UNIT:5 MASS TRANSFER

Definition:

Transfer of mass as a result of particle concentration difference in a mixture.

Air is a mixture of various gases. Whenever we have a multi component system with a concentration gradient, one constituent of the mixture gets transported from the region of higher concentration to the region of lower concentration till the concentration gradient reduces to zero. This phenomenon of the transport of mass as a result of concentration gradient is called 'Mass Transfer'.

Difference of Heat transfer and Mass Transfer

Heat Transfer		Mass transfer
Temperature Gradient	❖ a	Concentration Gradient
Occurs from higher temperature to lower temperature	❖ b	Occurs from higher Concentration to lower concentration

Modes of Mass Transfer

There are basically three modes of mass transfer:

i. Diffusion mass Transfer

❖ occurs due to concentration difference

❖ Transport of matter in microscopic level

❖ Occurs between higher concentration and lower concentration

Eg. Osmosis, Reverse osmosis, Leakage of air from automobile and leakage of LPG from tanks

ii. Convective Mass Transfer

❖ occurs due to concentration difference and velocity

❖ Concentration of particles at its surface differs from its concentration in a gas moving over the surface

Eg. Drying of clothes, evaporization of water from swimming pool.

iii. Phase change Mass Transfer

❖ occurs due to simultaneous effect of convection and diffusion mass transfer

Eg. Burnt gases from chimney rise by convection and then mixes with air by diffusion

Important Terms in concentration:

a. Mass concentration or mass density (ρ)

$$= \frac{\text{Mass of a component}}{\text{Unit volume}} = \frac{m_A}{V}$$

b. Molar Concentration or molar density (C_A)

$$= \frac{\text{Mass concentration of a component}}{\text{Molecular weight of a component}} = \frac{\rho_A}{M_A}$$

c. Mass fraction (x_A)

$$= \frac{\text{Mass concentration of a component}}{\text{Mass density of mixture}} = \frac{\rho_A}{\rho}$$

d. Mole fraction (m_A)

$$= \frac{\text{Mole concentration of a component}}{\text{Mole concentration of mixture}} = \frac{C_A}{C}$$

e. Mass flow rate ($\dot{m}_A$) $= N_A (M_A)$

where, N_A= Molar mass rate of flow in kg-mol/sec

We also Know that, $(\rho_A) = \frac{P_A}{RT}$, where, R = Characteristic Gas Constant

also, $(C_A) = \frac{P_A}{\bar{R}T}$, where, $\bar{R}$ = Universal gas constant = 8314.3 j/kg-mol K

Problem 1:

The composition of dry atmospheric air on a molar basis is 78.1% N_2, 20.9% O_2, and 1% Ar. Neglecting other constituents, Assuming atmospheric pressure 1bar and temperature 27°C. Find the mass fractions of the constituents of air.

Solution:

Since, | **Mass fraction (x_A)** $= \frac{\text{Mass concentration of a component}}{\text{Mass density of mixture}} = \frac{\rho_A}{\rho}$

To find Molar concentration of N_2, O_2, Ar,

$$C_{N2} = \frac{P_{N_2}}{\bar{R}T} = \frac{0.781 \times 1 \times 10^5}{8314 \times 300} = 0.0313 \text{ kg mole/m}^3$$

$$C_{O2} = \frac{P_{O_2}}{\bar{R}T} = \frac{0.209 \times 1 \times 10^5}{8314 \times 300} = 0.0084 \text{ kg mole/m}^3$$

$$C_{Ar} = \frac{P_{A_r}}{\bar{R}T} = \frac{0.01 \times 1 \times 10^5}{8314 \times 300} = 0.0004 \text{ kg mole/m}^3$$

To find mass Densities of N_2, O_2, Ar,

$$\rho_{N2} = M_{N2} \times C_{N2} = 28 \times 0.0313 = 0.8764 \text{ kg/m3}$$
$$\rho_{O2} = M_{O2} \times C_{O2} = 32 \times 0.0084 = 0.2688 \text{ kg/m3}$$
$$\rho_{Ar} = M_{Ar} \times C_{Ar} = 18 \times 0.0004 = 0.0072 \text{ kg/m}^3$$

Over all mass density are,

$$\rho = \rho_{N2} + \rho_{O2} + \rho_{Ar} = 0.8764 + 0.2688 + 0.0072 = 1.1524 \text{ kg/m}^3$$

