Three-dimensional modelling of a 300 MWe Flexi-Burn® CFB for multifuel combustion in oxygen-fired and air-fired modes

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Presentation outline

- Flexi-Burn CFB process
- Different scales of experiments and modelling
- Classification of multiphase model approaches
- Semi-empirical 3D-model
- Model results
- Conclusions
- References

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Flexi-Burn® CFB process

Flexi-Burn is a trademark of Foster Wheeler Energia Oy, registered in the US, EU, Finland.

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Different scales of experiments and modelling

**Bench scale**
- **Models and design tools**
  - Models for phenomena

**Pilot scale**
- **Models and design tools**
  - 1-D process models

**Boiler scale**
- **Models and design tools**
  - 3-D process models

**Experimental scales**
- Bench scale
- Pilot scale
- Boiler scale

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Classification of multiphase model approaches

- **Micro-scale**
  - Steady state
  - Quasi steady

- **Meso-scale**
  - Averaged CFD
  - 2D/3D

- **Macro-scale**
  - Empirical and semi-empirical models
  - 1D/1.5D/3D

- **Lumped scale**
  - Correlation models
  - 0D

- **Space scale**
  - 1 µm to 10...50 m

- **Time scale**
  - 1 µs to 1 year

- **Models**
  - Eulerian-Eulerian continuum models
    - CFD / TFM
    - 2D/3D
  - Lagrangian-Eulerian
    - DEM/DPM-CFD, DSMC
    - 2D/3D
  - Particle scale
    - DNS, LBM, DEM/DPM
    - 2D/3D
  - MP-PIC
Semi-empirical 3D-model

Heat transfer to walls and internal surfaces

Combustion, gasification & other reactions

Inlet sources
- sec. gas
- fuel
- limestone
- sand

Fluidization gas

Bottom ash

Flue gas, fly ash

Separator(s)
- separation eff.
- heat transfer
- reactions

Exchange of gas / solids

Solids

Gas

External heat exchangers
- heat transfer
- reactions

Solids to furnace

Gas, solids

Recirculation of flue gas / fly ash

External heat exchangers
- heat transfer
- reactions

Flue gas, fly ash

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Combustion model

- Inert
- Evaporation
- Devolatilization
- Char combustion
- Char gasification
- Gas combustion reactions
- Shift conversion

**Inert**
- HCN, NH₃
- H₂S
- CO, CO₂
- CH₄, C₂H₄
- H₂

**Evaporation**
- H₂O

**Devolatilization**
- Ash
- Moisture
- Volatiles
- Char

**Char combustion**
- CO
- H₂
- H₂S
- N₂
- NO, N₂O
- H₂O
- CO, CO₂
- SO₂

**Char gasification**
- +H₂O, +CO₂

**Gas combustion reactions**
- CO + 0.5O₂ → CO₂
- H₂ + 0.5O₂ → H₂O
- CH₄ + 2O₂ → CO₂ + 2H₂O
- C₂H₄ + 3O₂ → 2CO₂ + 2H₂O
- H₂S + 1.5O₂ → H₂O + SO₂

**Shift conversion**
- CO + H₂O ↔ CO₂ + H₂
Sorbent model

Calcination
\[ \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \]

Carbonation
\[ \text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3 \]

Sulphation
\[ \text{CaO} + \text{SO}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{CaSO}_4 \]

Direct sulphation
\[ \text{CaCO}_3 + \text{SO}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{CaSO}_4 + \text{CO}_2 \]

Desulphation
\[ \text{CaSO}_4 + \text{CO} \rightarrow \text{CaO} + \text{SO}_2 + \text{CO}_2 \]
Calculation mesh, furnace layout, process data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Air-fired</th>
<th>Oxygen-fired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel flow</td>
<td>kg/s</td>
<td>18.1 (70%)</td>
<td>22.0 (70%)</td>
</tr>
<tr>
<td>Anthracite</td>
<td></td>
<td>7.8 (30%)</td>
<td>9.4 (30%)</td>
</tr>
<tr>
<td>Petcoke</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone flow</td>
<td>kg/s</td>
<td>5.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Inlet gas flow to furnace</td>
<td>kg/s</td>
<td>272.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Ambient air</td>
<td></td>
<td>0.0</td>
<td>63.8</td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
<td>0.0</td>
<td>261.9</td>
</tr>
<tr>
<td>Recirculation gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen content of inlet gas</td>
<td>%</td>
<td>20.7</td>
<td>23.6</td>
</tr>
<tr>
<td>Primary gas ratio</td>
<td>%</td>
<td>62</td>
<td>60</td>
</tr>
<tr>
<td>Fly ash recirculation share</td>
<td>%</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

Outlets to separators (4)
Based on this study, the combustion reactions are fairly similar in oxygen- vs. air-fired mode, if the oxygen content of the inlet gas is close to air-fired mode.

