

CHEMICAL ENGINEERING

Mass Transfer



Comprehensive Theory
with Solved Examples and Practice Questions





MADE EASY Publications Pvt. Ltd.

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016 | **Ph. :** 9021300500

Email : infomep@madeeasy.in | **Web :** www.madeeasypublications.org

Mass Transfer

© Copyright by MADE EASY Publications Pvt. Ltd.

All rights are reserved. No part of this publication may be reproduced, stored in or introduced into a retrieval system, or transmitted in any form or by any means (electronic, mechanical, photo-copying, recording or otherwise), without the prior written permission of the above mentioned publisher of this book.



MADE EASY Publications Pvt. Ltd. has taken due care in collecting the data and providing the solutions, before publishing this book. In spite of this, if any inaccuracy or printing error occurs then **MADE EASY Publications Pvt. Ltd.** owes no responsibility. We will be grateful if you could point out any such error. Your suggestions will be appreciated.

EDITIONS

First Edition : 2021
Second Edition : 2022
Third Edition : 2023
Fourth Edition : 2024
Fifth Edition : 2025
Sixth Edition : 2026

CONTENTS

Mass Transfer

CHAPTER 1

Introduction and Basic Concepts	1-8
1.1 Introduction	1
1.2 Classification of Mass Transfer	2
1.3 Mechanism of Mass Transfer	3
1.4 Driving Force for Mass Transfer	3
1.5 Concentrations, Diffusion Velocities and Fluxes.....	4
1.6 Dimensionless Numbers used in Mass Transfer	7
<i>Student's Assignments</i>	8

CHAPTER 2

Diffusion	9-45
2.1 Introduction	9
2.2 Molecular Diffusion.....	9
2.3 Fick's Law of Diffusion (Steady State) for a Binary System (A and B)	10
2.4 Diffusivity.....	10
2.5 Steady State Molecular Diffusion in Fluids under Stagnant and Laminar Flow Conditions.....	11
2.6 Multicomponent Diffusivity	19
2.7 Molecular Diffusion in Liquids	20
2.8 Molecular Diffusion in Solids.....	20
2.9 Prediction of Diffusivities.....	21
2.10 Mass Transfer Coefficients	22
2.11 Convective Mass Transfer	27
2.12 Boundary Layer Theory	28
2.13 Analogies between Heat, Mass and Momentum.....	31
2.14 Mass Transfer Theories.....	34
2.15 Turbulent Diffusion.....	37
2.16 Interphase Mass Transfer	38
<i>Student's Assignments</i>	42

CHAPTER 3

Absorption and Stripping	46-67
3.1 Introduction	46
3.2 Equilibrium Solubility in a Gas-Liquid System	46
3.3 Selection of Solvent for Absorption and Stripping	46
3.4 Design of Packed and Tray Tower for Absorption	47
3.5 Gas Absorption Equipment	53
3.6 Comparison between Packed Tower and Tray Tower	57
3.7 Absorption with Chemical Reaction.....	57
<i>Student's Assignments</i>	64

CHAPTER 4

Distillation	68-112
4.1 Introduction	68
4.2 Boiling Point Diagram/Phase Diagram	70
4.3 Relative Volatility	71
4.4 Fractional Distillation	72
4.5 McCabe-Thiele Method.....	72
4.6 Reflux Ratio.....	86
4.7 Fenske Equation.....	89
4.8 Use of Open Steam/Live Steam.....	89
4.9 Flash/Equilibrium Distillation.....	89
4.10 Differential/Batch Distillation.....	90
4.11 Steam Distillation	91
4.12 Vacuum Distillation.....	92
4.13 Calculation of Diameter of Distillation Column.....	93
4.14 Effect of Pressure on Dia of Column	93
4.15 Plate Efficiency	94
4.16 Relation between Murphree and Point Efficiency.....	95
4.17 Multicomponent Distillation	96
4.18 Azeotropes.....	98
4.19 Azeotropic and Extractive Distillation.....	101
<i>Student's Assignments</i>	108

