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Visualisation and measurement of flames in a gas-fired multi-burner boiler.
Journal of Physics: Conference Series, 1065 . ISSN 1742-6588.

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To cite this article: J Cugley *et al* 2018 *J. Phys.: Conf. Ser.* **1065** 202009

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Visualisation and measurement of flames in a gas-fired multi-burner boiler

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Abstract. The paper presents the development of an instrumentation system for the visualisation and measurement of flames in a gas-fired multi-burner boiler based on digital imaging and spectrometric techniques. The system consists of a rigid optical probe and an optical fibre, a digital camera, a spectrometer and an embedded computer with associated application software. The characteristic parameters of the flame, including size, temperature and oscillation frequency are quantitatively determined based on flame images obtained. The spectral characteristics of the flame are analysed over the spectral range from the ultraviolet to near infrared. The system was evaluated on a gas-fired heat recovery boiler under different operation conditions. Results obtained suggest the promising correlation between computed flame parameters and operation conditions.

1. Introduction

In a multi-burner boiler, burners need to be operated to ensure that the fuel (either gas, oil or coal) burns safely, efficiently and cleanly. It is known that flame properties such as size, shape, temperature, oscillation frequency, colour/spectrum, etc. have a close correlation to the burner conditions and consequently the overall performance of the boiler. The flame size and its variation depend on many factors such as fuel type, furnace load, fuel and air supplies, as well as burner settings [1, 2]. Flame temperature is crucial for the understanding of the energy conversion, combustion efficiency and emission formation process [3–5]. Flame oscillation frequency is another important indicator of the flame stability [6, 7]. Although various techniques are used around the boiler for flame monitoring, most of them provide only single-point or off-line measurements. Significant progress was made in the past two decades in developing advanced sensing techniques for flame visualization and characterization on practical furnaces [1, 3, 6–9]. Most of the earlier work, however, focuses mainly on the flame monitoring of a single-burner combustion system, limited work has been done for the overall measurements of multi-burner boilers. There has been a growing interest in developing techniques for monitoring individual flames in a multi-burner boiler to understand how each burner performs with regard to the overall performance of the system. In addition, the spectroscopic analysis of a flame in a combustion

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system has been paid an increased attention. It provides the spectral characteristics of the flame over a wide spectral range from the UV (ultraviolet) to near IR (infrared), in particular, the detailed information about free radicals (such as OH^* , CH^* , CN^* and C_2^*) in the flame. It is believed that the spectral information of these flame radicals is closely linked to pollutant emission (e.g., NO_x , CO) formation of the combustion process [10, 11]. It is therefore desirable to develop an advanced flame monitoring technique to quantify these flame properties and use such information to assess and predict the overall performance of the combustion process.

This paper presents the development of an instrumentation technique for measuring flames in a multi-burner boiler. By combining digital imaging, spectroscopic and image processing techniques, the system offers a promising solution to measure concurrently a set of flame characteristic parameters (area, temperature, oscillation frequency and spectral distribution). Technical issues, including detailed sensing arrangement, computation of flame parameters and system evaluation, are addressed. Experimental results obtained on a gas-fired boiler are presented and discussed.

2. Methodology

2.1 System description

Figure 1 shows the block diagram and schematic of the flame monitoring system, respectively. The system consists of a rigid optical probe and an optical fibre, an RGB digital camera, a miniature spectrometer and an embedded computer with associated application software. The optical probe and fibre transmit the image and spectral signals to the camera and spectrometer. To prevent the probe/fibre from overheating due to the high temperature and to maintain positive pressure inside the furnace, a water/air cooled jacket with a single-valve isolating unit is designed as an integrated part of the probe assembly. The probe/fibre with a tilted view angle of 75° and cooling jacket is penetrated into the boiler from the back of the sidewall and so the front wall (burners) can be fully visualised [Figure 1(b)]. An industrial RGB camera is employed, which is programmable for two different modes, i.e., high-resolution mode [up to $1280(\text{H}) \times 1024(\text{V})$ at a frame rate of 25 fps (frames per second)] and high-speed mode (up to 900 fps with a reduced image resolution). The spectrometer has a 2048-element linear silicon CCD array with a sensing range from 180 nm to 876 nm. The motherboard, having a 2.42 GHz processor with 8 GB memory, provides fast on-board data processing, and transmits the processed data to a main computer system via Ethernet transmission. Such a system configuration allows both the camera and spectrometer to capture flame images and spectroscopic data concurrently. The application software permits the system to acquire flame signals, process the data and present the measurement results.

