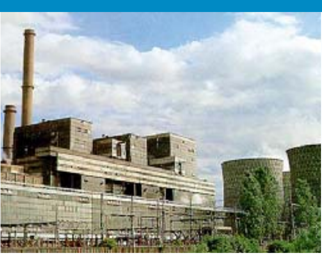
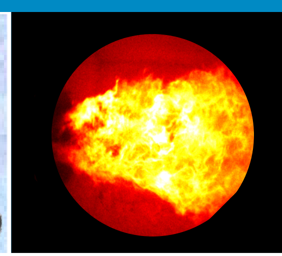
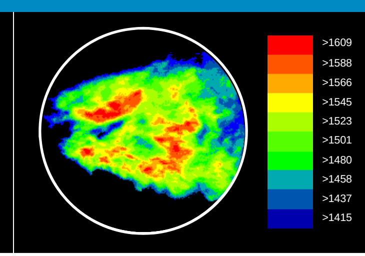
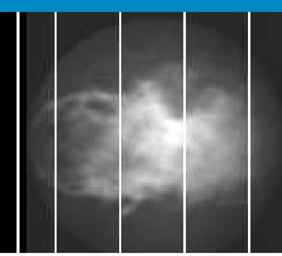
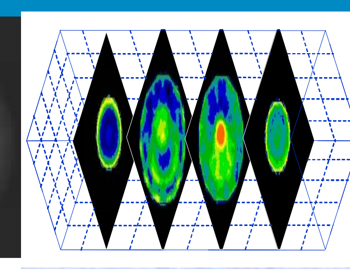
20th Annual Meeting and Meetings of the Combustion and Advance Power Generation Divisions, University of Leeds, 22nd April, 2009

# Advanced Monitoring and Characterisation of Combustion Flames



**Dr G Lu and Prof Y Yan**

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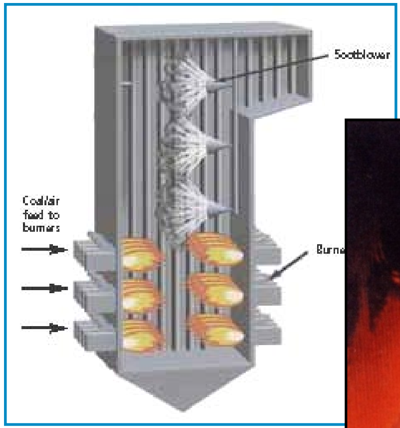
University of Kent

# Outline

- Introduction
- 2D flame imaging
- 3D flame imaging
- Concluding remarks

# Introduction

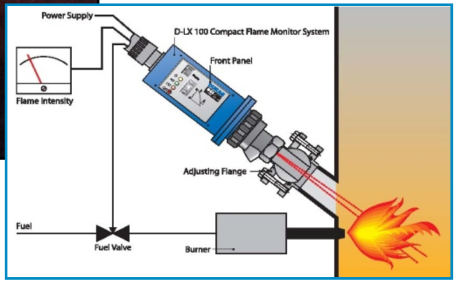
- Advanced monitoring of combustion flames plays an important role in the in-depth understanding of energy conversion and pollutant formation processes and subsequent combustion optimisation.
- Current practice of flame monitoring is limited to indicate whether the flame is present or absent for safety purpose only.




**Coal-fired boiler**
(*Source: DTI)*

**Flames** (*Source: DTI)*

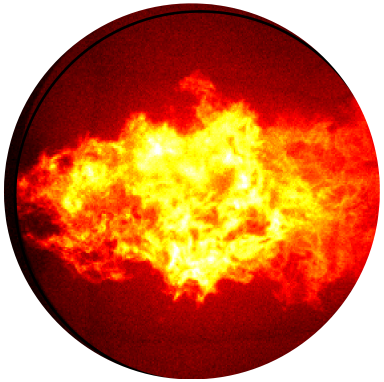
**Conventional flame detector**
*(Source: DURAG)*



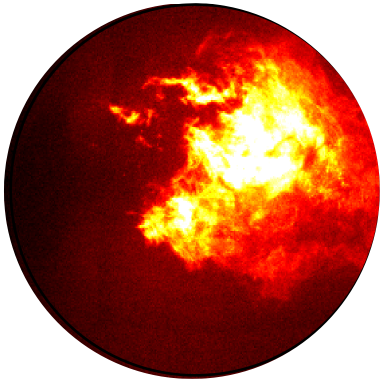
# Introduction

- 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



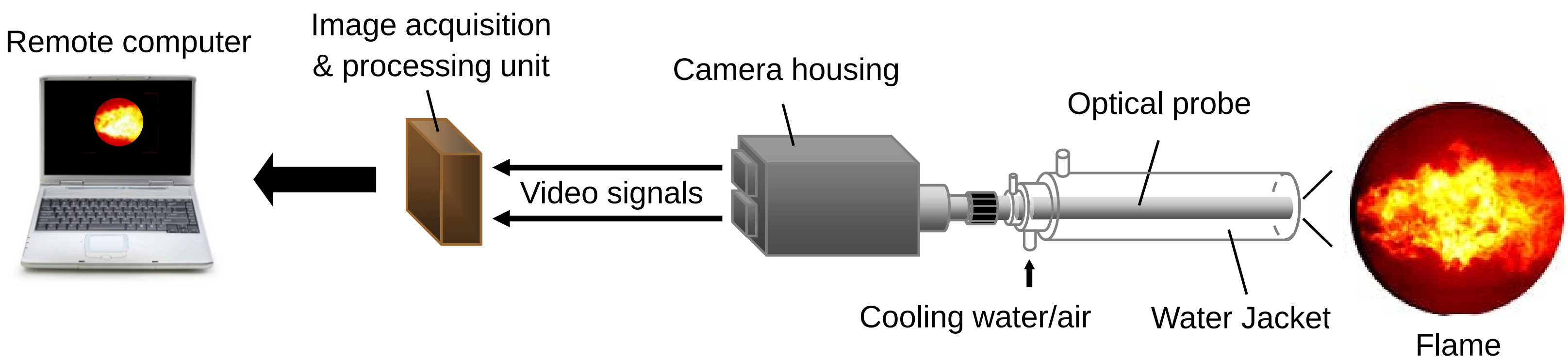
1.0 $MW_{th}$



0.75 $MW_{th}$

*(Flame images taken on a 1$MW_{th}$ 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**

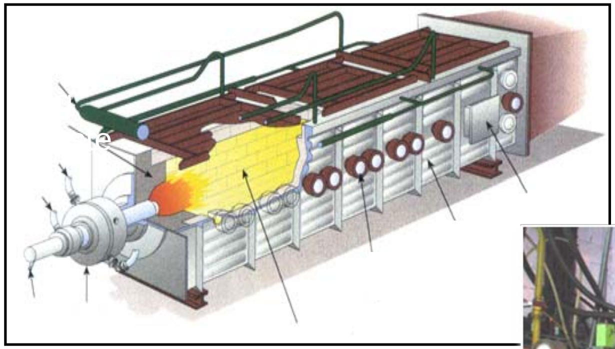
**Emissions**

**Other data**

**Computational modelling**

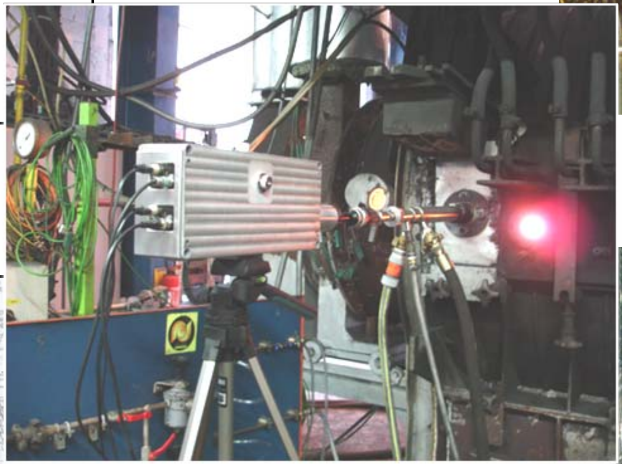
**Recommendation to Combustion optimisation**

