Contents

Preface xiii
Author xv
Notation xvii

Chapter 1 Introduction 1

1.1 Review of Units and Dimensions 1
1.1.1 Units 1
1.1.2 Fundamental Dimensions 1
1.1.2.1 Mass and Weight 1
1.1.2.2 Temperature 4
1.1.2.3 Mole 4
1.1.3 Derived Dimensional Quantities 5
1.1.3.1 Pressure 6
1.1.3.2 Volume 6
1.1.3.3 Equations of State 7
1.2 Dimensional Equation 7
1.3 Tips for Solving Engineering Problems 8
1.4 Conservation of Mass 10
1.4.1 Law of Conservation 10
1.4.2 Chemical Reactions 12
1.4.3 Material Balances 14
Problems 20

Chapter 2 A Review of Thermodynamic Concepts 23

2.1 First Law of Thermodynamics 23
2.1.1 Closed Systems 23
2.1.2 Steady Flow Processes 24
2.2 Second Law of Thermodynamics 25
2.2.1 Reversible Processes 26
2.3 Properties 27
2.3.1 Heat Capacity 27
2.3.2 Calculating the Change in Entropy 28
2.3.2.1 Entropy Change of an Ideal Gas 28
2.3.3 Gibbs and Helmholtz Free Energy 30
2.3.3.1 Gibbs Free Energy 30
2.3.3.2 Helmholtz Free Energy 30
2.4 Fundamental Property Relations 31
2.4.1 Exact Differentials 31
2.5 Single Phase Open Systems 33
2.5.1 Partial Molar Properties 33
2.5.1.1 Binary Systems 35
2.5.1.2 Property Changes of Mixing 35
2.5.1.3 Ideal Gas 35
2.5.1.4 Gibbs Free Energy of an Ideal Gas Mixture 38

2.5.2 Pure Component Fugacity 38
2.5.2.1 Calculating the Pure Component Fugacity 39
2.5.3 Fugacity of a Component in a Mixture 41
2.5.4 Ideal Solution 42
2.6 Phase Equilibrium 43
2.6.1 Pure Component Phase Equilibrium 45
2.6.1.1 Fugacity of a Pure Component as a Compressed Liquid 47
2.6.2 Excess Properties 48
2.6.3 Applications of Equilibrium Thermodynamics 51
2.6.3.1 Solubility of a Solid in a Liquid Solvent 51
2.6.3.2 Depression of the Freezing Point of a Solvent by a Solute 56
2.6.3.3 Equilibrium between a Solid and a Gas Phase 57
2.6.3.4 Solubility of a Gas in a Liquid 59
2.6.3.5 Osmotic Pressure 62
2.6.3.6 Distribution of a Solute between Two Liquid Phases 65
2.6.3.7 Vapor–Liquid Equilibrium 70
2.6.3.8 Flammability Limits 74
2.6.3.9 Thermodynamics of Surfaces 76
2.6.3.10 Equilibrium Dialysis 79
2.6.3.11 Gibbs–Donnan Effect 84
2.6.3.12 Donnan Potential 87
2.6.3.13 Chemical Equilibrium in Ideal Aqueous Solutions 89
Problems 94

Chapter 3 Physical Properties of the Body Fluids and the Cell Membrane 101

3.1 Body Fluids 101
3.2 Fluid Compositions 102
3.3 Capillary Plasma Protein Retention 102
3.4 Osmotic Pressure 104
3.4.1 Osmolarity 105
3.4.2 Calculating the Osmotic Pressure 105
3.4.3 Other Factors That May Affect the Osmotic Pressure 106
3.5 Formation of the Interstitial Fluid 106
3.6 Net Capillary Filtration Rate 108
3.7 Lymphatic System 110
3.8 Solute Transport across the Capillary Endothelium 110
3.9 Cell Membrane 111
3.10 Ion Pumps 116
Problems 117

Chapter 4 The Physical and Flow Properties of Blood and Other Fluids 121

4.1 Physical Properties of Blood 121
4.2 Cellular Components 121
4.3 Rheology 121
4.4 Relationship between Shear Stress and Shear Rate 125
4.5 Hagen–Poiseuille Equation 127
4.6 Other Useful Flow Relationships 128
4.7 Rheology of Blood 129

