## **Contents**

List of Symbols Preface to Third Edition		xiii	
		xix	
Pre	face	to Second Edition	xxi
1	Models for Diffusion		1
	1.1 1.2 1.3	The Two Basic Models Choosing Between the Two Models Examples	2 3 7
	1.4	Conclusions Questions for Discussion	9 10
PA	RT I	Fundamentals of Diffusion	
2	Diff	fusion in Dilute Solutions	13
	2.1 2.2 2.3 2.4 2.5 2.6	Unsteady Diffusion in a Semi-infinite Slab	13 17 26 33 41 49 50 51
3	Diff	56	
	3.1 3.2 3.3 3.4 3.5 3.6	Parallel Diffusion and Convection	56 59 67 75 84 90 90 91
4	Disp	persion	95
	4.1 4.2	Dispersion From a Stack Dispersion Coefficients	95 97

viii Contents Contents ix

101	8.3 Correlations of Mass Transfer Coefficients	249
104	8.4 Dimensional Analysis: The Route to Correlations	257
110	8.5 Mass Transfer Across Interfaces	261
110	8.6 Conclusions	269
111	Questions for Discussion	270
113	Problems	270
	Further Reading	273
	9 Theories of Mass Transfer	274
117	9.1 The Film Theory	275
117	· · · · · · · · · · · · · · · · · · ·	277
		281
	· · · · · · · · · · · · · · · · · · ·	284
		294
		298
		300
		300
		303
	· ·	20.4
159	10 Absorption	304
161	10.1 The Basic Problem	305
101	10.2 Absorption Equipment	307
161	10.3 Absorption of a Dilute Vapor	314
172	10.4 Absorption of a Concentrated Vapor	321
183	10.5 Conclusions	326
190	Questions for Discussion	326
205	Problems	327
206	Further Reading	331
206	TANK TO C ! D! L. LM P	332
209	11 Mass Transfer in Biology and Medicine	
211	11.1 Mass Transfer Coefficients	333
		339
		347
		350
	Questions for Discussion	351
	Problems	351
	Further Reading	352
	12 Differential Distillation	353
	12 Differential Distination	
	12.1 Overview of Distillation	353
234	12.2 Very Pure Products	356
	12.3 The Column's Feed and its Location	362
	12.4 Concentrated Differential Distillation	366
237	12.5 Conclusions	371
	Questions for Discussion	371
237	Problems	372
243	Further Reading	374
	104 110 110 111 113  117 117 126 134 135 139 142 156 157 157 159 161 161 172 183 190 205 206 206 209 211 211 211 214 218 224 225 231 232 232 234	104

