الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الثالثة

انتقال كتلة

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(*) What is chemical Engineering?

Chemical Engineering deals with industrial process in which raw materials are converted or seperated into useful products.

(*) Who is the chemical Engineer?

An engineer, who apply the chemistry of a particular industrial process through the use of scientific and engineering principles.
He must **develepe**, **design** and **engineer** both the industrial process and the equipment used.
To do the above purposes, the chemical engineer need to know well about :-

1. Stoichiometery
2. Thermodynamics
3. Kinetic
4. Unit operation
5. Economic

(*) What is Unit_Operation?

The physical operation for manufacturing chemicals deals mainly with the transfer and change of materials and Energy principles by physical and physical_chemical means, such as :- Mass, heat and momentum transfer.

- Classification of Unit-operation -

نوع العمليه

① process type

- a. Without chemical reaction
  - distillⁿ
  - absorptⁿ
- b. with chemical reaction
  - oxidatⁿ
  - Nitratⁿ

نوع الانتقال

② Type of transfer

a. Mass transf.

b. Heat transf.

c. Moment. transf.

(*) Mass-Transfer and Diffusion.

When mass is being transfered from one distinct phase to another or through a single phase, the basic mechanisum are the same wheather the phase is gas, liquid or Solid.

$$\boxed{\text{Rate of transfer process} = \frac{\text{driving force}}{\text{resistance}}}$$

i.e :- $\psi = -\delta \cdot \dfrac{dx}{dy}$

$\therefore \psi = N_A = -D_{AB} \cdot \dfrac{dC_A}{dz}$ — Mass Transfer → Fick's Law

$\psi = q = -K \cdot \dfrac{dT}{dz}$ — Heat Transfer → Fourier's Law

$\psi = \tau = -\mu \cdot \dfrac{du}{dz}$ — Moment. Transf. → Newton's Law

* Subjects to be Studied are:-

1) Diffusion
   - Steady
   - Unsteady
     - Binary System
     - Multi component
       - Gas
       - Liq.
       - Solid

2) Absorption
   - Tray tower
   - Packed tower
     - Dilute solution.
     - Concent solution.

3) Distillation
   - Binary system
   - Multi component
     - Ideal
     - Non ideal

4) Mechanical separation or Size reduction.

5) Boundary Layer.

Diffusion

The transport of molecules from a higher concent^n to lower conc^n is often called " diffusion".

Diffusion through →
ⓐ Stagnant media called molecular diffusion
ⓑ Turbulent media called eddy or turbulent diffusion.

Molecular diffusion is important when the medium is stagnant or laminar flow flowing. But does not have a significant role to play if the medium is turbulent except in region very close to the phase boundary.

Example:- vaporization of a layer of water
عملية تبخر طبقة ماء في الهواء ساكن ، وفي الهواء متحرك

Molecular - Diffusion

Since most of mass transfer operations are based on diffusional phenomena, the study of molecular diffusion is essential for understanding these phenomena.

Molecular diffusion or molecular transport can be defined as the transfer or movement of individual molecule through a fluid by means of the random individual movement of the molecules.
Since the molecules travel in random path, it is often called (Random - Walk - process).

The rate of molecular diffusion is connected with :-
1. molecular velocity
2. concentration difference (driving or Potential force)

* Concentration, Velocity and flux

① Concentration :- Generally expressed as :-

ρ_i = mass - Conc^n (Kg/m^3).

ρ = total mass : Conc^n = density (Kg/m^3) = $\sum \rho_i$

$\omega_i = \rho_i / \rho$ = mass fraction. $\sum \omega_i = 1$

C_i = molar. Conc^n (Kmol/m^3).

