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STRUCTURES IN DIFFUSION FLAMES - AN ACOUSTIC VIEWPOINT

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ABSTRACT

Schlieren photography was used to investigate two types of coherent structures found in diffusion flames. The structures were concentric and their respective passing frequencies were identified for propane gas flames by spectral analysis of optical and pressure signals. The frequency of the inner structures was related to acoustic characteristics of the experimental equipment and the convection velocity was found to be independent of the gas Reynolds number. The influence of external acoustic excitation applied to the fuel stream was examined.

INTRODUCTION

The study of fluid dynamic phenomena in gas diffusion flames has attracted increasing attention over recent years. In 1979, Chigier and Yule (1979) used a high-speed cine film to record the characteristics of a propane/air diffusion flame. They measured the passing frequency of vortices in the flame and predicted their coalescence into larger structures. In an extension of this work, Yule *et al.* (1980) used schlieren and LDA measurements which revealed two types of coherent structures located concentrically along the axis of the flame. The 'inner eddies' were convected downstream at a higher velocity and no observable correlation or interaction was found between the inner and outer structures for the first 10 D of the flame, where D represents the nozzle diameter. Beyond that position the outer eddies encroached increasingly into the centre of the jet. While the outer structures could be explained as a shear layer instability, variations in Reynolds number based on the fuel jet appeared to have little effect on the frequency of the inner vortices, suggesting to the authors that they could not be explained as being due to Kelvin-Helmholtz instabilities as generally found in cold jets.

Schlieren images published by Eickhoff (1982) and Eickhoff and Winandy (1985) showed two types of toroidal vortex structures in a propane flame. Experiments by Strawa (1986) also identified two flow regimes in a methane diffusion flame: an outer flow similar to that observed by Eickhoff and an inner luminous core flow. High-speed movies showed that the core gas flow was strongly influenced by buoyancy and was independent of the outer shear-driven flow. In contrast with the work of Eickhoff, no inner instability was observed by Strawa, presumably because of the lower jet exit velocity (0.2-0.5 m/s). This allowed the reaction to heat the core which was accelerated by buoyancy before an inner shear layer could be established.

In a study of turbulent flow regimes near a bluff body combustor, Roquemore *et al.* (1984) used TiO_2 particles for Mie scattering to show large vortical structures. High speed movies revealed the three-dimensional and unsteady nature of the flow and suggested the role of these vortices in the mixing mechanism. There was no evidence that the structures had a preferred frequency. In a more recent study of jet flames, Chen and Roquemore (1986) compared results obtained using Mie scattering and schlieren flow visualisation. They observed the two types of structure found by others in propane flames and attributed the growth of the inner structures to a vortex pairing phenomenon. Furthermore, they estimated a frequency for these structures of 550 Hz, based on a convection velocity equal to the fuel exit velocity of 2.4 m/s and a measured wavelength.

In the present work, schlieren photography was used to further describe the flow structures found in propane diffusion flames. Analysis was concentrated on the mechanism driving the inner structures.

EXPERIMENTAL APPARATUS AND FACILITIES

Experiments were carried out on a combustion research facility which allowed optical and other measurements to be made on a diffusion flame, formed by a jet of gaseous fuel and a co-flowing jet of air. The facility comprised an optical table of dimensions 2.4 m by 1.2 m, on which was mounted a vertical combustion tunnel. The tunnel was square in cross-section and had transparent glass windows on all sides over a 500 mm length.

A 150 mm diameter loudspeaker was mounted at the bottom of the fuel settling chamber, below an impervious membrane, to perturb the flow. A two-mirror schlieren system was used to image the gas flames. A circular rainbow filter, at the focal point of the second schlieren mirror, was used to colour the deflected rays and the resulting images were captured photographically.

RESULTS AND DISCUSSION

Flow Visualisation

Figure 1 is a composite picture of a typical flame and the corresponding schlieren image which exposes the fluid mechanic structures present in the combustion region. The two images are shown on the same scale. The larger structures were formed outside the luminous part of the flame and outlined the boundary between products of combustion and the cold airstream. The inner, smaller structures were well inside the flame and marked the interface between the cold fuel and the reaction zone.

