

Contents

Chapter 1

Separation Processes 1

- 1.1 Industrial Chemical Processes 1
- 1.2 Mechanism of Separation 5
- 1.3 Separation by Phase Addition or Creation 7
- 1.4 Separation by Barrier 14
- 1.5 Separation by Solid Agent 16
- 1.6 Separation by External Field or Gradient 18
- 1.7 Component Recoveries and Product Purities 19
- 1.8 Separation Power 22
- 1.9 Selection of Feasible Separation Processes 23
- Summary 27 References 28 Exercises 28

Chapter 2

Thermodynamics of Separation Operations 31

- 2.1 Energy, Entropy, and Availability Balances 31
- 2.2 Phase Equilibria 36
 - Fugacities and Activity Coefficients 37
 - K -Values 38
- 2.3 Ideal Gas, Ideal Liquid Solution Model 42
- 2.4 Graphical Correlations of Thermodynamic Properties 47
- 2.5 Nonideal Thermodynamic Property Models 51
 - P - v - T Equation-of-State Models 54
 - Derived Thermodynamic Properties from P - v - T Models 58
- 2.6 Activity Coefficient Models for the Liquid Phase 63
 - Activity Coefficients from Gibbs Free Energy 63
 - Regular Solution Model 64
 - Chao-Seader Correlation 66
 - Nonideal Liquid Solutions 68
 - Margules Equations 72
 - van Laar Equation 72
 - Local Composition Concept and Wilson Equation 74
 - NRTL Equation 78
 - UNIQUAC Equation 79
 - UNIFAC Equation 80
 - Liquid-Liquid Equilibria 82
- Summary 83 References 83 Exercises 84

Chapter 3

Mass Transfer and Diffusion 90

- 3.1 Steady-State Ordinary Molecular Diffusion 91
 - Fick's Law of Diffusion 92
 - Velocities in Mass Transfer 92
 - Equimolar Counterdiffusion 93
 - Unimolecular Diffusion 95
- 3.2 Diffusion Coefficients 99
 - Diffusivity in Gas Mixtures 99
 - Diffusivity in Liquid Mixtures 101
 - Diffusivity in Solids 109
- 3.3 One-Dimensional Steady-State and Unsteady-State Molecular Diffusion 117
 - Steady State 117
 - Unsteady State 118
- 3.4 Molecular Diffusion in Laminar Flow 126
 - Falling Liquid Film 127
 - Boundary-Layer Flow on a Flat Plate 133
 - Fully Developed Flow in a Straight, Circular Tube 136
- 3.5 Mass Transfer in Turbulent Flow 140
 - Reynolds Analogy 141
 - Chilton–Colburn Analogy 142
 - Prandtl Analogy 143
- 3.6 Models for Mass Transfer at a Fluid–Fluid Interface 144
 - Film Theory 145
 - Penetration Theory 146
 - Surface Renewal Theory 147
 - Film–Penetration Theory 149
- 3.7 Two-Film Theory and Overall Mass Transfer Coefficients 150
 - Gas–Liquid Case 150
 - Liquid–Liquid Case 153
 - Case of Large Driving Forces for Mass Transfer 154
- Summary 157 References 158 Exercises 159

Chapter 4

Single Equilibrium Stages and Flash Calculations 163

- 4.1 The Gibbs Phase Rule and Degrees of Freedom 163
 - Degrees-of-Freedom Analysis 164
- 4.2 Binary Vapor–Liquid Systems 166
- 4.3 Azeotropic Systems 173
- 4.4 Multicomponent Flash, Bubble-Point, and Dew-Point Calculations 176
 - Isothermal Flash 178
 - Bubble and Dew Points 181
 - Adiabatic Flash 184
- 4.5 Ternary Liquid–Liquid Systems 186
- 4.6 Multicomponent Liquid–Liquid Systems 195

4.7	Solid-Liquid Systems	198
	Leaching	198
	Crystallization	201
	Liquid Adsorption	204
4.8	Gas-Liquid Systems	207
4.9	Gas-Solid Systems	211
	Sublimation and Desublimation	211
	Gas Adsorption	212
4.10	Multiphase Systems	213
	Approximate Method for a Vapor-Liquid-Solid System	214
	Approximate Method for a Vapor-Liquid-Liquid System	215
	Rigorous Method for a Vapor-Liquid-Liquid System	218
Summary	220	References 221 Exercises 222