C = Total molar. conc^n (Kmol/m^3) = $\sum C_i$

$x_i = C_i / C$ = mole fraction. $\sum x_i = 1$

We usually denote to :-
gas mole fraction by $(y_i) = P_i / P$
liquid mole fraction by $(x_i) = C_i / C$

② * Mass average - Velocity (u)

$u = \frac{1}{\rho} \sum \rho_i u_i$ for n-component mixture

* Molar - average - velocity (U)

$U = \frac{1}{C} \sum C_i u_i$

or $\begin{cases} v_i = \dfrac{N_i}{C_i} & \text{Species} \\ v_m = \dfrac{N_T}{C_T} & \text{mixture} \end{cases}$

Prove [$u = U$ if the M.wt of all species are equal].

(*) Species diffusion velocity relative to molar av. velocity

$$v_{iD} = v_i - v_m \Rightarrow v_i = v_{iD} + v_m$$

3 (*) Flux :-

The net rate at which a species in a solution passes through a unit area in unit time. It is expressed in $kg/m^2 \cdot s$ or $kmol/m^2 \cdot s$

flux — mass flux
flux — molar flux

a) mass flux

1. relative to a stationary observer $\Rightarrow n_i = \rho_i u_i$.
2. relative to an observer moving with mass avg. velocity $\Rightarrow i_i = \rho_i (u_i - u)$.
3. relative to an observer moving with molar. avg. velocity $\Longrightarrow j_i = \rho_i (u_i - u)$.

b) Molar flux.

1. $N_i = C_i u_i$
2. $I_i = C_i (u_i - u)$
3. $J_i = C_i (u_i - u)$

Example(1) :- A gas mixture ($N_2 = 5\%$, $H_2 = 15\%$, $NH_3 = 76\%$ and $Ar = 4\%$) flows through a pipe 25.4 mm in diameter at 4.05 bar total pressure. If the velocities of the respective components are 0.03 m/s, 0.035 m/s, 0.03 m/s and 0.02 m/s.

Calculate :- mass.avg, molar avg and vol. avg. velocities of the mixture?

Take Mwt for :-

$N_2 = 28$, $NH_3 = 17$, $Ar = 40$

Solution :-

① to find mass. avg. velocity

$$u = \frac{1}{\rho}\left(\rho_1 u_1 + \rho_2 u_2 + \rho_3 u_3 + \rho_4 u_4\right)$$

$$\because \rho_i = P_i M_i / R.T \quad , \quad \rho_T = P_T M_T / R.T$$

$$\therefore u = \frac{R.T}{P_T.M_T}\left(\frac{P_1 M_1}{R.T}\cdot u_1 + \frac{P_2 M_2}{R.T}\cdot u_2 + \frac{P_3 M_3}{R.T}\cdot u_3 + \frac{P_4 M_4}{R.T}\cdot u_4\right)$$

$$u = \frac{1}{M_T}\left(\frac{P_1}{P_T} M_1 u_1 + \frac{P_2}{P_T} M_2 u_2 + \frac{P_3}{P_T} M_3 u_3 + \frac{P_4}{P_T} M_4 u_4\right)$$

$\because P_i / P_T = y_i$, therefore

$$u = \frac{1}{M_T}\left[y_1 M_1 u_1 + y_2 M_2 u_2 + y_3 M_3 u_3 + y_4 M_4 u_4\right]$$

$$\because M_T = y_1 M_1 + y_2 M_2 + y_3 M_3 + y_4 M_4$$

$$= 0.05 * 28 + 0.15 * 2 + 0.76 * 17 + 0.04 * 40$$

$$\therefore M_T = 16.22$$

$$\therefore u = \frac{1}{16.22}\left[0.05 * 28 * 0.03 + 0.15 * 2 * 0.03 + 0.76 * 17 * 0.03 + 0.04 * 40 * 0.02\right]$$

$u = 0.029$ m/sec.

