Concurrent Measurement of Temperature and Soot Concentration of Pulverised Coal Flames

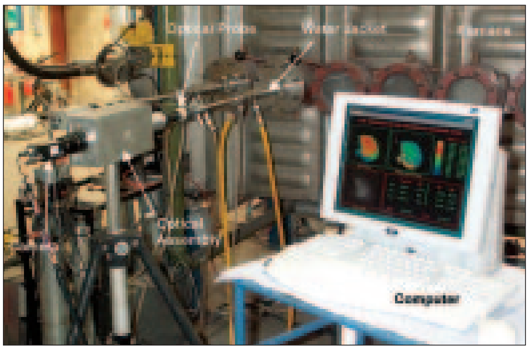

Figure 1. Digital imaging based instrumentation system in operation on Innogy's 0.5MWth combustion test facility

OBJECTIVES

- To develop a prototype optical instrumentation system capable of measuring the distributions and fluctuations of temperature and soot concentration of pulverised coal flames.
- To evaluate the performance of the system on a 0.5MWth combustion test facility at Innogy plc over a range of combustion conditions.
- To establish quantitative relationships between the flame temperature and soot concentration measured and the corresponding combustion input data, thermal output and emission levels.

SUMMARY

Accurate and reliable measurement of the temperature and soot concentration of a pulverised coal flame and their fluctuations provides important information for the in-depth understanding of combustion and pollutants formation processes, carbon-in-ash levels, deposition and corrosion problems. Such measurement would also provide useful data for the validation of mathematical models in relation to flames, furnaces and emissions.

As a result of this project, a prototype instrumentation system for the concurrent measurement of flame temperature and soot concentration has been developed. The system operates on the principle of multi-wavelength pyrometry combined with digital imaging and image processing techniques. A monochromatic imaging system is used to visualise the flame field in the furnace. The flame light incipient on the optical sensor installed on the furnace wall is split into separate beams passing through narrow band-pass filters of different wavelengths before reaching the imaging device. The resulting digital images are processed to determine temperature distribution of the flame field. The soot concentration of the flame is represented using a parameter called KL factor, which is derived from the temperature measured. The operability and effectiveness of the system have been evaluated on an industrial-scale combustion test facility operated by Innogy plc.

During the earlier stage of the project, extensive analytical and design work was directed to developing a prototype instrumentation system under a laboratory environment. A novel optical transmission and filtering system was designed to split the flame light into three identical beams and form instantaneous images on a single CCD camera. Dedicated computing algorithms were developed for the determination of the temperature and KL factor. Following the successful evaluation of the system on the laboratory combustion rig, the system was scaled up and then tested on the combustion test facility at Innogy plc.

Results obtained have demonstrated that the system is capable of measuring two-dimensional distributions and fluctuations of flame temperature and soot concentration. The accuracy of the system was verified using a tungsten lamp as a standard reference source. The relative error between the measured temperature and the reference temperature was found to be no greater than 1% throughout the measurement range from 1280°C to 1690°C. The resolution of the system was dependent upon the resolution of the camera and its installation on the furnace. The prototype system was applied to investigate the distributions of flame temperature and soot concentration of typical pulverised coals. Quantitative relationships between flame temperature, soot concentration and corresponding plant conditions were identified. Preliminary comparisons between the pulverised coal flames and other fossil fuel flames were also undertaken.

COST

The total cost of the project was £162,000 with the DTI contributing £70,000 (43.2%). The balance was met by Innogy plc and the University of Greenwich.

