Unit operation I

Diffusion

Sheet No. (1)

Q1) A gas is being transferred a cross a stagnant air film at total pressure of 100 kPa. The partial pressure of the gas is 40 kPa at one boundary of the film and 10 kPa at the other. If the partial pressure remains constant, calculate the total pressure to double the transfer rate of the gas.

$P_{T2} = ?$

Answer: P_T = 64 kPa

Q2) In a packed column operating at atmospheric pressure and 295 K, 10% ammonia – air mixture is scrubbed with water and the concentration is reduced to 0.1%. If the whole of the resistance to mass transfer may be regarded as lying within a thin laminar film on the gas side of the gas liquids interface, drive from the first principle an expression for the rate of absorption at any position in the column. At some intermediate point where the ammonia's concentration in the gas phase has been reduced to 5%, the partial pressure of ammonia is in equilibrium with the aqueous solution is 660 N/m^2, and the transfer flux is 10^{-3} $kgmol/m^2.s$. What is the thickness of the hypothetical gas film if the diffusivity of ammonia in air is 0.24 cm^2/s ?

Answer: Z= 0.043 mm.

Q3) In an experimental study of the absorption of ammonia by water in a wetted-wall column, the value of KG was found to be 2.75×10^{-6} $kmol/m^2 \cdot s \cdot kPa$. At one point in the column, the composition of the gas and liquid phases were 8.0 and 0.115 mole % NH_3, respectively. The temperature was 300 K and the total pressure was 1 atm. Eighty-five percent of the total resistance to mass transfer was found to be in the gas phase. At 300 K, ammonia-water solution follow Henry's law up to 5 mole % ammonia in the liquid, with H = 1.64 when the total pressure is 1 atm. Calculate the individual film coefficients and the interfacial concentrations.

K_g , K_L

Y_{Ai} , X_{Ai}

Answers: $K_g = 3.28\times10^{-4}$ $kmol/m^2 \cdot s$, $K_L = 3.05\times10^{-3}$ $kmol/m^2 \cdot s$, $y_A^* = 1.886\times10^{-3}$

$N_A = 2.18\times10^{-5}$ $kmol/m^2 \cdot s$, $y_{Ai} = 0.01362$, $x_{Ai} = 8.305\times10^{-3}$

Q4) A chamber, of volume 1 m^3, contains air at a temperature of 293 K and a pressure of 101.3 kN/m^2, with a partial pressure of water vapour of 0.8 kN/m^2. A bowl of liquid with a free surface of 0.01 m^2 and maintained at a temperature of 303 K is introduced into the t mass

chamber. How long will it take for the air to become 90% saturated at 293 K and how much water must be evaporated?

D

The diffusivity of water vapour in air is $2.4 * 10^{-5}$ m^2/s and the mass transfer resistance is equivalent to that of a stagnant gas film of thickness 0.25 mm. Neglect the effects of bulk flow. Saturation vapour pressure of water is $\boxed{4.3\ kN/m^2 \text{ at } 303\ K}$ and $\boxed{2.3\ kN/m^2 \text{ at } 293\ K}$

z Pa*

Answers: $mass_{H2O} = 9.38 * 10^{-3}$ kg, $t = 604$ s

Stagnant layer $P_{T1} = 100 \, kPa$

$P_{A1} = 40 \, kPa$, $P_{A2} = 10 \, kPa$ } constant in second condition

$P_{T2} = ?$ If $N_{A2} = 2 N_{A1}$

$$N_A = \frac{P_T * D_{AB}}{ZRT} * \ln\left[\frac{P_T - P_{A2}}{P_T - P_{A1}}\right]$$

For N_{A1}:-

$$N_{A1} = \frac{P_{T1} * D_{AB1}}{ZRT} * \ln\left[\frac{P_{T1} - P_{A2}}{P_{T1} - P_{A1}}\right] \text{----} ①$$

