

Table of Contents

Chapter 1	Introduction	1
1.1	Background.....	1
1.2	Fluidized Bed Equipment.....	4
1.2.1	Applications	4
1.2.2	Fluidized Bed Gasifiers	5
1.2.3	Fluidized Bed Boilers.....	6
1.2.4	Application in Cement Industries.....	9
1.3	Features of Fluidized Beds.....	10
1.3.1	Advantages of Fluidized Bed Boilers	10
1.3.2	Features Specific to CFB Boiler	12
1.4	Fluidized Bed and Other Technology Options	13
1.4.1	Technological Options for Generation of Power from Solid Fuels	13
1.4.2	Improved Firing.....	15
1.4.3	Combined-Cycle Plants	16
1.4.4	Cost Implications	18
	References.....	19
Chapter 2	Hydrodynamics.....	21
2.1	Regimes of Fluidization	21
2.1.1	Packed Beds.....	25
2.1.2	Bubbling Fluidized Beds	25
2.1.3	Slugging	29
2.1.4	Turbulent Beds	29
2.1.5	Bubbling to Turbulent Transition.....	29
2.1.6	Terminal Velocity of a Particle.....	31
2.1.7	Freeboard and Furnace Heights	35
2.2	Fast Fluidized Bed.....	35
2.2.1	Characteristics of Fast Beds	35
2.2.2	Transition to Fast Fluidization	37
2.2.3	Dense Suspension Up-Flow.....	42
2.3	Hydrodynamic Regimes in a CFB	42
2.3.1	Difference in Operating Regimes of CFB Boilers and Reactors	43
2.4	Hydrodynamic Structure of Fast Beds	43
2.4.1	Axial Voidage Profile	43
2.4.2	Lateral Distribution of Voidage in a Fast Bed	48
2.5	Gas–Solid Mixing	52
2.5.1	Gas–Solid Slip Velocity	52
2.5.2	Dispersion	52
2.6	Scale-Up.....	53
2.6.1	Circulating Fluidized Bed	53
2.6.2	Bubbling Fluidized Bed.....	54
2.6.3	Cyclone	54

Nomenclature.....	55
Greek Symbols.....	56
Dimensionless Numbers.....	56
References.....	57
Chapter 3 Fluidized Bed Gasification.....	59
3.1 Types of Gasifiers.....	60
3.1.1 Entrained Bed.....	61
3.1.2 Fluidized Bed.....	62
3.1.3 Spouted Bed.....	62
3.1.4 Fixed/Moving Bed.....	62
3.2 Theory.....	63
3.2.1 Pyrolysis or Devolatilization.....	64
3.2.2 Combustion.....	66
3.2.3 Gasification.....	66
3.2.4 Composition of Gas Yield.....	67
3.3 Effect of Operating Parameters on Gasification.....	69
3.3.1 Boudouard Reaction.....	69
3.3.2 Water–Gas.....	69
3.3.3 Methanation.....	69
3.4 Effect of Feed Properties on Gasification.....	71
3.4.1 Fuel Reactivity.....	71
3.4.2 Volatile Matter.....	72
3.4.3 Ash.....	73
3.4.4 Moisture.....	73
3.5 Fluidized Bed Gasification.....	74
3.5.1 Comparison of Bubbling and Circulating Fluidized Bed Gasifiers.....	75
3.5.2 Types of Fluidized Bed Gasifiers.....	75
3.6 Examples of Some Fluidized Bed Gasifiers.....	77
3.6.1 Winkler Gasifier.....	77
3.6.2 KRW Gasifier.....	79
3.6.3 Spouted Bed Partial Gasifier.....	79
3.6.4 Foster Wheeler Atmospheric CFB Gasifier.....	80
3.6.5 Battelle/Columbus Indirect Gasifier.....	81
3.6.6 Halliburton KBR Transport Reactor.....	82
3.6.7 Carbon Dioxide Acceptor Process.....	82
3.7 Gas Cleaning.....	83
3.7.1 Sulfur and Other Chemical Contaminants Removal.....	83
3.7.2 Tar Removal.....	84
3.7.3 Particulate Removal.....	85
3.8 Design Considerations.....	85
3.8.1 Gasifier Efficiency.....	85
3.8.2 Equivalence Ratio.....	86
3.8.3 Gas Composition.....	88
3.8.4 Energy and Mass Balance.....	89
3.8.5 Bed Materials.....	89
3.8.6 Gasifier Sizing.....	90
3.8.7 Alternative Design Approach.....	95
3.9 Modeling of Fluidized Bed Gasification.....	96
Appendix 3A.....	97
Estimating Equilibrium Gas Composition.....	97