(2) to find molar avg. velocity (U)

$$U = \frac{1}{C_T}[C_1U_1 + C_2U_2 + C_3U_3 + C_4U_3)$$

$$y_i = x_i = \frac{C_i}{C_T} \quad \text{for vap. and gas}$$

$$U = 0.05 * 0.03 + 0.15 * 0.035 + 0.76 * 0.03 + 0.04 * 0.02$$

$u = 0.0303$ m/sec

(3) Vol. avg. velocity = molar avg. velocity (for gases)

H.W :- Show that U_m can be expressed as:-

$$\boxed{U_m = X_A V_A + X_\beta \cdot V_B}$$

Fick's Law

The basic Law of diffusion called "Fick's Law".

flux of A in B $\rightarrow J_A \propto \dfrac{dC_A}{dz} \implies J_A = -D_{AB}\dfrac{dC_A}{dz}$

where D_{AB} = diffusion coeff. or diffusivity.

Diffusion is a M.T. process occurs when conc^n difference between two phases exists. Fick's Law express the molar flux (J) with respect to an observer moving with the molar avg. velocity. In practice, it is more useful to use expression for (N_A) instead of (J_A).

$$J_A = -D_{AB}\cdot\frac{dC_A}{dz} = C_A(u_A - u)$$

$$-D_{AB}\frac{dC_A}{dz} = C_A u_A - C_A\cdot u$$

$$= N_A - C_A\cdot\frac{1}{C}(C_A u_A + C_B u_B)$$

$$= N_A - \frac{C_A}{C}(N_A + N_B)$$

بدلالة التركيز $\quad N_A = \underbrace{\frac{C_A}{C}[N_A + N_B]}_{\text{bulk flow}} - \underbrace{D_{AB}\cdot\frac{dC_A}{dz}}_{\text{molecular diffusion}}$

For gas mixture: $P = C\cdot R\cdot T \Rightarrow C = \dfrac{P}{RT} \quad \therefore C_A = \dfrac{P_A}{RT}$

$$dP = RT\,dC \quad \therefore dC = \frac{dP}{RT} \quad \therefore dC_A = \frac{dP_A}{RT}$$

$$\boxed{N_A = \frac{P_A/\cancel{RT}}{P_T/\cancel{RT}}\left[N_A+N_B\right] - D_{AB}\frac{dP_A}{RT\cdot dZ}}$$

بدلالة pressi

To convert (N_A) interms of mole fraction (y_A)

$$y_A = \frac{P_A}{P_T} \Rightarrow P_A = y_A P_T \rightarrow dP_A = P_T\, dy_A$$

$$\therefore N_A = \left[N_A+N_B\right]\cdot y_A - \overbrace{\frac{D_{AB}}{R\cdot T}\cdot P_T}^{C_T}\frac{dy_A}{dz}$$

$$\boxed{\therefore N_A = \left[N_A+N_B\right] y_A - C_T D_{AB}\frac{dy_A}{dZ}}$$

بدلالة mole fraction

Note:- All the above equations for component (A) is derived in same way for species (B).

Then the total flux will be :-

$$\boxed{N_T = N_A + N_B}$$

Diffusion in Gases

The most important cases to be studied are :-

1. Equimolar - Counter diffusion (EMD).
2. Diffusion of species (A) through stagnant non-diffusing (B).

} No bulk movement

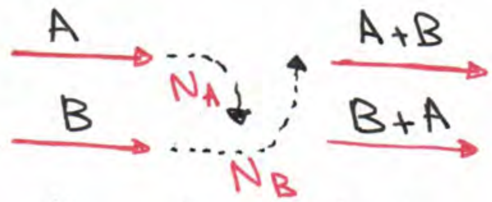
3. Diffusion of gas (A) and (B) plus-convection.
4. Diffusion through a varying :-
   - (a) Path-length (time dependent).
   - (b) Cross-sectional area.

(1) Equimolar - Counter - diffusion (EMD)

for species (A, B), both diffuses at equal rates but in opposite direction.

A real life example for this case is :-

(a) (partical of carbon burning in air)



The particle is surrounded by an air-film, through which the molecules of oxygen diffuse and reach the surface of the particle to sustain combution.

