Journal of Visualization, Vol. 1, No. 1 (1998) 79-85

Aspects of Oscillating Flames

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Received 9 January 1998.
Revised 2 February 1998.

***Abstract*:** Photography and chemieluminescence from CH radicals have been used to identify the reaction zones and quantify the areas and shapes of kerosene-fuelled flames with swirl numbers of 0.7 and 0.8 and an overall equivalence ratio of 0.25. The air flow was oscillated at a frequency of 350 Hz and the results suggest that the oscillations caused a sequence of vortex rings at the burner exit and that these distorted the reaction zone and increased its area in the near burner region leading to an overall shorter flame. For the swirl number of 0.7, the flame was lifted and the oscillations led to an increase in the average lift off length whereas the higher swirl number caused an attached flame with and without oscillations. The stretch rate, evaluated from the variation of the flame area in time, was higher for the lifted flame suggesting that lift off was caused by local extinction.

***Keywords*:** Kerosene flames, oscillations, photography, chemieluminescence.

1. Introduction

The present investigation follows from previous considerations of the stability of liquid fuelled flames by Hardalupas, Taylor and Whitelaw (1990, 1994), Hardalupas, Liu and Whitelaw (1994) and Bhidayasiri, Sivasegaram and Whitelaw (1997) which revealed some of the details of the variations of velocity, temperature and droplet size, including the essential contribution of recirculating small droplets of fuel in disk and swirl stabilized flames. It describes visualisation of the effects of imposed oscillations on the shape of kerosene-fuelled flames and of their reaction regions, and quantifies the stretch rates to suggest that the flame lift off was due to local extinction.

Interest in the addition of fluctuating energy systems from the investigation of Keller and Hongo (1990) which suggested reductions in NO_x in pulsed combustors and described a possible mechanism, from the preliminary experiments of Milosavljevic (1993) and Sivasegaram and Whitelaw (1994) which showed that flammability and stability limits could be altered substantially by discrete frequency oscillations, and by the results of Chao, Yuan and Jong (1994) which suggest that lifted flames can be reattached in the presence of oscillations.

The arrangement of the burner and the measurement methods are described in the following section and the results are described in the third section. The fourth section provides a summary of the more important conclusions.

2. Flow Configuration and Experimental Techniques

The burner of Fig. 1 provided swirl and a potential heat release of 22.6 kW. Kerosene fuel was delivered by a coaxial air-assist atomizer located on the axis with a flow-rate of 7.7×10^{-7} m^3/s and 1.8×10^{-4} m^3/s of atomizing air, so that droplet velocities ranged from 3 to 20 m/s and their diameters from 10 to 70 μm. Two flow conditions were considered and corresponded to swirl numbers of the air flow of 0.7 and 0.8 which resulted in lifted and attached flames respectively. The overall equivalence ratio was constant at 0.25 for both flames and its local value at the exit of the atomizer was 38. Oscillations were imposed on the air flow by the two acoustic drivers of Fig. 1, with a power of 38 W and at a frequency of 350 Hz, which corresponded to a Helmholtz resonance at the exit of the burner and visual observation of the flame suggested similar results for frequencies up to 460 Hz. The experimental arrangement is shown in Fig. 2.