Appendix 3B	99
An Example of a Fluidized Bed Biomass Gasifier	99
Nomenclature	99
Greek Symbols	100
References	100
 Chapter 4 Combustion.....	103
4.1 Stages of Combustion.....	103
4.1.1 Heating and Drying	103
4.1.2 Devolatilization.....	104
4.1.3 Volatile Combustion.....	106
4.1.4 Char Combustion.....	107
4.1.5 Burning Rate of Char in Fluidized Beds	109
4.1.6 Communion Phenomena during Combustion.....	115
4.2 Factors Affecting Combustion Efficiency	117
4.2.1 Feed Stock	117
4.2.2 Operating Conditions.....	119
4.3 Combustion in Bubbling Fluidized Bed Boilers.....	120
4.3.1 Recirculation of Fly Ash	120
4.3.2 Effect of Design Parameters on Combustion Efficiency	120
4.4 Combustion in Circulating Fluidized Bed Boilers	122
4.4.1 Combustion of Char Particles	123
4.4.2 Effect of Cyclone Design on Combustion Efficiency.....	125
4.4.3 Some Combustion Design Considerations.....	125
4.4.4 Performance Modeling	127
4.5 Biomass Combustion.....	127
4.5.1 Agglomeration	129
4.5.2 Fouling	130
4.5.3 Corrosion Potential in Biomass Firing.....	130
Nomenclature	130
Greek Symbols	131
Dimensionless Numbers	132
References	132
 Chapter 5 Emissions.....	135
5.1 Air Pollution	135
5.1.1 Pollutants	136
5.1.2 Emission Standards.....	141
5.2 Sulfur Dioxide Emission	141
5.2.1 Chemical Reactions.....	142
5.2.2 Reactions on Single Sorbent Particles	146
5.2.3 Reactivity of Sorbents	148
5.2.4 Sulfur Capture in Fluidized Beds.....	150
5.2.5 Simple Model for Sulfur Capture in CFB Boilers.....	154
5.2.6 Selection of Sorbent	157
5.3 Nitrogen Oxide Emission	159
5.3.1 Sources of NO _x	159
5.3.2 Methods of Reduction of NO _x Emissions.....	159
5.3.3 NO _x Emission from CFB.....	161

5.4	Nitrous Oxide Emission	162
5.4.1	Mechanism of Formation of N_2O in CFB	162
5.4.2	Effects of Operating Parameters on N_2O	163
5.4.3	Reduction of N_2O	164
5.5	Mercury Emission.....	164
5.5.1	Sorbent Injection.....	164
5.5.2	Electro-Catalytic Oxidation.....	164
5.5.3	Precombustion Technologies.....	165
5.6	Carbon Monoxide Emission	165
5.7	Carbon Dioxide Emission	165
5.8	Emission of Trace Organics	166
5.9	Particulate Emission	166
5.9.1	Ash Characteristics	166
	Nomenclature.....	168
	Greek Symbols	169
	References.....	169

