EXPERIMENTAL CHARACTERISATION OF AN OSCILLATING REACTING SHEAR LAYER

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ABSTRACT

An unsteady propane-air premixed flame stabilised in a bluff-body is investigated, in particular the reacting shear layer close to the burner base bounded by central recirculation zone, with hot products, and non-reacting vortex shedding. The flow field oscillates with frequency of 275Hz and the unsteady process is driven by an acoustic standing half-wave accommodated inside the upstream pipe. Optical and probe techniques, such as laser velocimetry, digitally-compensated thermocouples, chemiluminiscent sensor for $<C_2^*>$ emission and a microphone, were used for the analysis of the coupling mechanisms between pressure, velocity and heat release fluctuations typical of pulsed flames. Phase locked results show that the unsteady reacting shear layer features strong temporal and spatial deformations where the relation between turbulent and mean field can be modelled based on the gradient hypothesis, except in the presence of the vortex.

INTRODUCTION

Pulsed flames may occur in a variety of reacting systems and their evidence is well documented in laboratory arrangements typical of afterburners (Heitor et al., 1984) and gas turbines combustors chambers (Keller, 1995). The feedback process in these unsteady reacting flows are explained by the Rayleigh criterion who states that high coherence level must exist between heat release and pressure fluctuations. Pressure fluctuations are in general associated with a dominant wave structure of the cavity while the unsteady heat release, determinant in the acoustic resonance process, is controlled by pressure gradient fluctuations or turbulent mixture variations or flame area variation or vortex shedding (see review of Fernandes and Heitor, 1996). In the case of vortex shedding, data reported in literature shows that they affect seriously the turbulent mixing (Chao et al., 1994, Fernandes 1998), controls pollutant formation (Keller and Hongo, 1990, Chao et al., 1996, Delabroy et al., 1996), flame size (Willis et al., 1991, Fernandes 1998), enhances the stabilisation of flames (Chao et al., 1996), besides releasing heat periodically to sustain the oscillations. Due to the nature of the process and in the reacting case with large-scale vortices, analysis is restricted to resolve, in general, mean values of velocity, temperature and species (Lovett and Turns, 1993), heat release via short duration PLIF images (Gutmark et al., 1990) and via volume integrated C_2^* emission (Yip et al., 1992, Delabroy et al., 1996) with sparse information concerning the time resolved evolution of such properties, as quantified by Lovett and Turns (1993) and Tang et al., (1995). However, this information is important to provide physical understanding of the reacting shear layers behaviour under unsteady conditions as well as to provide useful guidance to modelling efforts.

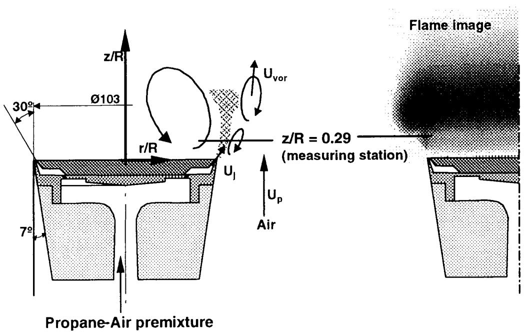

Figure 1. Schematic of the flame holder with identification of the principal dimensions, premixture and air injection angles, measuring station and a flame image.

EXPERIMENTAL APPARATUS AND TECHNIQUES

The measurements were performed on an unconfined premixed propane-air flame stabilised on a conical bluff-body burner. A schematic of the burner is presented in figure 1. The mixture is injected through radial slits of 0.5mm with an angle of 30º, a mean velocity of about U_j= 16m/s and an equivalence ratio of ϕ=6 and the primary air is injected with a velocity U_p=3.4m/s. The unsteady regime is characterised by a sound pressure level of 110dB and a predominant frequency of 275Hz associated with an internal acoustic standing half wave accommodated in the upstream pipe. The flow field is in fact dominated by vortex shedding at the same frequency, released on the outer shear layer supporting therefore the unsteady heat release as a closure factor for the feedback process and forcing the steady image of the flame to be as shown in figure 1. Measurements were taken at axial station z/R=0.29 and according to the scheme of figure 1, hot central recirculation zone and the non-reacting vortex shedding process bound the flame. The extent to which the periodic oscillations affect the time resolved temperature, velocity, heat flux and heat release characteristics is discussed here based on phase-averaged results obtained with simultaneous measurements of velocity, temperature heat release and pressure fluctuations, using LDV, thermocouples, light sensor and microphone.