The devolatilization and char combustion profiles are similar in shape, but in oxygen-fired mode, the values are higher due to higher boiler load and higher fuel flow rate.

The devolatilization rate is high near the fuel inlets. This produces high local concentrations of combustible gases above the fuel inlets.

The combustion rate of char is slower, thus, char has time to penetrate to the furnace and flow to the bottom of the furnace, where the maximum char concentrations are found.
Most of the heat originates from combustion of char at the bottom of the furnace. Local higher maximums can be noticed near the secondary air inlets, where the incoming oxygen mixes with combustible material.

The temperature is smaller towards the sides due to cooling effect of side walls.

The temperature profile of the oxygen-fired case is more uniform, partly due to re-carbonation reactions occurring in colder areas.

The heat release and temperature profiles could be adjusted by changing the fuel flow distribution.

In oxygen-fired case, modifying the oxygen content in lateral and vertical direction provides more methods to control the combustion process.
The concentration profiles of $O_2$ and $CO_2$ are similar, but due to recycling of flue gas, the $CO_2$ level is higher in oxygen-fired mode.

The location of secondary air inlets is shown by local high $O_2$ concentrations.

The $CO_2$ level increases towards upper furnace due to combustion reactions.

In oxygen-fired case, the $CO_2$ profile is affected by carbonation, e.g. in the corner of the roof.
Hydrogen concentration is high near the fuel inlets because most of the hydrogen originates from devolatilization.

- CO is found more uniformly across the bottom of the furnace, because the CO originates from burning of char as well.
Calcination and carbonation

- In air-fired mode, calcination of fresh limestone occurs quickly near the feed points of limestone.
- In oxygen-fired mode, re-carbonation can happen at locations, where the local temperature is below the calcination temperature.
- The re-carbonated limestone is re-calcined at areas with higher temperature.
- The cycling calcination-carbonation reactions affect the local gas composition, temperature, and gas velocities.
Sulphation and direct sulphation

- Highest sulphation rate at the bottom of the furnace, where the concentration of SO2 is high due to combustion reactions.
- In air-fired case, the amount of direct sulphation is practically zero.
- In oxygen-fired case, direct sulphation occurs near the side walls, where the temperature is lower and the concentration of CaCO3 is higher due to recarbonation.
In this model, the CaSO₄ can decompose in reducing conditions.

The desulphation rate is highest at the bottom of the furnace and near the centerline, where the local concentration of CO is high.

The SO₂ profile is a result of different sources and sinks, which are mainly due to combustion reactions and sulphation reactions.

The SO₂ concentration is higher at the centre of the furnace, where the temperature and CO concentration are higher, which promote the desulphation.
At this temperature level, sulphur capture is mostly by normal sulphation.

In oxygen-fired case, the sulphur capture is higher due to higher SO$_2$-content in the furnace, which is due to recirculated gas.
In air-fired case, most of the CO₂ originates from combustion reactions added by a small proportion from the calcination of fresh limestone and a very small amount due to shift conversion.

In oxygen-fired case, in addition to above, the inlet gas contains a large proportion of CO₂, which results in high molar flow of CO₂ through the system. A small proportion of CO₂ is consumed by carbonation, but this is again released by re-calcination.
Conclusions

- The combustion reactions are fairly similar in air-fired and oxygen-fired combustion, if the oxygen content of the input gas is moderate.
- Large differences may occur due to changing limestone reaction mechanisms when operating at high partial pressure of carbon dioxide.
- These differences have to be considered in the furnace design and operations in order to optimize the performance and the emission control, and to avoid operational problems.
- The findings of this study can be used to support the further design of the OXY-CFB-300 Compostilla demonstration plant.
- For future improvement, the different empirical correlations describing the essential phenomena need to be further validated based on experimental studies in bench-scale and pilot-scale test equipment.
References


Other semi-empirical, three-dimensional models: