Three-Dimensional Visualisation and Quantitative Characterisation of Fossil Fuel Flames Using Digital Imaging Techniques

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University Project Manager: Professor Yong Yan
Department of Electronics
University of Kent
Canterbury
Kent CT2 7NT
Tel: 01227 823015
Fax: 01227 456084
Email: y.yan@kent.ac.uk

BCURA Industrial Supervisor: Mr Steve Cornwell
RWE npower plc
Operations and Engineering
Windmill Hill Business Park
Whitehill Way
Swindon SN5 6PB
Tel: 01793 892692 (Mobile: 078 6645 0746)
Fax: 01793 896251
Email: steve.cornwell@RWEnpower.com
EXECUTIVE SUMMARY

Fossil fuel flames are widely seen in many areas of industry where a particular example is in pulverised fuel combustion in electrical power generation. Optimised operating conditions are required to enhance furnace safety, improve combustion efficiency and reduce pollutant emissions. A flame is the central reaction zone of a combustion process and its geometrical, luminous and thermal characteristics provide instantaneous information on the quality and performance of the combustion process. Visualisation and characterisation of fossil fuel flames have therefore become desirable to achieve in-depth understanding and subsequent optimisation of combustion conditions. Earlier flame imaging work undertaken by the Instrumentation Research Group led by Professor Y. Yan prior to this project was limited to two-dimensions (2D) only - the third dimension had not been taken into account. A flame is generally a 3D flow field. The shape of the burner outlet contributes enormously to the irregularity of the flame shape. As the flame emerges from the burner, the shape of the flame root usually develops according to the structure and geometry of the burner outlet. However, the burner outlet is not always practically perfect and depends on various factors such as wear and tear, corrosion of the burner material and its inelastic expansion at high temperatures. This entails that the flame should be visualised and characterised three-dimensionally. As a result of this BCURA project a novel, digital imaging based technology for the 3D monitoring and characterisation of fossil fuel flames has been established.

This report describes the fundamental principle of the technology developed and addresses the key design and implementation aspects of three prototype systems of varying imaging configurations. Experimental results obtained from tests on pulverised coal and gas fired combustion test rigs are presented and discussed. The operability and effectiveness of the prototype systems are reported in addition to recommendations for further research in the field.

The results presented in this report demonstrate that digital imaging is the best available approach to the 3D visualisation and quantitative characterisation of fossil fuel flames at present. Two of the prototype systems developed use three identical CCD (charge coupled device) cameras mounted equidistantly and equiangularly either around the flame or on one side of the flame. The third configuration uses only a single CCD camera with the assumption that the flame exhibits axisymmetrical properties either instantaneously or through a time averaging process. The pros and cons of the three configurations have been identified and compared in terms of practical installation, cost and performance. All relevant image processing algorithms for the three imaging configurations have been developed and tested. Two different approaches in reconstructing the 3D flame model have been investigated, i.e., the contour extraction method and the inverse Radon transformation (i.e., tomographic reconstruction). The contour extraction method has been found effective in tracking 3D external movement of a flame and the flame front structures. Measurement of 3D flame parameters, including volume, surface area, orientation, length and circularity, has been achieved. The tomography based algebraic reconstruction technique has been found suitable for reconstruction of the luminous distributions throughout a flame.

All three prototype systems developed have been evaluated under a range of conditions on the gas fired combustion test rig at the Universities of Kent and Greenwich. Meanwhile, the single-camera system has also been tested with pulverised coal flames on RWE npower’s 0.5MWth Combustion Test Facility in Didcot and Mitsui Babcock’s 100MWth Combustion Test Facility in Glasgow. The results obtained demonstrate that reconstructed cross sections
of the flame give a good indication of the internal structures of the flame and variations in its luminous and thermal properties along the burner axis and radial directions. Since a full-scale industrial burner was used in the tests at Mitsui Babcock, the results obtained are transportable to full-scale power station installations. In addition, the single-camera system has been applied for the measurement of 3D flame temperature distribution of a gaseous flame in the university laboratory under a range of conditions. Temperature results obtained from tests on the industrial Combustion Test Facilities are found inconclusive due to the absence of a reliable temperature reference. However, the blue and red component images from the three colour CCD cameras in the second multi-camera configuration are found useful for the measurement of flame temperature using two-colour pyrometry.

