

CONTENTS

PREFACE	xxi
ACKNOWLEDGMENTS	xxv
PART I REACTORS AND REACTIONS IN WATER QUALITY ENGINEERING	
1 Mass Balances	3
1.1 Introduction: The Mass Balance Concept, 3	
1.2 The Mass Balance for a System with Unidirectional Flow and Concentration Gradient, 7	
The Storage Term, 8	
The Advective Term, 10	
The Diffusion and Dispersion Terms, 11	
The Chemical Reaction Term, 15	
Combining the Terms into the Overall Mass Balance, 17	
The Differential Form of the One-Dimensional Mass Balance, 18	
1.3 The Mass Balance for a System with Flow and Concentration Gradients in Arbitrary Directions, 20	
The Advection Term, 20	
The Diffusion and Dispersion Terms, 21	
The Storage and Reaction Terms, 23	
The Overall Mass Balance, 23	
1.4 The Differential Form of the Three-Dimensional Mass Balance, 24	
1.5 Summary, 25	
References, 26	
Problems, 27	
2 Continuous Flow Reactors: Hydraulic Characteristics	29
2.1 Introduction, 29	
2.2 Residence Time Distributions, 30	
Tracers, 31	
Pulse Input Response, 33	

CONTENTS

- Step Input Response, 35
- Statistics of Probability Distributions and the Mean Hydraulic Detention Time, 37
- 2.3 Ideal Reactors, 42
 - Plug Flow Reactors, 42
 - Pulse Input to a PFR: Fixed Frame of Reference (Eulerian View), 43
 - Pulse Input to a PFR: Moving Frame of Reference (Lagrangian View), 44
 - Continuous Flow Stirred Tank Reactors, 45
 - Pulse Input to a CFSTR, 45
 - Step input to a CFSTR, 47
- 2.4 Nonideal Reactors, 48
 - Tracer Output from Nonideal Reactors, 48
 - Relating Tracer Input and Output Curves via the Convolution Integral, 48
 - Modeling Residence Time Distributions of Nonideal Reactors, 50
 - PFR with Dispersion, 50
 - CFSTRs in Series, 55
 - Modeling Short-Circuiting and Dead Space, 57
 - PFRs in Parallel and Series: Segregated Flow and Early Versus Late Mixing, 59
 - Nonequivalent CFSTRs in Series, 62
 - Simple Indices of Hydraulic Behavior, 62
- 2.5 Equalization, 62
 - Flow Equalization, 63
 - Concentration Equalization, 66
 - Concurrent Flow and Concentration Equalization, 69
- 2.6 Summary, 70
 - Appendix 2A. Introduction to Laplace Transforms as a Method of Solving (Certain) Differential Equations, 71
 - Examples of the Use of Laplace Transforms, 73
 - References, 73
 - Problems, 74

3 Reaction Kinetics

81

- 3.1 Introduction, 81
- 3.2 Fundamentals, 82
 - Terminology, 82
 - The Kinetics of Elementary Reactions, 84
 - Frequency of Molecular Collisions, 84
 - Energetics of Molecular Collisions, 84
 - The Kinetics of Nonelementary Reactions, 87
 - Power Law and Other Rate Expressions for Nonelementary Reactions, 88
- 3.3 Kinetics of Irreversible Reactions, 88
 - The Mass Balance for Batch Reactors with Irreversible Reactions, 89
 - The Integral Method of Reaction Rate Analysis, 89
 - Analysis of Reaction Half-Times, 91
 - Kinetics Expressions Containing Terms for the Concentrations of More Than One Reactive Species, 93
 - The Differential Method of Reaction Rate Analysis, 96
 - Analysis of Nonpower-Law Rate Expressions, 97
 - Characteristic Reaction Times, 97
- 3.4 Kinetics of Reversible Reactions, 99
 - Reversible Reactions, 99

- Characteristic Times and Limiting Cases for Reversible Reactions, 103
- Simplification of Reaction Rate Expressions for Limiting Cases, 104
 - Very Rapid and Very Slow Approach to Equilibrium as Limiting Cases, 104
 - Reaction Quotients, Equilibrium, and the Assumption of Irreversibility, 105
 - Nearly Complete Reaction as a Limiting Case, 106
 - Summary of Limiting Cases, 107
- 3.5 Kinetics of Sequential Reactions, 107
 - The Progress of Consecutive Reactions and the Rate-Controlling Step, 108
 - The Thermodynamics of Sequential Reactions, 111
 - Steady State: Definition and Comparison with Chemical Equilibrium, 112
- 3.6 The Temperature Dependence of the Rates of Nonelementary Reactions, 114
- 3.7 Summary, 115
 - References, 116
 - Problems, 116