Figure 2 shows the schlieren image of propane flames for various exit gas velocities. No change was detected in the outer vortices and the structures remained symmetrical about the axis of the flame. However, beyond a Reynolds number of 4000 (based on fuel jet exit velocity and exit diameter), the inner structures became turbulent. These coherent structures were photographed by Eickhoff and Winandy (1985). Lower Reynolds number flames exhibited reduced instability and the inner structures eventually disappeared. The flow at a Reynolds number of 1300 was similar to the contra-rotating vortices observed by Eickhoff and Winandy (1985). Clearly, the inner instability takes a finite time to develop and therefore, identifiable structures were only found well downstream of the jet exit.

The influence of acoustic excitation on large-scale structures in non-reacting jet flows is well documented in the literature [Tanna and Ahuja (1985)]. When a sinusoidal perturbation is imposed on the flow at a frequency near the natural frequency of the jet, the large-scale structures are found to lock to the acoustic signal, even for low amplitudes of the latter, and their coherence increases [Zaman and Hussain (1984)]. To find the dominant frequency of the structures, spectra were obtained of signals from a probe microphone sensing on the edge of the structure envelope, 15 D from the nozzle exit, and from a photo-transistor focused at the corresponding position in the schlieren image. (The colour filter was replaced by a circular diaphragm for this work.) The signals from the procedures correlated well (coherence = 0.75) and exhibited dominant frequency components at 13 Hz and 256 Hz, corresponding to the outer and inner structures respectively.

Figure 3 shows the evolution of the structures and the changing shape when the flame was excited with varying amplitude at 256 Hz. The development length was shorter than for the corresponding non-excited case of Fig. 2, and decreased for increasing amplitude of the acoustic signal. At relatively high levels of excitation (500 mV), the inner structures separated into distinct eddies at the nozzle exit. In general, the inner structures were consumed more rapidly and faded out within the viewing gate when the flow was excited.

The influence of outer structures on the formation of inner structures was studied by increasing the axial air velocity until the outer structures disappeared. No observable difference in the inner structure was noted. Figure 4 shows this in detail for air velocities up to 1.40 ms^{-1}; it also details how increasing the coaxial air velocity inhibits the formation of outer structures.

A new fuel delivery tube with constant internal bore was fitted to provide a fully developed fuel velocity profile. Thus the level of shear between the raw fuel and the combustion zone was decreased. Inner structures were still observed but with a far longer development length before they became apparent. Figure 5 shows the longer development length noted.

Spectral Analysis

Yule *et al.* (1980) showed laser schlieren spectra that suggested the inner structures were formed independent of Reynolds number (for values between 0.5 x 10^4 and 1.2 x 10^4). In the present work, a pressure probe sensing on the envelope of the outer structures, 15 D from the jet exit, produced a signal with a dominant spectral peak at approximately 13 Hz for flows corresponding to Reynolds numbers between 1500 and 5200. With the probe near the axis of the flame, the spectrum exhibited an additional peak at 256 Hz, corresponding to the frequency of the inner structures. A typical spectrum is shown in Fig. 6 for a Reynolds number approaching 3000. Figure 7 shows the spectra of a photo-transistor signal when the cell was located at a schlieren image point on the axis of a propane flame, approximately 4 D and again at 15 D from the jet exit. The spectrum confirms the results of Fig. 6 and avoids objections which relate to the intrusive nature of the pressure probe and the confounding effects of the turbulent and acoustic pressure fluctuations. These frequencies were found to be independent of the gas Reynolds number.

Other workers [Crow and Champagne (1971), Yule *et al.* (1980), and Eickhoff and Winandy (1985)] suggested that the inner structures may be the result of an acoustic resonance of the nozzle. The response of the experimental equipment used for the present study to band limited white noise applied at the loudspeaker terminals was measured with a flush-mounted microphone and the jet not ignited. Spectral analysis of the microphone signal revealed a tone at 257 Hz which coincides with the preferred frequency of the inner structures and confirms the nexus between the acoustic field and the structures. Therefore, it appears that broad band noise generated by the combustion process couples to the acoustic field of the gas line when the admittance is low, and produces pressure fluctuations at the nozzle at the corresponding frequencies. In effect, this is equivalent to an externally applied acoustic signal, except that the driving mechanism for the instability is provided by the combustion process. Further investigation into the nature of the coupling is in progress.

