

## Section -

- ① Consider species  $N_2, H_2, NH_3, Ar$  to be  $A, B, C, D$  respectively

Molar average velocity,  $U = \frac{1}{c} \sum_{i=A}^D c_i u_i$

$$U = \frac{1}{\sum_{i=A}^D y_i} \sum_{i=A}^D y_i u_i$$

Here  $y_i$  is the mole fraction of component  $i$  in the gas mixture.

$$U = (0.05)(0.03) + (0.15)(0.035) + (0.76)(0.03) + (0.04)(0.2)$$

$$\therefore U = 0.0303 \text{ m/s}$$

The mass average velocity is given by

$$U = \frac{1}{M} \sum_{i=A}^D P_i u_i$$

where  $P_i = \frac{P_i}{RT} M_i$  and  $P = \frac{P}{RT} M$

$$\therefore \frac{P_i}{P} = \frac{P_i}{P} \frac{M_i}{M} = y_i \frac{M_i}{M}$$

$$M = \sum_{i=A}^D y_i M_i = (0.05)(28) + (0.15)(2) + (0.76)(17) + (0.04)(40)$$

$$= 16.22$$

$$U = \frac{1}{M} \sum_{i=A}^D y_i M_i u_i$$

$$= \frac{1}{16.22} (0.05 \times 28 \times 0.03 + 0.15 \times 2 \times 0.035 + 0.76 \times 17 \times 0.03 + 0.04 \times 40 \times 0.02)$$

$$\therefore U = 0.029 \text{ m/s}$$

② Substituting  $T = 28^\circ\text{C} = 30\text{K}$  in Antoine

$$\text{eqn: } P_v = 0.0374 \text{ bar}$$

For air of  $28^\circ\text{C}$  dry bulb temp. and 60% R.H., using psychrometric chart may be used to obtain the wet-bulb temp. is  $22.5^\circ\text{C}$

The temp. in the gas film varies from  $22.5^\circ\text{C}$  at the water air interface to  $28^\circ\text{C}$  at the other end of the film.

$$\text{Mean air film temp: } = \frac{28 + 22.5}{2} = 25.25^\circ\text{C} = 298.2\text{ K}$$

$$P_{AL} = (0.6) (0.0374)$$

$$= 0.02244 \text{ bar} \quad \text{(at } 25.25^\circ\text{C)}$$

$$D_{AB} = \left( 0.853 \frac{\text{ft}^2}{\text{h}} \times 30.48^2 \frac{\text{cm}^2}{\text{ft}^2} \times \frac{1}{3600 \frac{\text{h}}{\text{s}}} \right) \left( \frac{298.2}{273} \right)$$

$$= 0.2567 \text{ cm}^2/\text{s} = 2.567 \times 10^{-5} \text{ m}^2/\text{s}$$

Here,  $T = 298.2 \text{ K}$ ,  $L = 2.5 \text{ mm}$ ,  $P = 1.013 \text{ bar}$ ;  $P_{AO} = 0.02718 \text{ bar}$

$$P_{AL} = (0.6) P_v = 0.02244 \text{ bar}$$

$$N_A = \frac{2.567 \times 10^{-5} \times 1.013 \times 10^3}{0.08317 \times 298.2 \times 2.5} \left( \ln \frac{1.013 - 0.02244}{1.013 - 0.02718} \right)$$

$$= 2.01 \times 10^{-6} \text{ kmol/m}^2\text{s}$$

The water layer on the floor is 2mm thick, amount of water per  $\text{m}^2$  of floor area  $= 2 \times 10^{-3} \times 1\text{m}^2 = 0.002 \text{ m}^3$  i.e. 2kg

$$\text{Time for complete evaporation} = \frac{2 \text{ kg/m}^2}{3.623 \times 10^{-5} \text{ kg/m}^2\text{s}} = 5.52 \times 10^4 \text{ s} = 15.3 \text{ hr}$$

b) The combined rate of loss of water by penetration in floor and by vaporization  $= 0.1 \text{ kg/m}^2\text{h}$  (penetration)  $+ 3.623 \times 10^{-5} \text{ kg/m}^2\text{s}$  (vaporization)  $= 0.2304 \text{ kg/m}^2\text{h}$

$$\text{Time for disappearance of water} = \frac{2 \text{ kg/m}^2}{0.2304 \text{ kg/m}^2\text{h}} = 8.68 \text{ hr}$$

- ③ a) This is the case of diffusing A ( $\text{NH}_3$ ) through non-diffusing B (air)
- $$\therefore N_B = 0, P_{AO} = 0.9 \text{ atm}, P_A = 0.1 \text{ atm}, D_{AB} = 0.214 \text{ cm}^2/\text{s},$$
- $$T = 298 \text{ K}, P = 1 \text{ atm}, L = 1 \text{ cm}, R = 82.1 \text{ cm}^3 \text{ atm/Kmol}$$

$$N_A = \frac{D_{AB} P_A}{RT L} \ln \frac{P - P_{AL}}{P - P_{AO}} = \frac{(0.214)(1)}{(82.1)(298)(1)} \ln \frac{1 - 0.1}{1 - 0.9}$$

$$\therefore N_A = 1.922 \times 10^{-5} \text{ gmol/cm}^2\text{s}$$

since,  $N_B = 0, N_A = UC \Rightarrow U = \frac{N_A}{C} = N_A \left( \frac{RT}{P} \right)$

$$U = \frac{1.922 \times 10^{-5} \text{ gmol/cm}^2\text{s}}{1/(82.1)(298) \text{ gmol/cm}^3} = 0.47 \text{ cm/s}$$

Molar avg velocity  $\approx 0.47 \text{ cm/s}$

Also,  $N_A = u_A C_A \Rightarrow u_A = N_A / C_A = UC / C_A = U / y_A$   
Since  $C_A$  varies along the diffusion path,  $u_A$  also varies. We calculate values at the end where  $[\text{NH}_3]$  is higher

$$P_{AO} = 0.9 \text{ atm}; y_{AO} = P_{AO}/P = 0.9 \Rightarrow u_{AO} = U / y_{AO} = 0.522 \text{ cm/s}$$

$$u_B = 0 \quad (\because N_B = 0)$$

$$u = \frac{u_A P_A + u_B P_B}{P} = \frac{u_A P_A}{P} = \frac{u_A (P_A M_A / RT)}{PM / RT} = \frac{u_A y_A M_A}{M}$$

