

given as
$$\ln\left(\frac{F}{W}\right) = \int_{x_w}^{x_f} \frac{dx}{y^* - x}$$

Where, $F = 100$ moles, $x_f = 0.28$, $x_w = 0.20$
and $y^* = 1.325x + 0.121$

$$\text{Thus, } \ln\left(\frac{100}{W}\right) = \int_{0.20}^{0.28} \frac{dx}{(1.325x + 0.121) - x}$$

On solving we get,

$$W = 66.85 \text{ moles}$$

\Rightarrow The correct range is between 66 – 67 moles

Q.29 (A)

The liquid mole fraction x_A at which the maximum difference between the equilibrium vapor mole fraction and liquid mole fraction occurs is

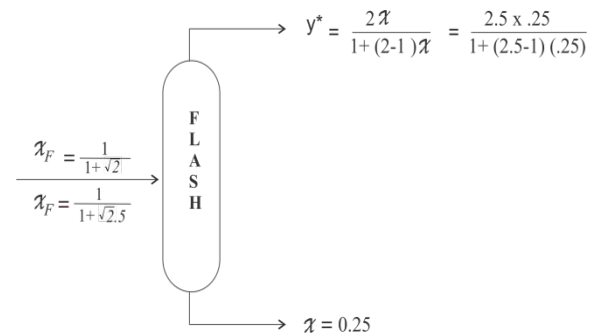
$$\text{Difference (D)} = y_A^* - x_A = \frac{\alpha_{AB} x_A}{1 + (\alpha_{AB} - 1)x_A} - x_A$$

$$\frac{dD}{dx_A} = 0$$

Hence Correct answer is (A)

Q.30(A)

We have



$$\frac{V}{F} = ?$$

$$F x_f = V y^* + L x \Rightarrow x_f = \frac{V}{F} y^* + \frac{L}{F} x \Rightarrow x_f = \frac{V^*}{f} + \left(\frac{F-V}{F}\right) x$$

$$\Rightarrow \frac{V}{f} = 0.67$$

The fraction of the feed vaporized is 0.67

Hence Correct answer is (C)

Q.31 3.75

Given that

Feed contains 20 % vapour, so $q = 0.8$ Slope

of q line = $\frac{q}{q-1} = \frac{0.8}{-0.2} = -4$ Now feed

contains 80% vapour, $q = 0.2$

Slope = $\frac{q}{q-1} = \frac{0.2}{-0.8} = \frac{-1}{4}$

Change in slope = $-\frac{1}{4} + 4 = 3.75$

Q.32 (C)

Q.33 1.4

We have

Given $q = 0.5$

$X_D = 0.95$

Equation of operating line for rectifying section

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

Since this passes through (0.35, 0.5).

$$0.5 = \frac{R}{R+1} \times 0.35 + \frac{0.95}{R+1} = \frac{0.35R + 0.95}{R+1}$$

$$\Rightarrow 0.5R + 0.5 = 0.35R + 0.95$$

$$\Rightarrow 0.15R = 0.45$$

$$\Rightarrow R = 3$$

For stripping section, $y_{m+1} = \frac{L_m}{V_{m+1}} x_m - \frac{Wx_w}{V_{m+1}}$

In stripping section $L_m = L_n + qF$

$$= 3D + 0.25 * 2D$$

$$L_m = 3.5D$$

And $V_{m+1} = L_m - W = 3D - 0.5D = 2.5D$

Slope of operating line in stripping Section

$$= \frac{L_m}{V_{m+1}} = \frac{3.5}{2.5} = 1.4$$

Q.34 1

Minimum reflux ratio is given by

$$R_{\min} = \frac{X_D Y^1}{Y^1 - x^1} = \frac{.9 - 7}{.7 - .5} = 1$$

Q.35 120

Murphree efficiency is defined as the actual change in average composition accomplished by a given tray divided by the change in average composition $\eta_m = \frac{y^1 - y}{y_e - y}$

$$\eta_m = \frac{0.53 - 0.47}{0.52 - 0.47} \times 100 = 120\%$$

Where

Y^1 = A average composition of vapour leaving the tray

Y_e = Equilibrium composition of vapour corresponding to the liquid leaving the tray.

Y = composition of vapour entering the tray

Q.36 0.88

$$y_A = 0.12, y_B = 0.28, y_C = 0.60$$

$$\alpha_{AC} = 10 = \frac{y_A x_C}{y_C x_A} = \frac{0.12 x_C}{0.60} = 10$$

$$x_A + x_B + x_C = 1$$

$$x_A = 1 - x_B - x_C$$

$$\text{We get, } \frac{0.12x_C}{0.60(1 - x_B - x_C)} = 10$$

$$x_B = 1 - 1.02x_C \rightarrow (1)$$

$$\alpha_{BC} = 4 \frac{y_B x_C}{y_C x_B} = \frac{0.2x_C}{0.60(1 - 0.02x_C)} = 4$$

$$\text{We get } x_C = 0.88$$

Q.37 2

For azeotropic mixtures the relation for degree of freedom becomes

$$F = C - P + 1$$

Here number of components is 3 and phase is 2 therefore degree of freedom is 2.

Q.38 0.667

Equation of enriching section

$$y = \frac{L}{G}x + \frac{x_D}{R+1}$$

slope
intersection

$$R = L/D, \quad G = L + D$$

$$x_D = 0.9 \Rightarrow \frac{x_D}{R+1} = 0.3$$

$$\therefore (R+1)0.3 = 0.9 \Rightarrow R = \frac{0.6}{0.3}$$

$$\boxed{R = 2}$$

$$\frac{L}{D} = 2 \Rightarrow L = 2D$$

$$G = 2D + D = 3D$$

Liquid evaporation rate in enriching section,

$$\frac{L}{G} = \frac{L}{L+D} = \frac{L/D}{L/D+1} = \frac{R}{R+1}$$

$$\boxed{\frac{L}{G} = \frac{2}{2+1} = 0.667}$$

4

ABSORPTION

4.1 INTRODUCTION

Absorption involves no change in the chemical species present in the system. Absorption is used to separate gas mixtures, remove impurities, or recover valuable chemicals. The operation of removing the absorbed solute from the solvent is called **stripping**. When water is used as the absorbent, it is normally separated from the solute by distillation rather than stripping.

The desired removal of solute from gas phase is achieved by adjusting the following parameters.

- Solvent (liquid) flow rate
- Height of column
- Gas flow rate
- Diameter of column

4.2 SELECTION OF SOLVENT

• GAS SOLUBILITY

The gas solubility should be high, thus increasing the rate of absorption and decreasing the quantity of solvent required.

• VOLATILITY

The solvent should have a low vapor pressure since the gas leaving an absorption operation is ordinary saturated with the solvent and much may thereby be lost.

• CORROSIVENESS

The materials of construction required for the equipment should not be unusual or expensive.

• COST

The solvent should be inexpensive, so that losses are not costly, and should be readily available.

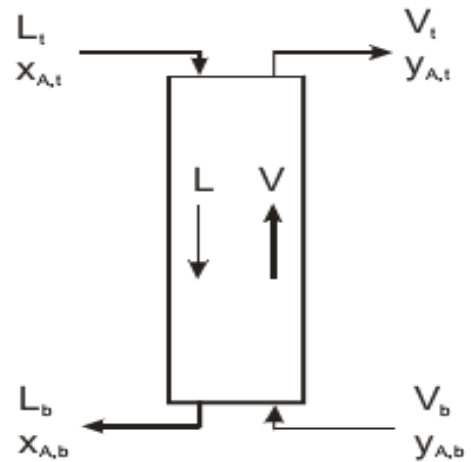
• VISCOSITY

Low viscosity is preferred for reasons of rapid absorption rates.

• MISCELLANEOUS

The solvent if possible should be nontoxic, nonflammable, and chemically stable.

4.3 COUNTER CURRENT ABSORPTION



Overall material balance,

$$L_b + V_t = L_t + V_b$$

Component balance,

$$L_b x_b + V_t y_t = L_t x_t + V_b x_b$$

(mole fractions are always for solute)

V = vapor flow rate

L = liquid flow rate

t, b = top and bottom of column

SOLUTE FREE BASIS

This basis is used to simplify the calculations.

$L_s = L_b$ – solute in bottom liq = L_t – solute in top liq

$V_s = V_b$ – solute in bottom vap = V_t – solute in top v

$$X = x / (1-x)$$

= mole frac of A in liq/mole frac of non-A in liq

$$Y = y / (1-y)$$

= mole frac of A in vap/mole frac of non-A in vap

Equation:

$$L_s X_b + V_s Y_t = L_s X_t + V_s Y_b$$

$$Y_t = \frac{L_s}{V_s} X_t + \frac{(V_s Y_b - L_s X_b)}{V_s}$$

Above equation is called as Operating Line

Example 4.1A solute A is to be recovered from an inert carrier gas B by absorption into a solvent. The gas entering into the absorber flows at a rate of 500 kmol / h with $y_A = 0.3$ and leaving the absorber with $y_A = 0.01$. Solvent enters the absorber at the rate of 1500 kmol / h with $x_A = 0.001$. The equilibrium relationship is $y_A = 2.8x_A$. The carrier gas may be considered insoluble in the solvent and the solvent may be considered nonvolatile. Construct the x - y plots for the equilibrium and operating lines using both mole fraction and solute-free coordinates.

Solution: $x_t = .001$, $y_b = .3$, $y_t = .01$, $L_t = 1500$, $V_b = 500$

$$V_s = 500 (1 - .3) = 350$$

$$L_s = 1500 (1 - .001) = 1498.5$$

Moles of A in $V_b = 500 \times .3 = 150$

Moles of A in $V_t = 350 (.01 / (1 - .01)) = 3.5354$

Moles of A in $L_t = 1500 \times .001 = 1.5$

Moles of A in $L_b = 150 + 1.5 - 3.5354 = 147.965$

$$x_b = 147.965 / (L_s + 147.965) = 0.0898$$

SOLUTE FREE BASIS

$$X_t = 0.001$$

$$X_b = 0.0987$$

$$Y_t = 0.0101$$

$$Y_b = 0.4286$$

The equilibrium curve using both mole fraction and solute-free coordinates

- i. Choose a value of x between 0.001 and 0.10
- ii. Evaluate $X = x / (1 - x)$
- iii. $y = 2.8 x$
- iv. $Y = y / (1 - y)$

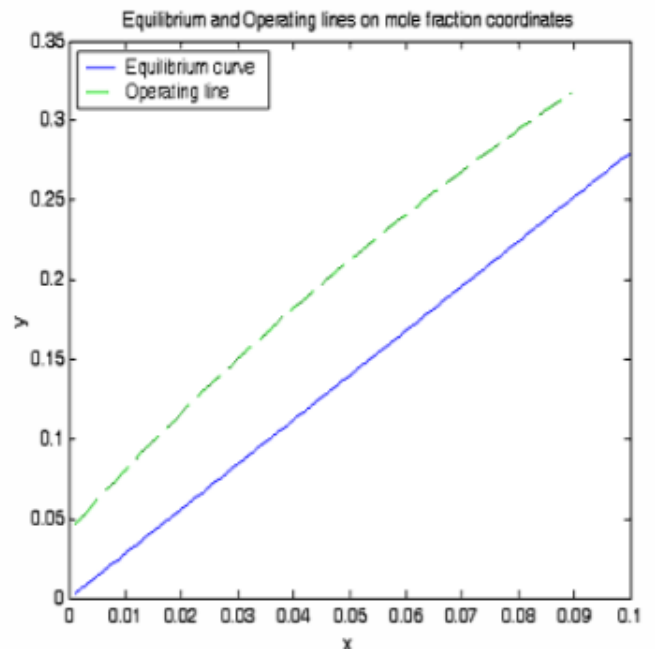
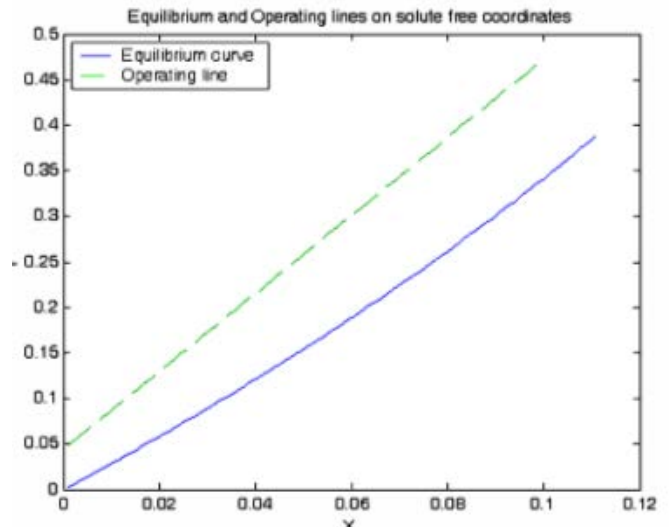
The operating curve using both mole fraction and solute-free coordinates

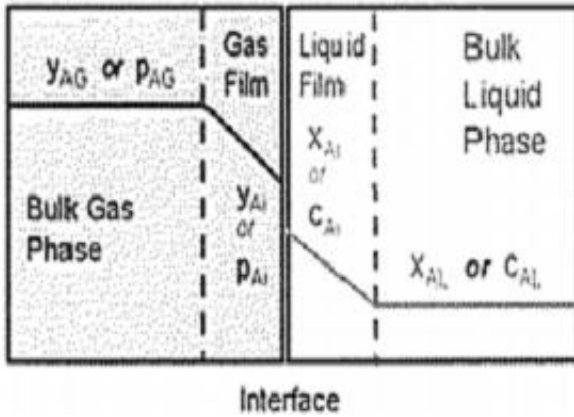
- i. Choose a value of x between 0.001 and 0.0898
- ii. Evaluate $X = x / (1 - x)$
- iii. $Y = \frac{L_s}{V_s} X_t + \frac{(V_s Y_b - L_s X_b)}{V_s}$

$$\text{iv. } y = Y / (1 + Y)$$

4.4 RATE OF ABSORPTION

The concentration gradient will exist between the solute and absorbent as long as equilibrium is not reached. Ideally, equilibrium is reached at the top of the column, and at the interface of gas – liquid phases.





$$R_0 = K * (C - C_0) \dots\dots\dots (3)$$

Where, K = proportionality factor (length/time)

The proportionality factor k is dependent upon the diffusivity of the gas in the liquid and the situation of the absorption, i.e. the surface area available for absorption and the flow rates of the gas and absorbent. The surface area available for absorption, the diffusivity, and the gas flow rate will remain constant, so k depends primarily on the flow rate of the absorbent.

The rate of absorption can be defined by:

$$R_0 = \frac{D}{\delta} * (C - C_0) \dots\dots\dots(1)$$

Where, R_0 = Rate of absorption (moles/length² *time)

D = Diffusivity of gas in solution (length² /time)

δ = Thickness of the stagnant film (length)

C = Concentration of gas at the liquid surface (moles/volume)

C_0 = Concentration of gas in the bulk phase (moles/volume)

The units of the rate of absorption (R_0) are the same as that of molar flux. However, it is impractical to attempt to determine the stagnant film thickness since the absorption is occurring inside the packed column. This being the case, an alternate equation exists which considers the average time of exposure between the gas and the absorbent. Equation that represents this relationship can be given as:

$$R_0 = K * \sqrt{\frac{D}{\tau}} * (C - C_0) \dots\dots\dots(2)$$

Where, R_0 = Rate of absorption (moles/length² *time)

D = Diffusivity of gas in solution (length² /time)

τ = Average time of exposure (time)

C = Concentration of gas at the liquid surface (moles/volume)

C_0 = Concentration of gas in the bulk gas phase (moles/volume)

K = Constant based on model (unitless)

With the help of both equations (1) and (2) the rate of absorption is proportional to the concentration gradient and both equations can be simplified to equation

Once equilibrium is reached between the gas and absorbent, the driving force for absorption becomes zero since the difference in concentration between the bulk gas and liquid no longer exists. The concentration gradient decreases as the gas rises in the column, constantly decreasing the driving force. This being the case, equation (3) can be differentiated with respect to height, z , and then integrated to determine the overall absorption within the column.

From equation (3),

$$R_0 dz = K * (C - C_0) dz \dots\dots\dots(4)$$

$$z = \frac{F_G}{k} * \int_{C_{A0}}^{C_A} \frac{1}{(C - C_0)} dC \dots\dots\dots(5)$$

$$R_0 dz = F_G dC$$

Where,

F_G = Flow rate of gas (volume/time)

C_A = Concentration of carbon dioxide at the top of the column (moles/volume)

C_{A0} = Concentration of carbon dioxide at the bottom of the column (moles/volume)

K = Proportionality Constant (area/time)

Equations (4) and (5) represent the differentiation and integration.

