530.47501512 THE

Contents

Preface xv

Part One Introduction

1. History of Chemical Engineering and Mass Transfer Operations 3

References 5

2. Transport Phenomena vs Unit Operations Approach 7

References 10

3. Basic Calculations 11

Introduction 11
Units and Dimensions 11
Conversion of Units 15
The Gravitational Constant g_c 17
Significant Figures and Scientific Notation 17
References 18

4. Process Variables 19

Introduction 19
Temperature 20
Pressure 22
Moles and Molecular Weight 23
Mass, Volume, and Density 25
Viscosity 25
Reynolds Number 28
pH 29
Vapor Pressure 31
Ideal Gas Law 31
References 35

5. Equilibrium vs Rate Considerations 37

Introduction 37
Equilibrium 37
Rate 38
Chemical Reactions 39
References 40

6. Phase Equilibrium Principles 41

Introduction 41
Gibb's Phase Rule 44
Raoult's Law 45
Henry's Law 53
Raoult's Law vs Henry's Law 59
Vapor–Liquid Equilibrium in Nonideal Solutions 61
Vapor–Solid Equilibrium 64
Liquid–Solid Equilibrium 68
References 69

7. Rate Principles 71

Introduction 71
The Operating Line 72
Fick's Law 73

Diffusion in Gases 75
Diffusion in Liquids 79

Mass Transfer Coefficients 80

Individual Mass Transfer Coefficients 81
Equimolar Counterdiffusion 83
Diffusion of Component *A* Through Non-diffusing Component *B* 84

Overall Mass Transfer Coefficients 87

Equimolar Counterdiffusion and/or Diffusion in Dilute Solutions 88
Gas Phase Resistance Controlling 89
Liquid Phase Resistance Controlling 89
Experimental Mass Transfer Coefficients 90

References 93

Part Two Applications: Component and Phase Separation Processes

8. Introduction to Mass Transfer Operations 97

Introduction 97

Classification of Mass Transfer Operations 97

Contact of Immiscible Phases 98
Miscible Phases Separated by a Membrane 101
Direct Contact of Miscible Phases 102

Mass Transfer Equipment 102

Distillation 103
Absorption 104
Adsorption 104
Extraction 104
Humidification and Drying 105
Other Mass Transfer Unit Operations 105
The Selection Decision 106

Characteristics of Mass Transfer Operations 107

Unsteady-State vs Steady-State Operation 108
Flow Pattern 109
Stagewise vs Continuous Operation 116

References 117

9. Distillation **119**

Introduction 119
Flash Distillation 120
Batch Distillation 127
Continuous Distillation with Reflux 133

Equipment and Operation 133
Equilibrium Considerations 140
Binary Distillation Design: McCabe–Thiele Graphical Method 142
Multicomponent Distillation: Fenske–Underwood–Gilliland (FUG) Method 161
Packed Column Distillation 184

References 185

10. Absorption and Stripping **187**

Introduction 187
Description of Equipment 189

Packed Columns 189
Plate Columns 196

Design and Performance Equations—Packed Columns 200

Liquid Rate 200
Column Diameter 207
Column Height 210
Pressure Drop 224

Design and Performance Equations—Plate Columns 227
Stripping 235
Packed vs Plate Tower Comparison 241
Summary of Key Equations 242
References 243

11. Adsorption **245**

Introduction 245
Adsorption Classification 247

Activated Carbon 248
Activated Alumina 248
Silica Gel 249
Molecular Sieves 249

Adsorption Equilibria 250

Freundlich Equation 253
Langmuir Isotherms 253

Description of Equipment 257
Design and Performance Equations 264
Regeneration 283
References 291

12. Liquid–Liquid and Solid–Liquid Extraction **293**

Introduction 293
Liquid–Liquid Extraction 294

The Extraction Process 294
Equipment 295
Solvent Selection 298
Equilibrium 300
Graphical Procedures 301
Analytical Procedures 304

Solid–Liquid Extraction (Leaching) 312

Process Variables 313
Equipment and Operation 315
Design and Predictive Equations 317

References 325

13. Humidification and Drying **327**

Introduction 327
Psychrometry and the Psychrometric Chart 327
Humidification 339

Equipment 341
Describing Equations 343

Drying 347

Rotary Dryers 352
Spray Dryers 361

References 369

14. Crystallization **371**

Introduction 371
Phase Diagrams 373
The Crystallization Process 379
Crystal Physical Characteristics 382
Equipment 391
Describing Equations 393
Design Considerations 397
References 404

15. Membrane Separation Processes **407**

Introduction 407
Reverse Osmosis 408

Describing Equations 414

Ultrafiltration 420

Describing Equations 421

Microfiltration 427

Describing Equations 428

Gas Permeation 432

Describing Equations 433

References 437

16. Phase Separation Equipment **439**

Introduction 439
Fluid–Particle Dynamics 442
Gas–Solid (G–S) Equipment 446

Gravity Settlers 447
Cyclones 449
Electrostatic Precipitators 454
Venturi Scrubbers 457
Baghouses 461

Gas–Liquid (G–L) Equipment 465
Liquid–Solid (L–S) Equipment 467

Sedimentation 467
Centrifugation 471
Flotation 472

Liquid–Liquid (L–L) Equipment 475
Solid–Solid (S–S) Equipment 477

High-Gradient Magnetic Separation 477
Solidification 477

References 479

Part Three Other Topics

17. Other and Novel Separation Processes **483**

Freeze Crystallization 484
Ion Exchange 484
Liquid Ion Exchange 484
Resin Adsorption 485
Evaporation 485
Foam Fractionation 486
Dissociation Extraction 486
Electrophoresis 486
Vibrating Screens 487
References 488

18. Economics and Finance **489**

Introduction 489
The Need for Economic Analyses 489
Definitions 491

Simple Interest 491
Compound Interest 491
Present Worth 492
Evaluation of Sums of Money 492
Depreciation 493
Fabricated Equipment Cost Index 493
Capital Recovery Factor 493
Present Net Worth 494
Perpetual Life 494
Break-Even Point 495
Approximate Rate of Return 495

Exact Rate of Return 495
Bonds 496
Incremental Cost 496
Principles of Accounting 496
Applications 499
References 511

19. Numerical Methods **513**

Introduction 513
Applications 514
References 531

20. Open-Ended Problems **533**

Introduction 533
Developing Students' Power of Critical Thinking 534
Creativity 534
Brainstorming 536
Inquiring Minds 536
Failure, Uncertainty, Success: Are They Related? 537
Angels on a Pin 538
Applications 539
References 547

21. Ethics **549**

Introduction 549
Teaching Ethics 550
Case Study Approach 551
Integrity 553
Moral Issues 554
Guardianship 556
Engineering and Environmental Ethics 557
Future Trends 559
Applications 561
References 563

22. Environmental Management and Safety Issues **565**

Introduction 565
Environmental Issues of Concern 566
Health Risk Assessment 568
Risk Evaluation Process for Health 570

Hazard Risk Assessment 571

Risk Evaluation Process for Accidents 572

Applications 574
References 591

Appendix

Appendix A. Units **595**

A.1 The Metric System 595
A.2 The SI System 597
A.3 Seven Base Units 597
A.4 Two Supplementary Units 598
A.5 SI Multiples and Prefixes 599
A.6 Conversion Constants (SI) 599
A.7 Selected Common Abbreviations 603

Appendix B. Miscellaneous Tables **605**

Appendix C. Steam Tables **615**

Index **623**