Department of Chemical Engineering
King Saud University

Test 1 **ChE 318** **Time: 90 min**

Roll Number

- **Carry out detailed calculations in answer sheet and provide final answer on this paper**
- **Open book examination (No notes allowed even if written on the book)**

Question 1 (33 pts):

Water in the bottom of a narrow metal tube is held at a constant temperature of 303 K. The total pressure of air (assumed dry) is 1.01325 x 10^5 Pa (1.0 atm) and the temperature is 303 K. Water evaporates and diffuses through the air in the tube and the diffusion path (z_2 - z_1) is 0.2 m long. The tube diameter is 10 mm. The diagram is similar to Fig. 6.2-2a. The vapor pressure of water vapors at 303 K is 4242 Pa. The experimental value of the diffusion coefficient at 298 K is 2.6×10^{-5} m^2/s.

I. Determine the molecular diffusion coefficient at 303 K. $\frac{D_{AB2}}{D_{AB1}} = \left(\frac{T_2}{T_1}\right)^{1.75}$; $D_{AB2} = 2.6 \times 10^{-5}\left(\frac{303}{298}\right)^{1.75} = \mathbf{2.68 \times 10^{-5}\, m^2/s}$		7
II. Determine p_{BM} in Pa. $p_{BM} = \frac{p_{B2} - p_{B1}}{ln\frac{p_{B2}}{p_{B1}}} = \frac{p_{A1} - p_{A2}}{ln\frac{p_{B2}}{p_{B1}}} = \frac{4242 - 0}{ln\frac{101325 - 0}{101325 - 4242}} = \mathbf{99,189 Pa}$		5
III. Calculate the rate of evaporation (N_A) at steady state in $kg\, mol/m^2 \cdot s$ and $kg/m^2 \cdot s$ $N_A = \frac{D_{AB}}{(z_2 - z_1)}\frac{P}{RT}\frac{p_{A1} - p_{A2}}{p_{BM}}$ $= \frac{2.68 \times 10^{-5}}{0.2}\frac{1.01325 \times 10^5}{8314 \times 303}\frac{(4242 - 0)}{99,189} = \mathbf{2.3 \times 10^{-7}\frac{kg\, mol}{m^2 \cdot s} = 41.4 \times 10^{-7}\frac{kg}{m^2 \cdot s}}$		13
IV. Calculate the steady state rate of evaporation (N_A) if the air is humid (not dry) and the percentage relative humidity, i.e. $100(p_A/p_A^o) = 30\%$, where p_A is the partial pressure of the water vapor in the air and p_A^o is the vapor pressure. $p_{A2} = \frac{30}{100}p_A^o = 0.3 \times 4242 = 1273 Pa$ $p_{BM} = \frac{4242 - 1273}{ln\frac{101325 - 1273}{101325 - 4242}} = 98,560\ Pa$ $N_A = \frac{D_{AB}}{(z_2 - z_1)}\frac{P}{RT}\frac{p_{A1} - p_{A2}}{p_{BM}}$ $= \frac{2.68 \times 10^{-5}}{0.2}\frac{1.01325 \times 10^5}{8314 \times 303}\frac{(4242 - 1273)}{98,560} = \mathbf{1.62 \times 10^{-7}\frac{kg\, mol}{m^2 \cdot s}}$ Note: There is almost 30% decrease in the flux due to a 30% decrease in driving force since the change in the p_{BM} is negligible.		8

Question 2 (33 pts):

Water drop (spherical) is suspended in still air (assumed dry) by a fine wire at 303K at 1.01325 x 10^5 Pa (1.0 atm). Its initial radius was r_0 = 4 mm. The vapor pressure of water at 303 K is $p_A^0 = 4242\ Pa$ and the density of water is 995.71 kg/m^3. Note that

- Conditions in this problem are same as in Question 1
- $Area, A = 4\pi r^2; Volume, V = (4/3)\pi r^3; Mass = \rho V$
- The time of evaporation can be computed using, $t_F = \frac{\rho_A}{M_A}\frac{(r_0^2 - r_F^2)}{2D_{AB}}\frac{RT}{P}\frac{p_{BM}}{p_{A1} - p_{A2}}$