where,  $M_A = 17$

$$M = M_A y_A + M_B y_B = (17)(0.9) + (29)(0.1) = 18.2$$

$$u = \frac{0.522 \times 0.9 \times 17}{18.2} = 0.439 \text{ cm/s}$$

d)  $I_A = C_A (u_A - u)$

$$= \frac{P_A}{RT} (u_A - u)$$

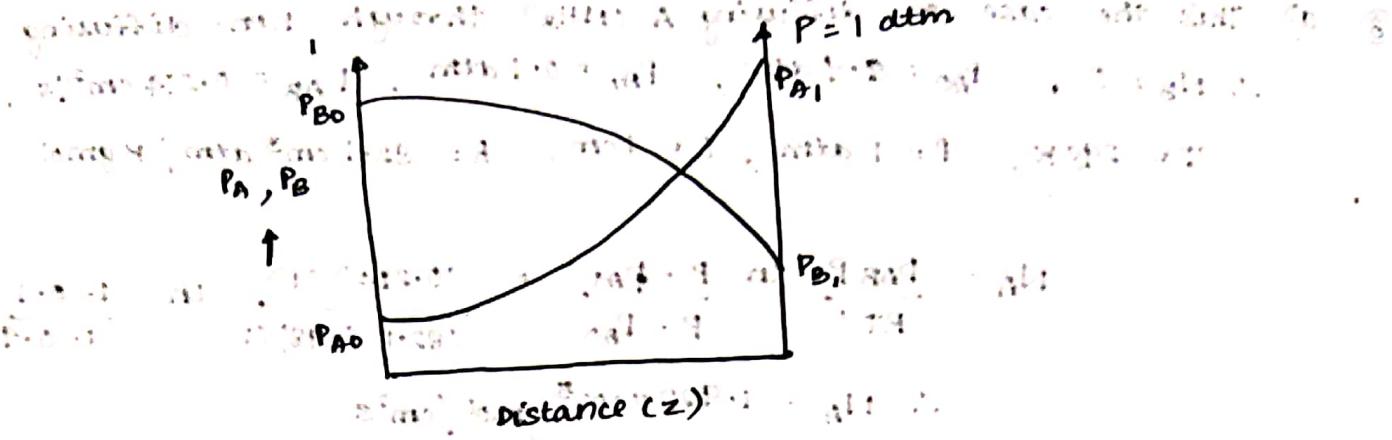
$$= \frac{0.9}{82.1 \times 298} (0.522 - 0.439)$$

$$= 3.05 \times 10^{-6} \text{ gmol/cm}^2\text{s}$$

$$N_A = 1.9225 \times 10^{-5} \text{ gmol/cm}^2\text{s}$$

$$= \frac{0.214 \times 1}{82.1 \times 298 \times 2} \ln \left( \frac{1 - P_A}{1 - 0.9} \right)$$

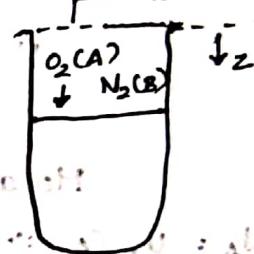
$$\therefore P_A = 1 - 0.1 \exp(2.197 z) \text{ mm}$$



Plot for  $P_A$  v/s  $z$

$$P_{AO} = 0.21 \text{ atm}$$

- ④ Oxygen (A) is absorbed quickly in an alkaline pyrogallate solution. Nitrogen (B) is virtually insoluble in it. Partial pressure of  $O_2$  at the liquid surface is  $P_{AL} = 0$ , that at the open mouth of the tube is  $P_{AO} = 0.21 \text{ atm}$



$$L = 5 \text{ cm} = 0.05 \text{ m}$$

$$D_{AB} = 2.1 \times 10^{-5} \text{ m}^2/\text{s}; R = 0.08317 \text{ m}^3 \text{ bar}/\text{kmol} \cdot \text{K}$$

$$N_A = \frac{D_{AB} P}{RT L} \ln \frac{P - P_{AL}}{P - P_{AO}}$$

$$= \frac{2.1 \times 10^{-5} \times 1.013}{0.08317 \times 298 \times 0.05} \ln \frac{1.013 - 0}{1.013 - 0.213}$$

$$= 4.05 \times 10^{-6} \frac{\text{kmol}}{\text{m}^2 \text{s}} = 1.3 \times 10^{-9} \frac{\text{kg O}_2}{\text{m}^2 \text{s}}$$

Area of diffusion = cross-section of the test tube

$$A = \frac{\pi}{4} (0.015)^2 = 1.767 \times 10^{-4} \text{ m}^2$$

$$\text{Rate of diffusion of } O_2 = a N_A = 7.16 \times 10^{-10}$$

The partial pressure distribution of A along the diffusion path can be calculated after putting the value of  $N_A$  in

$$N_A = \frac{D_{AB} P}{RT z} \ln \frac{P - P_A}{P - P_{AO}}$$

b) The partial pressure gradient of oxygen at any point on the diffusion path can be calculated from

$$\frac{dP_A}{dz} = - \frac{RT(P - P_A)}{D_{AB} P} N_A$$

$$\Rightarrow \frac{dP_A}{dz} = - \frac{0.08317 \times 298 \times (1.013 - 0.113)}{2.1 \times 10^{-5} \times 1.0}$$

$$= -4.15 \text{ bar/m}$$

c) Let us first calculate the quantities midway in the diffusion path ( $z = 0.025$ ;  $P_A = 0.113 \text{ bar}$ ). The velocities of the species w.r.t stationary observer can be obtained from,

$$\text{Oxygen: } u_A = \frac{N}{c_A} = N_A \left( \frac{RT}{P_A} \right) = (4.05 \times 10^{-6}) \cdot \frac{0.08317 \times 298}{0.113}$$

$$= 8.88 \times 10^{-4} \text{ m/s}$$

$$\text{Nitrogen: } u_B = \frac{N_B}{c_B} = 0 \quad (\text{since } B \text{ is non-diffusing})$$

The molar avg. velocity in  $z$ -direction,

$$V = \frac{1}{c} (u_A c_A + u_B c_B) = \frac{c_A}{c} u_A = \frac{P_A u_A}{P} = \frac{0.113 \times 8.88 \times 10^{-4}}{1.013} = 9.9 \times 10^{-5} \text{ m/s}$$

The diffusion velocity of oxygen,

$$v_{A,d} = u_A - V = 8.88 \times 10^{-4} - 9.9 \times 10^{-5} = 7.9 \times 10^{-4} \text{ m/s}$$