Equation (5) assumes a constant volumetric flow rate of gas. In order for this assumption to be valid, the liquid flow must have a constant density or negligible change in density. It will be assumed that the absorption of the solute will have a negligible effect on the liquid density, so

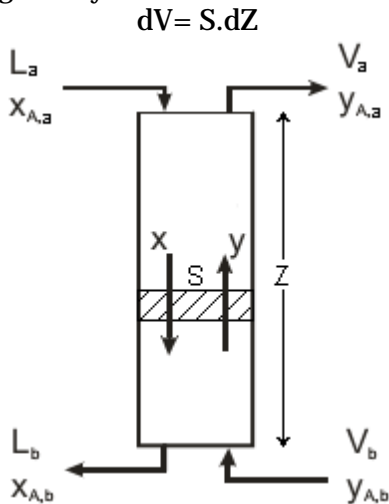
$$F_{G,entering} = F_{G,exiting}$$

$$F_{L,entering} = F_{L,exiting}$$

Where, F_G and F_L represents the volumetric flow rates of the gas at steady state

4.5 CALCULATION OF TOWER HEIGHT

Let a small differential element of volume dV , height dZ and cross sectional area S and the volume is given by,



The amount of solute absorbed in dZ height packing is given by,

$$= -V \cdot dy$$

We know that mass flux is given by

$$N_A = K_y a (y - y^*) S \cdot dZ$$

Which, is equal to the mass absorbed in small packing of dZ height,

$$-V \cdot dy = K_y a (y - y^*) S \cdot dZ$$

$$\frac{K_y a}{V} \int_0^Z dZ = - \int_{y_a}^{y_b} \frac{dy}{(y - y^*)}$$

On integration, we get

$$Z = \frac{V/S}{K_y a} \int_{y_a}^{y_b} \frac{dy}{(y - y^*)}$$

$$Z = HTU \times NTU$$

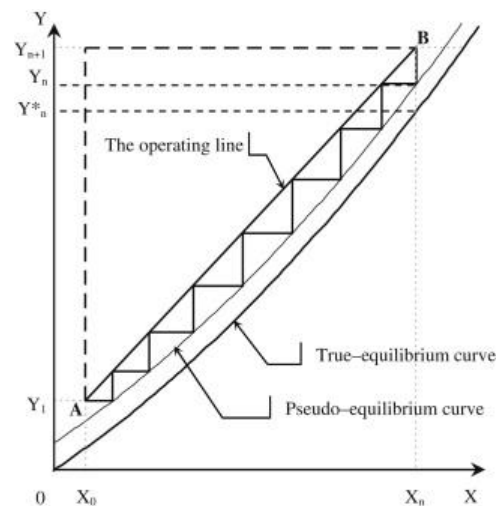
We have

$$NTU = N_{oy} = \int_{y_a}^{y_b} \frac{dy}{(y - y^*)}$$

$$HTU = H_{oy} = \frac{V/S}{K_y a}$$

4.5.1 WHEN EQUILIBRIUM CURVE AND OPERATING LINE ARE STRAIGHT AND PARALLEL:

This is the case where equilibrium curve and operating line are straight and parallel to each other, and hence the average driving force (i.e., the vertical and horizontal line are same and constant throughout the curve).



The NTU and HTU are given by,

$$NTU = N_{oy} = \int_{y_a}^{y_b} \frac{dy}{(y - y^*)} = \frac{1}{(y - y^*)} \int_{y_a}^{y_b} dy$$

$$NTU = N_{oy} = \frac{(y_b - y_a)}{(y - y^*)}$$

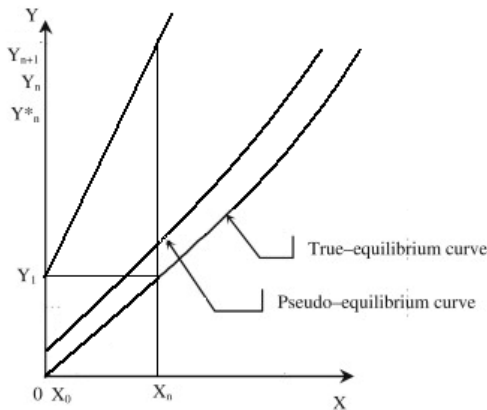
Similarly,

$$TU = N_{ox} = \frac{(x_b - x_a)}{(x - x^*)}$$

and $N_{ox} = N_{oy}$

4.5.2 WHEN EQUILIBRIUM CURVE AND OPERATING LINE ARE STRAIGHT AND NON PARALLEL:

This is the case where equilibrium curve and operating line are straight and parallel to each other, and hence the average driving force (i.e., the vertical and horizontal line are same and constant throughout the curve).



The NTU and HTU are given by,

$$NTU = N_{Oy} = \int_{y_a}^{y_b} \frac{dy}{(y - y^*)}$$

$$NTU = N_{Oy} = \frac{(y_b - y_a)}{(\Delta y_{ln})}$$

Where, $\Delta y_{ln} = \frac{\Delta y_1 - \Delta y_2}{\ln \frac{\Delta y_1}{\Delta y_2}}$

and $\Delta y_1 = y_b - y_b^*$

$\Delta y_2 = y_a - y_a^*$

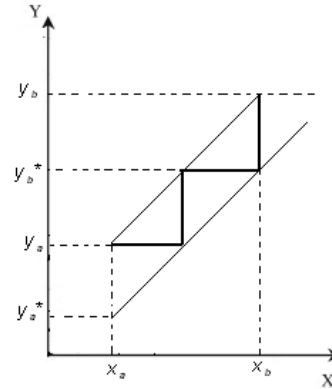
Here, $N_{Oy} > N_{Ox}$

and $H_{Ox} > H_{Oy}$

$$Z = H_{Oy} \times N_{Oy} = H_{Ox} \times N_{Ox}$$

4.6 CALCULATION FOR IDEAL NUMBER OF PLATES BY ABSORPTION FACTOR METHOD:

In the case of L_{min} (Minimum Solvent requirement) y_b will be in equilibrium with x_b and y_b can be calculated by equilibrium relation ($y^* = m x_b$) with the help of x_b .



And N is given by,

$$N = \frac{\ln \left(\frac{y_b - y_b^*}{y_a - y_a^*} \right)}{\ln(A)}$$

This is equation cannot be used when $A = 1$.

ABSORPTION FACTOR:

It can be defined as the ratio of slope of operating line to the slope of equilibrium curve.

$$A = \frac{\text{slope of operating line}}{\text{slope of equilibrium curve}}$$

$$A = \frac{L/V}{m}$$

$$A = \frac{L}{mV}$$

For the given figure

$$\text{Slope of operating line} = \frac{y_b - y_a}{x_b - x_a}$$

$$\text{Slope of equilibrium curve} = \frac{y_b^* - y_a^*}{x_b - x_a}$$

When $A < 1$, i.e. Operating line and equilibrium curve are parallel, then

$$N = \frac{\ln \left(\frac{y_b - y_b^*}{y_a - y_a^*} \right)}{\ln(S)}$$

Where, $S = 1/A =$ Stripping factor

4.7 HETP (HEIGHT EQUIVALENT TO THEORETICAL PLATE):

HETP can be defined as the Height of packing required equivalent to that of theoretical plate, for the same job as done by the equilibrium plate.

It is an experimental quantity, and is the function of

HETP = f (Size of packing, Nature of packing)

The HETP varies, not only with the type and size of the packing but also very strongly with the flow rates of each fluid and for every system with concentration as well.

Example 4.2 The gas and liquid flow rates are 0.16 and 0.40 kmol/s, respectively. The interfacial area of mass transfer is 37.5 m²/m³ froth on the plate. The residence time of both the liquid and gas in the froth zone is 8 seconds. The liquid phase and gas phase mass transfer coefficients are 0.9 x 10⁻² m/s and 1.2 x 10⁻³ m/s, respectively. Calculate:

- Liquid phase transfer units
- Gas phase transfer units
- Stripping factor, given that slope of equilibrium curve is 5
- Overall transfer units
- Murphree point efficiency

Solution: $G = 0.16$ kmol /s, $L = 0.40$ kmol /s, $a = 37.5$ m²/m³, $K_G = 1.2 * \frac{10^{-3} m}{s}$, $K_L = 0.9 * 10^{-2} m/s$

$$\begin{aligned} \text{Residence time of gas in froth zone} &= 8 \text{ sec} \\ &= \frac{\text{Volume of froth zone}}{\text{Volumetric gas flow rate}} = \frac{V}{G/C_T} \end{aligned}$$

$$\begin{aligned} \text{Residence time of liquid in froth zone} &= 8 \text{ sec} \\ &= \frac{\text{Volume of froth zone}}{\text{Volumetric liquid flow rate}} = \frac{V}{L/C_T} \end{aligned}$$

- Liquid phase transfer units:

$$NTU_L = K_L a \frac{V}{L/C_T} = 0.9 * 10^{-2} * 37.5 * 8 = 2.70$$

- Gas phase transfer units:

$$NTU_G = K_G a \frac{V}{G/C_T} = 1.2 * 10^{-3} * 37.5 * 8 = 0.36$$

- Stripping factor:

$$S = \frac{m G}{L} = \frac{5 * 0.16}{0.4} = 2$$

- Overall Transfer units:

$$\frac{1}{NTU_{OG}} = \frac{1}{NTU_G} + \frac{m G}{L} \frac{1}{NTU_L}$$

$$\frac{1}{NTU_{OG}} = \frac{1}{0.36} + 2 * \frac{1}{2.7}$$

$$NTU_{OG} = 0.486$$

- Murphree point efficiency:

$$E_{OG} = 1 - e^{-NTU_{OG}}$$

$$E_{OG} = 1 - e^{-0.486}$$

$$E_{OG} = 0.385$$

Example 4.3 If mass transfer resistance is essentially all in the gas phase, derive the following equation:

$$HTU_{OG} = HTU_G + \left(\frac{m G}{L}\right) HTU_L \frac{(1-x)_{iM}}{(1-y)_{*M}}$$

And for dilute solutions,

$$HTU_{OG} = HTU_G + \left(\frac{m G}{L}\right) HTU_L$$

Solution: HTU_{OG} , HTU_G , and HTU_L are defined by

$$HTU_{OG} = \frac{G}{K_y a (1-y)_{*M}} \dots\dots(1)$$

$$HTU_G = \frac{G}{K_y a (1-y)_{iM}} \dots\dots(2)$$

$$HTU_L = \frac{L}{K_x a (1-y)_{iM}} \dots\dots(3)$$

The overall and individual mass transfer coefficients are related by,

$$\frac{1}{K_Y} = \frac{1}{K_y} + \frac{m}{K_x} \dots\dots(4)$$

Where, m =slope of equilibrium curve
Equation (4) can be written as

$$\frac{1}{K_Y a} = \frac{1}{K_y a} + \frac{m}{K_x a}$$

From equation (1),

$$\frac{1}{K_y a} = \frac{HTU_{OG}(1-y)_{*M}}{G}$$

From equation (2),

$$\frac{1}{K_y a} = \frac{HTU_G(1-y)_{iM}}{G}$$

From equation (3),

$$\frac{1}{K_x a} = \frac{HTU_L(1-y)_{iM}}{L}$$

Hence,

$$\frac{HTU_{OG}(1-y)_{*M}}{G} = \frac{HTU_G(1-y)_{iM}}{G} + \frac{m * HTU_L(1-y)_{iM}}{L}$$

$$HTU_{OG} = \frac{HTU_G(1-y)_{iM}}{(1-y)_{*M}} + \frac{HTU_L(1-y)_{iM}}{(1-y)_{*M}} \left(\frac{mG}{L} \right)$$

If the mass transfer resistance is essentially all in the gas phase, then $y_i = y_i^*$ or

$$(1-y)_{iM} = (1-y)_{*M}$$

$$HTU_{OG} = HTU_G + \left(\frac{mG}{L} \right) \frac{HTU_L(1-x)_{iM}}{(1-y)_{*M}}$$

And for dilute solutions,

$$(1-x)_{iM} \approx 1, (1-y)_{*M} = 1$$

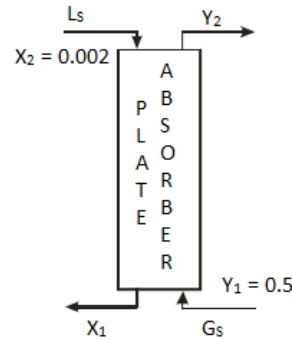
$$HTU_{OG} = HTU_G + \left(\frac{mG}{L} \right) HTU_L$$

Example 4.4 A counter current plate absorber is to be installed for scrubbing of an air mixture containing 5% v/v ammonia. The scrubber is fed with water containing 0.002 mole NH₃ per mole of water. The scrubbing water flows at a rate of 1 mol water per 1 mole of air. It is necessary to absorb 85% of ammonia present in the gas by operating the absorber at 293K.

$$K = 0.80 \frac{\text{mol NH}_3/\text{mol air}}{\text{mol NH}_3/\text{mol H}_2\text{O}}$$

Calculate the concentration of NH₃ in the outgoing liquid and estimate no. of stages necessary for this operation.

Solution:



Y1=0.05 (in fig)

Mol ratio will be calculated as

$$Y_1 = \frac{y_1}{1-y_1} = \frac{0.05}{1-0.05} = 0.0526$$

$$Y_2 = \frac{y_2}{1-y_2} = \frac{0.15 * 0.0526 G_s}{L_s} = 0.0079$$

$$\frac{L_s}{G_s} = 1$$

Ammonia balance:

$$G_s(Y_1 - Y_2) = L_s(X_1 - X_2)$$

$$(Y_1 - Y_2) = \frac{L_s}{G_s}(X_1 - X_2)$$

$$(0.0526 - 0.0079) = 1 * (X_1 - 0.002)$$

$$(X_1 = 0.0467)$$

Since

$$X_1 = \frac{x_1}{1-x_1}$$

$$x_1 = \frac{X_1}{1+X_1}$$

$$x_1 = \frac{0.0467}{1+0.0467}$$

$$x_1 = 0.0466$$

So, the number of ideal stages is given by Kremser's equation:

$$N_p = \frac{\ln \left[\left(\frac{Y_1 - mX_2}{Y_2 - mX_2} \right) \left(1 - \frac{1}{A} \right) + \frac{1}{A} \right]}{\ln A}$$

Equilibrium relationship is given by,

$$Y=0.8X$$

$$m=0.8$$

$$A = \frac{L_s}{mG_s} = \frac{1}{0.8} = 1.25$$

$$N_p = \frac{\ln \left[\left(\frac{0.0526 - 0.8 \cdot 0.002}{0.0079 - 0.8 \cdot 0.002} \right) \left(1 - \frac{1}{1.25} \right) + \frac{1}{1.25} \right]}{\ln(1.25)}$$

$$N_p = 3.96$$

GATE QUESTIONS

Q.1 For gas absorption, the height of a transfer unit, based on the gas phase, is given by (G : superficial molar gas velocity ; L : superficial molar liquid velocity ; F_G : mass transfer coefficient, mol/m²s ; a : interfacial area per unit volume of tower)

[GATE-2001]

- (A) $\frac{G}{F_G a}$ (B) $\frac{F_G}{G a}$
 (C) $\frac{G a}{F_G}$ (D) $\frac{L}{F_G G}$

Q.2 The interfacial area per unit volume of dispersion in a gas – liquid contractor, for fractional hold up of gas =0.1 and gas bubble diameter = 0.5 mm is given by (in m² / m³)

[GATE-2001]

- (A) 500 (B)1200
 (C) 900 (D)800

Q.3 H₂S is being absorbed in a gas absorber unit. The height of the transfer unit based on the overall mass transfer coefficient on the gas side is 0.4m. The equilibrium data given by $y = 1.5 x$. The bulk concentration of H₂S has to be reduced from 0.05 to 0.001 mole fraction in the gas side. The height of the tower (in meters) corresponding to an operating line given by $y = 5x + 0.001$ is

[GATE-2003]

- (A) 2.0 (B) 1.56
 (C) 1.0 (D) 0.56

Q.4 Acetone is to be removed from air in an isothermal dilute absorber using pure water as solvent. The incoming air contains 5 mol% of acetone ($y_m = 0.05$). The design equation to be used for obtaining the number of trays (N) of the absorber is

$$N + 2 = 6 \log \left(\frac{y_{in}}{y_{out}} \right).$$

For 98% recovery of acetone, the number of trays required is/are

[GATE-2004]

- (A) 1 (B) 8
 (C) 9 (D) 10

Q.5 At equilibrium, the concentration of water is vapor phase (C^*) in kg/m³ of air space and the amount of water (m) adsorbed per kg of dry silica gel are related by $C^* = 0.0667 m$. To maintain dry conditions in a room of air space 100 m³ containing 2.2 kg of water vapor initially, 10 kg of dry silica gel is kept in the room, The fraction of initial water remaining in the air space after a long time (during which the temperature is maintained constant) is

[GATE-2004]

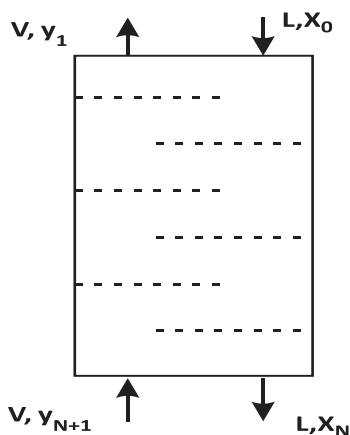
- (A) 0.0 (B) 0.2
 (C) 0.4 (D) 1.0

Linked Answer Questions 6 – 7

A binary gas mixture of a solute and a carrier gas is treated in a countercurrent gas absorption column, containing ideal

trays, using a solvent. The compositions y and x (see figure below) are the mole fractions of the solute in the gas and liquid respectively. Also, V and L are the molar flow rates of the gas and liquid respectively. Assume that the carrier gas is insoluble in the solvent and that the vapor pressure of the solvent is very low at the given conditions of the column. Further, the gas and liquid streams are sufficiently dilute that L and V may be assumed to be constant throughout the column. The equilibrium relation is given by y^*_{mx} , where m is a positive constant.