At the time of writing results arising from the project have been published in five refereed journal papers and six international conference papers in addition to presentations at four national and international events. It is recognised that very limited work was reported on 3D flame imaging prior to this project. The results published from this research have added considerably to the current body of knowledge on fundamental aspects of fossil fuel flames and imaging based instrumentation for combustion characterisation. Although the current embodiment is proposed particularly for application to fossil fuel fired furnaces, the basic concept and methodology are applicable to other combustion processes such as ramjet combustors. The results obtained may be used for future validation of Computational Fluid Dynamics (CFD) models of fossil fuel flames and furnaces. The publication of the papers has also enhanced the strong academic standing of the Instrumentation Research Group at University of Kent in this particular area of research.

It must be stressed that the results arising from this project are relevant not only to the retrofitting at existing power stations but also to the incorporation in the design of new power stations. The economic benefits that the new flame imaging technology will bring to equipment manufacturers and power generation organisations cannot be underestimated. The technology will certainly enhance the applicability of oxy-fuel combustion. As a prelude to carbon dioxide capture, the 3D flame imaging technology will allow complex flame shapes and temperature distributions to be monitored continuously in real time so that optimal combustion conditions are sustained and potential damages to burners minimised. Another application of the new technology is the on-line monitoring and closed-loop control of multiple flames in a gas turbine leading to reduced combustion oscillations and associated operational problems.
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1. Introduction

Fossil fuel fired combustion systems are widely used in many areas of industry to generate electrical power and thermal energy. Optimised operating conditions are required to enhance furnace safety, improve combustion efficiency and reduce pollutant emissions. A flame is the central reaction zone of a combustion process and its geometrical, luminous and thermodynamic characteristics provide instantaneous information on the quality and performance of the combustion process. Visualisation and characterisation of fossil fuel flames have therefore become desirable to achieve in-depth understanding and subsequent optimisation of combustion conditions.

The research group led by Professor Yan had developed several new instrumentation systems operating on digital imaging and image processing techniques for the measurement of geometric, luminous and thermodynamic parameters of fossil fuel flames [1-6]. Industrial trials of such systems had also been undertaken and results obtained had demonstrated their operability and effectiveness [2, 3, 6]. The systems, however, used single CCD cameras that allowed a flame to be visualised from one direction only. The information obtained was therefore limited to two-dimensions (2D) - the third dimension had not been taken into account. A flame is generally an asymmetrical 3D flow field. The shape of the burner outlet contributes enormously to the irregularity of the flame shape. As the flame emerges from the burner, the root of the flame usually shapes out according to the structure and geometry of the burner outlet. However, the burner outlet is not always practically perfect and depends on various factors such as wear and tear, corrosion of the burner material and its inelastic expansion at high temperatures. The flame parameters, measured from different viewing locations using a 2D imaging system, may not be identical and this fact has been confirmed by experimental work [7]. This entails that the flame should ideally be visualised three-dimensionally. This project aimed to develop a technology for 3D visualisation and characterisation of fossil fuel flames in furnaces.

Very limited work has previously been undertaken on 3D visualisation and characterisation of fossil fuel flames. An Italian group conducted preliminary work on the reconstruction of 3D models of a flame using digital imaging techniques [8], where only two flame parameters - volume and surface area were estimated. Tomographic approach has also been applied by a Russian group in an attempt to reconstruct 3D models of a flame, but no measurement of any of the aforementioned flame parameters has been made [9]. 3D temperature measurement has been performed through multi-spectral tomographic image analysis [10], but the work has not been extended for the measurement of any other parameters.

The digital imaging approach developed as a result of this project has led not only to an in-depth understanding of a flame and subsequent optimisation of combustion conditions, but also to the acquisition of ample practical data that could be used for the validation of Computational Fluid Dynamics (CFD) models of fossil fuel flames and furnaces. The results arising from this research have added considerably to the current body of knowledge on fundamental aspects of combustion and more efficient use of fossil fuels. This includes detailed knowledge of fuel and energy conversion in a furnace and an in-depth understanding of the fundamental physical behaviours of fuels and their relationships with the attributes of flames. Although the current embodiment is proposed particularly for application to fossil fuel fired furnaces, the basic concept and methodology are applicable to other combustion processes such as gas turbines and ramjet combustors.
The project was initially administered by the University of Greenwich and was later transferred to University of Kent following the move of Professor Y. Yan in June 2004. The project started on 1st September 2002 and was completed on 31st March 2006. It should be noted that the seven-month extension in time (01/09/05 to 31/03/06) was granted at no extra costs to BCURA in recognition of the delays during the relocation of the project team and research facilities and a change-over of the research personnel.