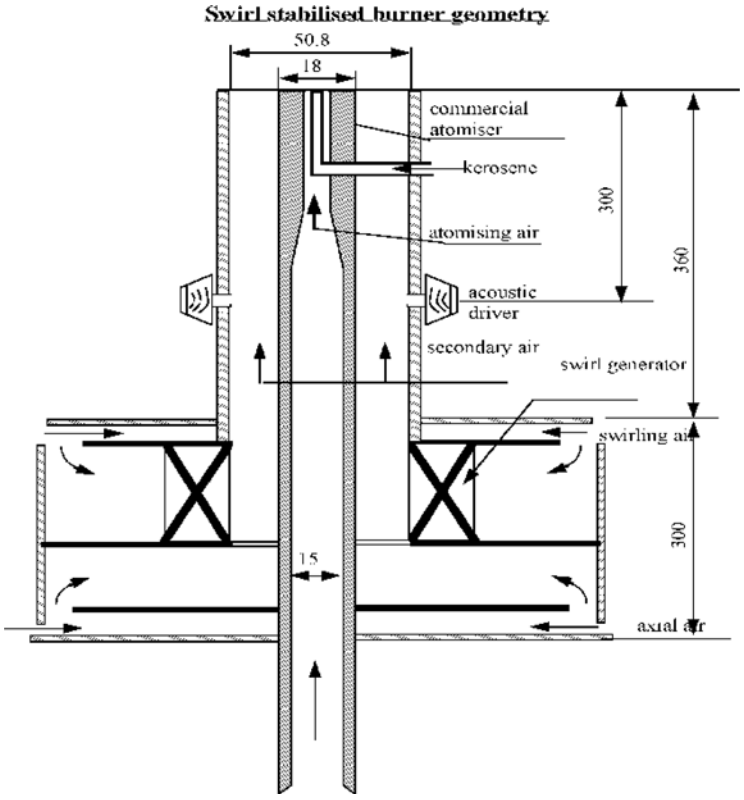


Fig. 1. The swirl stabilized burner geometry.

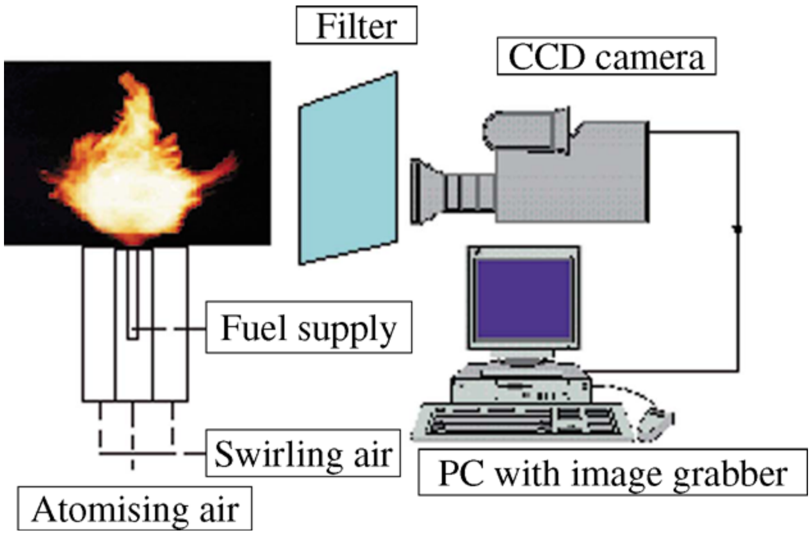


Fig. 2. Experimental arrangement.

The luminous zone of the flame was recorded in photographs of the total emitted light with a still camera (Nikon F-801), with an exposure of 8 ms, which provided pictures corresponding to 2.8 oscillation cycles at 350 Hz. A helium-neon laser was used in combination with a cylindrical lens (focal length of 0.6 mm) to mark the exit of the burner with a light sheet and thus, enabled the measurement of the distance between the burner exit and the flame front of lifted flames with an accuracy of ±3 mm.

Visualisation of the reaction zone was achieved in terms of chemieluminescence of CH radicals at a wavelength of 430 nm and with a lifetime of less than 0.1 micro-seconds. The detection of the chemieluminescence was achieved by installing an optical filter with a centre frequency of 429 nm, a bandwidth of 8.2 nm and a peak transmission of 45% in front of an eight-bit black and white intensified CCD camera (Proxitronic Fast-Motion-camera HF 1). The images had a resolution of 580 × 770 pixels and the intensity of each pixel was resolved on a scale from 0 to 255, the highest detectable value of CH radical concentration, with spatial resolution of 0.31 mm per pixel after considering the magnification of the lens. The CCD camera was connected to a PC with a frame grabber card (Data-Translation DT-3152) and used an exposure time of 0.5 ms. The images of the concentration distributions of the CH radical in the oscillating flames were obtained by gating the camera at specific times during the 2.9 ms period of the oscillation cycle, 45 degrees after the velocity maximum and minimum which were themselves 45 degrees out of phase with the imposed oscillation.

