COAL COMBUSTION
FURNACES OF COAL-FIRED BOILERS

Basic boiler furnaces:
- grate (steady and moving grates)
- fluidized beds (bubble and circulating beds),
- pulverized coal-furnace.

Others:
- cyclone,
- retort furnace,
- rotary furnace.
BASIC COAL FURNACES

System for coal burning:

a) Moving grate,
b) Fixed bed,
c) Fluidized bed
d) Pulverized coal flame
COMBUSTION PROCESS COAL SIZING
REQUIREMENTS

Grate furnaces (stoker firing systems):
• fixed beds: mud, dust, tiny, peas, nut, thick,
• moving grate: peas, nut (10-30 mm),

Fluidized bed:
• bubling <25 mm,
• circulating: 6 mm,

Pulverized coal furnaces:
• bituminous coal: \( R_{90} = 25-30\% \), \( R_{200} <8\% \),
• lignite: \( R_{90} = 48-55\% \), \( R_{200} = 25-32\% \), \( R_{1000} <2-3\% \)
BASIC PROCESSES OF COAL COMBUSTION

- evaluation and combustion of volatile matter,
- char combustion
SINGLE COAL PARTICLE COMBUSTION
SINGLE COAL PARTICLE COMBUSTION

Coal particle → Ignition of v.m. → Ignition of char → Ash

Heating → Volatile matter combustion → Char combustion → Combustion

COMBUSTION AND FUELS
HISTORY OF SINGLE COAL PARTICLE COMBUSTION

Particle temperature

Flue gas temperature

Particle diameter

Stage of heat. & ignit.

Stage of v.m. comb.

Stage of char combustion
STAGES OF BURNING OF SINGLE PARTICLE OF COAL

Induction ignition time:
- heating time,
- drying time.

Time of combustion:
- evaluation and combustion of volatile matter,
- burning of char.

Ratio of time of volatile matter combustion/time of char burning: 1:10
# VOLATILE MATTER CONTENT

<table>
<thead>
<tr>
<th>Component</th>
<th>Lignite Montana, %</th>
<th>Bituminous coal Pittsburgh, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.9 MPa He 1000 °C, 3–10 s</td>
<td>6.9 MPa He 850–1070 °C, 2–10 s</td>
</tr>
<tr>
<td>CO</td>
<td>9.0</td>
<td>2.5</td>
</tr>
<tr>
<td>CO₂</td>
<td>10.6</td>
<td>1.7</td>
</tr>
<tr>
<td>H₂O</td>
<td>12.9</td>
<td>9.5</td>
</tr>
<tr>
<td>CH₄</td>
<td>2.5</td>
<td>3.2</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Liquid HC</td>
<td>–</td>
<td>0.7</td>
</tr>
<tr>
<td>Tar</td>
<td>3.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Char</td>
<td>59.9</td>
<td>62.4</td>
</tr>
</tbody>
</table>
MECHANISMS OF VOLATILE MATTER EVALUATION

Diffusion flame
Volatile matter
Products of combustion
heat
Coal

Rotation
Bubbles
Volatile matter

COMBUSTION AND FUELS
THERMAL DECOMPOSITION OF COKING COAL

1st STAGE
(coal/metaplast)

RAW COAL ➔ metaplast

2nd STAGE
primary pyrolysis

tar ➔ soot
primary gases ➔ secondary gases
char

3rd STAGE
secondary pyrolysis

char ➔ char

COMBUSTION AND FUELS
DYNAMICS OF VOLATILE MATTER EVALUATION

![Graph showing the dynamics of volatile matter evaluation for different types of coal: Lignite, Young hard coal, Hard coal, Anthracite, and Coke. The x-axis represents temperature in °C, and the y-axis represents the intensity of volatile matter evaluation. Drying is indicated at the lower temperature range.](image-url)
CHAR STRUCTURE

Microscopic photo of char surface after coal devolatilization

Pores
CHAR COMBUSTION
MAJOR FACTORS INFLUENCING RATE OF CHAR PARTICLE COMBUSTION

a) chemical: chemical kinetic of oxidation reaction (temperature, \( \text{O}_2 \) concentration)

b) physical: transport of oxygen to the surface of char particle
Simple model of char particle combustion

Model of reaction: \[ \text{C} + \text{O}_2 = \text{CO}_2 \]

Rate of reaction: \[ W_c = \Omega Y_s k, \text{ g/}(\text{m}^2\text{s}) \]
CHEMICAL MECHANISM OF CHAR COMBUSTION

Basic chemical reactions of char combustion:

\[ C + O_2 = CO_2 - 393.5 \text{ kJ/mol} \] (I)

\[ C + 0.5O_2 = CO - 110.5 \text{ kJ/mol} \] (II)

\[ C + CO_2 = 2CO + 172.5 \text{ kJ/mol} \] (III)

\[ 2CO + O_2 = 2CO_2 - 283.0 \text{ kJ/mole} \] (IV)
COMBUSTION OF A SINGLE PARTICLE OF CHAR

Distribution of primary and secondary products of oxidation of char

2CO + O₂ → 2CO₂
C + CO₂ → 2CO
Assumption:

