Vision based monitoring and characterisation of combustion flames

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Abstract. With the advent of digital imaging and image processing techniques vision based monitoring and characterisation of combustion flames have developed rapidly in recent years. This paper presents a short review of the latest developments in this area. The techniques covered in this review are classified into two main categories: two-dimensional (2D) and 3D imaging techniques. Experimental results obtained on both laboratory- and industrial-scale combustion rigs are presented. Future developments in this area also included.

1. Introduction
The physical characteristics of the flame in an industrial furnace, such as geometrical and luminous profiles, temperature distribution and flicker frequency, provide important information on the quality of the flame, and consequently the performance of the combustion process. The recent trend of using low quality fuel, fuel blends and biomass has been reported and the combustion engineers are experiencing a range of combustion problems including poor flame stability, low combustion efficiency and high pollutant emissions. To meet increasingly stringent standards on energy saving and pollutant emissions, advanced technologies for the monitoring and characterization of the flame have become highly desirable [2].

In order to develop a suitable technology for advanced monitoring and characterisation of combustion flames, the research group at the University of Kent has conducted a number of interrelated projects in recent years in collaboration with leading UK power generation companies. Several prototype instrumentation systems have been developed for the on-line and two-dimensional (2D) and three-dimensional (3D) monitoring and characterisation of combustion flames. The systems, based on the latest optical sensing and digital image processing techniques, are capable of determining geometric (size and location), luminous (brightness and uniformity) and fluid-dynamic (temperature and flicker frequency) parameters of a flame. The systems have been evaluated on both laboratory- and industrial-scale combustion rigs under a variety of operation conditions. The results obtained demonstrate the applicability and potential of the systems in practical industrial furnaces. This paper presents a short review of recent developments in flame imaging techniques. Sampled experimental results obtained on both laboratory- and industrial-scale combustion rigs are also presented. Future developments in this area are also included.

2. 2D visualisation and characterisation of a flame
The most conspicuous characteristic of a flame is its luminosity. Visualisation techniques use electrical or optical sensors in conjunction with digital signal and image processing techniques to visualise the flame zone and consequently characterise the flame quantitatively. Figure 1(a) shows the

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concept of the 2D imaging based flame monitoring and characterisation technique. The characteristic parameters relating to geometrical and luminous properties, temperature profiles, and flicker frequency are derived directly from flame images using various computing algorithms. This information, together with furnace data such as fuel/air flow rates and emissions, can then be used to assess the quality of the flame. Figure 1(b) illustrates the constituent elements of the instrumentation system based on this technique [3, 4]. The system consists of an optical probe, an optical assembly, two CCD cameras, a control unit, a frame grabber and a PC with application software. The optical probe is used to penetrate the furnace wall and transmit the light of flame into the cameras. The optical assembly splits light from the flame into four beams with four distinct spectral ranges. Three of the four beams are received by the high-resolution CCD camera, which are used for geometric/luminous parameters and temperature measurements. The fourth beam is received by the high-speed CCD camera (up to 360 frames per second) for the measurement of the flicker frequency. The video signals from the two cameras are transmitted into the computer via the control unit, and digitised by the frame grabber into 2D digital images. Application software as an integral part of the system processes the digital images and then derives the flame parameters on an on-line continuous basis.

2.1. Measurement of geometric and luminous parameters

The geometric and luminous parameters of a flame can vary, depending upon the type of combustion systems and operation conditions [5, 6]. Since the root region of the flame is the primary reaction zone of a combustion process in terms of energy conversion and emission formation, the parameters presented here are specifically defined to quantify the root region of the flame [7].

*Ignition point.* Ignition point represents the absolute distance between the burner outlet and illuminating points where the flame is ignited. A stable flame requires steady ignition points at which the heat lost and heat release of the fuel are well balanced at the ignition temperature of the fuel.

*Ignition area.* Ignition area is a measure of the normalised shaded area encompassed between the burner outlet and flame ignition points which give the integrated information of flame ignitability.

