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Full Length Article

Investigation of ignition process from visible to infrared by a high speed colour camera

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HIGHLIGHTS

- Selective image processing is used to enhance the weak blue and infrared signals.
- Flame emission from visible to infrared spectrum is simultaneous visualised.
- The infrared emission is found to be associated with the soot formation process.
- The infrared emission only soot is in between blue flame and the visible soot.

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ABSTRACT

From the image processing of high speed colour images of flame ignition, areas of dominant infrared emission have been noticed, which has stimulated the more in depth investigation in this paper. Two test cases for propane and methane with co-flow air were carried out. By applying selective digital image enhancement technique, the weak chemiluminescence-induced visible flame and infrared signals are simultaneously resolved together with the much stronger visible soot radiation. It is found that the pockets of soot only emitting infrared signal exists in both propane and methane ignition process cases. In the ignition process, the chemiluminescence-induced blue flame is observed first, which is followed by soot only having infrared emission. The visible orange coloured sooty flame only appears afterwards. The soot only emitting infrared is found in between the blue flame and the visible sooty flame. The co-flow air is found to accelerate the ignition process and it also brings forward soot formation. The investigation demonstrates that a proper image enhancement technique is essential in the further understanding of combustion process taking place when using a high speed camera.

1. Introduction

The ignition of burner flames has been shown to be sensitive to ignition system [1], fuel flow rate and ignition location [2–4]. A good understanding of this process can be achieved through simultaneous multispectral time dependent visualisation of both the ignition physics and subsequent combustion. As a result, sophisticated experiments remain essential to enhance our understanding. Laser imaging is often used to study the flame development during the ignition process. For example, particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) techniques can simultaneously provide fluid velocity field conditions, radical (CH, OH, NO, etc.) distributions, flame structure and stability [5–7]. Ahmed and Mastorakos [2] applied OH-PLIF to study ignition and followed the edge flame propagation in turbulent non-premixed methane flames. They reported that the flame kernel growth rate increased with higher spark energy, thinner electrode diameter and wider gap. However, these techniques remain expensive to implement and the optical access required may result in a significant redesign of the combustion chamber.

Typical hydrocarbon flame consists of the broad band orange coloured soot particle radiation and spectral band emission of excited species in the ultra violet (UV), visible and infrared spectrums [8]. In the visible spectrum excited molecular radicals CH^* (430 nm) and C_2^* (Swan system, dominant emissive band head at 473.71 nm and 516.52 nm) produce 'blue' light [9], the intensity of which has been demonstrated to vary with fuel composition, flow rate, and heat release rate [10–12]. The ratio of $CH^*/C2^*$ can be used to determine the local equivalence ratio [13]. Orange coloured flames are produced by grey-body radiation of incandescent soot.

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Soot formation occurs via precursor species which mainly consist of polycyclic aromatic hydrocarbons (PAH) [14]. Subsequently, small particles are formed through chemical coagulation. As the soot particles travel through an oxidizing region, soot formation ceases. Within the UV, the hydroxyl radical, OH^* has the strongest band with the primary head at 309 nm [8]. Emission in the infrared spectrum has two primary components various emission bands and continuum radiation. The strongest band is around 4.4 μm due to CO_2, and there is another strong band at 2.8 μm as a result of emission from both CO_2 and H_2O [9]. The continuum radiation from heated soot particles in the flame has a peak emission in the mid infrared region of the spectrum [15].

The flame ignition process studies are generally relied on high speed cameras. Research indicated soot emission tends to obscure the CH^* and C_2^* signals at high shutter speeds [16,17]. Directed high speed imaging from the Rolls-Royce gas-turbine combustor seems to indicate that the flame is discontinuous during the ignition process [18]. However, through selective image enhancement technique Huang and Zhang reveal that there exists very weak visible blue coloured flame in the seemingly flameless image sequence. In our recent tests it is found that pockets of flame that only emits in the infrared spectrum can be detected by some high speed cameras besides the visible flame emission, which has not been reported before. Although Kapaku et al. [19] visualised soot and carbon dioxide radiation intensity of an ethylene diffusion flame using a high-speed mid-infrared camera with two band-pass filters, only infrared emissions were recorded instead of both the visible and infrared. Huang and Zhang [20] imaged a methane flame under various stable burning conditions with an Olympus E-100RS digital camera. In the investigation of the infrared emission, an infrared filter was applied. They found that the infrared emission distribution detected by the camera did not overlap with the visible flame colour in the hue space. Hue is referred to the colour appearance which is related to the spectrum [21]. However, the objective of the study focused on the stable flame and the infrared emission was not resolved simultaneously with the visible flame.