The diffusion velocity of nitrogen,

$$v_{B,d} = u_B - V = -9.9 \times 10^{-5} \text{ m/s}$$

$$\text{At } z=0, v_{A,d} = 3.72 \times 10^{-4} \text{ m/s}; v_{B,d} = -9.9 \times 10^{-5} \text{ m/s}$$

$$\text{At } z=0.05 \text{ m}, u_A \rightarrow \infty; v_{A,d} \rightarrow \infty; v_{B,d} = -9.9 \times 10^{-5} \text{ m/s}$$

d) Velocity of observer,  $v = -2V = -1.98 \times 10^{-4} \text{ m/s}$

Molar flux of A midway in diffusion path ( $z = 0.025 \text{ m}$ ,  $P_A = 0.113 \text{ bar}$ ) w.r.t observer moving with velocity  $v$ ,

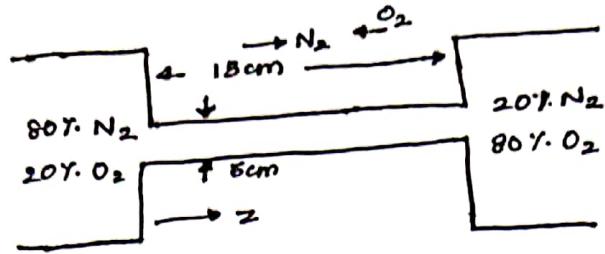
$$N'_A = c_A (u_A - v) = N_A - \frac{v P_A}{RT} = 4.05 \times 10^{-6} - \frac{(-1.98 \times 10^{-4}) \times 0.113}{0.08317 \times 298}$$

$$= 4.95 \times 10^{-6} \text{ kmol/m}^2 \text{s}$$

$$N'_B = c_B (u_B - v) = 0 - \frac{P_B v}{RT} = \frac{(-1.03 - 0.113)}{0.08317 \times 298} (-1.98 \times 10^{-4})$$

$$= 7.2 \times 10^{-6} \text{ kmol/m}^2 \text{s}$$

(5)



$$D_{AB} = \frac{1.0138 \times 10^{-7} T^{1.75}}{P \left[ \left( \sum v \right)_A^{1/3} + \left( \sum v \right)_B^{1/3} \right]} \left[ \frac{1}{M_A} + \frac{1}{M_B} \right]^{1/2} \text{ m}^2/\text{s}$$

$$= 0.23 \left( \frac{1}{2} \right) \left( \frac{273 + 20}{316} \right)^{1.75} \text{ cm}^2/\text{s}$$

$$\therefore D_{AB} = 1.01 \times 10^{-5} \text{ m}^2/\text{s}$$

Given,  $P_{A_1} = 1.6 \text{ atm}$ ,  $P_{A_2} = 0.4 \text{ atm}$

This is a case of steady state equimolar counter diffusion.

$$N_A = \frac{D_{AB}}{RTL} (P_{A_1} - P_{A_2})$$

$$= \frac{1.01 \times 10^{-5}}{0.0821 \times 293} \frac{(1.6 - 0.4)}{0.15}$$

$$\therefore N_A = 3.36 \times 10^{-6} \text{ kmol/m}^2\text{s}$$

$$\text{Area of cross section of tube, } a = (\pi/4)(0.05)^2 = 1.963 \times 10^{-3} \text{ m}^2$$

$$\text{The rate of transport of N}_2 \text{ from vessel 1 to 2} = aN_A = 1.963 \times 10^{-3} \times 3.36 \times 10^{-6}$$

$$= 6.6 \times 10^{-9} \text{ kmol/s}$$

- b) The flux and rate of transport of O<sub>2</sub> will be the same in magnitude as those of nitrogen but will occur in opp. direction,

$$N_B = -3.36 \times 10^{-6} \text{ kmol/m}^2\text{s}$$

- c) For steady state equimolar counter diffusion through constant area, the partial pressure changes linearly along the diffusion path.

$$\frac{dP_A}{dz} = \frac{P_{A_2} - P_{A_1}}{L} = \frac{0.4 - 1.6}{0.15} = -8 \text{ atm/m}$$

Partial pressure at a point 0.05m from vessel 1,

$$P_A = P_{A_1} + \left( \frac{dP_A}{dz} \right) dz = 1.6 - 8 \times 0.05 = 1.2 \text{ atm}$$

- d) Net or total mass flux,

$$n_T = N_A N_A + M_B N_B = (28 - 32) (3.36 \times 10^{-6})$$

$$= -1.344 \times 10^{-5} \text{ kmol/m}^2\text{s}$$

(6) Methanol being more volatile, it vaporizes during distillation and diffuses from the liquid surface to vapour phase whereas water molecules diffuse in the opposite direction.

$$\text{Methanol : } M_A = 32 ; \text{ Molar latent heat, } \Delta H_A^V = (274.8)(32) = 8787 \text{ kcal/kmol}$$

$$\text{water : } M_B = 18 ; \Delta H_B^V = 577.7 \times 18 = 10039 \text{ kcal/kmol}$$

$$N_A \Delta H_A^V = - N_B \Delta H_B^V \\ \Rightarrow N_B = - 0.8753 N_A$$

$$\text{From Raoult's law, } N_A = (N_A - 0.8753 N_A) \cdot \frac{P_A}{P} - \frac{\Delta_{AB}}{RT} \cdot \frac{dP_A}{dz}$$

$$N_A = \frac{RT}{PD_{AB}} \int_{z=0}^{L} dz = P_A - \int_{y_{AO}}^{y_{A1}} \frac{dy_A}{1 - 0.1247 y_A}$$

$$\Rightarrow N_A = \frac{\Delta_{AB} P}{0.1247 RT L} \ln \left( \frac{1 - 0.1247 y_{A1}}{1 - 0.1247 y_{AO}} \right)$$