Chapter 6 Heat Transfer..... 173

6.1	Gas-to-Particle Heat Transfer.....	173
6.1.1	Gas-to-Particle Heat Transfer Equations	173
6.1.2	Heating of Gas and Solids in the Fast Bed.....	176
6.2	Heat Transfer in Circulating Fluidized Beds.....	178
6.2.1	Mechanism of Heat Transfer.....	178
6.2.2	Theory.....	179
6.2.3	Experimental Observations in a CFB Boiler	184
6.2.4	Effect of Vertical Fins on the Walls	187
6.3	Heat Transfer in Bubbling Fluidized Bed.....	189
6.3.1	Mechanistic Model	190
6.3.2	Experimental Observations in Bubbling Fluidized Beds	195
6.3.3	Heat-Transfer Correlation in Bubbling Beds.....	197
6.3.4	Use of Design Graphs	197
6.3.5	Calculation Based on Tables.....	200
6.4	Freeboard Heat Transfer in Bubbling Fluidized Beds.....	201
6.5	Heat Transfer in Commercial-Size CFB Boilers.....	202
6.5.1	Heat Transfer to the Walls of Commercial CFB Boilers	202
6.5.2	Wing Walls.....	202
6.5.3	Heat-Transfer Variation along the Furnace Height	203
6.5.4	Circumferential Distribution of Heat-Transfer Coefficient	203
	Nomenclature.....	205
	Greek Symbols	207
	Dimensionless Numbers	207
	References.....	207

Chapter 7 Bubbling Fluidized Bed Boiler..... 211

7.1	Description of a BFB Boiler	211
7.1.1	Feedstock Preparation and Feeding	211
7.1.2	Air and Gas Handling.....	213
7.1.3	Ash and Emission Systems	213
7.1.4	Steam Generation System	215
7.1.5	Combustion Chamber.....	215

7.2	Features of BFB Boilers	215
7.2.1	Advantages.....	215
7.2.2	Limitations	216
7.3	Thermal Design of Bubbling Fluidized Bed Boilers.....	216
7.3.1	Overall Heat Balance of the Boiler.....	216
7.3.2	Boiler Efficiency	219
7.3.3	Energy Balance in Dense Bubbling Bed	221
7.3.4	Heat Balance of Boiler Components.....	223
7.3.5	Mass Flow Rates of Fuel and Air	226
7.3.6	Gas-Side Heat Balance	226
7.4	Combustion in Bubbling Fluidized Bed	228
7.4.1	Coal Combustion in BFB Boilers	228
7.4.2	Minimization of Combustible Losses in BFB Combustors.....	230
7.5	Furnace Design	234
7.5.1	Basic Design of Furnace	235
7.5.2	Part-Load Operations.....	238
7.5.3	Other Operating Conditions	240
7.6	Start-Up Procedure and Control.....	242
7.6.1	Start-Up Procedure	243
7.6.2	Control of BFB Boiler.....	243
7.7	Some Operational Problems and Remedies	246
7.7.1	Erosion of In-Bed Components.....	246
7.8	Design of Feed Systems for BFB Bed Boiler.....	248
	Nomenclature.....	249
	Greek Symbols	251
	References.....	251

Chapter 8 Circulating Fluidized Bed Boiler **253**

8.1	General Arrangement	253
8.1.1	Air System	253
8.1.2	Flue Gas Stream	255
8.1.3	Solid Stream	255
8.1.4	Water–Steam Circuit	255
8.2	Types of CFB Boilers.....	257
8.2.1	Boilers without Bubbling Bed Heat Exchangers.....	257
8.2.2	Boilers with Bubbling Fluidized Bed Heat Exchanger	258
8.2.3	Boilers with Inertial or Impact Separators.....	259
8.2.4	Boilers with Vertical, Noncircular Cyclones	259
8.2.5	Other Types	259
8.3	Non-CFB Solid Circulation Boilers	259
8.3.1	Circo-Fluid Boilers.....	259
8.3.2	Low-Solid Circulation Boiler.....	260
8.3.3	Circulating Moving Bed Boiler.....	260
8.4	Combustion in a Circulating Fluidized Bed Furnace	263
8.5	Design of CFB Boilers	264
8.5.1	Combustion Calculations.....	264
8.5.2	Heat Balance.....	264
8.5.3	Mass Balance.....	266
8.5.4	Flow Split.....	266
8.5.5	Control of Bed Inventory	267
8.5.6	Some Operating Issues	270