X Contents Contents xi

13.1 Sasped Distillation Equipment   376   17.1 Mass Trumfer with Fine-Order Chemical Reactions   479   13.2 Staged Distillation of New French Per Products   379   17.2 Mass Trumfer with Fine-Order Chemical Reactions   489   13.3 Concentrated Staged Distillation   385   17.3 Industrial Gas Tructing   481   13.4 Stage Fine-Incises   393   17.4 Diffusion-Controlled Fix Reactions   500   13.5 Conditions   400   17.5 Dependency of the Controlled Fix Reactions   500   13.5 Conditions   400   17.5 Dependency of the Controlled Fix Reactions   500   13.5 Conditions   401   17.5 Dependency of the Controlled Fix Reactions   500   13.5 Conditions   401   17.5 Dependency of the Controlled Fix Reactions   500   13.5 Conditions   401   17.5 Dependency   500   13.5 Conditions   401   17.5 Dependency   500   14.6 Controlled Fix Reacting   403   17.4 Diffusion   405   14.1 The Basic Problem   404   407   407   407   14.2 Latraction Equipment   404   407	13	Staged Distillation	375	17 Homogeneous Chemical Reactions	478
13.2 Staged Disillation of Nearly Pare Products   379   17.2 Mass Transfer with Second-Order Chemical Reactions   488   33.3 Concentrated Staged Distillation   385   17.3 Industrial Gas Treating   492   31.4 Staget Efficiencies   500   393   17.4 Diffusion-Controlled Fast Reactions   500   31.5 Conclusions   500   400   17.6 Conclusions   500   400   17.6 Dispersion Augustants for Discussion   500   400   41.5 Dispersion for Discussion   500		13.1 Staged Distillation Equipment	376	17.1 Mass Transfer with First-Order Chemical Reactions	479
1.3.   Concentrated Staged Distillation   385   1.2. Industria Gas Treating   492   1.3.   Stage Fiftenenies   393   1.2. Diffusion-Centrolled Fas Reactions   500   1.3.   Conclusions   400   1.5. Dispersion-Centrolled Fas Reactions   500   Problems   401   Questions for Discussion   507   Problems   401   Questions for Discussion   508   Problems   404   Return Reading   512   Problems   404   Return Reading   512   Pather Reading   513   Pather Reading   514   Pather Reading   514   Pather Reading   515   Pather Reading   516   Pather Reading   516   Pather Reading   516   Pather Reading   518   P		13.2 Staged Distillation of Nearly Pure Products	379		488
13.4   Stage Efficiencies		13.3 Concentrated Staged Distillation	385		492
1.5   Conclusions for Discussion		13.4 Stage Efficiencies	393	e e e e e e e e e e e e e e e e e e e	500
Questions for Discussion		13.5 Conclusions	400		
Problems		Questions for Discussion		·	
Extraction					
		Further Reading		The state of the s	
14					
14.1   The Basic Problem	14	Extraction	404		
14.2   Extraction Reupiment   407   18.1   Physical Factors in Membranes   514     14.3   Differential Extraction   409   18.2   Gas Separations   520     14.4   Staged Extraction   413   18.3   Reverse Osmosis and Ultrafiltration   526     14.5   Leaching   416   18.4   Pervaporation   534     14.6   Conclusions   420   18.5   Conclusions   539		14.1 The Basic Problem	404	18 Membranes	513
14.3   Differential Extraction				18.1 Physical Factors in Membranes	514
14.   Singed Extraction					520
14.5   Leaching   416   18.4   Pervaporation   534     14.6   Conclusions   420   18.5   Scalitated Diffusion   539     14.6   Conclusions   420   18.5   Scalitated Diffusion   539     14.6   Conclusions   5420   18.5   Scalitated Diffusion   539     14.6   Conclusions   5420   18.5   Scalitated Diffusion   549     14.6   Conclusions   5420   18.5   Conclusions   545     14.6   Conclusions   5420   18.5   Conclusions   545     14.7   Problems   5421   Questions for Discussion   545     15.1   Where Adsorption is Important   424   19   Controlled Release and Related Phenomena   549     15.1   Where Adsorption is Important   425   19.1   Controlled Release by Solute Diffusion   551     15.2   Adsorbents and Adsorption Isotherms   427   19.2   Controlled Release by Solute Diffusion   555     15.3   Breakthrough Curves   431   19.3   Barriers   558     15.4   Mass Transfer Effects   439   19.3   Barriers   558     15.5   Other Characteristics of Adsorption   443   19.4   Diffusion and Phase Equilibrium   562     15.5   Other Characteristics of Adsorption   443   19.4   Diffusion and Phase Equilibrium   562     15.6   Conclusions   450   Questions for Discussion   565     15.6   Conclusions   450   Questions for Discussion   565     15.6   Conclusions   450   Questions for Discussion   566     15.6   Conclusions   450   Purblem   560     15.7   Further Reading   560     15.8   Heart Transfer   568     15.9   Heart Transfer   568     15.0   Heart Transfer   568     15.1   Is the Reaction Heterogeneous Chemical Reactions   457   20.5   Conclusions   579     16.1   Is the Reaction Heterogeneous Reactions   459   Questions for Discussion   591     16.2   What is a Diffusion-Controlled Reactions   459   Questions for Discussion   591     16.3   Diffusion and First-Order Heterogeneous Reactions   459   Questions for Discussion   591     16.4   Finding the Mechanism of Inversible Heterogeneous Reactions   459   Questions for Discussion   591     16.5   Heterogeneous Reactions of Unusual Stoichiometrie   469   Further Rea					