In a recent investigation of ignition, it was noted that infrared emission was detected despite the fact that a high speed colour digital cameras usually have an infrared cut-off filter. With the aid of selective digital image enhancement techniques [20], the visible CH^* and C_2^* and the infrared emission were segmented, enhanced and visualised. Therefore a single digital high speed colour camera combined with selective digital image enhancement can be used to investigate the flame ignition process in both the visible to the infrared spectrum. In this work, the temporal ignition development of flames above fuel jets was captured and the evolving light emission from the flame was analysed.

2. Experimental procedure

2.1. Experimental setup

The ignition process was captured by a high speed camera (Photron FASTCAM SA4) with a full frame resolution of 1024 by 1024 pixels. A sigma 24–70 mm lens is applied to the camera. The aperture is set as f/2.8 in all the cases. The ignition was initiated with a Kawasaki ignition-coil (TEC-KP02), with approximately an output voltage of 30 kV. The spark was created between a pair of steel electrodes separated by a 9 mm gap. A schematic of the experimental setup is shown in Fig. 1.

Two test cases were investigated. In Test Case 1, a free propane non-premixed flame jet was established. The gas flow rate was regulated by a mass flow controller. The fuel was injected through a nozzle of 9.6 mm diameter. The fuel jet flow rate was 5 l/min,

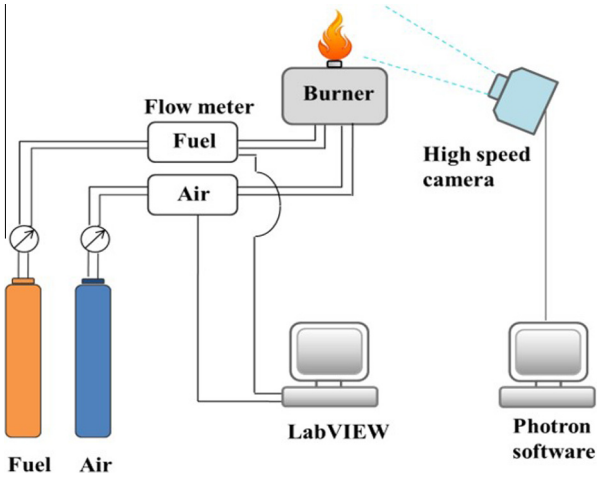

Fig. 1. The schematic experimental setup.

which corresponds to fuel jet velocity of 1.15 m/s and Reynolds number (*Re*) of 2451. The spark electrodes were located 90 mm above the fuel nozzle. In Test Case 2, non-premixed methane flames with co-flow air were investigated. The fuel was injected through a central nozzle of 18.28 mm diameter. Co-flow air surrounded the fuel in a coaxial condition. A fine meshed honeycomb was placed inside the nozzle to straighten the air. The detailed structure of the burner can be found in [22]. The co-flow air nozzle diameter was 37.8 mm. The fuel flow rate was 0.182 l/min which corresponding to a fuel Reynolds number of 55.4. Three co-flow air flow rates 0 l/min, 14 l/min (*Re* = 479) and 75 l/min (*Re* = 2565) were used. The electrodes were fixed at a distance of 14 mm above the nozzle.

2.2. Colour identification from visible to infrared spectrum

Although filters are installed to block infrared emission, the high speed camera (Photron SA4) is still sensitive in the near infrared (NIR) region. To verify that the camera is able to capture the infrared emission from the flame, a Pentax stereo adaptor [23] (Fig. 2), is applied to the front of the lens, which generates two parallel images with slight displacement.

Different filters can be applied to the left and right views. The left view without any filter directly captured the flame images. A wideband filter (385–725 nm wavelength, transmittance > 96%) is applied to the right view which allows the visible light to pass through only. An example of flame synchronous images pair and their corresponding colour distribution histograms in hue space are shown in Fig. 3(a) and (b) respectively. The x-axes of the histograms indicate the hue domain. The y-axes are the ratio of intensity which corresponds to a specific hue range over total pixel intensity of the image. The pixel intensity represents the brightness of the pixel. The intensity threshold of pixel intensity is 0 to 2^{16} in all the captured images presented in this paper. It is found that the flame image without the filter has an additional region which surrounds the orange sooty flame, and its colour distribution locates from H2 to H18. The image with visible wideband filter dominates the hue domain from H2 to H13. It has been tested that the Photron SA4 camera cannot detect the ultra-violet signals with the applied camera settings. Therefore the colour distribution from H14 to H18 has to be infrared signals from the flame. It should be noted that the presented flame images are post-processed through a selective enhancement technique which is introduced in Section 2.3. The original images are analysed to plot histograms.

Shown in Fig. 3(a), the infrared emission band occurs behind the CH^* and C_2^* emission region but slightly ahead of the soot emission.