# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>What Is a Circulating Fluidized Bed Boiler?</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>Features of a Circulating Fluidized Bed Boiler</td>
<td>6</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Description of the Boiler</td>
<td>6</td>
</tr>
<tr>
<td>1.2.2</td>
<td>Advantages of Circulating Fluidized Bed Boilers</td>
<td>7</td>
</tr>
<tr>
<td>1.3</td>
<td>Technology Choice</td>
<td>12</td>
</tr>
<tr>
<td>1.3.1</td>
<td>Technological Options for Generation of Energy from Solid Fuels</td>
<td>13</td>
</tr>
<tr>
<td>1.3.2</td>
<td>Carbon Capture by CFB</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Hydrodynamics</td>
<td>17</td>
</tr>
<tr>
<td>2.1</td>
<td>Regimes of Fluidization</td>
<td>19</td>
</tr>
<tr>
<td>2.1.1</td>
<td>Packed Beds</td>
<td>20</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Bubbling Fluidized Beds</td>
<td>22</td>
</tr>
<tr>
<td>2.1.3</td>
<td>Slugging</td>
<td>25</td>
</tr>
<tr>
<td>2.1.4</td>
<td>Turbulent Beds</td>
<td>25</td>
</tr>
<tr>
<td>2.2</td>
<td>Fast Fluidized Bed</td>
<td>29</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Characteristics of Fast Beds</td>
<td>29</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Transition to Fast Fluidization</td>
<td>31</td>
</tr>
<tr>
<td>2.2.3</td>
<td>Transition from Bubbling to Fast Bed</td>
<td>32</td>
</tr>
<tr>
<td>2.2.4</td>
<td>Transition from Pneumatic Transport to Fast Bed</td>
<td>34</td>
</tr>
<tr>
<td>2.2.5</td>
<td>The Flow Regime Diagram</td>
<td>35</td>
</tr>
<tr>
<td>2.3</td>
<td>Structure of Fast Beds</td>
<td>37</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Axial Voidage Profile</td>
<td>37</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Lateral Distribution of Voidage</td>
<td>41</td>
</tr>
<tr>
<td>2.4</td>
<td>Gas–Solid Mixing</td>
<td>45</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Gas–Solid Slip Velocity</td>
<td>45</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Dispersion</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>46</td>
</tr>
</tbody>
</table>
3 Heat Transfer

3.1 Gas-to-Particle Heat Transfer

3.1.1 Gas-Particle Heat Transfer Equations

3.1.2 Heating of Gas and Solids in the Fast Bed

3.2 Bed-to-Wall Heat Transfer

3.2.1 Mechanism of Heat Transfer

3.2.2 Experimental Observations

3.2.3 Theory

3.2.4 Effect of Vertical Fins on the Walls

3.3 External Fluid Bed Heat Exchanger

3.3.1 Bed-to-Tube Heat Transfer Coefficient in Bubbling Beds, \( h_0 \)

3.3.2 Tube-to-Steam Heat Transfer Coefficient, \( h_i \)

3.4 Heat Transfer in Commercial Size CFB Boilers

3.4.1 Heat Transfer to the Walls of Commercial CFB Boilers

3.4.2 Heat Transfer to Surfaces Immersed in Fast Beds

3.4.3 Heat Transfer Variation along the Furnace Height

3.5 Load Control and Part-Load Operations

3.5.1 Load Control in CFB Boilers

3.5.2 Part-Load Operation

3.5.3 Load Control Options

3.6 Heat Transfer in Supercritical Boilers

3.6.1 Circumferential Distribution of Heat Transfer Coefficient

3.7 Heat Transfer in Cyclone

References

4 Combustion

4.1 Stages of Combustion

4.1.1 Heating and Drying

4.1.2 Devolatilization

4.1.3 Devolatilization and Volatile Combustion

4.1.4 Char Combustion

4.1.5 Communication Phenomena During Combustion

4.2 Combustion Process in CFB Boilers

4.2.1 Burning Rate of a Single Coarse Char Particle in a Fast Bed

4.2.2 Feed Stock Characterization

4.2.3 Heat Release Profile
4.3 Design and Performance Modeling of CFB Combustors 115

4.3.1 Combustion Temperature 115
4.3.2 Grate Heat Release Rate 116
4.3.3 Effect of Fuel 116
4.3.4 Performance Modeling 117

References 117

5 Emissions 121

5.1 Air Pollution 124
5.1.1 Formations of Regional Pollutants 124
5.1.2 Effects 125
5.1.3 Global Warming and Climate Change 125
5.1.4 Emission Standard 127

5.2 Sulfur Dioxide Emission 127
5.2.1 Chemical Reactions 127
5.2.2 Reactions on Single Sorbent Particles 132
5.2.3 Reactivity of Sorbents 134
5.2.4 Sulfur Capture in a CFB Boiler 137
5.2.5 Selection of Sorbent 141

5.3 Nitrogen Oxide Emission 143
5.3.1 Source of NO\textsubscript{X} 144
5.3.2 Methods of Reduction of NO\textsubscript{X} Emission 145
5.3.3 NO\textsubscript{X} Emission from CFB Boilers 146

5.4 Nitrous Oxide Emission 147
5.4.1 Mechanism of Formation of N\textsubscript{2}O in CFB 147
5.4.2 Effects of Operating Parameters 148
5.4.3 Reduction of N\textsubscript{2}O 149