4 Continuous Flow Reactors: Performance Characteristics with Reaction 121

- 4.1 Introduction, 121
- 4.2 Extent of Reaction in Single Ideal Reactors at Steady State, 121
 - Extent of Reaction in a Continuous Flow Stirred Tank Reactor at Steady State, 121
 - First-Order Irreversible Reactions, 122
 - Non-First-Order Irreversible Reactions, 123
 - Extent of Reaction in a Plug Flow Reactor at Steady State, 123
 - Fixed Frame of Reference (Eulerian View), 124
 - Moving Frame of Reference (Lagrangian View), 125
 - Irreversible n th-Order Reactions, 125
 - Comparison of CFSTRs and PFRs for Irreversible Reactions, 126
 - Reversible Reactions, 129
- 4.3 Extent of Reaction in Systems Composed of Multiple Ideal Reactors at Steady State, 130
 - PFRs in Series, 130
 - CFSTRs in Series, 130
 - Application to Chemical Disinfection, 133
 - CFSTRs or PFRs in Parallel, 135
 - Using Reactors with Flow to Derive Rate Expressions, 135
- 4.4 Extent of Reaction in Reactors with Nonideal Flow, 135
 - Fraction Remaining Based on the Exit Age Distribution, 136
 - Fraction Remaining Based on the Dispersion Model, 140
 - Summary of Steady-State Performance in Nonideal Reactors, 141
- 4.5 Extent of Reaction Under Non-Steady-Conditions in Continuous Flow Reactors, 141
 - Extent of Conversion in PFRs Under Non-Steady-State Conditions, 141
 - Extent of Conversion in CFSTRs Under Non-Steady-State Conditions, 142
 - Extent of Conversion in Nonideal Reactors Under Non-Steady-State Conditions, 144
- 4.6 Summary, 146
 - References, 147
 - Problems, 147

PART II REMOVAL OF DISSOLVED CONSTITUENTS FROM WATER**5 Gas Transfer Fundamentals****155**

- 5.1 Introduction, 155
 - Importance of Gas Transfer in Environmental Engineering, 155
 - Overview of Gas/Liquid Equilibrium, 155
 - Overview of Transport and Reaction Kinetics in Gas Transfer Processes, 157
 - Incorporating Gas Transfer into Mass Balances, 157
 - Chapter Overview, 158
- 5.2 Types of Engineered Gas Transfer Systems, 159
- 5.3 Henry's Law and Gas/Liquid Equilibrium, 162
 - Volatilization and Dissolution as a Chemical Reaction, 162
 - Partition Coefficients, Equilibrium Constants, and the Formal Definition of Henry's Law, 162
 - Dimensions of c_L , c_G , and Henry's Law Constant, 164
 - Factors Affecting Gas/Liquid Equilibrium, 167
- 5.4 Relating Changes in the Gas and Liquid Phases, 170
- 5.5 Mechanistic Models for Gas Transfer, 170
 - Fluid Dynamics and Mass Transport in the Interfacial Region, 170
 - The Mass Balance on a Volatile Species Near a Gas/Solution Interface, 171
 - Gas Transfer and Transport Through a Fluid Packet at the Interface, 171
 - Flux Under Limiting-Case Scenarios: Short and Long Packet Residence Times, 174
 - Accounting for the Packet Age and Packet Residence Time Distribution, 175
 - The Gas Transfer Coefficient and Its Interpretation, 175
- 5.6 The Overall Gas Transfer Rate Coefficient, K_L , 179
 - The Combined Resistance of the Gas and Liquid Phases, 179
 - Comparing Gas-Phase and Liquid-Phase Resistances, 181
 - Coupled Transport and Reaction, 183
- 5.7 Evaluating k_L , k_G , K_L , and a : Effects of Hydrodynamic and Other Operating Conditions, 187
 - Approaches for Estimating Gas Transfer Rate Coefficients, 188
 - Gas-in-Liquid Systems, 188
 - Liquid-in-Gas Systems, 192
 - Effects of Other Parameters on Gas Transfer Rate Constants, 195
 - Temperature, 195
 - Solution Chemistry, 196
- 5.8 Summary, 196
 - Appendix 5A. Conventions Used for Concentrations and Activity Coefficients When Computing Henry's Constants, 197
 - Overview, 197
 - Conventions for the Physicochemical Environment in the Standard State, 198
 - Appendix 5B. Derivation of the Gas Transfer Rate Expression for Volatile Species That Undergo Rapid Acid/Base Reactions, 199
 - References, 202
 - Problems, 204