For N_{A2}:-

$$N_{A2} = \frac{P_{T2} * D_{AB2}}{ZRT} * \ln\left[\frac{P_{T2} - P_{A2}}{P_{T2} - P_{A1}}\right] \text{----} ②$$

$$N_{A2} = 2 N_{A1}$$

divide eq.1 in eq.2:-

$$\frac{\cancel{N_{A1}}}{2\cancel{N_{A1}}} = \frac{\frac{P_{T1} * D_{AB1}}{\cancel{ZRT}} * \ln\left[\frac{P_{T1} - P_{A2}}{P_{T1} - P_{A1}}\right]}{\frac{P_{T2} * D_{AB2}}{\cancel{ZRT}} * \ln\left[\frac{P_{T2} - P_{A2}}{P_{T2} - P_{A1}}\right]}$$

$$\frac{1}{2} = \frac{D_{AB1} * P_{T1}}{D_{AB2} * P_{T2}} * \frac{\ln\left[\frac{P_{T1} - P_{A2}}{P_{T1} - P_{A1}}\right]}{\ln\left[\frac{P_{T2} - P_{A2}}{P_{T2} - P_{A1}}\right]} \text{----} ③$$

<u>However</u>

$D_{AB1} \propto \frac{1}{P_{T1}}$, $D_{AB2} \propto \frac{1}{P_{T2}}$

$D_{AB1} = \frac{B}{P_{T1}}$, $D_{AB2} = \frac{B}{P_{T2}}$

$$\frac{D_{AB1}}{D_{AB2}} = \frac{\cancel{B}/P_{T1}}{\cancel{B}/P_{T2}} \longrightarrow \frac{D_{AB1}}{D_{AB2}} = \frac{P_{T2}}{P_{T1}}$$

$$D_{AB2} = \frac{D_{AB1} * P_{T1}}{P_{T2}} \text{----} ④$$

sub eq.4 in eq.3 for D_{AB_2}:-

$$\frac{1}{2} = \frac{\cancel{D_{AB_1}} * \cancel{P_{T_1}}}{\frac{\cancel{D_{AB_1}} * \cancel{P_{T_1}} * \cancel{P_{T_2}}}{\cancel{P_{T_2}}}} * \frac{\ln\left[\frac{P_{T_1}-P_{A2}}{P_{T_1}-P_{A1}}\right]}{\ln\left[\frac{P_{T_2}-P_{A2}}{P_{T_2}-P_{A1}}\right]}$$

$$\frac{1}{2} = \frac{\ln\left[\frac{P_{T_1}-P_{A2}}{P_{T_1}-P_{A1}}\right]}{\ln\left[\frac{P_{T_2}-P_{A2}}{P_{T_2}-P_{A1}}\right]} \rightarrow \frac{1}{2} = \frac{\ln\left[\frac{100-10}{100-40}\right]}{\ln\left[\frac{P_{T_2}-10}{P_{T_2}-40}\right]}$$

$$0.5 = \frac{0.4054651081}{\ln\left[\frac{P_{T_2}-10}{P_{T_2}-40}\right]} \rightarrow \ln\left[\frac{P_{T_2}-10}{P_{T_2}-40}\right] = \frac{0.4054651081}{0.5}$$

$$\ln\left[\frac{P_{T_2}-10}{P_{T_2}-40}\right] = 0.8109302162$$

$$\cancel{e^{\ln}}\frac{P_{T_2}-10}{P_{T_2}-40} = e^{0.8109302162}$$

$$\frac{P_{T_2}-10}{P_{T_2}-40} = 2.25$$

$$P_{T_2}-10 = 2.25(P_{T_2}-40)$$

$$P_{T_2}-10 = 2.25P_{T_2}-90$$

$$P_{T_2}-2.25P_{T_2} = 10-90$$

$$-1.25P_{T_2} = -80$$

$$P_{T_2} = \frac{-80}{-1.25}$$

$$\boxed{P_{T_2} = 64 \text{ KPa}}$$

1.B

$Y_{A1} = 0.05 \quad T = 295\,K \quad P_T = 101.3\,kPa$

$P_{A2} = 660\,N/m^2 * \frac{1\,Pa}{1\,N/m^2} * \frac{1\,kPa}{1000\,Pa} = 0.66\,kPa$