DURATION

24 months – March 2000 to February 2002

CONTRACTOR

Advanced Instrumentation and Control Research Centre
School of Engineering
University of Greenwich at Medway
Chatham Maritime
Kent ME4 4TB

For further information on technology transfer and export promotion matters please contact:
Dr Keith Burnard, Programme Manager, DTI Technology Transfer & Export Promotion Programme
Tel: +44 (0)1235 432120 Fax: +44 (0)1235 432753
E-mail: keith.burnard@aeat.co.uk

For Research & Development matters please contact:
Mr James Felton, Programme Manager, DTI Research & Development Programme
Tel: +44 (0)1273 365157 Fax: +44 (0)1273 365100
E-mail: jf2@mm-brig.mottmac.com
The DTI web site address is: www.dti.gov.uk/cct/

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CLEANER COAL TECHNOLOGY PROGRAMME

Project Summary 332

COLLABORATOR

Innogy plc
Windmill Hill Business Park
Whitehill Way
Swindon SN5 6PB

BACKGROUND

The development of flame monitoring techniques for advanced pulverised coal fired power plant has been recognised as one of the R&D priorities identified by the Foresight Task Force. Within the scope of the advanced flame monitoring techniques, reliable and continuous measurement of flame temperature and soot concentration plays an important part in the in-depth understanding of combustion and pollutants formation processes, carbon-in-ash levels and other combustion problems, particularly slagging and fouling. Conventional temperature monitoring devices such as thermocouples and suction pyrometers are intrusive in nature, sluggish in response and hence unsuitable for the measurement of flame temperature which fluctuates rapidly. Laser-based optical systems provide only local area measurement and require complex installation and regular maintenance. There is, therefore, a need for the development of a reliable, cost-effective, non-intrusive technique that can provide instantaneous measurement of flame temperature and its distributions in a pulverised coal-fired furnace. Very limited work has been previously conducted on the measurement of soot concentration in a coal-fired flame, though sophisticated optical techniques have been investigated for the determination of soot concentration in internal combustion engines. There are no reliable devices currently available for the on-line continuous measurement of soot concentration in a coal-fired flame.

Two-colour pyrometry has long been recognised as a practical technique for the measurement of temperature and soot concentration of sooting flames. Incorporating CCD sensing and image processing techniques, this approach offers a promising means of measuring temperature and soot concentration distributions in a flame. There are some two-colour based optical systems that have been developed in recent years for the temperature measurement in a furnace. However, these systems are very difficult to use and can provide only off-line measurements. As a result of this particular project, a novel, digital imaging based, instrumentation system has been developed for the concurrent measurement of temperature and soot concentration of pulverised coal flames. The system operates on the three-colour pyromatic principle combining advanced optical sensing and image processing techniques.

METHODOLOGY

One of the characteristics of a pulverised coal flame is its high luminosity due to the thermal reaction of soot discomposed from coal particles at high temperature. To take advantage of its luminous nature, the two-colour method has been widely used to measure the temperature of sooting flames. In this method, the thermal radiation of the flame is detected at two different wavelengths. The flame temperature is then derived from the radiation intensities based on Planck's radiation law. Although volumetric and gravimetric densities of soot particles can be obtained if certain assumptions are made, the value of the product KL, called KL factor, is used as an indication of the soot concentration in this project.

In a three-colour system an additional wavelength (the third wavelength) is available, so that three measurements of both temperature and KL factor can be obtained using the three wavelength pairs, i.e., λ_1/λ_2, λ_1/λ_3, and λ_2/λ_3. Averaged temperature and KL factor are then derived from these measurements.

It should be stressed that there exists a temperature difference between a particle and its surrounding gas. This difference depends upon the rate at which heat is transferred by radiation from the particle to the gas and by convection between the gas and the particle. A particle of a smaller size should result in a temperature closer to the gas temperature. In consideration of the fact that the soot particles in the flame are extremely small, the temperature difference between soot particles and their surrounding gas should be less than 10K based on previous studies. On the other hand, although coal particles can be as large as over a hundred micrometers, they are surrounded by a soot cloud which is generated from the volatile matter decomposed from the coal particles when secondary reactions take place at high temperature. The temperature obtained using the system developed is therefore more likely to be that of the soot temperature rather than that of coal particles.