6 Gas Transfer: Reactor Design and Analysis	207
6.1 Introduction, 207	
6.2 Case I: Gas Transfer in Systems with a Well-Mixed Liquid Phase, 207	
The Overall Gas Transfer Rate Expression for Case I Systems, 211	
Analysis of Case I Systems in Batch Liquid Reactors, 213	
Limiting Cases of the General Kinetic Expression, 216	
Overview, 216	
Macroscopic (Advective) Limitation on the Gas Transfer Rate, 217	
Microscopic (Interfacial) Limitation on the Gas Transfer Rate, 218	
Summary of Rate Limitations on Overall Gas Transfer Rate, 219	
Case I Systems with Continuous Liquid Flow at Steady State, 220	
Reactors with Plug Flow of Liquid, 220	
Reactors with Flow and a Uniform Liquid-Phase Composition (CFSTRs with Respect to Liquid), 220	
Case I CFSTRs in Series, 225	
Design Constraints and Choices for Case I Systems with Flow, 226	
6.3 Case II: Gas Transfer in Systems with Spatial Variations in the Concentrations of Both Solution and Gas, 226	
The Mass Balance Around a Section of a Gas Transfer Tower: The Operating Line, 226	
The Mass Balance Around a Differential Section of a Gas Transfer Tower: Development of the Design Equation for Case II Systems, 229	
Pressure Loss and Liquid Holdup, 233	
Use of the Design Equation for Case II Systems, 236	
Description of the Influent Stream, Treatment Objectives, and Design Assumptions, 236	
Exploration of Feasible Designs for Meeting the Treatment Criteria, 236	
Sensitivity of the Column Size to Design Choices and Uncertainty in Parameter Values, 240	
Case II Systems Other than Packed Columns, 240	
6.4 Summary, 241	
Appendix 6A. Evaluation of $K_L a$ in Gas-in-Liquid Systems for Biological Treatment, 243	
References, 246	
Problems, 246	
7 Adsorption Processes: Fundamentals	257
7.1 Introduction, 257	
Background and Chapter Overview, 257	
Terminology and Overview of Adsorption Phenomena, 259	
7.2 Examples of Adsorption in Natural and Engineered Aquatic Systems, 262	
Use of Activated Carbon for Water and Wastewater Treatment, 262	
Sorption of NOM During Coagulation of Drinking Water, 264	
Sorption of Cationic Metals onto Fe and Al Oxides, 265	
Reactors for Adsorption onto Metal Hydroxide Solids, 266	
7.3 Conceptual, Molecular-Scale Models for Adsorption, 266	
Two Views of the Interface and Adsorption Equilibrium, 267	
Adsorption as a Surface Complexation Reaction, 267	
Adsorption as a Phase Transfer Reaction, 267	
Adsorption of Ions as Electrically Induced Partitioning: Donnan Equilibrium, 268	
Which Model is Best?, 268	
7.4 Quantifying the Activity of Adsorbed Species and Adsorption Equilibrium Constants, 268	

