UNIT-5 MASS TRANSFER

Part-A

1. What is mass transfer?

The process of transfer of mass as a result of the species concentration difference in a mixture is known as mass transfer.

2. Give the examples of mass transfer.

Some examples of mass transfer.

1. Humidification of air in cooling tower
2. Evaporation of petrol in the carburetor of an IC engine.
3. The transfer of water vapour into dry air.

3. What are the modes of mass transfer?

There are basically two modes of mass transfer,

1. Diffusion mass transfer
2. Convective mass transfer

4. What is molecular diffusion?

The transport of water on a microscopic level as a result of diffusion from a region of higher concentration to a region of lower concentration in a mixture of liquids or gases is known as molecular diffusion.

5. What is Eddy diffusion?

When one of the diffusion fluids is in turbulent motion, eddy diffusion takes place.

6. What is convective mass transfer?

Convective mass transfer is a process of mass transfer that will occur between surface and a fluid medium when they are at different concentration.

7. State Fick's law of diffusion.

The diffusion rate is given by the Fick's law, which states that molar flux of an element per unit area is directly proportional to concentration gradient.

$$\frac{m_a}{A} = -D_{ab}\frac{dC_a}{dx}$$

where,

$\frac{ma}{A}$ – Molar flux, $\frac{kg\text{-}mole}{s\text{-}m^2}$

D_{ab} Diffusion coefficient of species a and b, m^2/s

$\frac{dC_a}{dx}$ – concentration gradient, kg/m^3

8. What is free convective mass transfer?

If the fluid motion is produced due to change in density resulting from concentration gradients, the mode of mass transfer is said to be free or natural convective mass transfer.

Example : Evaporation of alcohol.

9. Define forced convective mass transfer.

If the fluid motion is artificially created by means of an external force like a blower or fan, that type of mass transfer is known as convective mass transfer.

Example: The evaluation if water from an ocean when air blows over it.

10. Define Schmidt Number.

It is defined as the ratio of the molecular diffusivity of momentum to the molecular diffusivity of mass.

$$Sc = \frac{\text{Molecular diffusivity of momentum}}{\text{Molecular diffusivity of mass}}$$

11. Define Scherwood Number.

It is defined as the ratio of concentration gradients at the boundary.

$$Sc = \frac{h_m x}{D_{ab}}$$

hm – Mass transfer coefficient, m/s

D_{ab} – Diffusion coefficient, m^2/s

x – Length, m

Part-B

1. Hydrogen gases at 3 bar and 1 bar are separated by a plastic membrane having thickness 0.25 mm. the binary diffusion coefficient of hydrogen in the plastic is 9.1 × 10^{-3} m^2/s. The solubility of hydrogen in the membrane is 2.1 × 10^{-3} $\frac{kg-mole}{m^3\ bar}$

An uniform temperature condition of 20° is assumed.

Calculate the following

1. **Molar concentration of hydrogen on both sides**
2. **Molar flux of hydrogen**
3. **Mass flux of hydrogen**

Given Data:

Inside pressure $P_1 = 3$ bar

Outside pressure $P_2 = 1$ bar

Thickness, $L = 0.25\ mm = 0.25 \times 10^{-3}$ m

Diffusion coefficient $D_{ab} = 9.1 \times 10^{-8}\ m^2/s$

$$\text{Solubility of hydrogen} = 2.1 \times 10^{-3} \frac{kg-mole}{m^3-bar}$$

Temperature T = 20°C

To find

1. Molar concentration on both sides C_{a1} and C_{a2}
2. Molar flux
3. Mass flux

Solution :

1. Molar concentration on inner side,

C_{a1} = Solubility × inner pressure

$C_{a2} = 2.1 \times 10^{-3} \times 3$

$C_{a1} = 6.3 \times 10^{-3} \dfrac{kg - mole}{m^3}$

Molar concentration on outer side

C_{a1} = solubility × Outer pressure

$C_{a2} = 2.1 \times 10^{-3} \times 1$

$C_{a2} = 2.1 \times 10^{-3} \dfrac{kg - mole}{m^3}$

2. We know $\dfrac{m_o}{A} = \dfrac{D_{ab}}{L}[C_{a1} - C_{a2}]$

$$\text{Molar flux, } = \frac{9.1}{} - \frac{(6.3 \times 10^{-3} - 2.1 \times 10^{-3})}{.25 \times 10^{-3}}[1.2 - 0]$$

$$\frac{m_a}{A} = 1.52 \times 10^{-6} \frac{kg\text{-}mole}{s\text{-}m^2}$$

3. Mass flux = Molar flux × Molecular weight

$$= 1.52 \times 10^{-6} \frac{kg - mole}{s - m^2} \times 2 \text{ mole}$$

$[\because$ Molecular weight of H_2 is 2$]$

$$\text{Mass flux} = 3.04 \times 10^{-6} \frac{kg}{s - m^2}.$$

2. Oxygen at 25°C and pressure of 2 bar is flowing through a rubber pipe of inside diameter 25 mm and wall thickness 2.5 mm. The diffusivity of O2 through rubber is 0.21×10^{-9} m^2/s and the solubility of O2 in rubber is $3.12 \times 10^{-3} \dfrac{kg - mole}{m^3 - bar}$. Find the loss of O_2 by diffusion per metre length of pipe.