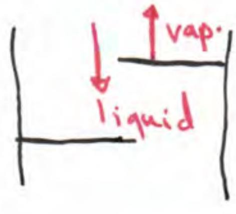
If [O_2] molecule diffuses to the surface, a molecule of CO_2 is formed which diffuses out through the air-film.

So (O_2 and CO_2) undergo (EMD).

علما
فرض
انه
CO_2
فقط
يتكون

$$C + O_2 \longrightarrow CO_2$$

(b) vapour rising in the distillation column remain in contact with the down-flowing liquid



$$N_A = -N_B$$

$$\therefore N_A = \frac{P_A}{P_T}\left[N_A + N_B\right] - \frac{D_{AB}}{RT}\,\frac{dP_A}{dZ}$$

for stationary bulk flow

$$\therefore N_A = -D_{AB}/RT \;\frac{dP_A}{dz}$$

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

by integration :-

$$N_A = \frac{D_{AB}}{RT} \cdot \frac{P_{A_1} - P_{A_2}}{Z}$$ for EMD

* In this case, total pressure (P_T) must be constant, therefore the net moles of (A) diffusing to the right must equal moles of (B) diffusing to the left.

* $N_A = -N_B$

$$\therefore -D_{AB}\,\frac{dC_A}{dZ} = +D_{BA}\,\frac{dC_B}{dZ}$$

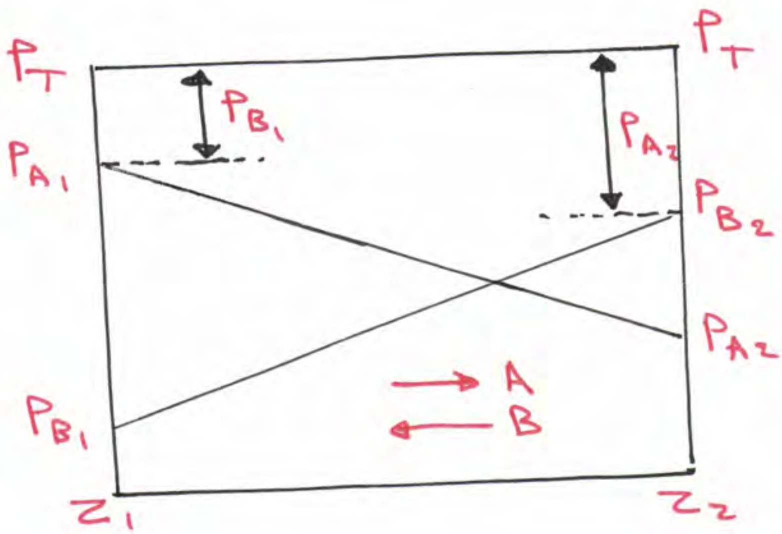
$$C_T = C_A + C_B \implies dC_A + dC_B = dC_T = 0$$

$$\therefore -dC_A = +dC_B$$

$$\boxed{\therefore D_{AB} = D_{BA} = D}$$

$\therefore$ for binary gas mixture the diffusivity of both (A) and (B) are the same.

The distribution of the partial pressure of (A) and (B) along the diffusion path in this case are linear.



(*) For a Non-equimolar-counter diffusion (NEMD)

Producing (CO_2) from (O_2) and hot-char-particle

$$\underset{(A)}{\tfrac{1}{2} O_2} + \underset{(B)}{CO} \longrightarrow CO_2$$

here $N_A = \frac{1}{2} N_B$

$$N_A = (N_A + N_B) \cdot \frac{P_A}{P_T} + (-D_{AB}) \frac{dP_A}{dZ}$$

Now substitute $N_B = 2N_A$ and then integrate.

