

Contents

Preface ix

Nomenclature xiii

1. Introduction 1

- 1.1. Biological Cycle 1
- 1.2. Green Chemistry 3
- 1.3. Sustainability 5
- 1.4. Biorefinery 6
- 1.5. Biotechnology and Bioprocess Engineering 9
- 1.6. Mathematics, Biology, and Engineering 11
- 1.7. The Story of Penicillin: the Dawn of Bioprocess Engineering 12
- 1.8. Bioprocesses: Regulatory Constraints 15
- 1.9. The Pillars of Bioprocess Kinetics and Systems Engineering 17
- 1.10. Summary 18
- Further Reading 19
- Problems 20

2. An Overview of Biological Basics 21

- 2.1. Cells and Organisms 21
- 2.2. Stem Cell 39
- 2.3. Cell Chemistry 41
- 2.4. Cell Feed 76
- 2.5. Summary 81
- Further Reading 83
- Problems 83

3. An Overview of Chemical Reaction Analysis 85

- 3.1. Chemical Species 86
- 3.2. Chemical Reactions 86
- 3.3. Reaction Rates 90
- 3.4. Approximate Reactions 95
- 3.5. Rate Coefficients 97
- 3.6. Stoichiometry 99
- 3.7. Yield and Yield Factor 102

3.8. Reaction Rates Near Equilibrium 104

3.9. Energy Regularity 110

3.10. Classification of Multiple Reactions and Selectivity 111

3.11. Coupled Reactions 113

3.12. Reactor Mass Balances 116

3.13. Reaction Energy Balances 119

3.14. Reactor Momentum Balance 126

3.15. Ideal Reactors 127

3.16. Bioprocess Systems Optimization 129

3.17. Summary 132

Further Reading 136

Problems 137

4. Batch Reactor 141

4.1. Isothermal Batch Reactors 142

4.2. Batch Reactor Sizing 155

4.3. Non-Isothermal Batch Reactors 159

4.4. Numerical Solutions of Batch Reactor Problems 165

4.5. Summary 172

Further Reading 173

Problems 173

5. Ideal Flow Reactors 177

5.1. Flow Rate, Residence Time, Space Time, Space Velocity, Dilution Rate 178

5.2. Plug Flow Reactor 180

5.3. Gasification and Fischer-Tropsch Technology 189

5.4. Continuous Stirred Tank Reactor (CSTR) and Chemostat 194

5.5. Multiple Reactors 206

5.6. Recycle Reactors 211

5.7. Distributed Feed and Withdraw 215

5.8. PFR or CSTR? 226

5.9. Steady Nonisothermal Flow Reactors 230

5.10. Reactive Extraction 237

5.11. Graphic Solutions using Batch Concentration Data 239	Further Reading 384 Problems 384
5.12. Summary 242	
Further Reading 244	
Problems 245	
6. Kinetic Theory and Reaction Kinetics 257	9. Chemical Reactions on Solid Surfaces 391
6.1. Elementary Kinetic Theory 258	9.1. Adsorption and Desorption 394
6.2. Collision Theory of Reaction Rates 264	9.2. LHHW: Surface Reactions with Rate-Controlling Steps 431
6.3. Reaction Rate Analysis/Approximation 267	9.3. Chemical Reactions on Nonideal Surfaces based on Distribution of Interaction Energy 448
6.4. Unimolecular Reactions 270	9.4. Chemical Reactions on Nonideal Surfaces with Multilayer Approximation 453
6.5. Free Radicals 272	9.5. Kinetics of Reactions on Surfaces Where the Solid Is Either a Product or Reactant 454
6.6. Kinetics of Acid Hydrolysis 274	9.6. Decline of Surface Activity: Catalyst Deactivation 460
6.7. Summary 277	9.7. Summary 461
Reading Materials 277	Further Reading 467
Problems 278	Problems 467
7. Parametric Estimation 281	10. Cell Metabolism 473
7.1. Regression Models 282	10.1. The Central Dogma 474
7.2. Classification of Regression Models 286	10.2. DNA Replication: Preserving and Propagating the Cellular Message 477
7.3. Criteria for "Best" Fit and Simple Linear Regressions 287	10.3. Transcription: Sending the Message 479
7.4. Correlation Coefficient 291	10.4. Translation: Message to Product 485
7.5. Common Abuses of Regression 293	10.5. Metabolic Regulation 492
7.6. General Regression Analysis 294	10.6. How a Cell Senses Its Extracellular Environment 509
