Contents

Preface xix

Acknowledgement xxi

1	Introduction, History, and Applications 1
	John R. Grace
1.1	Definition and Origins 1
1.2	Terminology 2
1.3	Applications 3
1.4	Other Reasons for Studying Fluidized Beds 4
1.5	Sources of Information on Fluidization 8
	References 8
	Problems 9
2	Properties, Minimum Fluidization, and Geldart
	Groups 11
	John R. Grace
2.1	Introduction 11
2.2	Fluid Properties 11
2.2.1	Gas Properties 11
2.2.2	Liquid Properties 12
2.3	Individual Particle Properties 12
2.3.1	Particle Diameter 12
2.3.2	Particle Shape 12
2.3.3	Density and Internal Porosity 13
2.3.4	Surface Roughness 14
2.3.5	Terminal Settling Velocity 14
2.3.6	Coefficients of Restitution (Particle-Particle and
	Particle-Wall) 15
2.3.7	Dielectric Constant and Electrical Conductivity 16
2.3.8	Thermal Properties 16
2.4	Bulk Particle Properties 16
2.4.1	Mean Particle Diameter and Particle Size Distribution 16
2.4.2	Bulk Density, Voidage, and "Flowability" 16
2.5	Minimum Fluidization Velocity 18
2.5.1	Measuring U_{mf} Experimentally 18
	C my 1



2.5.1

2.5.1.1	Pressure Drop vs. Superficial Velocity Method 18
2.5.1.2	Other Experimental Methods of Determining U_{mf}
	Experimentally 20
2.5.2	Predicting U_{mf} Based on Particle and Fluid Properties 20
2.5.3	Other Factors Influencing the Minimum Fluidization Velocity 23
2.6	Geldart Powder Classification for Gas Fluidization 24
2.7	Voidage at Minimum Fluidization 27
	Solved Problem 28
	Notations 28
	References 29
	Problems 31
	1100icins 31
3	Liquid Fluidization 33
3	Renzo Di Felice and Alberto Di Renzo
3.1	Introduction 33
3.2	Field of Existence 33
	Overall Behaviour 35
3.3	
3.4	Superficial Velocity–Voidage Relationship 37
3.5	Particle Segregation and Mixing 40
3.6	Layer Inversion Phenomena 41
3.6.1	Predicting the Layer Inversion Voidage (via the Particle Segregation
0.40	Model) 43
3.6.2	Layer Inversion Velocity 46
3.7	Heat and Mass Transfer 46
3.7.1	Interphase Transfer 46
3.7.2	Bed-to-Surface Transfer 47
3.8	Distributor Design 48
	Solved Problems 48
	Notations 51
	References 52
	Problems 53
4	Gas Fluidization Flow Regimes 55
	Xiaotao Bi
4.1	Onset of Fluidization 55
4.2	Onset of Bubbling Fluidization 55
4.3	Onset of Slugging Fluidization 57
4.4	Onset of Turbulent Fluidization 58
4.5	Termination of Turbulent Fluidization 62
4.6	Fast Fluidization and Circulating Fluidized Bed 62
4.7	Flow Regime Diagram for Gas-Solid Fluidized Beds 64
4.8	Generalized Flow Diagram for Gas-Solid Vertical Transport 65
4.9	Effect of Pressure and Temperature on Flow Regime
	Transitions 68
	Solved Problems 70
	Notations 71
	References 72
	Problems 74