1. Single chemical reaction of oxidation is considered

\[ C + O_2 \rightarrow CO_2 \]

2. Char particle is considered spherical and smooth.
RATE OF CHAR OXIDATION, \( W_c \)

**Formula**

\[
W_c = \frac{Y_0}{(1/k + 1/\alpha_D)}, \text{ kg/(m}^2\text{s)}
\]

Rate constant: \( k = k_0 \exp[-E/(RT)] \),

Stoichiometry coefficient: \( \Omega \) (\( \Omega = 0.375 \) when burning is to \( \text{CO}_2 \)),

Mass transfer coefficient: \( \alpha_D = (D/d)Sh \) -of (\( Sh = CRe^nPr^k \)),

Units: \( W_c [\text{kg/(m}^2\text{s)}] \)
COMPETITION OF TEMPERATURE AND DIFFUSION

![Graph showing the competition of temperature and diffusion](image)

- Mass transfer
- Overall rate
- Chemical reaction

Overall reaction rate vs. Temperature [°C]
REGIMES TEMPERATURE AND DIFFUSION REGIMES OF CHAR REACTION

*Overall rate:* $W_C = Y_0/(1/k + 1/\alpha_D)$

Remember:

*Arrhenius rate:* $k = k_0 \exp[-E/(RT)]$, temperature dependent

*Mass transfer coefficient:* $\alpha_D = (D/d)Sh$, temperature independent

Two regimes of char burning

**Kinetic (reaction) control regime (low temperature):**

$$1/k \gg 1/\alpha_D \rightarrow W_C = \Omega Y_0 k_0 \exp[-E/(RT)]$$

**Diffusion control regime (high temperature):**

$$1/k \ll 1/\alpha_D \rightarrow W_C = \Omega Y_0 \alpha_D$$
LOW - AND HIGH TEMPERATURE PROFILES AROUND CHAR PARTICLE

Profiles of oxygen concentration

a) Low temperature - reaction control

b) Transition

c) High temperature – diffusion control
REGIMES OF COMBUSTION OF POROUS CHAR PARTICLE

\[ k = k_0 \exp\left(-\frac{E}{RT}\right) \]
Influence of temperature on the course of combustion of solid particle of coal

650°C

450°C
INFLUENCE OF AERODYNAMICS ON THE RATE OF COMBUSTION OF SINGLE COAL PARTICLE
ROLE OF SECONDARY CHEMICAL REACTIONS IN BURNING OF SINGLE CHAR COMBUSTION

Convection and temperature influence on the chemical reactions participation in the rate of burning.
COAL COMBUSTION AND SLAGING PROCESSES
MINERAL MATTER OF COAL

Mineral matter of coal:

- included (a mineral associated with organic matter)

- excluded (liberated, like clay, sand and rocks).

There are four major groups of minerals in coal:

- aluminosilicates - mainly kaolinite,
- oxides - quartz $\text{SiO}_2$ and hematite $\text{Fe}_2\text{O}_3$,
- carbonates - calcite $\text{CaCO}_3$, syderyt $\text{FeCO}_3$ and dolomite $\text{CaCO}_3\text{MgCO}_3$,
- sulphur compounds - pyrite $\text{FeS}_2$ i gipsium $\text{CaSO}_4\ 2\text{H}_2\text{O}$. 
SOLID RESIDUES AFTER COAL COMBUSTION

COMBUSTION

MINERAL MATTER

FLY ASH, BOTTOM ASH
MEMBRANE WALLS DEPOSITS IN PULVERIZED COAL FIRED BOILERS

Fly ash

Wall deposits
During coal combustion mineral matter undergoes conversion:

- physical: melting, evaporation, sublimation and condensation,

- chemical: dehydratation, carbonates decomposition and oxidation of sulfides.
BASIC PROCESSES OF MINERAL MATTER CONVERSION IN THE FURNACE

-Coal particles with bound mineral matter
-Coal particles with bound and free mineral matter

Vaporasing of inorganic matter

-Condensation
-Condensation
-Homogenic nucleation and coalescence
-Heterogenic condensation

Surface covering

Small particles

Coalescence

Swelling

Cenospheres

Char disintegration
SLAGING PROCESS

Slaging a process of covering of walls (tubes) of furnace by deposit being a result of conversion of mineral matter of coal during combustion.