Chemiluminiscence Measurements

To visualise the heat release signals we select, based on spectral analysis of critical points in the flame, the light emitted by C_2* radical, due to extremely short life time, and because of the strong emission in the present situation. The latter characteristic makes it suitable to trace the flame zone for a qualitative interpretation besides it dependence on radical concentration, temperature and turbulent flow characteristics affecting reaction sequence. The receiving optical unit was designed to collect a cylinder of light with a spatial resolution of 2mm. The light is then carried by a multimode fibre optic, Polytec model 4531, to a photodetector (EMI-9538 S10) interfaced with an interference filter (Dantec, 60X225) centered at 514.5nm with a 4nm bandwidth. The output signal from the photocathode is then differentially amplified and injected into an A/D board. Due to the integrated nature of the light results along a line-of-sight, the Abel's transformation procedure was implemented to obtain the radial profile of radical emission coefficients, based on the assumptions that the flame is axysimmetric and non absorbing. The error associated with this mathematical inversion is dependent on the radial derivative, being lower than 5% if a smooth evolution is available (Fernandes, 1998).

Simultaneous Measurements of Velocity and Temperature

Detailed spatially- and temporally resolved gas velocity measurements were made using laser Doppler velocimetry (herein referred as LDV). The optical arrangement used comprised a dual beam system. The coherent light (λ=514.4nm) from an Argon-Ion laser (Spectra-Physics model Stabilite 2017) was driven to a modular transmitting optics (Dantec-55X), through an optical fibre (Dantec 60X25). Forward-scattered light was then collected and focused into a photomultiplier (Dantec 9055X0341). The flames studied were seeded with dried alumina Al_2O_3, with particles in the range of 0.5μm to 2μm before agglomeration. The Doppler signal is electronically downmixed (Dantec Frequency Shift 55N10), band-pass filtered (TSI filter-1982) and processed in the Dantec LDA-Counter 55L90a. Temperature measurements were obtained making use of digitally compensated fine-wires thermocouples, with 38μm in diameter, made of Pt/Pt-13%Rh and combined with the LDV measurements (e.g. Ferrão and Heitor 1998b). The position of the thermocouple was kept as close as possible to the LDV control volume within a distance smaller than 0.5mm monitorised using microscope lens. Detailed discussion and typical uncertainties encountered in the implementation and use of these systems in unsteady reacting flows can be found in Fernandes (1998).

Data Acquisition and Processing

Continuous signals of radical emission <C_2*> were acquired simultaneously with pressure fluctuations with a fixed sampling rate of 20kHz/channel. The Doppler frequency, pressure and temperature signals were also acquired simultaneously however controlled by the arrival of particle seeding at the LDV control volume. In both cases pressure fluctuations were used as a reference signal in order to process the data in the phase averaged mode and the acquisition system was based on a Fulcrum-DT3808 board. Time resolved measurements of velocity, temperature, pressure and radical emission data obtained under periodic oscillations were statistically analysed following the decomposition for a generic variable $\gamma(t)$:

$$\gamma(t) = \gamma_{med} + \gamma_{coh}(t) + \gamma''(t) \qquad [1]$$

where $\gamma(t)$ is the instantaneous value, $\bar{\gamma}$ is the long time average mean, $\tilde{\gamma}(t)$ is the statistical contribution of the organised wave, and $\gamma''(t)$ is the instantaneous value of turbulent fluctuations. An ensemble average over a large number of cycles yields:

$$<\gamma>(t) = \gamma_{med} + \gamma_{coh}(t) \qquad [2]$$

$$<\gamma_{rms}>(t) = \sqrt{\gamma''^2}(t \pm \Delta t) = \sqrt{\frac{\sum_{l=1}^{N} (\gamma(t_l \pm \Delta t) - "\gamma *_{med}")^2}{N-1}},$$

$$t - \Delta t < t_l < t + \Delta t \qquad [3]$$

$$\gamma_{rms} = \sqrt{\gamma''^2} = \frac{1}{T_{osc}} \int_0^{T_{osc}} <\gamma_{rms}>(t)dt \qquad [4]$$

In equation [3] "$\gamma *_{med}$" represents a best fit one degree adjusted polynomial to the interval ($t \pm \Delta t$) to minimise false turbulence generated by temporal gradient bias whenever conditions reveal higher flow acceleration. The phase interval, Δt was chosen to be 18°/360°, to minimise the influences of the phase averaging window size on the determination of turbulence quantities in unsteady turbulent flows (see Fernandes, 1998). At least 500-1000 data points were obtained per each time bin giving an estimated maximum error less than 5% and 2% for variance and mean values wih a 95% confidence level, assuming a turbulence intensity of 20%, according to Yanta and Smith (1978)

RESULTS AND DISCUSSION

The reaction zone studied here, at z/R=0.29, is bounded on the right hand side by travelling vortices with U_{vor}= 7.7m/s and on the left-hand side by an unsteady central hot recirculation zone (Fernandes, 1998). The behaviour of this reaction zone to the imposed unsteadiness was analysed through time-resolved and spectral analysis measurements of velocity, temperature, heat release and the correlation velocity-temperature. The oscillation occurs at a dominant frequency of 275Hz which is confirmed by spectral analysis of pressure fluctuations shown in figure 2a and by phase averaged signals of velocity shown in figure 2b.