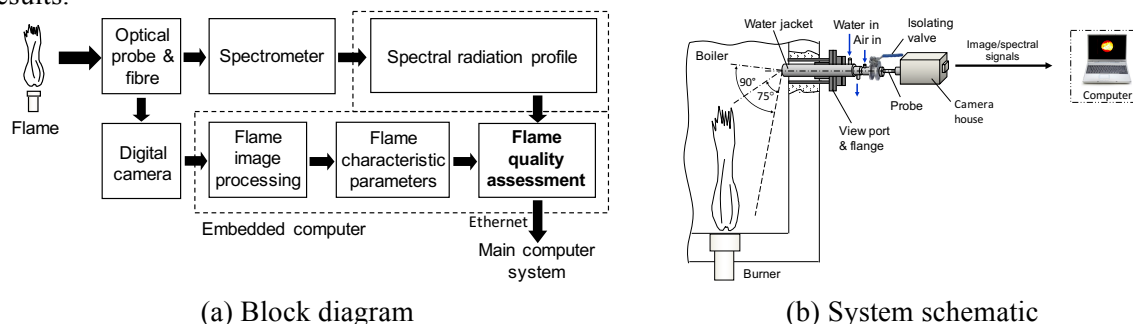


Figure 1. Block diagram and schematic of the flame measurement system.

2.2. Flame measurements

Flame area- Flame area, A (*pixels*), is computed by firstly transposing the flame image from RGB to grey-scale and then binary using an appropriate threshold to determine the outer contour of the flame within the image matrix. The area is then the total number of pixels within the flame region, R , defined by the outer contour. i.e.,

$$A = \sum_{i \in R} 1 \quad (1)$$

where i is a pixel within R . With the known geometric relationship between the optical probe and the flame, the flame area in pixels can be easily converted and presented with absolute dimensions.

Temperature- Flame temperature is determined based on the two-colour pyrometry [3], i.e.,

$$T = C_2 \times \left(\frac{1}{\lambda_G} - \frac{1}{\lambda_R} \right) / \left[\ln \frac{G(\lambda_R, T)}{G(\lambda_G, T)} + \ln \frac{S_{\lambda_R}}{S_{\lambda_G}} + \ln \left(\frac{\lambda_R}{\lambda_G} \right)^5 \right] \quad (2)$$

where T is the soot (solid particles) temperature inside the flame, C_2 is the second Planck's constant; $G(\lambda_R, T)$ and $G(\lambda_G, T)$ are the grey intensities of images from the red (R) and green (G) channels, respectively, λ_R and λ_G are the peak wavelengths of the R and G channels, and are 600 nm and 520 nm, respectively, in this study. $S_{\lambda_R}/S_{\lambda_G}$ is the instrument factor, which is determined through calibration using a blackbody furnace as a standard temperature source. Further information on the temperature calibration can be found elsewhere [3].

Oscillation frequency- Flame oscillation frequency is derived from the flame signal which is reconstructed from flame images captured by the camera at the high-speed mode (900 fps). The PSD (Power Spectral Density) of the flame signal is computed through the FFT (Fast Fourier Transform). The weighted oscillation frequency is then obtained over the frequency range (0-450 Hz) [4].

Flame spectra- The light of flame collected by the spectrometer includes information about the flame spectroscopic characteristics across the spectral range from 180 nm to 890 nm. The profiles of the spectral intensity and the peaks across the spectral range can then be quantified. The radiative intensity of free radicals [OH^* (308 nm), CN^* (387 nm), CH^* (432 nm) and C_2^* (514 nm)] can then be analysed, and their relationship to the emissions determined [11–13].

3. Results and discussion

The system was tested on a gas-fired heat recovery boiler, which has four front-wall fired burners, under two operation conditions, i.e., start-up and normal. Figure 2(a) shows the on-site installation of the system whilst Figure 2(b) gives the typical images of flames under the two test conditions.