Mass Fractions of Constituents of air are,

$$x_{N2} = \frac{\rho_{N_2}}{\rho} = \frac{0.8764}{1.1524} = 0.7605$$
$$x_{O2} = \frac{\rho_{O_2}}{\rho} = \frac{0.2688}{1.1524} = 0.2334$$
$$x_{Ar} = \frac{\rho_{A_r}}{\rho} = \frac{0.0072}{1.1524} = 0.00625$$

Fick's law of diffusion

The molar flux (Rate of Mass transfer) is directly proportional to concentration difference and inversely proportional to separation.

$$\text{Molar flux} \propto \frac{\text{Concentration Difference}}{\text{Separation}}$$

$$\frac{N_a}{A} \propto \frac{C_{a_2} - C_{a_1}}{dx}$$
$$\frac{N_a}{A} = -D_{ab}\frac{(C_{a_2} - C_{a_1})}{dx}$$

where, D_{ab} = Diffusion coefficient or Diffusivity (m^2/sec)

And C_a = concentration or molecules per unit volume of the particles

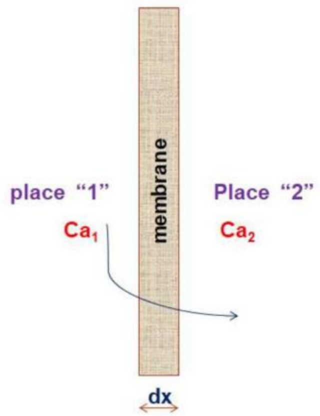
= Solubility x Pressure

A = Area through which the mass is flowing in m^2

-ve sign indicates that the diffusion takes place in the direction opposite to that of increasing concentration

Types of Diffusion Mass transfer

Type A: Steady State diffusion of a component "a" through the membrane



Problem 2:

Hydrogen diffuses through a plastic membrane of 1mm thick. The molar concentration of hydrogen on either side of the plastic membrane are 0.02 kg- mol/m^3, 0.005 kg- mol/m^3. Diffusion coefficient of H_2 through plastic 10^{-9} m^2/sec. determine molar flux and mass flux.

Solution:

Molar flux: From HMT data book, pg. no. 175

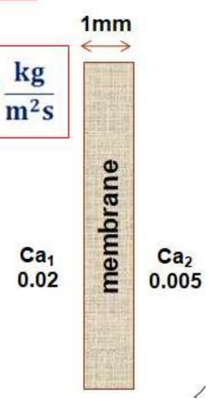
$$\frac{N_a}{A} = -D_{ab}\frac{(C_{a_2} - C_{a_1})}{dx} \quad \text{or} \quad \frac{N_a}{A} = D_{ab}\frac{(C_{a_1} - C_{a_2})}{dx}$$

$$\frac{N_a}{A} = 10^{-9}\frac{(0.02 - 0.005)}{1 \times 10^{-3}} = \boxed{\frac{N_a}{A} = 1.5 \times 10^{-8}\frac{kg}{m^2 s}}$$

Mass flux:

$$\frac{\dot{m}_a}{A} = \left[\frac{N_a}{A}\right] M_{wt} = \frac{\dot{m}_a}{A} = 1.5 \times 10^{-8} \times 2.016$$

$$\boxed{\frac{\dot{m}_a}{A} = 3.024 \times 10^{-8}\frac{kg}{m^2 s}}$$



Problem 3:

Oxygen at 25ºC and pressure of 2 bar flows through a rubber pipe of inside diameter 25 mm and wall thickness 2.5 mm. The diffusivity of oxygen through the rubber tube is 0.21 x 10^{-9} m^2/sec and the solubility of oxygen in rubber is 3.12 x 10^{-3} kg. mole/m^3 bar. Find the loss of oxygen by diffusion / m length of the pipe. Molar proportion of oxygen in air is 21%.

