Advanced Monitoring and Characterisation of Combustion Flames

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Outline

• Introduction
• 2D flame imaging
• 3D flame imaging
• Concluding remarks
• Advanced monitoring of combustion flames plays an important role in the in-depth understanding of energy conversion and pollutant formation processes and subsequent combustion optimisation.

• Current practice of flame monitoring is limited to indicate whether the flame is present or absent for safety purpose only.
Introduction

• Advanced techniques are required to provide reliable, non-intrusive and continuous monitoring of combustion flames.

• Substantial research has been carried out at the University of Kent to develop a vision based technology for 2D/3D monitoring and characterisation of combustion flames.

• This presentation presents an overview of recent developments in the 2D and 3D flame imaging techniques.
Typical coal-fired flames

(Flame images taken on a 1MW$_{th}$ CTF, E.ON, UK)
Flame characterisation through 2D imaging

Flame images → Flame characteristics
- Size/shape, Ignition point
- Luminous intensity, Uniformity
- Temperature
- Oscillation frequency

→ Flame assessment
  Fuel/air inputs
  Emissions
  Other data
  Computational modelling

→ Recommendation to Combustion optimisation
2D flame imaging – industrial trials

- 0.5 MW<sub>th</sub> CTF, RWE npower
- 1 MW<sub>th</sub> CTF, E.ON UK
- 90 MW<sub>th</sub> CTF, Doosan Babcock
- 3 MW<sub>th</sub> coal-fired CTF, Cerchar, France
Determination of flame geometric and luminous parameters

• Geometric and luminous parameters
  - Ignition point: \( I_p \)
  - Spreading angle: \( \alpha_s \)
  - Brightness: \( B_f \)
  - Non-uniformity: \( N_{uf} \)

• Techniques used
  - Edge detection
  - Pattern recognition
  - etc …
Example results
-- Tests on a 1MW$_{th}$ CTF, EON (UK)

- Flame images and the ignition point for variable furnace load.

![Flame images and ignition point](image_url)
Determination of flame temperature

• The two-colour method - The temperature is determined from flame radiation intensities at two wavelengths based on the Planck’s radiation law.

Spectral radiance of a blackbody (Wien’s radiation law)

\[ M(\lambda, T) = \frac{C_1}{\lambda^5} e^{-\frac{C_2}{\lambda T}} \]

• Spectral radiance of particles

\[ M(\lambda, T) = \varepsilon_{\lambda} \frac{C_1}{\lambda^5} e^{-\frac{C_2}{\lambda T}} \]

• The two-colour method

\[ T = f(\lambda_1, \lambda_2, M_1, M_2) \]
Determination of flame temperature

• Sensing arrangement

\[ T = f(\lambda_1, \lambda_2, G_1, G_2) \]

Temperature distribution

Image at \( \lambda_1 \)

Image at \( \lambda_2 \)
Example results
-- Tests on a 1MW_{th} CTF, E.ON (UK)

• Temperature profiles of a coal-fired flame for variable furnace load.

Temperature profiles

Temperature variation

Max • Min • Mean
Example results
-- Tests on a 3MW\textsubscript{th} CTF (France)

• Comparison of flame temperature profiles obtained by the imaging system and by a thermocouple.
Determination of oscillation frequency

- Oscillatory (flickering) characteristic of a flame is reflected by the dynamic alternating components (AC) superimposed on the steady state (DC) or ‘brightness’ level.

- The oscillation signal is reconstructed from the luminous intensity of pixels within flame images.

- Quantified frequency is the weighted average of the power spectra over the whole measuring range, i.e., 0 -180Hz.
Example results
-- Tests on a 1MWth CTF, EON (UK)

- Flame oscillation frequency for variable furnace load
3D flame monitoring and characterisation through imaging

A flame is a 3D flow field. To fully reveal the dynamic nature of the flame, 3D monitoring and characterisation techniques are required.

3D Characteristic Parameters of a Flame

- Geometric
  - Volume
  - Surface Area
  - Length
  - Orientation
  - Circularity

- Luminous
  - Brightness
  - Non-uniformity

- Fluid-dynamic
  - Temperature
  - Oscillation frequency
  - Soot concentration
3D flame geometric model

- Contour extraction
- Mesh generation
- Pseudo-colouring
3D tomographic reconstruction of the flame luminosity

MIRRORS/lenses → Flame → Camera

Reconstruction Algorithm
• Filtered Back Projection
• Algebraic Reconstruction Technique

Reconstructed grey-scale cross-sections
3D tomographic reconstruction of the flame luminosity

Gas flame images

Longitudinal-section reconstruction

Cross-section reconstruction
3D tomographic reconstruction of the flame temperature

- Image acquisition & digitisation
- Image 1 (for $\lambda_1$)
- Image 2 (for $\lambda_2$)
- Grey level reconstruction
- Grey level reconstruction
- Temperature calculation (Two-colour method)
- Data presentation

Flame
3D tomographic reconstruction of the flame temperature

A gas flame image

Flame temperature distribution

Temp (°C)

<table>
<thead>
<tr>
<th>Distance from the burner central line (mm)</th>
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</thead>
<tbody>
<tr>
<td>Distance from the burner central line (mm)</td>
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</tbody>
</table>

| Flame height (mm) | 50 | 40 | 30 | 20 |

| Flame height (mm) | 50 | 40 | 30 | 20 |

Temp (°C)

- 1400
- 1300
- 1200
- 1100
- 1000
- 900
- 800
- 700
3D tomographic reconstruction of a coal flame

A coal flame image

Cross-section reconstruction
Concluding remarks

- Digital imaging provides a viable approach to on-line 2D/3D monitoring and characterisation of combustion flames.

- Prototype systems have been evaluated on laboratory- and industrial-scale combustion test facilities. The test results have proven their effectiveness and operability.

- Work is being undertaken to,
  - study flame stability and burner condition monitoring under biomass/coal co-firing and oxyfuel combustion conditions (EPSRC projects)
  - study the internal structure of a flame under a wide range of conditions (EPSRC projects)
  - Scale up the 2D prototype systems for the installation on full-scale coal fired boilers (BCURA Project B95).

- The flame imaging techniques are being extended to other applications such as gas turbine combustors and blast furnaces.
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- Alstom Power
- EDF Energy
- Spectus Energy
- PCME
System calibration

• The imaging system is calibrated using a standard temperature source - black-body furnaces at NPL.

• Images of the blackbody furnace

Calibration curve (1/500sec, Iris 11)