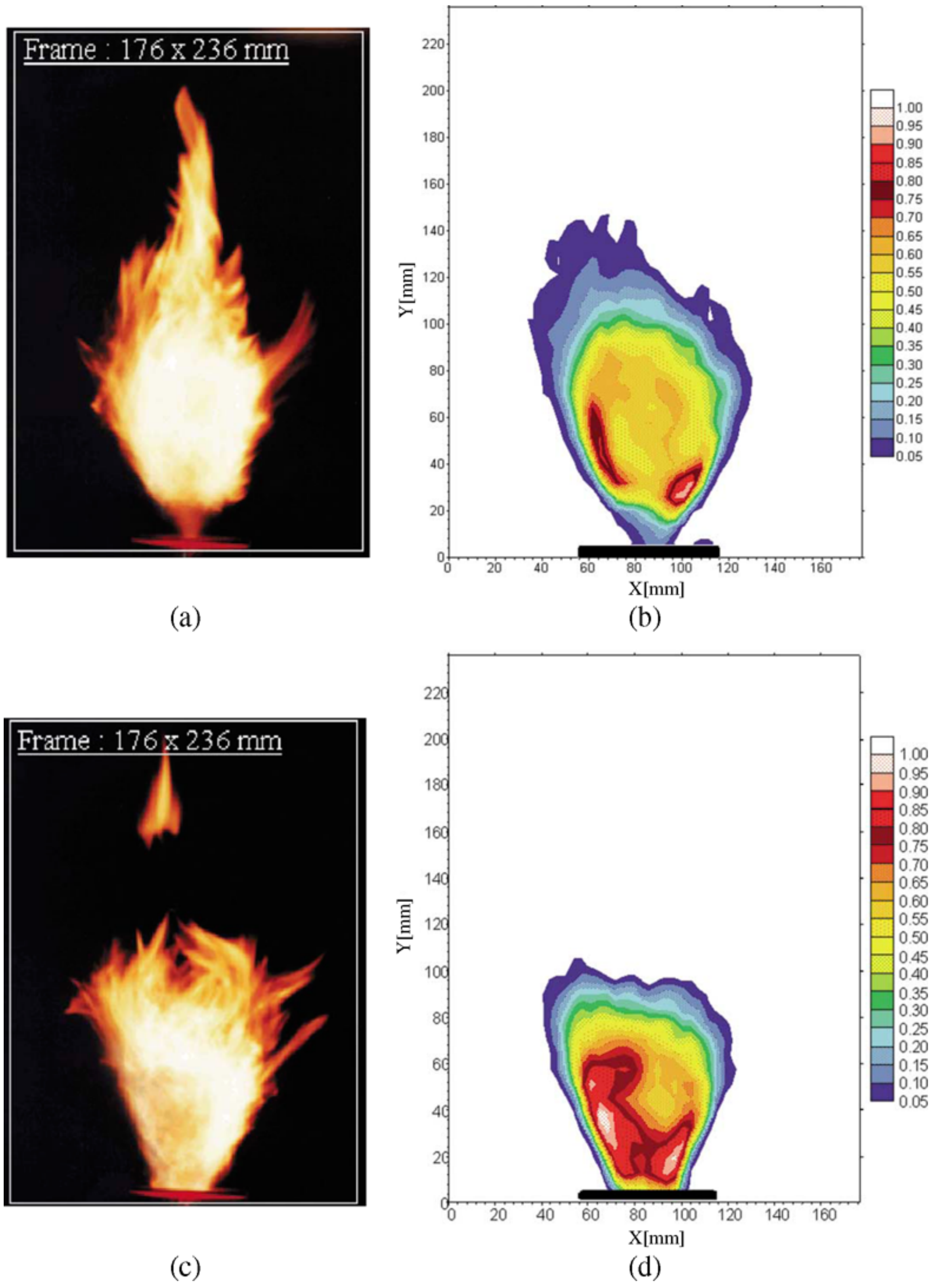
Mean grey levels were obtained from the recorded images by extracting the value of the grey level of every tenth pixel in the vertical and horizontal directions from 200 pictures and averaging at each position. The spatial distance between ten pixels was 3.1 mm and disturbances smaller than this distance on the contour plots of the intensity distributions were due to the interpolation of the data. The calculated values are presented as coloured contour plots normalised by the maximum intensity, graded linearly from black to white on a colour scale divided into twenty equally sized coloured steps with each representing an increase of the normalised pixel value by 0.05; the scale of the figures begins with 0.05, corresponding to a low value of CH radical concentration and represented by black and ends with 1, corresponding to a high value of CH-radical concentration and represented by white. The contribution of light from soot was evaluated and subtracted.

