CHEMICAL ENGINEERING

Mass Transfer

Comprehensive Theory
with Solved Examples *and* Practice Questions

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Mass Transfer

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Introduction and Basic Concepts

CHAPTER

1

LEARNING OBJECTIVES

The reading of this chapter will enable the students:

- To understand the classification of mass transfer.
- To understand the mechanism of mass transfer.
- To understand the concentrations, diffusion velocities and fluxes.

1.1 Introduction

- The mass transfer is the net movement of a component in a mixture from one location to the another location in presence of a difference in concentration or partial pressure. So, when there is a driving force then mass transfer will occur. The driving force over here is the concentration or partial pressure difference. Let us consider one common example of mass transfer. Suppose, if you have taken a lump of sugar added to a cup of tea which dissolves and then diffuses throughout the tea cup uniformly.
- So, another examples are the deliberate use of agarbati, the fragrance generally spreads uniformly when we put agarbati at home.
- The other examples is drying of clothes under the sun. Here, the drying occurs because the moisture diffuses into the air. So, the diffusion or the mass transfer is basically occurs with a particular driving force. Like, if we want to consider a movement of solid through the conveyer belts or movement of liquid through a pipe is not the mass transfer operations because it is not based on the concentration or partial pressure driving force.

Examples on Industrial Processes

- Separation of CO_2 from flue gas : Absorption Process
- Separation of a mixture of Ethanol and Water into its components : Distillation Process
- Separation of mixtures of Toluene and Water using Benzene as solvent : Extraction Process
- Drying of wet solid such as wood with the help of air : Drying Process

1.2 Classification of Mass Transfer

1.2.1 Distillation

Distillation is a vapour-liquid operation in which the mixture components are separated by use of thermal energy. When liquid mixture is heated, different components exert different vapour pressure, expressed in terms of relative volatility. This pressure difference results in separation of components in such a way that the top product contains higher amount of light component and bottom products contains higher amounts of heavier components, as shown in figure. A distillation example is separation of crude petroleum into gasoline, kersosene, etc.

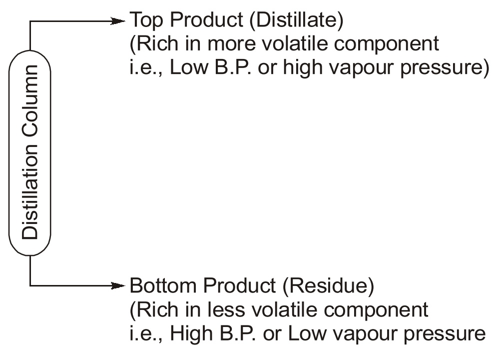


Fig. *Schematic diagram of a distillation column*

1.2.2 Absorption and Stripping

Gas absorption is a gas-liquid operation in which one or more constituents of a gas mixture are separated by using a suitable liquid solvent, i.e., component moves from gas phase to liquid phase as shown in figure. Example of gas absorption methods is ammonia washing from ammonia-air mixture by means of water. Stripping is opposite of absorption, i.e., a component moves from liquid phase to gas phase.

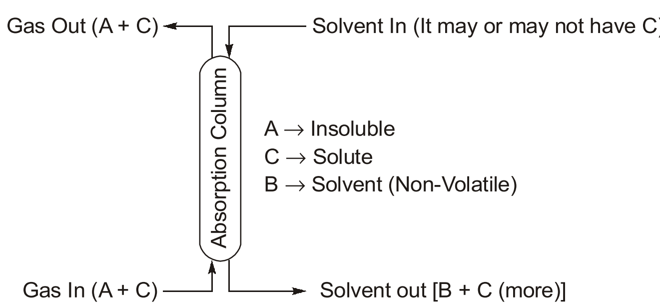


Fig. *Schematic diagram of an absorption column*

1.2.3 Liquid-Liquid Extraction

It is a liquid-liquid operation, also called as solvent extraction, in which components of a liquid mixture are separated by treating it with suitable solvent which dissolves one or more constituents of mixture more preferably. It is an efficient separation process in cases where separation is either not possible or not economical by using distillation. For example, separation of components of an azeotropic mixture.