SYSTEM DESCRIPTION

Figure 2 shows the schematic diagram of the new instrumentation system developed. The optical probe together with a purpose-designed water-cooled jacket is used to protect the camera from the excessive thermal radiation from the furnace. The objective lens of the probe has a wide viewing angle and its surface is kept dust-free by a purged air flow. The optical assembly, comprising beam splitters/prisms and three band-pass filters, splits the flame light into three beams at three distinct wavelengths. The CCD camera features progressive scan functions, being capable of providing clear and high resolution images. The frame grabber transfers the image signal into two-dimensional digital images. The entire imaging system provides a frame rate of 24 frames per second with 256 grey-levels. Dedicated application software processes the digital images and then derives the flame parameters on an on-line, continuous basis.

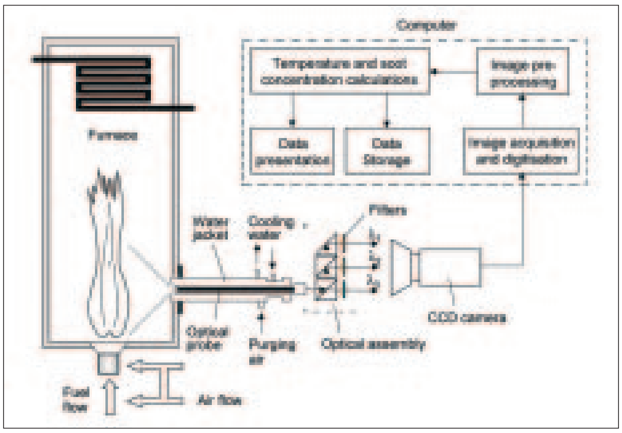

Figure 2. Constituent elements and structure of the system

The system is calibrated using a gas-filled tungsten lamp as a standard light source to establish the relationship between the apparent temperature of the flame at the selected three wavelengths and the grey-levels of the corresponding images. The lamp was pre-calibrated by the NPL with regard to the apparent temperature of the filament at a specific wavelength versus the electrical current fed to the lamp. The calibration data were stored in the system in the form of lookup tables in which every possible grey-level of the pixels in the three banded-images and the corresponding apparent temperatures were presented.

EXPERIMENTAL EVALUATION

The performance of the system was initially evaluated on the gas-fired combustion rig in the University Combustion Laboratory. The accuracy of the system was verified by applying the system to measure the temperature of the standard tungsten lamp in a range between 1280°C and 1690°C. Figure 3 shows the measured temperature of the tungsten lamp in comparison with its reference value. The results have indicated that the relative error is no greater than 1% for all the three wavelength pairs.