3. Results

Figure 3 shows photographs and chemieluminescence representations of the flames without imposed oscillations and with swirl numbers of 0.7 and 0.8 and Figure 4 provides similar information for the oscillated flames. The photographs of the two figures show that the flame with the swirl number of 0.7 was lifted by 10 mm and that imposed oscillations increased the lift of the average position of flame front to around 20 mm downstream, with a luminous region which was 50% shorter. The swirl number of 0.8 led to a flame which remained attached in both cases and imposing oscillations decreased the length of the luminous region by 10% and its diameter by 15%. Thus, the flames were reduced in length by oscillations, as in the investigation of Milosavljevic (1993), but the lifted flame with the lower swirl number remained lifted.

Images of intensity of emitted light from the flame are presented in Fig. 5 for the flow corresponding to the swirl number of 0.8 without imposed oscillations and the first three figures show the intensity distributions detected by the CCD camera at wavelengths 420, 442 and 430 nm respectively. Figure 5d shows the image of the intensity distribution corresponding to CH chemieluminescence at 430 nm and, therefore, to CH concentration, and represents the reaction zone in terms of the intensity distribution determined by subtracting the contribution from soot particles to the emitted intensity, as calculated after linear interpolation between the intensity distributions of Figs. 5a and b. It is evident from Fig. 5d that soot was responsible mainly for the intensity emitted by the flame at larger distances from the burner exit. In the near burner region, the subtraction of the soot contribution did not modify the shape of the flame. The images of CH concentration distributions in Figs. 3 and 4 have been corrected in this way and normalised with the maximum intensity.

The contour plots of Figs. 3 and 4 correspond to the near burner region, which is smaller than the corresponding region of the still photographs. In the absence of imposed oscillations, the time averaged images of the flames were smooth, since the random nature of the disturbances of the flame due to the air flow turbulence was removed by the averaging process and the small scale disturbances were due to noise associated with the spatial resolution of the images. The flow field in the near burner region was dominated by a recirculation zone and droplets up to 40 μm reversed their direction at distances up to around 40 mm and evaporated to provide fuel vapour at the base of the flame so that, without oscillations, reaction occurred in the shear layer of the secondary air stream where the fuel vapour mixed with the air stream, as in diffusion flames.

