

Contents

About the authors — IX

Acknowledgments — XI

Preface — XIII

List of Symbols — XXI

Part I: What It Is and Why It Matters

1 Importance and Overall Description — 5

1.1 Functional Design — 6

1.2 General Characteristics — 8

References — 16

2 Scale of Operation — 18

2.1 Commodity Chemical Separations — 18

2.2 Fine Chemical Separations — 20

2.3 Mini- and Micro-Separations — 21

3 Part of a Valued Tradition — 23

3.1 Historical Perspective — 24

3.2 Pioneers — 37

3.3 The Engineering Method — 48

References — 50

4 Addressing Universal and Changing Needs — 52

References — 58

Bibliography — 60

Part II: Design Fundamentals

5 Thermodynamics: Characterizing Dynamic Equilibrium — 69

5.1 Ideal and Real Mixtures — 69

5.2 Dynamic Equilibrium and Gibbs Free Energy — 71

5.3 Chemical Potential and Mass Transfer — 73

5.4 Specific Molecular Interactions — 75

5.4.1 Non-ideal intermolecular interactions — 75

5.4.2	Classification of chemical mixtures —	79
5.4.3	Activity coefficients —	81
5.4.4	Henry's law —	85
5.4.5	Equations of state —	87
5.4.6	COSMOtherm —	87
5.5	Key Expressions of Phase Equilibria —	88
5.5.1	Vapor-liquid equilibria —	88
5.5.2	Liquid-liquid equilibria —	91
5.5.3	Solid-liquid equilibria —	92
5.5.4	Adsorption isotherms —	94
5.6	Phase Diagrams: Equilibrium Curves, Azeotropes, and Eutectics —	97
5.6.1	Equilibrium curves —	98
5.6.2	Homogeneous azeotropes —	102
5.6.3	Heterogeneous azeotropes —	104
5.6.4	Liquid-liquid phase behavior —	106
5.6.5	Solid-liquid eutectic behavior —	108
5.7	Solvent Selection Methods —	114
5.8	Energy Consumption and Energy Efficiency —	117
	References —	122

6 Mass Transport: Characterizing Mass Transfer Drivers and Resistances — 126

6.1	Driving Forces and Key Descriptors —	127
6.1.1	Separations driven by deviation from equilibrium —	127
6.1.2	Drivers for membrane-based separations —	127
6.1.3	Partition ratio, separation factor, and transfer factor —	130
6.1.4	Assessing rate limitations and thermodynamic consistency —	135
6.2	Fluid Flow and Mixing: Imagine the Best Flow Path Through the Equipment —	137
6.2.1	Ideal fluid flow —	139
6.2.2	Mixing design —	141
6.3	Interfacial Area —	142
6.4	Residence Time Effects —	145
6.5	The Material Balance: Keeping Track of All Components —	147
6.5.1	Material balance split and separation power —	149
6.5.2	The impact of trace impurities: beware or be sorry —	154
6.6	Theoretical Stage Models —	157
6.6.1	Theoretical stage relationships —	158
6.6.2	Stage efficiency —	162
6.7	Rate-Based Models —	168
6.7.1	Mass transfer units and mass transfer coefficients —	169
6.7.2	Phenomenological and other models —	176

- 6.7.3 Adsorption dynamics: breakthrough curves — 177
- 6.7.4 Crystallization rates: nucleation, growth, and the population balance — 182
- 6.7.5 Membrane permeance and separation factor — 189
- References — 193

Bibliography — 198

Part III: Engineering Practice

- 7 Distillation: Rectification, Stripping, and Absorption – The Workhorse Methods — 205**
 - 7.1 General Features and Utility — 208
 - 7.2 Process Types — 216
 - 7.3 Distillation Operations and Design Considerations — 219
 - 7.3.1 Single-stage distillation: Rayleigh distillation and continuous evaporation — 220
 - 7.3.2 Batch distillation with reflux — 223
 - 7.3.3 Continuous stripping and absorption — 226
 - 7.3.4 Continuous fractional distillation — 240
 - 7.3.5 Short-cut calculations — 259
 - 7.3.6 Computer calculations — 271
 - 7.3.7 Reactive absorption for gas scrubbing — 281
 - 7.4 Equipment Design and Rating Methods — 286
 - 7.4.1 Column design — 286
 - 7.4.2 Packings — 300
 - 7.4.3 Trays — 314
 - 7.5 Process Control Considerations — 321
 - 7.6 Energy Utilization — 327
 - References — 331
- 8 Enhanced Distillation: Taking Advantage of Specific Molecular Interactions — 338**
 - 8.1 Heterogeneous Azeotropic Distillation and Steam Distillation — 341
 - 8.2 Extractive Distillation — 347
 - 8.3 Pressure Change Distillation — 348
 - References — 351
- 9 Liquid-Liquid Extraction: Employing Molecular Interactions Alone — 354**
 - References — 357

10 Adsorption-Based Processes: Adding an Active Solid Surface — 358

- 10.1 Adsorbent Materials — 359
- 10.2 General Process Features — 363
- 10.3 Continuous Versus Batch Operation — 364
- 10.4 Fixed-Bed Design Methods — 366
- 10.4.1 General approach to design — 367
- 10.4.2 Adsorber dimensions, internals, and piping diagram — 370
- 10.5 Temperature Swing Adsorption — 376
- 10.6 Pressure Swing Adsorption — 381
- 10.7 True Countercurrent Moving-Bed Adsorption — 392
- 10.8 Simulated Moving-Bed Chromatography — 393
- References — 399

11 Crystallization from Solution and from the Melt: Taking Advantage of Eutectic Behavior — 403

- 11.1 General Characteristics and Approach to Design — 404
- 11.2 Types of Processes and Equipment — 407
- 11.3 Process Analytical Technology — 414
- 11.4 Batch Crystallization from Solution — 416
- 11.5 Continuous Crystallization from Solution — 422
- 11.6 Crystallization from the Melt: Eliminating the Addition of Solvent — 425
- References — 430

12 Membrane-Based Separations: Adding a Semipermeable Barrier Between Phases — 435

- 12.1 General Features — 436
- 12.2 Water Treatment — 439
- 12.3 Organic Solvent Nanofiltration — 440
- 12.4 Gas Separations — 441
- 12.5 Pervaporation — 443
- References — 444

13 Specialized Separations — 447

- 13.1 Bioseparations — 447
- 13.2 Bio-designed Separations — 449
- 13.3 Polarity Switching Separations — 450
- 13.4 Separations Employing a Supercritical Fluid — 451
- 13.5 Chiral Separations — 451
- 13.6 Environmental Protection — 453
- References — 455

14 Inventive Engineering: Process Simplification, Intensification, and Hybrid Processing — 458

References — **468**

Bibliography — 471

Index — 477