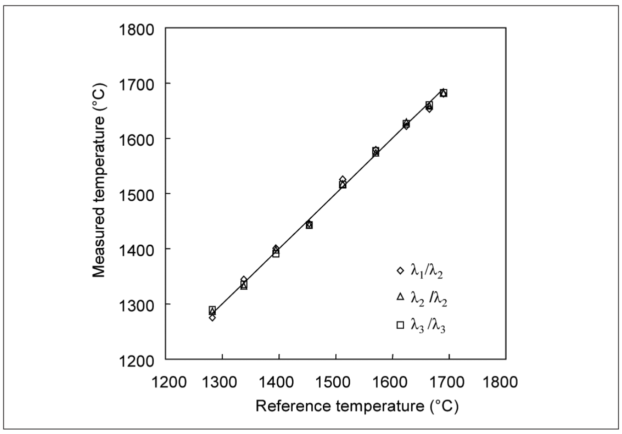

Figure 3. Measured temperature versus its reference value

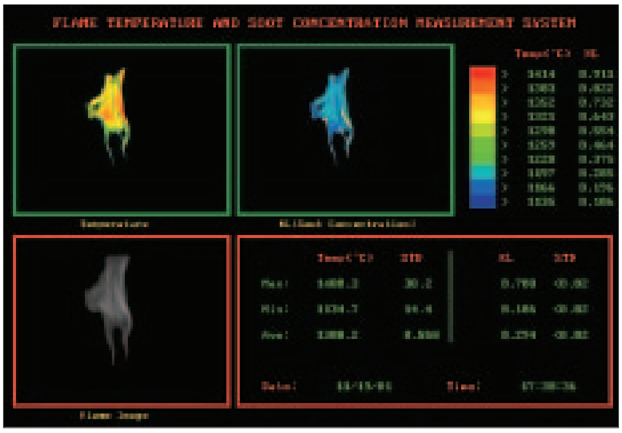

Figure 4. Temperature and KL distributions of a gas-fired flame

A series of experiments was conducted on the laboratory-scale combustion rig. The rig was fitted with a Benson type burner and was capable of generating highly repeatable combustion conditions. Figure 4 shows a typical example of a gas-fired flame image and the corresponding temperature and KL factor distributions.

TRIALS ON INNOGY'S COMBUSTION TEST FACILITY

Test Conditions

The 0.5MWth Combustion Test Facility (CTF) at Innogy is a scaled model of a burner, combustion zone and flue gas path in a typical 500/660MW power station. Figure 1 shows the installation of the prototype system on the CTF. The field of view of the imaging system was approximately one meter long along the burner axis. In such an installation, the root region of the flame was fully visualised. The resulting resolution of the imaging system was about 3mm per pixel. Three supplies of coal were fired, including El Cerrejon (ELC), Polish Blends 50% (PB50) and Polish Blends 75% (PB75). The latter two came from the same source but were processed differently and therefore had different particle size distributions.

Flame Temperature and KL Factor under Steady Conditions

The system was set up to measure the temperature and soot concentration (KL factor) of a flame continuously over a period of 4 hours under steady conditions. Figure 5 shows a typical example of a coal-fired flame image and the corresponding temperature and KL factor distributions. The variations of the maximum, minimum and average temperatures and KL factor with time are plotted in Figure 6. It is noted that both the maximum and the average temperatures and the KL factor increase slightly with time. This was believed to be due to the increasing temperature of the refractory walls because the cooling system of the furnace did not absorb the generated heat completely and hence the furnace was continuously heated up. This outcome is evidenced by the increasing temperature of the flue gas measured using a thermocouple installed at the exit of the furnace. The same test was repeated on a different day and the same trend was observed. Results obtained have demonstrated that the system has a good repeatability.

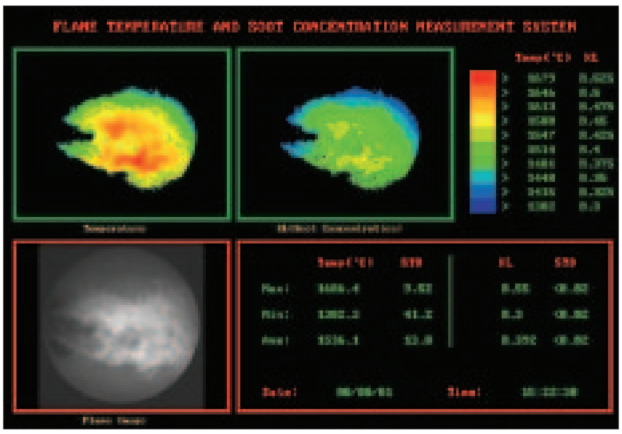

Figure 5. Typical example of temperature and soot concentration (KL) distributions of a pulverised coal flame

Flame Temperature and KL Factor in Relation to Excess Air

The excess air indicates the quantity of air exceeding its stoichiometric level required by the amount of coal fed into the furnace, which was considered to be an important factor influencing the flame temperature. The purpose of this test was to identify the relationships between the characteristics of the flame temperature and the excess air. The variations in excess air were achieved by adjusting the air supplies so that O_2% in the exit flue gas was set at four different levels.