$N_A = 10^{-3}\,kgmol/m^2 s \quad D_{AB} = 0.24\,\frac{cm^2}{s} * \frac{1\,m^2}{10000\,cm^2} = 0.24 * 10^{-4}\,m^2/s$

$Z = ?$

$N_A = J_A + C_A V$ ----- (1)

$N_T = N_A + N_B = C_T * V \rightarrow V = \frac{N_A + N_B}{C_T}$ ---- (2)

plug eq.(2) in eq.(1) for V:-

$$N_A = -D_{AB}\frac{dC_A}{dz} + \frac{C_A}{C_T}(N_A + N_B)$$

$$PV = nRT \rightarrow P = \frac{n}{V}RT \rightarrow P_T = C_T RT$$

$C_T = P_T/RT$

$C_A = P_A/RT$

$$\frac{C_A}{C_T} = \frac{P_A/RT}{P_T/\cancel{RT}} \rightarrow \frac{C_A}{C_T} = \frac{P_A}{P_T}$$

derivative for $C_A = P_A/RT$

$dC_A = 1/RT\, dP_A$

$$N_A = -\frac{D_{AB}}{RT} * \frac{dP_A}{dz} + \frac{P_A}{P_T}(N_A + N_B)$$

for equilibrium Diffusion:-

$$A \rightleftarrows B$$

$$N_A = -\frac{D_{AB}}{RT} * \frac{dP_A}{dz} + \frac{P_A}{P_T}(N_A + N_B)$$

$N_B = -N_A$

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

$$N_A = -\frac{D_{AB}}{RT} * \frac{dP_A}{dz} + 0$$

$$N_A = -\frac{D_{AB}}{RT} * \frac{dP_A}{dz}$$

$$N_A * dz = -\frac{D_{AB}}{RT} dP_A$$

$$N_A * \int_0^z dz = \frac{D_{AB}}{RT} - \int_{P_{A1}}^{P_{A2}} dP_A$$

$$N_A * \int_0^z dz = \frac{D_{AB}}{RT} \int_{P_{A1}}^{P_{A2}} dP_A$$

$$N_A * Z = \frac{D_{AB}}{RT} (P_{A1} - P_{A2})$$

$$N_A = \frac{D_{AB}}{ZRT} (P_{A1} - P_{A2})$$

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

$$Y_{A_1} = \frac{P_{A1}}{P_T} \rightarrow P_{A1} = Y_{A1} * P_T \rightarrow P_{A_1} = 0.05 * 101.33 \rightarrow \boxed{P_{A1} = 5.0665\ kPa}$$

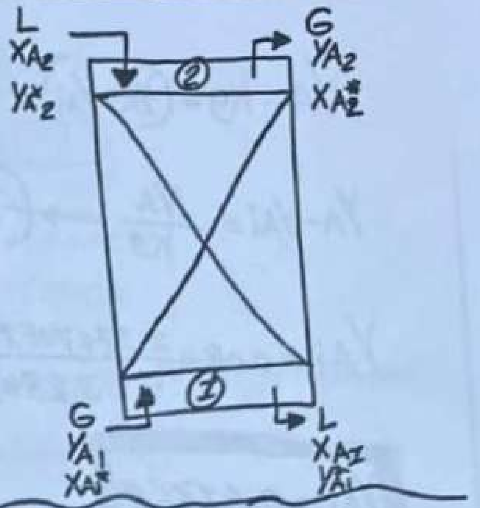
$$Z = \frac{0.24 * 10^{-4}}{10^{-3} * 8.314 * 295} * (5.0665 - 0.66)$$