4.8 Casson Equation 131
4.9 Using the Casson Equation 132
4.10 Velocity Profile for Tube Flow of a Casson Fluid 134
4.11 Tube Flow of Blood at Low Shear Rates 134
4.12 Effect of Diameter at High Shear Rates 134
4.13 Marginal Zone Theory 136
4.14 Using the Marginal Zone Theory 138
4.15 Boundary Layer Theory 141
4.15.1 Flow near a Wall That is Set in Motion 141
4.15.2 Laminar Flow of a Fluid along a Flat Plate 146
4.16 Generalized Mechanical Energy Balance Equation 151
4.17 Capillary Rise and Capillary Action 159
4.17.1 Equilibrium Capillary Rise 159
4.17.2 Dynamics of Capillary Action 161
Problems 164

Chapter 5 Solute Transport in Biological Systems 175

5.1 Description of Solute Transport in Biological Systems 175
5.2 Capillary Properties 175
5.3 Capillary Flow Rates 175
5.4 Solute Diffusion 177
5.4.1 Fick's First Law and Diffusivity 177
5.4.2 Fick's Second Law 179
5.4.3 Solution for the Concentration Profile for Diffusion from a Flat Plate into a Quiescent Fluid 180
5.4.4 Definition of the Solute Flux 181
5.4.5 Definition of the Mass Transfer Coefficient 181
5.4.6 Mass Transfer in Laminar Boundary Layer Flow over a Flat Plate 184
5.4.7 Mass Transfer from the Walls of a Tube Containing a Fluid in Laminar Flow 189
5.4.8 Mass Transfer Coefficient Correlations 194
5.5 Solute Transport by Capillary Filtration 198
5.6 Solute Diffusion within Heterogeneous Media 203
5.6.1 Diffusion of a Solute from a Polymeric Material 208
5.6.1.1 A Solution Valid for Short Contact Times 211
5.6.2 Diffusion in Blood and Tissue 213
5.7 Solute Permeability 215
5.8 Irreversible Thermodynamics of Membrane Transport 217
5.8.1 Finding L_p, P_m, and σ 219
5.8.2 Multicomponent Membrane Transport 220
5.9 Transport of Solutes across the Capillary Wall 221
5.10 Transport of a Solute between a Capillary and the Surrounding Tissue Space 225
5.10.1 The Krogh Tissue Cylinder 225
5.10.2 A Model of the Krogh Tissue Cylinder 226
5.10.2.1 Comparison of Convection and Diffusion Effects 231
5.10.3 The Renkin–Crone Equation 231
5.10.3.1 Determining the Value of P_mS 232
5.10.4 Solute Transport in Vascular Beds, the Well-Mixed Assumption 234
Problems 236

Chapter 6 Oxygen Transport in Biological Systems 245

6.1 Diffusion of Oxygen in Multicellular Systems 245
6.2 Hemoglobin 245
6.3 Oxygen–Hemoglobin Dissociation Curve 247
6.4 Oxygen Levels in Blood 247
6.5 The Hill Equation 248
6.6 Other Factors That Can Affect the Oxygen Dissociation Curve 250
6.7 Tissue Oxygenation 250
6.8 Oxygen Transport in Bioartificial Organs and Tissue-Engineered Constructs 255
6.9 Steady State Oxygen Transport in a Perfusion Bioreactor 261
6.10 Oxygen Transport in the Krogh Tissue Cylinder 265
6.11 Approximate Solution for Oxygen Transport in the Krogh Tissue Cylinder 268
6.12 Artificial Blood 272
Problems 276

Chapter 7 Pharmacokinetic Analysis 281

7.1 Terminology 281
7.2 Entry Routes for Drugs 281
7.3 Modeling Approaches 283
7.4 Factors Affecting Drug Distribution 284
7.4.1 Drug Distribution Volumes 284
7.4.2 Drug Metabolism 288
7.4.3 Renal Excretion of the Drug 289
7.5 Drug Clearance 290
7.5.1 Renal Clearance 290
7.5.2 Plasma Clearance 292
7.5.3 Biological Half-Life 293
7.6 Model for Intravenous Injection of Drug 293
7.7 Accumulation of Drug in the Urine 294
7.8 Constant Infusion of Drug 295
7.8.1 Application to Controlled Release of Drugs by Osmotic Pumps 297
7.8.2 Application to the Transdermal Delivery of Drugs 299
7.8.2.1 Predicting the Permeability of Skin 301
7.9 First Order Drug Absorption and Elimination 302
7.10 Two Compartment Model 306
7.10.1 Two Compartment Model for an Intravenous Injection 306
7.10.2 Two Compartment Model for First Order Absorption 310
Problems 312