Chen and Roquemore (1986) estimated the frequency of inner structures in propane flames by assuming that the convection velocity was equal to the mean gas velocity at the jet exit. In fact, this assumption was not far removed from the findings of Yule *et al.* (1980) who measured the convection velocity at 0.85 times the gas exit velocity. In the present work, the convection velocity was calculated from the measured 'preferred' frequency and the wavelength of the structures, early in their development. It was found that the ratio of the convection velocity to the exit velocity could exceed unity, approaching a value of 2 when the Reynolds number was equal to 1900 and decreasing to a value of 0.7 when the Reynolds number was increased to 5200. Since the preferred frequency was relatively unchanged for flames with Reynolds numbers in excess of 1500, it follows that the wavelength is proportional to the convection velocity. The velocity was typically 2.0 ms^{-1} and 2.4 ms^{-1} at axial positions respectively 8 and 15 D from the nozzle exit. The lack of correlation between Reynolds number and convection velocity, and the acceleration of the inner structures along the flame, suggest the influence of buoyancy effects on this shear layer.

CONCLUSION

Schlieren techniques were used for the visualisation of large-scale structures in propane flames. The influence of acoustic excitation was examined for one of these structures.

The instability of the inner shear layer was shown to take a finite time to develop in the absence of acoustic excitation and identifiable structures were only found well downstream of the exit from the gas jet. However, acoustic excitation of the gas flow promoted their earlier development. Schlieren spectra indicated a preferred frequency which was associated with acoustic characteristics of the gas line. The velocity of these structures was more or less insensitive to changes in Reynolds numbers (at a given height above the nozzle) over the range considered and increased slightly along the axis of the flame, suggesting the influence of buoyancy.

There is strong evidence to suggest that the inner structures are promoted by a shear layer instability as has been postulated previously for outer structures.

Figure 1 Typical propane diffusion flame and schlieren image.

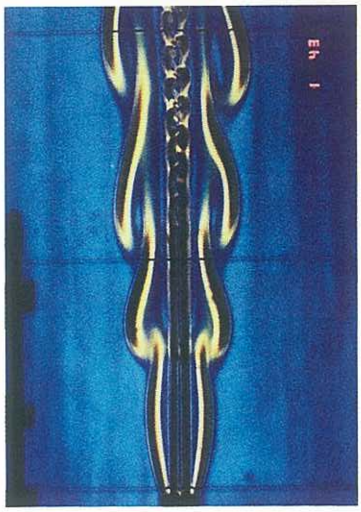

Figure 5 Propane diffusion flame with fully developed fuel velocity profile ; Re = 1300; excitation frequency = 248 Hz; excitation voltage = 100 mV.

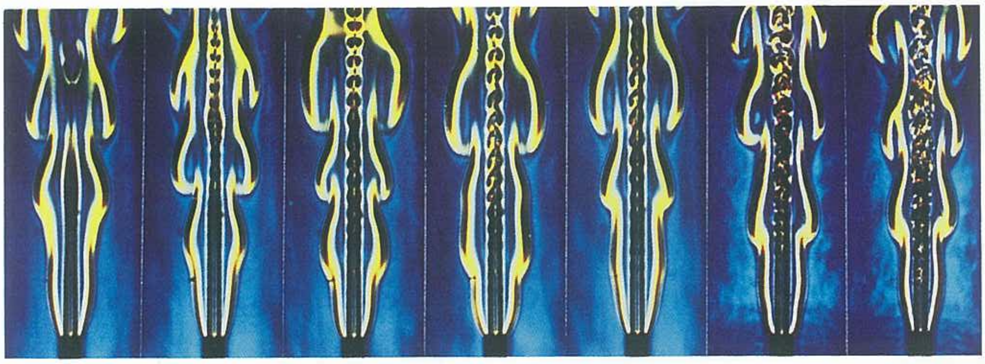

Figure 2 Influence of Reynolds number on the structure of a propane diffusion flame. Re = 1300, 1900, 2300, 2600, 3000, 4500 and 5200 respectively.