Given: D_{ab} = 0.21 x 10^{-9} m^2/sec ; dx = 2.5 mm = 2.5 x 10^{-3} m ; D = 25 mm = 25 x 10^{-3} m

Solution:

C_{a1} = Solubility x Pressure = 3.12 x 10^{-3} x 2 = $C_{a_1} = 6.24\text{x}10^{-3} \frac{\text{kg}-\text{mol}}{\text{m}^3}$

Since, molar proportion of oxygen in air is given in percentage, and we know that the atmospheric pressure is 1 bar,

P_{O2} = 0.21 x 1 = 0.21 bar

Therefore,

C_{a2} = Solubility x Pressure = 3.12 x 10^{-3} x 0.21= $C_{a_2} = 6.552\text{x}10^{-4} \frac{\text{kg}-\text{mol}}{\text{m}^3}$

Since,

Molar Flux,

$$\frac{N_a}{A} = D_{ab}\frac{(C_{a_1} - C_{a_2})}{dx} \quad \text{or} \quad \frac{N_a}{A} = 0.21\text{x}10^{-9}\frac{(6.24\text{x}10^{-3} - 6.552\text{x}10^{-4})}{2.5\text{x}10^{-3}}$$

$$\frac{N_a}{A} = 34.6914 \text{ x } 10^{-10}\frac{\text{kg}-\text{mol}}{\text{m}^2\text{s}}$$

Since the surface area of cylinder is,

A= π DL = π x 25 x 10^{-3} x 1 or **A= 0.07854 m^2**

Therefore, N_a = 34.6914 x 10^{-10} x 0.07854

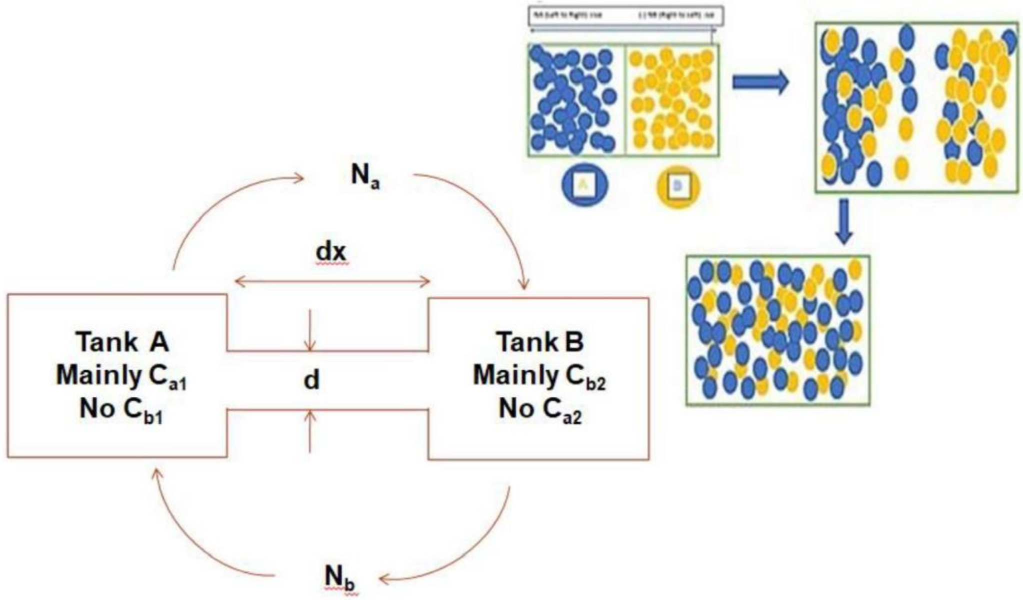
$$N_a = 3.6846 \text{ x } 10^{-10}\frac{\text{kg}-\text{mol}}{\text{s}}$$

But, mass flow rate,

$\dot{m}_a = M_{wt}N_a$ = 32 x 3.66846 x 10^{-11} = 1.1788 x 10^{-9} kg/s

∴ Loss of oxygen per meter length = 1.1788 x 10^{-9} kg/s

Type B: Steady State equimloar counter diffusion of a component "a" and "b"



Problem 4:

Ammonia and air experiences diffusion through 3 mm diameter, 20 mm long pipe. Total pressure is 1 atm and temperature 25°C. Determine the diffusion rate of ammonia and air

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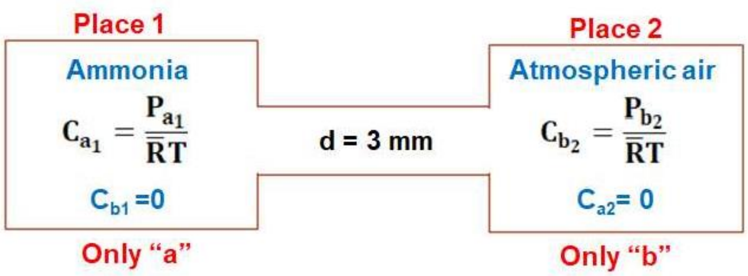