Example(1) :- A uniform tube (0.1) m long and (0.01 m di), containing N_2 gas, Ammonia gas (A) diffusing through the pipe. At point (1), $P_{A_1} = 1.013 * 10^4$ Pas, and at point (2) $P_{A_2} = 0.507 * 10^4$ pas. The total pressure is $1.013 * 10^5$ pas and the diffusivity $D_{AB} = 0.23 * 10^{-4}$ cm^3/sec. Calculate :-

1- fluxes of (A) and (B), at Temp = 298 K.
2- The rate of M.T for species (A) and (B).

Solution :-

1- Closed system with constant pressure and Temp., then the diffusion flow is EMD :-

$$\therefore N_A = \frac{D_{AB}}{RT} \cdot \frac{P_{A_1} - P_{A_2}}{Z_2 - Z_1}$$

$$= \frac{0.23 * 10^{-4}}{8.314 * 298} \cdot \frac{1.013 * 10^4 - 0.507 * 10^4}{0.1 - 0.0}$$

$N_A = 4.7 * 10^{-7}$ kgmol/m^2.sec

for species (B) , $P_{B_2} = P_T - P_{A_2}$, $P_{B_1} = P_T - P_{A_1}$

or $N_B = -4.7 * 10^{-7}$ kgmol/m^2.sec.

2- mass transfer rate (n_A)

$$\therefore N_A = \frac{n_A}{Area} \Longrightarrow n_A = N_A * A$$

$A = \frac{\pi}{4} d_i^2 \Rightarrow \frac{\pi}{4}(0.01)^2 \Rightarrow 7.8 * 10^{-5} m^2$ $\quad \therefore n_A = 4.7 * 10^{-7} * 7.8 * 10^{-5}$

$\therefore n_A = 36.66 * 10^{-12} \frac{kgmol}{sec}$

$\therefore n_B = -36.66 * 10^{-12} \frac{kgmol}{sec.}$

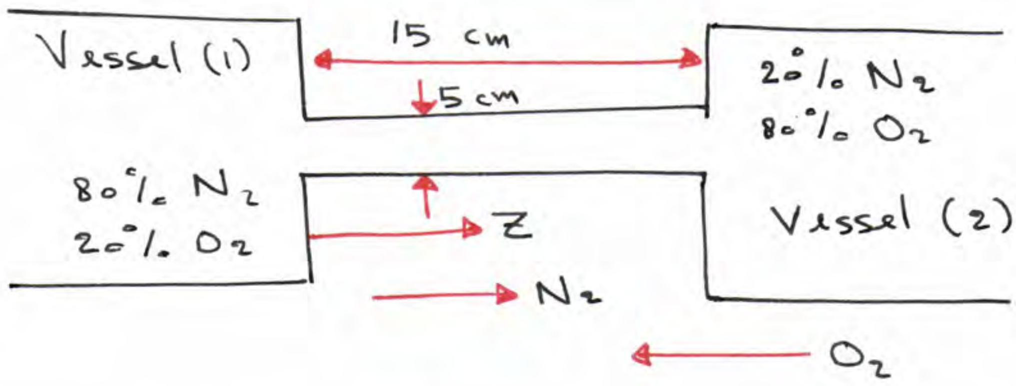
3- Try to calculate (U_A, U_B)

$U_A = \frac{N_A}{C_A}$ & $C_A = \frac{P_A}{RT}$

Example (2) :- Two large vessels are connected as shown in Figure. Vessel (1) contains 80% N_2 (A) and 20% O_2 (B), vessel (2) contains 20% N_2 and 80% O_2. The temp. (20°C) and the total pressure (2 atm). Calculate :-

1. The flux and rate of transport of N_2 from vessel 1 to 2, and same for O_2.
2. The partial pressure of N_2 and its gradient in the tube (0.05 m) from vessel (1). (dP_A/dz).
3. The net mass flux (n_T).

Given that diffusivity of N_2-O_2 pair is $1.01 * 10^{-5}$ m^2/s at 20°C and 2 atm.



