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Preliminary determination of flame speeds from infrared images using image processing techniques in a 150 kW_{th} coal-fired combustion test rig

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Abstract*—Flame speeds are important flame characteristics in combustion processes as it determines the stability of the flame. Accurate experimental measurements of flame speeds require optical systems and diagnostic instruments, such as those in schlieren photography. However, these systems are more suitable in laboratory environments. In industrial furnaces, simpler methods are required to determine the flame speeds for comparison. Infrared cameras are used to detect 'hot spots' in furnaces, and since the radiation intensity of the flame is indicated by the brightness of the pixels in the images, a sequence of images can be used to determine the difference in the pixels' brightness, allowing determination of the flame's movement and subsequently the flame speed. Thus, in this study, a tool to determine the flame speeds using an image processing technique is presented. Preliminary results of the flame speeds from a 150 kW_{th} coal fired combustion test rig were obtained. The combustion test rig contains a moveable block that imparts a swirling flow with a swirl number of 2.0. Infrared images were recorded for liquid petroleum gas (LPG) flames and coal-flames. The approximated flame speeds show that the coal flames are highly fluctuating compared to liquid petroleum gas flames. This may be caused by the inertia of the coal particulates that have increased the turbulence of the gas flow.

***Keywords*—coal flames, flame speeds, image processing, infrared imaging.**

I. Introduction

Flame diagnostics are necessary to determine the combustion characteristics of a system, such the combustion efficiency (in terms of unburnt carbon) and flame stability (air-fuel ratio limits before the flame is extinguished or blown-off) could be improved. One of the critical flame parameters is the flame speed, which is the rate of expansion of the flame in a combustion reaction. The flame speed is useful to quantify and determine if the flame is moving too fast (blow-off) or too slow (blow-back).

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There are various methods to determine the flame speed. Kuznetsov used a high speed camera with a schlieren system on a standard spherical bomb reactor to measure the flame speed accurately [1]. From their experimental results, a sequence of schlieren images was obtained, in which the flame develops into a sphere. The time-dependent flame radius in two perpendicular directions were then used for laminar burning velocity evaluations via data processing of the high speed images.

The schlieren approach was also used by Morones et al. [2]. Laminar flame speed measurements were conducted using a constant volume, heated cylindrical flame speed vessel. Two quartz windows were used for optical access and a z-type schlieren system together with a high speed camera was used to capture the flame spread. The captured images were used to determine the flame radius via a MATLAB based software routine that was developed in-house by the respective authors.

In another example, Broustail et al. [3] estimated the flame propagation with the shadowgraph technique. A MATLAB software routine was again used to determine the laminar burning velocity. The densities of the unburned gases were estimated from the EQUIL Code of the Chemkin package with an oxidation kinetic scheme of butanol.

Besides schlieren methods, other simpler methods have been utilized. For example, Suda et al. [4] applied a high speed CCD camera to monitor the evolution of coal particle combustion to within a millisecond. The flame propagation velocity (or flame speed) was calculated by measuring the rate of change of the flame diameter in the recorded images. In this experiment, different kinds of pulverized coal particles were chosen and the coal concentration, coal type and ambient gas temperature were varied.

The above examples show that determining the flame speed experimentally may involve combustion chambers and more advanced optical systems (i.e., using schlieren photography). However, the aforementioned methods are more applicable for laboratory scale studies. To determine the flame speeds in industrial furnaces (e.g. in thermal coal-fired power plants), simpler methods are required, and may involve using infrared (IR) or CCD cameras. This is possible since IR or CCD cameras are able to capture the radiation and movement of the combustion gases in the furnace [5].

In thermal coal-fired power plants, an IR camera maybe utilized to detect 'hot spots' in the furnace, which indicate a region of high solid surface temperatures. When IR cameras are used to detect radiation from solid surfaces, the brightness of the pixels in the recorded sequence of images contain information about the radiation intensity from the flame. By observing and analyzing the change in the brightness of the pixels with an image analysis software, the movement of the flame can be determined, along with the flame speed.