Chapter 5

Cascades 232

5.1	Cascade Configurations	232
5.2	Solid-Liquid Cascades	234
5.3	Single-Section Liquid-Liquid Extraction Cascades	237
	Cocurrent Cascade	238
	Crosscurrent Cascade	239
	Countercurrent Cascade	239
5.4	Multicomponent Vapor-Liquid Cascades	241
	Single-Section Cascades by Group Methods	242
	Two-Section Cascades	246
5.5	Degrees of Freedom and Specifications for Countercurrent Cascades	253
	Stream Variables	254
	Adiabatic or Nonadiabatic Equilibrium Stage	254
	Single-Section Countercurrent Cascade	255
	Two-Section Countercurrent Cascades	257
Summary	263	References 264 Exercises 264

Chapter 6

Absorption and Stripping of Dilute Mixtures 270

6.1	Equipment	273
6.2	General Design Considerations	281
6.3	Graphical Equilibrium-Stage Method for Trayed Towers	282
	Minimum Absorbent Flow Rate	284
	Number of Equilibrium Stages	285
6.4	Algebraic Method for Determining the Number of Equilibrium Stages	289
6.5	Stage Efficiency	292
	Performance Data	293
	Empirical Correlations	294
	Semitheoretical Models	299
	Scale-up from Laboratory Data	303

6.6	Tray Capacity, Pressure Drop, and Mass Transfer	305
	Tray Diameter	306
	Tray Vapor Pressure Drop	310
	Mass Transfer Coefficients and Transfer Units	312
	Weeping, Entrainment, and Downcomer Backup	315
6.7	Rate-Based Method for Packed Columns	317
6.8	Packed Column Efficiency, Capacity, and Pressure Drop	325
	Liquid Holdup	325
	Capacity and Pressure Drop	330
	Mass Transfer Efficiency	335
6.9	Concentrated Solutions in Packed Columns	342
	Summary	346
	References	347
	Exercises	348

Chapter 7

Distillation of Binary Mixtures 355

7.1	Equipment and Design Considerations	358
7.2	McCabe–Thiele Graphical Equilibrium-Stage Method for Trayed Towers	359
	Rectifying Section	362
	Stripping Section	365
	Feed-Stage Considerations	366
	Determination of Number of Equilibrium Stages and Feed-Stage Location	369
	Limiting Conditions	369
	Column Operating Pressure and Condenser Type	374
	Subcooled Reflux	376
	Reboiler Type	380
	Condenser and Reboiler Duties	381
	Feed Preheat	382
	Optimal Reflux Ratio	382
	Large Number of Stages	384
	Use of Murphree Efficiency	386
	Multiple Feeds, Side Streams, and Open Steam	387
7.3	Estimation of Stage Efficiency	391
	Performance Data	391
	Empirical Correlations	392
	Semitheoretical Models	395
	Scale-up from Laboratory Data	396
7.4	Capacity of Trayed Towers and Reflux Drums	397
	Reflux Drums	397
7.5	Rate-Based Method for Packed Columns	398
	HETP Method	399
	HTU Method	400
7.6	Ponchon–Savarit Graphical Equilibrium-Stage Method for Trayed Towers	404
	Summary	406
	References	407
	Exercises	408

Chapter 8**Liquid–Liquid Extraction with Ternary Systems 419**

- 8.1 Equipment 423
 - Mixer-Settlers 424
 - Spray Columns 426
 - Packed Columns 426
 - Plate Columns 426
 - Columns with Mechanically Assisted Agitation 427
- 8.2 General Design Considerations 432
- 8.3 Hunter and Nash Graphical Equilibrium-Stage Method 438
 - Number of Equilibrium Stages 440
 - Minimum and Maximum Solvent-to-Feed Flow-Rate Ratios 444
 - Use of Right-Triangle Diagrams 448
 - Use of an Auxiliary Distribution Curve 451
 - Extract and Raffinate Reflux 453
- 8.4 Maloney and Schubert Graphical Equilibrium-Stage Method 459
- 8.5 Theory and Scale-up of Extractor Performance 465
 - Mixer-Settler Units 465
 - Multicompartment Columns 475
 - Axial Dispersion 480
- Summary 484 References 485 Exercises 486

Chapter 9**Approximate Methods for Multicomponent, Multistage Separations 492**

- 9.1 Fenske–Underwood–Gilliland Method 492
 - Selection of Two Key Components 493
 - Column Operating Pressure 495
 - Fenske Equation for Minimum Equilibrium Stages 497
 - Distribution of Nonkey Components at Total Reflux 500
 - Underwood Equations for Minimum Reflux 501
 - Gilliland Correlation for Actual Reflux Ratio and Theoretical Stages 508
 - Feed-Stage Location 511
 - Distribution of Nonkey Components at Actual Reflux 512
- 9.2 Kremser Group Method 514
 - Strippers 514
 - Liquid–Liquid Extraction 518
- Summary 521 References 521 Exercises 522