CHAPTER 5**Liquid-Liquid Extraction, Leaching and Adsorption 113-131**

5.1	Introduction.....	113
5.2	Types of System.....	114
5.3	Equilibrium Diagram in Liquid-Liquid Extraction.....	114
5.4	Effect of Temperature on Liquid-Liquid Equilibria.....	116
5.5	Batch/Single Stage Extraction Unit.....	117
5.6	Counter Current Extraction.....	117
5.7	Multistage Cross-Current Extraction.....	119
5.8	Selection of Solvent.....	119
5.9	Leaching.....	120
5.10	Adsorption.....	121
5.11	Applications of Adsorption Process.....	121
5.12	Classification of Adsorption.....	122
5.13	Types of Adsorbents and Their Characteristics.....	122
5.14	Adsorption Equilibria.....	123
5.15	Batch Adsorption.....	123
	<i>Student's Assignments</i>	129

CHAPTER 6**Humidification 132-144**

6.1	Introduction.....	132
6.2	Vapour-Gas Mixture.....	132
6.3	Important Terminology to Measure Humidity.....	133
6.4	Humid Volume.....	134
6.5	Humit Heat.....	134
6.6	Enthalpy.....	134
6.7	Dry Bulb Temperature.....	135

6.8	Wet Bulb Temperature.....	135
6.9	Dew Point Temperature.....	137
6.10	Adiabatic Saturation Temperature.....	137
	<i>Student's Assignments</i>	142

CHAPTER 7**Drying..... 145-161**

7.1	Introduction.....	145
7.2	Movement of Moisture within Solid.....	146
7.3	Drying Operations.....	146
7.4	Important Definitions.....	146
7.5	Rate of Drying Curve.....	147
7.6	Drying Rate in Constant Rate Period with Help of Heat Transfer Coefficient.....	152
7.7	Humid Volume.....	152
	<i>Student's Assignments</i>	157

CHAPTER 8**Membrane Separation 162-175**

8.1	Introduction.....	162
8.2	Types of Membrane.....	163
8.3	Some Basic Definition in Membrane Separation Process.....	164
8.4	Microfiltration Membrane Processes.....	164
8.5	Reverse-Osmosis Membrane Process.....	165
8.6	Ultrafiltration Membrane Processes.....	169
8.7	Nanofiltration.....	170
	<i>Student's Assignments</i>	174

Introduction and Basic Concepts

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 agarbatti, the fragrance generally spreads uniformly when we put agarbatti 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, kerosene, etc.

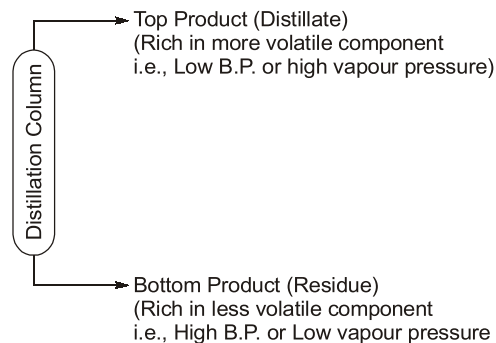


Fig. Schematic diagram of a distillation column

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.

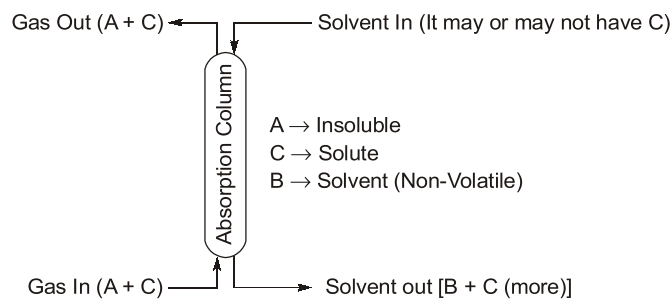


Fig. Schematic diagram of an absorption column

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.

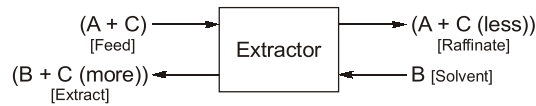


Fig. Schematic diagram of a Liquid-Liquid Extractor

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.

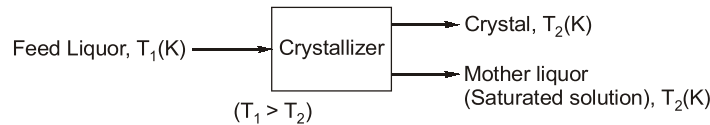


Fig. Schematic diagram of a crystallizer

1.2.5 Drying

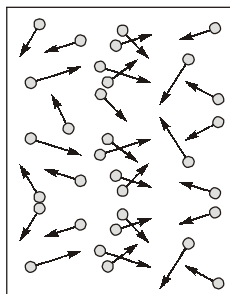
Drying is gas-solid operation in which a relatively small amount of water is removed from solid material, by contacting it with a continuous stream of gas (air) as shown in figure.