_	Formation and all throught making of Floridina d Dad
5	Experimental Investigation of Fluidized Bed
	Systems 75
	Naoko Ellis
5.1	Introduction 75
5.1.1	Design Goals 75
5.1.2	Purpose of Experiments 76
5.2	Configuration and Design 76
5.2.1	Column Material 78
5.2.2	Distributor Plate 79
5.2.3	Plenum Chamber 81
5.2.4	Feeding System (See Also Chapter 11) 81
5.2.4.1	Hopper Design 82
5.2.5	Auxiliary Components 83
5.2.5.1	Secondary Injection of Fluid 84
5.3	Fluidizability and Quality of Fluidization 84
5.3.1	Characterization of Flowability of Particles 84
	Particle Properties and Fluidizability 86
5.3.2	
5.3.3	Quality of Fluidization 86
5.4	Instrumentation and Measurements 87
5.4.1	Pressure Measurements 87
5.4.2	Thermal Sensors 89
5.4.3	Optical Probes 89
5.4.4	Non-invasive Measurements 90
5.4.5	Visualization Measurements 91
5.4.6	Acoustic Emission Measurements 92
5.4.7	Solids Circulation Flux 92
5.4.8	Gas or Solids Sampling 92
5.4.9	Mixing and Residence Time Distribution 93
5.5	Operation of Fluidized Beds 93
5.5.1	Start-Up and Shutdown 94
5.5.2	Steady-State Operation 94
5.6	Data Analysis 95
5.6.1	Frequency Analysis 95
5.6.2	Bivariate Time Series 96
5.6.2.1	Joint Probability Density Function 96
5.6.2.2	Cross-Correlation Function 96
5.6.2.3	Cross-Spectral Density Function 97
5.6.3	Other Signal Analyses 98
5.0.5	Solved Problem 98
	Notations 98
	References 100
	Problems 104
	I TODICHIS 107
6	Computational Fluid Dynamics and Its Application to
	Fluidization 109
	Tingwen Li and Yupeng Xu
6.1	Two-Fluid Model 110

Governing Equations 110

6.1.1

6.1.2	Kinetic Granular Theory 112
6.1.3	Frictional Model 114
6.1.4	Limitations of TFM 115
6.2	Discrete Particle Method 115
6.2.1	Governing Equations 116
6.2.2	Limitations of CFD-DPM 119
6.3	Gas-Solid Interaction 119
6.3.1	Gas-Solid Drag 119
6.3.2	Gas-Solid Heat Transfer 121
6.4	Boundary Conditions 122
6.5	Example and Discussion 123
6.5.1	TFM Simulation of a Bubbling Fluidized Bed with Tube
	Bundle 123
6.5.2	CFD-DPM Simulation of a Small-Scale Circulating Fluidized
	Bed 124
6.5.3	Discussion 125
6.6	Conclusion and Perspective 126
	Solved Problem 126
	Notations 127
	References 128
	120
7	Hydrodynamics of Bubbling Fluidization 131
	John R. Grace
7.1	Introduction 131
7.2	Why Bubbles Form 133
7.3	Analogy Between Bubbles in Fluidized Beds and Bubbles in
	Liquids 134
7.4	Hydrodynamic Properties of Individual Bubbles 135
7.4.1	Rising Velocity of Single Bubbles 135
7.4.2	Bubble Wakes 135
7.4.3	Bubble Breakup and Maximum Stable Size 137
7.4.4	Interphase Mass Transfer and Cloud Formation 137
7.5	Bubble Interactions and Coalescence 139
7.6	Freely Bubbling Beds 139
7.6.1	Flow of Gas by Translation of Bubbles 139
7.6.2	Mean Bubble Diameter as a Function of Height and Gas
,	Velocity 140
7.6.3	Rising Velocity of Bubbles in Freely Bubbling Bed 142
7.6.4	Bubble Volume Fraction (Holdup) 142
7.6.5	Bed Expansion 142
7.6.6	Radial Nonuniformity of Bubbles and Its Effect on Mixing 143
7.6.7	Turnover Time, Solids Mixing, and Particle Segregation 144
7.6.8	Gas Mixing 145
7.7	Other Factors Influencing Bubbles in Gas-Fluidized Beds 146
, . ,	Solved Problem 147
	Notations 147
	References 148
	Problems 152