[GATE-2005]



Q.6 For any value of m , the change in liquid composition across a tray is independent of the tray location if

- (A) $L / V = 1$
- (B) $m L / V = 1$
- (C) $m / (LV) = 1$
- (D) $L / (m V) = 1$

Q.7 Under the correct condition corresponding to part (a), the number of ideal trays in the volume is given by

- (A) $N = \frac{x_0 - x_N}{x_0 - (y_{N+1} / m)}$
- (B) $N = \frac{x_0 - (y_{N+1} / m)}{x_0 - x_N}$
- (C) $N = \frac{x_N - x_0}{(y_{N+1} / m) - x_N}$
- (D) $N = \frac{(y_{N+1} / m) - x_N}{x_N - x_0}$

Q.8 In a multistage countercurrent isothermal stripping column, feed containing 0.05 mol of solute/mol of solute free oil is treated with steam. The absorption factor $A = 0.65$. The equilibrium relation is given by $Y^* = 2X$, where Y^* and X refer to the equilibrium mole ratio in the steam and oil phases respectively. The Kremser equation is given as follows ('0' refers to liquid inlet at the top, 'Np' refers to the last stage at the bottom).

$$N_p = \frac{\log \left[\frac{\left(X_0 - \frac{y_{N_p+1}}{m} \right) (1-A) + A}{\left(X_{N_p} - \frac{y_{N_p+1}}{m} \right)} \right]}{\log \left[\frac{1}{A} \right]}$$

If the steam is initially free of solute and its exit mole ratio (mol solute/mol steam) is 0.0624, then the number of equilibrium stages required is

[GATE-2006]

- (A) 4.2
- (B) 5.2
- (C) 7.2
- (D) 8.2

Q.9 Given the following statements listed from P to T, select the correct combination of TRUE statements from the choices that follow this list.

[GATE-2007]

P) Plate columns are preferred when the operation involves liquids containing suspended solids

Q) Packed towers are preferred if the liquids have a large foaming tendency.

R) The pressure drop through packed towers is more than the pressure drop through plate columns designed for the same duty.

S) Packed columns are preferred when large temperature changes are involved in distillation operations.

T) Packed towers are cheaper than plate towers if highly corrosive fluids must be handled.

(A) T, S, P (B) P, Q, T

(C) S, R, T (D) R, Q, S

Q.10 In a countercurrent gas absorber, both the operating and equilibrium relations are linear. The inlet liquid composition and the exit gas composition are maintained constant. In order to increase the absorption factor

[GATE-2008]

(A) The liquid flow rate should decrease

(B) The gas flow rate should increase

(C) The slope of the equilibrium line should increase

(D) The slope of the equilibrium line should decrease

Q.11 A packed tower containing Berl saddles is operated with a gas-liquid system in the countercurrent mode. Keeping the gas flow rate constant, if the liquid flow rate is continuously increased,

[GATE-2008]

(A) the void fraction available for the gas to flow will decrease beyond the loading point

(B) the gas pressure drop will decrease,

(C) liquid will continue to flow freely down the tower beyond the loading point,

(D) the entrainment of liquid in the gas will considerably decrease near the flooding point.

Q.12 Air concentrated with solute P is brought in contact with water. At steady state, the bulk concentrations of P in air and water are 0.3 and 0.02 respectively. The equilibrium equation relating the interface compositions is $y_{P,i} = 0.25 x_{P,i}$. Assume that the mass transfer coefficients F_G and F_L are identical. The gas phase mole fraction of P at the interface ($y_{P,i}$) is

[GATE-2008]

(A) 0.0663 (B) 0.075

(C) 0.16 (D) 0.3

Q.13 The ratio of the liquid to gas flow rate in a counter-current gas absorption column is increased at otherwise identical conditions. Which **ONE** of the following statements is **TRUE**?

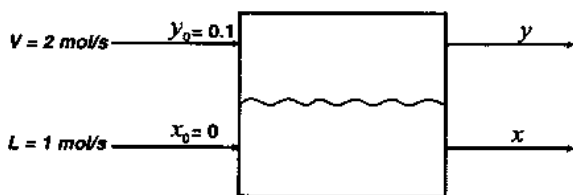
[GATE-2009]

- (A) The operating line shifts towards the equilibrium curve
- (B) The operating line shifts away from the equilibrium curve
- (C) The concentration of the absorbed species increases in the exit liquid stream
- (D) The operating line does not shift.

Linked Answer Questions 14 and 15

Water is used to absorb ammonia from a gas mixture in a single separation stage contactor. The process is schematically represented in the figure below, The molar gas and liquid flow rates, and the inlet mole fractions are given in the figure. Both the liquid and the gas phases are well mixed, and the equilibrium relation between y and x is given by $y^* = x$.

[GATE-2010]



Q.14 If the stage is ideal, then the value of y is

- (A) 1/15
- (B) 1/10
- (C) 2/15
- (D) 1/6

Q.15 If the stage efficiency is 50%, then the value of y is

- (A) 1/12
- (B) 1/6
- (C) 1/4
- (D) 1/3

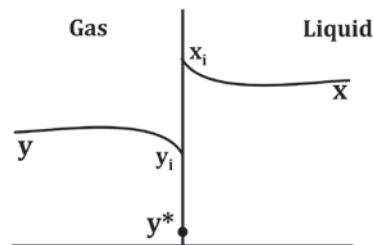
Q.16 A gas mixture is in contact with a liquid. Component P in the gas mixture is highly soluble in the liquid. Possible concentration profiles during absorption of P are shown in the choices, where x : mole fraction of P in bulk liquid, y : mole fraction of P in bulk gas,

x_i : mole fraction of P at the interface in liquid,

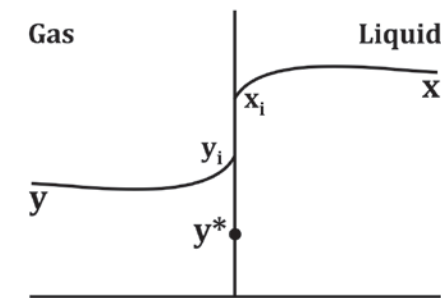
y_i : mole fraction of P at the interface in gas,

y^* : equilibrium gas phase mole fraction corresponding to x_i The **CORRECT** profile is

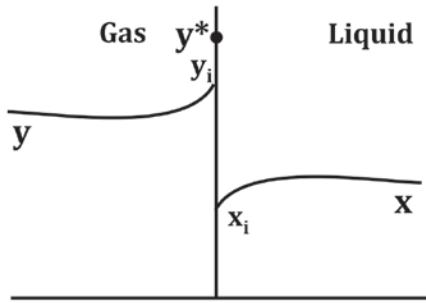
[GATE-2011]



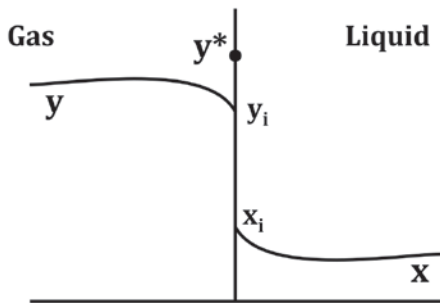
(a)



(b)



(c)



(d)

[GATE-2011]

Common Data Questions 17 and 18:

A counter extraction column is designed to remove 99% of solute C from a solution of solvent A and solute C using pure solvent B. The initial concentration of solute in the solution of A + C is wt % and the total flow of solution is 1000 kg/h if the equilibrium relationship is $Y = 2X$, where $Y = \text{MASS OF C/mass of A}$ and $X = \text{mass of / mass of B}$

[GATE-2012]

Q.17 The minimum flow rate of solvent B required (in kg/h) is

- (A) 1454 (B) 1584
(C) 1676 (D) 1874

Q.18 If the flow rate of B is 2400 kg/h, then the theoretical number of stages in the column using Kremser's equation (adjusted to the next integer) is

- (A) 5 (B) 9
(C) 11 (D) 13

Q.19 For which of the following combinations, does the absorption operation become gas film controlled?

[GATE-2012]

- P. The solubility of gas in the liquid is very high
Q. The solubility of gas in the liquid is very low
R. The liquid - side mass transfer coefficient is much higher than the gas-side mass Transfer Coefficient
S. The liquid -side mass transfer coefficient is much lower than the gas-side mass Transfer coefficient

- (A) P & Q (B) P & R
(C) P & S (D) Q & R

Q.20 The packing of an existing absorption tower is replaced with a new type of packing. The height of the packing and the inlet conditions are maintained the same as before. Tests reveal that the number of transfer units is lower than before. This indicates that the tower with the new packing when compared to that with the old packing will

[GATE-2013]

- (A) Have a higher rate of absorption of the solute from the gas stream
(B) Have a lower rate of absorption of the solute from the gas stream
(C) Have the same rate of absorption of the solute from the gas stream
(D) Have a lower height rate of transfer unit

Q.21 Packed towers are preferred for gas-liquid mass transfer operations with foaming liquids because

[GATE-2014]

- (A) in packed towers, high liquid to gas ratios are best handled
- (B) in packed towers, continuous contact of gas and liquid takes place
- (C) Packed towers are packed with random packing
- (D) in packed towers, the gas is not bubbled through the liquid pool

Q.22 Assuming the mass transfer coefficients in the gas and the liquid phases are comparable, the absorption of CO₂ from reformer gas (CO₂+H₂) into an aqueous solution of diethanolamine is controlled by

[GATE-2014]

- (A) gas phase resistance
- (B) liquid phase resistance
- (C) both gas and liquid phase resistances
- (D) composition of the reformer gas

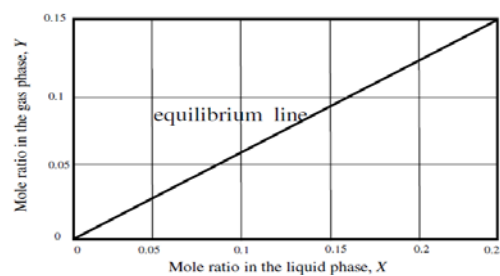
Q.23 Benzene is removed from air by absorbing it in a non-volatile wash-oil at 100kPa in a countercurrent gas absorber. Gas flow rate is 100 mol/min, which includes 2 mol/min of benzene. The flow rate of wash-oil is 50 mol/min. Vapour pressure of benzene at the column conditions is 50 kPa. Benzene forms an ideal solution with the wash-oil and the column is operating at steady state. Gas phase can be assumed to follow ideal gas law. Neglect the change in molar flow rates of liquid and gas phases inside the column.'

For this process, the value of the absorption factor (upto two decimal places) is ____.

[GATE-2015]

Q.24 The concentration of vapour is reduced from 0.25 to 0.05. The liquid feed flowrate, on a solute free basis, is 3 mole/s. The equilibrium line for the system is given in the figure below

[GATE-2017]



The minimum flowrate of pure steam for this process, rounded to 1 decimal place, is ____ mol/s.

Q.25 Two packed towers are designed for the same mass velocity of the gas. The first has liquid and gas flow rates of 30 kg/s and 1.2 kg/s, respectively, while the corresponding flow rates in the second tower are 67.5 kg/s and 1.8 kg/s. The ratio of design diameter of the wider tower to that of the narrower tower is

[GATE-2018]

- (A) 2
- (B) 1.8
- (C) 1.5
- (D) 1.225

Q.26 For absorption of H₂S from a mixture with hydrocarbon vapour into an aqueous alkalonamine solution, the liquid phase mass transfer resistance is

[GATE-2018]

- (A) Significantly higher than that of the gas phase
- (B) Negligible compared to that of the gas phase
- (C) Equal to that of the gas phase
- (D) Dependent on the gas phase mass transfer resistance

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(A)	(B)	(A)	(B)	(C)	(D)	(A)	(B)	(B)	(D)	(A)	(A)	(B)	(A)
15	16	17	18	19	20	21	22	23	24	25	26		
(A)	(D)	(C)	(A)	(B)	(C)	(D)	(A)	(1.02)	(4)	(1.225)	(B)		

EXPLANATIONS

Q.1 (A)

For packed bed absorption tower

$$HTU = \frac{G'}{M_B K_G P a}$$

Where $G = \frac{G'}{M_B}$ and $K_G P = F_G$

$$\therefore HTU = \frac{G}{F_G a}$$

Q.2 (B)

Fractional hold up

$$(\varepsilon) = \frac{\text{Total volume of bubbles}}{\text{Total volume of gas - liquid contactor}}$$

Basis = 1 m³ of g - l contactor

$$\therefore \varepsilon = \frac{n \times \frac{4}{3} \pi r^3}{1} \quad n = \frac{3\varepsilon}{4\pi r^3}$$

Interfacial area of n bubbles

$$a = 4\pi r^2 \times n$$

$$a = 4\pi r^2 \times \frac{3\varepsilon}{4\pi r^3} = \frac{6\varepsilon}{dP} = \frac{6 \times 0.1}{0.5} \times 1000$$

$$= 1200 \text{ m}^2 / \text{m}^3$$

Q.3 (A)

Height of tower $h = HTU \times NTU$

$$NTU = \frac{y_1 - y_2}{(y - y_1)_M}$$

$$Y_2 = 0.001 \text{ \{ Given \}}$$

$$\text{Operating line } y = 5x + 0.001$$

$$\text{at } y_1 = 0.05$$

$$x_1 = \frac{0.001}{5} = 0.0002$$

$$\text{Equilibrium line } y = 1.5x$$

$$\text{at } x_1 = 0.0002 \quad y_1 = 1.5 \times 0.0002 = 0.0003$$

$$(y - y_i)_{LM} = \frac{(y_1 - y_{i1}) - (y_2 - y_{i2})}{\ln \left(\frac{y_1 - y_{i1}}{y_2 - y_{i2}} \right)}$$

$$= \frac{(0.05 - 0.0003) - (0.001 - 0)}{\ln \left(\frac{0.05 - 0.0003}{0.001 - 0} \right)}$$

$$= 0.00964$$

Height of tower = HTU \times NTU

$$= 0.4 \times \frac{y_1 - y_2}{(y - y_i)_{LM}}$$

$$= \frac{0.4 \times (0.05 - 0.001)}{0.00964}$$

$$= 2 \text{ m}$$

Q.4 (B)

Basis: 100 mol incoming gas

Hence, Acetone = 5 mol

and Air = 95 mol

Since, 98 % recovery of acetone required

$$\text{Thus, Acetone in vent gas} = 5 \times (1 - 0.98)$$

$$= 0.1 \text{ mol}$$

Therefore,

Mole fraction of Acetone in vent gas (y_{out}) =

$$\frac{0.1}{95 + 0.1} = 1.0516 \times 10^{-3}$$

And

$$N + 2 = 6 \log \left(\frac{y_{in}}{y_{out}} \right) = 6 \log \left(\frac{0.05}{1.0516 \times 10^{-3}} \right) = 10.062$$

$\Rightarrow N = 9$ trays required.

Q.5 (C)

Here $C^* = 0.0667 m$

$$L_s = 100 \text{ m}^3$$

$$S_s = 10 \text{ kg}$$

$$C_b = \frac{1.6}{AR_c} = 0.022 \text{ kg/m}^2$$

$$C_1^* = 0.0667 m,$$

$$m_0 = 0$$

$$\text{we have } L_s(C_0 - C_1) = s_s(m_1 - m_0)$$

$$\Rightarrow 100(0.022 - 0.0667m_1) = 10(m_1)$$

$$2.2 - 6.67m_1 = 10 m_1$$

$$m_1 = 0.132 \frac{\text{kg water}}{\text{kg adsorbent}}$$

$$\text{kg of water adsorbed} = 0.132 \times 10 = 1.31 \text{ kg}$$

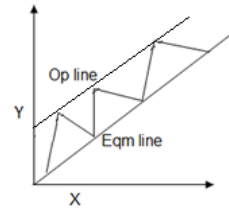
$$\text{kg of water remaining} = 2.2 - 1.31 = 0.89 \text{ kg}$$

$$\text{Fraction of water remaining, } \frac{0.89}{2.2} = 0.4$$

Hence (C) is the correct answer.