*Spreading angle.* Spreading angle is defined as the angle formed between the two straight lines scribing through the outer edges of the flame.

*Brightness.* Brightness is represented by the mean grey-level of the luminous region of the flame normalised to the full-scale grey-level of the imaging system (i.e., 255).

*Non-Uniformity.* Non-Uniformity is defined as the averaged deviation of the grey-levels of individual pixels over the luminous-region from the brightness.

Figure 2 shows the typical variations in geometrical and luminous parameters of a coal-fired flame on a 0.5MWth combustion test facility [8]. The flames were generated by two types of fuel, i.e., pure...
pulverised coal (PF) and a mixture of PF and biomass under different levels of excess air (O₂% in flue gas). The data points shown in the figures are average values of 25 instantaneous readings. The “error bar” of each data point indicates the variation of that parameter about its average value (based on the standard deviation of the data). The results show clear trends of variations in the flame parameters with different fuel and operation conditions. For example, the ignition point and area show a similar decreasing trend with the excess air for both fuels [Figures 2(a) and 2(b)]. The luminous region of the flame for both fuels increases slightly with the excess air [Figure 2(c)]. Furthermore, adding woodchips into the PF has resulted in a smaller flame in comparison with that of a PF flame. More interestingly, the brightness of the flame with 10% biomass addition has a decreasing trend whilst that of PF flame an increasing trend [Figure 2(d)]. However, the brightness levels of both flames have no notable differences when O₂ exceeds 4%.

![Figure 2](image_url)

**Figure 2.** Variations in geometrical and luminous parameters for different O₂ in flue gas

### 2.2. Measurement of fluid-dynamic parameters

#### 2.2.1. Temperature

The temperature and its distribution of a flame provide very important information for the in-depth understanding of combustion processes including combustion efficiency, pollutant formation process and the cause of combustion problems such as slagging and fouling.

The flame temperature measurement through a concurrent, non-intrusive and two-dimensional means is difficult due to the dynamic nature of the flame. Two colour pyrometry is known as the only practical and non-intrusive method of measuring the flame temperature in an industrial furnace. In such an approach, the temperature is determined by using radiative intensities of the flame at two specific wavelengths, disregarding the unknown emissivity of the flame [9, 10]. Figure 3(a) depicts the typical images for two selected wavelength and the corresponding temperature distributions of a coal-fired flame obtained from a 1MWth combustion test facility whilst Figure 3(b) demonstrates the variations of temperatures with furnace load [4]. An increasing trend can be observed in the maximum and mean temperatures when the furnace load increases. The difference between the maximum and mean temperatures can be as high as about 150°C. It is evident that the flame temperature reflects the variations of the combustion intensity.
2.2.2. Flicker frequency. Flicker frequency of a flame is believed to be attributed to a multitude of eddies as a result of turbulent mixing in the primary combustion zone. The characteristic of the flame flicker is therefore closely related to flame structure and stability.

Conventional flame detectors use a flicker signal to detect whether the flame is present or off. With using of a high speed CCD camera, a sequent series of flame images can be captured. The flicker signal of a flame can then be obtained by processing the luminous intensity of the individual pixels within the images. The Power Spectral Density (PSD) estimate is employed to analyse the flicker signal. A quantitative flicker is defined as the weighted average frequency over the measuring range [11, 12]. Figure 4(a) shows the typical flicker signal of a coal-fired flame in the time domain and its corresponding PSD obtained from a 1MWth combustion test facility [4]. The signal was reconstructed from a total of 2560 data points from five consecutive samples recorded at a sampling rate of 360 Hz. Figure 4(b) demonstrates the flicker frequency of the flame root and middle regions varying with furnace load [12]. It can be seen that the flicker increases with the furnace load, and generally, flicker at the root region is higher than that of the middle region.