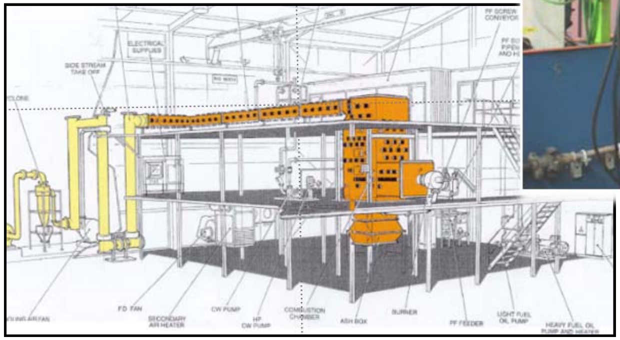
# 2D flame imaging – industrial trials



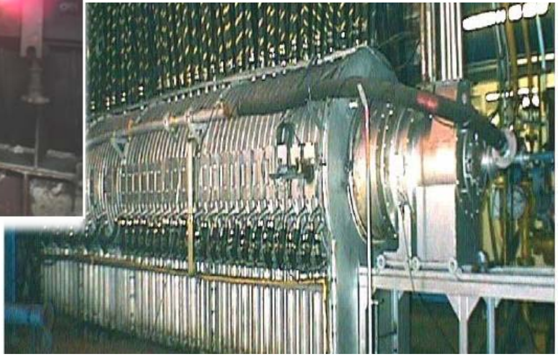
0.5MW$_{th}$ CTF, RWE npower

90 MW$_{th}$ CTF, Doosan Babcock





1MW$_{th}$ CTF, E.ON UK

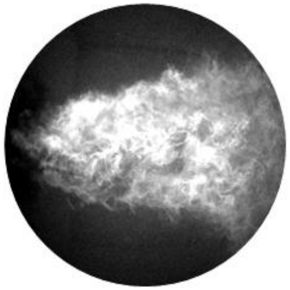


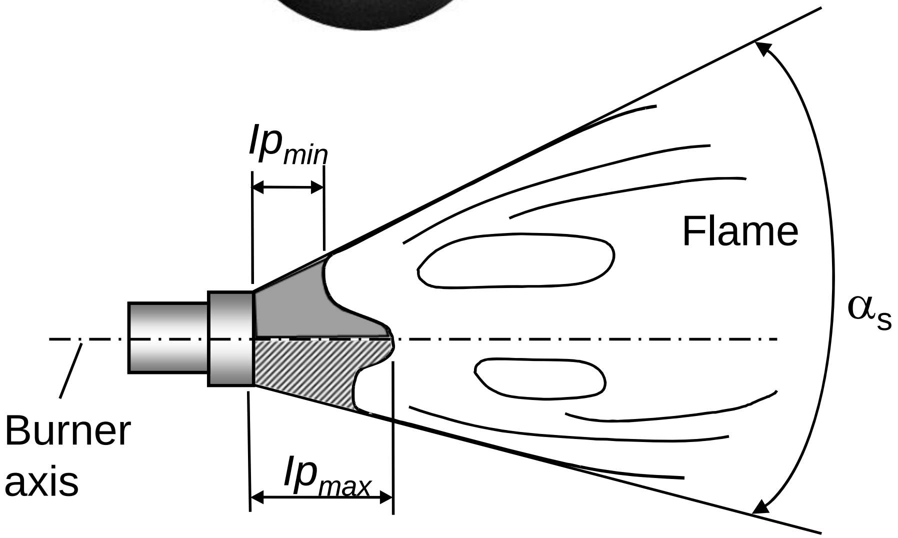
3MW$_{th}$ coal-fired CTF, Cerchar, France

# Determination of flame geometric and luminous parameters

- **Geometric and luminous parameters**

  - Ignition point: *Ip*
  - Spreading angle: $\alpha_s$
  - Brightness: $B_f$
  - Non- uniformity: $N_{uf}$





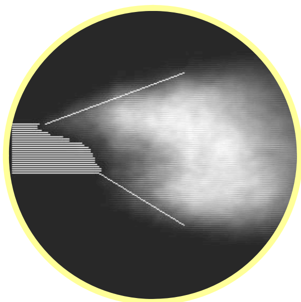

- **Techniques used**

  - Edge detection
  - Pattern recognition
  - etc …

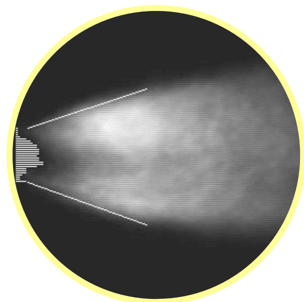
# Example results

## -- Tests on a 1MW$_{th}$ CTF, EON (UK)

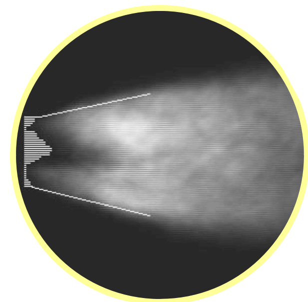
- Flame images and the ignition point for variable furnace load.



