FLUIDIZED COMBUSTION
Fluidization phenomenon

- Fixed bed
- Bubbling fluidized bed
- Circulating fluidized bed
- Pneumatic transport

Gas flow velocity:
- 0.5 – 2 m/s
- 2 – 3 m/s
- 3 – 7 m/s
- > 7 m/s

Dust
What does it mean fluidization

**Fluidization** is a two-phase process in which dispersed solid material is suspended in a stream of gas flowing upstream through the fluidized grate. The layer of solid body particles suspended in flowing gas forms fluidized bed.

The fluidized bed is in the quasi-equilibrium state only in some range of the velocity of the flowing upstream gas, depending on the size of particles of bed.

The fluidized bed of a boiler contains mainly particles of an inert material, like sand and ash, including particles of \( \text{SO}_2 \) sorbent. The coal content in a fluidized bed is not considerable, it is only from 3 to 5% of the whole mass of the bed.
Air flow velocity in boiler furnace vs. combustion pattern
Fluidized bed-combustion features

a) direct contact of particles with intensive mass and heat exchange,

b) uniform temperature in the fluidized bed

c) high heat capacity of fluidized bed making it possible to burn fuels of low quality, wet and with high content of ash

d) effectiveness of bed temperature control by supply of fuel, air and heat extraction
## Major features of fluidized bed boilers

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel flexibility</td>
<td>Higher power of air van</td>
</tr>
<tr>
<td><em>In situ</em> SO$_2$ removal</td>
<td>Larger cross-section of a furnace</td>
</tr>
<tr>
<td>Low NOx emission</td>
<td>Higher surface loss of heat</td>
</tr>
<tr>
<td>Good system availability</td>
<td>Higher carbon-in-ash level</td>
</tr>
<tr>
<td>No slaging</td>
<td>Higher erosion rate</td>
</tr>
<tr>
<td>Low corrosion rate</td>
<td></td>
</tr>
<tr>
<td>Easy sizing of fuel</td>
<td></td>
</tr>
</tbody>
</table>

**Advantages**
- Fuel flexibility
- *In situ* SO$_2$ removal
- Low NOx emission
- Good system availability
- No slaging
- Low corrosion rate
- Easy sizing of fuel

**Disadvantages**
- Higher power of air van
- Larger cross-section of a furnace
- Higher surface loss of heat
- Higher carbon-in-ash level
- Higher erosion rate
FLUIDIZED BED COMBUSTION SYSTEMS
Types of fluidized bed boilers

Concerning the structure of fluidized bed:

- boilers with **bubbling** (stationary) fluidized bed (BFB)
- boilers with **circulating** fluidized bed (CFB)
Bubbling fluidized bed BFB

- Coal
- Flue gas
- Water
- Ash
- Air
Circulating fluidized bed CFB

- Circulation duct
- Primary air
- Coal and sorbent
- Refractory chamber
- Secondary air
- Chamber
- Cyclone
- Steam superheaters
- Water heater
- Air heater
- Exhaust
Bubbling and circulating fluidized bed boilers
Types of fluidized bed boilers

Concerning the pressure in a furnace:

- **atmospheric** fluidized bed boilers (pressure approximately atmospheric) (ACFB),

- **pressure** fluidized bed boilers (pressure much higher than atmospheric) (PCFB).
ATMOSPHERIC FLUIDIZED BED BOILERS
BUBBLING FLUIDIZED-BED COMBUSTORS
Bubbling fluidized bed furnace (laboratory set)
Structure of bubbling fluidized bed

- **over-bed zone**
- **splash-zone**
- **fluidized bed**

Diagram showing the structure of a bubbling fluidized bed with labeled zones I, II, and III.
Burning of coal particles in fluidized bed
Mechanism of coal combustion

