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Heat release imaging of acoustically forced turbulent flames.

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Abstract: Simultaneous OH and CH_2O PLIF imaging provides instantaneous two-dimensional heat-release rate measurements for investigating an acoustically forced bluff body stabilized flame. Results will provide insight into combustion instabilities in low emission gas turbine combustors.

OCIS codes: (120.1740) Combustion diagnostics; (300.2530) Fluorescence, Laser-Induced

1. Introduction

The lean premixed (LP) combustion concept has become the dominant industrial approach towards the reduction of NOx emissions. However, LP flames are highly susceptible to combustion instabilities as a result of the coupling of heat release to acoustic oscillations. Instabilities decrease combustion efficiency, increase noise and pollutant emission, and at worst, may lead to catastrophic failure of the operating device [1]. Hence, the investigation of acoustic interactions with LP flames is fundamental to combustion dynamics research with particular relevance for the development of next generation, ultra-low emission gas turbine combustors.

This paper describes a fundamental study of the effects of acoustic forcing of a highly turbulent fuel-air mixture on the heat released in a model bluff body stabilized burner. The product of simultaneous OH and CH_2O PLIF (Planer Laser-Induced Fluorescence) measurements generates an image that is well correlated with the instantaneous distribution of the heat release rate. With a reliable indicator of heat release rate, flame-acoustic interactions can be thoroughly investigated to provide vital information for the prediction and control of unsteady behaviours such as combustion noise, combustion instabilities and pulsed combustion, in practical systems.

2. Experimental Details

2.1. Diagnostic Technique

The experimental scheme to correlate a measurable quantity with local heat release rate was developed by Najm et al. [2]. It was reported that the concentration of the formyl radical, HCO, correlates well with the heat release rate of a premixed hydrocarbon flame. The major reason for this correlation is the direct dependence of the production of HCO on formaldehyde, CH_2O, which is produced in the breakdown of CH_3; a reaction which is a major contributor to local heat release rate. However, the direct measurement of the HCO radical is experimentally difficult due to the relatively short lifetimes of the HCO fluorescence and its fast reaction rates. An alternative is to obtain a signal proportional to the forward reaction rate of the reaction:

$$CH_2O + OH \longrightarrow HCO + H_2O$$

using the pixel-by-pixel product of simultaneous OH and CH_2O PLIF measurements. Single-shot 2D measurements of this reaction rate are feasible since signals from OH and CH_2O are considerably stronger than from HCO. Since this reaction rate correlates well with heat release rate, the product of the OH and CH_2O LIF signals can be related to the local heat release rate [3]. In the present study, this measurement scheme is applied to a bluff body stabilized combustor to elucidate flame-acoustic interactions.

LIF excitation scans of OH and CH_2O were performed to ensure that suitable transitions were excited. The LIF signals are proportional to the species concentrations but also depend on temperature through the Boltzmann fraction population and collisional quenching. Polyatomic molecules, such as CH_2O, exhibit a strong temperature dependence of the Boltzmann fraction population. The spatial overlap of OH and CH_2O is confined to a narrow region in the reaction zone, and within this region it is possible to establish the following relationship between the LIF signals and the reaction rate:

$$(CH_2O\ \text{LIF}) \times (OH\ \text{LIF})\ \alpha\ k(T)[CH_2O][OH] = \text{Reaction Rate} \qquad (1)$$

2.2. Experimental Apparatus

The experiments were carried out on a 10kW, laboratory scale, bluff body combustor operating on premixed C_2H_4 and air. In order to impose controlled acoustic oscillations on the flame, 2 acoustic drivers are mounted diametrically opposite each other on the circumference of the burner plenum. A schematic of the bluff body combustor is shown Fig. 1 below. The burner is designed to mimic the phenomena that occur in larger scale, industrial LP combustors under well defined conditions.

The laser system consists of a cluster of 4 Nd:YAG lasers (Continuum Surelite), 2 dye lasers (Sirah Cobra-Stretch) and 2 high-resolution double-pulsed ICCD cameras (Lavision Nanostar). The camera used for imaging OH fluorescence was fitted with a UV f/4.5 Nikkor camera lens and UG 11 and WG 305 filters. The CH_2O camera was fitted with an f/1.2 Nikkor camera lens with UG 375 and 550-nm shortpass filters. For OH LIF, the frequency-doubled output from one dye laser was tuned near 283 nm to pump the $Q_1(5)$ transition of the A-X(1,0) band, and OH fluorescence from the (0,0) and (1,1) bands was measured. The frequency-doubled output from the second dye laser was tuned to pump the $\tilde{A}^1A_2 - \tilde{X}^1A_1 4^1_0$ band of CH_2O near 353 nm.