8	Slug Flow 153
	John R. Grace
8.1	Introduction 153
8.2	Types of Slug Flow 153
8.3	Analogy Between Slugs in Fluidized Beds and Slugs in Liquids 155
8.4	Experimental Identification of the Slug Flow Regime 155
8.5	Transition to Slug Flow 156
8.6	Properties of Single Slugs 156
8.7	Hydrodynamics of Continuous Slug Flow 158
8.7.1	Slug Rising Velocity 158
8.7.2	Slug Spacing and Length 158
8.7.3	Time Between Successive Slugs and Slug Frequency 159
8.7.4	Bed Expansion 159
8.7.5	Uniformity and Symmetry of Flow 159
8.8	Mixing of Solids and Gas in Slugging Beds 159
8.9	Slugging Beds as Chemical Reactors 160
	Solved Problem 160
	Notations 161
	References 161
9	Turbulent Fluidization 163
	Xiaotao Bi
9.1	Introduction 163
9.2	Flow Structure 165
9.2.1	Axial and Radial Voidage Distribution 165
9.2.2	Local Void Size and Rise Velocity 166
9.2.3	Void Phase Volume Fraction, Void Phase, and Dense Phase Solids
	Holdup 167
9.3	Gas and Solids Mixing 168
9.3.1	Gas Mixing 168
9.3.2	Solids Mixing 171
9.4	Effect of Column Diameter 172
9.5	Effect of Fines Content 173
,	Solved Problem 173
	Notations 175
	References 176
	Problems 180
10	Entrainment from Bubbling and Turbulent Beds 181
10	Farzam Fotovat
10.1	Introduction 181
10.1	Definitions 182
10.2.1	
	Transport Disengagement Height (TDH) 182 Elutriation 184
10.2.2	
10.3	Ejection of Particles into the Freeboard 184
10.4	Entrainment Beyond the Transport Disengagement Height 185
10.5	Entrainment from Turbulent Fluidized Beds 190

10.6	Parameters Affecting Entrainment of Solid Particles from Fluidized Beds 191
10.6.1	Properties of Particles 191
10.6.2	Geometry and Shape of Freeboard 192
10.6.3	Dense Bed Height 192
10.6.4	Internals 192
10.6.5	Pressure and Temperature 193
10.6.6	Electrostatic Charges 194
10.7	Possible Means of Reducing Entrainment 195
	Solved Problem 195
	Notations 196
	References 197
	Problems 201
11	Standpipes and Return Systems, Separation Devices,
	and Feeders 203
	Ted M. Knowlton and Surya B. Reddy Karri
11.1	Standpipes and Solids Return Systems 203
11.1.1	Packed Bed Flow 206
11.1.2	Fluidized Bed Flow 206
11.1.3	Types of Standpipes 206
11.1.3.1	Overflow Fluidized Standpipe 207
11.1.3.2	Underflow Packed Bed Standpipe 208
11.1.3.3	Underflow Fluidized Standpipes 210
11.2	Standpipes in Recirculating Solids Systems 212
11.2.1	Automatic Solids Recirculation Systems 212
11.2.2	Controlled Solids Recirculation Systems 213
11.2.3	Function of a Standpipe 215
11.3	Standpipes Used with Nonmechanical Solids Flow Devices 216
11.3.1	Nonmechanical Solids Control Mode Operation 216
11.3.2	Automatic Solids Flow Devices 219
11.3.2.1	Cyclone Diplegs 219
11.4	Solids Separation Devices 222
11.4.1	Cyclones 222 Cyclone Types 223
11.4.1.1 11.4.1.2	Flow Patterns in Cyclones 225
11.4.1.3	Cyclones in Series 226
11.4.1.4	Cyclones in Parallel 226
11.4.1.5	Internal vs. External Cyclones 227
11.4.1.6	Cyclone Inlet Design 227
11.4.1.7	Effect of Solids Loading 227
11.4.1.8	Gas Outlet Tube 228
11.4.1.9	Inlet Gas Velocity 228
11.4.1.10	Cyclone Dimensions and Design 228
11.4.2	Other Separation Devices 229
11.4.2.1	Particulate Scrubbers 229
11.4.2.2	Fabric Filters 229