7.7. Quality of Fit and Accuracy of Data 295	10.7. Major Metabolic Pathway 515
7.8. Batch Kinetic Data Interpretation: Differential Regression Model 297	10.8. Overview of Biosynthesis 534
7.9. Summary 317	10.9. Overview of Anaerobic Metabolism 536
Further Reading 317	10.10. Interrelationships of Metabolic Pathways 538
Problems 318	10.11. Overview of Autotrophic Metabolism 541
8. Enzymes 323	10.12. Summary 543
8.1. How Enzymes Work 327	Further Reading 545
8.2. Enzyme Kinetics 334	Problems 546
8.3. Immobilized Enzyme Systems 354	
8.4. Analysis of Bioprocess with Enzymatic Reactions 359	11. How Cells Grow 549
8.5. Large-Scale Production of Enzymes 366	11.1. Quantifying Biomass 550
8.6. Medical and Industrial Utilization of Enzymes 368	11.2. Batch Growth Patterns 553
8.7. Kinetic Approximation: Why Michaelis-Menten Equation Works 371	11.3. Biomass Yield 558
8.8. Summary 383	

- 11.4. Approximate Growth Kinetics and Monod Equation 562
- 11.5. Cell Death Rate 566
- 11.6. Cell Maintenance and Endogenous Metabolism 568
- 11.7. Product Yield 576
- 11.8. Oxygen Demand for Aerobic Microorganisms 577
- 11.9. Effect of Temperature 580
- 11.10. Effect of pH 582
- 11.11. Effect of Redox Potential 583
- 11.12. Effect of Electrolytes and Substrate Concentration 583
- 11.13. Heat Generation by Microbial Growth 584
- 11.14. Overview of Microbial Growth Kinetic Models 585
- 11.15. Performance Analysis of Batch Culture 596
- 11.16. Summary 599
- Reading Materials 601
- Problems 601
12. Continuous Cultivation 607
- 12.1. Continuous Culture 608
- 12.2. Choosing the Cultivation Method 620
- 12.3. Wastewater Treatment Process 634
- 12.4. Immobilized Cell Systems 641
- 12.5. Solid Substrate Fermentations 648
- 12.6. Summary 650
- Further Reading 651
- Problems 652
13. Fed-Batch Cultivation 663
- 13.1. Design Equations 667
- 13.2. Ideal Isothermal Fed-Batch Reactors 671
- 13.3. Isothermal Pseudo-Steady State Fed-Batch Growth 676
- 13.4. Advantages and Disadvantages of Fed-Batch Operations 684
- 13.5. Considerations in Implementing Fed-Batch Operations 686
- 13.6. Examples of Fed-Batch Use in Industry 686
- 13.7. Parameters to Be Controlled or Monitored During Fed-Batch Operations 687
- 13.8. Parameters to Start and Finish the Feed and Stop the Fed-Batch Fermentation 691
- 13.9. Summary 691
- Further Reading 692
- Problems 692
14. Evolution and Genetic Engineering 695
- 14.1. Mutations 696
- 14.2. Selection 703
- 14.3. Natural Mechanisms for Gene Transfer and Rearrangement 706
- 14.4. Techniques of Genetic Engineering 711
- 14.5. Applications of Genetic Engineering 719
- 14.6. The Product and Process Decisions 721
- 14.7. Host-Vector System Selection 723
- 14.8. Regulatory Constraints on Genetic Processes 733
- 14.9. Metabolic Engineering 736
- 14.10. Protein Engineering 738
- 14.11. Summary 739
- Further Reading 740
- Problems 740
15. Sustainability: Humanity Perspective 743
- 15.1. What is Sustainability? 744
- 15.2. Sustainability of Humanity 745
- 15.3. Water 748
- 15.4. CO₂ and Biomass 760
- 15.5. Woody Biomass Use and Desired Sustainable State 766
- 15.6. Solar Energy 774
- 15.7. Geothermal Energy 777
- 15.8. Summary 778
- Further Reading 781
- Problems 781
16. Sustainability and Stability 785
- 16.1. Feed Stability of a CSTR 787
- 16.2. Thermal Stability of a CSTR 801
- 16.3. Approaching Steady State 810
- 16.4. Catalyst Instability 815
- 16.5. Genetic Instability 818
- 16.6. Mixed Cultures 834
- 16.7. Summary 850
- Further Reading 852
- Problems 852