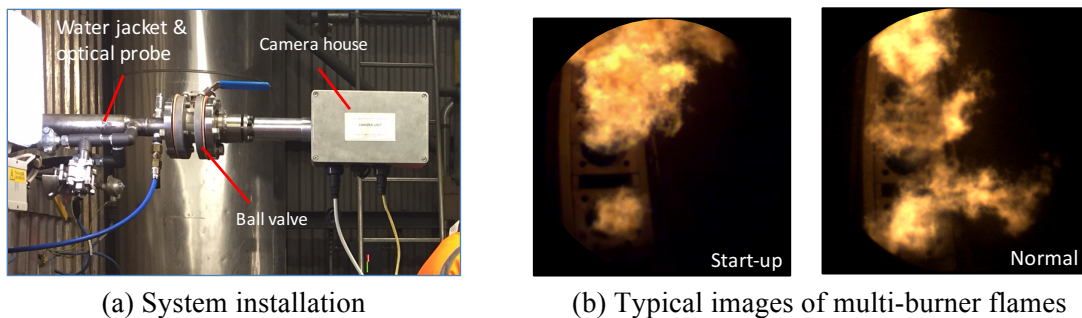


Figure 2. On-site system installation and flame images.

Figure 3 shows the flame images and measured parameters under the two test conditions [note that only the flame images of the bottom burner are presented, figure 3(a)]. There is a clear increase in the flame mean temperature from the start-up to normal operations [figure 3(b), over 120 readings for each condition]. The great standard deviation of the flame temperature is found under the start-up, suggesting an unstable combustion process under such a condition. Figure 3(c) shows that the flame area under the normal condition is significantly greater than that under the start-up due to the higher fuel flow rate. In addition, the standard deviation of the flame area is found greater under the normal condition than that under the start-up. This is mainly attributed to the fluctuation of the downstream of the flame under the normal condition. Figure 3(d) illustrates that the oscillation frequency of the flame is significantly higher in the normal condition than that in start-up, suggesting a stable luminous intensity of the flame. Figure 3(e) gives the averaged spectral distributions of the flame under the two test conditions, from which, the radiative intensities of free radicals (such as OH^* , CH^* , CN^* and C_2^*) can be determined. The

preliminary results have proven the effectiveness of the developed measurement technique. Further studies will focus on quantifying the relationship between the flame parameters and operation conditions, and establishing a computational model to gain further insight into the performance of a combustion process and to predict emissions from the flame characteristic parameters.

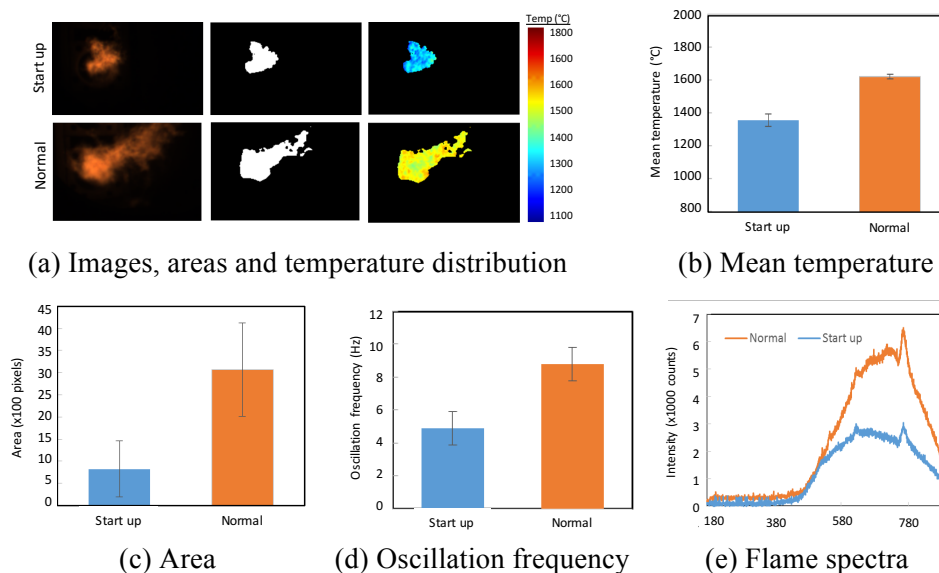


Figure 3. Flame images and computed flame parameters under the two different test conditions.

4. Conclusions

An instrumentation system for the visualisation and measurement of the flames in a multi-burner boiler has been developed. Through digital imaging, spectral analysis and embedded computing, the system is capable of measuring a set of characteristic parameters of the flame, including area, temperature, oscillation frequency and spectroscopic profiles. The system has been tested on a gas-fired heat recovery boiler. The results have demonstrated that the measured parameters can represent the fundamental characteristics of the flames under different operating conditions.

Acknowledgements

The authors wish to acknowledge the Biomass and Fossil Fuel Research Alliance (BF2RA) for providing financial support (Project 25) for the work presented in this paper.

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