Given that,

P_{a1} = 1 atm = 1 bar, $\overline{R}$ = 8314.3 J/kg mole.K (known), T = 25°C

Therefore,

$$C_{a_1} = \frac{P_{a_1}}{\overline{R}T} = \frac{1x10^5}{8314.3 \text{ x } 298} = 0.04036\ \frac{kg - mole}{m^3}\ ,\ C_{a_2} = 0$$

From HMT Data book, pg No.181

Diffusion Coefficient [for Ammonia and Air] $D_{ab} = 21.60 \times 10^{-6}\ m^2/s$

Since molar flux,

$$\frac{N_a}{A} = D_{ab}\left\{\frac{C_{a_1} - C_{a_2}}{dx}\right\}$$

$$\frac{N_a}{A} = 2.161 \text{ x } 10^{-5}\,\frac{(0.04036 - 0)}{20}$$

$$= \boxed{4.3611\text{x } 10^{-8}\,\frac{kg - mole}{m^2 sec}}$$

Since the cross-sectional area,

$$A = \frac{\pi d^2}{4} = \frac{\pi\left(3\text{x}10^{-3}\right)^2}{4} = \boxed{7.0685 \text{ x } 10^{-6} m^2}$$

Therefore,

$$N_a = 4.3611 \text{ x } 10^{-8}\text{x } 7.0685 \text{ x } 10^{-6}$$

$$= 3.0827 \text{ x } 10^{-13}\,\frac{kg - mol}{s} = N_b$$

Therefore, diffusion rate of Ammonia,

$$\dot{m}_a = (M_{wt})_a N_a = (M_{wt})_{NH_3} N_{NH_3} = 3.0827\text{x}10^{-13}\text{x}17.03$$

$$= \boxed{5.248\text{x}10^{-12}\,\frac{kg}{s}}$$

∵ From HMT Data book Pg.No 184
Molecular wt of NH_3 = 17.03

And, diffusion rate of air,

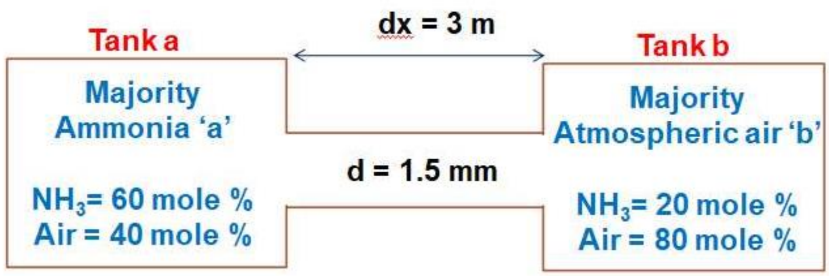
$$\dot{m}_b = (M_{wt})_b N_b = (M_{wt})_{air} N_{air} = 3.0827\text{x}10^{-13}\text{x}28.96$$

$$= \boxed{8.92\text{x}10^{-12}\,\frac{kg}{s}}$$

∵ From HMT Data book Pg.No 184
Molecular wt of air = 28.96

Problem 5:

Two large tanks, maintained at the same temperature and pressure are connected by a circular 0.15 m diameter direct, which is 3 m in length. One tank contains a uniform mixture of 60 mole % ammonia and 40 mole % air and the other tank contains a uniform mixture of 20 mole % air and the other tank contains a uniform mixture of 20 mole % ammonia and 80 mole % air. The system is at 273 K and 1.013 x 10^5 Pa. Determine the rate of ammonia transfer between the two tanks. Assuming a steady state mass transfer.



Tank a,

$$P_{a_1} = \frac{60}{100} \text{ x } 1.1013 = 0.6078 \text{ bar} \qquad P_{b_1} = \frac{40}{100} \text{ x } 1.1013 = 0.4052 \text{ bar}$$