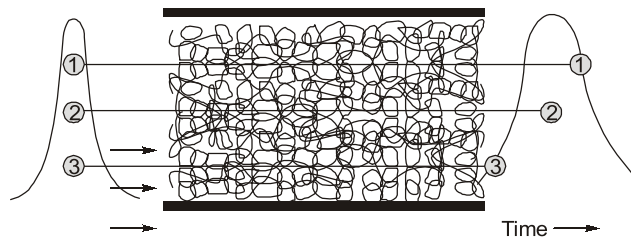
Fig. Schematic diagram of a dryer

1.3 MECHANISM OF MASS TRANSFER

Molecular Mass Transfer



Convective 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

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

- Molar Concentrations :

- Molar concentration of component i

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

- Total molar concentration

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

- Total molar concentration for ideal gas mixtures

$$c = \frac{1}{RT} \sum_{i=1}^n \rho_i = \frac{\rho_t}{RT}$$

- 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 ($\text{H}_2 = 15\%$, $\text{CO} = 30\%$, $\text{CO}_2 = 5\%$ and $\text{N}_2 = 50\%$) 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 $\text{H}_2 = 1$, $\text{CO} = 2$, $\text{CO}_2 = 3$ and $\text{N}_2 = 4$.

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

$$\begin{aligned} V_{\text{mol-avg}} &= \frac{1}{C} (C_1 v_1 + C_2 v_2 + C_3 v_3 + C_4 v_4) \\ &= y_1 v_1 + y_2 v_2 + y_3 v_3 + y_4 v_4 \end{aligned}$$

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

Putting the values, we get $V_{\text{mol-avg}} = (0.15)(0.05) + (0.3)(0.03) + (0.05)(0.02) + (0.5)(0.03)$
 $= 0.0325 \text{ m/s}$

Now, $M_{\text{avg}} = y_1 M_1 + y_2 M_2 + y_3 M_3 + y_4 M_4$
 $= (0.15)(2) + (0.3)(28) + (0.05)(44) + (0.5)(28) = 24.9$

$$V_{\text{mass-avg}} = \frac{1}{M} \sum_{i=1}^{n=4} y_i M_i v_i = \frac{1}{M_{\text{avg}}} (y_1 M_1 v_1 + y_2 M_2 v_2 + y_3 M_3 v_3 + y_4 M_4 v_4)$$

$$V_{\text{mass-avg}} = \frac{(0.15)(2)(0.05) + (0.3)(28)(0.03) + (0.05)(44)(0.02) + (0.5)(28)(0.03)}{24.9}$$

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

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.

$$\text{Mass Flux : } N_{i\text{-mass}} = \rho_i v_i$$

$$\text{Total Mass Flux : } N_{\text{mass}} = \rho V_{\text{mass-avg}}$$

- Calculated w.r.t. mass average velocity or relative to an observer moving with the mass average velocity.

- Mass Flux : $\rho_{i\text{-mass}} = \rho_i (v_i - V_{\text{mass-avg}})$

- Molar Flux :

- Calculated w.r.t. coordinates fixed in space or relative to stationary observer.

$$\text{Molar Flux : } N_{i\text{-mol}} = C_i v_i$$

$$\text{Total Molar Flux : } N_{\text{mol}} = C V_{\text{mol-avg}}$$

- Calculated w.r.t. mass average velocity or relative to an observer moving with the mass average velocity.

- Molar Flux : $J_{i\text{-mol}} = C_i (v_i - V_{\text{mol-avg}})$

1.5.4 Relation between Fluxes

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

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

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

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

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

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)

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

k' = Mass transfer coefficient

where, L is the characteristics length.

2. Schmidt Number (Sc)

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

4. Lewis Number (Le)

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

5. Reynold's Number (Re)

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

6. Stanton Number (St)

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

7. Peclet Number (Pe)

$$Pe = Re \times Sc$$

**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) Crystallization (b) Adsorption
 - (c) Leaching (d) Drying
- Q.4** Which of the following option(s) is/are example of gas-liquid operation?
- (a) Absorption (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)