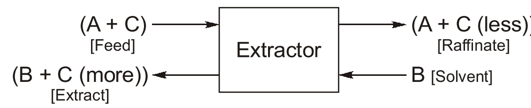


Fig. *Schematic diagram of a Liquid-Liquid Extractor*

1.2.4 Crystallization

It is liquid-solid operation in which we obtain uniform crystals of good purity. The saturated liquid is subjected to changes in temperature and pressure in such a way that crystals get separated from the feed liquor as shown in the figure.

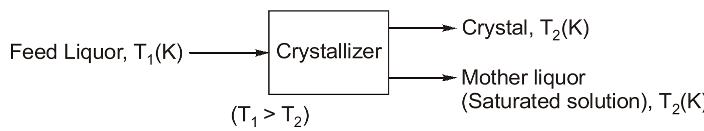


Fig. *Schematic diagram of a crystallizer*

1.2.5 Drying

Drying is gas-solid operation in which a relatively small amount of water is removed from solid material, by contacting it with a continuous stream of gas (air) as shown in figure.

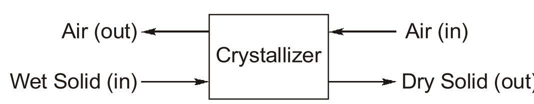
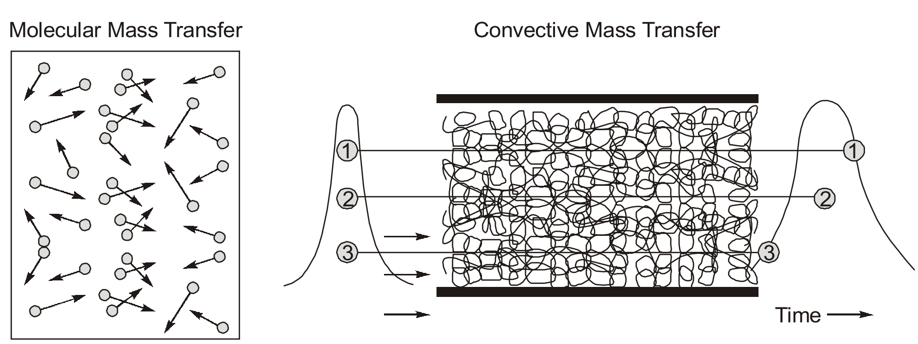


Fig. *Schematic diagram of a dryer*

1.3 Mechanism of Mass Transfer



In this case, eddy diffusion by random macroscopic fluid motion is the responsible for the convective mass transfer.

1.4 Driving Force for Mass Transfer

1.4.1 Two-Phase System

- Spontaneous alteration through molecular diffusion occurs.
- Ultimately brings the entire system to a state of equilibrium whereupon alteration stops.

- For example, NH_3 concentration will be uniform in the liquid phase at a particular concentration. It will be constant at a different concentration in the gas phase.

1.4.2 Multiphase System

- Diffusional processes in each phase separately.
- Within one phase it is usually described in terms of concentration changes.

1.5 Concentrations, Diffusion Velocities and Fluxes

1.5.1 Concentrations

- Mass Concentrations :
  - Mass concentration of component *i*

$$\rho_i = \frac{m_i}{V}$$

  - Sum of mass fraction

$$\sum_{i=1}^{n} W_i = \sum_{i=1}^{n} \frac{\rho_i}{\rho} = 1$$

  - Total mass concentration

$$\rho = \sum_{i=1}^{n} \rho_i$$

  - Mass fraction

$$w_i = \frac{\rho_i}{\sum_{i}^{n} \rho_i} = \frac{\rho_i}{\rho}$$

- Molar Concentrations :
  - Molar concentration of component *i*

$$C_i = \frac{p_i}{RT}$$

  - Total molar concentration

$$c = \sum_{i=1}^{n} C_i$$

  - Total molar concentration for ideal gas mixtures

$$c = \frac{1}{RT}\sum_{i=1}^{n} p_i = \frac{p_t}{RT}$$

  - Mole fraction of component *i* (liquid or solid)

