Numerical Simulation of a 3 MW$_{th}$ Oxycoal Burner

1$^{st}$ OXYFUEL COMBUSTION CONFERENCE
Cottbus, Germany

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Outline

Project
- Description
- Burner design
- Combustion chamber

Models
- Boundary conditions / IPSE Pro
- Fluent / Models
- Char combustion
- Radiation

Simulation

Summary and Outlook
RFCS-Project „Friendly Coal“

Focus on the comparison of 2 concepts

Commonly discussed concept: Oxyfuel-Process with high CO₂-recirculation rates

Alternative concept: Oxyfuel-Process with inversely staged combustion
Oxyfuel-Process with high CO$_2$-Recirculation rates

- Basic Design of a 3MW$_{th}$ Oxycoal Burner
- Manufacturing of the Burner
- Burner tests at test facility located in Livorno, Italy
- Modeling of a 3 MW$_{th}$ flame with high CO$_2$-Recirculation
- Large-Scale burner design
3MW\textsubscript{th} Oxyfuel Burner Design

swirl burner is designed for the operation with:

- Air or pure oxygen
- High recirculation rate (~63%)
- Thermal input of 3 MW\textsubscript{th}
- Different fuels: coal or natural gas

- Variable swirl generation
- Variable oxygen injection
- Variable deflector position
Test Facility located at Enel’s experimental area in Livorno, Italy

Modified test facility:
- Convective heat exchanger
- Ljungström heat exchanger
- Wet/dry recycle
- Flue gas is used for coal transport
- Preheater for primary and secondary streams
- Oxygen is mixed with secondary stream and can be injected into primary stream

Combustion Chamber:
- IFRF furnace #1
- 6.38x2x2m
- Maximum thermal load 5 MW\textsubscript{th}
- Modular structure: 11 segments with cooling loops and coaxial cooling tubes
- Observation openings and small orifices in each section for measurements

Source: Cavalheiro, 2007
In order to estimate flue gas compositions, thermodynamic process simulation with IPSE Pro:

- Minimization of Gibbs Energy
- Radiation model based on partial pressures of CO₂ and H₂O including ash

Variation calculations
Numerical simulation using Fluent

Simulation Program Fluent in order to calculate:

• Flow fields of the new designed burner
• Over all simulations

Using following models:

• Pressure Based Solver
• Turbulence Model: Reynolds Stress Model (RSM)
• Non Premixed Combustion Model:
  • Probability Density Function (PDF) for gas phase reaction
  • Discrete Phase Model (DPM) for particles:
    • Vaporization
    • Devolatilization: Single Kinetic Rate Model
    • Char combustion
• P-1 Radiation Model
Discrete Phase Model: Char Combustion

Model bases on a single-film model:
Murphy and Shaddix (Combustion and Flame, 2006) implemented successfully empirical fits to the obtained data for O₂ concentrations up to 36 vol.%
Model validation and correction performed by project partner DTU

➔ User Defined Function in order to implement the model into Fluent (Law 5)

\[
q = A \cdot \exp \left( \frac{-E}{R \cdot T_P} \right) \cdot p_{O_2,s}^n
\]

\[n^{th} \text{ order Arrhenius expression (char kinetic, mol/m}^2\cdot s)\]

\[A=475 \text{ (mol/m}^2\cdot \text{s.atm}^n); \ E=45,9 \text{ (kJ/mol)}; \ n=0,17\]

\[\psi - 1 \]

\[\psi + 1\]

\[\Psi = \text{Fraction of carbon oxidized in the form of CO}_2\]

\[
\frac{p_{O_2,s}}{p} = \frac{1}{\alpha} + \left( \frac{p_{O_2,\infty}}{p} - \frac{1}{\alpha} \right) \cdot \exp \left[ \frac{q \cdot (1 + \psi) \cdot d_p \cdot \alpha}{4 \cdot D_{O_2,mix} \cdot \mathcal{C}} \right]
\]

Gas phase diffusion equation
P-1 Radiation Model: Absorption coefficient

Problem: absorption coefficient is calculated with the Weighted Sum of Grey Gas Model (WSGGM) developed for air combustion

- higher partial pressures of CO₂ and H₂O (sum: air → 0.15 atm; oxyfuel → 0.95 atm)
- different H₂O/CO₂ ratios (air → 0.5; oxyfuel → 0.1)

Source: Gupta, 2006
Absorption Coefficient: Exponential Wide Band Model

Exponential Wide Band Model by Edwards and Menard considering H\textsubscript{2}O and CO\textsubscript{2} provided by project partner AE&E

Gaseous emission/absorption is not continuous but is concentrated in spectral bands of certain wavelengths.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Principle Bands (\textmu m)</th>
<th>Weaker Bands (\textmu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H\textsubscript{2}O</td>
<td>2.7, 6.3</td>
<td>1.4, 1.9</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>2.7, 4.3</td>
<td>1.4, 1.6, 2.0</td>
</tr>
</tbody>
</table>

