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Brief Communication

On the Importance of Temporal Context in Interpretation of Flame Discontinuities

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Introduction

Local discontinuities or 'holes' in the flame sheet of turbulent jet diffusion flames have been the focus of considerable experimental and theoretical interest in recent years [1 – 5]. Using single and two-shot CH-PLIF, Watson et al. [2] observed local discontinuities in the flame front of a turbulent, lifted CH_4/air flame. Similar local discontinuities were observed by Hult et al. [1] in a round, unpiloted, turbulent jet flame operated close to blow-off. Such discontinuities are frequently associated with large-scale flow structures and have been interpreted as being representative of local flame extinction [1-3]. It is well established [6] that strain resulting from vortex-flame interactions is often sufficiently large to induce local extinction of the reaction zone. In the case of burner-attached turbulent jet-flames, such flame front discontinuities are invariably associated with local extinction. However, in the case of lifted flames a variety of mechanisms including downstream flame propagation, local extinction and out-of-plane motion may give rise to such discontinuities.

Larger magnitude flame discontinuities have been observed in planar imaging experiments in what have been described as 'flame islands'. Flame islands appear as pockets of hot, possibly reacting gases upstream and apparently distinct from a lifted flamebase. The existence of such islands was predicted in the computational studies of Mizobuchi et al. [7,8] and confirmed experimentally by Lyons et al. [9], who suggest they may be related to out-of-plane motion induced by filament-like secondary instabilities described in the computational study of Demare et al. [10]. The exact nature, dynamics and impact on flame behaviour of such islands is still unclear.

Previous planar imaging studies on lifted turbulent jet flames have been limited by a lack of experimental access to the z- (through-plane) component of velocity and the quasi-instantaneous nature of single and short-burst measurement techniques. This paper presents observations of the dynamics of local discontinuities and islands in a turbulent lifted jet flame and illustrates the difficulties inherent in interpreting planar imaging data related to them. These observations are based on simultaneous application of 3-component stereoscopic PIV and OH-PLIF at high framerates over long-duration (0.68 sec) experimental runs.

Experiment

The experimental configuration is shown in Fig. 1. The burner consists of a 4mm diameter fuel nozzle surrounded by a concentric (126mm diameter), low-velocity co-flow of particle-seeded air. The fuel was a 75% C_3H_8, 25% Argon mixture and had a mean velocity of 17m/s for a jet-exit Reynolds number (based on ambient temperature and pressure conditions) of 10,000. Lift-off height was approximately 22mm, or x/d = 5.5.

Stereoscopic PIV and OH-PLIF images were acquired simultaneously in the region of the lifted flamebase at a repetition rate of 1500 frames per second (fps). The PLIF system used a frequency-doubled dye laser (Sirah Cobra-Stretch) pumped with a Q-switched solid-state Nd:YLF laser (Edgewave IS-811E) with a short (8ns) pulse duration. Kittler et al. [11] note that short pulse-duration in the pump laser is critical to efficient frequency doubling and results in significantly increased output at 283nm. In the present work, the laser delivered 0.3W at 1.5 kHz or 0.2mJ/pulse at 283nm. Fluorescence signal was acquired with a 10-bit CMOS camera (LaVision HSS5) with a 1K × 1K pixel array. The camera was coupled to an external two-stage lens-coupled intensifier (LaVision HS-IRO) and fitted with a 100mm, f/2 UV-achromatic lens (Halle Nachfl. GmbH). Background luminosity was eliminated using a 150ns intensifier gate and elastic scattering at 283nm was blocked using a high-transmission bandpass interference filter. The imaged region extended from approximately 19 to 54mm beyond the jet-exit and was offset to the right of the jet-centerline.

The PIV system consisted of a dual-cavity, pulsed solid-state Nd:YAG laser (Edgewave, ISS-411DE) and a pair of CMOS cameras with 1K × 1K pixel arrays (LaVision HSS5). The laser sheets of both the PIV and PLIF lasers (and thus the plane of imaging) were aligned parallel to the vertical (x, y) axis of the jet and at the plane of symmetry, i.e. z = 0, in the through-plane direction. TiO_2 particles of nominal diameter 0.5μm were seeded into the co-flow air, which entrained into and distributed throughout the jet fluid prior to it reaching the flamebase. In order to increase seed particle density at the imaging location, a secondary nozzle was placed just outside the outer rim of the co-flow confinement tube and directed almost parallel to the flow in order to provide local seeding. Flow-conditioning within the secondary nozzle assured a stable, non-pulsating flow of seeded air with a velocity similar to that of the co-flow. Although local seeding inevitably affects the uniformity of the low momentum co-flow, no change in flame characteristics was observed with and without the secondary seeding. Vectors were calculated using a commercial, multi-pass cross-correlation algorithm (LaVision DaVis 7.2) with a final window size of 32 × 32 pixels and 50% overlap, resulting in a spatial resolution of 1 mm and vector spacing of 0.5 mm.