11.4.2.3 11.4.2.4 11.4.2.5 11.5	Granular Bed Filters 230 Electrostatic Precipitators 230 U-Beams 230 Solids Flow Control Devices/Feeders 230 Solved Problem 232 Notations 233 References 235 Problems 237
12	Circulating Fluidized Beds 239 Chengxiu Wang and Jesse Zhu
12.1	Introduction 239
12.1.1	What Is a Circulating Fluidized Bed? 239
12.1.2	Key Characteristics of Circulating Fluidized Beds 240
12.2	Basic Parameters 241
12.3	Axial Profiles of Solids Holdup/Voidage 243
12.4	Radial Profiles of Solids Distribution 246
12.5	The Circulating Turbulent Fluidized Bed 249
12.6	Micro-flow Structure 250
12.7	Gas and Solids Mixing 256
12.8	Reactor Performance of Circulating Fluidized Beds 258
12.9	Effect of Reactor Diameter on CFB Hydrodynamics 261
	Notations 262
	References 263
	Problems 268
13	Operating Challenges 269 Poupak Mehrani and Andrew Sowinski
13.1	Electrostatics 269
13.1.1	Measurement and Prediction of Electrostatic Charge 271
13.1.2	Mitigation Techniques 272
13.1.3	Summary 273
13.2	Agglomeration 273
13.3	Attrition 274
13.3.1	Modelling Attrition 276
13.4	Wear 278
	Solved Problems 280
	Notations 286
	References 287
	Problem 290
14	Heat and Mass Transfer 291
	Dening Eric Jia
14.1	Heat Transfer in Fluidized Beds 291
14.1.1	Interphase Heat Transfer 293
14.1.2	Bed-to-Surface Heat Transfer 294
14.1.2.1	General Considerations 294

14.1.2.2	Particle Convective Component 294	
14.1.2.3	Gas Convection Component 298	
14.1.2.4	Maximum Heat Transfer Coefficient 299	
14.1.3	Heat Transfer Correlations for Fluidized Beds 302	
14.1.3.1	Correlations for Bed-to-Surface Heat Transfer 303	
14.1.4	Heat Transfer Between Fluidized Bed and Immersed Surfaces 3	304
14.1.4.1	Correlations for Vertical Tubes 306	
14.1.4.2	Martin's Correlations for Heat Transfer to Immersed Surfaces 3	809
14.1.4.3	Finned Tubes and Non-cylindrical Tubes 312	
14.1.4.4	Tubes in Freeboard Region 313	
14.1.4.5	Methods of Augmenting Bed-to-Surface Heat Transfer 314	
14.1.5	Radiative Heat Transfer 314	
14.1.6	Heat Transfer in Fast and Circulating Fluidized Beds 316	
14.2	Mass Transfer in Fluidized Beds 318	
14.2.1	Particle and Fluid Mass Transfer in the Dense Phase 318	
14.2.2	Bubble to Dense-Phase Interphase Mass Transfer 320	
	Solved Problem 320	
	Notations 323	
	References 325	
	Problem 329	
15	Catalytic Fluidized Bed Reactors 333	
	Andrés Mahecha-Botero	
15.1	Introduction 333	
15.1 15.2		
	Reactor Design Considerations 334	
15.2	Reactor Design Considerations 334	
15.2 15.2.1	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334	
15.2 15.2.1 15.2.2	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334	
15.2 15.2.1 15.2.2 15.3	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334	
15.2 15.2.1 15.2.2 15.3 15.3.1	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345	
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2 15.4.2	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345 Single-Phase Models 346 Models Based on Standard Two-Phase Theory 349	849
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2 15.4.2.1	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345 Single-Phase Models 346 Models Based on Standard Two-Phase Theory 349	249
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2 15.4.2.1 15.4.3	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345 Single-Phase Models 346 Models Based on Standard Two-Phase Theory 349 Division of Flow and Calculation of Fluidized Bed Parameters 3	349
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2 15.4.2.1 15.4.3.1 15.4.3.1	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345 Single-Phase Models 346 Models Based on Standard Two-Phase Theory 349 Division of Flow and Calculation of Fluidized Bed Parameters 3-More Sophisticated Models 352	349
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2 15.4.2.1 15.4.3.1 15.4.3.1 15.4.4	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345 Single-Phase Models 346 Models Based on Standard Two-Phase Theory 349 Division of Flow and Calculation of Fluidized Bed Parameters 3 More Sophisticated Models 352 Comprehensive Reactor Modelling 352	349
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2 15.4.2.1 15.4.3.1 15.4.3.1 15.4.4	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345 Single-Phase Models 346 Models Based on Standard Two-Phase Theory 349 Division of Flow and Calculation of Fluidized Bed Parameters 3 More Sophisticated Models 352 Comprehensive Reactor Modelling 352 Computational Fluid Dynamics (CFD) Models for Fluidized Bed	349
15.2 15.2.1 15.2.2 15.3 15.3.1 15.3.2 15.3.2.1 15.3.2.2 15.3.2.3 15.4 15.4.1 15.4.2 15.4.2.1 15.4.3 15.4.3.1 15.4.4.1 15.4.4.1	Reactor Design Considerations 334 Suitability of Fluidized Beds for Catalytic Processes 334 Reactor Types by Flow Regime and Phase 334 Reactor Modelling 334 Model Development 337 Model Structure and Reaction Considerations 338 Flow Regime Considerations 338 Reaction Equilibrium Considerations 339 Reaction Kinetics Considerations 340 Fluidized Bed Catalytic Reactor Models 342 Mass/Mole and Energy Balances 345 Reaction Rate Expressions 345 Single-Phase Models 346 Models Based on Standard Two-Phase Theory 349 Division of Flow and Calculation of Fluidized Bed Parameters 3 More Sophisticated Models 352 Comprehensive Reactor Modelling 352 Computational Fluid Dynamics (CFD) Models for Fluidized Bed Catalytic Reactors 353	249