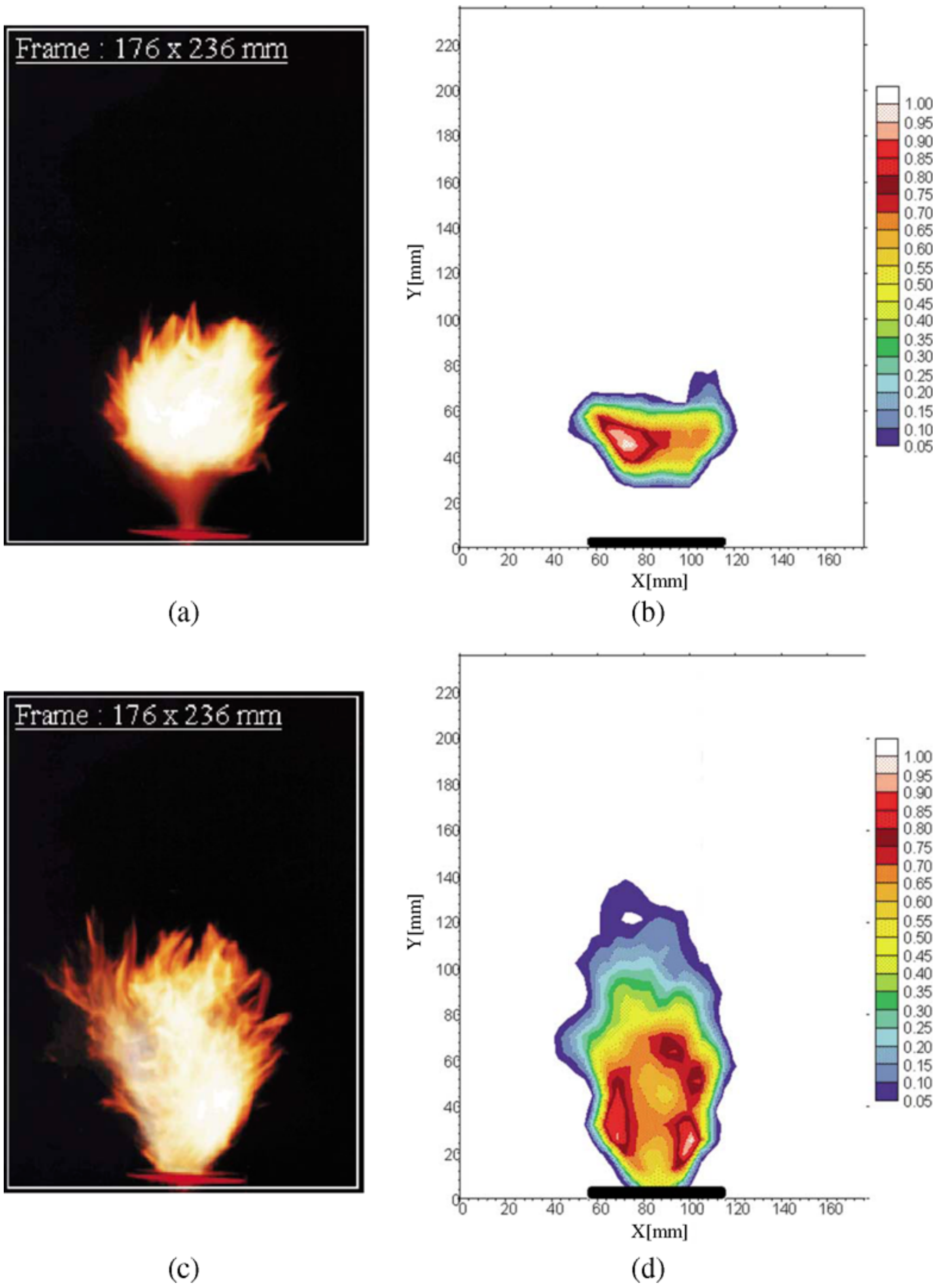


(a) (b)

(c) (d)

Fig. 3. Still photographs of the flame for swirl numbers of 0.7 (a) and 0.8 (c) without imposed oscillations and an exposure time of 8 ms; distributions of the CH radical concentration of the flame for swirl numbers of 0.7 (b) and 0.8 (d) without imposed oscillations and an exposure time of 0.5 ms averaged over 200 images, normalized by the maximum values.

The contours of the flames with imposed oscillations have larger scale wrinkles which were not evident on the still photographs and the attached flame with the higher swirl number had a reaction zone with two axi-symmetric wrinkles which were convected downstream from the burner exit. The shape of the wrinkles suggests that these were caused by a sequence of vortex rings shed at the burner exit with the same frequency as the oscillation and with initial length scale of the order of the annular width of the air supply to the burner and in keeping with the observations of Maxworthy (1972), Pullin (1979) and Weigand and Gharib (1997) in isothermal flows.