Thus, this study presents a tool using MATLAB to determine the flames speeds by analyzing IR images from an IR camera on a 150 kW_{th} combustion test rig. The results presented here demonstrate a simpler method that can be used to determine or approximate the flame speed in industrial applications.

II. Methods

A. *Combustion test facility & experiments*

Flame images were recorded during experiments in a 150 kW_{th} combustion test facility, shown in Figure 1. Table I shows the details and operating parameters of the combustion test rig. During the experiments, liquid petroleum gas (LPG) was supplied to a pilot flame burner to heat up the furnace to a temperature of 800°C. Adaro coal (properties shown in Table II) of 75 µm size was then injected from a hopper at a rate of 20 kg/h into the furnace to initiate the combustion of coal. The coal supply in the hopper is replenished by a screw feeder that is regulated by a level sensor in the hopper. Two blowers provide primary and secondary airflow into the combustion test rig. The amount of primary airflow rate was 14 m^3/h while secondary air flow rate was 200 m^3/h, which was preheated to a temperature of 250°C to improve the combustion process. Several thermocouples were used to measure the temperature of the furnace, and all temperatures were logged with a data logging and display system. For the sake of brevity, only the temperature in the first section of the furnace (where the IR camera is mounted) was reported. A swirl block (Figure 2.) based on the design from Fudiharal et al. [7] was used to induce a swirling flow in the furnace with a swirl number of 2 (calculation of the swirl number is based on [7]). The total gas velocity through the furnace was calculated based on the gas density of the furnace temperature, which was in the range of 500 to 800ºC. The mass flow rate of coal was also taken into account to determine the total gas velocity.

TABLE I. DETAILS OF COMBUSTION TEST FACILITY AND OPERATING PARAMETERS DURING EXPERIMENTATION

Diameter of furnace (m)	0.6
Length of furnace (m)	3.1
Primary air (m^3/h)	14
Secondary air (m^3/h)	200
Temperature of secondary air (ºC)	250
Swirl number	2.0
Liquid petroleum gas (LPG) flow rate (m^3/h)	5.0
Coal feed rate (kg/h)	20
Furnace temperature (ºC)	600-800

TABLE II. PROXIMATE AND ULTIMATE ANALYSIS OF ADARO COAL

Proximate analysis & energy content	
Moisture content (%)	25.16
Ash content (%)	1.39
Fixed carbon (%)	35.69
Volatile matter content (%)	38.19
Gross calorific value (kcal/kg)	5244
Ultimate analysis	
Carbon (%)	74.35
Hydrogen (%)	4.88
Nitrogen (%)	0.82
Sulphur (%)	0.12
Oxygen (%)	19.40

Figure 1. 150 kW_{th} Combustion test facility at TNB Research Sdn. Bhd.

Figure 2. Swirl block for imparting swirling flows in the furnace of the combustion test rig.

B. *Infrared camera & image processing*

An IR camera from FLIR (model A615) with a spectral range of 7.5-14 µm was installed on top on the combustion test rig at an angle of 45° from the horizontal plane, as shown in Figure 3. The IR camera is cooled by a cooling water jacket that is supplied with chilled water via a chiller. An optical window was installed in front of the camera to protect the lens from the flames in the furnace. The field of view of the camera was 25°×19°, with a focus distance of 0.25 m, and a focal length of 24.6 mm.

Figure 3. IR camera with water cooling system on the combustion test facility.

The IR camera recorded flame images for the following operation for at least 5 min:

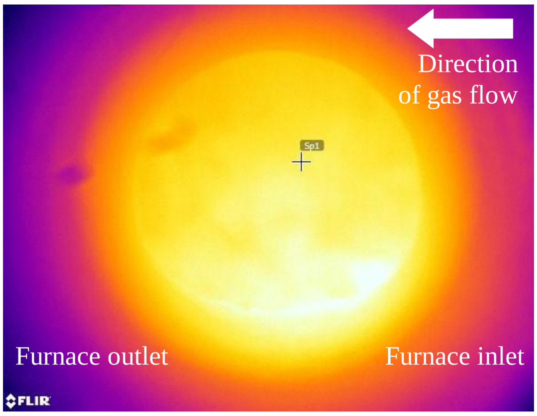
- With LPG turned on, at total air flow rates of 103 and 152 m^3/h
- With LPG turned off, total air flow rate of 214 m^3/h, and coal injection rate at 20kg/h.