17. Mass Transfer Effects: Immobilized and Heterogeneous Reaction Systems 861	18. Bioreactor Design and Operation 915
17.1. Molecular Diffusion and Mass Transfer Rate 862	18.1. Bioreactor Selection 916
17.2. External Mass Transfer 864	18.2. Reactor Operational Mode Selection 921
17.3. Reactions in Isothermal Porous Catalysts 872	18.3. Aeration, Agitation, and Heat Transfer 923
17.4. Mass Transfer Effects in Nonisothermal Porous Particles 884	18.4. Scale-up 927
17.5. External and Internal Mass Transfer Effects 894	18.5. Scale-down 930
17.6. Encapsulation Immobilization 897	18.6. Bioinstrumentation and Controls 930
17.7. External and Internal Surface Effects 899	18.7. Sterilization of Process Fluids 932
17.8. The Shrinking Core Model 900	18.8. Aseptic Operations and Practical Considerations for Bioreactor System Construction 946
17.9. Summary 904	18.9. Effect of Imperfect Mixing 950
Further Reading 908	18.10. Summary 957
Problems 908	Further Reading 961
	Problems 961
19. Parametric Estimation 949	Index 965
19.1. Regression Models 949	
19.2. Classification of Regression Models 952	
19.3. Criteria for Model Selection 954	
19.4. Correlation Coefficients 957	
19.5. What is Sustainability? 957	
19.6. Sustainability of Humanity 959	
19.7. General Regression Analysis 961	
19.8. Quality of Fit to Data 963	
19.9. Batch Kinetics 965	
19.10. Differential Regression 967	
19.11. Summary 971	
Further Reading 973	
Problems 973	
20. Sustainability and Energy 975	
20.1. Solar Energy 975	
20.2. Geothermal Energy 977	
20.3. Summary 978	
Further Reading 981	
Problems 981	
21. Sustainability and Stability 983	
21.1. How Far from Work 983	
21.2. Stability of a CSTR 985	
21.3. Thermal Stability of a CSTR 987	
21.4. Approaching Steady State 989	
21.5. Catalytic Inhibition 991	
21.6. Genetic Inhibition 993	
21.7. Mixed Cultures 994	
21.8. Summary 997	
Further Reading 997	
Problems 997	
22. Sustainability and Control 999	
22.1. The Central Control 999	
22.2. Choosing the Control Method 1001	
22.3. Water Treatment Process 1001	
22.4. Immobilized Cell Systems 1001	
22.5. Solid Substrate Fermentation 1001	
22.6. Summary 1001	
Further Reading 1001	
Problems 1001	
23. Fed-Batch Cultivation 1003	
23.1. Design Equations 1003	
23.2. Ideal Isothermal Fed-Batch Reactor 1003	
23.3. Isothermal Pseudo-Steady State 1003	
23.4. Advantages and Disadvantages of Fed-Batch Operations 1003	
23.5. Considerations in Implementing Fed-Batch Operations 1003	
23.6. Examples of Fed-Batch Use in Industry 1003	
23.7. Parameters to Be Controlled 1003	
23.8. Parameters to Start and Finish the Fed-Batch Fermentation 1003	