This Final Report summarizes the work that has been undertaken during the course of the project and highlights the achievements that have been made as a result of the project. All relevant technical issues imaging hardware and software are included.

2. System Design and Implementation

In the original proposal, multiple cameras were to be used to visualise the flame from different directions. However, during the course of the project a single-camera system was also considered in addition to the multi-camera system. Although the fundamental principle of the two designs is the same (i.e. digital imaging), their practical aspects in terms of costs, installation and maintenance are entirely different. It was therefore decided to design, implement and test both systems in the project. Their individual features and pros and cons of each system design are described in the following sections.

2.1 Multi-Camera System I

Two different configurations of the multi-camera system were implemented. The first configuration is illustrated in Fig.1. The system comprises of three identical monochromatic CCD cameras, a synchronisation circuit, frame grabber, and computer with associated software. Each camera has a 2/3 inch CCD panel with resolution of 816×606 pixels. The cameras were placed around the burner, separated by equal angles of 120° with an objective distance of 125mm. A synchronisation circuit was used to ensure that the three cameras capture flame images simultaneously from three different locations. The frame grabber converts the analogue signals from the cameras into digital images with 8-bit digitisation. Fig.2 shows the practical implementation of the three-camera system on the university combustion rig.

![Fig.1 Multi-camera system with cameras around the flame](image-url)
A clear advantage of this configuration is that the flame is visualised equally from three different directions around the flame so that nothing significant in changes in any part of the flame is missed. However, this arrangement has an obvious shortcoming in that the camera installation on an industrial furnace is difficult. The use of a system as such on a full scale power plant is impractical, however, the installation of the system on a small-scale industrial test rig as research tool is possible for purpose of combustion diagnosis.

This configuration has been used to achieve 3D visualization and characterization of flames. The outer contours of the flame front structure were extracted from its 2D images using various image processing techniques. Dedicated algorithms incorporating mesh generation techniques were developed for the 3D reconstruction of flame models based upon the information obtained from the image contours (Fig.3). A set of 3D parameters including volume, surface area, orientation, length and circularity were defined and computed from the reconstructed flame model, which were then used to characterise the flames. Results obtained are summarised in section 3.1.

2.2 Multi-Camera System II

The second multi-camera configuration also uses three identical cameras but all are arranged on one side of the flame, as shown in Fig.4.
An optical adapter consisting of mirrors and lenses is designed and fitted to each camera so that a total of six equiangular flame images (projections) are available concurrently. Dedicated tomographic algorithms have been developed to reconstruct the luminosity distribution of the flame from the acquired six projections (Fig.5). Additionally, all three cameras are in colour and the combinations of the R, G and B signals can be used to derive the temperature distribution of the flame using the two-colour principle [5, 6]. It must be stressed that the use of more cameras will produce better results in tomographic reconstruction and ultimately the measurement of various flame parameters. However, incorporation of more cameras in the system will not only increase the costs of the system but also make the practical installation more difficult. Following a systematic appraisal of various tomographic algorithms through computer simulation (Section 3.2), it was decided to use three colour CCD cameras generating six equiangular projections of the flame. Fig.6 shows a practical implementation of the second three-camera system on the university combustion rig. Since all cameras are the same side of the flame so their practical installation (Fig.6) is slightly easier than the first configuration (Fig.1). This configuration is ideal for identification of the internal variations of combustion flames. However, this configuration might only be suitable for diagnostic use in a laboratory environment instead of real power plant installations. The system shown in Fig.6 has been used to study the internal luminosity and temperature distribution of gaseous flames (see section 3.2 for details).
2.3 Single-Camera System

It was recognised that, although the multi-camera configurations visualise the external properties and internal structures of the flame and are more suited for use on a laboratory rig, their practical installation on a real furnace presents a major problem to its applicability not to mention higher capital costs and associated maintenance. It is for this reason that a single-camera system for 3D flame monitoring and characterisation is also designed, implemented and tested. Another advantage of the single camera system over multi-camera systems is that it avoids common problems such as synchronisation and mismatches in spectral response between the cameras.