CONTENTS

- 7.5 Quantitative Representations of Adsorption Equilibrium: The Adsorption Isotherm, 269
 - Model Adsorption Isotherms According to the Site-Binding Paradigm, 270
 - Characterizing the Adsorbent Sites: Surface Site Distribution Functions, 270
 - The Single-Site Langmuir Isotherm, 271
 - Possible Reasons for Non-Langmuir Behavior, 273
 - The Multisite Langmuir Isotherm, 274
 - Modeling Surfaces with a Semicontinuous Distribution of Site-Types: The Freundlich Isotherm, 276
 - Comparison of Multisite Langmuir and Freundlich Isotherms, 281
 - Bidentate Adsorption, 281
 - The Adsorption Distribution or Partition Coefficient, 282
 - Competitive Adsorption in the Context of the Site-Binding Model of Adsorption, 283
 - Competitive Langmuir Adsorption, 283
 - A Special Case of Competitive Langmuir Adsorption: Ion Exchange Equilibrium, 284
 - Sorption onto Ion Exchange Resins, 285
 - Homovalent Ion Exchange, 286
 - Heterovalent Ion Exchange, 288
 - Some Special Nomenclature and Conventions Used for Ion Exchange Reactions, 289
 - Modeling Ion Exchange Based on Donnan Equilibrium, 292
 - Competitive Adsorption in the Context of the Site-Binding Model for Adsorbates that Obey Freundlich Isotherms, 294
- 7.6 Modeling Adsorption Using Surface Pressure to Describe the Activity of Adsorbed Species, 296
 - The Surface Pressure Concept, 296
 - Computation of the Surface Pressure from Surface Tension or Isotherm Data, 297
 - Competitive Adsorption and Surface Pressure: The Ideal Adsorbed Solution Model, 302
- 7.7 The Polanyi Adsorption Model and the Polanyi Isotherm, 306
 - Description of the Polanyi Model, 306
 - Comparison of Conceptual Models for Adsorption and Their Relationships to the Linear, Langmuir, and Freundlich Isotherms, 313
- 7.8 Modeling Other Interactions and Reactions at Surfaces, 314
 - The Structure of Charged Interfaces and the Electrostatic Contribution to Sorption of Ions, 314
 - Effects of Electrical Potential on Binding of Ions to Surfaces, 314
 - The Profile of Adsorbates and Electrical Potential in the Interfacial Region, 315
 - The Electrostatic Contribution to the Equilibrium Constants in Competitive Adsorption Reactions, 318
 - Phase Transitions Involving Ionic Adsorbates: Pore Condensation and Surface Precipitation, 319
- 7.9 Summary, 320
 - References, 321
 - Problems, 323

8 Adsorption Processes: Reactor Design and Analysis	327
8.1 Introduction, 327	
8.2 Systems with Rapid Attainment of Equilibrium, 328	
Batch Systems, 328	
Systems with Continuous Flow of Both Water and Adsorbent, 331	
Sequential Batch Reactors, 332	
Fixed Bed Adsorption Systems, 333	
Qualitative Description, 333	
The Mass Balance on a Fixed Bed Reactor with Rapid Equilibration, 335	
Systems with Rapid Equilibration and Plug Flow, 336	
8.3 Systems with a Slow Approach to Equilibrium, 340	
Pore Diffusion Versus Surface Diffusion in Porous Adsorbent Particles, 341	
Adsorption in Batch Systems with Transport-Limited Adsorption Rates, 343	
Adsorption in Fixed Bed Systems with Transport-Limited Adsorption Rates, 350	
8.4 The Movement of the Mass Transfer Zone Through Fixed Bed Adsorbers, 354	
8.5 Chemical Reactions in Fixed Bed Adsorption Systems, 356	
8.6 Estimating Long-Term, Full-Scale Performance of Fixed Beds from Short-Term, Bench-Scale Experimental Data, 357	
8.7 Competitive Adsorption in Column Operations: The Chromatographic Effect, 359	
Systems with Rapid Attainment of Adsorptive Equilibrium, 359	
Competitive Adsorption in Systems That Do Not Reach Equilibrium Rapidly, 364	
8.8 Adsorbent Regeneration, 365	
8.9 Design Options and Operating Strategies for Fixed Bed Reactors, 366	
The Minimum Rate of Adsorbent Regeneration or Replacement, 366	
Design Options for Fixed Bed Adsorption Systems, 367	
Single Bed Designs, 367	
Packed Adsorption Beds in Series: "Merry-Go-Round" Systems, 368	
Packed Adsorption Beds in Parallel, 369	
8.10 Summary, 369	
References, 371	
Problems, 371	
9 Precipitation and Dissolution Processes	379
9.1 Introduction, 379	
9.2 Fundamentals of Precipitation Processes, 380	
Formation and Growth of Particles, 380	
Solute Transport, Surface Reactions, and Reversibility, 381	
Fundamentals of Solid/Liquid Equilibrium, 382	
The Solubility Product, 382	
The Activity of Solid Phases and Solid Solutions, 383	
Thermodynamics of Precipitation Reactions, 383	
9.3 Precipitation Dynamics: Particle Nucleation and Growth, 384	
Thermodynamics of Nucleation, 385	
Particle Growth and Size Distributions in Precipitation Reactors, 389	
9.4 Modeling Solution Composition in Precipitation Reactions, 394	
Quantitative Significance of the Solubility Product, 395	
Accounting for Soluble Speciation of the Constituents of the Solid, 395	
9.5 Stoichiometric and Equilibrium Models for Precipitation Reactions, 397	
Precipitation of Hydroxide Solids, 404	
Metal Speciation and the Metal Hydroxide—pH Relationship, 404	
Acid-Base Requirements for Metal Hydroxide Precipitation, 404	