Q. 6 (D)

Change in liquid composition across a tray is independent of tray location i. e. deference I liquid composition across a tray is same for each tray in the absorber) the eqm line and operating lines are parallel



i.e. slope of operating line (L / V) = slope of eqm line (m)

$$\frac{L}{V} = m \quad \text{or} \quad \frac{L}{mV} = 1 = A$$

Hence (D) is correct answer

Q.7 (A)

the correct condition corresponding to part (a) the number of ideal trays in the volume is given by

$$N = \frac{x_N - x_0}{(y_{N+1/m}) - x_N} \quad \text{and for absorption, } x_N > x_0$$

Q.8 (B)

$$x_0 = 0.05$$

$$y_{NP+1} = 0$$

$$y_1 = 0.0624$$

$$A = \frac{L}{mv} = 0.65$$

$$y = 2x$$

$$\Rightarrow m = 2$$

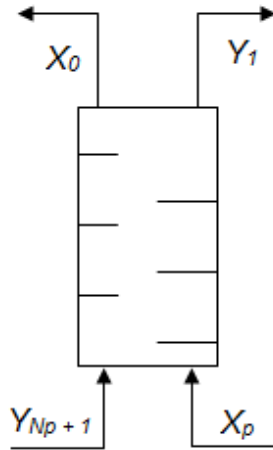
Solute balance:

$$L(x_0 - x_p) = v(Y_1 - Y_{NP+1})$$

$$\therefore x_p = x_0 - \frac{v}{L}(Y_1 - Y_{NP+1})$$

$$= 0.05 - \frac{1}{1.30}(0.0624 - 0)$$

$$= 0.002$$



$$N_p = \frac{\log \left[\left(\frac{X_0 - \frac{Y_{NP+1}}{m}}{X_1 - \frac{Y_{NP+1}}{m}} \right) (1-A) + (A) \right]}{\log(1/A)}$$

$$= \log \left[\frac{\left(\frac{0.05 - \frac{0}{2}}{0.002 - \frac{0}{2}} \right) (1-6.65) + 0.65}{\log(1/0.65)} \right]$$

$$= \frac{\log(9.4)}{\log(1.538)} = 5.205$$

Hence (B) is the correct answer

Q.9 (B)

Packed columns are more suitable for handling foaming liquids. Pressure drop in the case of packed tower is minimum. Packed towers are cheaper than plate towers if highly corrosive fluids must be handled,

Hence (B) is the correct answer.

Q.10 (D)

Q.11 (A)

Q.12 (A)

At equilibrium, $y_B - y_{pi} = x_{pi} - x_B$

$$\Rightarrow 0.3 - y_{pi} = x_{pi} - 0.02$$

$$\Rightarrow 0.3 - x_{pi} = x_{pi} - 0.02$$

$$\Rightarrow 0.3 - 0.25x_p := x_p : -0.02$$

$$\therefore y_{pi} = 0.25 x_{pi}$$

$$\text{and } y_{pi} = 0.256 \times 0.25 = 0.063$$

Q.13 (B)

Counter-current gas absorption equation is given by

$$G(Y_1 - Y_2) = L(X_1 - X_2)$$

$$(Y_1 - Y_2) = \frac{L}{G}(X_1 - X_2)$$

If liquid to gas ratio increases, then concentration of gas in liquid decreases and operating line shift away from the equilibrium

Hence, (B) is the correct answer.

Q.14 (A)

Ammonia balance in solution

$$(2 \times 0.1) + (1 \times 0) = 2y + (1 \times x)$$

Now $y^* = x$

$$y^* = \frac{1}{15}$$

Hence, (A) is the correct answer.

Q.15 (A)

Q.16 (D)

Component p is highly soluble in liquid

Component p diffuses from gas to liquid phase

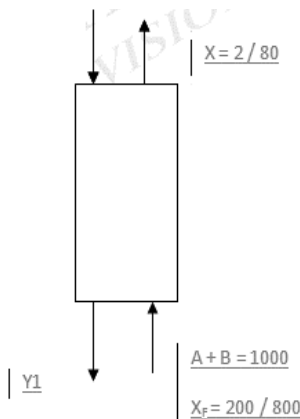
[$\therefore y$ must be $> y$ and x_i must be $> x$]

- ∴ B and C are not possible
 - ∴ A and D are two possible diagrams
 - ∴ $y_i = H x_i$ (Henry' law)
- For highly soluble system $y_i > x_i$
 System for $x_i = 0.297$ I y I = 0.945
 Hence (D) is correct diagram

Q.17 (C)

We know that

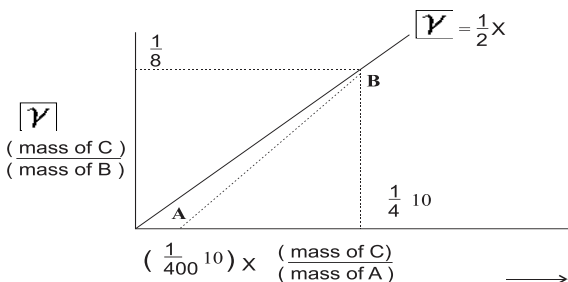
The amount of solvent A = $0.8 \times 1000 = 800$
 and C = 200



At equilibrium, both inlet streams are in equilibrium

Take balance on component C:

$$A (Y_1 - Y_2) = B (X_1 - X_2)$$



$$\text{Slope of line AB} = \left(\frac{R_s}{E_s} \right)_{\min} = \frac{\frac{1}{8} - 0}{\frac{1}{40} - \frac{1}{400}}$$

$$E_s = 1584 \text{ kg/hr}$$

Q.18 (A)

Use Kremser's equation

Kremser Equation is given by

$$N = \frac{N = \text{Log} \left[\left(\frac{x_0 - y_{N+1}/m}{x_N - y_{N+1}/m} \right) (1-A) + A \right]}{\text{Log} (1/A)}$$

$$= 8.7 \simeq 9$$

Q.19 (B)

In absorption, there are two step mass transfer and slowest step is rate controlling
 Then statement P and R tell us that gas film is controlling

Hence Answer is (B)

Q. 20 (C)

The ratio of the solute mole fraction in the original feed to that in the exit raffinate stream i.e. (x_0/x_N) is given by

$$\left[1 + \left(\frac{mS}{NE} \right) \right]^N$$

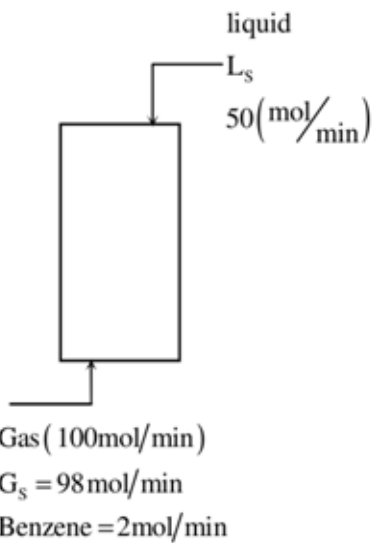
Hence Correct answer is (A)

Q.21 (D)

Q.22 (A)

Because Gas is not bubbled through liquid and thus less agitation of liquid is done by gas.

Q.23 (1.02)



We know that

Absorption factor

$$A = \frac{L_s}{mG_s}$$

Given Raoult's law is applicable for gas phase

$$yP = xp^{\text{sat}}$$

$$\Rightarrow y \times 100 = x \times 50$$

$$\Rightarrow y = 0.5x$$

$$\text{So, } m = 0.5$$

$$A = \frac{50}{0.5 \times 98} = 1.02$$

Q.24 (4)

Equation of equilibrium line =

$$\frac{0.15}{0.25} = 0.6 y = 0.6x$$

Material balance of solute gives L (0.25-0.05) = $G_{\min} [0.6(0.25)]$ here, L = 3 mol / sec, G = minimum flow rate of pure steam

$$G_{\min} = \frac{3(0.25 - 0.05)}{0.6(0.25)} = 4 \text{ mol / sec}$$

Q.25 (1.225)

$$\text{Mass velocity of gas (W)} = \frac{\text{Mass flow rate of Gas}}{\text{Area of tower}}$$

$$\text{For tower 1 } m_1 = 1.2$$

$$\text{For tower 2 } m_2 = 1.8$$

For mass velocity of gas in both tower

$$\frac{m_1}{A_1} = \frac{m_2}{A_2} \Rightarrow \frac{A_1}{A_2} = \frac{\frac{\pi}{4} d_1^2}{\frac{\pi}{4} d_2^2} = \frac{m_1}{m_2}$$

$$\frac{d_1}{d_2} = \sqrt{\frac{m_1}{m_2}} = \sqrt{\frac{1.2}{1.8}} \text{ or } \frac{d_2}{d_1} = 1.225$$

Q.26 (B)

H₂S is highly soluble in alkanolamine solution due to a chemical reaction. Since it is highly soluble total resistance offered is almost equal to the gas phase resistance and hence liquid phase resistance should be negligible.

5.1 INTRODUCTION

Humidity is used to indicate the concentration of vapors in gas-vapor mixture. It can be defined on mass basis or molar basis.

Molar basis (Molar Humidity):

$$H' = \frac{n_v \text{ (moles of vapor)}}{n_A \text{ (moles of air)}}$$

$$= \frac{\text{partial pressure of vapors}}{\text{partial pressure of air}} = \frac{P_v}{P_t - P_v}$$

Mass basis (Absolute Humidity):

$$H = \frac{m_v \text{ (mass of vapors)}}{m_A \text{ (mass of air)}}$$

For ideal case,

$$P_v V_v = m_v R_v T_v \quad (\text{moisture})$$

$$P_A V_A = m_A R_A T_A \quad (\text{air})$$

As vapor and air are in thermal equilibrium,

$$T_A = T_v$$

Volume occupied by vapor and air is same,

$$V_A = V_v$$

$$\frac{m_v}{m_A} = \frac{P_v}{P_A} \times \frac{R_A}{R_v}$$

$$R_A = R/m_A$$

$$R_v = R/m_v$$

$$P_A = P_t - P_v$$

$$H = \frac{P_v}{P_t - P_v} \cdot \frac{m_v}{m_A}$$

$$H = H' \cdot \frac{m_v}{m_A} = 0.622 H'$$

Where, m_v and m_A are molar masses of vapor and air, and P_t is total pressure

If gas is saturated with vapors (water),

Partial pressure of vapors = vapor pressure of vapors
(at same temperature)

Molar humidity at saturation,

$$H's = \frac{P_{vs}}{P_t - P_{vs}}$$

P_{vs} is vapor pressure of vapors (water)

Mass humidity at saturation,

$$H_s = H's$$

DEGREE OF SATURATION/ % HUMIDITY

It is defined as the ratio of mass of vapors per kg of air to the same ratio at saturation for a particular temperature.

$$\mu = \frac{H}{H_s} = \frac{H'}{H's} = \frac{P_v (P_t - P_{vs})}{P_{vs} (P_t - P_v)}$$

RELATIVE HUMIDITY (RH)

It is given by the ratio of partial pressure to the vapor pressure of vapors. At saturation RH = 1

$$RH = \frac{P_v}{P_{vs}} = \frac{\mu}{1 - (1 - \mu) \frac{P_{vs}}{P_t}}$$

Example 5.1 A vapor – air mixture at 302 K and 100 kPa having saturation temperature 291 K. Find out the Molar humidity, Relative humidity, Absolute humidity and percentage humidity.

Given Data: Vapor pressure of air – vapor mixture at 291 K = 2.0624 kPa

Vapor pressure of air – vapor mixture at 302 K = 4.004 kPa

Solution :

Molar humidity, $H' = 2.0624 / (100 - 2.0624) = 0.02106$

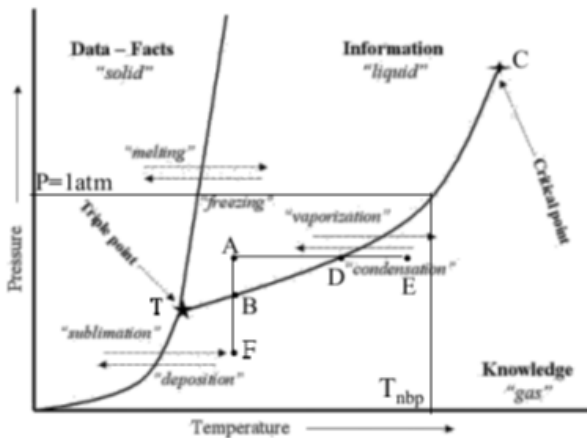
Absolute humidity, $H = 0.02106 (18/29) = 0.01307$

Saturation humidity, $H'_s = 4.004 / (100 - 4.004) = 0.04171$

Relative humidity, $RH = 2.0624 / 4.004 = 0.5151$

% humidity, $\%H = 0.02106 / 0.04171 \times 100\% = 50.5\%$

5.2 VAPOR PRESSURE CURVE



The vapor pressure of a liquid may be defined as “the equilibrium pressure of a vapor above its liquid (or solid); that is, the pressure of the vapor resulting from evaporation of a liquid (or solid) above a sample of the liquid (or solid) in a closed container.”

When, the vapor pressures of a liquid are plotted against the corresponding temperatures, a curve like TBDC results.

5.3 DRY BULB TEMPERATURE

The dry bulb temperature can be defined as the temperature measure by the thermometer while keeping its bulb completely dry, i.e. its bulb should not be affected by the atmospheric moisture.

5.4 WET BULB TEMPERATURE

Here, bulb of thermometer is covered with a wetted muslin wick and a stream of unsaturated gas mixture is passed with a velocity of 2 – 5 m/s. The moisture of wick tends to evaporate by picking up the heat from the surroundings and thus the temperature of air around the wick lowers down. This decrease in temperature is known as wet bulb temperature.

$$DBT > WBT$$

5.5 DEW POINT TEMPERATURE

Dew point is the lowest temperature at which a gas-vapor mixture can be cooled without condensation at constant pressure.

It is the temperature at which the vapor just begins to condense when cooled at constant pressure.

It is the temperature at which the exiting vapor content is sufficient to saturate the gas.

It is the temperature at which the vapor pressure of water is equal to the partial pressure of vapor in gas-vapor mixture.

$$\text{At dew point, } H = H_s \text{ and } H' = H_s$$

GATE QUESTIONS

Q.1 The lewis relation for air-water humidification is given by (k_y : Mass transfer coefficient of moisture in air; h_G : heat transfer coefficient ; C_s : heat capacity of vapor gas mixture)

[GATE-2001]

(A) $\frac{h_G^2}{k_y C_s} = 1$ (B) $\frac{k_y C_s^2}{h_G} = 1$

(C) $\frac{h_G}{k_y C_s} = 1$ (D) $\frac{K_y^2 h_G}{C_s} = 1$

Q.2 The following plot gives the saturated humidity (He) versus Temperature (T) Line joining (H1, T1) and (H2, T2) is the constant enthalpy line, Choose the correct one from among the alternatives A, B, C and D

[GATE-2003]

- (A) T1 – Dew point Temp; T2 –Dry bulb Temp; T3 – Wet Bulb Temp;
 (B) T1 – Dew point Temp; T2 – Wet Bulb Temp; T3 – Wet Bulb temp;
 (C) T1 – Wet Bulb Temp; T2 – Dry Bulb Temp; T3- Dew point temp;
 (D) T1 – Dry Bulb Temp; T2 – Wet Bulb Temp; T3 – Dew point temp;

Common Data Question 3 –4

An air-water vapor mixture has a dry bulb temperature of 60°C and a dew point temperature of 40°C. The total pressure is 101.3 kPa and the vapor pressures of water at 40°C and 60°C are 7.30 kPa and 19.91 kPa, respectively.

[GATE-2004]

Q.3 The humidity of air sample expressed as kg of water vapor / kg of dry air is

- (A) 0.048 (B) 0.079
 (C) 0.122 (D) 0.152

Q.4 The wet bulb temperature T_w for the above mixture would be

- (A) Less than 40°C (B) 40 °C
 (C) 40°C < T_w < 60°C (D) 60 °C

Q.5 If the percent humidity of air (30 °C, total pressure 100 kPa) is 24 % and the saturation pressure of water vapor at that temperature is 4 kPa, the percent relative humidity and the absolute humidity of air are

[GATE-2007]

- (A) 25.2, 0.0062 (B) 25, 0.0035
 (C) 20.7, 0.0055 (D) 18.2, 0.00

Q.6 At 25°C and 90% relative humidity, water evaporates from the surface of a lake at the rate of 1.0 kg/m²/h. The relative humidity that will lead to an evaporation rate of 3.0 kg/m²/h, with other conditions remaining the same, is

[GATE-2010]

- (A) 30% (B) 50%
 (C) 60% (D) 70%

Q.7 The humidity of air at a dry-bulb temperature of 65°C is 0.025 kg water / kg dry air. The latent heat of vaporization of

water at 0°C is 2500 kJ/kg. The psychrometric ratio of air is 0.95 kJ (kg dry air)⁻¹K⁻¹. Considering 0°C as the reference temperature, the enthalpy of air (in kJ/kg) at its adiabatic saturation temperature of 35°C is _____(rounded off to two decimal places).