8.6	Furnace Design	271
8.6.1	Furnace Cross-Section	273
8.6.2	Width and Breadth Ratio	273
8.6.3	Furnace Openings	276
8.7	Design of Heating Surfaces	277
8.7.1	Effect of Fuel Type on Furnace Heat Load	278
8.7.2	Heat Absorption in the External Heat Exchanger	280
8.7.3	Heat Absorption in the Furnace and Rest of the Boiler	280
8.7.4	Heat Balance around a CFB Loop	285
8.8	Auxiliary Power Consumption	287
8.9	Control of CFB Boilers	287
8.9.1	Part-Load Operation	287
8.9.2	Load Control Options	289
8.10	Supercritical CFB Boiler	291
8.10.1	Supercritical Operation	292
8.10.2	Vertical vs. Wrapped Tube Arrangement	292
8.10.3	Low Heat Flux	293
8.10.4	Cost Advantage	293
	Nomenclature	293
	Greek Symbols	296
	References	296

Chapter 9 Material Issues..... 299

9.1	Material Selection Criteria	299
9.1.1	Structural Requirements	299
9.1.2	Heat-Transfer Duty	300
9.2	Erosion Potential	301
9.2.1	Basics of Erosion	301
9.2.2	Types of Erosion	304
9.2.3	Erosion in Bubbling Fluidized Beds	304
9.2.4	Options for Reduction of Erosion in Bubbling Beds	306
9.2.5	Erosion in CFB Boilers	307
9.3	Corrosion Potentials	311
9.3.1	Corrosion Mechanisms	312
9.3.2	Examples of Fire-Side Corrosion	312
9.3.3	Chemistry of Fire-Side Corrosion of Heating Surfaces	313
9.3.4	Chlorine Corrosion	315
9.3.5	Vanadium Corrosion	316
9.3.6	Prevention of High-Temperature Corrosion	316
9.3.7	Erosion–Corrosion	317
9.3.8	Fouling and Deposit Formation	318
9.4	Steels Used in Fluidized Bed Boilers	318
9.4.1	Carbon and Alloy Steels	318
9.5	Refractory and Insulations	320
9.5.1	Importance of Lining	320
9.5.2	Properties of Refractory	320
9.5.3	Types of Refractory	321
9.5.4	Types of Insulation	322
9.5.5	Anchors	324
9.5.6	Design Considerations of Lining	325
9.5.7	Areas of Refractory Use in Fluidized Bed Boilers	325

9.5.8	Failure Analysis	329
9.5.9	Refractory Maintenance	331
9.6	Expansion Joints	333
	Nomenclature.....	334
	Greek Symbols	334
	References.....	334
Chapter 10	Solid Handling Systems for Fluidized Beds.....	337
10.1	Solid Handling Systems	337
10.1.1	Fossil Fuel Plants.....	337
10.1.2	Municipal Solid Waste	339
10.2	Biomass Handling Systems	341
10.2.1	Feeding of Harvested Fuels.....	341
10.2.2	Feeding of Nonharvested Fuels.....	341
10.3	Feed System for Bubbling Beds.....	342
10.3.1	Types of Feeders.....	342
10.3.2	Mode of Feeding in Bubbling Beds.....	347
10.3.3	Feed Point Allocation.....	350
10.4	Feed System for Circulating Fluidized Beds.....	352
10.4.1	Fuel Feed Ports.....	352
10.4.2	Limestone Feed System.....	353
10.5	Design of Pneumatic Transport Lines for Solids.....	353
10.5.1	Pressure Drop in a Pneumatic Transport Line.....	353
10.5.2	Design of a Pneumatic Injection System.....	355
10.5.3	Fuel Splitter	355
	Nomenclature.....	357
	Greek Symbols	357
	References.....	357
Chapter 11	Air Distribution Grate	359
11.1	Distributor Plates	359
11.1.1	Plate-Type Distributor	360
11.1.2	Nozzle-Type Distributor.....	362
11.1.3	Sparge Pipe Distributor	363
11.1.4	Distributor Grids for CFB	364
11.1.5	Distributor Grids for Bubbling Beds.....	365
11.2	Operation of Distributors.....	366
11.2.1	What Causes Nonuniform Fluidization.....	366
11.3	Design Methods.....	368
11.3.1	Design Procedure for Bubbling Fluidized Beds	368
11.3.2	Design Procedure for Circulating Fluidized Beds	370
11.4	Practical Considerations	371
11.4.1	Plenum or Air Box	372
11.4.2	Sealing of Distributor	373
11.4.3	Attrition.....	374
11.4.4	Back-Flow of Solid.....	375
11.4.5	Opening and Closing of Nozzles	377
11.4.6	Erosion and Corrosion of Nozzles	378
	Nomenclature.....	379
	Greek Symbols	379
	References.....	380

