

Contents

About the Authors	v
Preface to the Second Edition	vii
Nomenclature	xxi
Dimensions and Units	xxxi

PART 1 FUNDAMENTAL CONCEPTS 1

Chapter 1

Separation Processes 3

1.0	Instructional Objectives	3
1.1	Industrial Chemical Processes	4
1.2	Mechanism of Separation	6
1.3	Separation by Phase Addition or Creation	8
1.4	Separation by Barrier	14
1.5	Separation by Solid Agent	15
1.6	Separation by External Field or Gradient	16
1.7	Component Recoveries and Product Purities	17
1.8	Separation Power	19
1.9	Selection of Feasible Separation Processes	21
Summary	23	References 24 Exercises 24

Chapter 2

Thermodynamics of Separation Operations 27

2.0	Instructional Objectives	27
2.1	Energy, Entropy, and Availability Balances	27
2.2	Phase Equilibria	30
	Fugacities and Activity Coefficients	31
	K-Values	32
2.3	Ideal-Gas, Ideal-Liquid-Solution Model	34
2.4	Graphical Correlations of Thermodynamic Properties	37
2.5	Nonideal Thermodynamic Property Models	42
	P - v - T Equation-of-State Models	42
	Derived Thermodynamic Properties from P - v - T Models	44
2.6	Activity-Coefficient Models for the Liquid Phase	47
	Activity Coefficients from Gibbs Free Energy	48
	Regular-Solution Model	48
	Nonideal Liquid Solutions	49
	Margules Equations	52
	van Laar Equation	52
	Local-Composition Concept and the Wilson Model	53

	NRTL Model	55
	UNIQUAC Model	56
	UNIFAC Model	57
	Liquid–Liquid Equilibria	58
2.7	Difficult Mixtures	58
	Predictive Soave–Redlich–Kwong (PSRK) Model	59
	Electrolyte Solution Models	59
	Polymer Solution Models	59
2.8	Selecting an Appropriate Model	59
Summary	60	References 60 Exercises 61

Chapter 3

	Mass Transfer and Diffusion	66
3.0	Instructional Objectives	67
3.1	Steady-State, Ordinary Molecular Diffusion	67
	Fick's Law of Diffusion	68
	Velocities in Mass Transfer	68
	Equimolar Counterdiffusion	69
	Unimolecular Diffusion	70
3.2	Diffusion Coefficients	72
	Diffusivity in Gas Mixtures	72
	Diffusivity in Liquid Mixtures	74
	Diffusivities of Electrolytes	77
	Diffusivity of Biological Solutes in Liquids	78
	Diffusivity in Solids	78
3.3	One-Dimensional, Steady-State and Unsteady-State, Molecular Diffusion Through Stationary Media	84
	Steady State	84
	Unsteady State	85
3.4	Molecular Diffusion in Laminar Flow	90
	Falling Liquid Film	90
	Boundary-Layer Flow on a Flat Plate	93
	Fully Developed Flow in a Straight, Circular Tube	95
3.5	Mass Transfer in Turbulent Flow	97
	Reynolds Analogy	99
	Chilton–Colburn Analogy	99
	Other Analogies	100
	Theoretical Analogy of Churchill and Zajic	100
3.6	Models for Mass Transfer at a Fluid–Fluid Interface	103
	Film Theory	103
	Penetration Theory	104
	Surface-Renewal Theory	105
	Film-Penetration Theory	106
3.7	Two-Film Theory and Overall Mass-Transfer Coefficients	107
	Gas–Liquid Case	107
	Liquid–Liquid Case	109
	Case of Large Driving Forces for Mass Transfer	109
Summary	111	References 112 Exercises 113

Chapter 4**Single Equilibrium Stages and Flash Calculations 117**

- 4.0 Instructional Objectives 117
- 4.1 The Gibbs Phase Rule and Degrees of Freedom 117
 - Degrees-of-Freedom Analysis 118
- 4.2 Binary Vapor–Liquid Systems 119
- 4.3 Azeotropic Systems 123
- 4.4 Multicomponent Flash, Bubble-Point, and Dew-Point Calculations 126
 - Isothermal Flash 126
 - Bubble and Dew Points 128
 - Adiabatic Flash 130
- 4.5 Ternary Liquid–Liquid Systems 131
- 4.6 Multicomponent Liquid–Liquid Systems 137
- 4.7 Solid–Liquid Systems 138
 - Leaching 138
 - Crystallization 141
 - Liquid Adsorption 142
- 4.8 Gas–Liquid Systems 144
- 4.9 Gas–Solid Systems 146
 - Sublimation and Desublimation 146
 - Gas Adsorption 146
- 4.10 Multiphase Systems 147
 - Approximate Method for a Vapor–Liquid–Solid System 148
 - Approximate Method for a Vapor–Liquid–Liquid System 149
 - Rigorous Method for a Vapor–Liquid–Liquid System 150
- Summary 151 References 152 Exercises 152

