3-D Reconstruction and Characterisation of Oxy-Gas Flames and Coal Flames on the PACT 250kW Facility

Md. M. Hossain, D. Sun, G. Lu, Y. Yan, University of Kent
J. Szuhanski, S. Black, W. Nimmo, L. Ma, M. Pourkashanian, University of Leeds

10th European Conference on Coal Research and Its Applications,
15th -17th September 2014.
The Business School, University of Hull.
Outline

• Background
• System Description
• Methodology
• Tests on Lab-scale Oxy-gas Rig
• Tests on PACT 250kW Facility
• Concluding Remarks
Background

• Oxy-coal combustion is a new and promising technology that utilizes highly concentrated oxygen and recycled flue gas instead of air in a combustor. The key advantages are,
  • it could deliver environmental benefits while providing power from an abundant energy source.
  • it could reduce NOx emission and enhance the combustion efficiency in addition to the recovery of CO₂ from exhaust gas.
  • it can easily be adapted at both new and existing coal-fired power plants.
• Advanced technique is required to provide a reliable, non-intrusive, and online monitoring of oxy-flames.
• 3-D visualisation and characterisation techniques are desired for fully revealing the dynamic nature of oxy-flames.
Technical Challenges

Technical challenges of 3-D imaging system

In view of the nature of flame on a practical furnace, the development of a 3-D flame imaging technique faces a number of technical challenges,

- Suitable system setup for a large-scale installation.
- The number of image projections available for the reconstruction.
- Improved accuracy of the reconstruction.
- Computer algorithms for characterisation of combustion flames including flame stability, and identification of the internal flame structure and flame front movement.
System Description

- The 3-D flame imaging system has 8 imaging fibre bundles, each having 30k individual optical fibres with a 92° objective lens.
- Four of the eight fibre bundles are joined onto a single eyepiece, forming four identical images into the same camera.
Tomographic reconstruction of a flame

Methodology

Projections 7 & 8

Projections 5 & 6

Reconstructed cross-sections

Reconstruction Algorithm

Projections 3 & 4

Projections 1 & 2

Flame
An innovative tomographic algorithm which combines the LFBP (logical filtered back-projection) and SART (simultaneous algebraic reconstruction technique) is developed for the 3-D grey-level reconstruction of flame sections.

3-D gray-level reconstruction procedure:

1. Generation 2-D flame image matrices
2. Generation of projections
3. Filtering and back-projection
4. Computation of LFBP algorithm
5. Determination of external contour
6. Position identification of the external contour
7. Computation of SART algorithm
8. Generation of 3-D flame sections
9. Reallocation and rotation of the flame sections
10. Data presentation

Mathematical expressions:

\[ P_\phi(x') = \int_{\mathbb{R}^2} g(\vec{x}) \delta(\vec{x} \cdot \vec{n} - x') d^2 \vec{x} \]

\[ P_\phi(\theta) \text{ known as the Radon Transform} \]

\[ g(\vec{x}) = \int_0^{\pi} Q_\phi(\vec{x} \cdot \vec{n}) d\theta \]

\[ Q_\phi(\vec{x} \cdot \vec{n}) = (h \ast P_\phi)(x') \]

\[ g(\vec{x}) \approx \frac{\pi}{M_p} \sum_{i=1}^{M_p} Q_{\theta_i}(\vec{x} \cdot \vec{n}_i) \]
Methodology

- Example results for flame grey-level reconstruction

2-D flame images captured by the imaging system

Grey-level reconstruction of cross- and longitudinal-sections of a laminar diffusion flame
Tests on Lab-scale Oxy-gas Rig

- Experiments have been carried out on a small-scale oxy-gas burner rig to monitoring the oxy-gas flames using the 3-D flame imaging system.

Composition gases
- Oxygen (O₂)
- Carbon dioxide (CO₂)
- Propane
- Air

Schematic of experimental set-up
Tests on Lab-scale Oxy-gas Rig

• Four oxy-fuel conditions (i.e., OF35, OF40, OF45 and OF50) under a fixed fuel flow rate were investigated.