The video recording was then used to obtain a sequence of images for image analysis. At least seven images from each operating condition were analyzed to obtain an averaged flame speed.

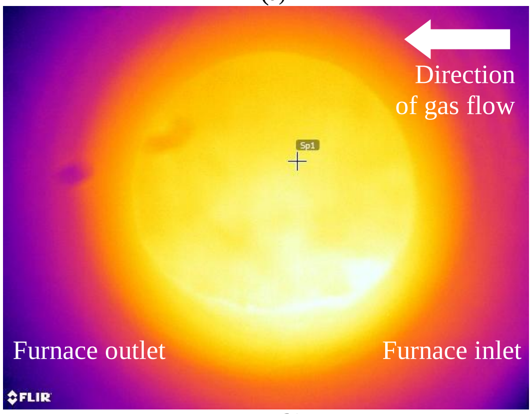
The images were then analyzed with MALAB. Two subsequent images in RGB format (Figures 4(a) and 4(b)) that were recorded 0.02 s apart are converted to gray format to extract the brightness component of the pixels only (Figures 4(c) and (d)), since this would represent the radiation intensity of the flame [5]. The images were then compared to determine if there are any differences in the brightness. This is done by subtracting the brightness of the earlier image from the latter image to yield the magnitude of the differences. After subtraction, a 8-bit image is produced, and the threshold level is adjusted to segment the image and reveal the pixels of interest. Pixels with brightness values greather than level 4 are set to white. The rest of the pixels are shown in black. The pixels in white represent the pixels that have the largest difference in brightness values between the two images (represented by the clusters of pixels as shown in Figure 4. This cluster of pixels could represent the movement of the flame, which is from the right of the figure (the furnace inlet) to left (furnace outlet) [5].

The pixel length of these clusters were used to determine its physical length by direct proportion to the known diameter of the viewport, indicated in (a). The length of the flame is approximated by direct proportion of the length of the cluster (in pixels) to the measured length and known diameter of the view port (i.e., 323 pixels=75mm).

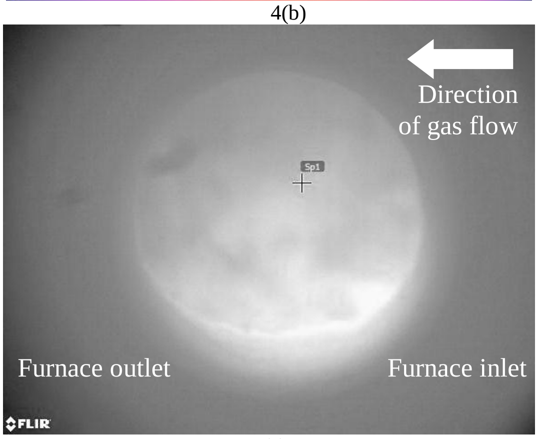
The cluster of pixels is a snap shot of the propagating flame with the highest radiation intensity, and may represent the region where unburned gases or volatiles are undergoing peak reaction rates. However, the cluster of pixels is not the actual flame front during the start of ignition. Therefore, the velocities determined in this study is not representative of the more commonly reported flame speeds or flame propagation velocities in literature. Thus, the flame speeds presented in this study should be regarded as an approximation only. Nevertheless, the image processing technique would be a useful tool for in-house comparisons of the flame characteristics, especially for industrial applications.