Chapter 5**Cascades and Hybrid Systems 161**

- 5.0 Instructional Objectives 161
- 5.1 Cascade Configurations 161
- 5.2 Solid–Liquid Cascades 163
- 5.3 Single-Section, Liquid–Liquid Extraction Cascades 165
 - Cocurrent Cascade 165
 - Crosscurrent Cascade 165
 - Countercurrent Cascade 166
- 5.4 Multicomponent Vapor–Liquid Cascades 167
 - Single-Section Cascades by Group Methods 167
 - Two-Section Cascades 171
- 5.5 Membrane Cascades 175
- 5.6 Hybrid Systems 176
- 5.7 Degrees of Freedom and Specifications for Countercurrent Cascades 177
 - Stream Variables 178
 - Adiabatic or Nonadiabatic Equilibrium Stage 178
 - Single-Section, Countercurrent Cascade 179
 - Two-Section, Countercurrent Cascades 179
- Summary 184 References 185 Exercises 185

PART 2 SEPARATIONS BY PHASE ADDITION OR CREATION 191

Chapter 6

Absorption and Stripping of Dilute Mixtures 193

- 6.0 Instructional Objectives 193
 - Industrial Example 194
- 6.1 Equipment 196
- 6.2 General Design Considerations 200
- 6.3 Graphical Equilibrium-Stage Method for Trayed Towers 201
 - Minimum Absorbent Flow Rate 202
 - Number of Equilibrium Stages 203
- 6.4 Algebraic Method for Determining the Number of Equilibrium Stages 205
- 6.5 Stage Efficiency 207
 - Performance Data 208
 - Empirical Correlations 208
 - Semitheoretical Models 212
 - Scale-up from Laboratory Data 214
- 6.6 Tray Diameter, Pressure Drop, and Mass Transfer 215
 - Tray Diameter 215
 - High-Capacity Trays 218
 - Tray Vapor Pressure Drop 219
 - Mass-Transfer Coefficients and Transfer Units 220
 - Weeping, Entrainment, and Downcomer Backup 222
- 6.7 Rate-Based Method for Packed Columns 223
- 6.8 Packed-Column Efficiency, Capacity, and Pressure Drop 228
 - Liquid Holdup 228
 - Column Diameter and Pressure Drop 233
 - Mass-Transfer Efficiency 237
- 6.9 Concentrated Solutions in Packed Columns 242
- Summary 244 References 244 Exercises 246

Chapter 7

Distillation of Binary Mixtures 252

- 7.0 Instructional Objectives 252
 - Industrial Example 253
- 7.1 Equipment and Design Considerations 255
- 7.2 McCabe–Thiele Graphical Equilibrium-Stage Method for Trayed Towers 255
 - Rectifying Section 257
 - Stripping Section 259
 - Feed-Stage Considerations 259
 - Determination of Number of Equilibrium Stages and Feed-Stage Location 261
 - Limiting Conditions 261
 - Column Operating Pressure and Condenser Type 265
 - Subcooled Reflux 266
 - Reboiler Type 268
 - Condenser and Reboiler Duties 269
 - Feed Preheat 270

	Optimal Reflux Ratio	270
	Large Number of Stages	271
	Use of Murphree Efficiency	272
	Multiple Feeds, Side Streams, and Open Steam	273
7.3	Estimation of Stage Efficiency	275
	Performance Data	275
	Empirical Correlations	276
	Semi-Theoretical Models	278
	Scale-up from Laboratory Data	278
7.4	Diameter of Trayed Towers and Reflux Drums	279
	Reflux Drums	279
7.5	Rate-Based Method for Packed Columns	280
	HETP Method	280
	HTU Method	281
7.6	Ponchon–Savarit Graphical Equilibrium-Stage Method for Trayed Towers	283
	Summary	284
	References	285
	Exercises	285

Chapter 8

Liquid–Liquid Extraction with Ternary Systems 295

8.0	Instructional Objectives	295
	Industrial Example	296
8.1	Equipment	298
	Mixer-Settlers	299
	Spray Columns	299
	Packed Columns	300
	Plate Columns	300
	Columns with Mechanically Assisted Agitation	300
8.2	General Design Considerations	305
8.3	Hunter–Nash Graphical Equilibrium-Stage Method	309
	Number of Equilibrium Stages	310
	Minimum and Maximum Solvent-to-Feed Flow-Rate Ratios	313
	Use of Right-Triangle Diagrams	315
	Use of an Auxiliary Distribution Curve with a McCabe–Thiele Diagram	317
	Extract and Raffinate Reflux	318
8.4	Maloney–Schubert Graphical Equilibrium-Stage Method	322
8.5	Theory and Scale-Up of Extractor Performance	325
	Mixer-Settler Units	325
	Multicompartment Columns	332
	Axial Dispersion	334
	Summary	337
	References	338
	Exercises	339