$y_{A1} = 0.76$ ; the mole fraction of methanol in the liquid = 0.6 and corresponding eq. mole fraction of methanol in the vapour at liq-liq interface

$$y_{AO} = 0.825, P = 1 \text{ atm}, L = 0.001 \text{ m}$$

$$T = 77.2^\circ\text{C} = 344.2 \text{ K}$$

Methanol flux,

$$N_A = \frac{(1.816 \times 10^{-5})(1)}{(0.1247)(0.0821)(344.2)(10^{-3})} \ln \left( \frac{1 - 0.1247 \times 0.76}{1 - 0.1247 \times 0.825} \right)$$

$$\therefore N_A = 4.65 \times 10^{-5} \text{ kmol/m}^2\text{s}$$

Water flux,

$$N_B = - 0.8753 N_A = - 4.07 \times 10^{-5} \text{ kmol/m}^2\text{s}$$

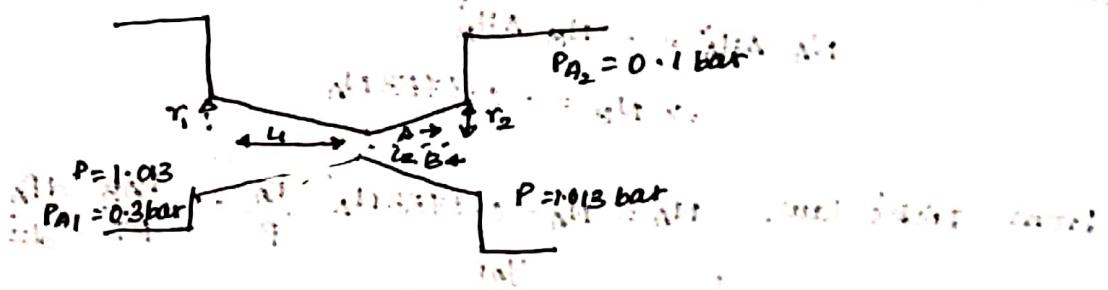
④ Given,  $T = 600\text{ K}$ ,  $r_p = 100 \text{ \AA} = 10^{-6} \text{ cm}$  is effective radius of tube.   
 $M = 28$ ,  $R = 82.1 \text{ cm}^3 \text{ atm/K g mol}$

$$D_K = \frac{2}{3} r_p \left( \frac{8RT}{\pi M} \right)^{1/2}$$

$$= \frac{2}{3} \times 10^{-6} \times \left( \frac{8 \times 8.21 \times 1.013 \times 10^6 \times 600}{\pi \times 28} \right)^{1/2}$$

$$= 0.045 \text{ cm}^2/\text{s}$$

⑤



At steady state, equimolar counterdiffusion occurs through the tapered connecting tube.

$$W = \frac{\pi D_{AB}}{RT} \frac{r_1 r_2}{L_1} (P_{A1} - P_{A2})$$

$$= \frac{\pi D_{AB}}{RT} \frac{r_2 r}{L_2} (P_{A2} - P_{A1})$$

$$\text{Now } P_{An} = \frac{r_1 L_2 + r_2 L_1}{r_1 L_2 + r_2 L_1} P_{A1} + \frac{r_2 L_2 + r_1 L_1}{r_1 L_2 + r_2 L_1} P_{A2}$$

$$W = \frac{\pi D_{AB}}{RT} \frac{r_1 r_2 r}{r_1 L_2 + r_2 L_1} (P_{A1} - P_{A2})$$

$$\left[ \frac{dP_B}{dz} \right]_n = - \left[ \frac{dP_A}{dz} \right]_n = \left[ \frac{W}{\pi r^2} \frac{RT}{D_{AB}} \right]_n$$

Now  $\frac{dP_B}{dz} = - \frac{dP_A}{dz}$

$\Rightarrow \frac{dP_A}{dz} = \frac{W}{\pi r^2} \frac{RT}{D_{AB}}$

$\Rightarrow \frac{dP_A}{dz} = \frac{W}{\pi r^2} \frac{RT}{D_{AB}}$

④ At any time  $t$ , the liquid level is at a depth  $z$  where the radius is  $r$ .  
 At the bottom of the tube,  $z = L = 15\text{ cm}$ , where  $r = r_2 = 12\text{ mm}$ ; at  
 the top,  $z = 0$  and  $r = r_1 = 1\text{ mm}$ .

If  $N_A$  is the local net ethyl acetate vapour (A) through air (B),  
 $\chi r N_A = \text{const.} = W$   
 The local flux can be written as,

$$N_A = \frac{D_{AB} P}{RT(P-P_A)} \frac{dP_A}{dz} \quad \text{and} \quad r = r_1 - \frac{r_1 - r_2}{L}(z)$$

$$\Rightarrow \frac{\pi D_{AB} P}{RT} \int_0^z \frac{dP_A}{P - P_A} = W \int_0^z \frac{dz}{[r_1 - (r_1 - r_2)z/L]^2}$$

On integration and simplification,

$$W = \frac{\pi D_{AB} P}{RT} \frac{r_1}{z} \left[ r_1 - (r_1 - r_2) \left( \frac{z}{L} \right) \right] \ln \frac{P}{P - P_A^V}$$

The initial rate of vapourization loss ( $z = 7.5\text{ cm}$ ),  $W = 1.58 \times 10^{-10} \text{ kmol/s}$

If the fall in the level of the liquid in time  $dt$  is  $dz$ ,

$$\left( \pi r^2 \frac{dz}{dt} \right) \frac{P_A}{M_A} = W$$

$$\Rightarrow \int_{z_1}^{z_2} z \left[ \frac{r_1 - (r_1 - r_2)z}{L} \right] dz = \frac{D_{AB} P M_A}{RT} \frac{P}{P - P_A^V} t$$

On integrating, using  $r_1 = 0.01\text{ m}$ ,  $r_2 = 0.006\text{ m}$ ,  $z_1 = 0.075\text{ m}$ ,  
 $z_2 = 0.095\text{ m}$ ,  $L = 0.15\text{ m}$ ,  $P = 1.013 \text{ bar}$ ,  $P_A^V = 0.1264 \text{ bar}$

After evaluation,  $t = 79\text{ hr}$

(10) Initial mass of ball = 48 g, final mass of ball = 18 g,  
 $r_{s0} = 0.943 \text{ cm}$ , final mass of ball = 18 g,  
 $r_s' = 0.594 \text{ cm}$ ,  $P_{AB} = 0.0692 \text{ cm}^2/\text{s}$

$P = 1 \text{ atm}$ ,  $T = 318 \text{ K}$ ,  $M_A$  (molar wt. of naphthalene) = 128 g/mol

$P_{A0}$  = Partial pressure of naphthalene in bulk air = 0.8654 mm Hg

$P_{AS}$  = Sublimation pressure of naphthalene at 318 K = 0.00114 atm

$$r_{s0}^2 - r_s'^2 = \frac{2P_{AB}PM_A t'}{RT P_A} \ln \left( \frac{P - P_{A0}}{P - P_{AS}} \right)$$

$$0.943^2 - 0.594^2 = \frac{2 \times 0.0692 \times 1 \times 128 t'}{R \times 318 \times P_A} \ln \left( \frac{1 + 0.8654}{1 - 0.00114} \right)$$

$$\therefore t' = 219.5 \text{ hr}$$

(11) This is a case of diffusion of A (naphthalene) through a non-diffusing B (air) through a variable area.

$$(2\pi r L) N_A = 2\pi r L \left( - \frac{P_{AB} P}{RT (P - P_A)} \right) \frac{dP_A}{dr} = W$$

where,  $L$  is the length of cylinder of bulk air.