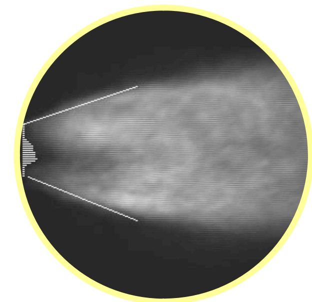
0.8MW



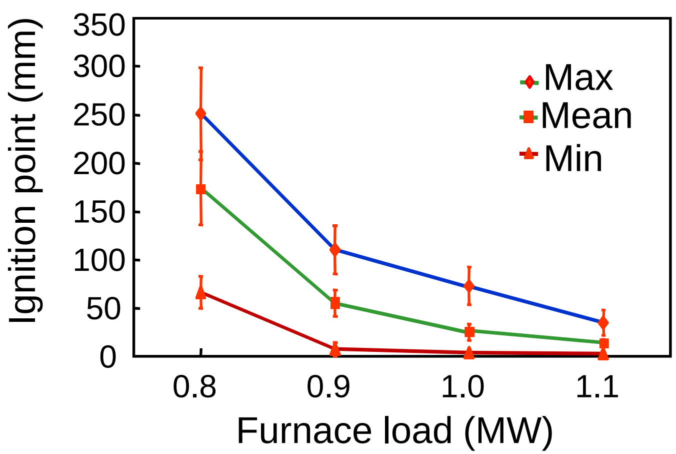
0.9MW

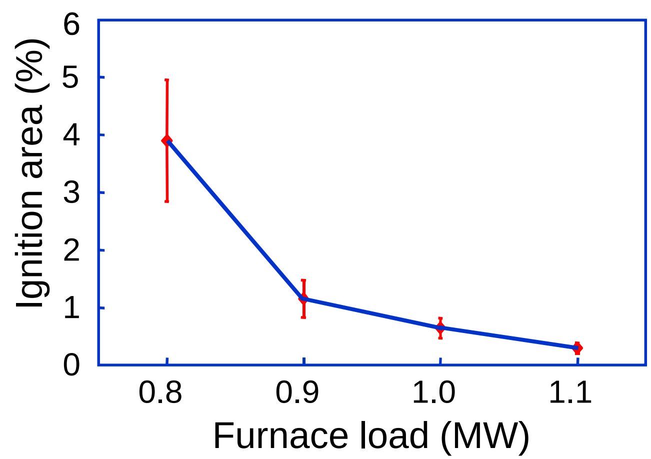


1.0MW



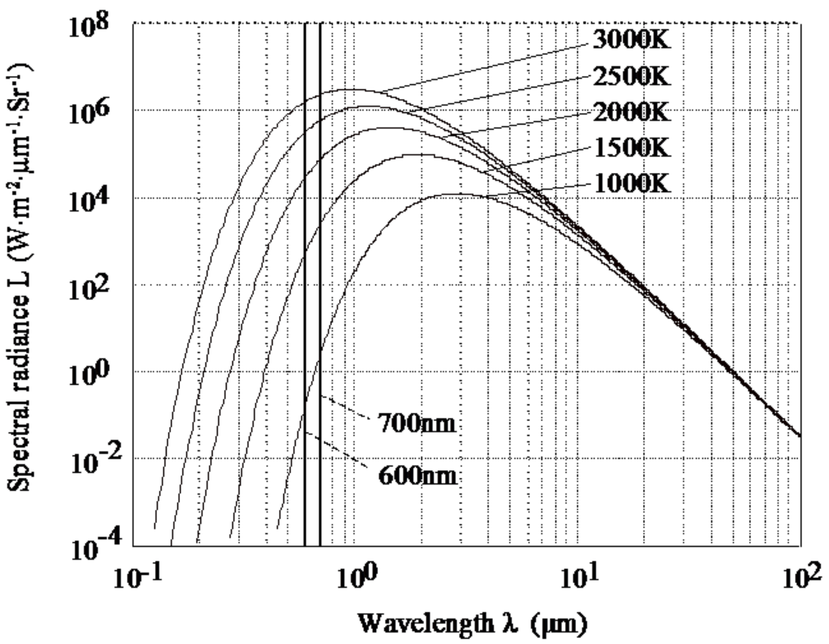
1.1MW



# 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
for selected temperatures

- Spectral radiance of a blackbody (*Wien's radiation law*)

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

- Spectral radiance of particles

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

Emissivity of particles

- The two-colour method

$$T=f(\lambda_1,\lambda_2,M_1,M_2)$$

# Determination of flame temperature

- **Sensing arrangement**

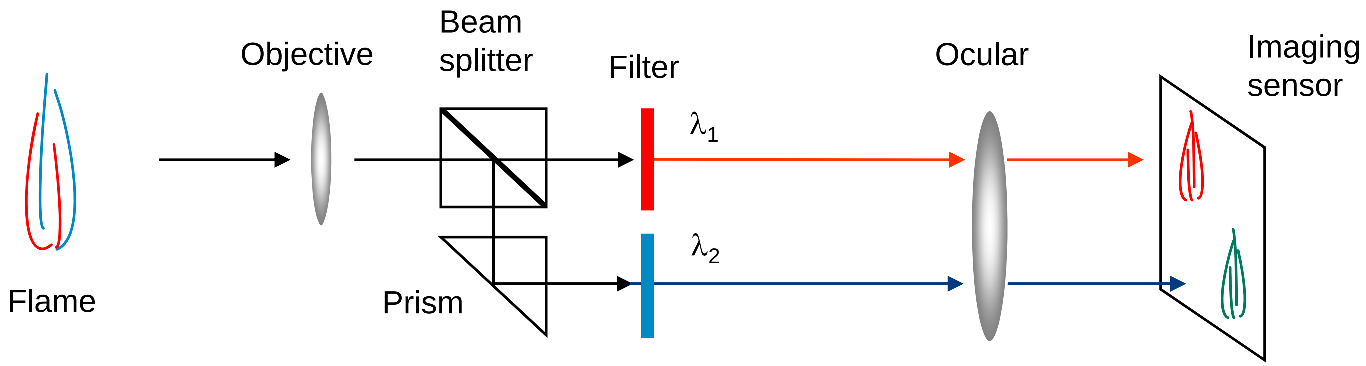
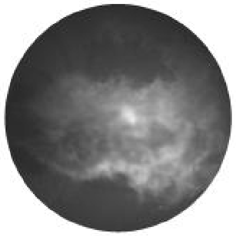
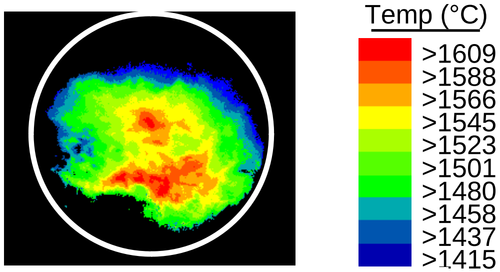