[GATE-2018]

ANSWER KEY:

1	2	3	4	5	6	7
(C)	(D)	(A)	(C)	(B)	(D)	(124)

EXPLANATIONS

Q.1 (C)

For air water vapour mixture $\frac{h_G}{K_y C_s} = 1$

Where, h_G – heat transfer coefficient
 K_y – mass transfer coefficient

C_s – molar specific heat

Q.2 (D)

T_1 = dry bulb temperature

T_2 = Wet bulb temperature

T_3 = Dew point temperature

Q.3 (A)

P_w → partial pressure of water vapor in air

P_r → total pressure

M_w → molecular weight of the water vapor

M_A → Molecular weight of air

Vapor pressure at the dew point is same as the partial pressure of given system. Therefore vapor pressure at 40° C = partial pressure at 60° C

$$P_w = 7.30 \text{ kPa}$$

$$P_T = 101.3 \text{ kPa}$$

$$\frac{M_w}{M_A} = 0.622$$

$$\text{Humidity, } H_w = \left(\frac{p_w}{p_T - p_w} \right) \left[\frac{M_w}{M_A} \right]$$

$$H_w = \left(\frac{7.30}{101.3 - 7.30} \right) (0.622) = 0.048$$

Hence (A) is the correct answer.

Q.4 (C)

Wet bulb temperature always lies between the dry bulb temperature and the dew point temperature therefore T_w is between 40°C and 60°C

Hence (C) is the correct answer

Q.5 (B)

$$\text{Percent humidity} = \frac{H}{H_s} = .24$$

Saturation pressure = 4 kPa

$$H_s = 0.622 \left(\frac{P_s}{P - P_s} \right) = 0.259$$

$$H = .24 \times 0.259 = 6.22 \times 10^{-3}$$

Q.6 (D)

We know

$$N_v = K_g (P_v^v - P_v)$$

$$\text{Or } N_v \propto \left(1 - \frac{p_v}{p_v^v} \right) \propto (1 - RH)$$

$$RH_1 = 90\% \Rightarrow NV_1 = 1.0 \text{ kg} / \text{m}^2 \text{hr}$$

$$RH_2 = ? \Leftarrow NV_2 = 3.0 \text{ KG} / \text{m}^2 \text{hr}$$

$$RH_2 = 70\%$$

Q.7 (124)

$$(T - T_s) = \frac{\lambda}{h/k_y} (Y - Y_s)$$

And enthalpy of stream = $\lambda T_0 + C_H(T_s - T_0)$

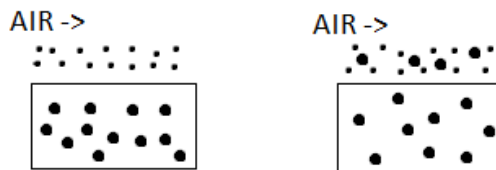
Hence enthalpy is 124 kJ/Kg

6.1 INTRODUCTION

The removal of moisture (complete removal is not a compulsion) from a wet solid is called **Drying**.

MECHANISM:

Generally a wet solid is heated to vaporize the moisture to the surface and then heat required for drying is supplied by hot air.



6.2 MECHANISM OF MOISTURE CONTENT

- BY LIQUID DIFFUSION

The concentration of the moisture inside the bulk solid is generally more than that at the surfaces, and the concentration difference causes flow of moisture from inside to the outside.

- BY CAPILLARY FORCES

In porous solids, moisture transport occurs due to the capillary force.

- PRESSURE INDUCED TRANSPORT

For solids, which shrinks while drying, pressure is induced in the inside of solid and the moisture travels from inside to outside.

- VAPOR DIFFUSION

Sometimes liquid vaporizes inside the surface of solid and these vapors come to the surface known as vapor diffusion.

6.3 RESISTANCES IN DRYING

- Resistance to liquid and vapor diffusion from inside to the surface.

- Resistance of convective MT of vapors from surface to the bulk of air.
- Resistance to convective HT from bulk drying air to the solid surface.
- Resistance to conductive HT from outer surface to the inside of body.

6.4 IMPORATNT TERMS

BONE DRYING:

A solid totally free from moisture.

CASE HARDENING:

Sometimes drying action is so rapid that the outer layer becomes dry, stiff and hard and stops drying while there is enough amount of moisture inside.

UNBOUND MOISTURE:

The moisture content present over the surface of solid such that no resistance is offered by the solid in the movement of this moisture or the moisture content whose relative humidity is 1.

The rate of drying is constant during the removal of unbound moisture.

BOUND MOISTURE:

The moisture content present inside the solid such that the relative humidity is less than 1.

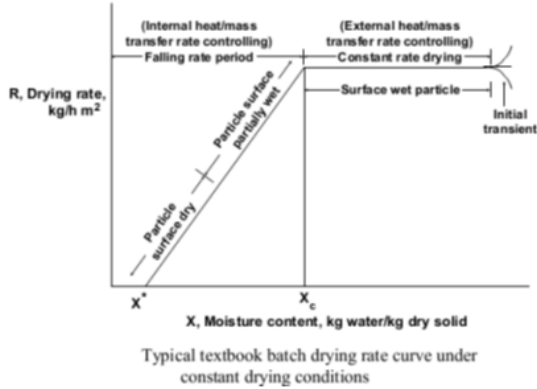
Here, the solid offers resistance in the movement of the moisture.

FREE MOISTURE:

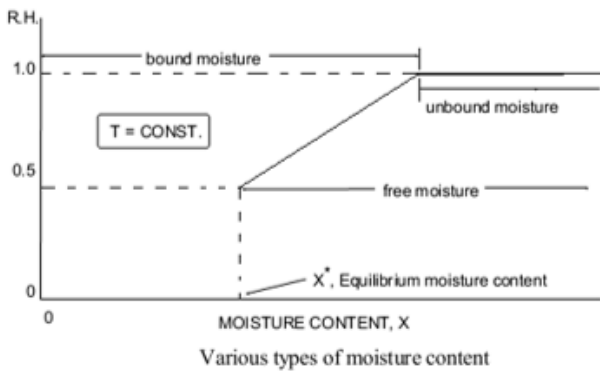
The moisture content which can be removed from the solid. (bound + unbound moisture)

EQUILIBRIUM MOISTURE CONTENT:

The moisture content after which drying is impossible. Rate of drying becomes zero.

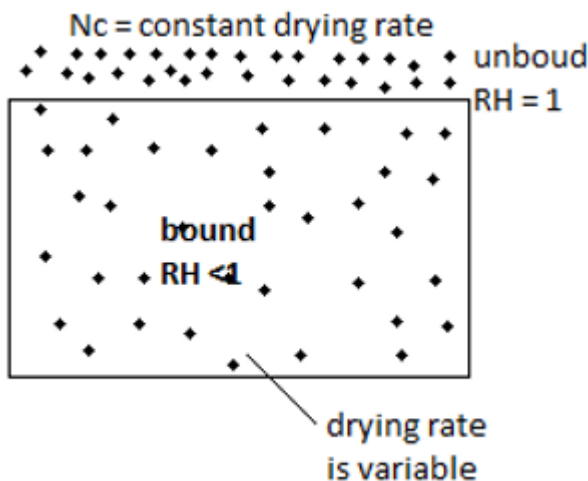


The vapor pressure of moisture inside the solid is equal to the partial pressure of water vapor in air.



Moisture content (X) is on dry basis.

$$X = \text{kg moisture} / \text{kg wet solid}$$



6.5 RATE OF DRYING

The rate of drying is directly proportional to the rate of moisture removed from the solid.

$$N \propto \frac{dX}{dt}$$

$$N = \frac{-Ws}{A} \frac{dX}{dt}$$

N: rate of drying, A: Area of drying, Ws: Wt. of bone dry, X: moisture content, t: time

(X is always taken on dry basis till it is not mentioned)

TIME OF DRYING

$$\int dt = \frac{-Ws}{A} \int_{X_i}^{X_f} \frac{dX}{N}$$

$$t = \frac{Ws}{N} \left[\int_{X_c}^{X_i} \frac{dX}{N_c} + \int_{X_f}^{X_c} \frac{dX}{N} \right]$$

Assumption,

$$N = pX + q$$

$$N_c = pX_c + q$$

$$t = \frac{Ws (X_i - X_c)}{N_c A} + \frac{Ws}{A} \int_{X_f}^{X_c} \frac{dX}{pX + q}$$

$$t = \frac{Ws (X_i - X_c)}{N_c A} + \frac{Ws}{pA} \ln \frac{pX_c + q}{pX_f + q}$$

$$t = \frac{Ws (X_i - X_c)}{N_c A} + \frac{Ws}{pA} \ln \frac{pX_c + pX^*}{pX_f + pX^*}$$

$$t = \frac{Ws (X_i - X_c)}{N_c A} + \frac{Ws}{pA} \ln \frac{X_c - X^*}{X_f - X^*}$$

$$t = \frac{Ws (X_i - X_c)}{N_c A} + \frac{Ws}{N_c A} (X_c - X^*) \ln \frac{X_c - X^*}{X_f - X^*}$$

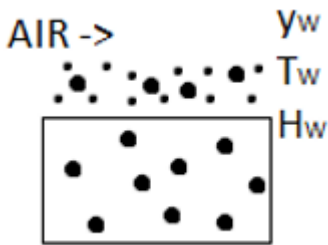
$$t = t_c + t_v$$

$$t = \frac{W_s}{N_c A} \left[(X_i - X_c) + (X_c - X^*) \ln \frac{X_c - X^*}{X_f - X^*} \right]$$

X = kg of moisture/kg of dry solid

x = kg of moisture/ kg of wet solid

$$X = x/(1-x)$$



$$Q = h A (T - T_w)$$

[T : dry bulb temp; T_w : wet bulb]

$$N_A = K_y (y_w - y)$$

$$H = \frac{P_v}{P_t - P_v} \cdot \frac{M_v}{M_a}$$

$$P_t \gg P_v$$

$$H = \frac{P_v}{P_t} \cdot \frac{M_v}{M_a} = y \frac{M_v}{M_a}$$

Similarly,
$$H_w = y_w \frac{M_v}{M_a}$$

$$N_A = K_y \frac{M_v}{M_a} (H_w - H)$$

$$Q = M_v N_A \lambda$$

λ is the latent heat of vaporization.

$$\frac{h (T - T_w)}{\lambda} = K_y M_a (H_w - H)$$

Assumption,

HT by radiation and conduction to the solid surface are neglected.

6.6 EFFECT OF VARIABLES ON DRYING

1. When air flows parallel to the surface

$$h = 0.0204 G^{0.8}$$

2. When air flows perpendicular to surface

$$h = 0.0204 G^{0.37}$$

3. As air velocity increases, rate of drying increases.
4. As gas humidity increases, N decreases.
5. As temperature increases, N increases.
6. As thickness of solid increases, N_c remains same but N decreases. Therefore, T_c remains constant but T_v increases.

Example 6.1 A wet solid is to be dried from 35% to 10% moisture under constant drying conditions in 5 hours. If the equilibrium moisture content is 4% and the critical moisture content is 14%, how long it will take to dry the solids to 6% moisture under the same conditions?

Solution:

Initial content = 35% = 0.5385 (dry basis)

Final content (part 1) = 10% = 0.111 (dry basis)

Critical content = 14% = 0.1628 (dry basis)

Equilibrium content = 4% = 0.0417 (dry basis)

Time required (t) = 5 hrs

$$t = \frac{W_s}{N_c A} \left[(X_i - X_c) + (X_c - X^*) \ln \frac{X_c - X^*}{X_f - X^*} \right]$$

$$5 = \frac{W_s}{N_c A} \left[(0.5385 - 0.1628) + (0.1628 - 0.0417) \ln \frac{0.1628 - 0.0417}{0.111 - 0.0417} \right]$$

$$\frac{W_s}{N_c A} = 11.28$$

Final content (part 2) = 6% = 0.0638 (dry basis)

$$t = 11.28 \left[(0.5385 - 0.1628) + (0.1628 - 0.0417) \ln \frac{0.1628 - 0.0417}{0.0638 - 0.0417} \right]$$

t = 6.56 hr

GATE QUESTIONS

Q.1 200 kg of solid (on dry basis) is subjected to a drying process for a period of 5000 s. The drying occurs in the constant rate period with the drying rate as $N_c = 0.5 \times 10^{-3} \text{ kg} / \text{m}^2 \text{ s}$. The initial moisture content of the solid is 0.2 kg moisture kg dry solid. The interfacial area available for drying is $4 \text{ m}^2 / 100 \text{ kg}$ of dry solid. The moisture content at the end of the drying period is (in kg moisture kg dry solid).

- (A) 0.5 (B) 0.05
(C) 0.1 (D) 0.15

[GATE-2001]

Q.2 It takes 6 hours to dry a wet solid from 50% moisture content to the critical moisture content of 15%. How much longer will it take to dry the solid to 10 % moisture content, under the same drying conditions (the equilibrium moisture content of the solid is 5%)

- (a) 15 min (b) 51 min
(c) 71 min (d) 94 min

[GATE-2002]

Q.3 A solid is being dried in the linear drying rate regime from moisture content X_0 to X_F . The drying rate is zero at $X = 0$ and the critical moisture content is the same as the initial moisture, X_0 . The drying time for $M = (LS/LC)$ is

- (A) $M(X_0 - X_F)$ (B) $M(X_0 / X_F)$
(C) $M \ln(X_0 / X_F)$ (D) $M X_0 \ln(X_0 / X_F)$

[GATE-2003]

Where L_s : total mass of dry solids, A : total surface area for drying, R_c : constant maximum drying rate per unit area, and X : moisture content (in mass of water/mass of dry solids)

Q.4 A 25 cm x 25 cm x 1 cm flat sheet weighing 1.2 kg initially was dried from both sides under constant drying rate conditions. It took 1500 seconds for the weight of the sheet to reduce to 1.05 kg. Another 1 m x 1 m x 1 cm flat sheet of the same materials is to be dried from one side only. Under the same constant drying rate conditions, the time required for drying (in seconds) from its initial weight of 19.2 kg to 17.6 kg is

- (A) 1000 (B) 1500
(C) 2000 (D) 2500

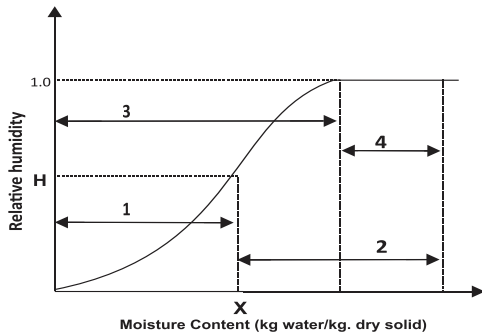
[GATE-2004]

Q.5 A 50 cm X 50 cm X 1 cm flat wet sheet weighing 2 kg initially was dried from both the sides under constant drying rate period. It took 1000 sec for the weight of the sheet to reduce to 1.75 kg. Another 1m X 1m X 1cm flat sheet is to be dried from one side only. Under the same drying rate and other conditions, time required for drying (in sec) from initial weight of 4 kg to 3 kg is

- (A) 1000 (B) 1500
(C) 2000 (D) 2500

[GATE-2007]

Q.6 The equilibrium moisture curve for a solid is shown below:



The total moisture content of the solid is **X** and it is exposed to air of relative humidity **H**. In the table below, **Group I** lists the types of moisture, and **Group II** represents the region in the graph above

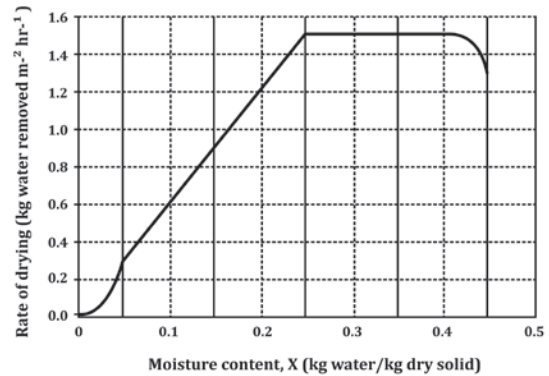
Group I	Group II
P. Equilibrium moisture	1
Q. Bound moisture	2
R. Unbound moisture	3
S. Free moisture	4

Which **ONE** of the following is the correct match?

- (A) P-1, Q-2, R-3, S-4
- (B) P-1, Q-3, R-4, S-2
- (C) P-1, Q-4, R-2, S-3
- (D) P-1, Q-2, R-4, S-3

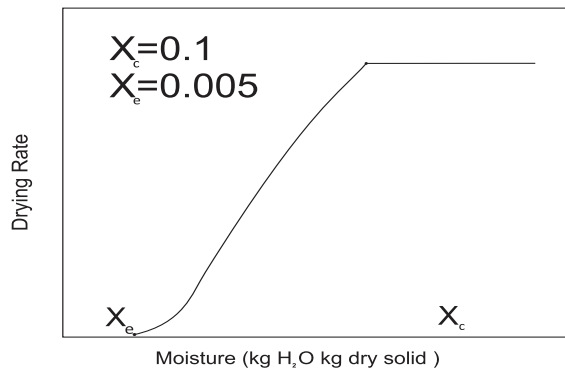
Q.7 A batch of 120 kg wet solid has initial moisture content of 0.2 kg water / kg dry solid. The exposed area for drying is 0.05 m²/kg dry solid. The rate of drying follows the curve given below. The time required (in hours) for drying this batch to a moisture content of 0.1 kg water/kg dry solid is

[GATE-2011]



- (A) 0.033
- (B) 0.43
- (C) 0.6
- (D) 2.31

Q.8 Consider the drying operation shown in the figure below for a solid loading (dry basis) of 50 kg/m² with a constant drying rate of 5 kg / m² .h The falling rate of drying is linear with moisture content.