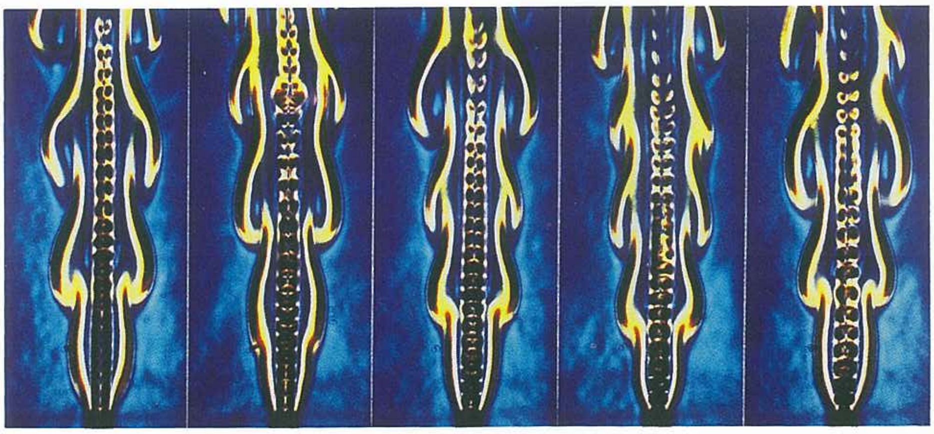

Figure 3 Influence of acoustic excitation on the structure of a propane diffusion flame excited acoustically. Re = 2300; excitation frequency = 256 Hz; voltage applied at the loudspeaker terminals = 30, 100, 500, 1000 and 1500 mV respectively

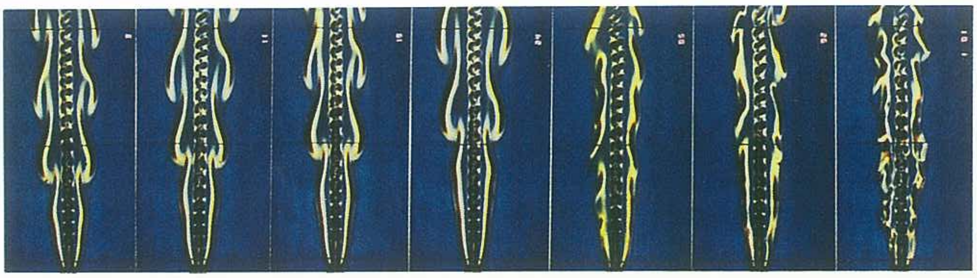

Figure 4 Influence of coaxial air flow velocity on the structure of a propane diffusion flame excited acoustically. Re = 1300; excitation frequency = 248Hz; excitation voltage = 100 mV; coaxial air flow velocities = 0.17, 0.30, 0.43, 0.50, 0.70, 0.95, 1.40 ms^{-1} respectively.

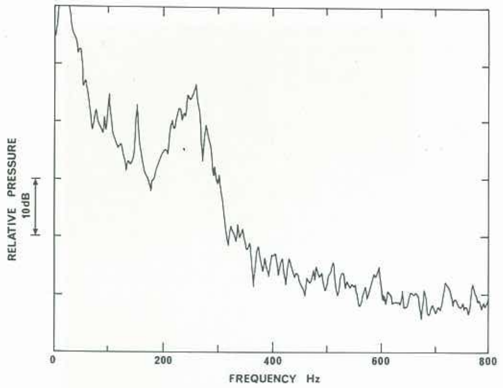

Figure 6 Pressure spectrum in a propane diffusion flame; outer structures at 13 Hz, inner structures at 256 Hz. Re = 3000; x = 15 D.

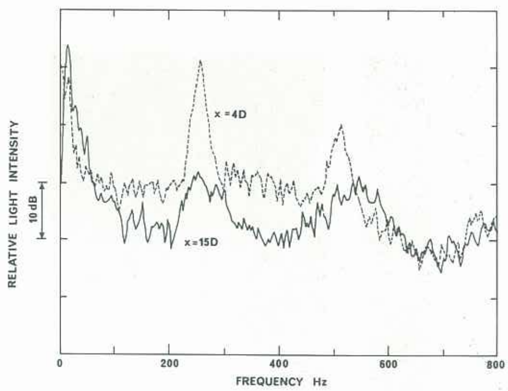

Figure 7 Schlieren spectrum of a propane diffusion flame; Re = 3000.

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