Here  $r$  is the radial distance of any point within the surrounding air-film from the axis of the cylinder.

$W$  is the molar rate of sublimation. The distance  $r$  varies from  $r_c$  to the outer edge of the air-film, i.e.,  $r_c + \delta$ . The corresponding values of partial pressure of naphthalene are,

At  $r = r_c$ ,  $P_A = P_{AS}$

At  $r = r_c + \delta$ ,  $P_A = 0$

$$-\int_{P_{AS}}^0 \frac{dP_A}{P - P_A} = \frac{RTW}{2\pi D_{AB} PL} \int_{r_c}^{r_c + \delta} \frac{dr}{r}$$

$$\therefore W = \frac{2\pi P_{AB} PL}{RT \ln((1+\delta/r_c))} \left( \frac{P}{P - P_{AS}} \right)$$

In order to calculate the req: time of sublimation, we make steady state approximation. If at any time  $t$ , the mass of cylinder is  $m = \pi r_c^2 L P_A$ , the rate of sublimation can be,

$$W = - \frac{d(m/M_A)}{dt} = - \frac{d}{dt} (\pi r_c^2 L P_A / M_A)$$

$$= - 2\pi L (P_A / M_A) r_c \frac{dr_c}{dt}$$

$$\frac{2\pi D_{AB} PL}{RT \ln(1 + 8/r_c)} \ln \left( \frac{P}{P - P_{AS}} \right) = - 2\pi L \frac{P_A}{M_A} r_c \frac{dr_c}{dt}$$

On integrating,

$$\frac{1}{2} r_{c1}^2 \ln \left( 1 + \frac{8}{r_{c1}} \right) - \frac{1}{2} r_{c2}^2 \ln \left( 1 + \frac{8}{r_{c2}} \right) + \frac{8}{2} \left[ (r_{c1} - r_{c2}) - 8 \ln \frac{r_{c1} + 8}{r_{c2} + 8} \right]$$

$$= \frac{D_{AB} P}{RT} \frac{M_A}{P_A} \left( \ln \frac{P}{P - P_{AS}} \right) +$$

$$\text{Initial vol. of cylinder} = 10g / (1.148/cm^3)$$

$$= 8.772 \text{ cm}^3$$

$$\pi r_{c1}^2 L = 8.772 \text{ cm}^3 \Rightarrow r_{c1} = 0.3736 \text{ cm}$$

$$\text{Final vol. of cylinder} = 8.772/2 = 4.386 \text{ cm}^3$$

$$\pi r_{c2}^2 L = 4.386 \Rightarrow r_{c2} = 0.2642 \text{ cm}$$

$$8 = 3 \text{ mm} = 0.3 \text{ cm} ; D_{AB} = 0.0692 \text{ cm}^2/\text{s} ; P = 1 \text{ atm}$$

$$P_{AS} = 0.00114 \text{ atm}$$

Substituting these values in the above eqn:-,

$$t = 10.35 \text{ hr}$$

## Section - 2

$$\textcircled{1} \quad \text{For } O_2, \quad Y_{O_2} = 0.21$$

$$\text{For } N_2, \quad Y_{N_2} = 0.79$$

Let the total number of moles be 100,

$$\text{No. of moles of } O_2 = 21$$

$$\text{No. of moles of } N_2 = 79$$

$$\begin{aligned} \text{Total mass of mixture} &= [(21 \times 0.032) + (79 \times 0.028)] \\ &= 2.884 \text{ kg} \end{aligned}$$

$$\text{Mass fraction of } O_2 = \frac{21 \times 0.032}{2.884} = 0.233$$

$$\text{Mass fraction of } N_2 = 1 - 0.233 = 0.767$$

$$\begin{aligned} \text{Mean molecular weight} &= (0.21 \times 0.032) + (0.79 \times 0.028) \\ &= 0.02884 \text{ kg/mol} \end{aligned}$$

$$\textcircled{2} \quad \omega_D = 1.047$$

|        | $\sigma \text{ in } \text{\AA}$ | $\epsilon \text{ in } \text{K}$ |
|--------|---------------------------------|---------------------------------|
| $CO_2$ | 3.996                           | 190                             |
| Air    | 3.617                           | 97                              |

$$E_{AB} = \sqrt{\epsilon_A \epsilon_B} = 135.757 \text{ K}$$

$$\sigma_{AB} = \frac{\sigma_A + \sigma_B}{2} = 3.8065 \text{ \AA}$$

Using Chapman - Enskog eqn,

$$D_{AB} = \frac{1.858 \times 10^{-7} T^{3/2}}{P \sigma_{AB}^2 \omega_D} \left( \frac{1}{M_A} + \frac{1}{M_B} \right)^{1/2}$$

$$\begin{aligned} D_{AB} &= \frac{1.858 \times (293)^{3/2} \times 10^{-7}}{1 \times 3.8065^2 \times 1.047} \times \left( \frac{1}{44} + \frac{1}{29} \right)^{1/2} \\ &= 0.0000147 \text{ m}^2/\text{s} \end{aligned}$$

$$\therefore D_{AB} = 0.147 \text{ cm}^2/\text{s}$$

$$\begin{aligned}
 \textcircled{3} \quad & y_{\text{SiH}_4} = 0.0075 \quad y_{\text{H}_2} = 0.015 \quad y_{\text{N}_2} = 0.9775 \quad \Omega_D(\text{SiH}_4 - \text{N}_2) = 0.8 \\
 & T = 900 \text{ K}, \quad P = 100 \text{ Pa} = \frac{100}{1.01325 \times 10^6} \text{ atm} \quad \Omega_D(\text{SiH}_4 - \text{H}_2) = 0.679 \\
 & \frac{\epsilon_A}{K} (\text{calorie}) = 207.6 \text{ K} \quad , \quad \sigma_A = 908 \text{ \AA}
 \end{aligned}$$

$$\frac{\epsilon_{\text{H}_2}}{K} = 59.7 \text{ K} \quad , \quad \sigma_B = 3.798 \text{ \AA}$$