Results

Figure 2 shows an instantaneous planar measurement acquired with the system. The background colour contours represent the in-plane extensional strain rates and vector arrows correspond to in-plane components of velocity, as one would measure with a single-camera (i.e. two component) PIV system. The flame front edge is based on a threshhold of the OH-PLIF image and displayed as a heavy black line overlaid on the vector map.

In this figure we see a discontinuity in the flame front reminiscent of those observed by Lyons et al. [3], who conclude such discontinuities are indicative of local extinction. Similar to the discontinuities seen in Lyons et al. (ibid), this one appears in a region containing a high curvature flame 'bulge'. The flame front edges curve outwards, away from the higher-velocity fuel-rich side of the flame. One observes a significant strain rate ($1329 s^{-1}$) at the flame front breach, suggesting this discontinuity may have arisen from local extinction caused by strain from a passing vortex structure that has since decayed in strength. The regions of even higher strain rate observable within the OH-zone toward the lower part of the image could be interpreted as supporting such a conclusion as they suggest different timescales for strains induced by turbulent fluctuations and local extinction of the flame front. Taken in its correct temporal context, one quickly comes to a different conclusion regarding this sequence.

Figure 3 shows the measurement sequence from which Figure 2 was extracted. In this figure however, the vector arrows correspond to the in-plane components of velocity and the background represents the z- (out of plane) component. Rather than showing a local extinction event, the previous figure was part of a temporal sequence wherein an upstream flame island appears in the field of view, grows, distorts and finally coalesces with the contiguous flame front. The moderate Vz-velocity associated with the appearance of the upstream flame island suggests it is associated with out-of-plane flame propagation, or possibly bulk convection. This may be indicative of re-orientation of a contiguous flame sheet from an out-of-plane region, or the merging of two independent flame sheets. In either case, the discontinuity is associated with the propagation a large-scale flow structure but clearly does not represent a local extinction event.

A thorough fundamental understanding of local extinction and its effect on turbulent flames depends upon reliable identification of the phenomenon in planar imaging experiments. Figure 3 illustrates the difficulty of attempting such an interpretation without experimental access to the Vz-component of velocity and/or sufficient temporal resolution and context. The current paper makes no attempt to statistically quantify the likelihood of these flame island appearance/coalescence events compared to local-extinctions however sequences similar to those in Figure 3 were seen repeatedly throughout each 0.68sec experimental run. Thus it is reasonable to conclude that the mechanism responsible for the discontinuity seen in

Figure 3 is statistically non-negligible and therefore should be considered when analyzing planar images of lifted jet flames.