5.5 Carbon Emissions 149
5.5.1 Carbon Monoxide 149
5.5.2 Carbon Dioxide 149

References 151

6 Design Considerations 155

6.1 Stoichiometric Calculations 158

6.2 Heat and Mass Balance 158
6.2.1 Heat Balance 159
6.2.2 Mass Balance 164
6.2.3 Division of Solid Stream (Bed Ash vs. Fly Ash) 164
6.2.4 Control of Particle Size Distribution in Bed 166

6.3 Furnace Design 168
6.3.1 Furnace Cross Section 170
6.3.2 Width and Depth Ratio 172
6.3.3 Furnace Openings 173
6.4 CFB Boiler Configuration ................................. 178
   6.4.1 CFB Design Without External Heat Exchanger .... 178
   6.4.2 CFB Design with External Fluid Bed
       Heat Exchanger (FBHE) ............................. 180
   6.4.3 Design with Internal Fluid Bed Heat Exchanger .. 181
   6.4.4 CFB Design Without Cyclone ....................... 182
   6.4.5 Cooled Cyclone Versus Hot Cyclone ............... 182
6.5 Design of Heating Surfaces ............................. 183
   6.5.1 Disposition of Heating Surfaces .................... 185
   6.5.2 Effect of Fuel Type .............................. 186
   6.5.3 Biomass Fired CFB Boiler ......................... 187
   6.5.4 Waste Fired CFB Boiler ........................... 188
   6.5.5 Heat Absorption in External Heat Exchanger (EHE) 188
   6.5.6 Heat Absorption in the Furnace and Back pass
       of the Boiler ...................................... 189
   6.5.7 Energy and Mass Balance Around CFB Loop .......... 192
6.6 Example of Thermal Design of a CFB Boiler .......... 195
References .................................................. 198

7 Gas–Solid Separators ................................. 201
   7.1 Centrifugal Separators ............................... 204
       7.1.1 Types of Cyclone .............................. 204
       7.1.2 Theory ....................................... 207
       7.1.3 Critical Size of Particles .................... 208
       7.1.4 Overall Versus Grade Efficiency of Separation 210
       7.1.5 Pressure Drop Through Cyclone ................ 211
       7.1.6 Re-Entrainment of Solids ...................... 212
       7.1.7 Cyclones for CFB Boilers ...................... 214
       7.1.8 Cyclone Geometry ............................. 216
       7.1.9 Design Steps ................................... 216
   7.2 Inertial Separators ................................ 220
       7.2.1 Features and Types ............................ 220
       7.2.2 Design Steps .................................. 225
References .................................................. 226

8 Design of CFB Components ............................. 229
   8.1 Types of Non-mechanical Valves ........................ 230
       8.1.1 Principle of Operation .......................... 231
   8.2 Design of L-Valve .................................. 235
       8.2.1 Maximum Solid Flow Rate Through L-Valve .... 237
       8.2.2 Practical Considerations ....................... 237
   8.3 Design of Loop Seal ................................ 238
       8.3.1 Pressure Balance ............................... 238
       8.3.2 Size of Loop Seal .............................. 239
8.4 Grate or Fluidizing Air Distributor ....................................................... 242
  8.4.1 Types of Distributors ................................................................. 242
  8.4.2 Design Methods ............................................................................. 244
  8.4.3 Practical Considerations .............................................................. 248
References ................................................................................................. 252

9 Management of Solid Residues ................................................................. 255
  9.1 Nature of Solid Wastes ........................................................................ 255
    9.1.1 Amount of Waste .......................................................................... 257
    9.1.2 Waste Characteristics ................................................................... 257
  9.2 Utilization of Wastes ........................................................................... 263
    9.2.1 Wastes Without Spent Sorbent ..................................................... 264
    9.2.2 Wastes Containing Spent Sorbents ................................................. 267
  9.3 Disposal of Wastes............................................................................... 269
    9.3.1 Conditioning of Wastes ................................................................. 269
    9.3.2 Landfills ....................................................................................... 271
    9.3.3 Leachate ....................................................................................... 272
    9.3.4 Water Requirements for Conditioning ......................................... 273
    9.3.5 Calcium Sulfide in Solid Wastes .................................................... 274
References ................................................................................................. 275

10 Material Issues ........................................................................................ 277
  10.1 Material Selection Criteria ............................................................... 277
    10.1.1 Pressure Part Materials ............................................................... 278
  10.2 Commonly Used Materials ............................................................... 286
    10.2.1 Carbon and Alloy Steels ............................................................. 286
    10.2.2 Refractory and Insulations ........................................................ 289
    10.2.3 Expansion Joints ......................................................................... 301
  10.3 Materials-Related Problems .............................................................. 302
    10.3.1 Lower Combustor ...................................................................... 302
    10.3.2 Water-Cooled Cyclones ............................................................. 303
References ................................................................................................. 303

11 Operation and Maintenance Issues ......................................................... 305
  11.1 Introduction ....................................................................................... 305
  11.2 Degradation of Boiler Components .................................................. 306
    11.2.1 Erosion Issues in CFB Boilers .................................................... 306
    11.2.2 Corrosion Issues in CFB Boilers ............................................... 315
  11.3 Refractory Failure ............................................................................. 323
  11.4 Maintenance Issues .......................................................................... 326
    11.4.1 Preventive and Remedial Measures for Fireside Corrosion ......... 327
    11.4.2 Preventive Maintenance for Refractory ...................................... 327
Circulating Fluidized Bed Boilers
Design, Operation and Maintenance
Basu, P.
2015, XV, 366 p. 119 illus., 8 illus. in color., Hardcover
ISBN: 978-3-319-06172-6