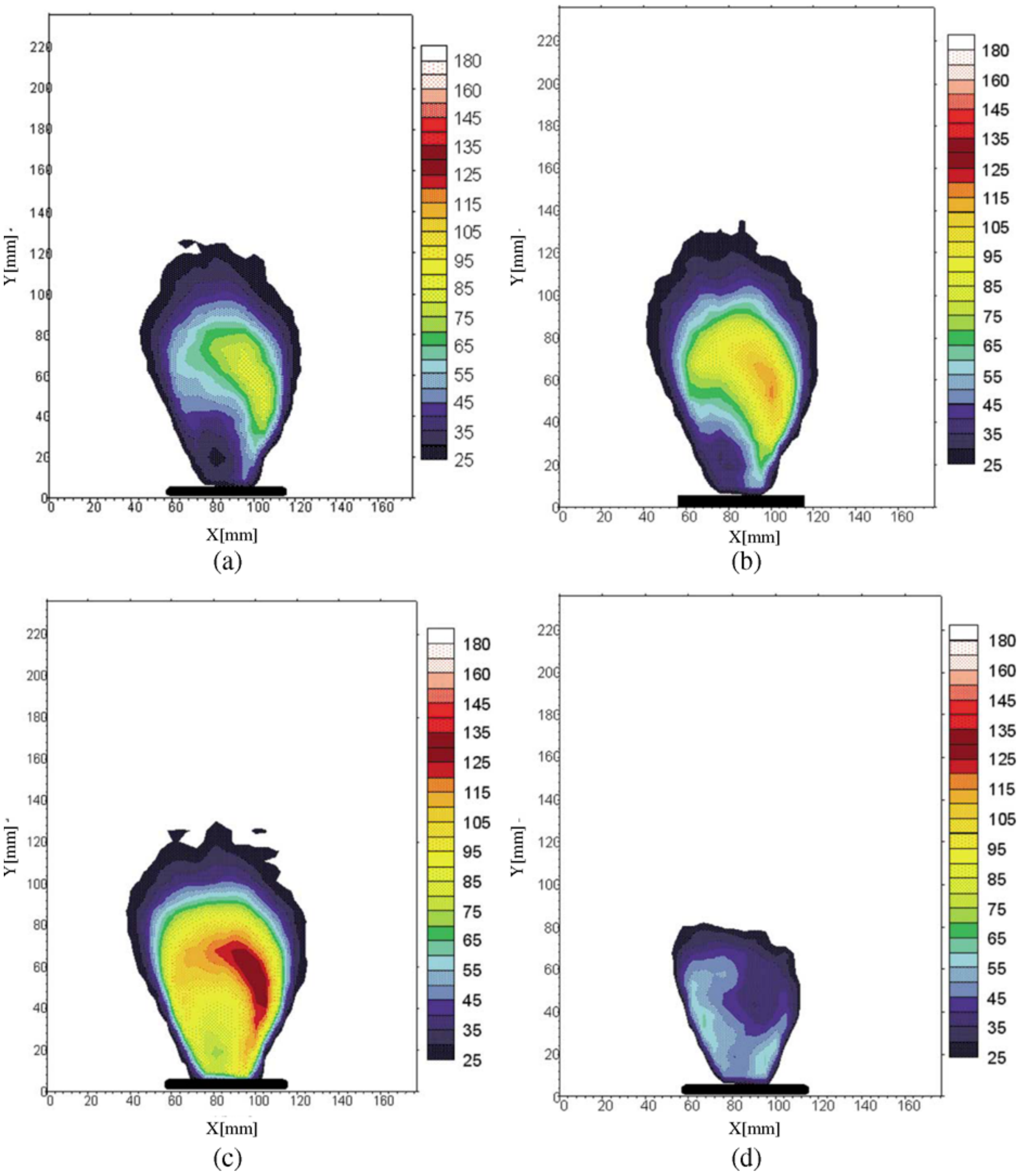
(a) (b)

(c) (d)

Fig. 4. Still photographs of the flame for swirl numbers of 0.7 (a) and 0.8 (c) with imposed oscillations and an exposure time of 8 ms; distributions of the CH radical concentration of the flame for swirl numbers of 0.7 (b) and 0.8 (d) with imposed oscillations at the maximum of the cycle, and an exposure time of 0.5 ms averaged over 200 images, normalized by the maximum values.