$$Z = 4.3 * 10^{-5}\ m * \frac{1000\ mm}{1\ m}$$

$$\boxed{Z = 0.043\ mm}$$

2.B

$K_g = 2.75 * 10^{-6}$ kmole/m².s.kPa

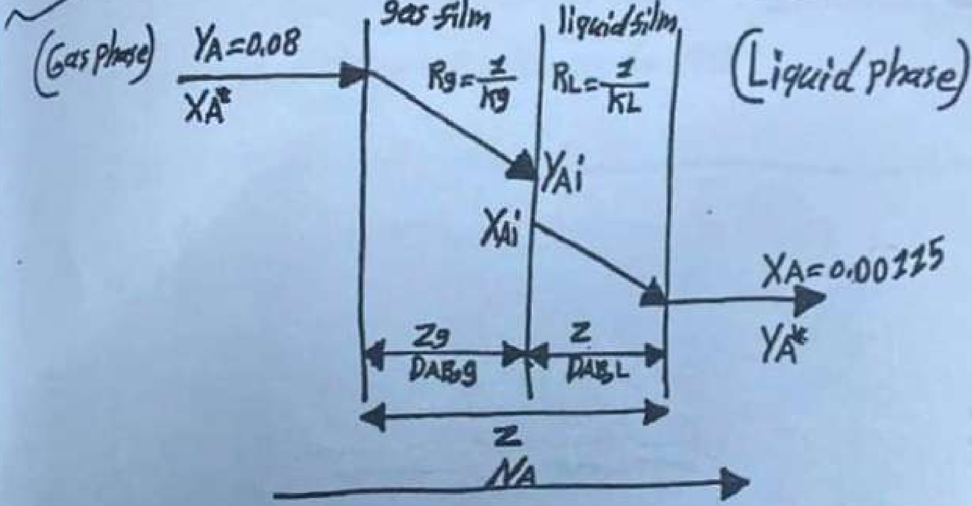


$Y_A = 0.08\ NH_3$ $\quad T = 300k$

$X_A = 0.00115\ NH_3$ $\quad P_T = 1atm * \frac{101.33kPa}{1atm} = 101.33 kPa$

$k_g = 0.85 K_{OG}$ so $K_L = 0.15 K_{OG}$ $\quad H = 1.64$

$k_g = ?\ \ K_L = ?\ \ Y_{Ai} = ?\ \ X_{Ai} = ?$



$$K_{OG} = K_g * P_T \rightarrow K_{OG} = 2.75*10^{-6} * 101.33 = 2.786575*10^{-4}\ kmole/m^2.s$$

$$\frac{1}{k_g} = 0.85 \frac{1}{K_{OG}} \rightarrow \frac{1}{k_g} = 0.85 * \frac{1}{2.786575*10^{-4}} \rightarrow k_g = \frac{2.786575*10^{-4}}{0.85} \rightarrow \boxed{k_g = 3.28*10^{-4}\ kmol/m^2.s}$$

$$\frac{H}{k_L} = 0.15 \frac{1}{K_{OG}} \rightarrow K_L = \frac{K_{OG}*H}{0.15} \rightarrow K_L = \frac{2.786575*10^{-4}*1.64}{0.15} \rightarrow \boxed{K_L = 3.05*10^{-3}\ kmol/m^2.s}$$

$$Y_A^* = H*X_A \rightarrow Y_A^* = 1.64*0.00115 \rightarrow \boxed{Y_A^* = 1.886*10^{-3}}$$

$$N_A = K_{OG}(Y_A - Y_A^*)$$

$$N_A = 2.786575*10^{-4} * (0.08 - 1.886*10^{-3})$$

$$\boxed{N_A = 2.176705196*10^{-5}\ kmol/m^2.s}$$

$$N_A = k_g * (y_A - y_{Ai})$$

$$y_A - y_{Ai} = \frac{N_A}{k_g} \longrightarrow \left(-y_{Ai} = \frac{N_A}{k_g} - y_A\right) * -1 \longrightarrow y_{Ai} = y_A - \frac{N_A}{k_g}$$