Given data:

Temperature, T = 25°C fig

Inside pressure P_1 = 2 bar

Inner diameter d_1 = 25 mm

Inner radius r_1 = 12.5 mm = 0.0125 m

Outer radius r_2 = inner radius + Thickness

= 0.0125 + 0.0025

r_2 = 0.015 m

Diffusion coefficient, $D_{ab} = 0.21 \times 10^{-9}\ m^2/s$

Solubility, $= 3.12 \times 10^{-3} \frac{kg-mole}{m^3}$

Molar concentration on outer side,

C_{a2} = Solubility × Outer pressure

$C_{a2} = 3.12 \times 10^{-3} \times 0$

$C_{a2} = 0$

[Assuming the partial pressure of O_2 on the outer surface of the tube is zero]

We know,

$$\frac{m_a}{A} = \frac{D_{ab}\left[C_{a1} - C_{a2}\right]}{L}$$

$$\text{For cylinders, } L = r_2 - r_1;\ A = \frac{2\pi L\,(r_2 - r_1)}{\ln\left[\frac{r_2}{r_1}\right]}$$

$$\text{Molar flux, (1)} \Rightarrow \frac{m_a}{2\pi L(r_2 - r_1)} = \frac{D_{ab}\left[C_{a1} - C_{a2}\right]}{(r_2 - r_1)}$$

$$\Rightarrow m_a = \frac{2\pi L.D_{ab}\left[C_{a1} - C_{a2}\right]}{\ln\frac{r_2}{r_1}} \qquad [\because \text{ Length} = 1m)$$

$$m_a = 4.51 \times 10^{-11} \frac{kg-mole}{s}.$$

3. **An open pan 210 mm in diameter and 75 mm deep contains water at 25°C and is exposed to dry atmospheric air. Calculate the diffusion coefficient of water in air. Take the rate of diffusion of water vapour is 8.52×10^{-4} kg/h.**

Given :

Diameter d = 210 = .210 m

Deep $(x_2 - x_1)$ = 75 mm = .075 m

Temperature, T = 25°C + 273 = 298K

Diffusion rate (or) mass rate, = 8.52×10^{-4} kg/h

= 8.52×10^{-4} kg/3600s = 2.36×10^{-7} kg/s

Mass rate of water vapour = 2.36×10^{-7} kg/s

To find

Diffusion coefficient (D_{ab})

Solution

Dry atmospheric air

We know that, molar rate of water vapour.

$$\frac{m_a}{A} = \frac{D_{ab}}{GT}\frac{P}{(x_2 - x_1)} \times \text{in}\left[\frac{P - P_{w2}}{P - P_{w1}}\right]$$

$$m_a = \frac{D_{ab} \times A}{GT}\frac{P}{(x_2 - x_1)} \times \text{in}\left[\frac{P - P_{w2}}{P - P_{w1}}\right]$$

We know that,

Mass rate of water vapour = Molar rate of water vapour × Molecular weight of steam

$$2.36 \times 10^{-7} = \frac{D_{ab} \times A}{GT} \times \frac{P}{(x_2 - x_1)} \times \text{in}\left[\frac{P - P_{w2}}{P - P_{w1}}\right] \times 18 \ldots.(1)$$

where,

A – Area = $\frac{\pi}{4}d^2 = \frac{\pi}{4} \times (0.210)^2 = 0.0346\ m^2$

G – Universal gas constant = $8314 \frac{1}{\text{kg-mole-k}}$

P – total pressure = 1 bar = $1 \times 10^5\ N/m^2$

P_{w1} – Partial pressure at the bottom of the test tube corresponding to saturation temperature 25°C

At 25°C

$P_{w1} = 0.03166$ bar

$P_{w1} = 0.03166 \times 10^5\ N/m^2$

P_{w2} = Partial pressure at the top of the pan, that is zero

$P_{w2} = 0$

(1) $\Rightarrow$ 2.36×10^{-7}

$$= \frac{D_{ab} \times .0346}{8314 \times 298} \times \frac{1 \times 10^{5}}{0.075} \times \ln\left[\frac{1 \times 10^{5} - 0}{1 \times 10^{5} - 0.03166 \times 10^{5}}\right] \times 18$$

$$D_{ab} = 2.18 \times 10^{-5} \ m^{2}/s.$$

4. **An open pan of 150 mm diameter and 75 mm deep contains water at 25°C and is exposed to atmospheric air at 25°C and 50% R.H. Calculate the evaporation rate of water in grams per hour.**

Given :

Diameter, d = 150mm = .150m

Deep $(x_2 - x_1)$ = 75 mm = .075m

Temperature, T = 25 + 273 = 298 K

Relative humidity = 50%

To find

Evaporation rate of water in grams per hour

Solution:

Diffusion coefficient (D_{ab}) [water + air] at 25°C

$$= 93 \times 10^{-3} \ m^{2}/h$$

$$\Rightarrow \quad D_{ab} = \frac{93 \times 10^{-3}}{3600} m^{2}/s$$

$$\boxed{D_{ab} = 2.58 \times 10^{-5} m^{2}/s}.$$

Atmospheric air 50% RH (2)

We know that, for isothermal evaporation,

Molar flux,

$$\frac{m_a}{A} = \frac{D_{ab}}{GT}\frac{P}{(x_2 - x_1)}\ln\left[\frac{P - P_{w2}}{P - P_{w1}}\right]......(1)$$

where,

$$A \text{ - Area} = \frac{\pi}{4}d^2 = \frac{\pi}{4}\times(.150)^2$$

$$\left[\text{Area} = 0.0176 \ m^2\right]$$

$$G - \text{ Universal gas constant} = 8314 \ \frac{J}{\text{kg-mole-K}}$$

$P -$ Total pressure = 1 bar = 1×10^5 N/m^2

P_{w1} – Partial pressure at the bottom of the test tube corresponding to saturation temperature 25°C

At 25°C

P_{w1} = 0.03166 bar

$P_{w1} = 0.03166 \times 10^5$ N/m^2

P_{w2} = Partial pressure at the top of the test pan corresponding to 25°C and 50% relative humidity.

At 25°C

P_{w2} = 0.03166 bar = $0.03166\times10^5\times0.50$

$P_{w2} = 0.03166\times10^5\times0.50$

$$\boxed{P_{w2} = 1583 \ N/m^2}$$

$$(1) \Rightarrow \quad \frac{a}{0.0176}$$

$$= \boxed{\frac{2.58\times10^{-5}}{8314\times298}\times\frac{1\times10^5}{0.075}\times\ln\left[\frac{1\times10^5 - 1583}{1\times10^5 - 0.03166\times10^5}\right]}$$

Molar rate of water vapour, $m_a = 3.96 \times 10^{-9} \frac{kg - mole}{s}$

Mass rate of water vapour = Molar rate of water vapour × Molecular weight of steam

$= 3.96 \times 10^{-9} \times 18$

Mass rate of water vapour = 7.13×10^{-8} kg/s.

$$= 7.13 \times 10^{-8} \times \frac{1000g}{1/3600^h}$$

Mass rate of water vapour = 0.256 g/h

If $Re < 5 \times 10^5$, flow is laminar

If $Re > 5 \times 10^5$, flow is turbulent

For laminar flow :

Sherwood Number (Sh) = $0.664\, (Re)^{0.5}\, (Sc)^{0.333}$

[From HMT data book, Page No.179]

where, Sc – Schmidt Number = $\frac{\nu}{D_{ab}}$

D_{ab} – Diffusion coefficient

Sherwood Number, Sh = $\frac{h_m x}{D_{ab}}$

Where, h_m – Mass transfer coefficient – m/s

For Turbulent flow :

Shedwood Number (Sh) = $[.037\, (Re)^{0.8} – 871]\, Sc^{0.333}$

$Sh = \frac{h_m x}{D_{ab}}$ [From HMT data book, Page No.180]

Solved Problems on Flat Plate.

5. Air at 10°C with a velocity of 3 m/s flows over a flat plate. The plate is 0.3 m long. Calculate the mass transfer coefficient.

Given :

Fluid temperature, $T_\infty = 10°C$

Velocity, U = 3 m/s

Length, $x = 0.3$ m

To find: Mass transfer coefficient (h_m)

Solution: Properties of air at 10°C [From HMT data book, Page No.22]

Kinematic viscosity. V = 14.16×10^{-6} m^2/s

We know that,

$$\text{Reynolds Number, Re} = \frac{Ux}{\nu}$$

$$= \frac{3 \times 0.3}{14.16 \times 10^{-6}}$$

$$Re = 0.63 \times 10^5 < 5 \times 10^5$$

Since, $Re < 5 \times 10^5$, flow is laminar

For Laminar flow, flat plate,

Sherwood Number (Sh) = 0.664 $(Re)^{0.5}$ $(Sc)^{0.333}$ ….(1)

[From HMT data book, Page No.179]

Where, Sc – Schmidt Number = $\frac{\nu}{D_{ab}}$……(2)

D_{ab} – Diffusion coefficient (water+Air) at 10°C = 8°C

$$= 74.1 \times 10^{-3} \frac{m^2}{3600s}$$

$$\boxed{D_{ab} = 2.50 \times 10^{-5} m^2/s.}$$

$$(2) \Rightarrow Sc = \frac{14.16 \times 10^{-6}}{2.05 \times 10^{-5}}$$

$$\boxed{Sc = 0.637}$$

Substitute Sc, Re values in equation (1)

$(1) \Rightarrow \; Sh = 0.664\,(0.63 \times 10^{5})^{0.5}(0.687)^{0.333}$

$\boxed{Sh = 147}$

We know that,

$$\text{Sherwood Number, } Sh = \frac{h_m x}{D_{ab}}$$

$$\Rightarrow \quad 147 = \frac{h_m \times 0.3}{2.05 \times 10^{-5}}$$

$\boxed{\text{Mass transfer coefficient, } h_m = .01 \text{ m/s.}}$