Solution:-

1. $$N_A = \frac{+D_{AB}}{RT} \frac{P_{A_1} - P_{A_2}}{Z_2 - Z_1}$$

$D_{AB} = 1.01 * 10^{-5}$ (m^2/s), $R = 0.0821$, $T = 293$ K

$Z = Z_2 - Z_1 = 0.15$ m, To find P_{A_1}, P_{A_2}

$P_{A_1} = y_{A_1} \cdot P_T$
$= 0.8 * 2$
$= 1.6$ atm
$P_{A_1} = 1.62 * 10^5$ $\frac{N}{m^2}$

, $P_{A_2} = y_{A_2} \cdot P_T$
$= 0.2 * 2$
$= 0.4$ atm
$P_{A_2} = 0.406 * 10^5$ N/m^2

$\therefore N_A = 3.3 * 10^{-6}$ Kmol / m^2.Sec.

rate of transport $= n_A = N_A \cdot \text{Area} \leftarrow \frac{\pi}{4} d_i^2 \leftarrow \frac{\pi}{4}(0.05)^2$

قطر
الأنبوب

$= n_A = 6.6 * 10^{-9}$ Kmol/sec.

$N_B = -N_A = -3.36 * 10^{-6}$ Kmol/m^2.s

$n_A = -n_B = -6.6 * 10^{-9}$ Kmol / sec.

2) Partial press. changes linearly with diffusion Path.

$$\therefore \frac{dP}{dZ} = \frac{P_{A_2} - P_{A_1}}{Z} = \frac{(0.4 - 1.6)}{0.15} = -8 \text{ atm/m}$$

at point 0.05

$$\boxed{P_A = P_T + \left[\frac{dP_A}{dZ}\right] \cdot \Delta Z}$$ قانون حفظا

$$= 1.6 + (-8) \cdot 0.05$$

$P_A \cancel{\frac{dP}{dZ}} = 1.2$ atm.

3) $n_T = N_A \cdot M_{wt_A} + N_B M_{wt_B}$

$$= (3.36 * 10^{-6} * 28) - (3.36 * 10^{-6} * 32)$$

$n_T = -1.344 * 10^{-5}$ Kmol / m^2.s

(2) Diffusion of (A) through non-diffusing (B)

In this case one boundary at the end of the diffusion path is impermeable to other species, so it can not pass through.

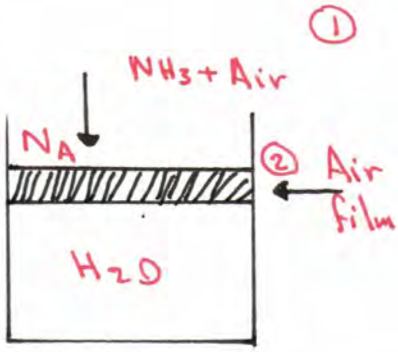
A real life example: Dry air in sulphuric acid plant.

تحتاج الهواء الجاف لغرض حرق الكبريت في معمل إنتاج حامض H_2SO_4 ،
لذلك يمرر الهواء الرطب على حامض كبريتيك مركز في أبراج محشوة، الرطوبة
ستنفذ خلال طبقة من الهواء وتصل إلى سطح الحامض وبعد ما تمتص.
لكن الهواء لا يذوب في الحامض وبالتالي لا يستطيع النفاذ.

∴ moisture (H_2O) has → Source (bulk of air)
→ Sink (the acid)

but (dry air) has (source) but no (sink).

- Another example (NH_3 in Air) removal. NH_3 diffuses easily across air film to water, but (Air) is insoluble.