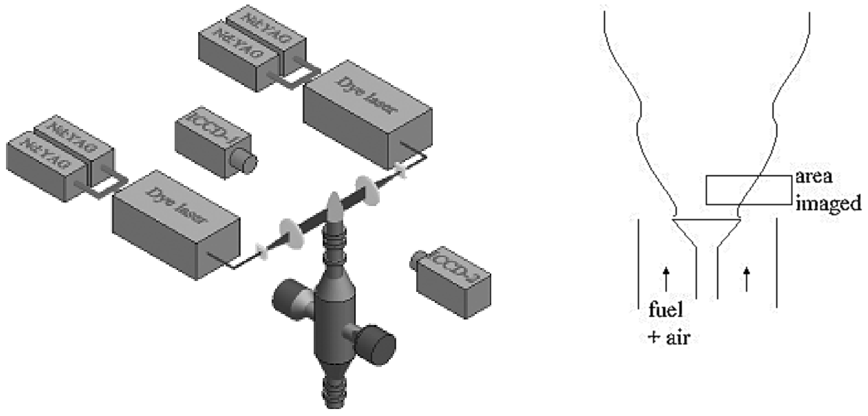


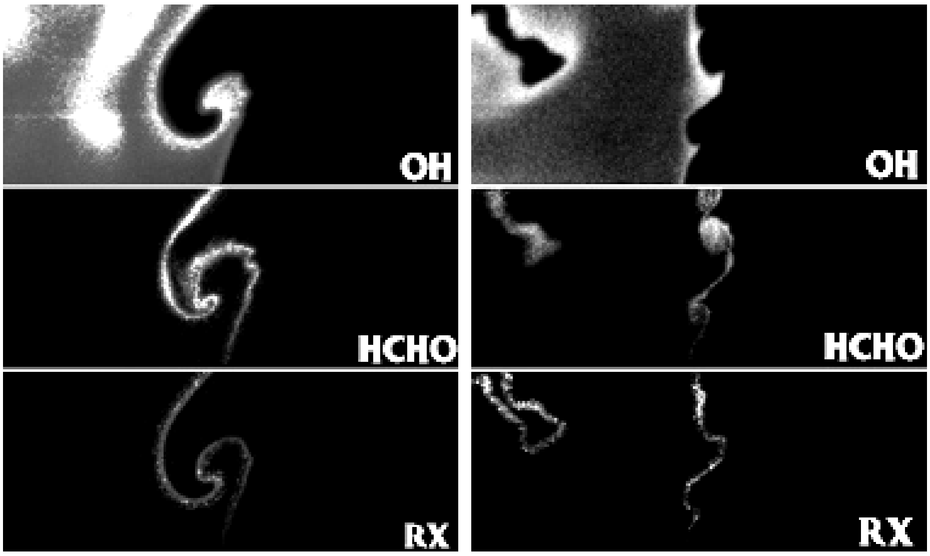
Fig. 1: Schematic of the laser imaging facility and the bluff body stabilized combustor.

3. Results and Discussion

Since the acoustic oscillations of the flame are induced with acoustic drivers, as opposed to self-excitation, this burner provides a well-controlled system in which to study the response of flames to acoustic oscillations. The flame response is investigated by phase-locking the lasers to the frequency of the acoustic drivers. Measurements can be taken at any phase angle throughout the acoustic cycle by varying the delay between the signal for the acoustic drivers and the laser trigger. A series of measurements was obtained for several forcing amplitudes and frequencies. These heat-release rate measurements are used to evaluate the transfer function between the flame response and the acoustic excitation.

The raw fluorescence images were processed as follows. Firstly, we subtract a background image, which is measured in the absence of the PLIF signal. Secondly, both fluorescence images are overlapped on a pixel-by-pixel basis. In order to do this, a target image was aligned in the measurement plane defined by the laser sheets and in the field of view of both cameras. From the coordinates of the target images, polynomial warping coefficients were extracted and used to geometrically transform one of the images to overlap with the other. The precision of the image matching was in the sub-pixel range. Finally, beam profiles of each beam were recorded in homogeneous vapours of premixed bi-acetyl and air to correct for laser sheet in-homogeneities.

Figure 2 shows sample results of two instantaneous OH/CH_2O PLIF measurements. In the figures, the burner exit plane is aligned with the bottom of each image, and the burner centre line is located at the left border of each image. The burner diameter is 35mm.



(a) *(b)*

Fig. 2 Instantaneous PLIF measurements of OH, CH_2O, *and the product* OH x CH_2O, *which correlates with local heat release rate; The burner was run at 160Hz with (a) low amplitude forcing (b) high amplitude forcing.*

The top and middle images are OH and CH_2O PLIF measurements, respectively. The bottom images correspond to local heat release rate. The measurements shown were taken at a forcing frequency of 160Hz, Re of 15000 with a bluff body blockage ratio of 50%. Image (a) shows the flame response at low amplitude forcing, and the vortex induced by the excitation signal can clearly be seen. Image (b) is taken under similar conditions but at higher forcing amplitudes. Flame wrinkling and the effects of high turbulence are evident. It can be seen from these images that the region of overlap between the two images, which marks the heat release zone, is relatively thin compared to the raw images. In the high turbulence case, entrainment of un-reacted mixture into the hot product zone is evident. From the corresponding heat release image, it can be seen that this un-burnt mixture is being consumed by reaction.

4. Conclusion

The investigation of the flame response to the interaction between acoustic oscillations and heat release provides valuable data for controlling instabilities in LP combustion systems. Experiments are carried out on an axis-symmetric burner that mimics the physics behind these instabilities by acoustically forcing a bluff-body stabilized premixed flame. The application of a diagnostic scheme using the product of OH and CH_2O PLIF images to obtain a measurement proportional to the local heat release rate is described, and some sample results are shown. The results indicate that this diagnostic scheme can be used to elucidate the interactions between acoustic oscillations and heat release rate in a turbulent flame. Detailed transfer functions are currently being evaluated for the system with a view to develop control concepts for industrial scale LP combustors.

5. References

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