Types of deposits:

- loose,
- bound (sintered, melted).
SLAG DEPOSIT ON THE WALL OF A FURNACE
PULVERIZED COAL FLAME
STRUCTURE OF PULVERIZED COAL FLAME

- Pyrolysis
- Basic part of flame
- Char
- End of flame
- Recirculation
- Flame front
- Unburned coal particles
JET OF PULVERIZED COAL FLAME
PULVERIZED COAL FLAME IN THE BOILER FURNACE

A typical pulverized coal flame
UNBURNED CARBON (UBC) IN FLY ASH
The most important factors determining UBC (LOI):

- reactivity of coal
- stoichiometric ratio
- temperature
- quality of grinding

Petrographic components of UBC: inertenite, ksylite
INFLUENCE OF MINERAL MATTER IN COAL ON UBC

High content of mineral matter in coal decreases UBC

UBC UNITS: %
Accepted level of UBC: 5%
BURNERS AND BOILER FURNACES
SELECTION OF PULVERIZED COAL FURNACES

<table>
<thead>
<tr>
<th>Volatile matter content, %</th>
<th>LCV, MJ/kg (daf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antr.</td>
<td>9.5</td>
</tr>
<tr>
<td>Hard coal</td>
<td>8.5</td>
</tr>
<tr>
<td>Lignite</td>
<td>7.5</td>
</tr>
<tr>
<td>Peat</td>
<td>6.5</td>
</tr>
<tr>
<td>Biomass</td>
<td>5.5</td>
</tr>
</tbody>
</table>

- Vertical furnace, jet burners
- Wall front furnace, swirl burners
- Tangential furnace, jet burners
Swirl burners

Swirl number: $S = 0.4-0.7$

Outlet velocity of pulverized coal/air mixture: 20-22 m/s

Secondary air velocity: 26-30 m/s
FRONT OF SWIRL BURNER (40-50 MWth)
BACK OF THE SWIRL BURNER
AIR BOX - VANES OF AIR SWIRLER

vanes
SWIRL BURNERS ON FRONT WALL OF THE OP-650
STRUCTURE OF SWIRLED PULVERIZED COAL FLAME
INFLUENCE OF AIR SWIRL ON THE PULVERIZED COAL STRUCTURE
JET BURNER IN BOILER FURNACE OP 430
### Outlet velocities from the burner:

<table>
<thead>
<tr>
<th>Source</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulverized lignite/gas</td>
<td>11-13 m/s</td>
</tr>
<tr>
<td>Upper and lower air</td>
<td>45-55 m/s</td>
</tr>
<tr>
<td>Middle air</td>
<td>45-55 m/s</td>
</tr>
<tr>
<td>Cooling and core air</td>
<td>20-25 m/s</td>
</tr>
</tbody>
</table>

**Diagram:**

- Nozzle for ceramics cooling air
- Nozzle for upper air
- Nozzle for pulverised coal with core air
- Nozzle for middle air
- Nozzle for pulverised coal with core air
- Nozzle for lower air
- Nozzle for ceramics cooling air
HOW PULVERIZED COAL IS TRANSPORTED FROM THE MILL TO BURNERS?

Media transporting pulverized coal:

Bituminous coal: hot air,
Lignite: flue gas.
JET BURNERS: PULVERIZED LIGNITE BURNING

Ventilation ratio of the coal mill: 1.6 kg/kg

Volumetric rate of flue gas/ Volumetric rate of air

<table>
<thead>
<tr>
<th>Ventilation, m³/h (flue gas)</th>
<th>No. of pulverized lignite nozzles in the burner</th>
</tr>
</thead>
<tbody>
<tr>
<td>do 80 000</td>
<td>2</td>
</tr>
<tr>
<td>80 000–200 000</td>
<td>3</td>
</tr>
<tr>
<td>200 000–300 000</td>
<td>4</td>
</tr>
<tr>
<td>300 000–400 000</td>
<td>6</td>
</tr>
<tr>
<td>400 000–500 000</td>
<td>8</td>
</tr>
</tbody>
</table>

No. of nozzles in a jet burner depending on the ventilation of a mill
FLAME PATTERN OF TANGENTIALLY FIRING FURNACE

Corner furnace
BOILER DUCTS IN TANGENTIALLY FIRING FURNACES
FLUIDIZED COMBUSTION
BURNING IN CIRCULATING FLUIDIZED BED BOILERS
COMPOSITION AND TEMPERATURE OF FLUIDIZED BED

Composition of fluidized bed:
- inert material (sand and ash),
- dolomite/calcite (and products of desulfurization),
- 2-6% of coal.

Temperature of fluidized bed: 800 - 900 °C
Optimal temperature with respect to desulfurization: 850 °C
LIGNITE BURNING IN LABORATORY FLUIDIZED BED
COAL COMBUSTION IN FREE BOARD ZONE OF FB
FRAGMENTATION OF COAL PARTICLES IN FLUIDIZED BED

Coal particles undergo fragmentation in fluidized bed due to:
- increase of porosity of char particles (percolative fragmentation),
- collision of coal particles with bed particles,
- attrition of coal particles in bed.
SPECIAL BOILER FURNACES
RETORT FURNACE FOR SMALL BOILERS
RETORT FURNACE: COAL COMBUSTION
Cyclone combustion chambers with tangent (a) and secant (b) injection of pulverised coal / air mixture.
BOILER WITH CYCLONE COMBUSTION CHAMBER

- Primary air
- Coal
- Liquid slag
- Water
- Main combustion zone
- Secondary air
- Coal
- Primary air
- Cyclone burner
- OFA
- Reburning zone
- Postcombustion zone