15.5	Conclusions 356
	Notations 357
	References 358
	Problems 361
16	Fluidized Beds for Gas-Solid Reactions 363
	Jaber Shabanian and Jamal Chaouki
16.1	Introduction 363
16.2	Gas-Solid Reactions for a Single Particle 364
16.2.1	Reaction Models for Non-porous Particles 365
16.2.1.1	Shrinking Particle 366
16.2.1.2	Shrinking Unreacted Core Model 369
16.2.2	Reaction Models for Porous Particles 373
16.2.2.1	Reactions of Complete Consumption of the Particle 373
16.2.2.2	Reactions for Porous Particles of Unchanging Overall Size 374
16.2.3	Reaction Models for Solid-Solid Reactions Proceeding Through
	Gaseous Intermediates 377
16.3	Reactions of Solid Particles Alone 377
16.4	Conversion of Particles Bathed by Uniform Gas Composition in a
	Dense Gas-Solid Fluidized Bed 378
16.5	Conversion of Both Solids and Gas 381
16.5.1	Reactor Performance Calculation for a Bed of Fine Particles
	(Case I) 382
16.5.2	Reactor Performance Calculation for a Bed of Coarse Particles
	(Case II) 385
16.6	Thermal Conversion of Solid Fuels in Fluidized Bed Reactors 386
16.7	Final Remarks 390
	Solved Problems 391
	Acknowledgments 398
	Notations 398
	References 401
	Problems 403
17	Scale-Up of Fluidized Beds 405
	Naoko Ellis and Andrés Mahecha-Botero
17.1	Challenges of Scale 405
17.2	Historical Lessons 407
17.3	Influence of Scale on Hydrodynamics 408
17.3.1	Bubbling Fluidization 408
17.3.2	Turbulent Fluidization Flow Regime 410
17.3.3	Fast Fluidization 411
17.4	Approaches to Scale-Up 412
17.4.1	Framing Questions 412
17.4.2	General Approaches 412
17.4.3	Dimensional Similitude (Scaling Models) 413
17.4.4	Other Models 414