$$x_i = \frac{C_i}{C}$$

– Mole fraction of component i (ideal gas mixture)

$$y_i = \frac{p_i}{p_t}$$

– Mole fraction of component i (gases)

$$y_i = \frac{C_i}{C}$$

– Sum of mole fractions

$$\sum_i x_i = 1; \sum_i y_i = 1$$

1.5.2 Diffusion Velocities

- Mass Average Velocity :
  – Defined in terms of mass concentrations :

$$V_{\text{mass–avg}} = \frac{\sum_{i=1}^{n} \rho_i v_i}{\sum_{i=1}^{n} \rho_i} = \sum_{i=1}^{n} \left(\frac{\rho_i}{\rho}\right) v_i = \sum_{i=1}^{n} \omega_i v_i$$

where, v_i = absolute velocity of species i with respect to a fixed reference frame

ω_i = mass fraction of species i

- Molar Average Velocity :
  – Defined in terms of molar concentrations :

$$V_{\text{mol–avg}} = \frac{\sum_{i=1}^{n} C_i \times v_i}{\sum_{i=1}^{n} C_i} = \sum_{i=1}^{n} \left(\frac{C_i}{C}\right) v_i = \sum_{i=1}^{n} x_i v_i$$

where, x_i = mole fraction of species i

Example 1.1 A gas mixture containing (H_2 = 15%, CO = 30%, CO_2 = 5% and N_2 = 50%) flows through a tube of 1 inch diameter, at 15 bar total pressure. If the velocities of the respective components are 0.05 m/s, 0.03 m/s, 0.02 m/s and 0.03 m/s. Calculate the mass average and molar average velocities of the mixture.

Solution :

Rename H_2 = 1, CO = 2, CO_2 = 3 and N_2 = 4.

The volume average velocity (= molar average velocity) given by

$$V_{\text{mol–avg}} = \frac{1}{C}(C_1 v_1 + C_2 v_2 + C_3 v_3 + C_4 v_4)$$

$$= y_1 v_1 + y_2 v_2 + y_3 v_3 + y_4 v_4$$

Here, y_1 is the mole fraction of component i in the gas mixture.

Putting the values, we get $V_{mol-avg} = (0.15)(0.05) + (0.3)(0.03) + (0.05)(0.02) + (0.5)(0.03)$

$= 0.0325$ m/s

Now, $M_{avg} = y_1M_1 + y_2M_2 + y_3M_3 + y_4M_4$

$= (0.15)(2) + (0.3)(28) + (0.05)(44) + (0.5)(28) = 24.9$

$$V_{mass-avg} = \frac{1}{M}\sum_{i=1}^{n=4} y_i M_i v_i$$

$$= \frac{1}{M_{avg}}(y_1M_1v_1 + y_2M_2v_2 + y_3M_3v_3 + y_4M_4v_4)$$

$$V_{mass\text{-}avg} = \frac{(0.15)(2)(0.05) + (0.3)(28)(0.03) + (0.05)(44)(0.02) + (0.05)(28)(0.03)}{24.9}$$