Using Chapman-Eckong Equation,

$$D_{AB} = \frac{1.858 \times 10^{-7} T^{3/2}}{P \sigma_{AB}^2 \Omega_D} \left( \frac{1}{M_A} + \frac{1}{M_B} \right)^{1/2}$$

$$\frac{\epsilon_{AB}}{TK} = \frac{1}{T} \sqrt{\frac{\epsilon_A}{K} \frac{\epsilon_B}{K}} = 0.76 \text{ K}$$

$$\sigma_{AB} = \frac{\sigma_A + \sigma_B}{2} = \frac{4.08 + 3.798}{2} = 3.939 \text{ \AA}$$

$$D_{AB} = \frac{1.858 \times 10^{-7} \times 900^{3/2}}{100 \times 3.939^2 \times 0.76} \left( \frac{1}{32.12} + \frac{1}{2.0158} \right)^{1/2}$$

$$\therefore D_{AB} = 40.7 \text{ m}^2/\text{s}$$

$$\text{(ii)} \quad D_{\text{SiH}_4 - \text{N}_2} = \frac{1.858 \times 10^{-7} T^{3/2}}{P \sigma_{AB}^2 \Omega_D} \left( \frac{1}{M_A} + \frac{1}{M_B} \right)^{1/2}$$

$$\frac{\epsilon_{AB}}{TK} = \frac{1}{T} \left( \frac{\epsilon_A}{K} \cdot \frac{\epsilon_B}{K} \right)^{1/2} = \frac{1}{T} \sqrt{207.6 \times 41.4} = 6.135267$$

$$\Rightarrow \Omega_B = 0.801$$

$$D_{\text{SiH}_4 - \text{N}_2} = \frac{1.858 \times 10^{-7} \times 900^{3/2}}{100 \times 3.939^2 \times 0.801} \left( \frac{1}{32.12} + \frac{1}{28} \right)^{1/2} = 10.5 \text{ m}^2/\text{s}$$

$$\text{Also, } y'_{\text{N}_2} = \frac{0.9775}{1 - 0.0075} = 0.9848 \quad y'_{\text{H}_2} = \frac{0.015}{1 - 0.0075} = 0.01511$$

$$D_{\text{SiH}_4 - \text{mix}} = \frac{0.9848}{10.5} + \frac{0.01511}{40.7} = 10.62 \text{ m}^2/\text{s}$$

④ Given  $C_6H_{14}O_6$  in  $H_2O$   
 $T_{H_2O} = 283\text{ K}$ ,  $\mu_{H_2O} = 0.00105\text{ kg/m s}$   
 $M_{H_2O} = 18\text{ g/mol}$

$$D_{AB} = \frac{1.173 \times 10^{-16} \times (2.26/18)^{1/2} \times 283}{0.00105 (V_m)^{0.6}}$$

$$V_m = 6V_C + 14V_H + 6V_O  
= 6 \times \frac{14.8}{1000} + 14 \times \frac{3.7}{1000} + 6 \times \frac{7.9}{1000}$$

$$\therefore V_m = 0.185\text{ m}^3/\text{kmol}$$

$$\therefore D_{AB} = 0.579 \times 10^{-9}\text{ cm}^2/\text{s}$$

Observed value is  $0.56 \times 10^{-9}\text{ cm}^2/\text{s}$

Error =  $\frac{(0.579 - 0.56) \times 10^{-9}}{0.56 \times 10^{-9}} \times 100 = 3.39\%$   
The error permissible is 5%, and the given value is with an error of 3.39%, hence can be used.

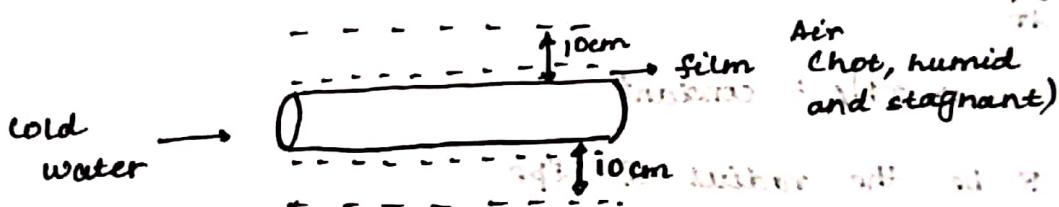
$$\textcircled{5} \quad \begin{aligned} D_A &= 103.6 \text{ cm}^2/\text{s} \\ \phi_B &= 2.26, \quad T = 288 \text{ K} \\ M_B &= 18 \text{ gm/mol (water)} \end{aligned}$$

The liquid diffusivity,

$$D_{AB} = \frac{7.5 \times 10^{-8} (\phi_B M_B)^{1/2}}{T^{3/2}}$$

$$= \frac{7.5 \times 10^{-8} \times (2.26 \times 18)^{1/2}}{(103.6)^{0.6} \times 1.14} \times \frac{288}{288}$$

$$\therefore D_{AB} = 7.46 \times 10^{-6} \text{ cm}^2/\text{s}$$



Points to be noted

- Moisture content in air at 10cm from pipe surface is constant on both sides.
- Near pipe, the moisture content approaches v.p. at temp. of pipe.

### a) Assumptions

- Steady state, not changing with time
- Homogeneous composition
- Properties change only in radial direction, (cylindrical system)
- No accumulation
- Conc. at a distance of 10cm from pipe wall is constant.  $y_n = \frac{P_A}{P}$

b) W.K.T.,  $P_A = J_A + y_A (N_A + N_B)$ , for a binary system

This is the case of diffusion of A diffusing and B non-diffusing

$$N_A = J_A + y_A N_A$$

$$(1-y_A) N_A = - D_{AB} \frac{dC_A}{dr} = - D_{AB} C \frac{dy_A}{dr}$$

c) writing material balance for shell,

$$\text{In - out} - \dot{P}_{\text{gen}}^{\circ} = \text{Accumulation}^{\circ}$$

$$2\pi r L N_A|_{r+\Delta r} - 2\pi r L N_A|_r = 0$$

$$\Rightarrow \frac{r N_A|_{r+\Delta r} - r N_A|_r}{\Delta r} = 0$$

$$\begin{aligned} & \text{in} \\ & \text{out} \\ & \text{constant flow rate} \end{aligned}$$