Fig. 7 shows a schematic diagram of the single camera system for 3D flame imaging. Since the temperature distribution is the most important and most difficult to measure, this system was aimed for the flame temperature measurement though other measurements may also be derived from the temperature results. The system operates on image reconstruction techniques and two-colour radiation thermometry. A custom optical assembly splits the light of flame into two filtered beams which are then captured by the CCD camera. The resulting images are used to reconstruct the two grey-scale models of the flame through the use of filtered back-projection based inverse Radon transformation (i.e., deconvolution of the two-dimensional flame data). Fig. 8 illustrates the key steps in the reconstruction algorithm that has been utilised in the system software.
An assumption of rotational symmetry in the structure of the flame is made to compensate for the lack of raw flame data present in a single flame image. If a laminar or stable premixed flame is set as the target to be monitored, it is expected that this type of flame exhibits a high level of rotational symmetry, i.e. the flame appears to be identical when observed from different viewpoints around the burner axis. In this case a single projection is deemed sufficient for the purpose of reconstruction and subsequent measurements. Fig.9 shows the installation of the single-camera system on RWE npower’s test rig, where instantaneous images were used for reconstruction. In the case of a fluctuating flame, when averaged over a period of time, should exhibit significant rotational symmetry allowing the same reconstruction algorithm to be applied. This averaging method was used to monitor a pulverised coal flame at Mitsui Babcock (Fig.10).

Fig.8 Block diagram of the reconstruction algorithm

Fig.9 On site installation of the single-camera system at RWE npower

Fig.10 On site installation of the single-camera system at Mitsui Babcock
Once the reconstruction of the band limited grey-levels is complete, temperature distributions of the flame are derived from these grey-level representations based on the principle of two-colour pyrometry. Experimental work was undertaken to establish the relationship between the measured flame temperature and the air-fuel inputs on the gas fired combustion rig in the university laboratory (section 3.3).

3. Experimental Results and Discussion

3.1 Multi-Camera System I

The multi-camera system shown in Fig.1 and Fig.2 has been used to conduct a range of experiments in order to assess the efficacy of the system for 3D visualisation and quantitative characterisation of gaseous flames in the university research laboratory.

In the first series of experiments the system was applied to visualise the external 3D movements of the flame as well as the measurement of a number of 3D flame parameters under a range of combustion conditions. To ensure the accuracy of the dimensional measurement in relation to the measured flame parameters, the system was calibrated using a number of reference templates prior to the experiments. The maximum deviation of the measured length from the reference length, ranging from 50mm to 175 mm, is found to be less than 2%. The spatial resolutions of the system are 0.23mm/pixel and 0.21mm/pixel in the horizontal and vertical directions, respectively, for the objective distance of 125mm [11]. Fig.11(a) shows a typical example of the instantaneous flame images simultaneously captured at locations A, B and C (Fig.1). The corresponding 3D model reconstructed is illustrated in Fig.11(b), which is viewed at three different points of view. Continuous rotation of the entire contour arrangement by 60° allows 3D visualization of the flame front at six different points of view (Pv) with Pv=0° chosen as a viewer reference point. Computer animations of the flame models are also created so that the viewer can continuously perceive all around the model. Fig.12 illustrates a set of examples of the flame models reconstructed for a range of different air-fuel ratios (r).

![Location A](image1.png) ![Location B](image2.png) ![Location C](image3.png)

(a) Typical flame images captured by the three cameras
(b) 3D visualisation of the flame at three different points of view

Fig. 11 Typical flame images and their corresponding reconstructed 3D model

It is evident that the flame shape is very dynamic when $r \leq 5$ because of the diffusive nature of the flame. When $r \geq 10$ the flame has more stable shape due to its premixed nature, although there is a decrease in the flame size.