Chapter 8 Extracorporeal Devices 319

8.1 Applications 319
8.2 Contacting Schemes 319
8.3 Membrane Solute Transport 321
8.4 Estimating the Mass Transfer Coefficients 322
8.5 Estimating the Solute Diffusivity in Blood 323
8.6 Hemodialysis 325
8.6.1 Background 325
8.6.2 Dialysate Composition 326

8.6.3 Role of Ultrafiltration 326
8.6.4 Clearance and Dialysance 328
8.6.5 Solute Transfer 329
8.6.6 Single Compartment Model of Urea Dialysis 332
8.6.7 Peritoneal Dialysis 332
8.6.8 Aquapheresis 335
8.7 Blood Oxygenators 336
8.7.1 Background 336
8.7.2 Operating Characteristics of Blood Oxygenators 336
8.7.3 Types of Oxygenators 338
8.7.4 Analysis of a Membrane Oxygenator, Oxygen Transfer 339
8.7.5 Analysis of a Membrane Oxygenator, Carbon Dioxide Transfer 343
8.7.6 Example Calculations for Membrane Oxygenators 346
8.8 Immobilized Enzyme Reactors 347
8.8.1 Background 347
8.8.2 Examples of Medical Application of Immobilized Enzymes 347
8.8.3 Enzyme Reaction Kinetics 349
8.8.4 Reaction and Diffusion in Immobilized Enzyme Systems 352
8.8.5 Solving the Immobilized Enzyme Reaction–Diffusion Model 354
8.8.6 Special Case of a First Order Reaction 355
8.8.7 Observed Reaction Rate 356
8.8.8 External Mass Transfer Resistance 356
8.8.9 Reactor Design Equations 357
8.8.9.1 Packed Bed Reactor 357
8.8.9.2 Well-Mixed Reactor 358
8.9 Affinity Adsorption 361
Problems 365

Chapter 9 Tissue Engineering 369

9.1 Introduction 369
9.2 Cell Transplantation 369
9.3 Extracellular Matrix 372
9.3.1 Glycosaminoglycans 373
9.3.2 Collagens 374
9.3.3 Elastin 374
9.3.4 Fibronectin 374
9.3.5 Basement Membrane 374
9.4 Cellular Interactions 375
9.4.1 Cadherins 376
9.4.2 Selectins 376
9.4.3 Cell Adhesion Molecules 376
9.4.4 Integrins 376
9.4.5 Cytokines and Growth Factors 377
9.5 Polymeric Support Structures 378
9.6 Biocompatibility and Initial Response to an Implant 382
9.7 Tissue Ingrowth in Porous Polymeric Structures 383
9.8 Measuring Blood Flow within Scaffolds Used for Tissue Engineering 386
9.9 Cell Transplantation into Polymeric Support Structures 387
9.10 Bioreactor Design for Tissue Engineering 389
Problems 392

Chapter 10 Bioartificial Organs 395

10.1 Background 395
10.2 Some Immunology 395
10.2.1 B Lymphocytes 396
10.2.2 Antibodies 396
10.2.3 T Lymphocytes 398
10.2.4 Interaction between APCs, B Cells, and T Cells 399
10.2.5 Immune System and Transplanted Cells 400
10.3 Immunoisolation 401
10.4 Permeability of Immunoisolation Membranes 403
10.5 Membrane Sherwood Number 406
10.6 Examples of Bioartificial Organs 406
10.6.1 Bioartificial Pancreas 407
10.6.1.1 Bioartificial Pancreas Approaches 408
10.6.1.2 Intravascular Devices 409
10.6.1.3 Microencapsulation 411
10.6.1.4 Macroencapsulation 413
10.6.1.5 Organoid 415
10.6.2 Number of Islets Needed 415
10.6.3 Islet Insulin Release Model 416
10.6.4 Pharmacokinetic Modeling of Glucose and Insulin Interactions 418
10.6.5 Using the Pharmacokinetic Model to Evaluate the Performance of a Bioartificial Pancreas 421
10.7 Bioartificial Liver 424
10.7.1 Artificial Liver Systems 425
10.7.2 Bioartificial Livers 426
10.7.3 Examples of Extracorporeal Bioartificial Livers 427
10.8 The Bioartificial Kidney 431
10.9 Design Considerations for Bioartificial Organs 434
Problems 435

References 437

Index 451