

# Contents

Preface

*xi*

<b>1. Introduction</b>	<b>1-12</b>
1.1 Chemistry versus Chemical Engineering	1
1.2 Chemical Process Industry	2
1.3 Greatest Achievements in Chemical Engineering	4
1.4 History of Chemical Engineering	5
1.5 Chemical Engineering in India	6
1.6 Unit Operations and Unit Processes	7
1.6.1 Fluid Flow Operations	8
1.6.2 Heat Transfer Operations	8
1.6.3 Evaporation	9
1.6.4 Mass Transfer Operations	9
1.6.5 Mechanical Separations	11
1.6.6 Size Reduction	11
1.6.7 Mixing	11
1.7 Stoichiometry and Process Calculations	12
<b>2. Units and Dimensions</b>	<b>13-39</b>
2.1 Units and Dimensions	13
2.2 System of Units	14
2.2.1 SI Units	15
2.2.2 Derived Units	15
2.2.3 SI Prefixes	17
2.2.4 General Guidelines on the Use of SI Units	18

2.3	Conversion of Units	20
2.3.1	Some Important Derived Quantities and Their Conversion	20
2.3.2	Conversion of Empirical Equations	27
2.4	Dimensionless Equations	31
2.5	Dimensional Analysis	31
2.5.1	Dimensionless Groups in Chemical Engineering Practice	33
	<i>Exercises</i>	36

### 3. Fundamental Concepts of Stoichiometry 40-75

3.1	The Mole Concept	40
3.2	Chemical Calculations and Use of Molal Quantities	42
3.2.1	Molar Volume of Gaseous Substances	44
3.2.2	Equivalent Weight	45
3.3	Density and Specific Gravity	46
3.4	Specific Gravity Scales	47
3.5	Composition of Solids, Liquids and Gases	50
3.5.1	Mass Fraction (Weight Fraction)	50
3.5.2	Mass Percent (Weight Percent)	50
3.5.3	Mass Ratio	51
3.5.4	Dry Basis and Wet Basis	51
3.5.5	Mole Fraction and Mole Percent	53
3.5.6	Volume Fraction and Volume Percent	54
3.6	Other Expressions for Concentrations	56
3.7	Chemical Reactions and Process Calculations	59
3.7.1	Excess and Limiting Reactant	59
3.7.2	Conversion	61
3.7.3	Yield	62
3.7.4	Extent of Reaction	63
	<i>Exercises</i>	66

### 4. Ideal Gases and Gas Mixtures 76-104

4.1	Ideal Gas	76
4.1.1	Ideal Gas Equation	77
4.1.2	Calculations for Ideal Gas	79
4.2	Mixtures of Ideal Gases	81
4.2.1	Dalton's Law	82
4.2.2	Amagat's Law of Additive Volumes	83
4.2.3	Average Molecular Weight	84
4.2.4	Density and Specific Gravity	84
4.2.5	Calculations Involving Change in the Mass	87
4.3	Reactions Involving Gases	91
	<i>Exercises</i>	96

<b>5. Properties of Real Gases</b>	<b>105–129</b>
5.1 Real Gases	105
5.2 Critical Properties	106
5.3 Equations of State	107
5.3.1 The van der Waals Equation	108
5.3.2 Other Equations of State	110
5.4 Compressibility Charts	113
5.4.1 Compressibility Factor	113
5.4.2 Principle of Corresponding States	114
5.4.3 Generalized Compressibility Charts	114
5.4.4 Methods Based on the Generalized Compressibility Charts	115
5.5 Mixture of Real Gases	121
5.5.1 Equations of State	121
5.5.2 Mean Compressibility Factor	121
5.5.3 Pseudo-critical Properties	122
<i>Exercises</i>	125
<b>6. Vapour Pressure</b>	<b>130–148</b>
6.1 Vapour Pressure and Boiling Point	130
6.1.1 Vapour Pressure	130
6.1.2 Boiling Point	131
6.2 Phase Behaviour of Pure Substances	131
6.3 Vapour Pressure and Temperature	133
6.3.1 The Clapeyron Equation	133
6.3.2 The Clausius–Clapeyron Equation	134
6.3.3 The Antoine Equation	135
6.4 Vapour Pressure Plots	137
6.4.1 Equal-Temperature Reference-Substance Plots	138
6.4.2 Equal-Pressure Reference-Substance Plots	142
<i>Exercises</i>	145
<b>7. Solutions and Phase Behaviour</b>	<b>149–204</b>
7.1 Ideal Solutions and Raoult's Law	149
7.1.1 Ideal Solutions	149
7.1.2 Raoult's Law	150
7.1.3 Raoult's Law and Vapour–Liquid Equilibrium Calculation	150
7.1.4 $P$ - $x$ - $y$ Diagram	151
7.1.5 Boiling-point Diagram ( $T$ - $x$ - $y$ Diagram)	152
7.1.6 Equilibrium Diagram ( $y$ - $x$ Diagram)	153
7.1.7 Flash Vaporization	153