Mean profiles of velocity, temperature and heat release characteristics are shown in figure 3. Heat release profile is shown in figure 3a and denotes a maximum value, around r/R=1.05, that occurs on the left-hand side of maximum axial velocity (see figure 3c). Besides that, flame (or heat release) develops where temperature gradient is maximum (see figure 3b), but the largest temperature fluctuation occurs outside the flame zone. While local velocity is clearly dominated by axial momentum with positive values for both velocity directions, axial normal shear stresses, u''^2, does not show the typical evolution based on the gradient law hypothesis, with two local maximums located at around the maximum axial velocity. The evolution of radial normal shear stresses, v''^2, show maximum values around r/R=1.2 aligned with the region where vortices are moving downstream, which is followed by the evolution of w''^2, as presented in figure 3d. In the region of interest, i.e. 0.95<r/R<1.1, where flame is located, turbulence is anisotropic in that $U_{rms}=1.5V_{rms}=3W_{rms}$. The distribution of shear stresses, $u''v''$, is shown in figure 3e, and the result follows the turbulent viscosity hypothesis, with a sign related to that of the shear strain dU/dr, as also found by for example Heitor et al., (1987), Ferrão and Heitor (1998b) in baffle stabilised flames.

The time-resolved evolution of local heat release (C_2* emission), temperature, velocity and correlation velocity-temperature is compared in figure 4. The phase-averaged velocity vectors in figure 4a shows a non-stationary profile with relatively large temporal variation of radial component due to the presence of the vortex. Since the vortex moves with an axial velocity of about 7.7m/s the main consequence of adopting <U-7.7m/s> is that the observer in now travelling with the vortex core and the results, presented in figure 4b, allow us to identify the instant when the vortex crosses the station z/R=0.29, corresponding to the t/T=0.75 associated with the temporal saddle point.

In the absence of any vortex influence (t/T<0.5), the flame (figure 4c) is stabilised along the inner shear layer where spatial gradients of temperature (figure 4d) are maxima. Turbulent heat flux, or the velocity-temperature correlation $u_i''t'$, presented in figure 4e, is located along the heat release zone pointing outwards and upstream, in direction of the burner base.

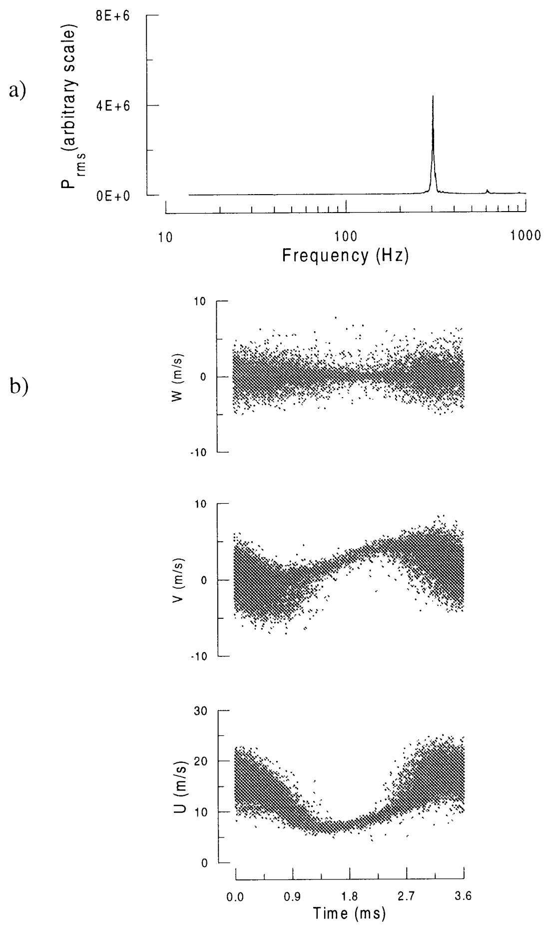

Figure 2. Unsteady shear layer characterisation
a) Spectral analysis of pressure fluctuations
b) Cycle-resolved evolution of the three velocity components at r/R=1, z/R=0.29