Absorption coefficient (ANSYS Fluent, 2007)

\[ \alpha = -\frac{\ln(1 - \varepsilon)}{s} \]

Emissivity

\[ \varepsilon = \sum_{i=1}^{N} \left( \frac{\pi \cdot l_{b\eta 0}}{\sigma T^4} \right)_i \cdot A_i \]

Band Black Body Intensity

\[ l_{b\eta 0} = \frac{C_1 \cdot \eta^3}{\pi \cdot n^2 \cdot \left( \frac{C_2 \cdot n}{e^{nT} - 1} \right)} \]

Mean beam length

Stefan-Boltzmann constant (5.670x10\textsuperscript{-8} W/m\textsuperscript{2}.K\textsuperscript{4})

Total Band Absorptance

\[ A_i(\alpha, \beta, \tau_0) \] (Modest)
Basic Boundary Conditions

Thermal load: $2.5 \text{ MW}_{th}$
Combustion chamber outlet temperature: 1100°C

Primary stream:
~0.2 kg/s (500m³/h) at ~70°C
Flue gas composition depends on condensation temperature

Pulverized Coal (transported with primary stream):
0.1 kg/s (~2.5MWth) and 70°C

Secondary stream:
Mass stream depends on recirculation rate ($R=0.61-0.63$) and oxygen injection
$\rightarrow 0.286-0.42 \text{ kg/s at 130-250°C}$

Oxygen:
max 0.06 kg/s at 20°C (ambient temperature)
Calculated Boundary Conditions

<table>
<thead>
<tr>
<th>Component</th>
<th>Dry rec. PrimO₂(0%)</th>
<th>Dry rec. SecO₂(100%)</th>
<th>Dry rec. PrimO₂(30%)</th>
<th>Dry rec. SecO₂(70%)</th>
<th>Air Prim/Sek</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.9273</td>
<td>0.4859</td>
<td>0.7144</td>
<td>0.5279</td>
<td>0.000</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.0246</td>
<td>0.0129</td>
<td>0.0184</td>
<td>0.0136</td>
<td>0.000</td>
</tr>
<tr>
<td>N₂</td>
<td>0.0052</td>
<td>0.0027</td>
<td>0.0040</td>
<td>0.0029</td>
<td>0.767</td>
</tr>
<tr>
<td>O₂</td>
<td>0.0430</td>
<td>0.4985</td>
<td>0.2633</td>
<td>0.4556</td>
<td>0.233</td>
</tr>
</tbody>
</table>

⇒ multiplicity of simulation possibilities, because of:

• Swirl number  \( S = \frac{Tangential \text{Momentum}}{Axial \text{Momentum} \cdot Characteristic \text{Length}} \)

• Deflector position

• Deflector angle

• Oxygen distribution
Simulation of Swirl Generator

Simulation of the secondary velocity profile:
• Boundary conditions obtained from IPSE Pro

![Velocity profile for overall simulation](image1)
![Velocity profile at outlet](image2)

0 Velocity Magnitude (m/s) 41
Typical Oxyfuel Flame of the 3 MW$_{th}$ Burner

Swirl Number=1.0, deflector angle 45°, 100% Oxygen in secondary stream

- $O_2$ concentration in the flame core is zero
- High flame core temperature

![Graph showing temperature and concentrations of $O_2$, CO, and CO$_2$.]
Effect of Swirl Number and Deflector angle

- Ignition starts earlier at higher swirl numbers and major deflector angles
- By increasing the deflector angle and the swirl number the flame shape becomes shorter and wider

Simulation Models

O₂,sek = 100%

Summary

Project
Effect of Oxygen Injection into the primary stream

Swirl Number=0.8, deflector angle 30°

- Earlier ignition because of the higher oxygen content in the flame core
- Flame is significantly shorter in the case of oxygen injection

![Diagram showing temperature and CO percentage with oxygen injection effects](image)
Effect of air leakage into the recirculated flue gas

20% Oxygen injected into primary stream, estimated air leakage

- Lower flame temperature (due to higher N₂ content)
- Simulation result corresponds to the measured data

![Graph showing temperature, O₂, and CO concentrations](image-url)
Summary and Outlook

• First simulation results of the new designed burner show good agreement with measured data
  ⇒ simulation model is appropriate for this kind of application

• Used models for CFD-Simulations allow due to their “simplicity” fast solutions
  ⇒ computational time for big boiler design is manageable

• Due to the adapted radiation model, the incident radiation in big boilers can be better predicted
  ⇒ possible hot spots can be detected

THANK YOU FOR YOUR ATTENTION