Image at $\lambda_1$

Image at $\lambda_2$



$$T=f(\lambda_1, \lambda_2, G_1, G_2)$$

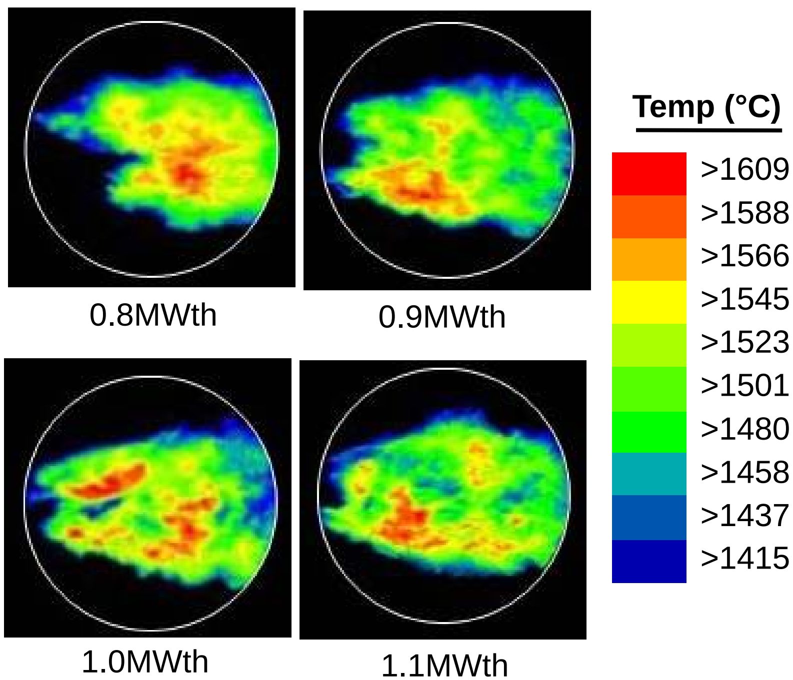



Temperature distribution

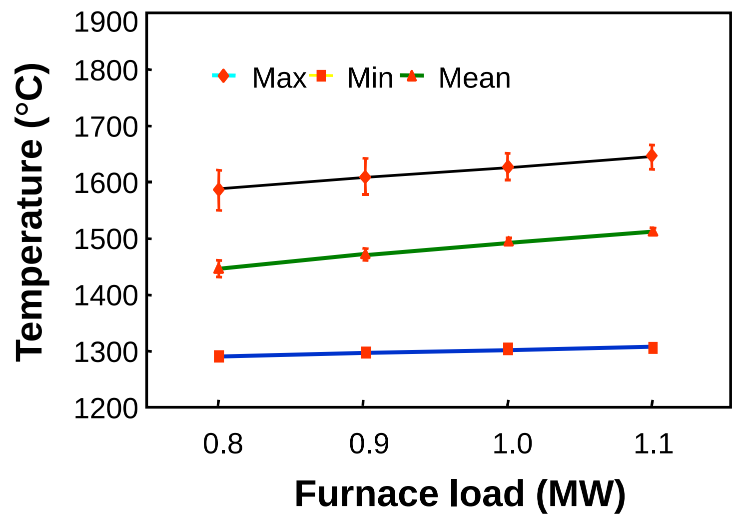
# Example results

## -- Tests on a 1MW$_{th}$ CTF, E.ON (UK)

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




Temperature profiles

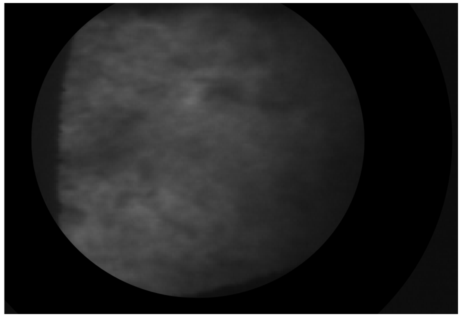



Temperature variation

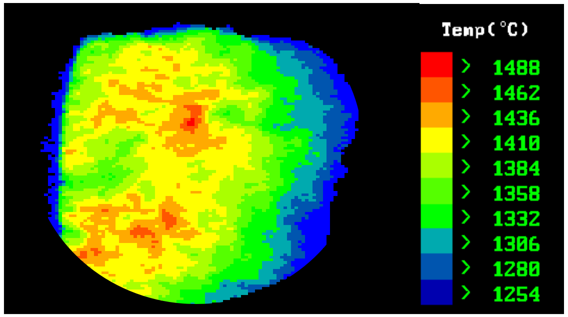
# Example results

## -- Tests on a $3MW_{th}$ CTF (France)

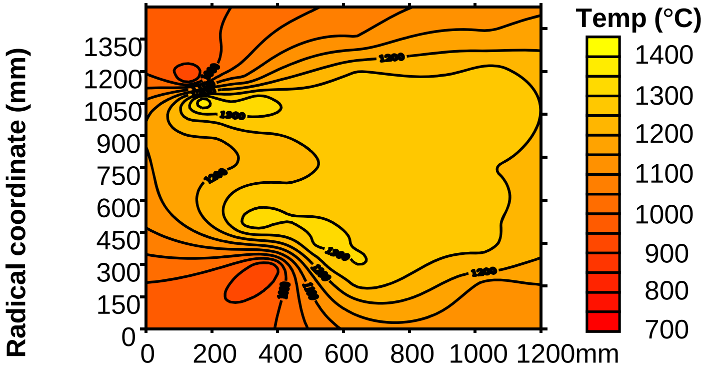
- Comparison of flame temperature profiles obtained by the imaging system and by a thermocouple.



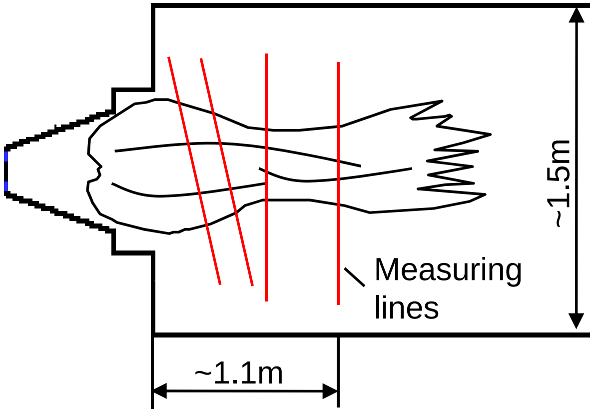
**Flame image**




**Temperature from imaging system**



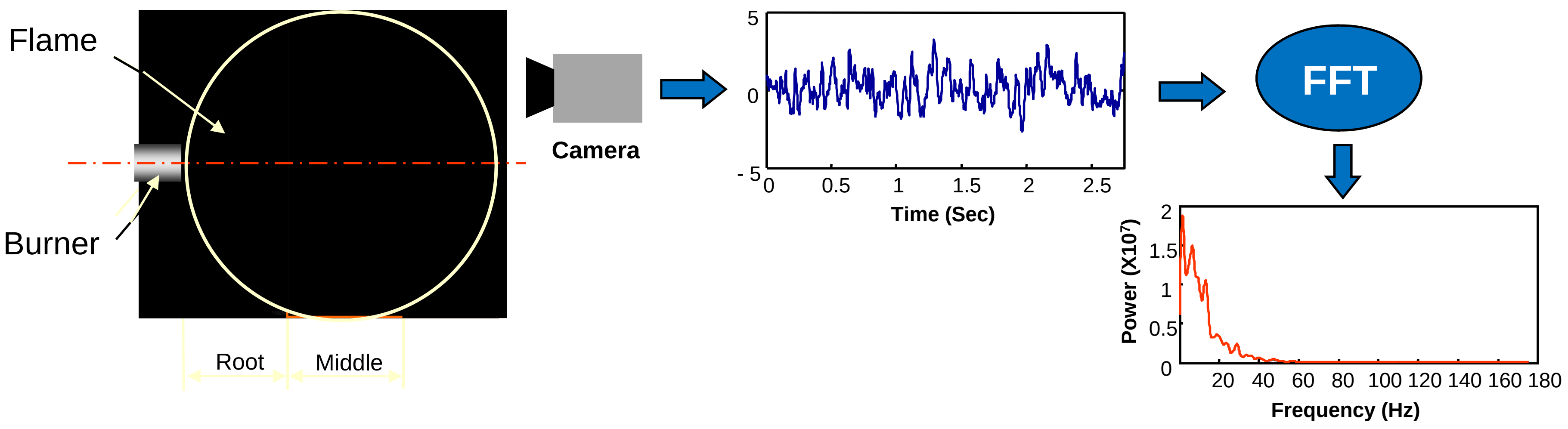

**Temperature from thermocouple from 44 measuring points** *(Source: Cerchar, France)*




**Location of measurement points**

# Determination of oscillation frequency

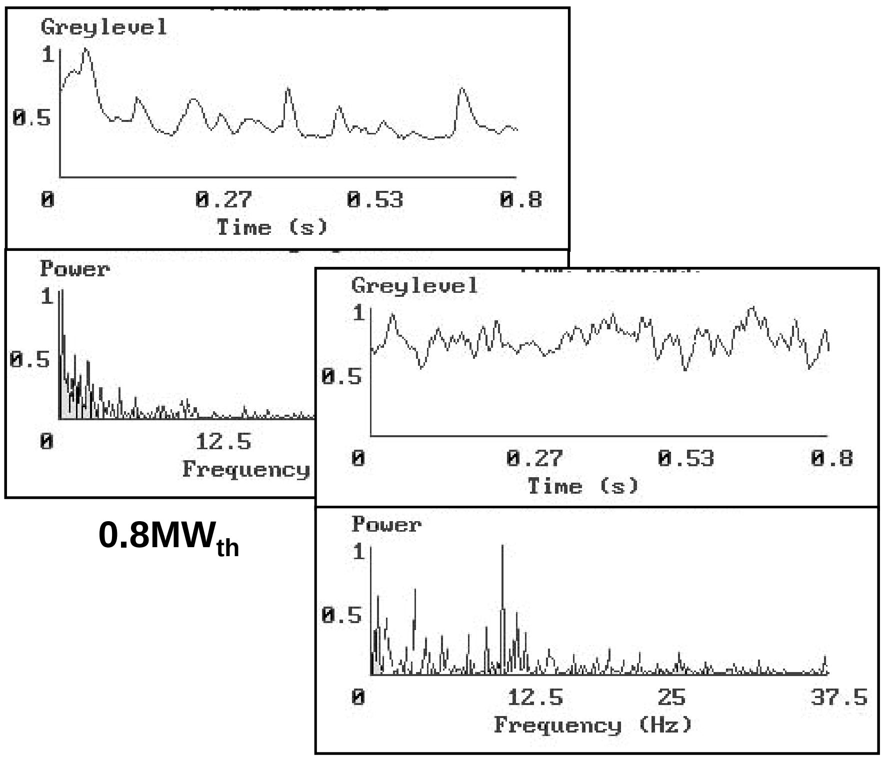
- Oscillatory (flickering) characteristic of a flame is reflected by the dynamic alternating components (AC) superimposed on the steady state (DC) or 'brightness' level.
- The oscillation signal is reconstructed from the luminous intensity of pixels within flame images.
- Quantified frequency is the weighted average of the power spectra over the whole measuring range, i.e., 0 -180Hz.