The reaction zone without oscillations was at the shear layer, Fig. 3b, and imposed oscillations lifted the flame further and led to a reaction zone close to the axis of symmetry of the burner, Fig. 4b. This suggests a change in the mixing pattern with the fuel vapour close to the burner axis over a longer distance and this was verified by visualisation in isothermal flow, which showed that the recirculation zone moved downstream with oscillations so that the reaction zone was established at the base of the lifted recirculation zone.

Contours from the chemieluminescence were observed as a function of time during the cycle and, with the oscillation period of 2.9 ms, suggested a convection velocity of 15.5 m/s which was lower than the area averaged



(a) (b) (c) (d)

Fig. 5. Intensity distributions of emitted light from the flame for the swirl number of 0.8 without imposed oscillations, measured with the CCD camera at wavelengths of (a) 420 nm, (b) 442 nm and (c) 430 nm. (d) Intensity distribution of the chemieluminescence from the CH radicals after correction for the contribution of emitted light from soot particles.

velocity at the exit of the burner, 17 m/s. This is expected since the vortex ring entrained surrounding gas as it was convected and provided an estimate of the mass flow rate entrained of approximately 10% of its initial flow rate. This process suggests that the induced vortex rings provided an additional mixing mechanism in the near burner region and can be responsible for reduction of NO_x emissions, but further work is required to establish the conditions leading to increased entrainment. Also, the increased strain rate due to the vortex could imply local flame extinction with lift off and this can lead to reduction of thermal NO_x by quenching, Drake and Blint (1989) and Vranos and Hall (1993), so that the wrinkling of the flame due to the vortices could have a similar effect, provided the strain rate was not excessive.

The area of the reaction zone in the near burner region was estimated at the two observation times during the cycle of the imposed oscillation. The term $[A^{-1}dA/dt]$ is proportional to the propagation velocity normal to the reaction zone over the radius of curvature and the velocity gradient of the flow normal to the reaction zone, Bradley et al. (1992), so that the stretch rates with the lower and higher swirl numbers were found to be 200 and 750 s^{-1} respectively. Therefore, the stretch rate was three times higher for the lifted flame.

4. Conclusions

The influence of imposed oscillations on the secondary air supply to the flame shape and area of a kerosene fuelled swirl-stabilised burner has been examined for swirl numbers of 0.7 and 0.8, an overall equivalence ratio of 0.25 and a frequency of imposed oscillations of 350 Hz. A summary of the main findings follows.

(i) A method for visualisation of the reaction zone in liquid fuelled flames, based on the detection of the chemieluminescence from CH radicals present in the reaction zone emitted at wavelength of 430 nm, has been introduced. The intensity of the emitted light was corrected for the contribution of the emitted light by soot and was shown to be less important in the near-burner region.

(ii) The details of the reaction zone were compared with photographs of the flames obtained with a still camera and collecting the total spectrum of the light emitted from flames. The photographs provided values of flame and lift off lengths and an indication of flame width but failed to identify the local structure of the flame.

(iii) For the swirl number of 0.7, the flame was lifted by 10 mm and the lift off length increased by 10 mm with oscillations. For the swirl number of 0.8, the flame was attached with and without oscillations. The flame area was increased in the near burner region by imposed oscillations, consistent with shorter flames.

(iv) The acoustic excitation shed a sequence of vortex rings at the burner exit with the frequency of the imposed oscillation, and this led to wrinkling of the reaction zone and an increase of the flame area. The change of the flame area during the cycle allowed estimates of the stretch rate of the reaction zone, which was larger for the flow with the lower swirl number and suggested that the increased stretch rate could be responsible for local flame extinction and lift off.

(v) The change of the shape of the reaction zone suggested potential mechanisms for reduction of NO_x emissions, namely the increase of the strain rate due to the vortex rings which may have quenched the associated reactions, and the additional mixing which they caused.

Acknowledgments

The authors gratefully acknowledge support from the EPSRC, Grant G/K 97097 and US Navy Contract N68171-97-C-9009. Y. Hardalupas was supported by an EPSRC Advanced Fellowship.

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