Chapter 9

Approximate Methods for Multicomponent, Multistage Separations 344

9.0	Instructional Objectives	344
9.1	Fenske–Underwood–Gilliland Method	344
	Selection of Two Key Components	345
	Column Operating Pressure	347

	Fenske Equation for Minimum Equilibrium Stages	347
	Distribution of Nonkey Components at Total Reflux	349
	Underwood Equations for Minimum Reflux	349
	Gilliland Correlation for Actual Reflux Ratio and Theoretical Stages	353
	Feed-Stage Location	355
	Distribution of Nonkey Components at Actual Reflux	356
9.2	Kremser Group Method	356
	Strippers	357
	Liquid-Liquid Extraction	358
Summary	360	References 360 Exercises 360

Chapter 10

Equilibrium-Based Methods for Multicomponent Absorption, Stripping, Distillation, and Extraction 364

10.0	Instructional Objectives	364
10.1	Theoretical Model for an Equilibrium Stage	365
10.2	General Strategy of Mathematical Solution	366
10.3	Equation-Tearing Procedures	367
	Tridiagonal Matrix Algorithm	367
	Bubble-Point (BP) Method for Distillation	369
	Sum-Rates Method for Absorption and Stripping	374
	Isothermal Sum-Rates Method for Liquid-Liquid Extraction	378
10.4	Newton-Raphson Method	380
10.5	Inside-Out Method	388
	MESH Equations	389
	Rigorous and Complex Thermodynamic Property Models	390
	Approximate Thermodynamic Property Models	390
	Inside-Out Algorithm	391
Summary	393	References 394 Exercises 394

Chapter 11

Enhanced Distillation and Supercritical Extraction 401

11.0	Instructional Objectives	402
11.1	Use of Triangular Graphs	402
	Residue-Curve Maps	405
	Distillation-Curve Maps	410
	Product-Composition Regions at Total Reflux (Bow-Tie Regions)	411
11.2	Extractive Distillation	413
11.3	Salt Distillation	417
11.4	Pressure-Swing Distillation	419
11.5	Homogeneous Azeotropic Distillation	421
11.6	Heterogeneous Azeotropic Distillation	425
	Multiplicity of Solutions	429
11.7	Reactive Distillation	432
11.8	Supercritical-Fluid Extraction	439
Summary	445	References 445 Exercises 447

Chapter 12**Rate-Based Models for Distillation 449**

- 12.0 Instructional Objectives 451
- 12.1 Rate-Based Model 451
- 12.2 Thermodynamic Properties and Transport-Rate Expressions 454
- 12.3 Methods for Estimating Transport Coefficients and Interfacial Area 456
- 12.4 Vapor and Liquid Flow Patterns 457
- 12.5 Method of Calculation 457
 - ChemSep Program 457
 - RATEFRAC Program 461
- Summary 462 References 463 Exercises 463

Chapter 13**Batch Distillation 466**

- 13.0 Instructional Objectives 466
- 13.1 Differential Distillation 466
- 13.2 Binary Batch Rectification with Constant Reflux and Variable Distillate Composition 469
- 13.3 Binary Batch Rectification with Constant Distillate Composition and Variable Reflux 470
- 13.4 Batch Stripping and Complex Batch Distillation 471
- 13.5 Effect of Liquid Holdup 472
- 13.6 Shortcut Method for Multicomponent Batch Rectification with Constant Reflux 472
- 13.7 Stage-by-Stage Methods for Multicomponent, Batch Rectification 474
 - Rigorous Model 474
 - Rigorous Integration Method 476
 - Rapid-Solution Method 480
- 13.8 Optimal Control 482
 - Slop Cuts 482
 - Optimal Control by Variation of Reflux Ratio 484
- Summary 486 References 487 Exercises 487

PART 3 SEPARATIONS BY BARRIERS AND SOLID AGENTS 491**Chapter 14****Membrane Separations 493**

- 14.0 Instructional Objectives 493
 - Industrial Example 494
- 14.1 Membrane Materials 496
- 14.2 Membrane Modules 499
- 14.3 Transport in Membranes 502
 - Porous Membranes 502
 - Bulk Flow 503
 - Liquid Diffusion in Pores 504
 - Gas Diffusion 505
 - Nonporous Membranes 505
 - Solution-Diffusion for Liquid Mixtures 506