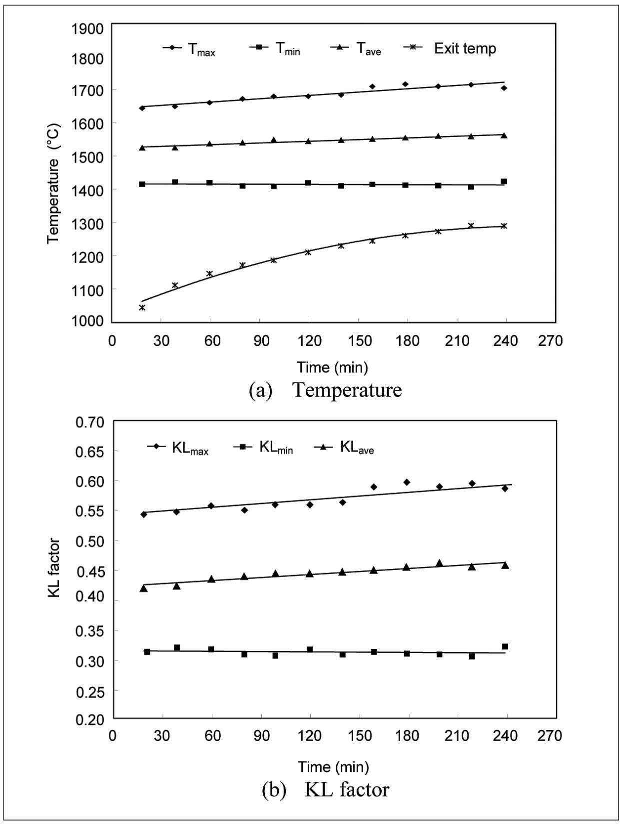

Figure 6. Flame temperature and KL factor under steady conditions

Figure 7 depicts that the maximum and average temperatures of the ELC coal flame increase by 60°C and 50°C respectively when the excess air increases from 10.5% to 32%. The minimum temperature remains largely unchanged. The error bars in Figure 7 indicate that the standard deviation is typically about 40°C. The variations in KL factor show a very similar trend as that of flame temperature.

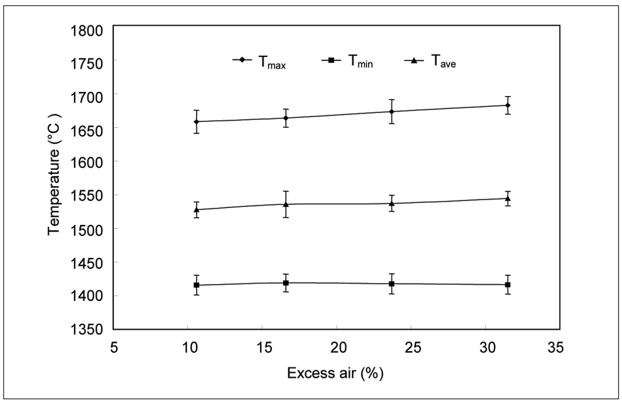

Figure 7. Variation of flame temperature with excess air

Flame Temperature and KL Factor in Relation to Furnace Load

Flame stability is often a problem under lower-load operation since a combustion system is normally designed to give the best performance when the furnace is on full load. It is important to ensure the system operates satisfactorily at lower-load operation such as during ignition phase. The characteristics of the flame temperature and KL of the ELC coal flame was therefore investigated under three different furnace loads, i.e., 0.3, 0.4 and 0.5MWth (full load). Figure 8 presents the flame temperature varying with furnace load. As can been seen, the temperature increases with furnace load because the combustion becomes more intensive when more fuel is fed into the furnace. A significant variation in average temperature occurs under the furnace load of 0.3MWth as its standard deviation is about 35°C. The KL factor has similar characteristics to the flame temperature. It can, therefore, be concluded that the flame has a poorer stability under a lower load.