**Test conditions**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel: Propane ($C_3H_8$)</td>
<td>0.014 g/s</td>
</tr>
<tr>
<td>Oxygen ($O_2$)</td>
<td>0.064 g/s</td>
</tr>
<tr>
<td>Primary supply ($O_2 + CO_2$)</td>
<td>15% of total gas composition</td>
</tr>
<tr>
<td>Secondary supply ($O_2 + CO_2$)</td>
<td>85% of total gas composition</td>
</tr>
<tr>
<td>Relative stoichiometric oxygen-fuel ratio</td>
<td>1.25</td>
</tr>
<tr>
<td>Supply error (%)</td>
<td>&lt; ± 1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tests</th>
<th>Volume (%)</th>
<th>Mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$O_2$</td>
<td>$CO_2$</td>
</tr>
<tr>
<td>OF35</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>OF40</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>OF45</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>OF50</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Averaged images of the oxy-gas flame

- OF35
- OF40
- OF45
- OF50
The grey-level distributions of oxy-gas flames have been reconstructed at different heights from the burner outlet.

Remarks: It is observed that the grey-level luminosity of OF50 flame is much higher than that of OF35, OF40 and OF45 flames, particularly in the root region of the flame. This is due to that the higher concentration of CO$_2$ reduces the luminous radiation of the flame whilst the higher concentration of O$_2$ increase band radiation of the flame.
Reconstructed temperature distributions at different heights from the burner outlet.

Measured mean temperature at different heights from the burner outlet.
Soot Measurement

Reconstructed soot distributions at different heights from the burner outlet.

Measured mean soot at different heights from the burner outlet.
Mean Temperature and Soot Volume Fraction

The mean temperature and soot volume fraction of the flame under four oxy-gas conditions were also measured.

**Remark:** It is also observed that the flame under the OF50 condition has higher temperature, emissivity and soot volume fraction than that under the OF35, OF40 and OF45 conditions.
Test on the PACT 250kW Facility at Beighton

- The industrial trials were conducted on the PACT 250kW \text{th} Facility at Beighton with the University of Leeds in April 2014.
- Due to the limitation of the fibre length, only four of eight probes of the 3-D flame imaging system were used.
- The 2-D flame imaging system previously developed by Kent was applied in parallel with the 3-D system.
- A variety of air-coal firing conditions were created including variation of primary air and secondary air and tertiary air splitter settings.

**Test conditions**

<table>
<thead>
<tr>
<th>Test</th>
<th>Load (KW)</th>
<th>PA (%)</th>
<th>Sec. air-Ter. air splitter setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>260</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>20</td>
<td>0, 1, 2, 2.5, 3, 3.5, 4, 5, 6, 7</td>
</tr>
</tbody>
</table>
Test on the PACT 250kW Facility at Beighton
Overview of 2-D Flame Imaging System

• The 2-D flame imaging system is capable of measuring flame temperature and oscillation frequency.

![Diagram of 2-D Flame Imaging System]

**Meet industrial requirements**
- Robust
- Fast response
- Compact
- Acceptable cost

(12×22×8cm)
Test on the PACT 250kW Facility at Beighton

3-D image system

2-D image system

System operation

Thermocouple probe
Flame Images, Temperature and Oscillation Frequency for Different Primary Air Flows

Instantaneous images

Averaged images

Temperature distribution

18% 20% 22%
Primary air (SA-TRA splitter: 3)

Oscillation frequency

Average temperature
Flame Images, Temperature and Oscillation Frequency for Different SA-to-TA splitter positions (PA: 20%)
Flame Images from the 3-D System

Note: 260KW\textsubscript{th}, SA-to-TA splitter: 3
3-D Grey-level Reconstruction

Burner side

2-D flame image

Grey-level reconstruction of flame cross-sections

Grey-level

200 180 160 140 120 100 80 60 40 20
Concluding Remarks

• 3-D optical tomographic system has been developed for the visualisation and characterisation of oxy-fuel flames, including flame temperature, emissivity and soot distribution.

• LFBP-SART tomographic techniques have successfully reconstructed the grey-level intensities of flame sections from only eight image projections.

• Tests have been conducted on the lab-scale oxy-gas rig and the PACT 250kW Facility under air-firing conditions.

• Oxy-coal tests on the PACT 250kW Facility will be conducted soon.

• It is expected that a combination of the data from measurement systems and CFD modelling results will lead to an in-depth understanding and subsequent optimisation of oxy-fuel combustion.