14.6 Conclusions   420   18.5   Facilitated Diffusion   539					
Questions for Discussion		· · · · · · · · · · · · · · · · · · ·		<u>-</u>	
Problems					
Further Reading					
Sabstration					
15.1   Where Adsorption is Important		Further Redaing	423		
15.1   Where Adsorption is Important	15	Adsorption	424		
15.2   Adsorbents and Adsorption Isotherms		15.1 Where Adsorption is Important	425		
15.3   Breakthrough Curves					
15.4   Mass Transfer Effects					
15.5   Other Characteristics of Adsorption					
15.6   Conclusions   450   Questions for Discussion   450   Questions for Discussion   565   Problems   450   Problems   566   Problems   450   Further Reading   566					
Questions for Discussion Problems Further Reading  PART IV Diffusion Coupled With Other Processes  General Questions and Heterogeneous Chemical Reactions  16. General Questions and Heterogeneous or Homogeneous?  16.1 Is the Reaction Heterogeneous or Homogeneous?  16.2 What is a Diffusion-Controlled Reaction?  16.3 Diffusion and First-Order Heterogeneous Reactions  16.4 Finding the Mechanism of Irreversible Heterogeneous Reactions  16.5 Heterogeneous Reactions of Unusual Stoichiometries  16.6 Conclusions Questions for Discussion Questions for Discussion  473 Questions for Discussion  474  Problems  179  Questions for Discussion  475  Questions for Discussion  476  Questions for Discussion  477  Analogies Among Mass, Heat, and Momentum Transfer  594  Mathematical Analogies Among Mass, Heat, and Momentum Transfer  595  456  20.1 Fundamentals of Heat Conduction  568  Further Reading  507  508  Fundamentals of Heat Conduction  568  Fundamentals of Heat Conduction  568  20.2 General Energy Balances  575  20.3 Heat Transfer Coefficients  579  20.4 Rate Constants for Heat Transfer  585  585  587  586  290  486  487  487  487  487  488  489  Questions for Discussion  591  594  594  594  594  594  594  595  594  596  597  598  598  598  598  598  598  598					
Problems Further Reading  PART IV Diffusion Coupled With Other Processes  6 General Questions and Heterogeneous Chemical Reactions 16.1 Is the Reaction Heterogeneous or Homogeneous? 16.2 What is a Diffusion-Controlled Reaction? 16.3 Diffusion and First-Order Heterogeneous Reactions 16.4 Finding the Mechanism of Irreversible Heterogeneous Reactions 16.5 Heterogeneous Reactions of Unusual Stoichiometries 16.6 Conclusions Questions for Discussion Questions for Discussion Questions for Discussion Questions for Discussion Problems  16.4 Simultaneous Heat and Mass Transfer  Sound Mathematical Analogies Among Mass, Heat, and Momentum Transfer  Sound Further Reading Sound Further Reading Sound Further Reading Sound Further Reading Sound Mathematical Analogies Among Mass, Heat, and Momentum Transfer Sound Further Reading Sound Further Reading Sound Mathematical Analogies Among Mass, Heat, and Momentum Transfer Sound Further Reading Further Reading Sound Further Reading Further Reading Sound Further Reading Sound Further Reading Sound Further Reading Sound Further Reading Further Reading Sound Further Reading Further Reading Further Reading Sound Further Reading					
Further Reading 452  20 Heat Transfer 568  PART IV Diffusion Coupled With Other Processes 20.1 Fundamentals of Heat Conduction 568  20 General Energy Balances 575 20.3 Heat Transfer Coefficients 579 20 Heat Transfer Coefficients 579 20 General Energy Balances 575 20 Heat Transfer Coefficients 579 20 Heat Transf					
PART IV Diffusion Coupled With Other Processes  20.1 Fundamentals of Heat Conduction 568 General Questions and Heterogeneous Chemical Reactions 579 16.1 Is the Reaction Heterogeneous or Homogeneous? 456 20.2 General Energy Balances 579 16.1 Is the Reaction Heterogeneous or Homogeneous? 456 20.3 Heat Transfer Coefficients 579 16.2 What is a Diffusion-Controlled Reaction? 457 20.5 Conclusions 591 16.3 Diffusion and First-Order Heterogeneous Reactions 459 16.4 Finding the Mechanism of Irreversible Heterogeneous Reactions 465 16.5 Heterogeneous Reactions of Unusual Stoichiometries 469 16.6 Conclusions Questions for Discussion Problems 591 16.6 Conclusions Questions for Discussion 473 Questions for Discussion 473 Problems 594 21.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer 598				Further Reading	566