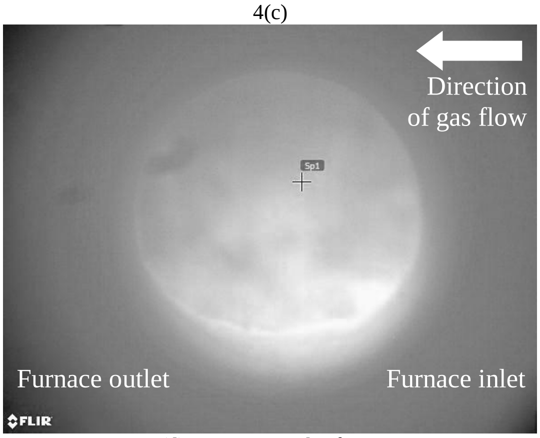
4(a)



4(b)



4(c)



4(d) images in 32-bit format

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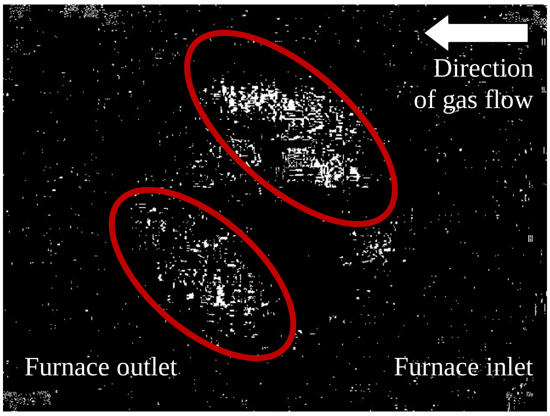

4(e)

Figure 4. (a) and (b) two subsequent infrared images (c) and (d) images in 32-bit format (e) subtracted and threshold adjusted image. Circled areas indicate pixels with the largest difference in brightness.

III. Results and Discussion

A. *Flame speeds of pilot and coal flames.*

Figure 5. shows the approximate flame speeds with variation in furnace temperature. When LPG supply was turned on (i.e. with the pilot flame still heating up the furnace) without the primary air supply, the temperature of the furnace was lower (515ºC). This was because the lower velocities caused a lower heating rate in the furnace. The flame speed under these conditions was 2.2±0.8 mm/s

When the primary air was turned on to increase the rate of heating of the furnace, the temperature of the furnace increased gradually. At a temperature of 562ºC, the infrared images were taken and analyzed to yield a flame speed of 3.0±0.6 mm/s.

The furnace temperature continued to increase further to 800ºC, at which point coal was injected into the furnace. The pilot flame was switched off with the primary airflow still turned on. Once coal was injected, there was instantaneous devolatilization of coal, which increased the amount of unburnt gases that were flowing through to the flame. The higher volume of gases increased the flame speed to 3.1±1.1 mm/s.

The flame speed during coal injection fluctuated at a wider range (indicated by the vertical error bars in figure), possibly caused by the turbulence induced from the inertia of the injected coal particles. In fact, if the fluctuation of the flame speed is taken into account, there would be no significant difference in the flame speeds between pilot flame and coal feeding operation. However, a statistical F-test shows that the variance of the two flame speeds are different (F value = 0.523, higher than $F_{critical}$=0.162), indicating that the flame characteristics between the LPG (pilot) flames and coal flames are different.

The flame speed is not strong correlation with the temperature as shown in Figure 5. as shown in Figure 6. and **Error! Reference source not found.**This is because (unlike the furnace temperature) the total gas velocity and the furnace pressure takes into account devolatilization of coal and gas expansion that occurs during combustion process.