Tank b,

$$P_{a_2} = \frac{20}{100} \text{ x } 1.1013 = 0.2026 \text{ bar} \qquad P_{b_2} = \frac{80}{100} \text{ x } 1.1013 = 0.8104 \text{ bar}$$

$$A = \frac{\pi d^2}{4} = \frac{\pi (0.15)^2}{4} = 0.017671 m^2$$

$$C_{a_1} = \frac{P_{a_1}}{\bar{R}T} = \frac{0.6078 \text{ x } 10^5}{8314.3 \text{ x } 273} = 0.02677 \frac{kg - mole}{m^3}$$

$$C_{a_2} = \frac{P_{a_2}}{\bar{R}T} = \frac{0.2026 \text{ x } 10^5}{8314.3 \text{ x } 273} = 0.008925 \frac{kg - mole}{m^3}$$

From HMT Data book, pg No.181

Diffusion Coefficient [for Ammonia and Air] D_{ab} = 21.60 x 10^{-6} m^2/s

Since molar flux, $$\frac{N_a}{A} = D_{ab}\left\{\frac{C_{a_1} - C_{a_2}}{dx}\right\}$$

$$= 21.61 \times 10^{-6}\left\{\frac{0.02677 - 0.008925}{3}\right\}$$

$$= 1.28543 \times 10^{-7}\,\frac{kg - mol}{m^2 sec}$$

Therefore,

$$Na = 1.28543 \times 10^{-7} \times A = 1.28543 \times 10^{-7} \times A\ 0.017671 =$$

$$N_a = 2.27149 \times 10^{-9}\,\frac{kg - mole}{m^3} = N_b$$

Therefore the rate of ammonia transfer between two tanks,

$$\dot{m}_a = \dot{m}_{NH_3} = M_{wt}N_a = 2.27149 \times 10^{-9} \times 17.03$$

$$= \boxed{3.8683 \times 10^{-8}\,\frac{kg}{s}}$$

∵ From HMT Data book Pg.No 184
Molecular wt of NH_3 = 17.03

Therefore the rate of air transfer between two tanks,

$$\dot{m}_b = \dot{m}_{air} = (M_{wt})_b N_b = 2.27149 \times 10^{-9} \times 28.96$$

$$= \boxed{65.782 \times 10^{-9}\,\frac{kg}{s}}$$

∵ From HMT Data book Pg.No 184
Molecular wt of air = 28.96

Type C: Steady State evaporation of a component "a" into a stagnant air

Assumptions:

- **Water vapor and air behaves as ideal gases**
- **System is held at isothermal conditions**
- **Evaporation Process is steady**

Problem 6:

Determine the rate of water from bottom of a test tube of 10 mm diameter, 150 mm long, into a dry stagnant air at 25°C

Points to be remembered:

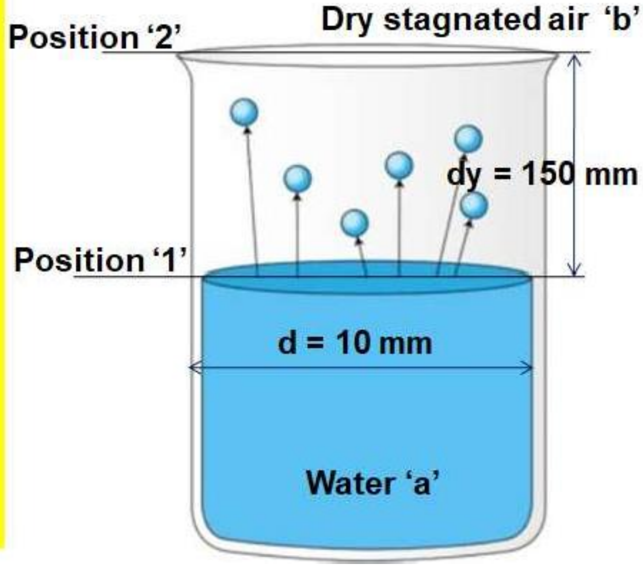
From Dalton's law,

$$P_{a1} + P_{b1} = P_{atm}$$

$$P_{a2} + P_{b2} = P_{atm}$$

$P_{a2} = \phi P_{a1}$
Where ϕ = Relative Humidity

$P_{a2} = 0$
(dry air or ϕ = 0 or no humidity)



Since the Temperature of air is given as 25ºC,

The partial pressure of water vapor (p_{a1}) corresponds to the saturation pressure at 25ºC in steam tables.