	Solution-Diffusion for Gas Mixtures	507
	Module Flow Patterns	510
	Cascades	512
	External Mass-Transfer Resistances	513
	Concentration Polarization and Fouling	515
14.4	Dialysis and Electrodialysis	516
	Electrodialysis	518
14.5	Reverse Osmosis	521
14.6	Gas Permeation	525
14.7	Pervaporation	527
14.8	Ultrafiltration	531
	Process Configurations	532
14.9	Microfiltration	540
	Constant-Flux Operation	541
	Constant-Pressure Operation	542
	Combined Operation	542
Summary	543	References 544 Exercises 545

Chapter 15

Adsorption, Ion Exchange, and Chromatography 548

15.0	Instructional Objectives	549
	Industrial Example	550
15.1	Sorbents	551
	Adsorbents	551
	Ion Exchangers	555
	Sorbents for Chromatography	557
15.2	Equilibrium Considerations	559
	Pure Gas Adsorption	559
	Liquid Adsorption	563
	Ion Exchange Equilibria	565
	Equilibria in Chromatography	568
15.3	Kinetic and Transport Considerations	568
	External Transport	568
	Internal Transport	571
	Mass Transfer in Ion Exchange and Chromatography	572
15.4	Sorption Systems	573
	Adsorption	573
	Ion Exchange	576
	Chromatography	577
	Slurry Adsorption (Contact Filtration)	577
	Fixed-Bed Adsorption (Percolation)	580
	Thermal-Swing Adsorption	587
	Pressure-Swing Adsorption	590
	Continuous, Countercurrent Adsorption Systems	596
	Simulated-Moving-Bed Systems	598
	Ion-Exchange Cycle	607
	Chromatographic Separations	608
Summary	612	References 613 Exercises 615

PART 4 SEPARATIONS THAT INVOLVE A SOLID PHASE 621**Chapter 16****Leaching and Washing 623**

- 16.0 Instructional Objectives 623
 - Industrial Example 623
- 16.1 Equipment for Leaching 624
 - Batch Extractors 625
 - Espresso Machine 626
 - Continuous Extractors 627
 - Continuous, Countercurrent Washing 629
- 16.2 Equilibrium-Stage Model for Leaching and Washing 631
 - McCabe–Smith Algebraic Method 633
 - Variable Underflow 635
- 16.3 Rate-Based Model for Leaching 637
 - Food Processing 637
 - Mineral Processing 639
- Summary 641 References 641 Exercises 642

Chapter 17**Crystallization, Desublimation, and Evaporation 644**

- 17.0 Instructional Objectives 644
 - Industrial Example 645
- 17.1 Crystal Geometry 648
 - Crystal-Size Distributions 648
 - Differential Screen Analysis 651
 - Cumulative Screen Analysis 651
 - Surface-Mean Diameter 652
 - Mass-Mean Diameter 652
 - Arithmetic-Mean Diameter 652
 - Volume-Mean Diameter 653
- 17.2 Thermodynamic Considerations 653
 - Solubility and Material Balances 653
 - Enthalpy Balances 656
- 17.3 Kinetic and Transport Considerations 658
 - Supersaturation 658
 - Nucleation 659
 - Crystal Growth 660
- 17.4 Equipment for Solution Crystallization 663
 - Circulating, Batch Crystallizers 664
 - Continuous, Cooling Crystallizers 665
 - Continuous, Vacuum, Evaporating Crystallizers 665
- 17.5 The MSMPR Crystallization Model 666
 - Crystal–Population Balance 667
- 17.6 Precipitation 671
- 17.7 Melt Crystallization 673
 - Equipment for Melt Crystallization 674
- 17.8 Zone Melting 677

17.9	Desublimation	679
	Desublimation in a Heat Exchanger	680
17.10	Evaporation	681
	Evaporator Model	683
	Multiple-Effect Evaporator Systems	685
	Overall Heat-Transfer Coefficients in Evaporators	688
Summary	688	References 689 Exercises 690

Chapter 18

Drying of Solids		695
18.0	Instructional Objectives	695
	Industrial Example	696
18.1	Drying Equipment	696
	Batch Operation	697
	Continuous Operation	699
18.2	Psychrometry	711
	Wet-Bulb Temperature	713
	Adiabatic-Saturation Temperature	715
	Moisture-Evaporation Temperature	716
18.3	Equilibrium-Moisture Content of Solids	719
18.4	Drying Periods	721
	Constant-Rate Drying Period	722
	Falling-Rate Drying Period	724
18.5	Dryer Models	734
	Material and Energy Balances for Direct-Heat Dryers	734
	Belt Dryer with Through-Circulation	735
	Direct-Heat Rotary Dryer	738
	Fluidized-Bed Dryer	739
Summary	742	References 742 Exercises 743
Index		748