Mass Transfer

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Lecture #1

Dr. Haydar Aljaafari

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Background:

PhD Chemical & Biochemical Engineering, University of Iowa, IA, United States, 2022

MSc Chemical Engineering, University of Technology, Iraq, 2012

BSc Chemical Engineering, University of Technology, Iraq, 2006

Contact Information:

Email: haydar-aljaafari@uiowa.edu

Academic Profile:

DR. ALJAAFARI

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Course Objectives

1- Understand the basics of diffusion.

2- Estimate Molar fluxes in convective and inter-phase mass transfer.

3- Explain the concept of diffusion theories.

4- Learn how to calculate mass transfer rates in multiple unit operations.

Resources

- Coulson, J. M & Richardson J. F. (2006). “Chemical engineering, Volume 1”, 3P rdP Edition, Robert Maxwell. M. C.
- Dutta Binary K. (2007), “Principles of Mass Transfer & Separation Process”, Bvt. Ltd. Prentice Hall, ISPN 8-1203-2990-2.
- Treybal Robert E. (1975), “Mass transfer Operation” 2ed Edition, Mc-Graw-Hill Book.
- McCabe, W., Smith, J., Harriott, P. (2004), “Unit Operations of Chemical Engineering”, M Graw-Hill Co., 7P thP Edition, ISBN0072848235.

Topics

- Definitions
- Diffusion in binary gaseous
- Diffusion in multi-component mixtures
- Diffusion in liquids
- Diffusion in solids
- Diffusion theories
- Diffusion resistances
- Unsteady state mass transfer

Definitions

Chemical Engineering

Is a discipline of engineering that deals with transforming raw materials into products employing a variety of processes (**unit operations**), including fluid mechanics, heat transfer, mass transfer, and others.

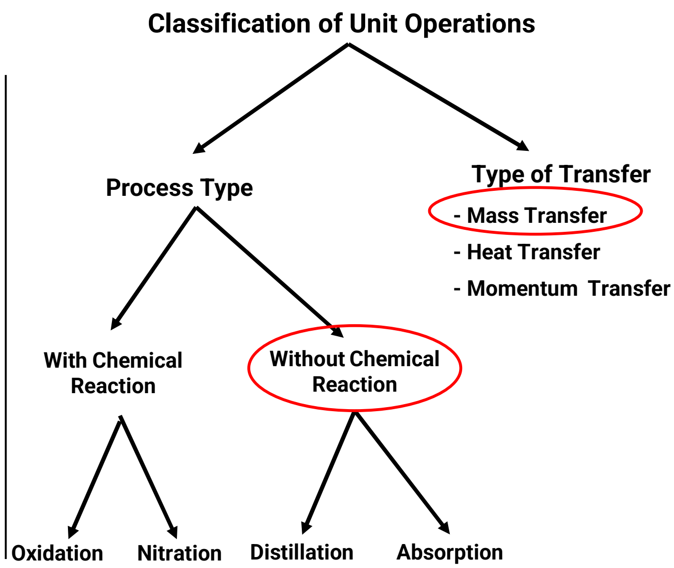
Chemical Engineers

Develop, design, and operate chemical manufacturing processes. Chemical engineers use the principles of chemistry, physics, and engineering to design equipment and **unit operations** for manufacturing products.

Definitions

Unit Operations

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



Definitions

Mass Transfer is the movement of molecules or atoms from one location to another, driven by a concentration difference. It occurs in processes like **diffusion**, evaporation, and absorption, and is essential in many chemical engineering operations where substances need to be separated or mixed.

$$Rate\ of\ Transfer\ process\ \alpha\ \frac{Driving\ Force}{Resistance}$$ .... **General**

$$\mathcal{T} = -\eta \frac{du}{dz}$$
Newton's Law
Momentum Transfer

$$J_A = -D_{AB}\frac{dC_A}{dz}$$
Fick's Law
Mass Transfer

$$q = -k\frac{dT}{dz}$$
Fourier's Law
Heat Transfer

Important Laws

1- ***Ideal gas law*** (***Boyle's law***)

$PV = nRT$

R = gas constant

= 8314 $\frac{m^3 . p_a}{Kmol . K}$

= 0.082 $\frac{m^3 . atm}{Kmol . K}$

$\frac{P_1 . V_1}{T_1} = \frac{P_2 . V_2}{T_2}$

2- ***Ideal Gas Mixture*** (***Dalton's law***)

$P_t = P_1 + P_2 + P_3 + \ldots\ldots = \sum P_i$

P_t = Total Pressure

P_i = Partial Pressure of component (i)

$P_i = P_t . y_i$

y_i = Mole fraction of component (i)

3- ***Ideal Liquid*** (***Rault's law***)