- splash-zone
- bed

Reaction formulas:
- \( \text{CaO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CaSO}_4 \)
- \( \text{CaO} + \text{CO} + \text{H}_2\text{O} \rightarrow \text{CaSO}_4 \)
- \( \text{CaO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CaO}_2 \)
- \( \text{C}_n\text{H}_m + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2 + \frac{1}{2} \text{H}_2\text{O} \)
- \( \text{CO}_2 + \text{CaO} \rightarrow \text{CaCO}_3 \)
Sources of unburned coal in fluidized bed boilers

Very small particles of coal are blow-up from the bed due to:

- increase of porosity of coal particles due to oxidation
- particles decomposition as a result of thermal thermal tension in particles
- collision of particles in a bed
- friction of particles in a bed
Decomposition of coal particle due to inner oxidation and contact with particles of bed
CIRCULATING FLUIDIZED BED BOILERS (CFB)
Structure of circulating fluidized bed

Raising flow

Falling flow
Types of boilers with circulating fluidized beds

Circulating fluidized bed boilers:
1 – cyclone separator, 2 – inner separator
CFB with cyclone separator
Circulating fluidized bed boiler

Circulating fluidized bed boiler CFB-670 with cyclone separator
Bottom of the CFB boiler
Bottom part of the furnace
CFB-670 boiler

furnace (lined with refractory)
IR detectors
solids return
air nozzles
bed press.
bed temp.
Closing of the siphon of CFB-670 boiler

Solids discharge to furnace

Solids from cyclone $G_s$

Air distributor

$H_s$
Bottom of fluidized bed furnace CFB-670 boiler
Air nozzles of the fluidizing bed
Exploitation parameters of the CFB-670 boiler

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stoichiometric ratio $\lambda$</td>
<td>1.1-1.2</td>
</tr>
<tr>
<td>Temperature of the bed, $T_z$</td>
<td>850-870 °C</td>
</tr>
<tr>
<td>Burnout of coal</td>
<td>96-98%</td>
</tr>
<tr>
<td>Effectiveness of sulfur removal</td>
<td>90%</td>
</tr>
<tr>
<td>$\text{NO}_x$ emission</td>
<td>200-400 mg/m$^3$</td>
</tr>
<tr>
<td>(Ca/S = 1.5-2.6)</td>
<td></td>
</tr>
</tbody>
</table>
CFB boilers with inner separator
Separation of bed material in inner separator
CFB - 700 boiler
CFB - 700 boiler with inner separator
FUEL HANDLING IN FLUIDIZED BEDS BOILERS
Systems of fuel handling

Underbed

Intobed

Overbed
Bubbling bed: pneumatic handling of fuel
Bubbling bed - worm-gear coal handling
Circulating bed: overbed handling of fuel
Circulating fluidized bed: silos and coal feeders

- Coal silos
  - Silosy węgla
  - 20-115 m³/h

- Coal feeders (4 pcs.)
  - Dwa długie podajniki celkowe, zgarniakowe 6-60 m³/h
  - Zsypy z dyszkami powietrza 10 sztuk

- Shorter cell coal feeders (3 pcs.)
  - Trzy krótsze podajniki celkowe 6-60 m³/h

- Chutes with air nozzles (10 pcs.)
  - long cell/rake coal feeders (2 pcs.)
CFB: gallery of coal handling
SELECTED FEATURES OF FLUIDIZED BED BOILERS
Effectiveness of combustion in fluidized beds

<table>
<thead>
<tr>
<th>Coal</th>
<th>Time of burnout, s</th>
<th>Degree of burnout, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>20 ÷ 30</td>
<td>93 ÷ 96</td>
</tr>
<tr>
<td>Hard coal</td>
<td>50 ÷ 125</td>
<td>86 ÷ 93</td>
</tr>
<tr>
<td>Anthracite</td>
<td>200 ÷ 300</td>
<td>78 ÷ 85</td>
</tr>
</tbody>
</table>
Advantages of fluidized bed firing over pulverized-bed firing systems

