LES of a 250kW oxy-coal burner: an investigation into flame stability

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**Introduction**

**Oxy-fuel combustion**
- Can be retrofitted to existing power stations
- Thermochemical differences when $N_2$ is replaced with a $CO_2$ rich stream

**Flame stability**
- Affects heat transfer, pollutant emissions, burnout and performance
- Oscillation frequency can be used to characterise the flame

**Computational Fluid Dynamics (CFD)**
- CFD can provide insight into combustion problems
- Large eddy simulations (LES) can give details into the transient nature of a flame, important for analysing flame stability
Objectives

- Numerically assess flame stability in oxy-coal flames using LES
  - Animations
  - Oscillation frequency

- Examine the stability in a 250kWth Combustion Test Facility (CTF)
  - Air-coal combustion
  - Oxy-coal 21% (Oxy21)
  - Oxy-coal 25% (Oxy25)
  - Oxy-coal 30% (Oxy30)
250kW\textsubscript{th} Combustion Test Facility (CTF)

- Designed for solid-fuel combustion under air and oxy-fuel conditions
- Located at the PACT facilities in Yorkshire, UK
- Down-fired furnace, approximately 4m x 0.9m (I.D.)

Figure: Image of the top section of the facility and burner

Figures: (a) CAD of furnace (b) Full 3D mesh of the burner and furnace
**Numerical study: air and wet-recycle (CO₂ + H₂O)**

<table>
<thead>
<tr>
<th></th>
<th>AIR</th>
<th>OXY21</th>
<th>OXY25</th>
<th>OXY30</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ mass flow rate (kg/s)</td>
<td>2.24x10⁻²</td>
<td>2.15x10⁻²</td>
<td>2.11x10⁻²</td>
<td>2.08x10⁻²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>AIR</th>
<th>OXY21</th>
<th>OXY25</th>
<th>OXY30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycle Ratio (%)</td>
<td>-</td>
<td>77</td>
<td>73</td>
<td>67</td>
</tr>
</tbody>
</table>

**Thermal input**

- ALL CASES: 250kW<sub>th</sub>

**Exit O₂ (dry)**

- ALL CASES: 3% (vol.)

RecycleRatio (%) = \( \frac{\text{Mass flow of recycle}}{\text{Mass flow of recycle + mass flow of products}} \)
Numerical study: air and wet-recycle (CO₂ + H₂O)

- Doosan Babcock low-NOₓ burner, 250kWₜℎ
- Coal carried through the primary annulus
- Secondary and tertiary swirled, preheated air

<table>
<thead>
<tr>
<th>Oxygen concentration</th>
<th>AIR</th>
<th>OXY21</th>
<th>OXY25</th>
<th>OXY30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary (mass %)</td>
<td>23.2</td>
<td>19.0</td>
<td>19.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Secondary (mass %)</td>
<td>23.2</td>
<td>19.0</td>
<td>23.6</td>
<td>29.5</td>
</tr>
<tr>
<td>Tertiary (mass %)</td>
<td>23.2</td>
<td>19.0</td>
<td>23.6</td>
<td>29.5</td>
</tr>
</tbody>
</table>

Figure: Simplified mesh of the burner
**CFD approach: air and oxy-fuel cases**

- Commercial software: ANSYS FLUENT v14.0
- Full 3D mesh: 3.0 million cells
- High volatile bituminous coal: El-Cerrejon
- Turbulence: LES (WALE subgrid scale model)
- Radiation: WSGG model\(^1\), Discrete Ordinates
- Turbulence chemistry interaction: eddy dissipation
- Two step global reaction for volatile combustion
- Devolatilisation: single rate (FG-DVC)
- Char combustion: intrinsic model
- Particles: Euler-Lagrange approach

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\(^1\) R. Johansson et. al., Combustion and Flame. 158:5, 893-901. 2011.
Oscillation frequency and instability

Cross section of a CFD variable, e.g. temperature distribution (K)

First section \(^1\)

Region of interest

Average value at each timestep

Oscillation frequency \( F \)

\[
F = \frac{\sum_{i=0}^{i-1} P_{xx}(f_i) \cdot f_i}{\sum_{i=0}^{i-1} P_{xx}(f_i)} 
\]

Instability \( I \)

\[
I = \frac{\sigma}{\mu} 
\]

\(^1\) From burner exit to first section \((z = 0.5\text{m})\)
**Benchmark: Oscillation frequency**

- 200$kW_{th}$ air coal combustion
- 2D flame imaging by Kent University

<table>
<thead>
<tr>
<th>Oscillation frequency (Hz) exp</th>
<th>Oscillation frequency LES (Hz) [First section]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-9</td>
<td>5.27</td>
</tr>
</tbody>
</table>

Instantaneous experimental temperature distribution

LES instantaneous temperature distribution

1 Experimental Images and data courtesy of Kent University
Numerical predictions

- Air-coal combustion
- Oxy-coal 21% (Oxy21)
- Oxy-coal 25% (Oxy25)
- Oxy-coal 30% (Oxy30)
Predicted mean temperature distribution

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Exit Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1356</td>
</tr>
<tr>
<td>Oxy21</td>
<td>1306</td>
</tr>
<tr>
<td>Oxy25</td>
<td>1350</td>
</tr>
<tr>
<td>Oxy30</td>
<td>1402</td>
</tr>
</tbody>
</table>
Predicted instantaneous temperature distribution

Air  Oxy21  Oxy25  Oxy30
Predicted instantaneous temperature distribution

\[ t = t_0 \]

\[ t = t_i \]

Air  Oxy21  Oxy25  Oxy30

Temperature [K]

2000 1900 1800 1700 1600 1500 1400 1300 1200 1100 1000 900 800 700 600 500 400
**Predicted oscillation frequency**

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Oxy21</th>
<th>Oxy25</th>
<th>Oxy30</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIA (%)</td>
<td>0.04</td>
<td>0.37</td>
<td>0.17</td>
<td>0.17</td>
</tr>
</tbody>
</table>
**Summary**

**Conclusions**

- Flame stability was numerically examined in oxy-coal flames using LES.
- Lower oscillation frequency in oxy-coal cases compared to air.
- Oscillation frequency appears to decrease with higher recycle ratios.
- The work presented demonstrates the potential importance of using measured data for validation of LES for coal combustion.

**Way forward**

- 3D flame imaging data: Further validation and understanding of flicker.
Acknowledgements

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