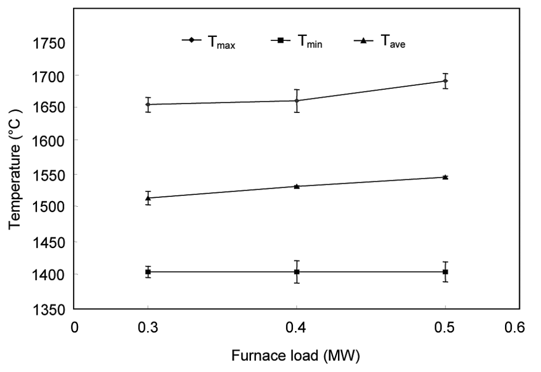

Figure 8. Variation of flame temperature with furnace load

Figure 9 shows typical examples of temperature contours of the flame for two different furnace loads. It is clear that there are two higher temperature regions (>1600°C) in the primary reaction zone. The areas of the regions vary with furnace load. For 0.5MWth load, the lower region is much greater than the upper region, whilst for 0.3MWth the opposite occurs. This variation in temperature distribution is attributed to the complex nature of coal-air mixings under different furnace loads.

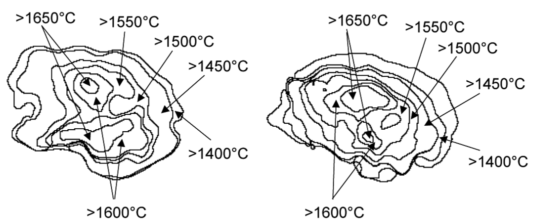

Figure 9. Temperature contours of the flame

Flame Temperature and KL Factor in Relation to Particle Size

This test was conducted for the PB50 and PB75 coals in order to reveal the impact of coal particle size on the thermal characteristics of the flame. It was found that the PB75 coal flame had a higher temperature than PB50 coal. The KL factor had shown very similar characteristics to the temperature. These results suggest that the coarser coal generate more soot particles than the finer coal. Figure 10 shows the temperature contours for PB75 and PB50 coals. It is clear that PB75 coal flame has a larger high-temperature region (>1500°C) than PB50 coal flame. This is because larger particles require longer time to complete the combustion.

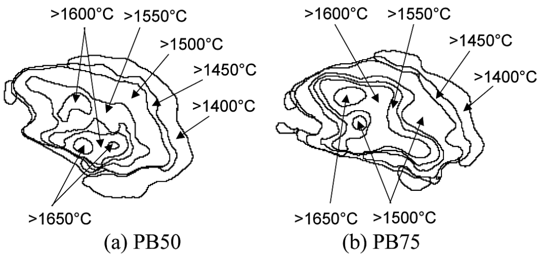

Figure 10. Effect of particle size on flame temperature

CONCLUSIONS

The following conclusions have been reached from the work undertaken:

- The three-colour pyrometry incorporating advanced optical sensing and digital imaging techniques offers an effective means of measuring the distributions of flame temperature and soot concentration of pulverised coal and other fossil fuels.
- A prototype instrumentation system developed has been tested on both laboratory and industrial scale combustion test facilities. Results obtained have demonstrated that the system is capable of measuring two-dimensional distributions of flame temperature and soot concentration under a range of combustion conditions.
- The accuracy of the system has been verified using a tungsten lamp as a reference source. The relative error between the measured temperature and the reference value is no greater than 1% throughout the measurement range from 1280°C to 1690°C. The resolution of the system depends on the resolution of the camera and its installation on the furnace. The prototype system installed on the Combustion Test Facility at Innogy gives a resolution of about 3mm per pixel.
- The prototype system has been applied to investigate the two-dimensional characteristics of flame temperature and soot concentration of typical pulverised coals under a range of operation conditions. Quantitative relationships between flame temperature, soot concentration and corresponding plant conditions and emissions have been identified. Preliminary comparisons between the pulverised coal flames and other fossil fuel flames have been made.

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