- Precipitation of Carbonate Solids, 409
 - Precipitative Softening, 409
 - The Stoichiometric Model of Precipitative Softening , 410
 - The Equilibrium Model of Precipitative Softening, 414
 - Recarbonation of Softened Water, 417
 - Precipitation of Other Metal Carbonates and Hydroxy-Carbonates, 418
- Other Solids with pH-Dependent Metal and Ligand Speciation, 420
- Effects of Complexing Ligands on Metal Solubility, 421
- Precipitation Resulting from Redox Reactions, 421
- 9.6 Solid Dissolution Reactions, 422
- 9.7 Reactors for Precipitation Reactions, 426
- 9.8 Summary, 428
- References, 429
- Problems, 431

10 Redox Processes and Disinfection

435

- 10.1 Introduction, 435
- 10.2 Basic Principles and Overview, 435
 - Applications of Redox Processes in Water and Wastewater Treatment, 435
 - Oxidation, 436
 - Control of Iron and Manganese, 436
 - Destruction of Tastes and Odors, 436
 - Color Removal, 436
 - Aid to Coagulation, 436
 - Oxidation of Synthetic Organic Chemicals, 436
 - Destruction of Complexing Agents in Industrial Wastes, 437
 - Reduction, 437
 - Thermodynamic Aspects, 437
 - Terminology for Oxidant Concentrations, 441
 - Kinetics of Redox Reactions, 441
- 10.3 Oxidative Processes Involving Common Oxidants, 441
 - Oxygen, 441
 - Chlorine, 444
 - Reactions of Free Chlorine with Inorganic Compounds, 446
 - Reactions with Iron and Manganese, 446
 - Reaction with Reduced Sulfur Compounds, 447
 - Reactions with Bromide, 448
 - Reactions with Organic Compounds, 448
 - Chloramines, 455
 - Formation of Chloramines, 455
 - Reactions of Chloramines with Inorganic Compounds, 458
 - Chlorine Dioxide, 459
 - Generation of Chlorine Dioxide, 460
 - Reactions of Chlorine Dioxide with Inorganic Compounds, 460
 - Reactions of Chlorine Dioxide with Organic Compounds, 461
 - Ozone, 461
 - Ozone Generation, 462
 - Potassium Permanganate, 466
 - Generation of Permanganate, 467
 - Reactions of Permanganate with Ferrous and Manganous Species, 467
- 10.4 Advanced Oxidation Processes, 469
 - Reactions of OH Radicals with Inorganics, 470
 - Reactions of OH Radicals with Organics, 470

- Generation and Fate of OH Free Radicals in Ozonation and Some Specific AOPs, 476
 - UV/Hydrogen Peroxide, 476
 - Ozone, 477
 - O₃/UV and O₃/H₂O₂, 480
 - UV/Semiconductor, 481
 - Wet Air Oxidation, 482
 - Sonolysis, 483
- Fenton-Based Systems, 483
 - Dark Fenton Process, 483
 - Light-Mediated Fenton Processes, 485
 - Heterogeneous Fenton Processes, 485
 - Electrochemical Fenton Processes, 486
 - Cathodic Fenton Processes, 486
 - Anodic Fenton Processes, 486
 - Full-Scale Applications, 486
- 10.5 Reductive Processes, 486
 - Sulfur-Based Systems, 486
 - Iron-Based Systems (Fe(II), Fe(s)), 487
- 10.6 Electrochemical Processes, 488
- 10.7 Disinfection, 488
 - Modeling Disinfection, 489
 - Design and Operational Considerations, 493
 - Characteristic Performance of Specific Disinfectants, 494
 - Chlorine, 494
 - Chloramines, 495
 - Chlorine Dioxide, 497
 - Ozone, 498
 - Ultraviolet Radiation, 500
 - OH Free Radicals, 502
- 10.8 Summary, 502
 - References, 503
 - Problems, 509

PART III REMOVAL OF PARTICLES FROM WATER

- 11 Particle Treatment Processes: Common Elements** **519**
 - 11.1 Introduction, 519
 - 11.2 Particle Stability, 521
 - Particle Charge, 522
 - Isomorphic Substitution, 522
 - Chemical Reactions at the Surface, 522
 - Adsorption on the Particle Surface, 523
 - Characteristics of the Diffuse Layer, 524
 - Interaction of Charged Particles, 525
 - Van der Waals Attraction, 526
 - Interactions of a Particle and Flat Plate, 530
 - Experimental Measurements Related to Charge and Potential, 531
 - 11.3 Chemicals Commonly Used for Destabilization, 532
 - Inorganic Species, 532
 - Organic Polymers, 533
 - 11.4 Particle Destabilization, 535
 - Compression of the Diffuse Layer, 535
 - Adsorption and Charge Neutralization, 536