The drying time (in hrs) required to reduce an initial moisture content of 25 % to final moisture content of 2% is

[GATE-2012]

- (A) 1.55
- (B) 1.75
- (C) 3.25
- (D) 4.55

Q.9 A wet solid is dried over a long period of time by unsaturated air of nonzero constant relative humidity. The moisture content eventually attained by the solid is termed as the

- (A) Unbound moisture content
- (B) Bound moisture content
- (C) Free moisture content
- (D) Equilibrium moisture content

[GATE-2013]

Q.10 A wet solid of 100 kg is dried from a moisture content of 40 wt% to 10 wt%. The critical moisture content is 15wt% and the equilibrium moisture content is negligible. All moisture contents are on dry basis. The falling rate is considered to be linear. It takes 5 hours to dry the material in the constant rate period. The duration (in hours) of the falling rate period is _

[GATE-2014]

Q.11 A fiberboard sheet (1.5m x 2.0 m x 15 mm) is being dried by suspending it horizontally in a current of hot, dry air. The edges are insulated so that drying takes place only from the top and bottom surfaces. The wet sheet weighing 16kg with initial moisture content of 60% loses moisture at a constant rate of $1.25 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ until the moisture content falls to 30%. All moisture contents are on dry basis. The time required for drying during constant rate period (in hour) is _____ (rounded off to third decimal place).

[GATE-2018]

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11
(C)	(C)	(D)	(C)	(C)	(B)	(D)	(C)	(D)	(1.216)	(7.111)

EXPLANATIONS

Q.1 (C)

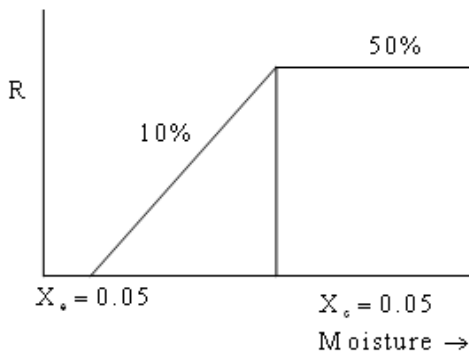
$$N_c = \frac{L_s}{A} \frac{(x_1 - x_2)}{r}$$

= drying rate at constant rate period

$$0.5 \times 10^{-3} = \frac{200}{8} \times \frac{(0.2 - x_2)}{5000} \quad x_2 = 0.1$$

Q.2 (C)

$x_1 = 0.5$ (50%) $x_c = 0.15$ (15%)
 $x_e = 0.05$ (5%) $x_f = 0.10$ (10%)



For constant rate period

$$t = \frac{L_s}{AR_c} [x_1 - x_e] - (x_c - x_e)$$

$$t = \frac{L_s}{AR_c} [0.5 - 0.05] - (0.15 - 0.05)$$

$$t = \frac{L_s}{AR_c} \times 0.35$$

$$\frac{L_s}{AR_c} = \frac{6}{0.35} = 17.14 \frac{\text{kg H}_2\text{O}}{\text{kg solid}} \text{h}$$

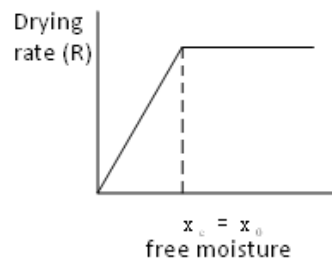
Now for, falling rate period

$$t_2 = \frac{L_s}{AR_c} (x_c - x_e) \ln \frac{(x_c - x_e)}{(x_f - x_e)}$$

$$= 17.14 \times (0.15 - 0.05) \ln \frac{(0.15 - 0.05)}{(0.10 - 0.05)}$$

$$= 17.14 \times 0.10 \ln \frac{0.10}{0.05} = 1.18 \text{ h} = 70.80 \text{ min}$$

Q.3 (D)



At $x = 0$
 $\therefore R = mx$
 at $x = x_0$
 $m = \frac{R_c}{X_c} = \frac{R_c}{X_c} Q X_c = X_c$
 $\therefore R = mx$
 $R = \frac{R_c}{X_0} X$

Drying rate $R = \frac{-L_s}{A} \frac{dx}{dt}$

$$\int_0^t dt = \int_{x_0}^{x_f} -\frac{L_s}{A} \frac{dx}{R}$$

$$t = \frac{-L_s}{A} \int_{x_0}^{x_f} \frac{X_0}{R_c X} dx$$

$$t = \frac{-L_s}{A R_c} \frac{X_0}{R_c} \ln \left(\frac{X_F}{X_0} \right)$$

$$t = \frac{-L_s}{A R_c} \frac{X_0}{R_c} \ln \left(\frac{X_0}{X_f} \right)$$

$$t = M X_0 \ln \left(\frac{X_0}{X_f} \right) \text{ where } M = \frac{L_s}{A R_c}$$

Q.4 (C)

Equation for constant drying rate condition

is

$$\theta_c = \frac{W_s}{A R_c} (x_1 - x_c)$$

$$1500 = \frac{W_s}{2 A R_c} \frac{(2 - 1.05)}{W_s} \left[\begin{array}{l} 2 \text{ is here as drying} \\ \text{is from both sides} \end{array} \right]$$

$$t = \frac{W_s}{A_2 R_c} \frac{(19.2 - 17.6)}{W_s}$$

By solving above two equations we get $t = 1000 \text{ sec}$

Hence (A) is the correct answer.

Q.5 (C)

We know that, time required for constant rate period of drying,

$$t = \frac{L_s}{A R_c} (X_1 - X_2).$$

$t =$ time of drying

$L_s =$ kg dry solid

$R_c =$ constant Rate of drying

$x_1, x_2 \Rightarrow$ Initial and final moisture content in

$\frac{\text{kg water}}{\text{kg dry solid}}$

Case (I)

$L_s =$ unknown $A = 0.50 \text{ m}^2$ both side

$$X_1 = \frac{(L_2 - L_1)}{L_s}, X_2 = \frac{(1.75 - L_s)}{L_s}$$

$$\therefore (X_1 - X_2) = \frac{0.25}{L_s}$$

$$\therefore t_1 = \frac{L_s}{0.50 R_c} \times \frac{0.25}{L_s} = \frac{1}{2 R_c}$$

Case (II)

$$x_1 = \frac{4 - L_s}{L_s}, x_2 = \frac{3 - L_s}{L_s}$$

$$\therefore (x_1 - x_2) = \frac{1}{L_s}$$

$$A = 1 \text{ m} \times 1 \text{ m} = 1 \text{ m}^2 \text{ (one side only)}$$

$$\therefore t_2 = \frac{L_s}{1 \times R_c} \frac{1}{L_s} = \frac{1}{R_c}$$

$$\therefore \frac{t_2}{t_1} = 2 \quad \therefore T_2 = 2 \times 1000 = 2000 \text{ sec}$$

Hence (C) is the Correct answer.

Q.6 (B)

The total moisture content of the solid is x and it is exposed to air of relative humidity H . In the table below, Group I lists the types of moisture, and Group II represents the region in the graph above

(B) P - 1, Q - 3, R - 4, S - 2

Q.7 (D)

Falling rate Region

$$t = \frac{L_s (X_1 - X_2)}{a (R_1 - R_2)} \ln \frac{R_1}{R_2}$$

$t =$ Time (h) $L_s =$ kg dry solid

$A =$ Exposed content area (m^2)

$X =$ Moisture content (kg water /kg dry solid)

Wet solid = 120 kg

Moisture content = 0.2 kg water / kg dry solid

Dry solid = 120 kg wet solid
 $L_s = 100$ kg dry solid

$$A = 0.05 \frac{\text{m}^2}{\text{kg dry solid}} \times 100 \text{ kg dry} = 5 \text{ m}^2$$

$$X_1 = 0.2 \text{ kg water / kg dry solid} / R_1 = 10.2 \frac{\text{Kg water}}{\text{m}^2 \text{h}}$$

$$X_2 = 0.1 \quad R_2 = 0.6$$

$$t_0 = \frac{100}{5} \times \frac{(0.2-0.1)}{(1.2-0.6)} \ln \frac{1.2}{0.6} = 2.31 \text{ h}$$

Hence (D) is the correct answer.

Q.8 (C)

Initial moisture content is in constant period region and final moisture content is in falling rate region, use combined equation for calculation of time required for drying

Constant drying time = 1.5

Variable drying time = 1.753

Total drying time = 3.253

Q.9 (D)

Q.10 (1.216)

We have

Given $X_1 = 0.4$

$X_2 = 0.10$

$X_c = 0.15$

$X^* = 0$

Constant rate period

$$5 = \frac{S}{AN_c} (X_1 - X_c) \Rightarrow \frac{S}{AN_c} = \frac{5}{0.25} = 20$$

$$\text{Falling rate period, } N = m (X - X^*) = \frac{N_c (X - X^*)}{(X_c - X^*)}$$

$$t_f = - \int_{X_c}^{X_2} \frac{S}{A} \left(\frac{N_c}{X_c - X^*} \right) (X - X^*) dX$$

$$= \frac{S(X_c - X^*)}{AN_c} \ln \frac{X_c - X^*}{X_2 - X^*}$$

$$t_f = 20 \times 0.15 \ln \frac{0.15}{0.10} = 1.216 \text{ hr}$$

Q.11 (7.11)

Fiber sheet area = $1.5 \times 2 \text{ m}^2 = 3 \text{ m}^2$

\therefore Drying take place (top \times bottom) (A) = $2 \times 3 = 6 \text{ m}^2$

On dry basis

$x_i = 60\% = 0.6$

$x_f = 30\% = 0.3$

wet sheet = 16kg

wt of dry solid $S_s = 16(1 - 0.6) = 6.4 \text{ kg}$

Constant rate (N) = $1.25 \times 10^{-5} \text{ kg/m}^2 \text{ s}$

Time of drying in constant rate period

$$t_c = \frac{S_s [x_i - x_f]}{A N}$$

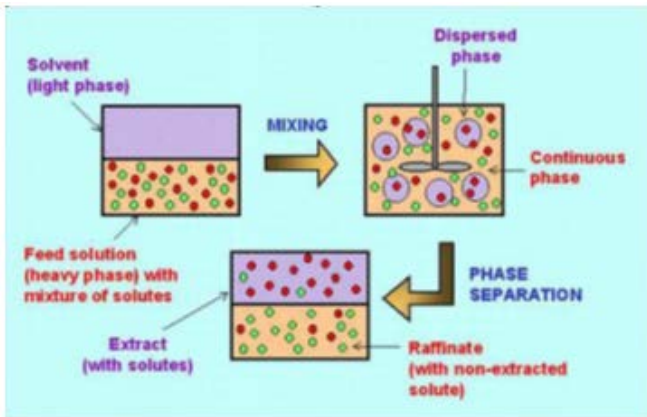
$$= \frac{6.4 \text{ kg} [0.6 - 0.3]}{6 \text{ m}^2 \times 1.25 \times 10^{-5} \text{ kg/m}^2 \cdot \text{sec}}$$

= 25600 sec

$$t_c = 7.111 \text{ hrs}$$

7.1 INTRODUCTION

It is a process of transferring a solute from one liquid phase to another immiscible or partially miscible liquid in contact with the first. The two phases are chemically quite different, which leads to a separation of the components according to their distribution or partition between the two phases, normally one organic and one water.



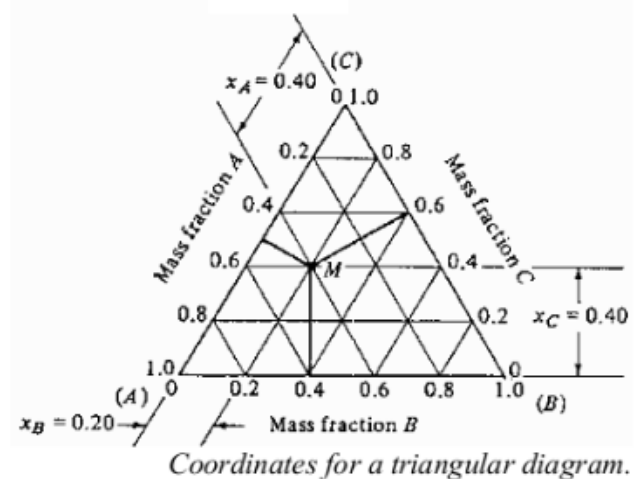
7.2 EQUILIBRIUM RELATIONS IN EXTRACTION

7.2.1 PHASE RULE

In a liquid-liquid system, the minimum number of components is three and we have two phases in equilibrium. For a ternary system, the number of degrees of freedom is three, as calculated by the phase rule ($F = C - P + 2 = 3 - 2 + 2 = 3$). We have six variables: temperature, pressure, and four concentrations. If the pressure and temperature are specified, then setting one concentration will fix the system. The other three concentrations must be calculated from the phase equilibrium.

7.2.2 TRIANGULAR COORDINATES AND EQUILIBRIUM DATA

Since we have three components, the equilibrium data are often expressed in equilateral triangular coordinates. This is shown in the following figure.



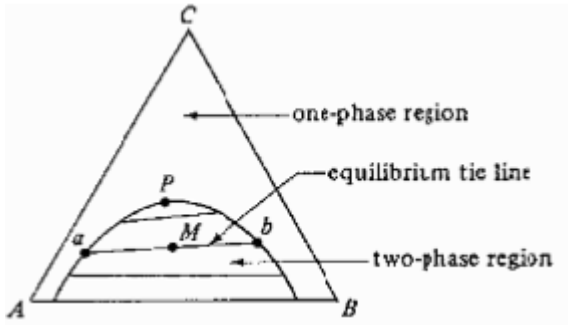
The three corners represent three pure components, A, B and C. The point M is a mixture. The perpendicular distance from the point M to any base line is the mass fraction of the component at the corner opposite to that base line. For example, the distance from M to base AB is the mass fraction of C ($x_C = 0.40$).

7.3 TYPES OF SYSTEM IN EXTRACTION

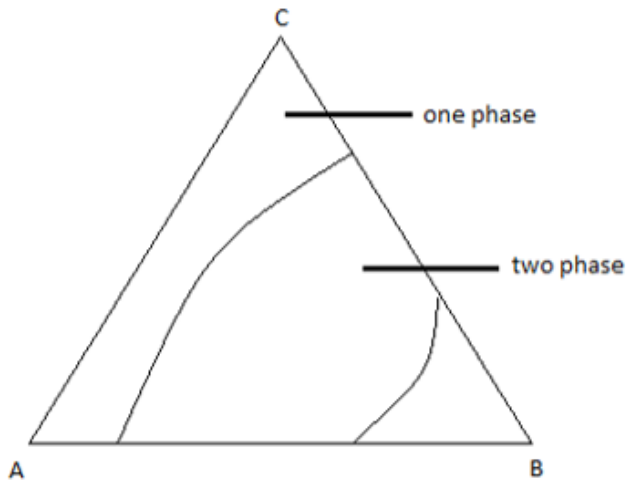
7.3.1 TYPE 1 (one pair is partially miscible)

A common phase diagram is Type I system (80% mixture lie in this type) and shown in figure given below, where a pair of components A and B are partially miscible, and liquid C dissolves completely in A or B. The two phase region is include inside below the curved envelope. An original mixture of composition M will separate into two conjugate phases *a* and *b* which are on equilibrium tie line through point M. other tie lines are also plotted.

The two phases are identical at point P, which is called the **Plait Point**. Outside the envelope is one phase region.



7.3.2 TYPE 2 (two pairs are partially miscible)



System of A + B + C has two pairs that are partially miscible. A & C completely soluble, A & B partially soluble, B & C partially soluble.

7.3.3 EFFECT OF TEMPERATURE

As the temperature increases, solubility increases, one phase region increases and the equilibrium region shrinks.

TYPE 1:



So, extraction is done at room temperature for type 1 system.

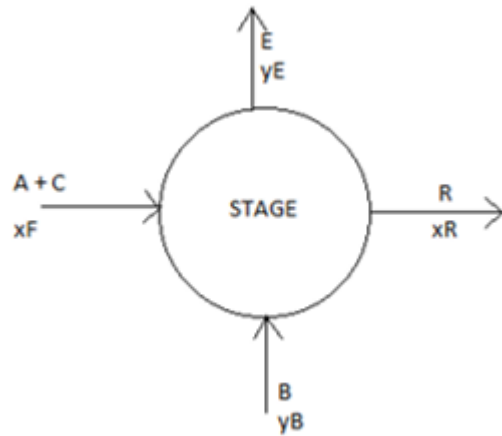
TYPE 2:



Here, extraction is done at high temperature for type 2 systems.

7.4 STAGES

Two streams are brought in contact for sufficiently long time for equilibrium mass transfer. And thus the stage is known as ideal stage.