Chapter 12	Gas–Solid Separators	381
12.1	Cyclones	381
12.1.1	Types of Cyclone	382
12.1.2	Theory	385
12.1.3	Critical Size of Particles	385
12.1.4	Working of Cyclones for CFB Combustors or Gasifiers	390
12.1.5	Pressure Drop through a Cyclone	392
12.1.6	Cyclone Collection Efficiency	394
12.1.7	Reentrainment of Solids	399
12.1.8	Cyclone Geometry	400
12.1.9	Effect of the Vortex Finder	400
12.1.10	Practical Considerations for CFB Cyclones	402
12.2	Impact Separator	405
12.2.1	Features and Types	405
12.2.2	Separation through Impaction	406
12.2.3	Separation through Interception	407
12.2.4	Grade Efficiency of Impingement Collectors	409
12.2.5	Some Types of Impact Separators	409
12.3	Inertial Separators	410
12.3.1	Separation through Gravity Settling	411
12.3.2	Cavity Separator	411
12.3.3	Design Steps	411
	Nomenclature	413
	Greek Symbols	415
	References	415

Chapter 13	Solid Recycle Systems	417
13.1	Types of Nonmechanical Valves	417
13.1.1	Loop-Seal	418
13.1.2	L-Valve	420
13.1.3	V-Valve	420
13.2	Principles of Operation	421
13.2.1	Solid Flow from Standpipe to Recycle Chamber	422
13.2.2	Flow of Solids through Recycle Chamber	424
13.3	Design of Loop-Seal	426
13.3.1	Pressure Balance	426
13.3.2	Size of Loop-Seal	427
13.3.3	Air-Flow through Loop-Seal	428
13.4	Design of L-Valve	431
13.4.1	Maximum Solid Flow Rate	432
13.4.2	Additional Design Considerations	433
13.5	Practical Considerations	433
13.5.1	Plugging of Loop-Seal	433
13.5.2	Pressure Surge	434
13.5.3	Avoiding Loop-Seal Plugging	434
	Nomenclature	435
	Greek Symbols	436
	References	436

Appendix 1	Characteristics of Solid Particles.....	439
A1.1	Solid Particles	439
A1.1.1	Equivalent Diameters	439
A1.1.2	Sphericity (ϕ)	440
A1.1.3	Mean Particle Size and Its Measurement.....	440
A1.2	Packing Characteristics.....	442
A1.3	Particle Classification	442
A1.3.1	Group C	443
A1.3.2	Group A	443
A1.3.3	Group B	444
A1.3.4	Group D	444
	Nomenclature.....	444
	References.....	444
Appendix 2	Stoichiometric Calculations	445
A2.1	Chemical Reactions	445
A2.2	Air Required	446
A2.3	Sorbent Requirement	446
A2.4	Solid Waste Produced.....	446
A2.5	Gaseous Waste Products.....	447
A2.5.1	Carbon Dioxide.....	447
A2.5.2	Water Vapor.....	448
A2.5.3	Nitrogen.....	448
A2.5.4	Oxygen	448
A2.5.5	Sulfur Dioxide.....	448
A2.5.6	Fly Ash.....	448
A2.6	Heating Value of Fuels.....	448
	Nomenclature.....	450
	Reference	451
Appendix 3	Simplified Model for Sulfur Capture	453
	Nomenclature.....	454
Appendix 4	Tables of Design Data	455
Index		461