$$y_{Ai} = 0.08 - \frac{2.176705196 * 10^{-5}}{3.28 * 10^{-4}}$$

$$\boxed{y_{Ai} = 0.01362}$$

$$y_{Ai} = H\, x_{Ai}$$

$$x_{Ai} = \frac{y_{Ai}}{H}$$

$$x_{Ai} = \frac{0.01362}{1.64}$$

$$\boxed{x_{Ai} = 8.305 * 10^{-3}}$$

3.B

chamber

$V = 1\,m^3$

$T = 293K$

$P_T = 101.3\,\cancel{kN/m^2} * \frac{1kPa}{1\,\cancel{kN/m^2}} = 101.3\,kPa$

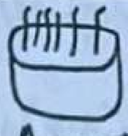
$P_{A1} = 0.8\,\cancel{kN/m^2} * \frac{1kPa}{1\,\cancel{kN/m^2}} = 0.8\,kPa$

Neglet the effect of bulk flow

$P_{Ai}^* = 4.3\,\cancel{kN/m^2} * \frac{1kPa}{1\,\cancel{kN/m^2}} = 4.3\,kPa$ at $T = 303K$

$P_{A2}^* = 2.3\,\cancel{kN/m^2} * \frac{1kPa}{1\,\cancel{kN/m^2}} = 2.3\,kPa$ at $T = 293K$

Bowl



$A = 0.01\,m^2$

$T = 303K$

$t = ?$ mass $H_2O = ?$ If %90 saturated

$D_{AB} = 2.4 * 10^{-5}\,m^2/s$

$Z = 0.25\,\cancel{mm} * \frac{1m}{1000\,\cancel{mm}} = 0.00025m$

$N_A = J_A + C_A V$

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

Neglet the effect of bulk flow so

$N_A = -D_{AB}\frac{dC_A}{dz} + \cancel{C_A V}^{0}$

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

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

$N_A\int_0^Z dz = -D_{AB}\int_{C_{A1}}^{C_{A2}} dC_A$

$N_A * \int_0^Z dz = D_{AB}\int_{C_{A2}}^{C_{A1}} dC_A$

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

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

$$X_{A_1} = \frac{C_{A1}}{C_T} \rightarrow C_{A1} = X_{A_1} * C_T$$

$$X_{A2} = \frac{C_{A2}}{C_T} \rightarrow C_{A2} = X_{A2} * C_T$$

$$N_A = \frac{D_{AB}}{Z}\left(X_{A_1} * C_T - X_{A_2} * C_T\right)$$

$$\left[\underbrace{N_A}_{\frac{kgmol}{m^2.s}} = \frac{D_{AB} * C_T}{Z}\left(X_{A1} - X_{A_2}\right)\right] * A$$

$$\overline{N}_A\left[\frac{kgmol}{s}\right] = \frac{D_{AB} * \widehat{A} * C_T}{Z} * \left(X_{A_1} - X_{A_2}\right)$$

$$\frac{dn}{dt} = \frac{D_{AB} * A * C_T}{Z} * \left(X_{A_1} - X_{A_2}\right)$$

$$PV = nRT \rightarrow P = \frac{n}{V}RT \rightarrow P_T = C_T RT \rightarrow C_T = \frac{P_T}{RT} \rightarrow C_T = \frac{101.3}{8.314 * 303}$$

$C_T = 0.0402\ kmol/m^3$ at $303K$

$$X_{A_1} = \frac{P^*_{A1}}{P_T} = \frac{4.3}{101.3} = 0.04244817374$$

$$X_{A2} = \frac{P_{A2}}{P_T} = \frac{1}{101.3} P_{A2} \rightarrow X_{A_2} = 9.872 * 10^{-3} P_{A_2}$$

$$\frac{dn}{dt} = \frac{2.4 * 10^{-5} * 0.01 * 0.0402}{0.00025} * \left(0.04244817374 - 9.872 * 10^{-3} P_{A_2}\right)$$

$$\frac{dn}{dt} = 3.8592 * 10^{-5} * \left(0.04244817374 - 9.872 * 10^{-3} P_{A_2}\right)$$