Material balance'

$$F + B = M = E + R$$

$$F x_F + B x_B = M x_M = E x_E + R x_R$$

Example 7.1 The compositions of the two equilibrium layers are:

for the extract layer (V), $y_A = 0.04$, $y_B = 0.02$, $y_C = 0.94$

for the raffinate layer (L), $x_A = 0.12$, $x_B = 0.86$, $x_C = 0.02$

The original mixture contained 100 kg and $x_{AM} = 0.10$. Determine the amounts of V and L.

Solution: overall material balance,

$$V + L = M = 100 \text{ kg}$$

Component balance for A,

$$0.04V + 0.12L = 0.1 \times 100$$

$$V = 75 \text{ kg}, L = 25 \text{ kg}$$

$$\frac{R_s}{E_s} = \frac{m X_n}{(X_n - 1) - X_n}$$

$$\frac{(X_n - 1) - X_n}{X_n} + 1 = \frac{E_s}{R_s} m + 1$$

$$\frac{(X_n - 1)}{X_n} = \frac{E_s}{R_s} m + 1$$

7.4.1 CROSS CURRENT STAGES

During the mathematical interpretation we assume that A and B are completely immiscible such that R contains only A & C and E contains only B & C.

During separation, at each and every point the flow rates of R and E changes, therefore the slope changes. So, for the ease of understanding and calculation, we work on solute free basis.

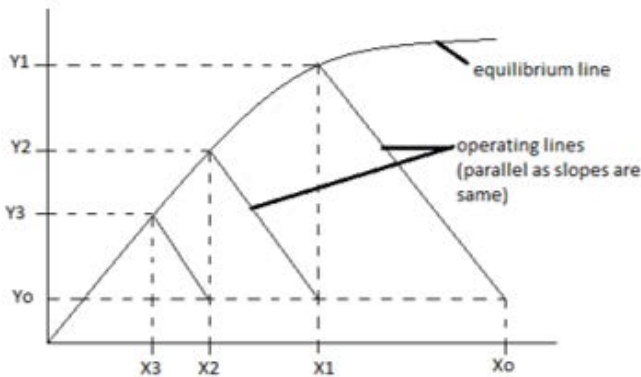
$$R \rightarrow R_s, \quad E \rightarrow E_s, \quad x \rightarrow X, \quad y \rightarrow Y$$

Material balance,

$$R_s X_o + E_s Y_o = R_s X_n + E_s Y_n$$

$$Y_n = \frac{-R_s}{E_s} X_n + \left[\frac{R_s X_o + E_s Y_o}{E_s} \right]$$

n is the no. stages.



If composition of solvent changes at every stage, then the lines will not start from Y_o .

MULTISTAGE CROSS CURRENT FLOW:

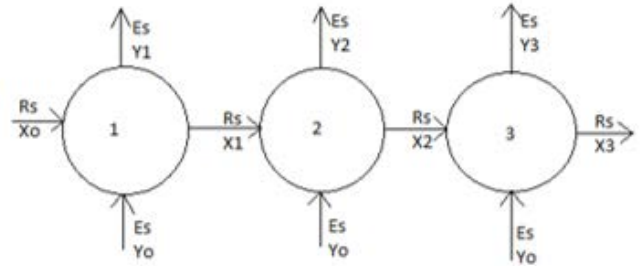
Assumption,

$$Y_o = 0, Y = m X, E_s \text{ is constant}$$

For n^{th} stage,

$$R_s X_{n-1} + E_s Y_o = R_s X_n + E_s Y_n$$

For 1st stage,



$$\frac{(X_o)}{X_n} = \frac{E_s}{R_s} m + 1$$

For 2nd stage,

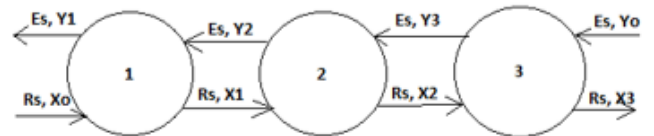
$$\frac{(X_1)}{X_n} = \frac{E_s}{R_s} m + 1$$

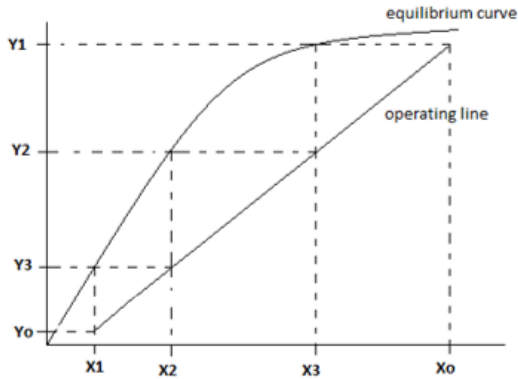
$$\frac{(X_o)}{X_n} = \left[\frac{E_s}{R_s} m + 1 \right]^n$$

n is the no. of stages.

$$\frac{(X_o)}{X_n} = \text{Reduction Ratio}$$

7.4.2 COUNTER-CURRENT FLOW





Overall material balance,

$$R_s (X_o - X_3) = E_s (Y_1 - Y_o)$$

$$Y = \frac{R_s}{E_s} X + \frac{E_s Y_1 + R_s X_o}{E_s}$$

$X_o, Y_1 ; X_1, Y_2 ; X_2, Y_3$ are the points for operating line.

$X_1, Y_1 ; X_2, Y_2 ; X_3, Y_3$ are points for equilibrium line.

KREMSER EQUATION:

$$N_p = \frac{\ln \left[\left(\frac{X_o - \frac{Y_o}{m}}{X_n - \frac{Y_o}{m}} \right) (1 - A) + A \right]}{\ln \left[\frac{1}{A} \right]}$$

N_p is the no. of stages,

A = Extraction Factor

$$= \frac{\text{slope of operating line}}{\text{slope of equilibrium}} = \frac{R_s/E_s}{m}$$

Example 7.2 an extraction process is going on to separate a feed mix (A+C) in which C = 15% wt/wt and total feed flow rate is 1000 kg/hr. For extraction we are using solvent B (no C). Find the flow rate of solvent required for the process such that C is removed by 95%.

i) When single stage is used

ii) When 3 stages are used

$$Y = 3.75 X \text{ (solute free basis)}$$

Solution:

- i) C in feed = $1000 \times .15 = 150$ kg
 C should be removed = C in Extract = $150 \times .95 = 142.5$ kg
 C in Refinate = $150 - 142.5 = 7.5$ kg
 $X_o = 150/850 = 3/17$
 $Y_o = 0$
 $X_1 = 7.5/850 = 1.5/170$
 $Y_1 = 142.5/E_s$

$$Y_1 = 3.75 X_1$$

$$142.5/E_s = 3.75 \times 1.5/170$$

$$E_s = (142.5 \times 170) / (3.75/1.5)$$

$$E_s = 4306.667 \text{ kg/hr}$$

- ii) $\frac{(X_o)}{X_n} = \left[\frac{E_s}{R_s} m + 1 \right]^n$
- $$\frac{3/17}{1.5/170} = \left[\frac{E_s \times 3.75}{850} + 1 \right]^3$$
- $$E_s = 388.6 \text{ kg/hr}$$

GATE QUESTIONS

Q.1 .In a single stage extraction process, 10kg of pure solvent S (containing no solute A) is mixed with 30kg of feed F containing A at a mass fraction $X_F = 0.2$. The mixture splits into an extract phase E and raffinate phase R, containing A at $X_E = 0.05$ and $X_R = 0.05$ respectively. The total mass of the extract phase is (in kg).

[GATE -2001]

- (A) 6.89 (B) 8.89
(C) 10 (D) 8.25

Q.2 Compound A is extracted from a solution of A + B into a pure solvent S. A co-current unit is used for the liquid-liquid extraction. The inlet rate of the solution containing A is 200 moles of B/hr m^2 and the solvent flow rate is 400 moles of S/hr m^2 . The equilibrium data is represented by $Y = 3x^2$ where Y is in moles of A/moles of B and X is in moles of A/moles of S. The maximum percentage extraction achieved in the unit is

[GATE -2003]

- (A) 25% (B) 50%
(C) 70% (D) 90%

Q.3 In liquid-liquid extraction 10 kg of a solution containing 2 kg of solute C and 8 kg of solvent A is brought into contact with 10 kg of solvent B. Solvents A and B are completely immiscible in each other whereas solute C is soluble in both the

solvents. The extraction process attains equilibrium. The equilibrium relationship between the two phases is $Y^* = 0.9X$ where Y^* is kg of C / kg of B and X is kg of C / kg of A. Choose the correct answer

[GATE -2004]

- (A) The entire amount of C is transferred to solvent
(B) Less than 2 kg but more than 1 kg of C is transferred to solvent B
(C) Less than 1 kg of C is transferred to solvent B
(D) No amount of C is transferred to B.

Q.4 An ideal single stage extraction process is used to treat 100 mol/s of an organic feed solution. The solute concentration in this solution is to be reduced from 0.5 mol% to 0.1 mol%. A pure solvent S is used. To reduce the solvent requirement by half for the same separation,

[GATE -2006]

- (A) Add one more ideal co-current stage
(B) Use another pure solvent S^* whose partition coefficient is twice that of S
(C) Use solvent S containing 0.02 mole fraction of the solute,
(D) Double the residence time of the solvent S in the contactor

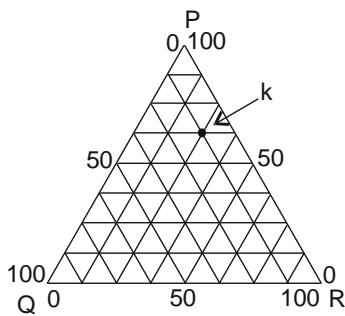
Q.5 It is desired to reduce the concentration of pyridine in 500 kg of aqueous solution from 20 weight percent to 5 wt percent in a single batch extraction using chloro- benzene as solvent. Equilibrium compositions (end points of the tie line) in terms of weight percent of pyridine-water-chloro-benzene are (5, 95, 0) and (11, 0, 89). The amount of pure solvent required in kg for the operation is

[GATE -2007]

- (A) 607 (B) 639
(C) 931 (D) 1501

Q.6 For a system containing species P, Q and R, composition at point k on the ternary plot is

[GATE -2008]



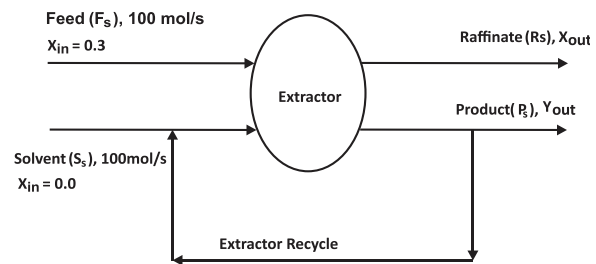
- (A) 62.5% P, 12.5% Q, 25% R
(B) 25% P, 62.5% Q, 12.5% R
(C) 12.5% P, 62.5% Q, 25% R
(D) 12.5% P, 25% Q, 62.5% R

Q.7 A feed (F) containing a solute is contacted with a solvent (S) in an ideal stage as shown in the diagram below. Only the solute transfers into the solvent. The flow rates of all the streams are shown on a solute free basis and indicated by the subscript S. The compositions of the streams are

expressed on a mole ratio basis. The extract leaving the contactor is divided into two equal parts, one part collected as the product (P) and the other stream is recycled to join

the solvent. The equilibrium relationship is $Y^* = 2X$. The product flow rate (P_S) and composition (Y_{out}) are

[GATE -2008]



- (A) $P_S = 50 \text{ mol/s}$, $Y_{out} = 0.3$
(B) $P_S = 100 \text{ mol/s}$, $Y_{out} = 0.2$
(C) $P_S = 200 \text{ mol/s}$, $Y_{out} = 0.1$
(D) $P_S = 100 \text{ mol/s}$, $Y_{out} = 0.4$

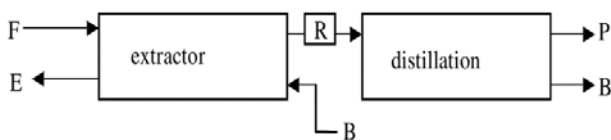
Q.8 A crosscurrent cascade of N ideal stages is used to treat a feed stream of molar flow rate E. The feed stream contains a solute which is to be recovered by a pure solvent having a molar flow rate S. The solvent is divided equally between these N stages. The linear equilibrium curve relating the mole fractions x and y^* of the solute in the raffinate and the extract respectively, is given by $y^* = mx$. Assume dilute conditions. The ratio of the solute mole fraction in the original feed to that in

the exit raffinate stream i.e. (x_0/x_N) is given by

[GATE -2013]

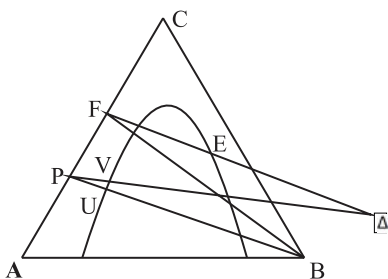
- (A) $\left[1 + \left(\frac{mS}{NE}\right)^N\right]$ (B) $\left[1 + \left(\frac{NS}{mE}\right)^N\right]$
 (C) $\left[1 + \left(\frac{NE}{mS}\right)^N\right]$ (D) $\left[1 + \left(\frac{mE}{NS}\right)^N\right]$

Q.9 A multi-stage, counter-current liquid-liquid extractor is used to separate solute C from a binary mixture (F) of A and C using solvent B. Pure Solvent B is recovered from the raffinate R by distillation, as shown in the schematic diagram below:



Locations of different mixtures for this process are indicated on the triangular diagram below. P is the solvent-free raffinate, E is the extract, F is the feed and Δ is the difference point from which the mass balance lines originate. The line PB intersects the binodal curve at U and T. The lines P Δ and FB intersect the bimodal at V and W respectively.

[GATE -2015]

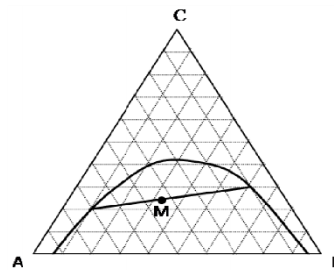


The raffinate coming out of extractor is represented in the diagram by the point:

- (A) T (B) U
 (C) V (D) W

Q.10 Solute C is extracted in a batch process from its homogenous solution of A and C, using solvent B. The combined composition of the feed and the extracting solvent is shown in the figure below as point M, along with the tie line passing through it. The ends of the tie line are on the equilibrium curve.

[GATE -2016]



What is the selectivity for C?

- (A) 3.5 (B) 7
 (C) 10.5 (D) 21

Q.11 Which of the following condition are valid at the plait point?

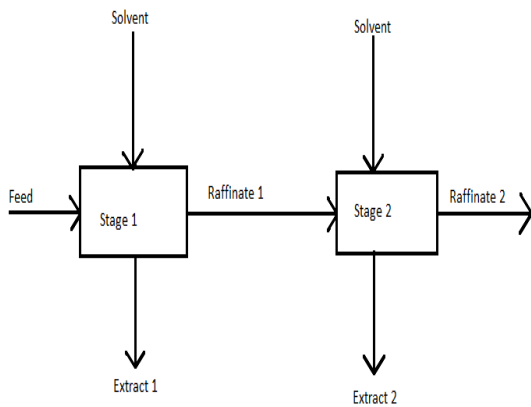
- (P) Density difference between the extract and raffinate phases is zero
 (Q) Interfacial tension between the extract and raffinate phases is zero
 (R) Composition difference between the extract and raffinate phase is zero

[GATE -2017]

- (a) P and Q only
- (b) Q and R only
- (c) P and R only
- (d) P, Q and R

Q.12 It is decided to extract A from a feed containing 20 mol % A and 80 mol% B in two ideal cross current stages as shown below using equal amount of pure solvent C in each stage.

[GATE -2018]



Components B and C are immiscible. 60% of A in the feed is extracted in Stage 1 . The equilibrium relation is given by $Y^* = 1.5 X$ where. X = moles of A per mole of B in raffinate

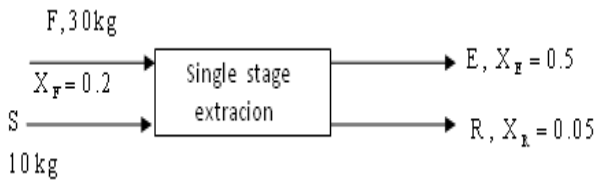
Y^* = moles of A per mole of C in extract in equilibrium with raffinate. The mol % of A in raffinate from Stage 2 is _____ (rounded off to second decimal place).