# Example results

-- Tests on a 1MWth CTF, EON (UK)

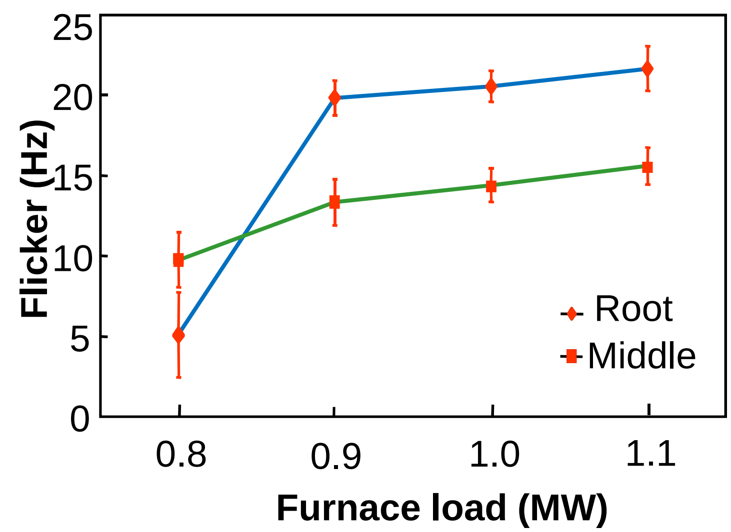
- Flame oscillation frequency for variable furnace load