Fig. 12 Reconstructed 3D models of the flame for different air-to-fuel ratios
Fig. 13 illustrates the variations of the flame parameters with air flow rate for different fuel flow rates. As expected, the flame parameters increase with fuel flow rate. It is also observed that under very air lean conditions ($r \leq 5$), volume, surface area and length of the flame increase with the air flow rate. This is due to the fact that the stoichiometric ratio of the gas (butane) is relatively higher in comparison of other fuels such as methane and ethylene [12, 13]. In the case where the combustion flow is laminar (Re<2000), a small amount of air has a very little effect on the thermal/chemical reaction, but only increases the combustion flow velocity. As the air-fuel ratio increases beyond 5, more air is mixed with the fuel giving the flame a premixed nature, resulting in a dramatic decrease in these three parameters.
The second series of experiments conducted was to visualise and quantify the internal flame front structures, which has been an important aspect in combustion understanding. The profile of the flame front was determined by all the ignition points of the flame, i.e., where the fuel becomes ignited. The luminous variation nearby the flame front is expected to be significant [14]. The contour extraction method previously developed [11] is still valid but has to be modified to extract the contours, particularly the vortices within the inner combustion region. Furthermore, the detection of the maximum gradients of the grey-level variations is restricted within the root region of the flame [3]. Since the flame root, i.e., where the flame front is located, is our primary interest, the image of the upper section of the flame is deliberately clipped off during the image acquisition. The formation of a virtual hollow can therefore be imagined in the reconstructed 3D model, which will allow visualization of the back structure of the flame front. This is accomplished by firstly reconstructing intermediate contours of the flame front structures vertically and joining all the points of each horizontal segment of the flame front by \( \beta \)-spline curves [15]. Fig.14 shows a typical example of the instantaneous images of the flame front captured at locations A, B and C, and the resulting 3D model. A virtual planar grid is added into the model for improved 3D visualization.
Once the 3D model of the flame front structures has been reconstructed, a set of flame parameters including ignition point, ignition volume, ignition surface area and circularity can be derived from the model. The depiction of these parameters as a function of air-fuel ratio is illustrated in Fig.15. To analyse the dynamic nature of the flame front, the uncertainty of each parameter is determined as shown in Fig.15(f).

(a) Minimum ignition point

(b) Maximum ignition point

(c) Ignition volume

(d) Surface area
It can be seen from Fig.15 that the minimum ignition point increases significantly with the air-fuel ratio, indicating that the flame accelerates away from the burner outlet. Furthermore, the variation of the minimum ignition point under the small air-fuel ratio (r=11) is significantly higher than that under the large air-fuel ratio (r≥13). This suggests that flame stabilises with an increase in air-fuel ratio. The maximum ignition point (Fig.15(b)) varies between 180 to 210mm, irrespective of combustion conditions. This is due to the structure of the combustor which prevents the horizontal expansion of the flame beyond the boundaries. Fig.15(c) suggests that the ignition volume increases with the air-fuel ratio because of the increased minimum ignition point. However, the ignition surface area (Fig.15(d)) decreases significantly with air-fuel ratio due to the fact that the difference between the maximum and minimum ignition points has decreased. Fig.15(e) shows that, under the air-fuel ratio of 11, the circularity increases gradually along the burner axis. The circularity is about 30% at the minimum ignition point and over 95% near the maximum ignition point. This indicates that the shape of the cross section of the flame front is irregular near the minimum ignition point, but appears to be more regular and stable along the burner axis.

The uncertainties of all the parameters measured under r=14 (Fig.15(f)) are no greater than 8%, in comparison with 23% under r=11, indicating that the stability of the flame front enhanced with increase in air-fuel ratio. It is worth mentioning that, when r>14, the velocity of the air-fuel flow and the propagation velocity of the flame are in complete disequilibrium, causing the flame to blow out.

In the third series of experiments the internal luminous distributions of the flame were determined from the three 2D images. Fig.16(a) illustrates a typical set of 2D images, from which the luminous cross and longitudinal sections of the flame were reconstructed. The reconstructed results, as viewed from position ‘A’ for cross sections 160, 230, 300 and 350 and longitudinal sections 72, 74, 76 and 78, are presented in both grey and colour scales, as shown in Fig.16(b) and Fig.16(c). As can be seen, the system is capable of determining detailed luminous distributions throughout the flame.
Fig. 16 Original flame images and reconstructed cross and longitudinal sections of the flame.
3.2 Multi-Camera System II

Before practical implementation of this sensing configuration, significant design and simulation work was undertaken in order to determine the optimal number of flame image projections in terms of quality of reconstruction and simplicity in system implementation. More specifically, two different computing algorithms, i.e., filtered back-projection (FBP) and algebraic reconstruction technique (ART), for the tomographic reconstruction of a flame from a limited number of projections were investigated. Computing simulation was carried out for a direct comparison between the two different approaches for a varying number of projections in respect of their reconstruction effectiveness.