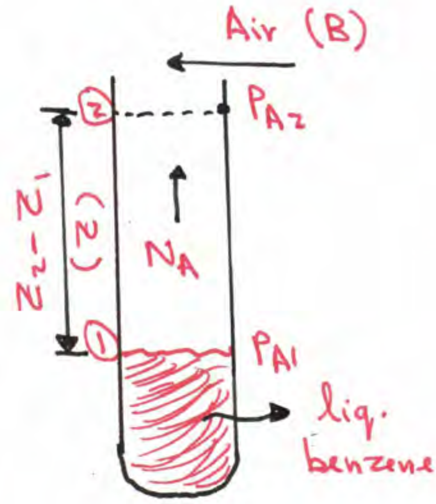


$$\therefore N_A = (N_A + N_B)\frac{P_A}{P_T} - \frac{D_{AB}}{RT}\frac{dP_A}{dZ}$$

$$\because N_B = 0$$

$$\therefore N_A = N_A\frac{P_A}{P_T} - \frac{D_{AB}}{RT}\frac{dP_A}{dZ}$$

$$\therefore N_A * dZ = -\frac{D_{AB}\,P_T}{RT\,(P_T - P_A)}\,dP_A$$



integrating over $Z = 0$, $P_A = P_{A1}$
and $Z = L$, $P_A = P_{A2}$

$$N_A = \frac{D_{AB} P_T}{RTZ} \ln \frac{\overbrace{P_T - P_{A2}}^{P_{B2}}}{\underbrace{P_T - P_{A1}}_{P_{B1}}}$$

It is more convienent to use [Log mean partial pressure]

$$N_A = \frac{D_{AB} P_T}{RTZ} \cdot \frac{P_{A1} - P_{A2}}{P_{BM}}$$ for $N_B = 0$

where $$P_{BM} = \frac{P_{B2} - P_{B1}}{\ln \frac{P_{B2}}{P_{B1}}}$$

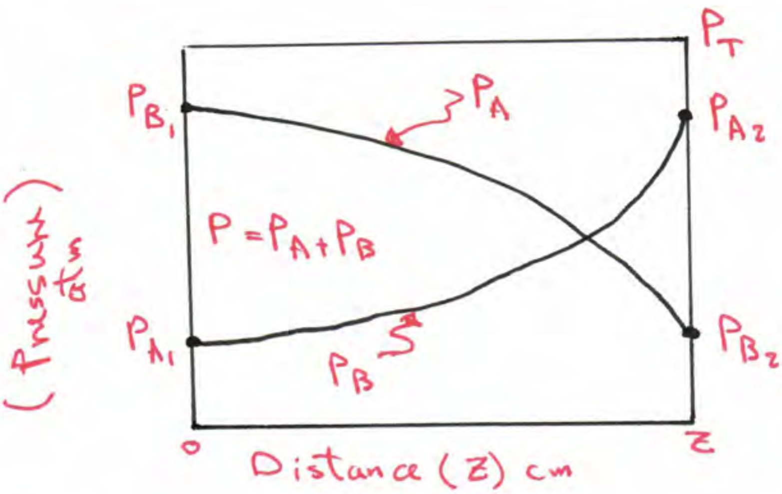
This equation express the flux in terms of driving force of species (A), $(P_{A1} - P_{A2})$.
We also can Calculate the partial pressure (P_A) of (A) at any intermediate point and the distribution of the partial pressure of (A) along the diffusion path, by using :-

$$N_A = \frac{D_{AB} P_T}{RTZ} \ln \frac{P_T - P_A}{P_T - P_{A1}}$$

H.W 3 Try To find

$$N_A = \frac{C_T D_{AB}}{Z_2 - Z_1} \cdot \frac{X_{A1} - X_{A2}}{X_{BM}}$$

Typical distribution of the partial pressure of the components along the diffusion path



هنا عندنا (A) ينفذ من

$Z = 0$ الى $Z = L$

كذلك (B) ينفذ من

$Z = 0$ الى $Z = L$

أي له Press. gradient

ولكن نحن عندنا $N_B = 0$

أي flux = 0 مثال :-

سمكة تسبح بسرعة باتجاه معاكس لجريان الماء. فالذي نراه ان السمكة لا تتحرك تقريباً في الماء، ولكن في الحقيقة إنها لها حركة، ولكن حركة الماء المعاكس تهمش سرعة السمكة وبالتالي نعتبر flux لها = صفر.