17.5	Practical Considerations 415
17.5.1	Purpose of Pilot-Scale Units 415
17.5.2	Pilot-Scale Units 416
17.5.2.1	Biomass Combined Heat and Power (CHP) Güssing Case 416
17.5.2.2	Dual Gasifier with CO ₂ Capture 417
17.5.2.3	Calcium Looping Technologies 419
17.6	Scale-Up and Industrial Considerations of Fluidized Bed Catalytic
17.0	Reactors 419
17.6.1	Challenges of Scale-Up of Fluidized Bed Catalytic Reactors 419
17.6.2	Practical Recommendations for Industrial Implementation of
	Reactor Systems 422
	Solved Problems 424
	Notations 426
	References 426
	Problems 429
4.0	
18	Baffles and Aids to Fluidization 431
101	Yongmin Zhang Industrial Motivation 431
18.1	
18.2	Baffles in Fluidized Beds 432
18.2.1	Clarification of Baffles in Low-Velocity Dense Fluidized Beds 432
18.2.2	Geometric Characteristics of Baffles 432 Horizontal Baffles 432
18.2.2.1 18.2.2.2	
18.2.2.3	Fixed Packings 436
18.2.3	Baffles in Low-Velocity Dense Fluidized Beds 439
18.2.3.1	Effect of Baffles on Bed Hydrodynamics 439 Performance of Baffles in Industrial Fluidized Bed Reactors 445
18.2.3.2 18.2.3.3	Performance of Baffles in Industrial Fluidized Bed Reactors 445 Other Findings and Applications 446
18.2.4	Baffles or Inserts in High-Velocity Fast Fluidized Beds 446
18.2.5	Design of Baffles for Industrial Fluidized Beds 447
18.3	Other Aids to Fluidization 449
18.3.1	Brief Introduction 449
18.3.2	Electrical Fields 450
18.3.3	Magnetic Fields 450
18.3.4	Pulsations and Vibrations 451
18.3.5	Glidants and Antistatic Agents 451
18.4	Final Remarks 452
10.1	Notations 452
	References 452
	Problem 455
19	Jets in Fluidized Beds 457
	Cedric Briens and Jennifer McMillan
19.1	Introduction 457
19.2	Jets at Gas Distributors 457
19.2.1	Criterion for Uniform Gas Distribution 459

19.2.1.1	"Dry" Distributor Pressure Drop 461
19.2.1.2	Actual Distributor Pressure Drop 461
19.2.2	Defluidized Zones 462
19.2.3	Erosion of Internals 464
19.2.3.1	Penetration of Upward Vertical Jets 465
19.2.3.2	Penetration of Horizontal, Inclined, and Downward Vertical Jets 466
19.2.3.3	Angle of Upward Jets 466
19.2.3.4	Merging and Coalescence 466
19.3	Mass Transfer, Heat Transfer, and Reaction in Distributor Jets 467
19.4	Particle Attrition and Tribocharging at Distributor Holes 467
19.5	Jets Formed in Fluidized Bed Grinding 469
19.5.1	Mechanisms 469
19.6	Applications 471
19.7	Jet Penetration 471
19.8	Solids Entrainment into Jets 471
19.9	Nozzle Design 472
19.9.1	Nozzle Inclination 472
19.9.2	Impact of Bed Hydrodynamics 473
19.9.3	Opposing Jets 473
19.10	Jet-Target Attrition 473
19.10.1	Prediction of Attrition Rates 474
19.11	Jets Formed When Solids Are Fed into a Fluidized Bed 475
19.11.1	Mechanisms 475
19.11.2	Applications 475
19.11.3	Jet Penetration 476
19.11.4	Solids Entrainment 476
19.11.5	Injection System Design 476
19.11.6	Nozzle Inclination 476
19.11.7	Impact of Bed Hydrodynamics 476
19.12	Jets Formed When Liquid Is Sprayed into a Gas-Fluidized
	Bed 477
19.12.1	Pure Liquid Jets 477
19.12.2	Mechanism for Gas-Liquid Jets 477
19.12.3	Applications 478
19.13	Jet Penetration 478
19.13.1	Solids Entrainment 478
19.13.2	Injection System Design 479
19.13.2.1	Upstream Piping Design 479
19.13.2.2	Spray Nozzle Design 480
19.13.2.3	Laboratory Nozzles 480
19.13.2.4	Non-rodable Commercial Nozzles 480
19.13.2.5	Rodable Commercial Nozzles 480
19.13.2.6	Downstream Attachments 481
19.13.2.7	Impact Attachments 481
19.13.2.8	Shrouds 481