$$\frac{dn}{dt} = 1.64 * 10^{-6} - 3.81 * 10^{-7} P_{A_2} \text{ ---- } (1)$$

For the room :-

$$\frac{P_1V_1}{n_1RT_1}=\frac{P_sV_s}{n_sRT_s}\rightarrow n_1=\frac{P_1*V_1*n_s*T_s}{P_s*V_s*T_1}$$

let $P_1=P_{A2}$

$$n_1=\frac{P_{A2}*V_1*n_s*T_s}{P_s*V_s*T_1}\rightarrow n_1=\frac{P_{A2}*1*1*273}{101.3*22.4*293}$$

$n_1=4.10676026*10^{-4}P_{A2}$ Derivation over dt

$$\frac{dn}{dt}=4.10676026*10^{-4}\frac{dP_{A2}}{dt}\text{ ----- } (2)$$

sub eq.2 in eq.1

$$\left[4.10676026*10^{-4}\frac{dP_{A2}}{dt}=1.64*10^{-6}-3.81*10^{-7}P_{A2}\right]\div 3.81*10^{-7}$$

$$1077.889832\frac{dP_{A2}}{dt}=(4.3-P_{A2})$$

$$\frac{dP_{A2}}{(4.3-P_{A2})}=\frac{1}{1077.889832}dt$$

$$\int_{P_{A1}}^{P_{A2}^*}\frac{1}{4.3-P_{A2}}dP_A*\frac{-1}{-1}=9.277385966*10^{-4}\int_0^t dt$$

$$-\int_{P_{A1}}^{P_{A2}^*}\frac{-1}{4.3-P_A}dP_A=9.277385966*10^{-4}\int_0^t dt$$

$$-\left[\ln(4.3-P_{A2}^*)-\ln(4.3-P_{A1})\right]=9.277385966*10^{-4}t$$

$$-\left[\ln(4.3-2.3)-\ln(4.3-0.8)\right]=9.277385966*10^{-4}t$$

$$t=\frac{-\ln\left[\frac{4.3-2.3}{4.3-0.8}\right]}{9.277385966*10^{-4}}\rightarrow \boxed{t=604s}$$

For the room :-

$P_T * V_T = n_T R T \rightarrow n_T = \frac{P_T * V_T}{RT} \rightarrow n_T = \frac{101.3 * 1}{8.314 * 293} \rightarrow \boxed{n_T = 0.0416 \text{ kmole}}$

$Y_1 = \frac{P_{A1}}{P_T} \rightarrow Y_1 = \frac{0.8}{101.3} \rightarrow Y_1 = 7.9 * 10^{-3}$

$Y_1 = \frac{n_1 H_2O}{n_T} \rightarrow n_1 H_2O = Y_1 * n_T \rightarrow n_1 H_2O = 7.9 * 10^{-3} * 0.0416 \rightarrow \boxed{n_1 H_2O = 3.2864 * 10^{-4} \text{ kmole}}$

$Y_2 = \frac{P^*_{A2}}{P_T} = \frac{2.3}{101.3} = 0.0227$

%90

$Y_2 = \frac{n_2 H_2O}{n_T} \rightarrow n_2 H_2O = Y_2 * n_T * 5 \rightarrow n_2 H_2O = 0.0227 * 0.0416 * 0.9$

$\boxed{n_2 H_2O = 8.5 * 10^{-4} \text{ kmole}}$

$n_{\text{water evaporate}} = n_2 H_2O - n_1 H_2O$

$n_{\text{water evaporate}} = 8.5 * 10^{-4} - 3.2864 * 10^{-4} = 5.2136 * 10^{-4} \text{ kgmole}$

$\text{mass}_{\text{water evaporate}} = M.Wt_{H_2O} * n_{\text{water evaporate}}$

$\text{mass}_{\text{water evaporate}} = 18 * 5.2136 * 10^{-4}$

$\boxed{\text{mass}_{\text{water evaporate}} = 9.38 * 10^{-3} \text{ kg}}$

4.0