- Enmeshment in a Precipitate–Sweep Flocculation, 537
- Adsorption and Interparticle Bridging, 541
- 11.5 Interactions of Destabilizing Chemicals with Soluble Materials, 542
 - Combinations of Additives, 543
- 11.6 Mixing of Chemicals into the Water Stream, 544
- 11.7 Particle Size Distributions, 546
 - Experimental Measurements of Size Distributions, 550
- 11.8 Particle Shape, 551
- 11.9 Particle Density, 552
- 11.10 Fractal Nature of Floccs, 552
- 11.11 Summary, 553
 - References, 555
 - Problems, 557

12 Flocculation

563

- 12.1 Introduction, 563
- 12.2 Changes in Particle Size Distributions by Flocculation, 564
- 12.3 Flocculation Modeling, 565
 - Rate Equation for Floc Formation, 567
 - Interpretation of the Rate Constant, 567
 - The Smoluchowski Equation, 568
 - Characteristic Reaction Times in Flocculation, 570
 - Design Implications of the Smoluchowski Equation, 571
- 12.4 Collision Frequency: Long-Range Force Model, 572
 - Collisions by Fluid Shear, 572
 - Collisions by Differential Sedimentation, 575
 - Collisions by Brownian Motion, 577
 - The Total Collision Frequency Function, 578
 - Design Implications of the Long-Range Force Model, 580
- 12.5 Collision Efficiency: Short-Range Force Model, 581
 - Design Implications of the Short-Range Model, 589
- 12.6 Turbulence and Turbulent Flocculation, 589
 - Turbulence, 589
 - Turbulent Flocculation, 589
- 12.7 Floc Breakup, 592
- 12.8 Modeling of Flocculation with Fractal Dimensions, 594
- 12.9 Summary, 596
 - Appendix 12A. Calculation Equations for Collision Efficiency Functions in the Short-Range Force Model, 597
 - References, 598
 - Problems, 599

13 Gravity Separations

603

- 13.1 Introduction, 603
- 13.2 Engineered Systems for Gravity Separations, 605
- 13.3 Sedimentation of Individual Particles, 607
 - Stokes' Law, 607
 - Inertial Effects on Sedimentation, 610
- 13.4 Batch Sedimentation: Type I, 612
 - Monodisperse Suspension, 612
 - Bimodal Suspension, 614
 - Heterodisperse Suspension, 614

- 13.5 Batch Sedimentation: Type II, 618
 - Mathematical Analysis, 619
 - Experimental Analysis, 620
- 13.6 Continuous Flow Ideal Settling, 622
 - Separating Influences of Suspension and Reactor, 622
 - Interpreting the Reactor Settling Potential Function, 623
 - Upflow Reactor, 624
 - Ideal Horizontal Flow Reactors, 626
 - Rectangular Reactor, 626
 - Circular Reactor, 629
 - Type I versus Type II Suspensions in Horizontal Flow Reactors, 631
 - Correspondence of Batch and Continuous Flow Reactors for Ideal Horizontal Flow, 633
 - Tube Settlers, 634
 - Summary of Sedimentation in Ideal Flow Reactors, 638
- 13.7 Effects of Nonideal Flow on Sedimentation Reactor Performance, 639
 - Nonideal, Tiered Flow, 639
 - Nonideal, Channeled Flow, 640
 - Mixed Flow, 642
 - Summary of Nonideal Flow Effects, 644
- 13.8 Thickening, 644
 - Batch Thickening, 645
 - Solids Flux, 647
 - Continuous Flow Thickening, 650
 - Design of Continuous Flow Gravity Thickeners, 655
- 13.9 Flotation, 655
 - Flotation Systems Overview, 657
 - Saturator, 658
 - Bubble Formation, 661
 - Flotation for Low Concentration Suspensions, 663
 - Contact Zone Modeling, 663
 - Flocculation Model, 664
 - Filtration Model, 665
 - Comparison of the Contact Zone Models, 667
 - Separation Zone Modeling, 667
 - Sludge Thickening by Dissolved Air Flotation, 668
- 13.10 Summary, 669
 - References, 670
 - Problems, 671