$$N_A \left(1 - \frac{c}{C}\right) = -D_{AB} \frac{dc}{dr}$$

$$N_A = -\frac{D_{AB} C}{C - c} \frac{dc}{dr}$$

$$\therefore \frac{d}{dr}(r N_A) = 0$$

d) since  $\frac{d}{dr}(r N_A) = 0$

$$\Rightarrow r N_A = \text{constant}$$

Let  $R$  be the radius of pipe

$$\text{At } r = R + 10, \quad y_A = y_A^{\circ}$$

$$r = R, \quad y_A = y_A^{\circ} = \frac{P_A}{P}$$

$$r \times \left(-D_{AB} C \frac{dy_A}{dr}\right) = k_1$$

$$-D_{AB} C \int dy_A = \int \frac{k_1 dr}{r}$$

On Integrating,  $-D_{AB} C y_A = k_1 \ln r + k_2$

$$\text{At } r = R + 10, \quad -D_{AB} C y_A^{\circ} = k_1 \ln(R + 10) + k_2$$

$$r = R, \quad -D_{AB} C y_A^{\circ} = k_1 \ln R + k_2$$

$$\text{On solving, } N_A = -\frac{D_{AB} C}{(C - c)} \frac{dc}{dr}$$

$$y_A = -\frac{k_1 R}{D_{AB} C} \ln \frac{r}{R} - \frac{k_2}{D_{AB} C}$$

$$y_A = -\frac{k_1 R}{D_{AB} C} \ln \frac{r}{R} + C$$

⑦ water film thickness,  $\delta = 4\text{mm} = 4 \times 10^{-3}\text{m}$

$$C_{A_1} @ z=0. = 0.1 \text{ mol/m}^3$$

$$C_{A_2} @ z=4\text{mm} = 0.02 \text{ mol/m}^3$$

$$\mu_B = 1.4 \text{ cP}$$

$$D_{AB} = 13.26 \times 10^{-5} (\mu_B)^{-1.4} \times (v_A)^{-0.5}$$

$$v_A = 2v_C + 6v_H + v_B = 2 \times 14.8 + 6 \times 3.7 + 7.4 = 59.2 \text{ cm}^3/\text{mol}$$

$$\therefore D_{AB} = 8.2 \times 10^{-6} \text{ cm}^2/\text{s}$$

Counter diffusion (equimolar),  $N_A = -N_B$

$$N_A = \frac{D_{AB}}{L} (C_{A_1} - C_{A_2})$$

$$= \frac{8.2 \times 10^{-6} \times 10^{-4} (0.1 - 0.02)}{4 \times 10^{-3}}$$

$$\therefore N_A = 1.64 \times 10^{-8} \text{ mol/m}^2\text{s}$$

Let  $C_A = R_1 z + R_2$  at  $z=0$ ,  $C_A = C_{A_1} = 0.1 \text{ mol/m}^3$

WKT, At  $z=0$ ,  $C_A = C_{A_1} = 0.1 \text{ mol/m}^3 \Rightarrow R_2 = 0.1 \text{ mol/m}^3$

At  $z=4\text{mm}$ ,  $C_{A_1} = C_{A_2} = 0.02 \text{ mol/m}^3 \Rightarrow R_1 = -20 \text{ mol/m}^4$

$$\therefore C_A = -20z + 0.1$$

Diffusion in air,

$$N_A = \frac{D_{AB} C}{L} \ln \left( \frac{C - C_{A_1}}{C - C_{A_2}} \right)$$

$$= \frac{D_{AB} P}{R T L} \ln \left( \frac{P - P_{A_1}}{P - P_{A_2}} \right)$$

Given,  $D_{AB} = 1.32 \times 10^{-5} \text{ m}^2/\text{s}$

$$P_{A_1} = 0.1 RT, \quad P_{A_2} = 0.02 RT$$

$$\therefore N_A = 2.64 \times 10^{-9} \text{ mol/m}^2\text{s}$$

$\therefore$  Concentration profile is same

⑥ Let A be acetic acid, B be water soln.  
 Molecular weight of A,  $M_A = 60$   
 Molecular weight of B,  $M_B = 18$   
 $z = 1 \text{ mm} = 10^{-3} \text{ m}$ ,  $N_A = 0.95 \times 10^{-9} \text{ m}^2/\text{s}$

Assume density,  $\rho = 10^3 \text{ kg/m}^3$

$$x_2 = \frac{9/60}{9/60 + 9/18} = 0.028, (\text{M}_{\text{avg}})_1 = \frac{9}{100} \times 60 + \frac{9}{100} \times 18 \\ = 21.78$$

$$x_1 = \frac{3/60}{3/60 + 9/18} = 0.00919, (\text{M}_{\text{avg}})_2 = \frac{3}{100} \times 60 + \frac{9}{100} \times 18 \\ = 19.26$$

$$c = \frac{\rho}{\text{M}_{\text{avg}}} = \frac{1000}{(21.78 + 19.26)} = 48.733 \text{ mol/m}^3$$

The above is the case for diffusing A and non-diffusing B,

$$\therefore N_A = \frac{CDAB}{z} \ln \left( \frac{1 - x_{21}}{1 - x_{12}} \right) \\ = \frac{48.733 \times 0.95 \times 10^{-9}}{10^{-3}} \left[ - \ln \left( \frac{1 - 0.0288}{1 - 0.00919} \right) \right]$$

$$\therefore N_A = 0.92548 \times 10^{-6} \text{ mol/m}^2 \text{s}$$

$$N_A = 9.2548 \times 10^{-7} \text{ mol/m}^2 \text{s},$$

$$⑨ (i) N_A = -N_B$$

$$N_A = -CD_{AB} \frac{dy_A}{dz} + (N_A + N_B)y_A$$

$$N_A = -CD_{AB} \frac{dy_A}{dz} = -D_{AB} \frac{dc_A}{dz} \quad [y_A c = c_A]$$

$$\text{WRT, } c_A = P_A / RT$$

$$\Rightarrow N_A = -\frac{D_{AB}}{RT} \frac{dp_A}{dz}$$

$$N_A \int_{z_1}^{z_2} dz = -\frac{D_{AB}}{RT} \int_{P_{A_1}}^{P_{A_2}} \frac{dp_A}{p_A}$$

$$\Rightarrow N_A = \frac{D_{AB}}{RTz} (P_{A_1} - P_{A_2}) = \frac{0.275 \times 10^{-9}}{(8.314 \times 273 \times 20 \times 10^{-12})} (1.5 - 0.5) \times 10^5 \\ = 0.06058 \text{ mol/m}^2\text{s}$$

$$\text{Rate of diffusion} = N_A S = 6.058 \times 10^{-8} \text{ mol/m}^2\text{s}$$

$$(ii) N_B = -0.75 N_A$$

$$N_B = - \left( D_{AB} \frac{dy_A}{dz} + y_P (0.25 N_A) \right)$$

$$N_A dz = -CD_{AB} \frac{dy_A}{1 - 0.25 y_A}$$

$$N_A \int_{z_1}^{z_2} dz = -CD_{AB} \int_{y_{P_1}}^{y_{P_2}} \frac{dy_A}{1 - 0.25 y_A}$$