$$V_{mass\text{-}avg} = 0.014 \text{ m/s}$$

1.5.3 Fluxes

- Rate of transport of species *i* through unit area normal to the transport.
- Flux of a given species is a vector quantity.
- Flux may be calculated w.r.t. coordinates fixed in space and coordinates moving with the mass or molar average velocity.
- Mass Flux :
  - Calculated w.r.t. coordinates fixed in space or relative to stationary observer.
    - Mass Flux : $N_{i-mass} = \rho_i v_i$
    - Total Mass Flux : $N_{mass} = \rho V_{mass-avg}$
  - Calculated w.r.t. mass average velocity or relative to an observer moving with the mass average velocity.
    - Mass Flux : $\rho_{i-mass} = \rho_i(v_i - V_{mass-avg})$
- Molar Flux :
  - Calculated w.r.t. coordinates fixed in space or relative to stationary observer.
    - Molar Flux : $N_{i-mol} = C_i v_i$
    - Total Molar Flux : $N_{mol} = CV_{mol-avg}$
- Calculated w.r.t. mass average velocity or relative to an observer moving with the mass average velocity.
    - Molar Flux : $J_{i-mol} = C_i(v_i - V_{mol-avg})$

1.5.4 Relation between Fluxes

$$J_{i-mass} = \rho_i(v_i - V_{mass-avg})$$

$$N_{i-mass} = \rho_i v_i$$

$$J_{i-mass} = \rho_i \times \frac{N_{i-mass}}{\rho_i} - \rho_i V_{mass-avg}$$

$$N_{i-mass} = J_{i-mass} + \rho_i V_{mass-avg}$$

$$= J_{i-mass} + \frac{\rho_i}{\rho} N_{mass}$$

Similarly,

$$N_{i\text{–mol}} = J_{i\text{–mol}} + C_i V_{\text{mol–avg}}$$
$$= J_{i\text{–mol}} + \frac{C_i}{C} N_{\text{mol}}$$

1.6 Dimensionless Numbers used in Mass Transfer

1. Sherwood Number (Sh)

$$\text{Sh} = \frac{k'L}{D_{AB}} = \frac{\text{Convective mass transport}}{\text{Molecular mass transport}},$$
$$k' = \text{Mass transfer coefficient}$$

where, L is the characteristics length.

2. Schmidt Number (Sc)

$$\text{Sc} = \frac{\nu}{D_{AB}} = \left(\frac{\mu}{\rho}\right)\left(\frac{1}{D_{AB}}\right) = \frac{\text{Momentum diffusivity}}{\text{Mass diffusivity}}$$

4. Lewis Number (Le)

$$\text{Le} = \frac{\text{Sc}}{\text{Pr}} = \frac{\alpha}{D_{AB}} = \left(\frac{K}{\rho C_P}\right)\left(\frac{1}{D_{AB}}\right) = \frac{\text{Thermal diffusivity}}{\text{Mass diffusivity}}$$

5. Reynolds Number (Re)

$$\text{Le} = \frac{\rho v D}{\mu} = \frac{\text{Inertial force}}{\text{Viscous force}}$$

6. Stanton Number (St)

$$\text{St} = \frac{k'}{\upsilon} = \frac{\text{Sh}}{\text{Re} \times \text{Sc}}$$

7. Peclet Number (Pe)

$$\text{Pe} = \text{Re} \times \text{Sc}$$

Student's Assignments

Q.1 Driving force for mass transfer in a binary system is
(a) Temperature difference
(b) Chemical potential
(c) Concentration difference
(d) Pressure difference

Q.2 Which of the following is/are a mechanism for mass transfer?
(a) Difference in pressure
(b) Difference in solubility
(c) Difference in volatility
(d) Difference in viscosity

Q.3 Which of the following is/are example of solid-liquid mass transfer operation?
(a) Crystalization (b) Adsorbtion
(c) Leaching (d) Drying

Q.4 Which of the following option(s) is/are example of gas-liquid operation?
(a) Absorbtion (b) Distillation
(c) Drying (d) Humidification

Q.5 Molecular mass transfer takes place either fluid is
(a) stagnant or in laminar flow
(b) in turbulent flow
(c) forced to flow in bulk with eddies
(d) None of these

Q.6 Molecular mass transfer (molecular diffusion) can be increased by
(a) Increasing temperature
(b) Decreasing temperature
(c) Increasing pressure
(d Decreasing pressure

ANSWERS

1. (b) **2.** (b, c) **3.** (a, b, c) **4.** (a, b, d)
5. (a) **6.** (a, d)

■■■■