**$0.8MW_{th}$**

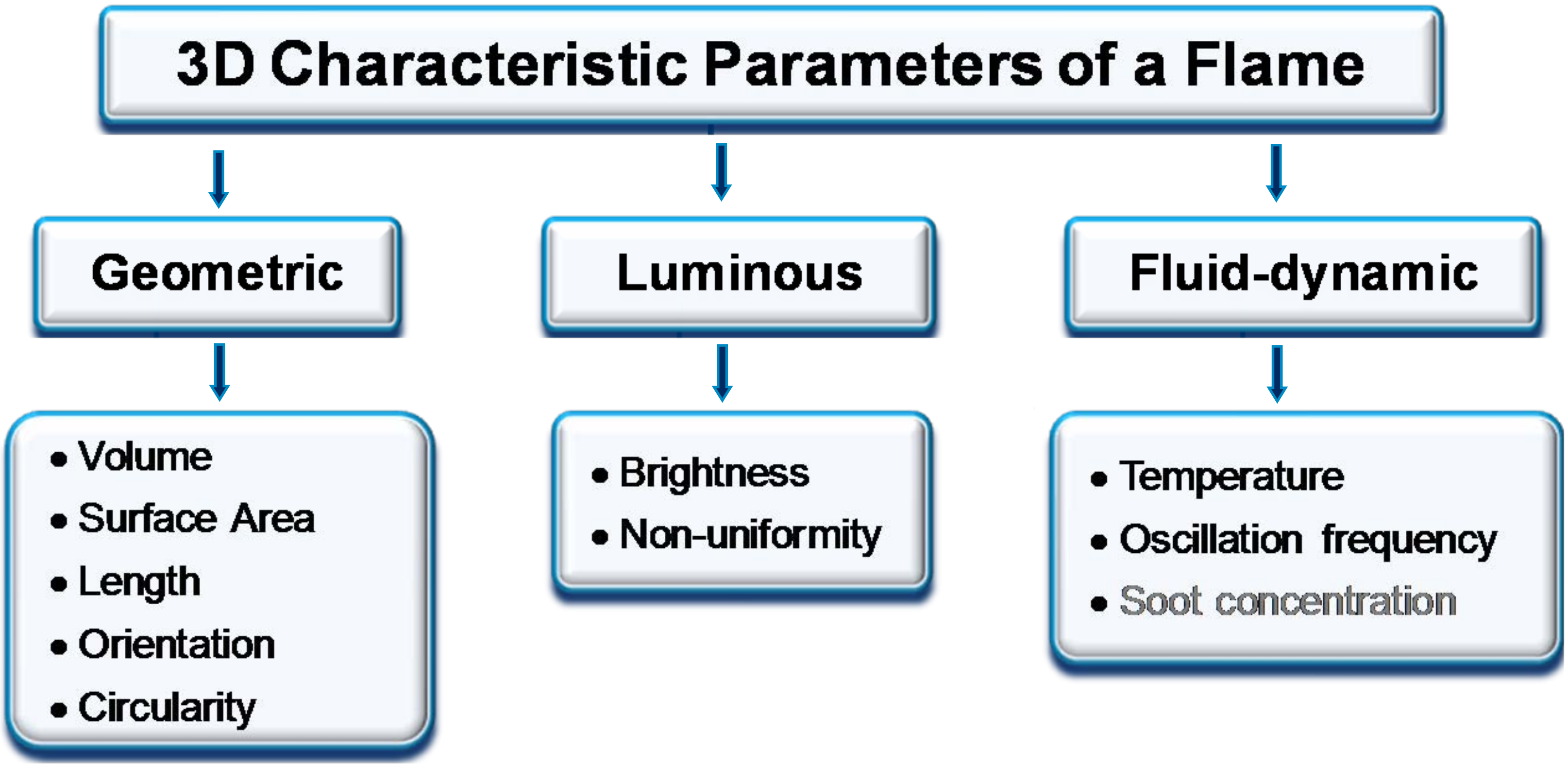
**$1.0MW_{th}$**

Variation of the oscillation frequency

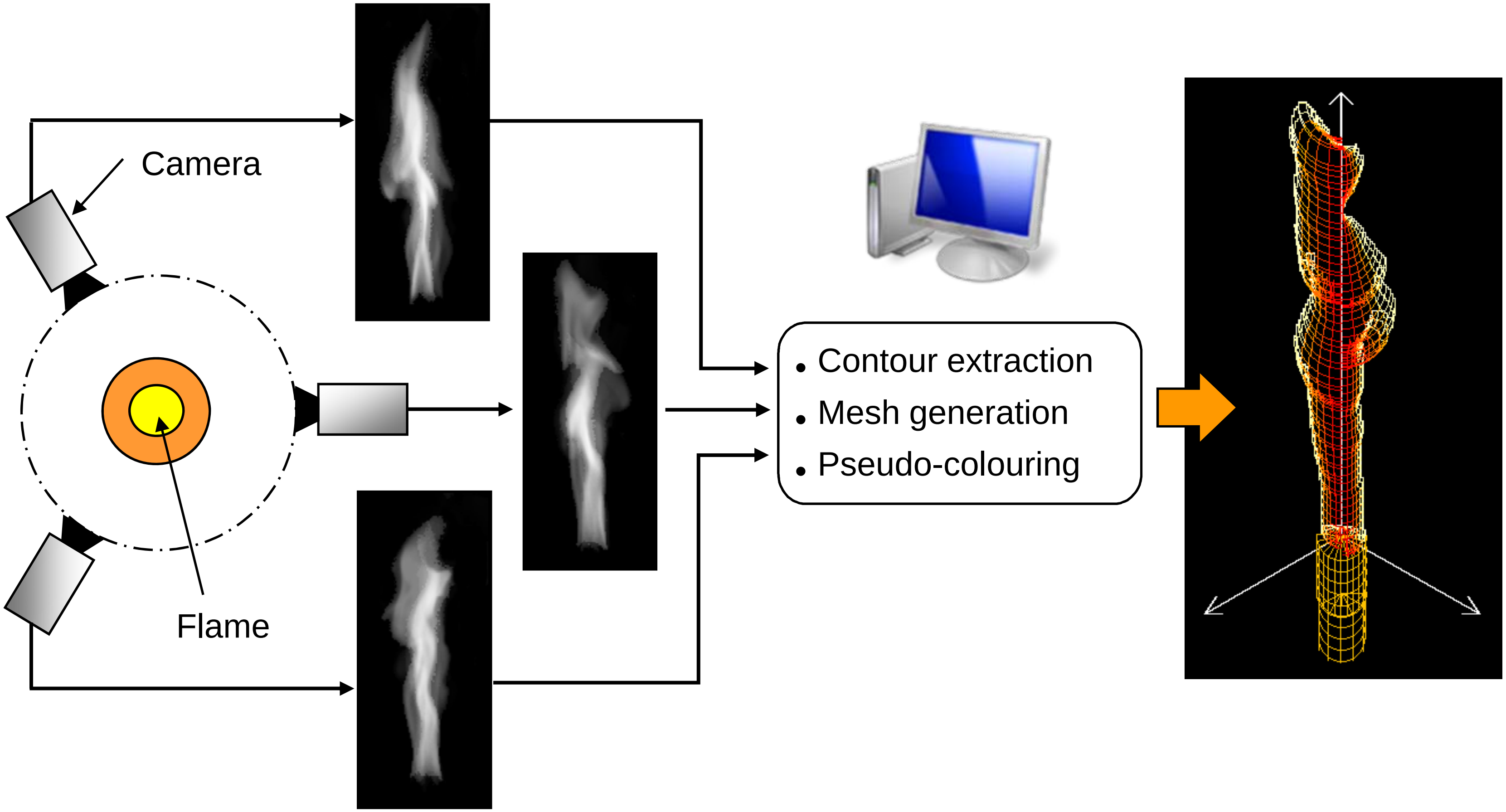


# 3D flame monitoring and characterisation through imaging

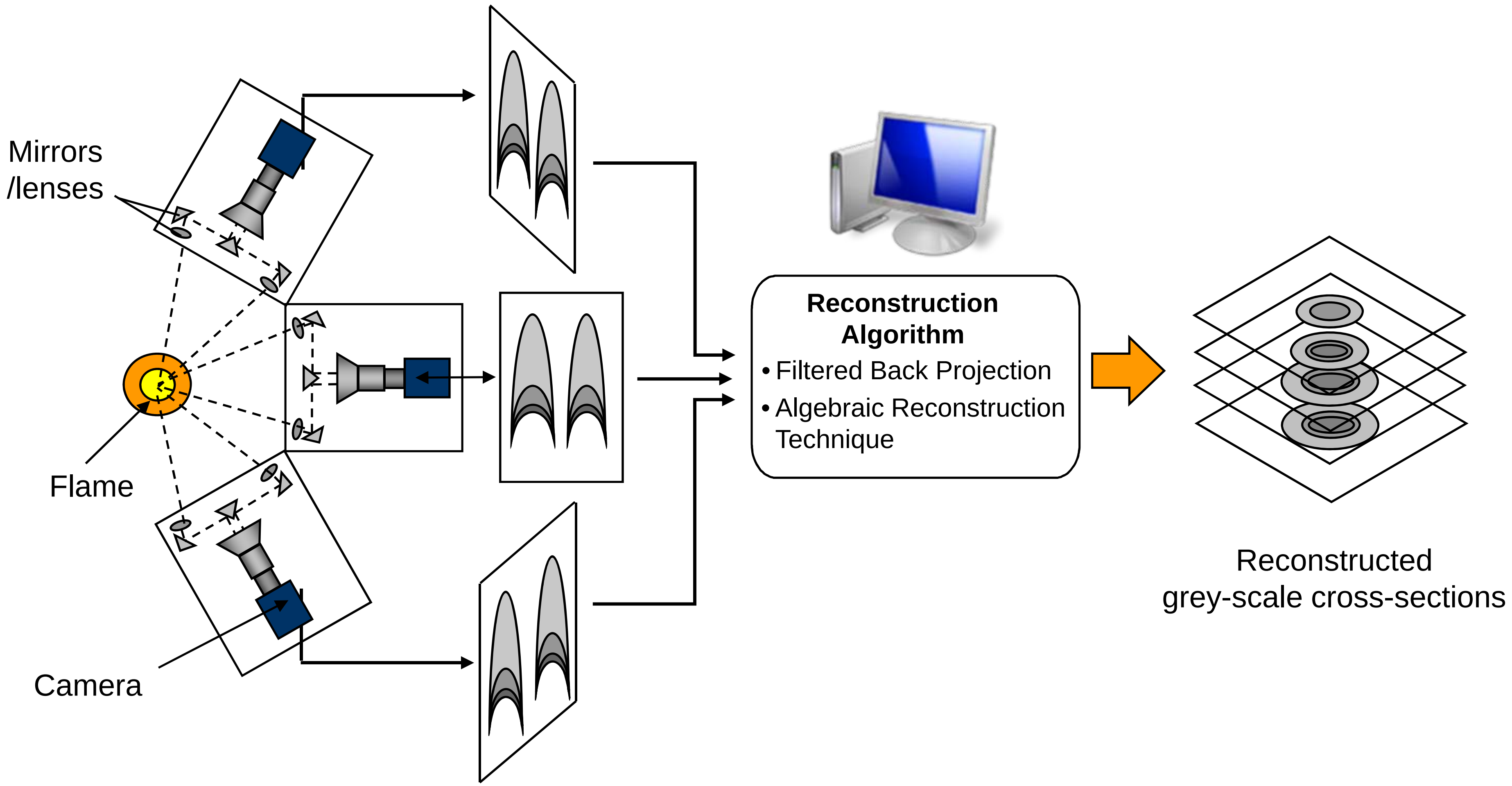
A flame is a 3D flow field. To fully reveal the dynamic nature of the flame, 3D monitoring and characterisation techniques are required.