Saturated Water and Steam

T [°C]	p_s [bar]	v_g [m³/kg]
0.01	0.006112	206.1
1	0.006566	192.6
2	0.007054	179.9
3	0.007575	168.2
4	0.008129	157.3
5	0.008719	147.1
6	0.009346	137.8
7	0.01001	129.1
8	0.01072	121.0
9	0.01147	113.4
10	0.01227	106.4
11	0.01312	99.90
12	0.01401	93.83
13	0.01497	88.17
14	0.01597	82.89
15	0.01704	77.97
16	0.01817	73.38
17	0.01936	69.09
18	0.02063	65.08
19	0.02196	61.34
20	0.02337	57.84
21	0.02486	54.56
22	0.02642	51.49
23	0.02808	48.62
24	0.02982	45.92
25	0.03166	43.40
26	0.03360	41.03

Therefore, P_{a1} = **0.03166 bar**

Since,

Dry air or ϕ = 0 or no humidity

$$P_{a2} = 0$$

And since,

$$P_{a1} + P_{b1} = P_{atm}$$

Therefore,

$$P_{b1} = 0.96834 \text{ bar}$$

From HMT Data book Pg.No. 181, Diffusion Coefficient

[for Water and Air at 25ºC] D_{ab} = **25.83 x 10^{-6} m²/s**

From HMT Data book, pg No. 175,

$$\frac{N_a}{A} = \frac{D_{ab}}{dy}\frac{P_{atm}}{\bar{R}T}\ln\left[\frac{P_{b_2}}{P_{b_1}}\right]$$

$$\therefore \frac{N_a}{A} = \frac{2.583 \times 10^{-5}}{0.15} \times \frac{1 \times 10^5}{8314.4 \times 298} \ln\left[\frac{1}{0.96834}\right]$$

$$= 2.23598 \times 10^{-7} \frac{kg-mol}{m^2 s}$$

$$A = \frac{\pi d^2}{4} = \frac{\pi (0.01)^2}{4} = 78.539 \times 10^{-6} m^2$$

Therefore,

$$N_a = 2.2359 \times 10^{-7} \times 78.539 \times 10^{-6}$$

$$= 1.75607 \times 10^{-11} \frac{kg-mol}{s}$$

From HMT data Book, Pg.No. 184, Molecular Weight of steam = 18.016

Therefore, Rate of Evaporation is,

$$\dot{m}_a = N_a (M_{wt})_a = 1.75607 \times 10^{-11} \times 18.016$$

$$= 3.106929 \times 10^{-10} \frac{kg}{s}$$

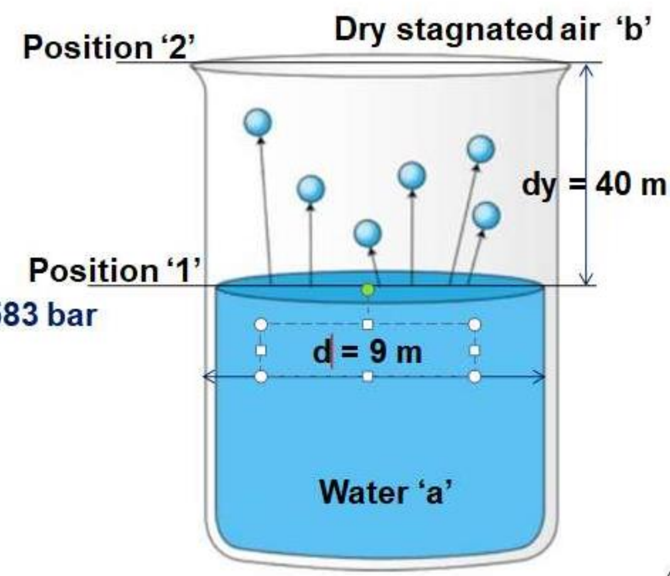
Problem 7:

A well of 40 m deep 9m diameter is exposed to atmospheric air at 25 C, 50% R.H. determine the rate of atmospheric evaporation of water from well.

Solution:

Since the Temperature of air is given as 25°C,

The partial pressure of water vapor (p_{a1}) corresponds to the saturation pressure at 25°C in steam tables.