4. 3D monitoring and characterisation of a flame
A flame is a 3D flow field and the shape of flame is dependent upon many factors such as fuel type, fuel-to-air ratio, fuel-air flow rate and structure of the burner. Therefore, the flame parameters,
measured from different directions using a 2D imaging system, may be different. To fully reveal the
dynamic nature of a flame, it is desirable to monitor and characterise a flame three-dimensionally.
Such a technique would also lead to the acquisition of ample practical data for the validation of
Computational Fluid Dynamics (CFD) models of flames and furnaces, which are now being developed
worldwide.

4.1. 3D reconstruction of a flame model

Figure 5 illustrates the schematic diagram of a 3D flame imaging system which uses three cameras
placing equidistantly around the flame being monitored [13]. A synchronisation circuit ensures that the
three cameras capture the images simultaneously from the three different locations. Flame images
captured are then used for the reconstruction of the flame, and consequently the quantification of 3D
flame geometric and luminous parameters.

To achieve 3D reconstruction of a flame from its 2D images, the boundaries between the luminous
region of the flame and the surrounding are first determined [13]. Figure 6 shows the typical example
of instantaneous flame images captured simultaneously at locations A, B and C (Figure 5) and the
Corresponding 3D model [13]. Following the 3D reconstruction of the flame model, a set of geometric
and luminous parameters, including flame volume, surface area, orientation, length, circularity,
brightness and luminosity distribution, can be defined to characterise the flame from the model
generated [13-15].

![Figure 5. Schematic diagram of the 3D flame imaging system](image)

**Figure 5.** Schematic diagram of the 3D flame imaging system

**Figure 6.** Typical flame images captured by three cameras and the corresponding 3D model

4.2. 3D temperature measurement

Due to both dynamic and translucent nature of a flame it is very difficult to measure flame temperature
three dimensionally using conventional 3D techniques such as tomography. Preliminary work has
been undertaken to use a single imaging device for 3D flame temperature measurement [16]. The light
of flame is split/filtered into two narrow banded beams which are then captured by a CCD camera.
The resulting images are used to reconstruct two grey-scale models of the flame based on the back
projection theory. An assumption of rotational symmetry in the flame structure has been made to
compensate for the lack of raw flame data in a single flame image. Temperature distribution is
calculated from the ratio of grey-level values of corresponding elements within the two grey-scale
models using the two-colour method. Figure 7 illustrates a typical example of the grey-scale
reconstruction and temperature distributions of the cross-sections of a gaseous flame on a laboratory-
scale combustion rig. It is noted that there are some circular structures in each section of grey-scale
reconstruction and temperature distribution, which can be accounted for by the imperfections in the
rotational symmetry displayed by the actual flame. An improved computing algorithm has been
proposed where three 2D images captured simultaneously by three CCD cameras from different
locations around the flame were used to reconstruct the grey-level sections [17]. The information
obtained can then be directly used for determining the 3D geometrical, luminous and temperature characteristics of the flame.

180
165
150
135
0
Flame height (pixel)
343
Flame height (pixel)
521
Temperature (°C)
90
Flame height (pixel)
152
Grey level
359
Flame height (pixel)
548
Grey-level reconstruction and temperature distribution of flame cross-sections

Figure 7. Grey-level reconstruction and temperature distribution of flame cross-sections

5. Conclusions
Vision based instrumentation systems have been developed for the 2D and 3D monitoring and characterisation of combustion flames. The systems, based on the latest optical sensing and digital image processing techniques, are capable of determining geometric, luminous, and fluid-dynamic parameters of a flame. Results obtained on both laboratory- and industrial-scale combustion rigs have demonstrated that the techniques have provided an effective means for monitoring and characterising the physical parameters of flames on an on-line, continuous basis. The developed flame imaging techniques, once combined with subsequent control algorithms, will enable the power industry to produce electricity more efficiently by firing cheaper fuels and biomass materials, therefore reducing harmful emissions and improving the local and global environment. This technology is also potentially applicable to other industries such as steel production.

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