![Phantom head image and grey-level distribution](image)

(a) Phantom head image  (b) Grey-level distribution

Fig. 17 Image of a phantom head and its grey-level distribution

An 8-bit grey-level scale digital image of a phantom head, as shown in Fig. 17, was generated as a template. Both ART and FBP algorithms were implemented using Microsoft Visual C++. Two evaluation criteria are applied in this study. One is the mean absolute error and the other is the correlation coefficient between the phantom head and the reconstruction results. Because the original phantom head image and the reconstructed one were stored in the computer memory as 256×256 matrices which can easily be converted into 65536 pixels long vectors, a pixel by pixel treatment was utilized to calculate the errors and the correlation coefficients. Fig. 18 depicts the reconstructed results for a different number of projections by using the ART and FBP respectively. The projections were taken on an equiangular basis within a semicircle in both cases. For instance, as the angle between the first and the last projection has to be 180° at maximum, the case of using six projections gives the equiangular distance of 30° between two consecutive projections. It can be seen that the reconstruction using the ART with six projections gives definitive contours and main internal features of the phantom head (Fig. 18(e)). In contrast, the FBP proves itself to be unable to establish the shape and presents a very fuzzy inner structure of the object for such a limited number of projections (Fig. 18(a)).
A further comparison between the two algorithms is illustrated in Fig.19, which shows clearly that the ART provides consistently better reconstruction results for the same number of projections. However, as the FBP is not sensitive to small angles between projections, it commences to produce better results when the number of projections reaches 64. Since the practical implementation is an important factor in system design, the number of projections required should be as small as possible. This has led to the conclusion that the ART is more adequate than the FBP in this application.

Experimental work was conducted in the university laboratory to assess the efficacy of the ART algorithm. Fig.20 illustrates an example of the 2D image of a candle flame and the luminosity reconstruction of the cross-sections. A total of six images (i.e., projections) were captured simultaneously by the three CCD cameras from different directions on one side of the flame and were then used to reconstruct the luminosity of the cross-sections along the flame axis using the ART. It can be seen that there is a correlation between the luminous distributions of the reconstructed cross-sections and the original image. For instance, slice (b) shows a more homogeneous luminous distribution, whilst slices (c) and (d) show vaguely darker inner structure than the periphery, as can also be observed in the original image.
Fig. 20 Luminosity reconstruction of cross-sections of a candle flame

Fig. 21 Luminosity reconstruction of cross-sections of a fully premixed gaseous flame

Similar tests were also taken for a partially premixed flame. Fig. 22 and Fig. 23 show the six 2D images of the flame from the three cameras and the resulting luminosity reconstruction of the cross-sections, respectively. It is apparent that the diffusion flame was rather unsteady and not as axisymmetrical as the premixed flame, as seen in the four reconstructed luminous cross sections of the flame (Fig. 23) and its corresponding temperature distributions (Fig. 24). Vortices within the flame are clearly visible, although this is not obvious in the original 2D images. It should be noted that the cross sectional data obtained through reconstruction (Fig. 20 to Fig. 23) could be used for quantitative determination of 3D geometrical and luminous characteristics of a flame.
<table>
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Fig. 22 Original images of a partially premixed flame acquired from the three cameras.

Fig. 23 Reconstructed cross sections of a partially premixed gaseous flame (green channel).
3.3 Single-Camera System

To evaluate the performance of the single-camera system (Fig.7) and the effectiveness of the proposed algorithms, various tests were conducted on the gas-fired combustion rig at the University of Kent and on RWE npower's 0.5MWth Combustion Test Facility in Didcot. Tests were also carried out on Mitsui Babcock’s 100MWth Combustion Test Facility in Glasgow. Since a full-scale power station burner is used on the CTF, the investigation into the practicality of the single-camera approach for the 3D monitoring and characterisation of flames was essentially preserved.