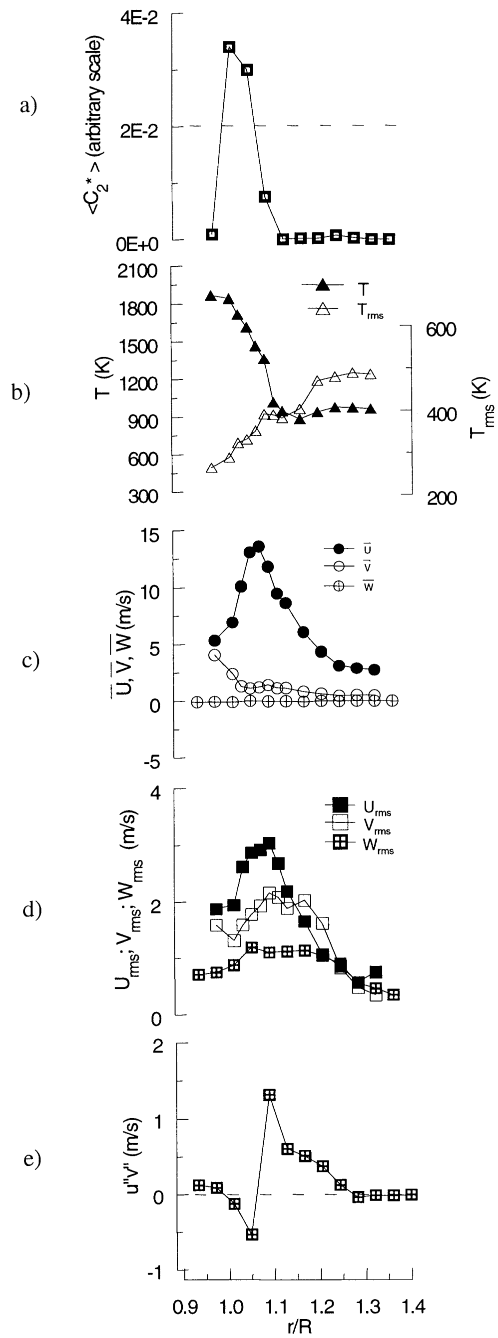

Figure 3. Radial profiles of time averaged properties as measured at z/R=0.29
a) <C_2*> emission
b) Mean and R.M.S of fluctuating temperature
c) Mean velocity components
d) Velocity normal stresses
e) Velocity shear stresses

This pattern and the time averaged vectors (see figure 4d) are similar to the time-averaged turbulent fluxes reported by Heitor et al. (1987) and Ferrão and Heitor (1998b) for disk stabilised flames with Re=10000 and Re=40000, respectively, and in general agrees with the observed local temperature gradient.

The influence of vortex occurs during t/T=0.5-0.8 and starts with the outwards shift of the hot zone and of <C_2>* zone as shown in figure 4c and large activity of V_{rms}, as shown in figure 4g. This process is accompanied with a decrease of axial velocity relatively to the radial velocity component.

The transport of heat by the turbulent velocity field is essentially radial, follows the gradient law, and it is suggested to be due to the influence of the strong pressure gradient associated with curved streamlines imposed by the vortex, as well as due to the unsteadiness of the recirculation zone. In fact t/T=0.5 corresponds to the time when the recirculation zone is more "axially compressed" (Fernandes, 1998). As time t/T=0.8 is approached, the $<C_2^*>$ signal decreases significantly which is associated with a reduction in $<u_i''t''>$. Based on the evolution of temperature and $<v''t''>$, it is argued that a high concentration of hot combustion products transported into direction of the flame is affecting the local kinetics, by diluting the local available mixture. As the vortex moves further downstream, the local mixture is restored and flame is re-ignited. Also, there is a tendency for turbulent flux to point upwards in a counter-gradient mode, as expected from the local streamline curvature imposed by the vortex.

This explanation is conceptually similar to that used by Takahashi et al. (1996) to explain the local extinction of diffusion flames based on the transport of fuel by vortices. The sudden increase of fuel relatively to air cause temporary extinction of the flame. Therefore, as long as the balance between reactants and oxidants exists outside the flammability limit, the flame is not re-ignited. Depending on local flow conditions in restoring the flammability limits, i.e. transport of reactants and oxidants, the flame might be re-ignited. It is believed that this behaviour exists along the flame as the vortex moves downstream, resulting in the complex distribution of turbulent fluxes, $<u''t''>$ and $<v''t''>$, found here. In the same context, Mastorakos et al. (1995) have shown that flame stabilisation mechanisms may benefit from the presence of hot combustion products. However, it needs an increase of temperature of 100K per every 0.02 of oxygen mole fraction lost by dilution, in order to maintain stability, which is a situation that may not occur in the present case.