Therefore, P_{a1} = **0.03166 bar**

and

$$P_{a2} = \phi P_{a1}$$

Since,

R.H or ϕ = 50%

$$P_{a2} = 0.5 \times 0.03166 = 0.01583 \text{ bar}$$

And since,

$$P_{a1} + P_{b1} = P_{atm} = 1$$

Therefore,

$$P_{b1} = 0.96834 \text{ bar}$$

Since,

$P_{a2} + P_{b2} = P_{atm}$

Therefore,

$P_{b2} = 0.98417$ **bar**

From HMT Data book Pg.No. 181, Diffusion Coefficient [for Water and Air at 25°C]

$D_{ab} = 25.83 \times 10^{-6}\ m^2/s$

From HMT Data book, pg No. 175,

$$\frac{N_a}{A} = \frac{D_{ab}}{dy}\frac{P_{atm}}{\bar{R}T}\ln\left[\frac{P_{b_2}}{P_{b_1}}\right]$$

$$\therefore \frac{N_a}{A} = \frac{2.583 \times 10^{-5}}{40} \times \frac{1 \times 10^5}{8314.4 \times 298} \ln\left[\frac{0.9847}{0.96834}\right]$$
$$= 4.226 \times 10^{-10} \frac{kg - mol}{m^2 s}$$

and the area of the well,

$$A = \frac{\pi d^2}{4} = \frac{\pi(9)^2}{4} = 63.6175\ m^2$$

Therefore,

$$N_a = 2.6880 \times 10^{-8} \frac{kg - mole}{m^3}$$

From HMT data Book, Pg.No. 184, Molecular Weight of steam = 18.016

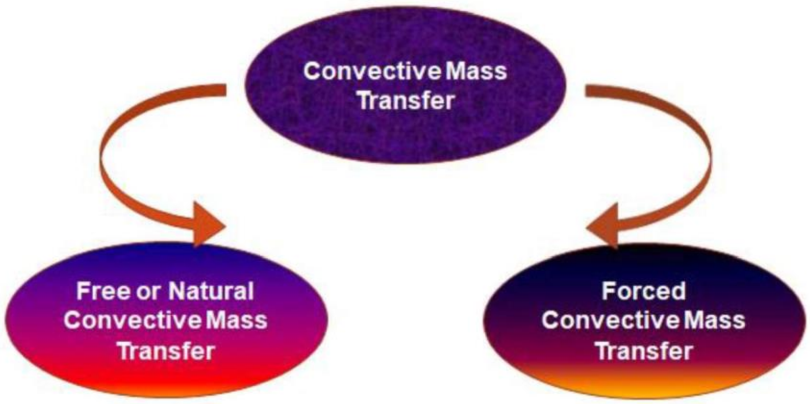
Therefore, Rate of Evaporation is,

$$\dot{m}_a = N_a (M_{wt})_a = 2.688 \times 10^{-8} \times 18.016$$
$$= 4.8441 \times 10^{-7} \frac{kg}{s}$$

Covective Mass Transfer

Definition:

Mass transfer between surface and liquid / gas due to concentration difference.



Terms used in Connective mass Transfer:

Sherwood number: [HMT Data Book Pg.No. 112]

The ratio of concentration gradient at the boundary by diffusion to concentration gradient at the boundary by convection

$$S_h = \frac{h_m L}{D_{ab}} \text{ (for plates) and } S_h = \frac{h_m d}{D_{ab}} \text{ (for Tubes)}$$

Where,

h_m = Mass transfer coefficient (m/sec); L = Length (m); d = Diameter (m);
D_{ab} = Diffusion Coefficient (m^2/sec)

Schmidt number: [HMT Data Book Pg.No. 112]

The ratio of Molecular diffusivity of momentum to the molecular diffusivity of mass.

$$S_c = \frac{v}{D_{ab}} = \frac{\mu}{\rho D_{ab}}$$

Where,

v = Kinematic viscosity (m^2/sec), D_{ab} = Diffusion Coefficient (m^2/sec)

Reynolds number: [HMT Data Book Pg.No. 112]

The ratio of Inertia force to viscous force

$$R_e = \frac{uL}{v} \quad \text{(for plates)} \quad \text{and} \quad R_e = \frac{ud}{v} \quad \text{(for Tubes)}$$

Where,

u = Velocity (m/sec); v = Kinematic viscosity (m^2/sec) ; L = Length (m); d = Diameter (m)

It used to classify the type of flow

Flat Plate	Tubes
if $R_e < 5 \times 10^5$ flow is laminar if $R_e > 5 \times 10^5$ flow is turbulent	if $R_e < 2000$ flow is laminar if $R_e > 2000$ flow is turbulent

Lewis number: [HMT Data Book Pg.No. 112]