19.13.2.8 19.13.2.9

Gas Jets 482

19.13.2.10 19.13.3 19.13.4 19.13.5	Draft Tubes 482 Nozzle Inclination 482 Interactions Between Spray Jets 483 Impact of Bed Hydrodynamics 483 Solved Problems 483 Notations 487
	References 488 Problem 497
20	Downer Reactors 499 Changning Wu and Yi Cheng
20.1	Downer Reactor: Conception and Characteristics 499
20.2	Hydrodynamics, Mixing, and Heat Transfer of Gas-Solid Flow in Downers 501
20.2.1	Basic Hydrodynamic Behaviour 501
20.2.2	Mixing Behaviour of Solids in Downers 503
20.2.3	Heat Transfer in Downers 506
20.3	Modelling of Hydrodynamics and Reacting Flows in Downers 508
20.3.1	Reaction Engineering Model 509
20.3.2	Eulerian–Eulerian Model 509
20.3.3	Eulerian–Lagrangian Model 511
20.4	Design and Applications of Downer Reactors 514
20.4.1	Inlet Design 514
20.4.2	Fast Separation of Gas and Solids at Downer Exit 517
20.4.3	High-Density Downer 518
20.4.4	Downer-Riser Coupled Reactors 518
20.4.5	Application Case 1: FCC 519
20.4.6	Application Case 2: Gasification 521
20.4.7	Application Case 3: Coal Pyrolysis in Plasma 521
20.5	Conclusions and Outlook 523
	Solved Problem 523
	Notations 525
	References 526
	Problems 528
21	Spouted (and Spout-Fluid) Beds 531 Norman Epstein
21.1	Introduction 531
21.2	Hydrodynamics 532
21.2.1	Constraints on Fluid Inlet Diameter and Cone Angle 532
21.2.2	Minimum Spouting Velocity 533
21.2.3	Maximum Spouting Velocity 535 Maximum Spouting Velocity 535
21.2.4	Fluid Flow in Annulus 535
21.2.5	Fluid Flow in Spout 536
21.2.6	Pressure Drop 536
21.2.7	Behaviour of Solid Particles 537
21.3	Heat and Mass Transfer 538

21.4	Chemical Reaction 538
21.5	Spouting vs. Fluidization 539
21.6	Spout-Fluid Beds 540
21.7	Non-conventional Spouted Beds 543
21.8	Applications 546
21.9	Multiphase Computational Fluid Dynamics 547
	Solved Problem 547
	Notations 548
	References 549
22	Three-Phase (Gas-Liquid-Solid) Fluidization 553
	Dominic Pjontek, Adam Donaldson, and Arturo Macchi
22.1	Introduction 553
22.1.1	General Description and Classification 553
22.1.2	Applications 554
22.2	Reactor Design and Scale-up 556
22.2.1	Reactor Design 556
22.2.2	Reactor Scale-up 558
22.3	Compartmental Flow Models 558
22.3.1	Plenum and Fluid Distributor 560
22.3.2	Fluidized Bed 561
22.3.3	Freeboard 562
22.4	Fluid Dynamics in Three-Phase Fluidized Beds 562
22.4.1	Flow Regimes 562
22.4.1.1	Minimum Fluidization 562
22.4.1.2	Bubbling Regimes 564
22.4.2	Phase Holdups 565
22.4.2.1	Modelling: Global (Bed Volume Averaged) 565
22.4.2.2	Bed Contraction vs Expansion 568
22.4.2.3	Particle Entrainment 568
22.5	Phase Mixing, Mass Transfer, and Heat Transfer 569
22.5.1	Phase Mixing 569
22.5.2	Surface-to-Bed Heat Transfer 570
22.5.3	Interphase Gas-Liquid and Liquid-Solid Mass Transfer 571
22.5.3.1	Gas-Liquid Mass Transfer 572
22.5.3.2	Liquid–Solid Mass Transfer 572
22.6	Summary 574
	Solved Problems 574
	Notations 582
	References 585

Index *591*

Problems 587