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Figures

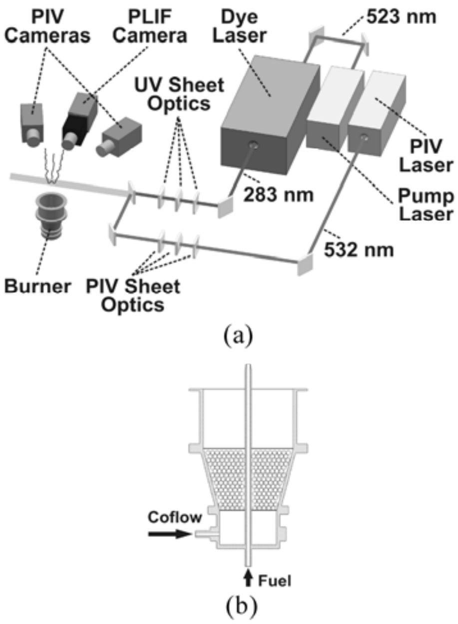

Figure 1. a) Experimental Configuration b) Burner

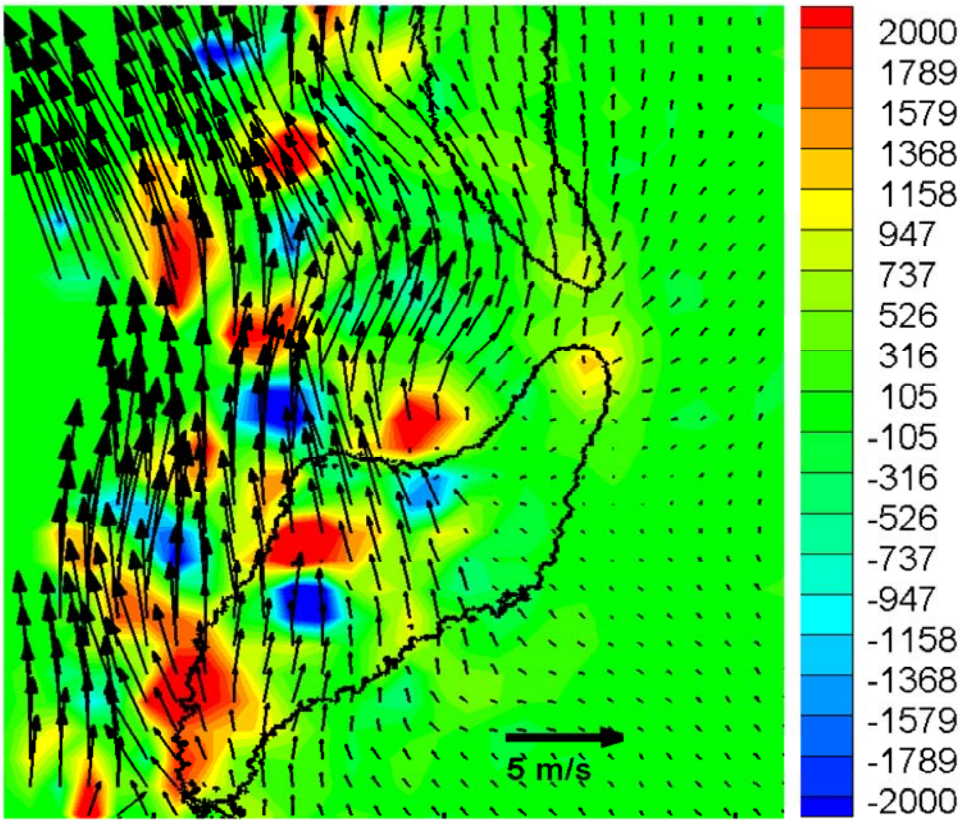

Figure 2. Discontinuity in flame front. Vector lengths correspond to in-plane components of velocity. Background colours correspond to strain rates in (1/s).

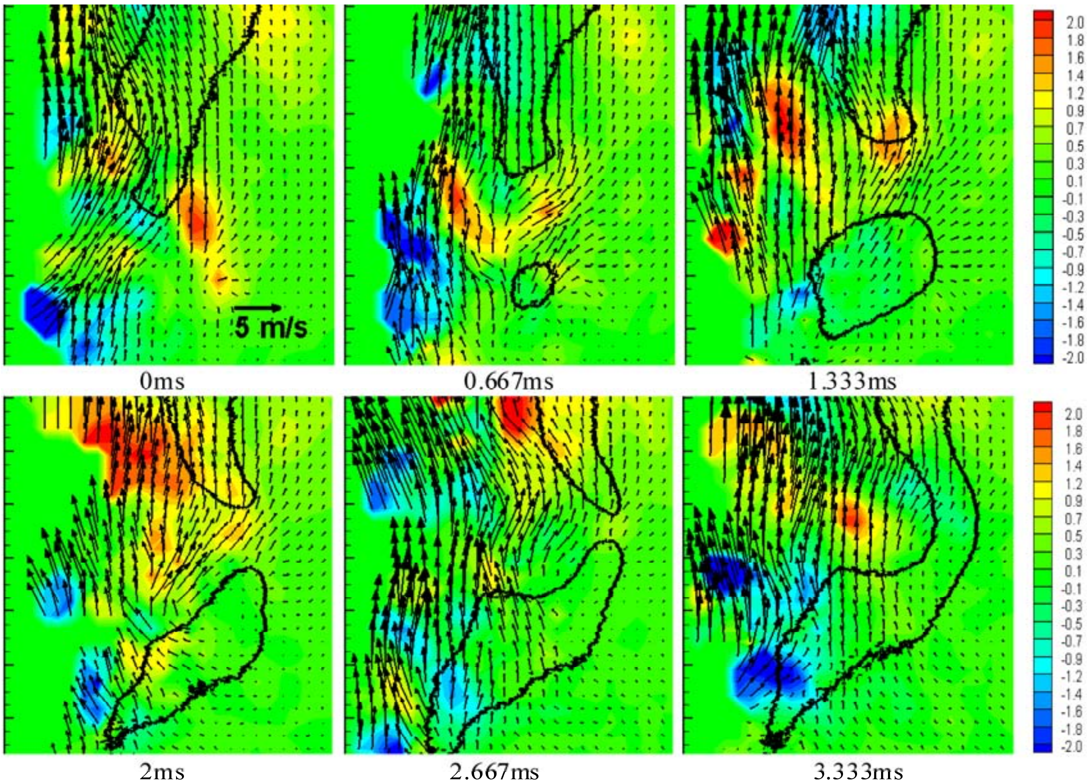

Figure 3. Appearance, distortion and coalescence of flame island with contiguous flame front. Vector lengths represent in-plane components of velocity. Background colour represents Vz velocity in m/s