- Simplification of the fuel supply system,
- Possibility of burning low-caloric fuels,
- Possibility of flue gas desulfurization in the bed
- Reduction of NO\textsubscript{x} emission due to the lower temperature of burning.
Comparison of PF and fluidized bed boilers

<table>
<thead>
<tr>
<th>Boiler</th>
<th>Temperature</th>
<th>Fuel</th>
<th>Fuel sizing</th>
<th>Ash/slaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF</td>
<td>High: 1100-1400 °C</td>
<td>Hard coal 31-33 Lignite</td>
<td>&lt; 0.3 mm</td>
<td>Melted/yes</td>
</tr>
<tr>
<td>CFB</td>
<td>Low: 800-900 °C</td>
<td>Hard coal, lignite, biomass, wastes</td>
<td>3-30 mm</td>
<td>Not melted/no</td>
</tr>
</tbody>
</table>
Comparison of thermal load of PF and fluidized bed boilers

<table>
<thead>
<tr>
<th>Type of boiler</th>
<th>Parameter</th>
<th>CFB</th>
<th>BFB</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface thermal load:</td>
<td>$q_A, \text{MW/m}^2$</td>
<td>1.8-2.5</td>
<td>1.2-1.5</td>
<td>3.0-5.5</td>
</tr>
<tr>
<td>Volume thermal load:</td>
<td>$q_v, \text{MW/m}^3$</td>
<td>0.2-0.4</td>
<td>0.1-0.2</td>
<td>0.08-0.2</td>
</tr>
</tbody>
</table>
# Comparison of PF and CFB ashes

<table>
<thead>
<tr>
<th>Compound</th>
<th>PF</th>
<th>CFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>2-12</td>
<td>25</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>40-55</td>
<td>26</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>0.5-6</td>
<td>10.8</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>13-30</td>
<td>9.6</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>4-17</td>
<td>15.4</td>
</tr>
<tr>
<td>MgO</td>
<td>1.8-8</td>
<td>0.8</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.3-0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>LOI</td>
<td>0.7-15</td>
<td>2-12</td>
</tr>
</tbody>
</table>
YEAR OF INITIAL OPERATION

UNIT CAPACITY (MW_e)

Developing trends
Scale-Up and Some Key References

Pilot plant
Pihlava
Kauttua
Tri-State
Leykam
Kajaani
Vaskiluodon Voima
JEA
Turow 1
Turow 5
Lagisza
NPS
Novo Scotia
Thai Kraft
Kuhmo
Kokkola
Pilot plant

FIRST GENERATION DESIGN
SECOND GENERATION DESIGN
Supercritical once-through CFB, PKE ŁAGISZA 460 MWₑ PLANT
Comparison of Turów and Łagisza boilers
Boiler’s furnace

- BENSON low mass flux technology
- Furnace circuit:
  - Vertical tubing
  - Membrane walls, smooth tubes $\varnothing 38 \times 8.0 \text{ mm}$, mass flux $\sim 600 \text{ kg/m}^2\text{s}$
  - Evaporation panels, rifled tubes $\varnothing 51 \times 8.8 \text{ mm}$, mass flow flux $\sim 600 \text{ kg/m}^2\text{s}$
- INTREX casing and support in economizer circuit
- Furnace roof in primary superheater circuit
- Solid separators in tertiary superheater circuit
- INTREX-heat exchanger in final superheater / reheater circuit
Integrated Heat Exchanger
- Heat exchange from solid bed material to tube surface
- High heat transfer rate
- Heat exchange rate can be controlled
- Less heat transfer surface than in conventional gas to solid heat exchangers
- Suitable for large-scale units

Simple Design
- No moving parts: no wear

Resistant to Erosion
- Low erosion rate due to low velocities

Resistant to Corrosion
- Tube corrosion rate reduced by Cl-free environment
Intrex
FW CFB SOLIDS SEPARATOR

FEATURES:
- Integrated with furnace:
- Panel wall structure
- No / few expansion joints
- Water or steam cooled
- Normal insulation
  - Lower radiation loss
- Less refractory
  - Shorter start-up time
- Smaller foot-print

