

# Contents

---

<b>About the Authors</b>	<b>v</b>
<b>Preface to the Second Edition</b>	<b>vii</b>
<b>Nomenclature</b>	<b>xxi</b>
<b>Dimensions and Units</b>	<b>xxxi</b>

## PART 1 FUNDAMENTAL CONCEPTS 1

### Chapter 1

<b>Separation Processes</b>	<b>3</b>
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

<b>Thermodynamics of Separation Operations</b>	<b>27</b>
2.0	Instructional Objectives 27
2.1	Energy, Entropy, and Availability Balances 27
2.2	Phase Equilibria 30
	Fugacities and Activity Coefficients 31
	<i>K</i> -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
	<i>P</i> - <i>v</i> - <i>T</i> Equation-of-State Models 42
	Derived Thermodynamic Properties from <i>P</i> - <i>v</i> - <i>T</i> 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

	<b>Mass Transfer and Diffusion</b>	<b>66</b>
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

<b>Equilibrium-Based Methods for Multicomponent Absorption, Stripping, Distillation, and Extraction 364</b>	
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

<b>Enhanced Distillation and Supercritical Extraction 401</b>	
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

	<b>Adsorption, Ion Exchange, and Chromatography</b>	<b>548</b>
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**

<b>Leaching and Washing</b>	<b>623</b>
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**

<b>Crystallization, Desublimation, and Evaporation</b>	<b>644</b>
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