Chapter 10**Equilibrium-Based Methods for Multicomponent Absorption, Stripping, Distillation, and Extraction 526**

- 10.1 Theoretical Model for an Equilibrium Stage 526
- 10.2 General Strategy of Mathematical Solution 530
- 10.3 Equation-Tearing Procedures 531
 - Tridiagonal Matrix Algorithm 531

Bubble-Point Method for Distillation	534
Sum-Rates Method for Absorption and Stripping	544
Isothermal Sum-Rates Method for Liquid-Liquid Extraction	551
10.4 Simultaneous Correction Procedures	555
10.5 Inside-Out Method	569
MESH Equations	571
Rigorous and Complex Thermodynamic Property Models	571
Approximate Thermodynamic Property Models	572
Inside-Out Algorithm	573
Summary	577
References	578
Exercises	579

Chapter 11

Enhanced Distillation and Supercritical Extraction 586

11.1 Use of Triangular Graphs	587
Residue-Curve Maps	591
Distillation-Curve Maps	599
Product-Composition Regions at Total Reflux	602
11.2 Extractive Distillation	604
11.3 Salt Distillation	611
11.4 Pressure-Swing Distillation	612
11.5 Homogeneous Azeotropic Distillation	616
11.6 Heterogeneous Azeotropic Distillation	621
Multiplicity	627
11.7 Reactive Distillation	631
11.8 Supercritical-Fluid Extraction	641
Summary	650
References	651
Exercises	653

Chapter 12

Rate-Based Models for Distillation 655

12.1 Rate-Based Model	658
12.2 Thermodynamic Properties and Transport-Rate Expressions	662
12.3 Methods for Estimating Transport Coefficients and Interfacial Area	667
12.4 Vapor and Liquid Flow Patterns	668
12.5 Method of Calculation	668
ChemSep Program	668
RATEFRAC Program	674
Summary	677
References	677
Exercises	677

Chapter 13

Batch Distillation 681

13.1 Differential Distillation	681
13.2 Binary Batch Rectification with Constant Reflux and Variable Distillate Composition	685
13.3 Binary Batch Rectification with Constant Distillate Composition and Variable Reflux	688
13.4 Batch Stripping and Complex Batch Distillation	689
13.5 Effect of Liquid Holdup	691

13.6	Shortcut Method for Multicomponent Batch Rectification with Constant Reflux	691
13.7	Stage-by-Stage Methods for Multicomponent Batch Rectification	695
	Rigorous Model	695
	Rigorous Integration Method	698
	Rapid Solution Method	705
Summary	708	References 708 Exercises 709

Chapter 14

Membrane Separations 713

14.1	Membrane Materials	718
14.2	Membrane Modules	722
14.3	Transport in Membranes	725
	Porous Membranes	725
	Bulk Flow	726
	Liquid Diffusion	728
	Gas Diffusion	729
	Nonporous Membranes	731
	Solution-Diffusion for Liquid Mixtures	731
	Solution-Diffusion for Gas Mixtures	733
	Module Flow Patterns	738
	Cascades	741
	Concentration Polarization	745
14.4	Dialysis and Electrodialysis	747
	Electrodialysis	750
14.5	Reverse Osmosis	755
14.6	Gas Permeation	761
14.7	Pervaporation	765
Summary	771	References 773 Exercises 773

Chapter 15

Adsorption, Ion Exchange, and Chromatography 778

15.1	Sorbents	781
	Adsorbents	782
	Ion Exchangers	789
	Sorbents for Chromatography	792
15.2	Equilibrium Considerations	794
	Pure Gas Adsorption	794
	Liquid Adsorption	802
	Ion Exchange Equilibria	806
	Equilibria in Chromatography	810
15.3	Kinetic and Transport Considerations	811
	External Transport	812
	Internal Transport	816
	Mass Transfer in Ion Exchange and Chromatography	818

15.4 Sorption Systems	820
Adsorption	820
Ion Exchange	824
Chromatography	825
Slurry Adsorption (Contact Filtration)	827
Fixed-Bed Adsorption (Percolation)	831
Thermal-Swing Adsorption	843
Pressure-Swing Adsorption	848
Continuous Countercurrent Adsorption Systems	856
Ion-Exchange Cycle	861
Chromatographic Separations	863
Summary	870
References	872
Exercises	873
Index	881