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12
(B)	(B)	(B)	(B)	(B)	(A)	(B)	(C)	(A)	(C)	(B)	(C)

EXPLANATIONS

Q.1 (B)



Overall balance ;

$$F + S = E + R$$

$$E + R = 40 + 30 = 40 \text{ KG}$$

Balance for A;

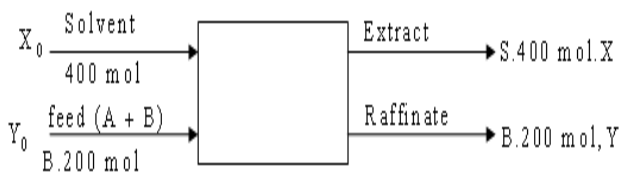
$$FX_F + S X_S = EX_E + RX_R$$

$$30 \times 0.2 + S \times 0 = E \times 0.5 + R \times 0.05$$

$$6 = E \times 0.5 + (40 - E) \times 0.05$$

$$E = 8.89 \text{ kg}$$

Q.2 (B)



$X_0 = 0$ (pure solvent) material balance

$$SX_0 + By_0 = X S + y B \quad QX_0 = 0$$

$$200 y_0 = 400x + 200 y$$

$$x = \frac{y_0 - y}{2}$$

For maximum extraction $y = 2x$

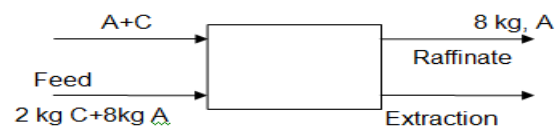
$$y = 2 \frac{(y_0 - y)}{2} \quad y = \frac{y_0}{2}$$

For maximum extraction =

$$\frac{y - y_0}{y_0} \times 100 = \frac{y_0 - y_0/2}{y_0} \times 100 = 50\%$$

Q.3 (B)

We have



$$M_{\text{solvent B}} = 10 \text{ kg}$$

$$M_{\text{solute}} = 2 \text{ kg}$$

$$M_{\text{solvent A}} = 8 \text{ kg}$$

$$\therefore x_{\text{solute i}} = \frac{2}{8} = 0.25 \frac{\text{kg of C}}{\text{kg of A}}$$

$$\therefore M_{\text{solvent A}}(X_{\text{solute i}} - X_{\text{solute 0}}) = M_{\text{solvent B}}(\gamma_{\text{solute i}} - \gamma_{\text{solute 0}})$$

putting values, we get

$$8(0.25 - X_{\text{solute 0}}) = 10(0.9x_{\text{solute 0}})$$

$$x_{\text{solute 0}} = 0.118 \frac{\text{kg of C}}{\text{kg of A}}$$

$$\text{Solute remaining} = X_{\text{solute 0}} \times M_{\text{solvent A}}$$

$$= 0.118 \times 8 = 0.941 \text{ kg}$$

$$= 2 - 0.941 = 1.05 \text{ kg}$$

Q.4 (B)

Q.5 (B)

Water in feed = $500 \times (1 - 0.2) = 400$ kg.

Water present in raffinate is 90 %

$$\text{Amount of Raffinate} = \frac{400}{0.95} = 421 \text{ kg.}$$

Applying mass balance

$$F + X = E + R$$

$$\text{Also } F_{XF} + X\delta_f = E_{XE} + R_{XR}$$

$$\therefore 500 \times 0.2 + 0 = E \times 0.11 + 421 \times 0.05$$

$$\therefore E = 718$$

$$\therefore 500 + X = 718 + 421$$

$$\Rightarrow X = 0.1139 - 500 = 639 \text{ kg}$$

Hence, amount of pure solvent is 639 kg

Hence (B) is the Correct answer.

Q.6 (A)

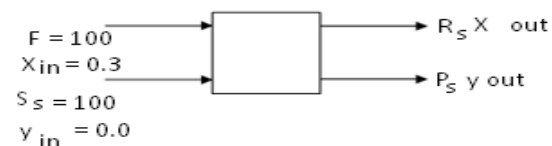
Q.7 (B)

$$F = 100$$

$$X_{in} = 0.3 \quad R_S X_{out}$$

$$S_S = 100 \quad P_S Y_{out}$$

$$Y_{in} = 0.0$$



$$Y = 2X$$

$$\therefore F + S_S = R_S + P_S = 200$$

$$\Rightarrow R_S = P_S = 100$$

$$\text{Also, } 0.3 \times 100 + 0 = x \times 100 + y \times 100$$

$$\Rightarrow 30 = 300x$$

$$\Rightarrow X = 0.1$$

$$\therefore Y = 0.2$$

Q.8 (C)

The ratio of the solute mole fraction in the original feed to that in the exit raffinate stream i.e. (X_0/X_N) is given by

$$\left[1 + \left(\frac{mS}{NE} \right) \right]^N$$

Hence Correct answer is (A)

Q.9 (B)

Mixing rule says if $A + B = C$ then

In the given diagram $R = P + B$ therefore R is represented by the point

Q.10 (C)

Selectivity is given by

$$\beta_{C/A} = \frac{Y_C/Y_A}{X_C/X_A} = \frac{0.3/0.1}{0.2/0.7} = 10.5$$

Q.11 (D)

Plait point signifies the condition at which the composition of two liquid phases in equilibrium become identical and indeed transforms to a single phase. At this point interfacial tension and density difference between extract and raffinate phase is zero as both phase united to form one phase.

Q.12 (3.846)

$$\text{In feed } A = 20 \text{ moles, } B = 80 \text{ moles, } X_F = \frac{20}{80} = 0.25$$

Step 1:- \therefore 60 % of A is extracted

$$\therefore \text{Raffinate } A = 20 (1 - 0.6) = 20(0.4) = 8$$

$$Y_0 = 0$$

Mass balance at stage 1 gives

$$BX_F + CY_0 = CY_1 + BX_1$$

$$BX_F + 0 = CY_1 + BX_1$$

$$80(0.25) = C(1.5(0.1)) + 80(0.1)$$

$Y_1 = 1.5X_1 = 1.5(0.1)$, on solving we get

$$C = 80$$

State 2: Mass balance gives

$$BX_1 + CY_0 = BX_2 + CY_2, \quad \{Y_2 = 1.5X_2\}$$

$$80(0.1) = 80X_2 + 80(1.5X_2)$$

We get $X_2 = 0.04$ = molaratio of raffinate

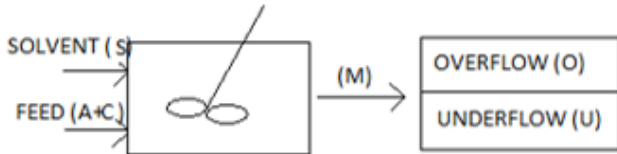
$$x_2 = \frac{x_2}{1 + x_2} = \frac{0.04}{1 + 0.04} = 0.03846 \Rightarrow \text{mole \%} = 3.846$$

8

LEACHING

8.1 INTRODUCTION

It is a process of separation of soluble constituent of a solid material using suitable solvent.



Material balance,

$$F + S = M$$

$$M = O + U$$

$$F_{X_F} + S_{X_S} = M_{X_M}$$

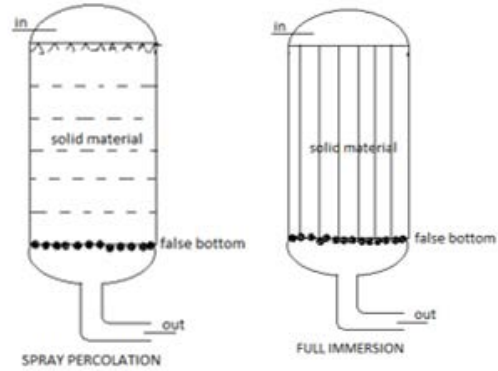
$$M_{X_M} = O_{X_O} + U_{X_U}$$

8.2 FACTORS AFFECTING RATE OF LEACHING

1. Type of solvent.
2. For the porous or powdered form, the rate is generally high.
3. Rate of leaching increases with the increase in agitation.
4. As the temperature increases, solubility increases, viscosity decreases and thus the rate of leaching increases.

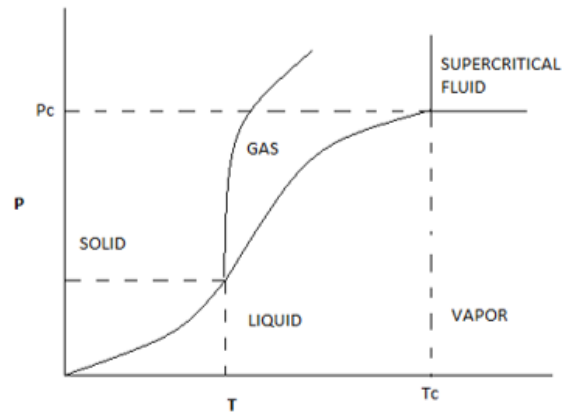
8.3 CONTACTING PATTERN

There the stream is recirculated again and again till the required exit stream is achieved. The solvent amount required is very high.



A proper mixing is done in the whole process using different contacting pattern.

8.4 SUPER CRITICAL FLUID EXTRACTION



The fluid is called super critical if both temperature and pressure are above critical values. At supercritical state a fluid remains as a highly condensed phase and may have a density more than its density in the liquid state.

Critical point is a point of a material above which distinction between liquid and gas becomes impossible.

Super critical fluid shares the properties of both gas and liquid. Its viscosity is a little smaller than the normal liquid viscosity and the diffusivity of solute in the super critical fluid becomes than the normal solvent.

9.1 INTRODUCTION

Adsorption is a process that occurs when a gas or liquid solute accumulates on the surface of a solid or a liquid (adsorbent), forming a molecular or atomic film (the adsorbate). It is different from absorption, in which a substance diffuses into a liquid or solid to form a solution. The term sorption encompasses both processes, while desorption is the reverse process.

Adsorption is operative in most natural physical, biological, and chemical systems, and is widely used in industrial applications such as activated charcoal, synthetic resins and water purification.

Similar to surface tension, adsorption is a consequence of surface energy. In a bulk material, all the bonding requirements (be they ionic, covalent or metallic) of the constituent atoms of the material are filled. But atoms on the (clean) surface experience a bond deficiency, because they are not wholly surrounded by other atoms. Thus it is energetically favorable for them to bond with whatever happens to be available. The exact nature of the bonding depends on the details of the species involved, but the adsorbed material is generally classified as exhibiting physisorption or chemisorption.

9.2 TYPES OF ADSORPTION

Physical Adsorption

Adsorbate is held by the surface by weak van-der-waal forces.

It is a physical process.

The enthalpy of adsorption is of the order 20kJ/mol.

Usually takes place at low temperature.

It is not specific, all the gases are adsorbed to the same extent on all the solid.

Multi-molecular layer may form

Chemical Adsorption

Adsorbate is held on the surface by chemical bonding.

It features a chemical process.

The enthalpy of adsorption is of the order 200kJ/mol.

Usually takes place at relatively high temperature.

Highly specific in nature.

Single layer is formed

9.3 ADSORPTION ISOTHERMS

9.3.1 LANGMUIR ISOTHERM

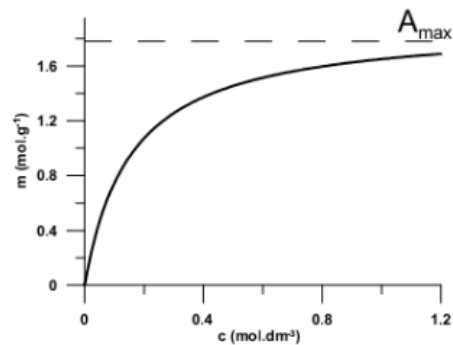
It is an empirical isotherm derived from a proposed kinetic mechanism. It is based on four hypotheses:

1. The surface of the adsorbent is uniform, that is, all the adsorption sites are equal.
2. Adsorbed molecules do not interact.
3. All adsorption occurs through the same mechanism.
4. At the maximum adsorption, only a monolayer is formed: molecules of adsorbate do not deposit on other, already adsorbed, molecules of adsorbate, only on the free surface of the adsorbent.

For liquids (adsorbate) adsorbed on solids (adsorbent), the Langmuir isotherm can be expressed by

$$m = \frac{A_{\max} k \cdot c}{1 + k c}$$

Where, m is the substance amount of adsorbate adsorbed per gram (or kg) of the adsorbent, the unit of m is $\text{mol}\cdot\text{g}^{-1}$, resp. $\text{mol}\cdot\text{kg}^{-1}$. A_{\max} is the maximal substance amount of adsorbate per gram (or kg) of the adsorbent. The unit of A_{\max} is $\text{mol}\cdot\text{g}^{-1}$, respectively. k is the adsorption constant ($\text{mol}^{-1}\cdot\text{dm}^3$); c ($\text{mol}\cdot\text{dm}^{-3}$) is the concentration of adsorbate in liquid. In practice, activated carbon is used as an adsorbent for the adsorption of mainly organic compounds along with some larger molecular weight inorganic compounds such as iodine and mercury.



Langmuir isotherm

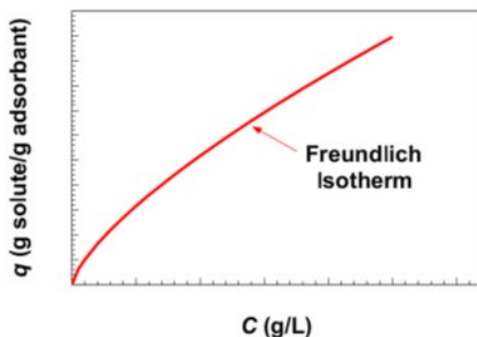
9.3.2 FREUNDLICH ISOTHERM

The data for physical adsorption can be expressed by an empirical equation. The Freundlich equation is an empirical relation that fits equilibrium adsorption data in many cases.

The Freundlich adsorption isotherm is represented by the equation:

$$c^* = k (x/m)^n$$

For liquids c^* is the equilibrium concentration of the adsorbate in the fluid phase and x/m is the mass of the substance adsorbed per unit mass of the adsorbent. For gases c^* can be replaced by the p^* which is the equilibrium partial pressure of the adsorbed gas in the fluid phase.



GATE QUESTIONS

Q.1 Adsorption on activated carbon is to be used for reducing phenol concentration in wastewater from 0.04 mol / l to 0.008 mol / l. The adsorption isotherm at the operating temperature can be expressed as $q = 0.025 C^{1/3}$; where q is the phenol concentration in solid (mol / g solid) and C is the phenol concentration in water (mol / l). The minimum amount of solid (in grams) required per liter of wastewater (up to one decimal place) is _____

[GATE-2015]

Q.2 At 30°C, the amounts of acetone adsorbed at partial pressures of 10 and 100 mmHg are 0.1 and 0.4 kg acetone/kg activated carbon, respectively. Assume Langmuir isotherm describes the adsorption of acetone on activated carbon. What is the amount of acetone adsorbed (in kg per kg of activated carbon) at a partial pressure of 50 mmHg and 30°C?

[GATE-2016]

- (A) 0.23 (B) 0.25
(C) 0.30 (D) 0.35

Q.3 For a solid catalyzed gas phase reversible reaction, which of the following statements is always true?

- (a) Adsorption is rate limiting
(b) Desorption is rate limiting
(c) Solid catalyst does not affect equilibrium conversion
(d) Temperature does not affect equilibrium conversion

[GATE-2017]

Q.4 In a batch adsorption process, 5 g of fresh adsorbent is used to treat 1 litre of an aqueous phenol solution. The initial phenol concentration is 100 mg/litre. The equilibrium relation is given by $q^* = 1.3C$ Where, q^* is the amount of phenol adsorbed in mg of phenol per gram of adsorbent; and C the concentration of phenol in mg/litre in the aqueous solution. When equilibrium is attained between the adsorbent and the solution, the concentration of phenol in the solution, rounded to 1 decimal place is _____mg/litre

[GATE-2017]

ANSWER KEY:

1	2	3	4
(6.4)	(c)	(c)	(13.34)

EXPLANATIONS

Q.1 (6.4)

By using the curve $q = 0.025 C^{1/3}$

Minimum amount of solid (10 gm) required per litre of waste water can be calculated.

Q.2 (C)

According to Langmuir adsorption isotherm,

$$\theta_A = \frac{K_A P_A}{1 + K_A P_A}$$

where, $\theta_A = \frac{q}{q_m}$

$$\theta_A = \frac{\frac{\text{Amount of 'A' adsorbed}}{\text{kg of Adsorbent}}}{\frac{\text{maximum amount of 'A' that can be adsorbed}}{\text{kg of Adsorbent}}}$$

$$\Rightarrow \frac{q}{q_m} = \frac{K_A P_A}{1 + K_A P_A}$$

for case I at $P_A = 10$ mm Hg and $q = 0.1$

$$\frac{0.1}{q_m} = \frac{K_A \times 10}{1 + K_A \times 10} \quad (1)$$

For case II $P_A = 100$ mm Hg $\Rightarrow Q = 0.4$

$$\frac{0.4}{q_m} = \frac{K_A \times 100}{1 + K_A \times 100} \quad (2)$$

On solving we get K_A & q_m

So for $P_A = 50$ mm Hg

therefore, $q = \frac{0.3 \text{ kg Adsorbed}}{\text{kg of Adsorbent}}$

Q.3 (C)

Solid catalyst does not affect the equilibrium conversion

Q.4 (13.34)

Suppose y mg of phenol is adsorbed

$$q^* = \frac{\text{Amount of phenol adsorbed in mg}}{\text{wt. fresh adsorbent}} = \frac{y}{5}$$

$$q^* = 1.3C$$

$$C = 100 - y$$

$$\frac{y}{5} = 1.3(100 - y)$$

$$0.15384y = 100 - y$$

$$y = 86.66 \text{ mg}$$

Concentration of phenol in solution = $100 - 86.66 = 13.34$ mg/it