14 Granular Media Filtration

677

- 14.1 Introduction, 677
 - A Typical Filter, 679
- 14.2 A Typical Filter Run, 680
- 14.3 General Mathematical Description of Particle Removal: Iwasaki's Model, 683
- 14.4 Clean Bed Removal, 684
 - The Single Spherical Isolated Collector Model, 684
 - Removal Mechanisms and Transport Efficiencies for a Single Isolated Collector, 686
 - Particle-Collector Collisions by Interception, 686
 - Particle-Collector Collisions by Sedimentation, 687
 - Particle-Collector Collisions by Brownian Motion, 688
 - Overall Particle-Collector Collision Efficiency, 689

CONTENTS

- Single Spherical Collector in Packed Medium Model, 690
- Updated Packed Medium Model, 692
- Other Advanced Models, 693
- 14.5 Predicted Clean Bed Removal in Standard Water and Wastewater Treatment Filters, 694
 - Design Tradeoffs, 696
- 14.6 Head Loss in a Clean Filter Bed, 698
- 14.7 Filtration Dynamics: Experimental Findings of Changes with Time, 700
 - Immediately After Backwashing, 700
 - Ripening, 701
 - Breakthrough, 701
 - Head Loss, 703
 - Filtration Dynamics: Effects of Design and Operational Variables, 705
 - Bed Depth, 705
 - Media Size, 706
 - Filtration Velocity, 707
 - Depth, Media Size, and Velocity, 708
 - Influent Concentration, 709
 - Summary of Effects of Independent Variables, 709
- 14.8 Models of Filtration Dynamics, 709
 - Macroscopic Models, 710
 - Ripening Model of O'Melia and Ali, 710
 - Ripening Models of Tien and Coworkers, 712
 - Mackie et al. Ripening Model, 713
 - Use and Value of Dynamic Models, 713
- 14.9 Filter Cleaning, 714
 - Surface Wash, 716
 - Air Scour, 716
- 14.10 Summary, 717
 - References, 718
 - Problems, 720

PART IV MEMBRANE-BASED WATER AND WASTEWATER TREATMENT

15 Membrane Processes

731

- 15.1 Introduction, 731
- 15.2 Overview of Membrane System Operation, 732
- 15.3 Membranes, Modules, and the Mechanics of Membrane Treatment, 734
 - Membrane Structure, Composition, and Interactions with Water, 734
 - Driving Forces for Membrane Processes, 736
 - Pressure-Driven Processes, 736
 - Processes Driven Primarily by Concentration Differences or Electrical Forces, 738
 - Configuration and Hydraulics of Membrane Systems, 738
 - Configuration of Membrane Elements, 738
 - Configuration of Membrane Arrays, 741
- 15.4 Parameters Used to Describe Membrane Systems, 742
 - Location, Concentration, and Pressure, 742

- Transport of Fluid and Solutes, 743
 - Recovery, 743
 - Flux, 743
 - Specific Flux and Permeance, 744
 - Resistance, 744
 - Permeability, 745
 - Effect of Temperature on Water Permeation, 746
- Membrane Selectivity: Rejection and Separation, 747
 - Polarization, 747
 - Rejection, 748
 - Challenge Tests and MWCO, 748
 - Separation, 749
- 15.5 Overview of Pressure-Driven Membrane Systems, 749
 - Similarities and Differences Among MF, UF, NF, and RO, 749
 - Operation and Trends in the Performance of Pressure-Based Membrane Systems, 750
- 15.6 Quantifying Driving Forces in Membrane Systems, 752
 - Energy and Driving Force in Membrane Systems, 752
 - The Osmotic Pressure, 754
 - Relative Magnitudes of Different Driving Forces for Transport in Membrane Systems, 757
- 15.7 Quantitative Modeling of Pressure-Driven Membrane Systems, 759
 - Conceptual Models for Transport in Pressure-Driven Membranes, 759
 - The Pore-Flow Model, 760
 - Changes in Solution Composition at the Concentrate/Membrane Interface, 760
 - Permeation of Solution, 764
 - Relating Permeation to Contaminant Rejection, 764
 - The Solution–Diffusion Model, 766
 - The Transmembrane Pressure Profile According to the Solution–Diffusion Model, 766
 - Concentration Changes at the Membrane/Solution Interfaces, 766
 - Permeation Through the Membrane and the Concentration Profile Across the Membrane, 767
 - Comparison of Predicted Fluxes and Transmembrane Parameter Profiles in the Pore-Flow and Solution–Diffusion Models, 771
 - Summary of Transport Through Membranes, 772
- 15.8 Modeling Transport of Water and Contaminants From Bulk Solution to the Surface of Pressure-Driven Membranes, 773
 - Overview, 773
 - Physicochemical State of Contaminants Near the Membrane, 773
 - Transport Through the Boundary Layer and Concentration Polarization in Frontal Filtration, 774
 - Relating Permeation to TMP in Systems with Frontal Filtration, 777
 - The Coupling Force Exerted by Rejected Contaminants on the Permeate Flow, 778
 - Effect of Rejected Particles on Flux, 778
 - Effect of Rejected Solutes on Flux, 780
 - Expressing the Effects of the CP Layer on Permeation in Terms of Resistance, 781
 - Comparing the Effects of Particles and Solutes on Flux Through the CP Layer, 782
 - The Formation of Cakes, Gels, or Scales, and the Limiting Flux, 782
 - Formation of a Compact Layer and the Definition of c_{lim} , 782
 - The Limiting Flux and the Film-Gel Model, 783