7.2	Non-ideal Solutions	161
7.2.1	Deviation from Ideal Behaviour	161
7.2.2	Henry's Law	162
7.2.3	Henry's Law and Gas Solubility	163
7.3	Vapour-Liquid Equilibrium Calculations	163
7.3.1	Vaporization Equilibrium Constants	163
7.3.2	Bubble-point Temperature and Pressure	164
7.3.3	Dew-point Temperature and Pressure	164
7.3.4	Flash Vaporization Calculations	165
7.3.5	Computer Program for Solution of VLE Problems	166
7.4	Vapour Pressure of Immiscible Systems	183
7.5	Vapour Pressure of Solutions of Non-volatile Solutes	187
7.5.1	Relative Vapour Pressure	188
	<i>Exercises</i>	189

## 8. Humidity and Humidity Chart 205–247

8.1	Saturation	205
8.2	Humidity, Percent Humidity and Dew Point	207
8.2.1	Humidity	207
8.2.2	Relative Humidity and Percent Humidity	210
8.2.3	Dew Point	214
8.3	Humidity Chart	217
8.4	Humid Heat	221
8.5	Wet-bulb Temperature	222
8.6	Adiabatic Saturation Temperature	225
8.7	Humid Volume and Enthalpy	230
8.7.1	Humid Volume	230
8.7.2	Enthalpy of Humid Air	230
	<i>Exercises</i>	233

## 9. Material Balance in Unit Operations 248–323

9.1	Basic Material Balance Principles	248
9.1.1	Total and Component Balances	249
9.1.2	Steady-state and Unsteady-state Processes	250
9.1.3	Batch and Continuous Processes	251
9.1.4	Tie Element	251
9.1.5	Basis for Calculation	252
9.1.6	Independent Material Balance Equations and Degrees of Freedom	254
9.1.7	Steps for Solving Material Balance Problems	257
9.2	Material Balance without Chemical Reactions	259
9.2.1	Evaporation	259
9.2.2	Crystallization	263
9.2.3	Leaching	269

9.2.4	Adsorption	273
9.2.5	Drying	273
9.2.6	Liquid-Liquid Extraction	277
9.2.7	Absorption	279
9.2.8	Distillation	284
9.3	Bypass, Recycle and Purging	289
9.3.1	Bypass	289
9.3.2	Recycle	291
9.3.3	Blowdown and Purge	295
<i>Exercises</i>		297

## 10. Material Balance with Chemical Reaction 324-400

10.1	Combustion of Solid, Liquid and Gaseous Fuels	325
10.1.1	Orsat Analysis	325
10.1.2	Proximate and Ultimate Analysis of Coal	328
10.2	Oxidation of Sulphur Compounds and Related Processes	341
10.3	Carbon Dioxide from Limestone	349
10.4	Reactions Involving Phosphorus and Phosphorus Compounds	352
10.5	Recovery of Metals and Non-metals from Ores	355
10.6	Nitrogen, Ammonia and Nitric Acid	356
10.7	Chlorine, Hydrochloric Acid and Chlorination	360
10.8	Hydrogenation, Hydration and Oxidation	364
10.9	Recycle and Purge Involving Chemical Reactions	365
10.9.1	Recycle Operation	365
10.9.2	Purging Operation	369
<i>Exercises</i>		373

## 11. Energy Balance: Thermophysics 401-472

11.1	Law of Conservation of Energy	402
11.2	Components of Energy Balance Equations	403
11.2.1	Heat and Work	403
11.2.2	Kinetic Energy, Potential Energy and Flow Energy	404
11.2.3	Internal Energy	407
11.2.4	Enthalpy	407
11.3	Heat Capacities	410
11.3.1	Mean Heat Capacity	415
11.3.2	Heat Capacity of Mixtures of Gases	416
11.4	Prediction of Heat Capacities of Solids and Liquids	418
11.4.1	Heat Capacity of Solids	418
11.4.2	Heat Capacities of Liquids	419
11.5	Enthalpy Change of Phase Changes	421
11.5.1	Estimation of Heat of Fusion	423
11.5.2	Estimation of Heat of Vaporization	424

11.6	Steam Tables	429	
11.7	Heat of Mixing	431	
	11.7.1	Enthalpy–Composition Diagrams	436
11.8	Energy Balance in Cyclic Processes	438	
11.9	Energy Balance in Non-flow Processes	438	
	11.9.1	First Law of Thermodynamics for Non-flow Process	438
	11.9.2	Energy Changes in Ideal Gas Processes	441
11.10	Energy Balance for Flow Processes	445	
	11.10.1	Mechanical Energy Balance	447
	11.10.2	Bernoulli's Equation	447
	<i>Exercises</i>	455	

**12. Energy Balance: Thermochemistry** **473–507**

12.1	Heat Effects Accompanying Chemical Reactions	473	
	12.1.1	The Standard Heat of Reaction	473
	12.1.2	The Standard Heat of Combustion	475
	12.1.3	The Standard Heat of Formation	476
	12.1.4	Hess's Law of Constant Heat Summation	477
	12.1.5	Heat of Reaction at Constant Pressure and Constant Volume	483
12.2	Effect of Temperature on Standard Heat of Reaction	485	
	12.2.1	Temperature of Reaction	493
	<i>Exercises</i>	496	

***Appendix: Tables of Properties*** **509–521**

***Objective Type Questions*** **523–553**

*Answers to Objective Type Questions* 553

***Bibliography*** **555–557**

***Answers to Exercises*** **559–586**

***Index*** **587–592**