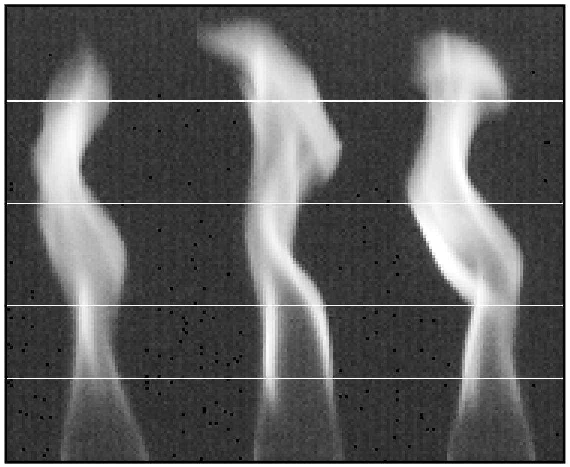
# 3D flame geometric model



# 3D tomographic reconstruction of the flame luminosity

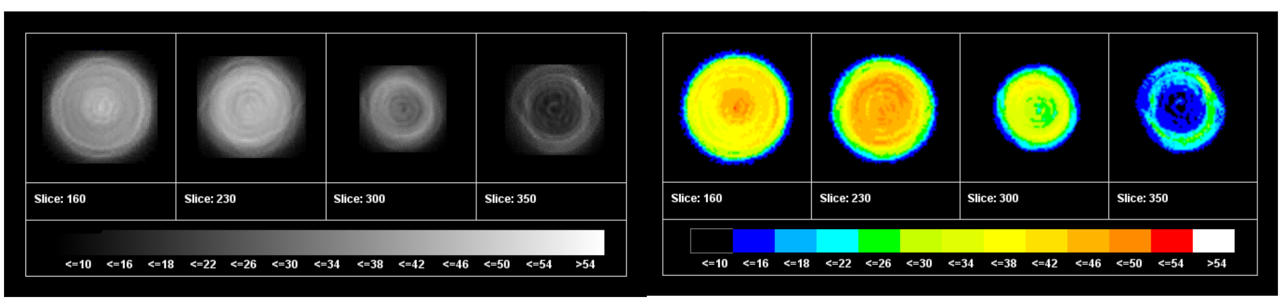


# 3D tomographic reconstruction of the flame luminosity



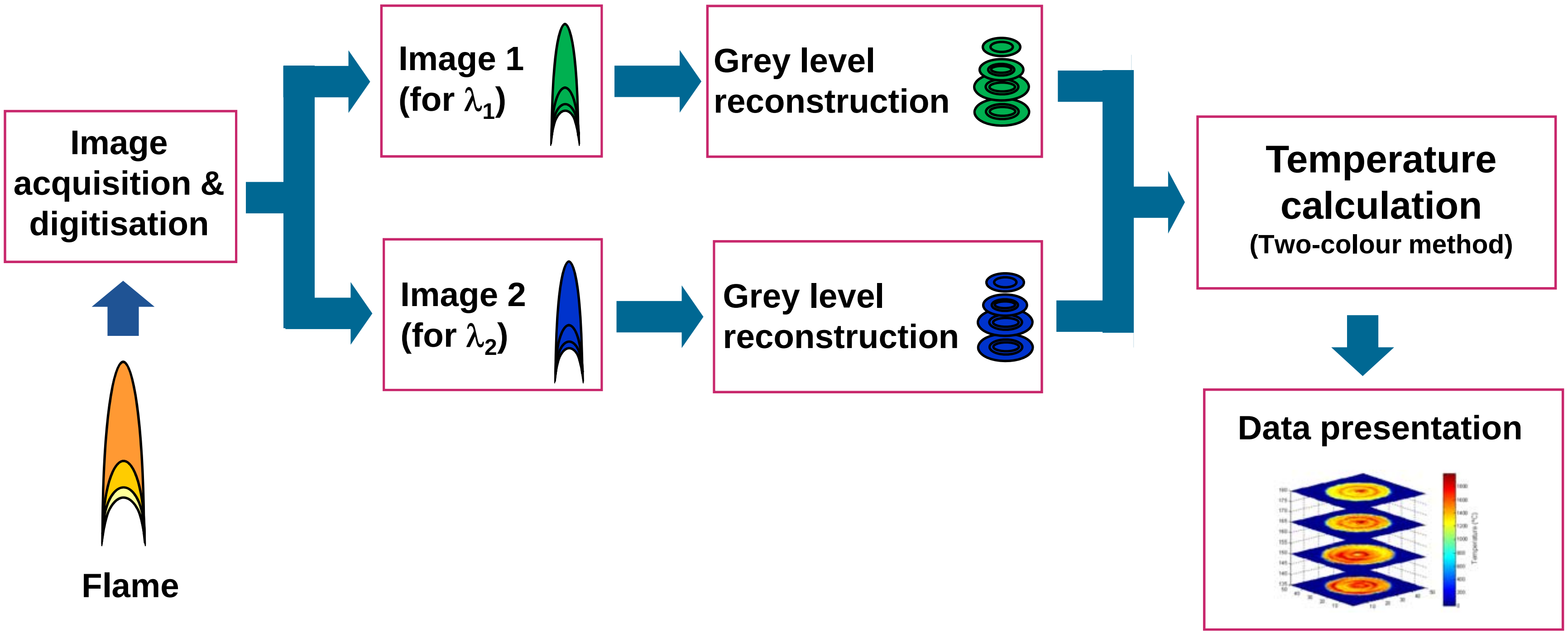
Gas flame images

Longitudinal-section reconstruction



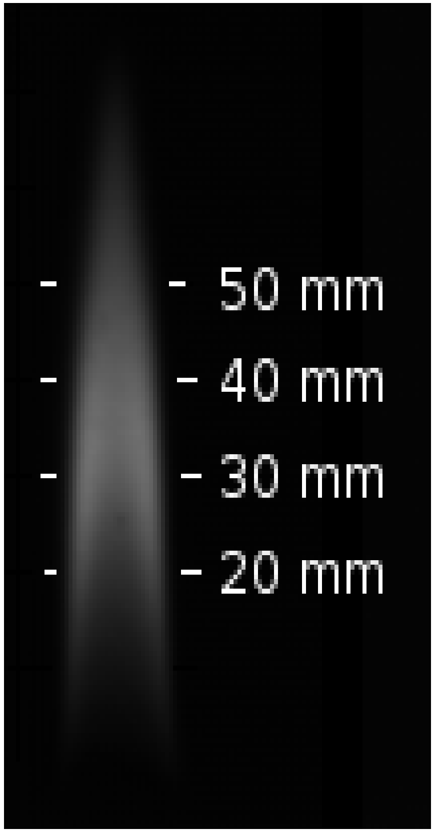

Cross-section reconstruction

# 3D tomographic reconstruction of the flame temperature

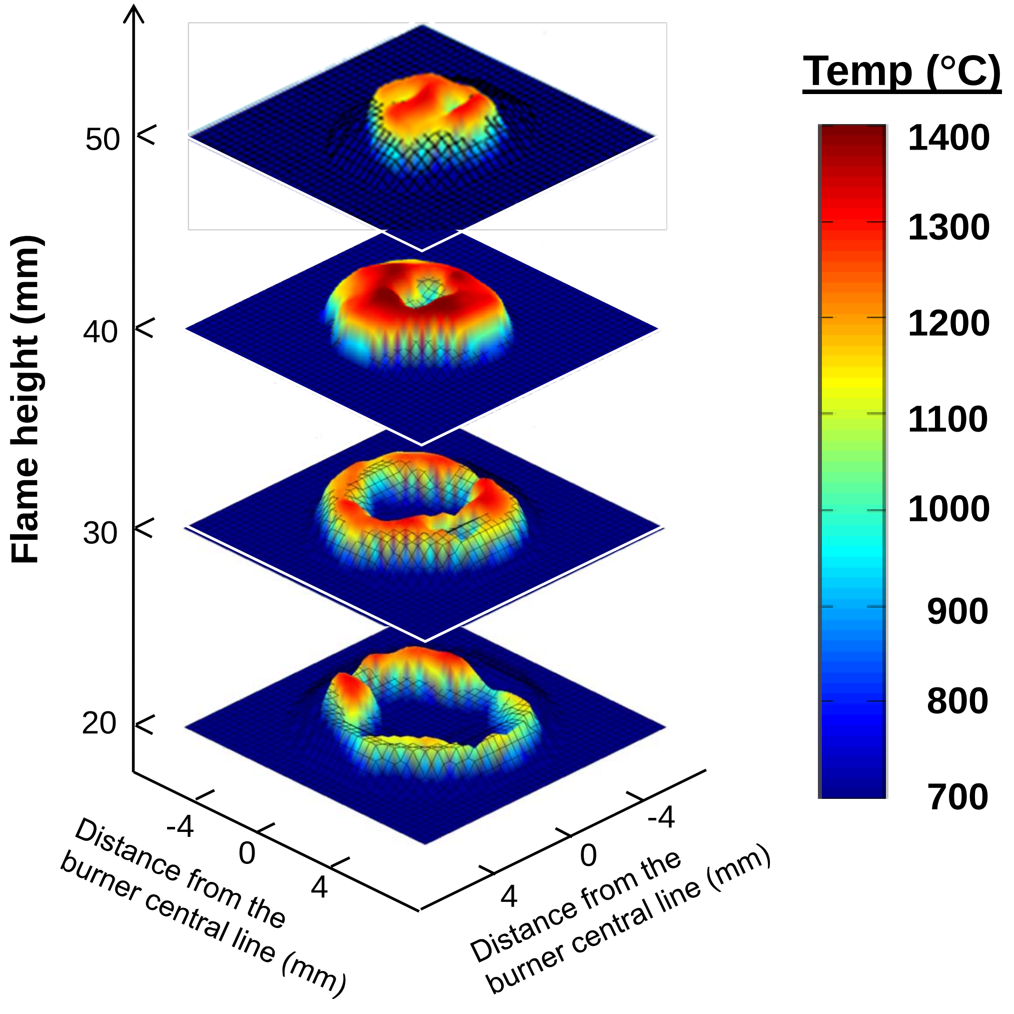


# 3D tomographic reconstruction of the flame temperature

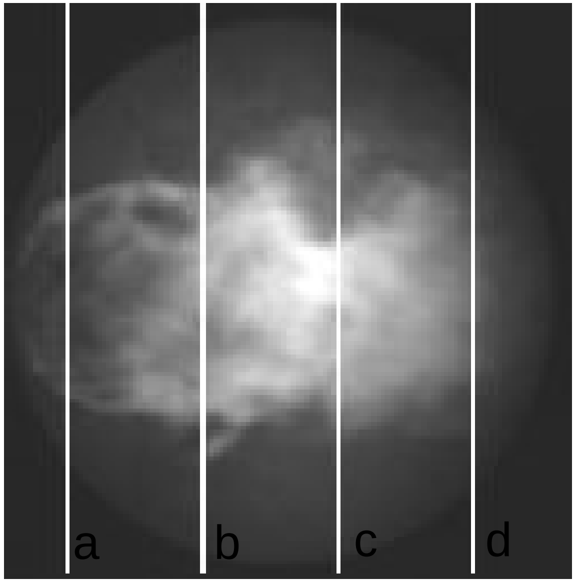