CONTENTS

- The Hydraulic Resistance of the Compact Layer, 783
- Estimating c_{lim} and k_{mt} in Systems with Compact Layers and the Flux Paradox, 784
- Concentration Polarization and Precipitative Fouling, 784
- Relating Parameter Profiles in the CP Layer with Those in the Membrane, 786
- Nonsteady-State Fouling During Frontal or Dead-End Filtration, 787
- Empirical Measures of Fouling: The MFI and SDI Tests, 790
- Summary: Modeling Membrane Performance in Frontal Filtration, 792
- 15.9 Effects of Crossflow on Permeation and Fouling, 792
 - General Considerations in Modeling Fluid Flow and Particle Transport in Crossflow Filtration, 792
 - Fluid Flow in Crossflow Filtration, 793
 - The Pressure Profile on the Concentrate Side of Crossflow Membrane Systems, 795
 - Contaminant Transport Mechanisms in Crossflow Filtration, 798
 - Brownian and Shear-Induced Diffusion, 798
 - Deterministic Transport Mechanisms in Crossflow Filtration, 800
 - Relative Importance of Different Back-Transport Mechanisms, 802
 - Modeling Contaminant Transport and Flux in Crossflow Filtration Systems, 802
 - Overview, 802
 - Assumptions Commonly Used in Modeling Crossflow Filtration, 803
 - The Mechanics of Crossflow Filtration Modeling, 803
 - Modeling the Thickness of the CP Layer and $k_{mt,CP}$ in Crossflow Filtration, 804
 - Systems with a Ubiquitous Compact Layer: Applying the Film-Gel Model in Systems with Crossflow Filtration, 805
 - Modified Versions of the Film and Film-Gel Models for Systems with Crossflow, 807
 - Systems with no Compact Layer, 809
 - Systems in which a Compact Layer is Present along only a Portion of the Membrane Element, 811
 - Modeling Crossflow Filtration of Particles Subject to Significant Inertial Lift, 813
 - Summary of Equations for Modeling Crossflow Filtration, 814
 - Nonsteady-State Fouling Patterns in Crossflow Filtration, 814
 - Summary of Modeling Approaches and Results for Crossflow Filtration, 815
- 15.10 Electrodialysis, 816
 - Transport in Systems with a Gradient in Electrical Potential, 819
 - Transport due to Advection, 819
 - Transport due to Diffusion, 819
 - Transport in Solution due to an Electric Field, 820
 - Overall Transport and Current Densities in Systems with a Gradient in Electrical Potential, 821
 - Modeling Electrodialysis Systems, 822
 - Overview, 822
 - Transport in the x Direction in a Single Cell-Pair, 822
 - Relating Ion Fluxes, Electrical Current Density, and the Electrical Potential Difference, 825
 - Analysis of the Two-Dimensional ED System, 828
 - Macroscopic Mass Balance on ED Reactor, 828

- Microscopic Mass Balance on a Differential Element in an ED Reactor, 829
- Ramifications for Design of Electrodialysis Systems, 830
- Complications of Real Systems, 832
 - Water Flow Through Ion-Exchange Membranes, 832
 - Nonideal Behavior of Membranes, 832
 - Multicomponent Systems, 832
 - Overlimiting Current, 833
 - Additional Sources of Potential Drop, 833
 - Summary, 834
- 15.11 Modeling Dense Membrane Systems Using Irreversible Thermodynamics, 834
- 15.12 Summary, 838
 - References, 839
 - Problems, 841