In addition, it is evident from the results of figure 4f and 4h that the evolution of U_{rms} and u''v'', normal and shear stresses, follows the gradient law hypothesis when the vortex is not present. Nevertheless, the time-averaged profile of U_{rms} does not show this dependence, suggesting therefore the influence of time and spatial deformation of the shear layer. Based on the above results it is suggested that the turbulent production mechanisms of this unsteady reaction shear layer are capable of following changes of the mean flow condition, at a frequency of 275Hz, in the absence of a more strong perturbation such as the presence of a vortex.

CONCLUSIONS

In general the results quantify the time resolved process of turbulent mixing along a full pressure cycle in a pulsed reacting shear layer and suggests that: a) the flame behaves as a typical bluff-body stabilised flame, although the influence of a strong unsteady flowfield results in appreciable spatial and temporal deformations; b) the phase averaged flame fronts occupy successively regions where temperature exhibit high radial gradients and large temperature fluctuations; c) the cycle-resolved nature of the momentum flux may be represented, at least qualitatively, by gradient hypothesis, as long as the vortex is absent; d) the turbulent heat flux show zones of either gradient and non-gradient characteristics, which appears to be influenced by the temporal evolution of the streamline curvature and local mixture along a cycle of flame oscillation.

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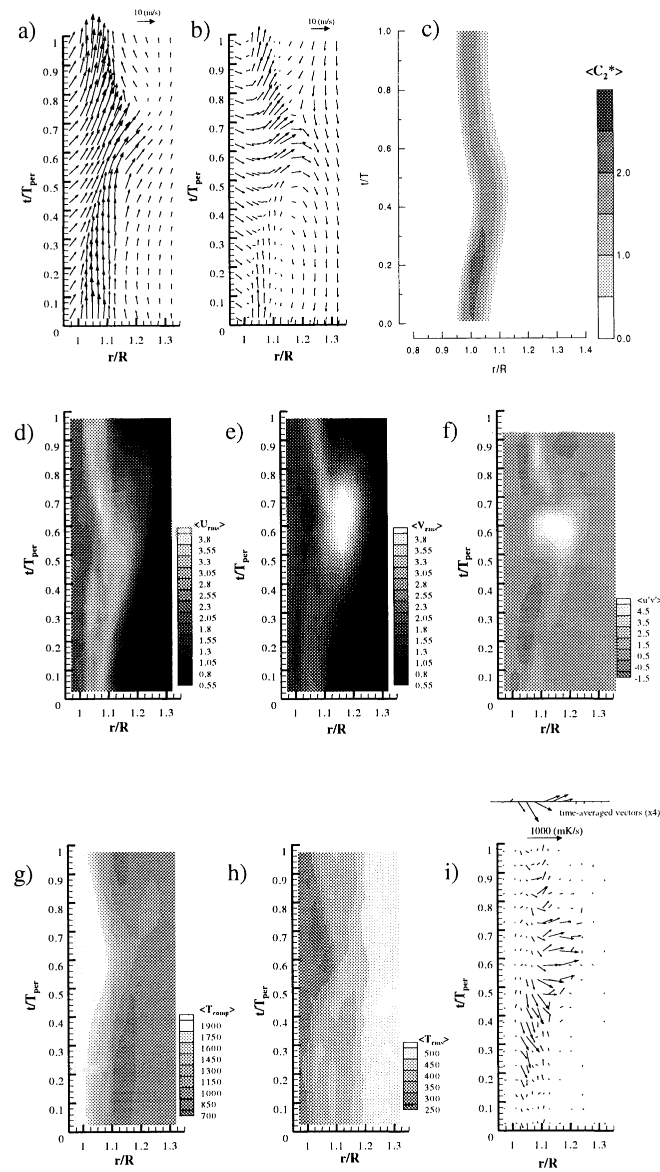

Figure 4. Cycle-resolved results of:

a) Resultant velocity vector <U,V>
b) Resultant vector after Galelian transformation <U-7.7,V>
c) <C_2*> emission
d) Normal stress U_{rms}
e) Normal stress V_{rms}
f) Shear stress u''v''
g) Temperature
h) Temperature fluctuations
i) Turbulent transport of heat <u''t', v''t'>