General Questions and Heterogeneous Chemical Reactions  455  20.2 General Energy Balances 575 20.3 Heat Transfer Coefficients 579 16.1 Is the Reaction Heterogeneous or Homogeneous? 456 20.4 Rate Constants for Heat Transfer 585 16.2 What is a Diffusion-Controlled Reaction? 457 20.5 Conclusions 591 16.6 Finding the Mechanism of Irreversible Heterogeneous Reactions 16.5 Heterogeneous Reactions of Unusual Stoichiometries 469 16.6 Conclusions 473 Questions for Discussion 473 Questions for Discussion 473 Problems 474  474  21.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer 594		Tarvier Accusing	732	20 Heat Transfer	568
General Questions and Heterogeneous Chemical Reactions  455  20.2 General Energy Balances 575 20.3 Heat Transfer Coefficients 579 16.1 Is the Reaction Heterogeneous or Homogeneous? 456 20.4 Rate Constants for Heat Transfer 585 16.2 What is a Diffusion-Controlled Reaction? 457 20.5 Conclusions 591 16.6 Diffusion and First-Order Heterogeneous Reactions 16.5 Heterogeneous Reactions of Unusual Stoichiometries 469 16.6 Conclusions 473 Questions for Discussion 473 Questions for Discussion 473 Problems 474  474  21.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer 594	PAR	RT IV Diffusion Coupled With Other Processes		20.1 Fundamentals of Heat Conduction	568
20.3 Heat Transfer Coefficients 579  16.1 Is the Reaction Heterogeneous or Homogeneous? 456 20.4 Rate Constants for Heat Transfer 585  16.2 What is a Diffusion-Controlled Reaction? 457 20.5 Conclusions 591  16.3 Diffusion and First-Order Heterogeneous Reactions 459 Questions for Discussion 591  16.4 Finding the Mechanism of Irreversible Heterogeneous Reactions 465 Problems 591  16.5 Heterogeneous Reactions of Unusual Stoichiometries 469 Further Reading 593  16.6 Conclusions 473 Questions for Discussion 473 Problems 474 21.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer 594	16	Conoral Questions and Heterogeneous Chamical Desetions	455		575
16.1 Is the Reaction Heterogeneous or Homogeneous?45620.4 Rate Constants for Heat Transfer58516.2 What is a Diffusion-Controlled Reaction?45720.5 Conclusions59116.3 Diffusion and First-Order Heterogeneous Reactions459Questions for Discussion59116.4 Finding the Mechanism of Irreversible Heterogeneous Reactions465Problems59116.5 Heterogeneous Reactions of Unusual Stoichiometries469Further Reading59316.6 Conclusions473Simultaneous Heat and Mass Transfer594Questions for Discussion47321.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer594	0	General Questions and reterogeneous Chemical Reactions	455		579
16.2What is a Diffusion-Controlled Reaction?45720.5Conclusions59116.3Diffusion and First-Order Heterogeneous Reactions459Questions for Discussion59116.4Finding the Mechanism of Irreversible Heterogeneous Reactions465Problems59116.5Heterogeneous Reactions of Unusual Stoichiometries469Further Reading59316.6Conclusions473Simultaneous Heat and Mass Transfer594Problems47421.1Mathematical Analogies Among Mass, Heat, and Momentum Transfer594		16.1 Is the Reaction Heterogeneous or Homogeneous?	456		585
16.3Diffusion and First-Order Heterogeneous Reactions459Questions for Discussion59116.4Finding the Mechanism of Irreversible Heterogeneous Reactions465Problems59116.5Heterogeneous Reactions of Unusual Stoichiometries469Further Reading59316.6Conclusions473Simultaneous Heat and Mass Transfer594Problems47421.1Mathematical Analogies Among Mass, Heat, and Momentum Transfer594		16.2 What is a Diffusion-Controlled Reaction?	457		
16.4 Finding the Mechanism of Irreversible Heterogeneous Reactions 465 16.5 Heterogeneous Reactions of Unusual Stoichiometries 469 16.6 Conclusions Questions for Discussion Problems 473 Problems 473 Simultaneous Heat and Mass Transfer 474 21.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer 594		16.3 Diffusion and First-Order Heterogeneous Reactions			
16.5 Heterogeneous Reactions of Unusual Stoichiometries 469 Further Reading 593 16.6 Conclusions 473 Questions for Discussion 473 Problems 474 Simultaneous Heat and Mass Transfer 594 21.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer 594		16.4 Finding the Mechanism of Irreversible Heterogeneous Reactions	465		
16.6 Conclusions Questions for Discussion 473 Problems 473 And Discussion 473 And Discussion 473 And Discussion 474 And Discussion 473 And Discussion 473 And Discussion 473 And Discussion 474 And Discussion 473 And Mass Transfer 474 And Mass Transfer 594					
Questions for Discussion473Simultaneous Heat and Mass Transfer594Problems47421.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer594					
Problems 474 21.1 Mathematical Analogies Among Mass, Heat, and Momentum Transfer 594		Questions for Discussion		Simultaneous Heat and Mass Transfer	594
		- · · · · · · · · · · · · · · · · · · ·		21.1 Mathematical Analogies Among Mass. Heat, and Momentum Transfer	594
		Further Reading			

	٠	٠	
X	1	1	

21.3	Drying	604
21.4	Design of Cooling Towers	609
21.5	Thermal Diffusion and Effusion	615
21.6	Conclusions	621
	Questions for Discussion	621
	Problems	622
	Further Reading	624
Index		626