I. Calculate the time in seconds for its complete evaporation (rF = 0 mm). $t_F = \frac{\rho_A}{M_A}\frac{(r_0^2 - r_F^2)}{2D_{AB}}\frac{RT}{P}\frac{p_{BM}}{p_{A1} - p_{A2}} = \frac{995.71}{18}\frac{(0.004^2 - 0)}{2 \cdot 2.68 \times 10^{-5}}\frac{8314 \times 303}{101325}\frac{99{,}189}{4242 - 0} = \mathbf{9599\ s}$	12
II. Calculate the time in second required for the evaporation of half of the total initial mass of the water drop $\frac{Mass_F}{Mass_i} = \frac{Volume_F}{Volume_i} = \frac{r_F^3}{r_i^3} = 0.5;\ r_F^3 = 0.5r_i^3; r_F = 3.175\ mm$ $t_F = \frac{\rho_A}{M_A}\frac{(r_0^2 - r_F^2)}{2D_{AB}}\frac{RT}{P}\frac{p_{BM}}{p_{A1} - p_{A2}} = \frac{995.71}{18}\frac{(0.004^2 - 0.003175^2)}{2 \cdot 2.68 \times 10^{-5}}\frac{8314 \times 303}{101325}\frac{99{,}189}{4242 - 0}$ $= \mathbf{3551\ s}$	10
III. How much time in seconds will be required for its complete evaporation (r_F = 0 mm) if initial radius was r_0 = 2 mm. (Detailed calculations not required). Since $t_F \propto r_0^2$ decreasing the initial radius by (1/2) will cause a (1/4) in the time of evaporation, i.e. (9599/4) = **2400 s**.	5
IV. Calculate the time in seconds for its complete evaporation when P = 0.1 atm = 1.01325 x 10^4 Pa $t_F = \frac{\rho_A}{M_A}\frac{(r_0^2 - r_F^2)}{2D_{AB}}\frac{RT}{P}\frac{p_{BM}}{p_{A1} - p_{A2}} = \frac{995.71}{18}\frac{(4^2 - 0)}{2 \cdot 26.8 \times 10^{-5}}\frac{8314 \times 303}{10132.5}\frac{7{,}821}{4242 - 0} = \mathbf{757s}$ **Note:** $(D_{AB}P)$is independent of pressure, but (p_{BM}) will change.	6

Question 3 (34 pts):

A tube is coated on the inside with naphthalene and has an inside diameter of 25 mm and a length of 3.0-m. Air at 318 K and an average pressure of 101.3 kPa flows through this pipe at a velocity of 2 m/s. The surface temperature of the naphthalene can be assumed to be at 318 K and its vapor pressure at 318 K is 74 Pa = 2.8 ×10^{-5} $(kg\ mol/m^3)$. Assume that the D_{AB} of naphthalene in air at 318 K is 6.92×10^{-5} m^2/s. For air, μ = 1.932 ×10^{-5} Pa·s, $\rho = 1.114\ (kg/m^3)$.

I. Compute Reynold number (N_{Re}), Schmidt number (N_{Sc}) $N_{Re} = \left(\frac{Dv\rho}{\mu}\right) = \left(\frac{0.025 \times 2 \times 1.114}{1.932\ \times 10^{-5}}\right) = 2883$ $N_{Sc} = \frac{(\mu/\rho)}{D_{AB}} = \frac{(1.932\ \times 10^{-5}/1.114)}{6.92\ \times 10^{-5}} = 0.25$	6
II. What is the flow regime (laminar/turbulent) Since $N_{Re} > 2100$, flow regime is turbulent	2
III. Determine k_c' using appropriate equation or figure $N_{Sh} = k_c' \frac{D}{D_{AB}} = 0.023\ (2883)^{0.83}(0.25)^{0.33} = 10.84$ $k_c' = 10.84 \frac{D_{AB}}{D} = 0.030\ m/s$	12
IV. Compute the volumetric flow rate in m^3/s Volumetric flow rate = Velocity × X-al area of tube $A = \frac{\pi}{4}\left(\frac{25}{1000}\right)^2$; $v \times A = 9.82\ \times 10^{-4}$	2
V. Compute the total mass transfer area in m^2 $= \pi DL = 0.2356$	2
VI. Compute mean driving force if the inlet concentration, $C_{A1} = 0\ kg\ mol/m^3$ and outlet concentration, $C_{A2} = 2.2 \times 10^{-5}\ kg\ mol/m^3$ $(C_{Ai} - C_{Am}) \cong \left(C_{Ai} - \frac{C_{A1} + C_{A2}}{2}\right) \cong \frac{C_{A2} - C_{A1}}{ln \frac{(C_{Ai} - C_{A2})}{(C_{Ai} - C_{A1})}} (recommended)$ $= \frac{2.2 \times 10^{-5} - 0}{ln \frac{(2.8\ \times 10^{-5} - 2.2 \times 10^{-5})}{(2.8\ \times 10^{-5} - 0)}} = 1.428 \times 10^{-5}\ kg\ mol/m^3$	5
VII. Compute mass transfer rate, N_A, in $kg\ mol/s$ $N_A(kg\ mol/s) = k_c(\pi DL)(c_{Ai} - c_{Am}) = 0.03\ \frac{m}{s} \times 0.2356\ m^2 \times 1.428 \times 10^{-5}\ \frac{kg\ mol}{m^3}$ $= 1 \times 10^{-7}$	5