Mineral wool
Refractory 25-50 mm
Membrane wall
Electrostatic precipitator
PRESSURIZED FLUIDIZED BED BOILERS (PFBB)
1\textsuperscript{st} generation PFBC
Karita, Japan
## Technical data PFBC - Karita

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output</strong></td>
<td></td>
</tr>
<tr>
<td>Steam turbine</td>
<td>290MW</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>75MW</td>
</tr>
<tr>
<td>Total</td>
<td>360MW</td>
</tr>
<tr>
<td><strong>Power generation System</strong></td>
<td>PFBC combined cycle generation</td>
</tr>
<tr>
<td>Fuel used</td>
<td>Coal</td>
</tr>
<tr>
<td>Desulfurizing agent</td>
<td>Limestone</td>
</tr>
<tr>
<td>Commercial operations</td>
<td>July, 2001</td>
</tr>
<tr>
<td><strong>Emissions restriction value</strong></td>
<td></td>
</tr>
<tr>
<td>SOx</td>
<td>76ppm</td>
</tr>
<tr>
<td>NOx</td>
<td>60ppm</td>
</tr>
<tr>
<td>Dust</td>
<td>30mg/m3N</td>
</tr>
<tr>
<td><strong>Smoke treatment method</strong></td>
<td></td>
</tr>
<tr>
<td>SOx</td>
<td>Furnace desulfurizing</td>
</tr>
<tr>
<td>NOx</td>
<td>Low temperature combustion + denitrification equipment</td>
</tr>
<tr>
<td>Dust</td>
<td>Cyclones + Electrostatic precipitator</td>
</tr>
</tbody>
</table>

**P = 1.5 MPa**
Bird’s-eye view of Karita new unit 1 generation facilities

- Primary and secondary cyclones
- Pressure vessel
- Electrostatic precipitator
- Fluidized bed boiler
- Coal bunker
- Denitrification equipment
- Economizer
- Gas turbine
- Fuel slurry pump
- Steam turbine
Diagram of pressurized fluidized bed boiler 1st generation (combined cycle with the PFBC)
Cottbus, Germany
PFBC 2nd generation Cottbus
Gas turbine, Cottbus in Germany
Main technical parameters

Combined cycle data
Plant type 1 x P200, combined heat and power
Gas turbine 1 x GT35P
Steam turbine 1 x G32 + 1 x VEE63
Net output (MWe/MWth) 71/40 (P200, low heat output)
(MWe/MWth) 62/90 (P200, high heat output)
(MWe/MWth) 74/220 (P200 + peak load 1 boilers)

Emissions requirements
Sulphur emissions (mg/Nm³) 115 (7% O₂)
NOₓ emissions (mg/Nm³) 115 (7% O₂)
Particulate emissions (mg/Nm³) 20 (7% O₂)

Technical data (full load, 15°C)
Coal feed system Dry feed
Coal feed rate (kg/s) 11.3
Sorbent type Limestone
Sorbent feed rate (kg/s) 1.0
Ash flow (kg/s) 1.8
Combustion temperature (°C) 840
Steam data (bar(a)/°C/°C) 142 /537/537
Condenser pressure (bar(a)) 0.07
Ambient temperature (°C) 15

Coal data
Coal type Lausitzer brown coal
Heating value (MJ/kg, LHV) 14.3 - 20.4
Sulphur content (%) 0.5 - 1.2
Ash content (%) 4 - 12
Moisture content (%) 16 - 25
2nd generation PFBB
PCFB 2\textsuperscript{nd} generation

Desulfurization

Partial gasification

Oxidizer PFBC

Syngaz

CaS

Cyclone

Gas cooler

Cyclone

Ceramic filter

Combustor

Gas turbine

Steam turbine

Flue gas
Scheme of PCFB - 2nd generation

(Kita Kyushu City), Electric Power Development Co., Ltd.