A series of tests was undertaken on Mitsui Babcock’s 100MWth Combustion Test Facility on a period of two days (22 and 23 March 2005). The optical probe/camera was installed at Probe Port 3 on the furnace, perpendicular to the burner axis. In view of the highly fluctuating nature of the pulverised coal flame, time averaged images of the flame were used to reconstruct its 3D luminous distributions of the flame. Fig.25 shows a typical, averaged flame image from a total of nine instantaneous images. The cross sections of the flame were reconstructed with illustrative results being given in Fig.26. As can be seen, the time-averaged flame image is reasonably axisymmetrical, so the assumption for flame rotational symmetry is more or less valid for 3D reconstruction of the flame luminosity. The four reconstructed cross sections, as marked by “a”, “b”, “c” and “d” in Fig.25, appear to give a good indication of the internal structures of the flame and the variations in luminous properties of the flame along the burner axis and radial directions.
RWE npower made their CTF in Didcot available to the project for a range of tests. In the majority of the test runs the pulverised coal flame in the furnace was steady and fairly axisymmetrical. Fig.27 shows a typical instantaneous image of the flame. Similarly, the reconstructed cross sections of the flame, as shown in Fig.28, appear to give a good indication of the variations in the internal structures and luminous properties of the flame along the burner axis and radial directions.
Tests were also conducted on the gas-fired combustion rig at the University of Kent. Butane was used as a test fuel. In addition to the reconstruction of the luminous distributions, an attempt was also made to derive the 3D temperature distribution of the flame using the two-colour methods [5, 6]. Fig.29 illustrates a typical example of the luminous reconstruction of the cross sections of a gaseous diffusion laminar flame. It is observed that there are some circular type patterns in cross sections, which can be accounted for by the imperfect rotational symmetry due to the slightly fluctuating nature of the flame.
The temperature distribution and mean temperature of the flame on different cross-sections along the burner axis were determined for different fuel flow rates. Fig. 30 shows a typical example of the temperature distributions of cross sections of the flame obtained for a fuel flow rate of 3.94 cm$^3$ s$^{-1}$. Again, the irregular patterns in the cross-sections are believed to be due to the rotational asymmetry of the flame in the luminous reconstructions. The variation of the mean temperature with the fuel flow rate is plotted in Fig. 31. Each data point is an average of thirty readings of the mean temperature of the flame taken at the corresponding region. It is clear that the average temperatures measured in the three regions of the flame tend to increase with the fuel flow rate. This tendency can be accounted for as more fuel was fed in, more rigorous thermal reaction took place, resulting in a higher flame temperature. The results have also demonstrated that the middle region of the flame appears to have a higher temperature than other regions, suggesting more intensive reaction took place in that region. The tip region of the flame shows a lower temperature simply because most of the fuel has combusted before reaching this region.
In addition to the above experiments, the overall mean temperature of a premixed flame was also monitored for different air-to-fuel ratios. The variation in air-to-fuel ratio was achieved by adjusting the air supply whilst holding the fuel flow constant. For an effective comparison, the air-to-fuel ratio is converted into the equivalence ratio, $E$, using the following equation,

$$E = \frac{r_a}{r_s}$$

where $r_a$ is the actual air-fuel ratio and $r_s$ is the stoichiometric ratio for the fuel in use and equals 30.9 for butane in this study. Fig.32 shows the variation of the overall mean temperature of the flame with the equivalence ratio for three different fuel flow rates. As can be seen from the results that the flame temperature tends to increase with the fuel flow rate when $E < 1$ and reaches its maximum when $E = 1$. When $E > 1$, the air supply exceeds the stoichiometric requirement of the fuel, and eventually “cools” the flame down, resulting in a lower flame temperature.
3.4 Discussion

The project aimed to develop a technology for 3D visualisation and characterisation of fossil fuel flames in furnaces. The original objectives of the research programme were defined as:

1. To develop an advanced instrumentation system capable of visualising a flame and quantifying its geometrical, luminous and fluid-dynamic parameters.
2. To evaluate the performance of the system as an industrial research tool on E.ON’s 1MWth combustion test facility under a wide range of combustion conditions.
3. To quantify the relationships between the flame parameters measured and the corresponding combustion efficiency and emission data and to study the suitability of the information obtained for the improved control of the combustion processes and the validation of CFD models.

As a result of this project digital imaging based methodology for the 3D monitoring and characterisation of fossil fuel flames in furnaces has been established and three prototype systems based on the three different imaging configurations have been designed and implemented. This means that the original first objective has been met. With regard to the second objective, the evaluation of the prototype systems was conducted not only on RWE power’s 0.5MWth combustion test facility but also on Mitsui Babcock’s 100MWth combustion test facility instead of the originally planned E.ON’s 1MWth facility. The results presented in the preceding sections mean that the third objective has also been achieved broadly. It must be stated that the objectives have been exceeded in many ways. For instance, extensive experimental work was undertaken on the gas fired combustion test rig at the University of Kent under a wide range of rig conditions, though this aspect of the activity was not mentioned specifically in the original objectives. Significant time and effort were also put into the development of the image processing algorithms for the reconstruction of the flame sections and subsequent calculation of the flame parameters for the three different imaging configurations, including the visualisation and quantification of 3D flame front structures. Since a full-scale industrial burner was used in the tests at Mitsui Babcock, the results obtained are transportable to full-scale power station installations.