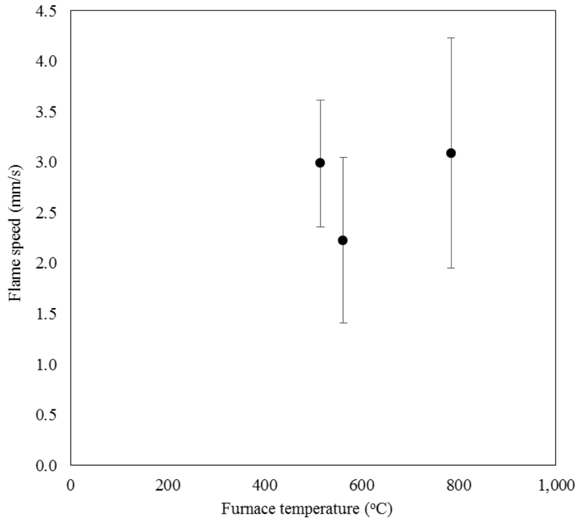

Figure 5. Approximate flame speeds vs furnace temperature

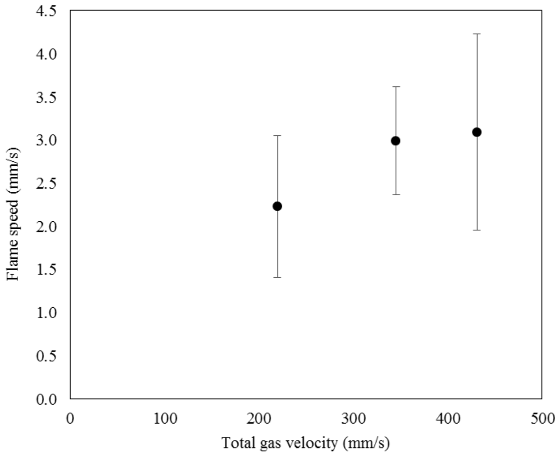

Figure 6. Approximate flame speeds vs total gas velocity

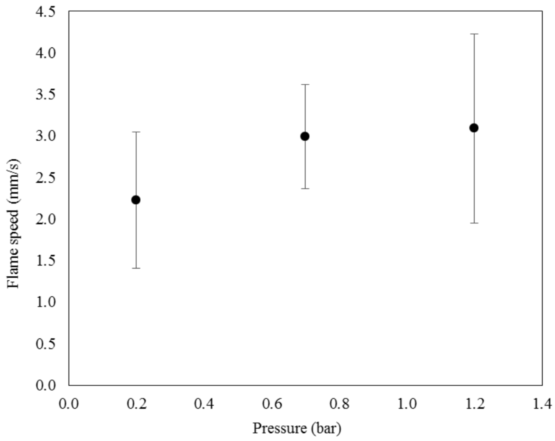

Figure 7. Approximate flame speeds vs variation in furnace pressure

B. *Comparison with flame speeds from literature*

To validate the image processing technique in this study, flame speeds were compared with values from literature. For coal concentrations of 0.09 kg/m^3 of air, the flame speeds in this study (2.3 to 3.1 m/s) were within the range of those reported by Suda et al. [4] and Cao et al. [8], who measured coal flames to be from 0.3 m/s to 7.8 m/s for coal concentrations of 0.1 and 0.25 kg/m^3 respectively. However, it should be noted that these measurements were conducted in different settings. Suda et al. performed the experiments in a micro-gravity experiment, spherical-shaped combustion chamber. Cao et al. measured the flame propagation velocities in a vertical combustion tube that was equipped with a high-pressure dispersion system. The other experimental work mentioned in the Introduction measured the fame velocities for different fuels to be between 0.2 to 2.2 m/s [1]. Zhou et al. [9] and Allous et al. [10] utilized IR cameras for flame diagnostics via digital signal processing and frequency analysis, but flame propagation velocities were not reported.

With limited values of flame velocities from image processing of IR images, further work is required to validate and determine if the image processing technique is accurate, such that comparisons can be made with values for literature, although the flame velocities determined in this study are within the range of those reported in literature. However, comparisons of the flame characteristics using the image processing technique in this study is possible, and maybe useful for industrial combustors where more robust diagnostic equipment is more suitable. In situations where IR cameras are used to inspect 'hot-spot' regions, this image processing technique can also be used to determine the flame characteristics.

Conclusions

An image processing technique to determine the flame speeds from infrared images is presented. Preliminary flame speeds from a 150 kW_{th} coal fired combustion test rig were obtained. The flame speeds were determined for liquid petroleum gas (LPG) flames, and coal-flames. The flame speeds with coal injection were 3.1±1.1 m/s, compared with LPG flames that had a value of 3.0±0.6 m/s. The higher standard deviations show that the coal flames are highly fluctuating compared to liquid petroleum gas flames. This is possibly caused by the inertia of the coal particulates.

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