$$\Rightarrow N_A = -\frac{CD_{AB}}{z} \left[ 4 \ln \left( \frac{1 - 0.25 y_{A_2}}{1 - 0.25 y_{A_1}} \right) \right]$$

$$c = P/RT = 2 \times 10^5 / 8.314 \times 273 = 88.11 \text{ mol/m}^3$$

$$y_{A_1} = \frac{P_{A_1}}{P} = \frac{1.5}{2} = 0.75 \Rightarrow y_{A_2} = 0.25$$

$$\text{So, } N_A = -\frac{88.11 \times 0.275 \times 10^{-4}}{0.2} \left( 4 \ln \frac{1-0.25 \times 0.25}{1-0.25 \times 0.75} \right) \\ = 69.3474 \times 10^{-4} \text{ mol/m}^2\text{s}$$

$$\therefore N_A = 6.935 \times 10^{-3} \text{ mol/m}^2\text{s}$$

$$\text{Rate of diffusion} = (6.935 \times 10^{-3}) (\pi \times (0.5 \times 10^{-2})^2) \\ = 5.4467 \times 10^{-7} \text{ mol/sec}$$

(iii)  $N_B = 0$

$$N_A = -D_{AB} C \cdot \frac{dy_A}{dz} + y_A (N_A + N_B)$$

$$\Rightarrow N_A = -D_{AB} C \cdot \frac{dy_A}{dz} + y_A N_A$$

$$N_A \int_{z_1}^{z_2} dz = -CD_{AB} \int \frac{dy_A}{1-y_A} \Rightarrow N_A = \frac{CD_{AB} C}{z} \ln \left( \frac{1-y_{A2}}{1-y_{A1}} \right)$$

$$C = \frac{P}{RT} = \frac{2 \times 10^5}{273 \times 8.314} = 88.11 \text{ mol/m}^3$$

$$N_A = \frac{88.11 \times 0.275 \times 10^{-4}}{0.2} \ln \left( \frac{1-0.25}{1-0.75} \right) \\ = 133.098 \times 10^{-4} = 1.331 \times 10^{-2} \text{ mol/m}^2\text{s}$$

$$\text{Rate of diffusion} = 1.331 \times 10^{-2} \times (\pi \times (0.5 \times 10^{-2})^2)$$

$$= 1.045 \times 10^{-6} \text{ mol/s}$$

~~Final answer: 1.045 × 10<sup>-6</sup> mol/s~~

(ii) Let A be naphthalene,

Rate of input of naphthalene into thin shell ( $r=r$ ) =  $4\pi r^2 N_A |_r$

Rate of input of A from thin shell (at  $r=r+\Delta r$ ) =  $4\pi r^2 N_A |_{r+\Delta r}$

Considering material balance at steady state, rate of accumulation = 0,

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

Taking limit  $\Delta r \rightarrow 0$  on both sides,

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

$$\Rightarrow 4\pi r^2 N_A = \text{const.} = W \quad (\text{assume})$$

Here, naphthalene diffuses through non-diffusing air,

$$N_A = (N_A + N_B) \frac{P_A}{P} - \frac{D_{AB}}{RT} \frac{dP_A}{dr}$$

WKT,  $N_B = 0 \Rightarrow N_A = -\frac{D_{AB}}{RT} \frac{dP_A}{dr}$

$$\Rightarrow - \int_{P_{A0}}^{P_{As}} \frac{dP_A}{P - P_A} = \frac{WRT}{4\pi D_{AB} P} \int_{r_s}^{r_e} dr$$

$$\Rightarrow \ln \left( \frac{P - P_{A0}}{P - P_{As}} \right) = \frac{WRT}{4\pi D_{AB} P} \times \frac{1}{r_e}$$

$$\therefore W = \frac{4\pi D_{AB} P r_s}{RT} \ln \left( \frac{P - P_{A0}}{P - P_{As}} \right)$$

Given,  $D_{AB} = 6.92 \times 10^{-6} \text{ m}^2/\text{s}$ ,  $T = 318 \text{ K}$

$P = 1 \text{ atm} = 10^5 \text{ Pa}$ ,  $r_s = 2 \times 10^{-3} \text{ m}$

$P_{As} = 0.555 \text{ mm of Hg} = 0.00073026 \text{ atm}$

$P_{A0} = 0$  [Partial pressure of naphthalene will be zero at inf]

$$W = \frac{4\pi (6.92 \times 10^{-6}) (10^5) (2 \times 10^{-3})}{(8.314)(318)} \ln \left( \frac{1-0}{1-0.00073026} \right)$$

$$\therefore W = 4.805 \times 10^{-9} \text{ mol/sec} \quad (\text{Initial rate of evaporation})$$

⑩ consider oxygen to be species A,  $\text{CO}_2$  to be species B  
 Oxygen is diffusing through  $\text{CO}_2$ :  
 $A \leftarrow B \rightarrow$  from left to right

$$N_A = \frac{D_{AB}}{RT(z_2 - z_1)} \ln \left( \frac{P_1 - P_{A2}}{P_1 - P_{A1}} \right)$$

$$\text{Given, } P = 10^5 \text{ N/m}^2$$

$$T = 273 \text{ K}$$

$$z_2 - z_1 = 2 \text{ mm}$$

$$D_{AB} = 1.77 \times 10^{-5} \text{ m}^2/\text{s}$$

$$P_{A1} = 13500 \text{ N/m}^2$$

$$P_{A2} = 6500 \text{ N/m}^2$$

$$N_A = \frac{(1.77 \times 10^{-5})(10^5)}{(8.314)(273)(2 \times 10^{-3})} \ln \left( \frac{10^5 - 6500}{10^5 - 13500} \right)$$

$$= 3.205 \times 10^{-2} \text{ mol/m}^2\text{s}$$

$$\text{Rate of diffusion} = s N_A$$

$$= 1 \text{ m}^2 \times 3.205 \times 10^{-2} \text{ mol/m}^2\text{s}$$

$$= 0.03205 \text{ mol/m}^2\text{s}$$

$$\frac{\text{Rate of diffusion}}{\text{Area}} = \frac{\text{Rate of diffusion}}{\text{Area}}$$

$$\frac{\text{Rate}}{\text{Area}} = \frac{1}{2} \text{ mol/s/m}^2$$

If this rate of diffusion is constant, then

the diffusion coefficient is constant.

That means if the concentration is suddenly altered, the rate

$$\frac{\text{Rate}}{\text{Area}} = \frac{1}{2} \text{ mol/s/m}^2$$

is also constant until the new steady state is reached.