A gas flame image



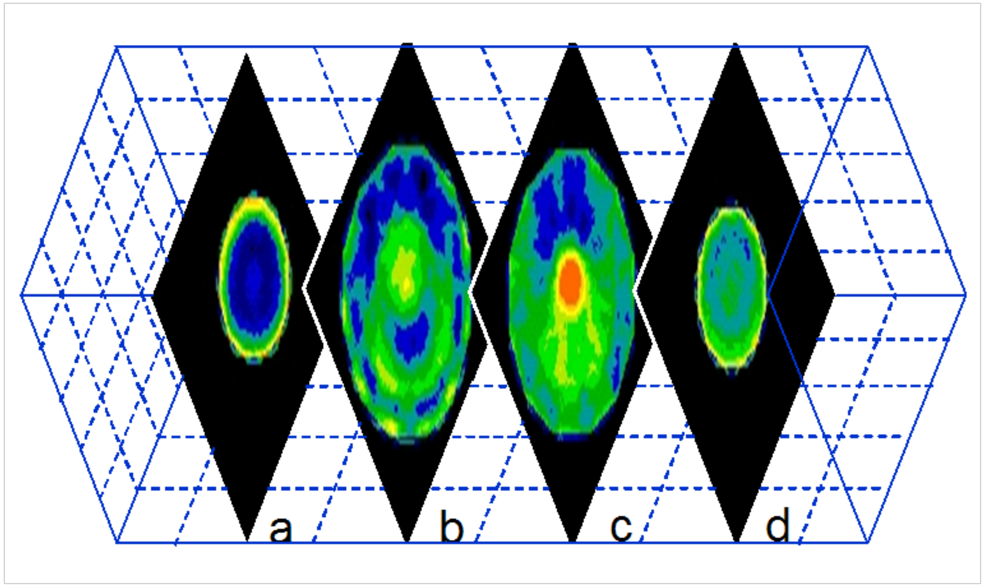

Flame temperature distribution



# 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.

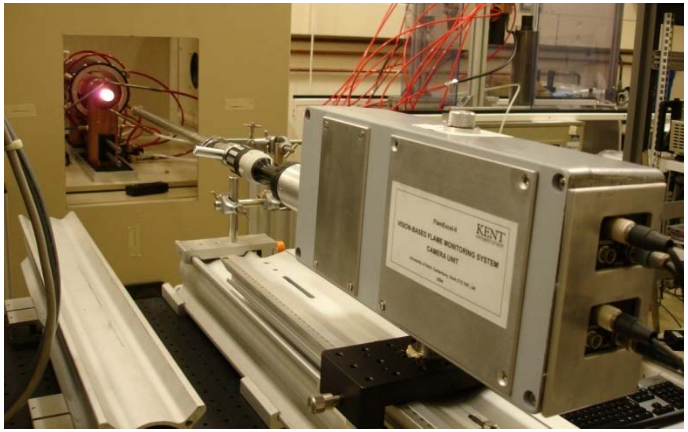
Acknowledgements

The following organisations are acknowledged for their support for the flame imaging work at Kent:

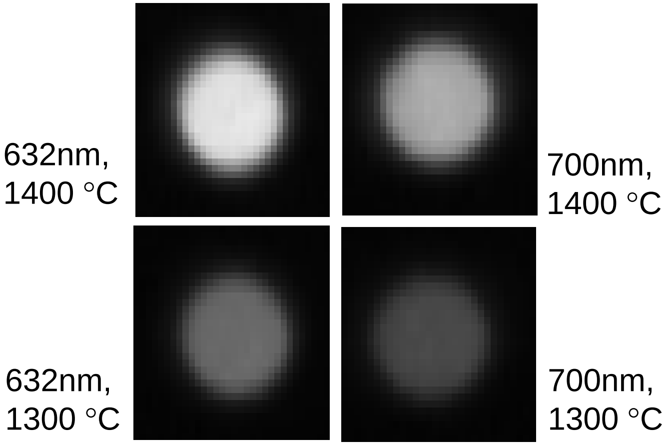
- EPSRC
- BCURA
- DIUS/TSB
- RWE npower
- E.ON
- Doosan Babcock Energy
- Alstom Power
- EDF Energy
- Spectus Energy
- PCME

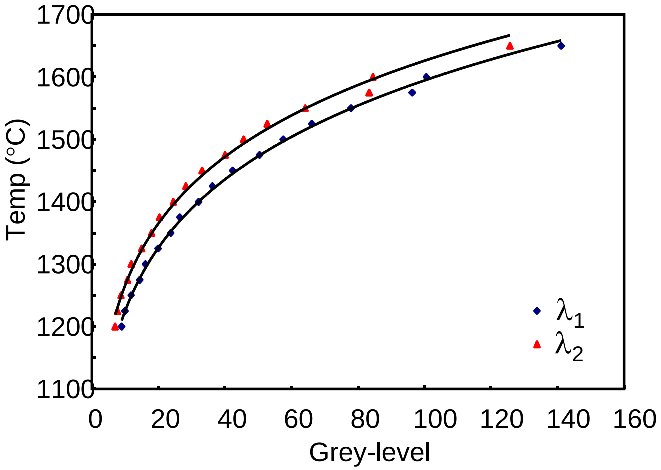
# System calibration

- 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)