$P_i = P_i^\circ . x_i$

P_i = Partial Pressure of component (i)

P_i° = Vapor Pressure of component (i)

x_i = Mole fraction of component (i) in liquid phase

4- **Non** − ***Ideal Mixture*** (***Henry's law***)

$P_i = H . x_i$

H = Henry's Constant

5- ***Equilbirium Constant***

$y_i = K_i . x_i$

6- ***Relative Volatility*** α_{AB}

$$\alpha_{AB} = \frac{K_A}{K_B} = \frac{y_A/x_A}{y_B/x_B} = \frac{P_A^\circ}{P_B^\circ}$$

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Concentration, Velocity and Flux

1- ***Concentratoin expressed as:***

ρ_i = *Mass concentration of i* $\left(\frac{Kg}{m^3}\right)$

ρ_t = *Total mass concentration* $\left(\frac{Kg}{m^3}\right) = \sum \rho_i . y_i$

$\omega_i = \left(\frac{\rho_i}{\rho_t}\right)$ *Mass fraction* ; $\sum \omega_i = 1$

C_i = *Molar concentration of i* $\left(\frac{Kmol}{m^3}\right)$

C_t = *Total molar concentration* $\left(\frac{Kmol}{m^3}\right) = \sum C_i . X_i$

$X_i = \left(\frac{C_i}{C_t}\right)$ *Mole fraction* ; $\sum X_i = 1$

Note

- Gas mole fraction is expressed $y_i = \left(\frac{P_i}{P_t}\right)$
- Liquid mole fraction is expressed $X_i = \left(\frac{C_i}{C_t}\right)$

2- ***Average velocity expressed as***:

Mass average velocity $u = \left(\frac{1}{\rho_t}\right) . \sum \rho_i . u_i$

Molar average velocity $U = \left(\frac{1}{C_t}\right) . \sum C_i . u_i$

3- ***Flux is expresed as***

Flux is a measure of the quantity of material (mass, moles, or volume) moves through a given area per unit time.

Mathematically Flux = $\frac{Amount\ of\ substance\ transferred}{Area\ .\ Time}$

- *Mass flux expressed in* $\left(\frac{Kg}{m^2 . Sec}\right)$
- *Molar flux expressed in* $\left(\frac{Kmol}{m^2 . Sec}\right)$

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Example (1)

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

Calculate: Mass avg. , Molar avg., and Volume avg. velocities of the mixture?

Given that: Mwt for N_2 =28, NH_3 = 17, Ar = 40 $(\frac{Kg}{Kmol})$

Solution

- Mass avg. velocity $u = \left(\frac{1}{\rho_t}\right).\sum \rho_i . u_i$; $\rho_i = \frac{P_i . Mwt_i}{R . T}$; $\rho_t = \frac{P_t . Mwt_t}{R . T}$

$$u = \frac{R.T}{P_t . Mwt_t}\left(\frac{P_1 . Mwt_1}{R.T}.u_1 + \frac{P_2 . Mwt_2}{R.T}.u_2 + \frac{P_3 . Mwt_3}{R.T}.u_3 + \frac{P_4 . Mwt_4}{R.T}.u_4\right) \quad ; \quad y_i = \left(\frac{P_i}{P_t}\right)$$

$$u = \frac{1}{Mwt_t}(y_1.Mwt_1.u_1 + y_2.Mwt_2.u_2 + y_3.\ Mwt_3.u_3 + y_4.\ Mwt_4.u_4) \quad ; \quad Mwt_t = \sum y_i . Mwt_i$$

$$Mwt_t = y_1 . Mwt_1 + y_2 . Mwt_2 + y_3 . Mwt_3 + y_4 . Mwt_4$$

$$= 0.05 \times 28 + 0.15 \times 2 + 0.76 \times 17 + 0.04 \times 40 \quad \rightarrow \quad Mwt_t = 16.22 \frac{Kg}{Kmol}$$

$$u = \frac{1}{16.22}(0.05 \times 28 \times 0.03 + 0.15 \times 2 \times 0.035 + 0.76 \times 17 \times 0.03 + 0.04 \times 4 \times 0.02) \quad \rightarrow \quad u = 0.029\ m/sec.$$

Example (1)

Solution

- Molar avg. velocity $U = \left(\frac{1}{C_t}\right).\sum C_i . u_i$

$$= \frac{1}{C_t}(C_1 . u_1 + C_2 . u_2 + C_3 . u_3 + C_4 . u_4)$$

For gases $y_i = x_i = \left(\frac{C_i}{C_t}\right)$

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

U = 0.0303 m/sec

- Volume avg. velocity

For gases (Volume avg. velocity = Molar avg. velocity)

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Prove that

$$U_t = x_a . u_a + x_b . u_b$$