The ratio heat diffusivity to mass diffusivity

$$L_e = \frac{S_c}{P_r}$$

Where,

Pr = Prandtl Number

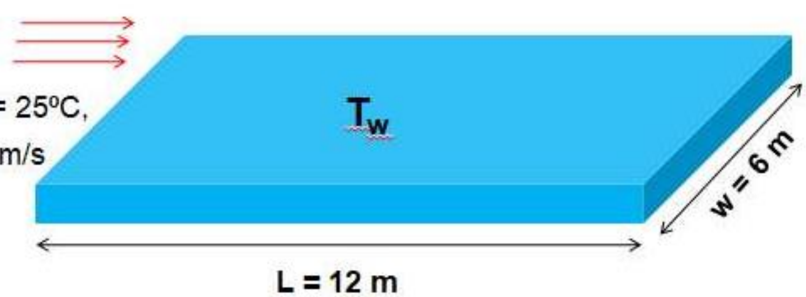
Problem 1:

Air at 25ºC, 50% R.H, flows over a swimming pool at a surface temperature of 25ºC of 12 m x 6 m. The velocity of air in the length direction is 2m / sec. Determine the (a) mass transfer coefficient (b) mass rate of water evaporation

Given :

T_∞ = 25ºC, ϕ = 50%, T_w = 25ºC,

L = 12 m, w = 6 m, u = 2 m/s



Solution:

Since velocity is given in the problem, it is a convection mass transfer.

Step 1: Determination of film temperature (T_f)

$$T_f = \frac{T_w + T_\alpha}{2} = \frac{25 + 25}{2} = 25^0C$$

Step 2: Taking properties of air, [from HMT Data book, Pg.No. 34]

Corresponding to $T_f = 25^oC$,

$$v = 15.53 \text{ x } 10^{-6} \frac{m^2}{s}$$

$$P_r = 0.702$$

Step 3: Determination of type of flow:

$$R_e = \frac{uL}{v} = \frac{2 \text{ x } 12}{15.53 \text{ x } 10^{-6}} = 1545396 > 5 \text{ x } 10^5$$

Since greater than $5 \text{ x } 10^5$, the flow can be assumed as turbulent or Laminar - turbulent

Here we assume the flow is Laminar – turbulent.

Step 4: Determination of Diffusion coefficient, [from HMT Data book, Pg.No. 181]

Corresponding to the medium, (water – air) at $T_f = 25^oC$

$$D_{ab} = 25.83 \text{ x } 10^{-6} \text{ m}^2/\text{s}$$

Step 5: Determination of Schmidt Number (S_c),

$$S_c = \frac{v}{D_{ab}} = \frac{15.53 \text{ x } 10^{-6}}{25.83 \text{ x } 10^{-5}} = 0.60123$$

Step 6: Determination of Sherwood Number (S_h), From HMT data book, Pg.No. 177,

$$S_h = [0.037 {R_e}^{0.8} - 871] {S_c}^{0.33}$$

$$S_h = [0.037 \text{ x } 1545396 - 871] 0.60123^{0.33}$$
$$= 2059.4906$$

But we know that, [HMT Data Book Pg.No. 112]

$$S_h = \frac{h_m L}{D_{ab}} = 2059.4906$$

Step 7: Determination of mass transfer coefficient (h_m),

$$h_m = \frac{S_h D_{ab}}{L} = \frac{2059.49 \text{ x } 2.583 \text{ x } 10^{-5}}{12}$$
$$= 4.43305 \text{ x } 10^{-3} \frac{m}{s}$$

Step 8: Mass of flow rate evaporated ($\dot{m}_w$),

$$\dot{m}_w = h_m A(\rho_{aw} - \varphi\rho_{a\infty})$$

Where,

ρ_{aw} = Density of water vapor at T_w = $\frac{1}{v_g}$

$\rho_{a\infty}$ = Density of water vapor at T_∞ = $\frac{1}{v_g}$

From steam tables, corresponding to $T_w = T_\infty = 25^0C$,

$$v_g = 43.402 \frac{m^3}{kg}$$

$$\rho_{aw} = \frac{1}{v_g} = 0.02304 \frac{m^3}{kg}$$

∴ Mass of flow rate evaporated

$$\dot{m}_w = 4.43305 \text{ x } 10^{-3} \text{x } (12 \text{ x } 6)(0.02304 - 0.5 \text{ x } 0.02304) = 3.6769 \text{ x } 10^{-3} \frac{kg}{sec}$$