4. Conclusions

A number of conclusions can be drawn from the results that have been presented in the report:

(i). Digital imaging based methodology for the 3D monitoring and characterisation of fossil fuel flames has been established as a result of this project. The results presented in this report have demonstrated that digital imaging is the best available approach to the 3D visualisation and quantitative characterisation of fossil fuel flames at present.

(ii). Prototype systems based on three different imaging configurations have been designed and implemented. Two of the prototype systems use three identical CCD cameras either mounted around the flame or on one side of the flame. The third configuration uses only a single CCD camera. The pros and cons of the three configurations have been identified and compared in terms of practical installation, cost and capability.

(iii). All relevant image processing algorithms for all three imaging configurations have been developed and tested. Two different approaches in reconstructing the 3D flame model have been investigated, i.e., the contour extraction method and the inverse Radon transformation (i.e., deconvolution or tomographic reconstruction). The contour extraction method has been
found effective in tracking 3D external movement of a flame and the internal structure of the flame front. Measurement of 3D flame parameters, including volume, surface area, orientation, length and circularity, has been achieved. The tomography based Algebraic Reconstruction Technique (ART) has been found suitable for reconstruction of the luminous distributions throughout a flame.

(iv). All three prototype systems developed have been evaluated under a range of conditions on the gas fired combustion test rig at the University of Kent. Meanwhile, the single-camera system has also been tested with pulverised coal flames on RWE npower’s and Mitsui Babcock’s Combustion Test Facilities. The results obtained have indicated that reconstructed cross sections of the flame give a good indication of the variations in the internal structures and luminous properties of the flame along the burner axis and radial directions.

(v). The single-camera system has also been applied for the measurement of 3D flame temperature distribution of the gaseous flame in the university laboratory under a range of conditions. Temperature results obtained from tests on the industrial Combustion Test Facilities have been found inconclusive due to the absence of a reliable temperature reference. However, the Blue and Red component images from the three colour cameras in the second multi-camera configuration have been found useful for the measurement of flame temperature using the two-colour pyrometry.

5. Proposed Work for a Subsequent Project

The work presented in this report has demonstrated the viability and potential of a digital imaging based technology for 3D visualisation and characterisation of combustion flames. However, the technology is still at an earlier stage of development and many areas require further research and investigations. A number of areas that should be pursued in the near future have been identified.

One of the main areas of further research that seems encouraging is the on-line and continuous 3D visualisation and presentation of measurement results using the three-camera systems. With the implementation of more advanced computing hardware such as 3D graphics cards with DMA access and DirectX, the imaging software can be further improved to achieve improved real-time functionalities. A user-friendly interface should also be developed.

Significant further work is required to pursue the 3D measurement of flame temperature for all configurations, particularly when colour CCD cameras are used. Suitable calibration sources and methods should be sought in order to validate the accuracy of the temperature measurement across the flame. Combining the temperature measurement with simultaneous measurement of other 3D physical parameters such as volume and surface area should be undertaken. Other non-physical parameters such as gaseous emission levels in a flame also using digital imaging techniques should also be explored.

The practical installation of multiple CCD cameras on an industrial furnace poses a challenging problem. This problem is likely to escalate when multiple flames are present in the same furnace which is common in the power generation industry. The minimum number of cameras for reasonable performance of the system should be studied in consultation with the end users. The suitability of the multi-camera systems for long term installation on industrial combustion test facilities and their applicability should be investigated. Further
work is required to assess the operability and efficacy of the single-camera system on an industrial test facility as well as on full-scale power plant.

Embedded systems technologies with on-board bespoke digital imaging hardware should be incorporated in order to improve the compactness, robustness and real-time responsiveness of the 3D flame imaging systems.

Although the current embodiment is proposed particularly for application to fossil fuel fired furnaces, the basic concept and methodology are applicable to other combustion processes such as gas turbines and ramjet combustors. Applications of the developed methodology to other combustion processes should be explored. In addition, validation of Computational Fluid Dynamic models of fossil fuel flames and furnaces should be undertaken using the results obtained from the 3D flame imaging systems. The CFD models may also provide a useful reference for the interpretation of the measurement results from the imaging systems.
6. List of Publications Arising from the Project

**Publications in Refereed Journals**


**Publications at International Conferences**


**Presentations at International Conferences and Other Events**


7. References


(9) http://www.itam.nsc.ru/lab17/res01/gold/R71/dif_frames/collection_01.htm


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