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Upstream Islands of Flame in Lifted-Jet Partially Premixed Combustion

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Abstract: Contemporary interest exists in understanding the roles of leading edge flow deflection, secondary jet instabilities and islands of ignited gases in permitting lifted flames to stabilize. To assess these issues, elements of the leading-edge of a lifted turbulent jet flame have been investigated using laser-imaging techniques. Images of flame position, morphology and dynamics are presented primarily from CH planar laser-induced fluorescence (CH-PLIF) measurements. In particular, evidence of flame islands, or flame fragments, upstream of the bulk-flame leading edge are reported and discussed. This evidence is presented in the form of sequential CH-PLIF images and well as CH-PLIF/Rayleigh scattering images. Images showing thermal characteristics of the regions surrounding the edge flame are also described.

Keywords: Edge flames, Flame stabilization, Ignition, Jet flames

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INTRODUCTION

The stabilization of reaction zones in lifted jet diffusion flames has received considerable attention and Pitts (1988) presents an overview of the important theories that have been considered. Recently, intermediate approaches have commenced where the fully premixed and diffusion flame approaches are bridged by *partially premixed* and, more specifically, triple flame arguments; Peters (2000) offers a thorough review. Triple flames consist of fuel-rich and fuel-lean premixed branches in addition to an ordinary diffusion flame that extends downstream from the intersection of the two premixed zones. In this picture, the premixed regions allow for flame propagation against the incoming unburned flow while anchoring the trailing diffusion flame. Watson et al. (1999a, 2000) provide experimental evidence for "leading-edge flames" in lifted turbulent methane-air flames evidenced through CH planar laser-induced fluorescence (PLIF), which often consist of an outward (i.e., air-side) radial projection at the base of the trailing diffusion flame. It is conceivable that this is a distorted triple flame where the unobserved fuel-side branch has been overlapped into the trailing diffusion flame by the relatively high-speed fuel jet (into low speed air co-flow) as suggested by Veynante et al. (1994). While double- and triple-flames are well documented in layered galleys, mixing layers and laboratory-scale burners designed specifically to permit triple/double structures (Qin et al., 2002), their morphology and presence as the dominant mechanism of stabilization in lifted non-premixed flames from the turbulent round jet has yet to be fully established.

While important questions remain on the details of the leading-edge reaction zone structure, research is appearing that focuses on the importance of streamline divergence in leading edge flame propagation (Muñiz and Mungal, 1997). Numerical studies have predicted the shift in liftoff height due to incorporating heat release into combustion models (Boulanger et al., 2003). Upatnieks et al. (2004) revealed the presence of islands of low seeding density upstream of the bulk combustion that is hypothesized to be islands of combusting reactants. Of relevance in explaining these islands is the work of Demare and Baillot (2001), who argue for the importance of secondary instabilities and "arms" or ejected filaments of jet fluid in the stabilization of lifted flames and oscillation of flame height. In short, while the current theories of lifted-jet flame stabilization involve elements of double-, triple- and edge-flame propagation, scalar dissipation, streamline divergence, partial premixing and secondary instabilities, a complete understanding of the relative importance of each is not in hand.

The purpose of this article is to report on structures witnessed at the leading edge of lifted methane jet flames, based in part on the notions developed in the aforementioned studies. Reported are experimental results of the presence, structure and characteristics of islands of combustion upstream of the bulk leading edge. The relation of these structures to broken flame structures in locally extinguished zones (Lyons et al., 2005) has yet to be determined. These structures may indicate out-of-sheet phenomena (secondary instabilities) at the flame leading edge that some theories argue are critical to flame propagation/ignition/oscillation (Demare and Baillot, 2001).

FINDINGS FROM EXPERIMENTS

Experiments have been performed to examine the region upstream from the bulk leading edge flame form a lifted methane turbulent jet utilizing both dual-pulsed CH-PLIF (Planar Laser Induced Fluorescence) and Rayleigh Scattering. The experimental details can be found in Watson et al. (1999b) and Watson et al. (2002) and will not be repeated here. Figure 1 shows the regions that have been examined with a particular eye toward phenomena upstream of the bulk reaction zone. These regions are particularly important in assessing how the behavior of the

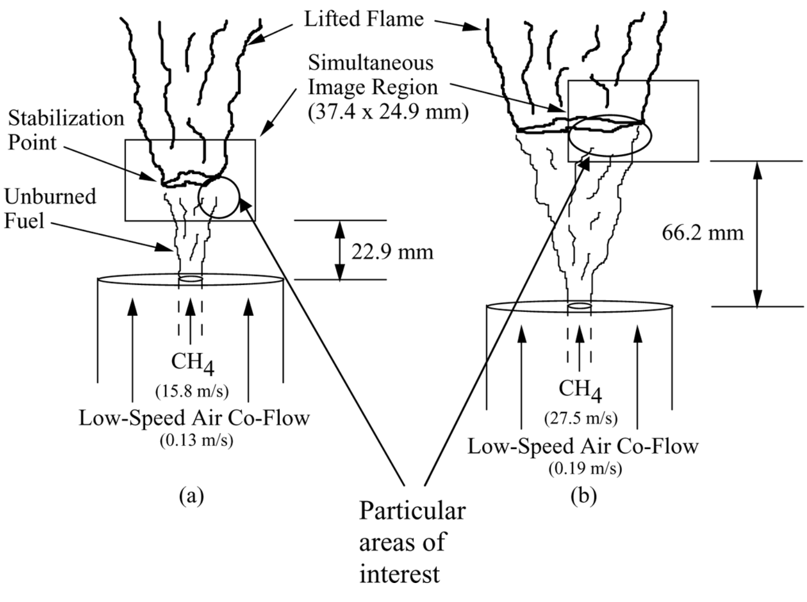

Figure 1. Test conditions and measurement locations for (a) the $Re_d = 4800$ flow (case 1) and (b) the $Re_d = 8300$ flow (case 3). The jet exit velocity for the $Re_d = 6400$ flow (case 2, not shown) is 21.2 m/s and the bottom of the image region is 39.2 mm from the jet exit and includes both sides of the lifted flame.

non-reacting fluid upstream from the bulk flame corresponds to that in a jet free of combustion. An event that is frequently witnessed from the two-shot CH-PLIF results is the presence of flame fragments that appear to move into the plane of the image region from the azimuthal direction. Figure 2 includes some CH-PLIF image pairs illustrating this

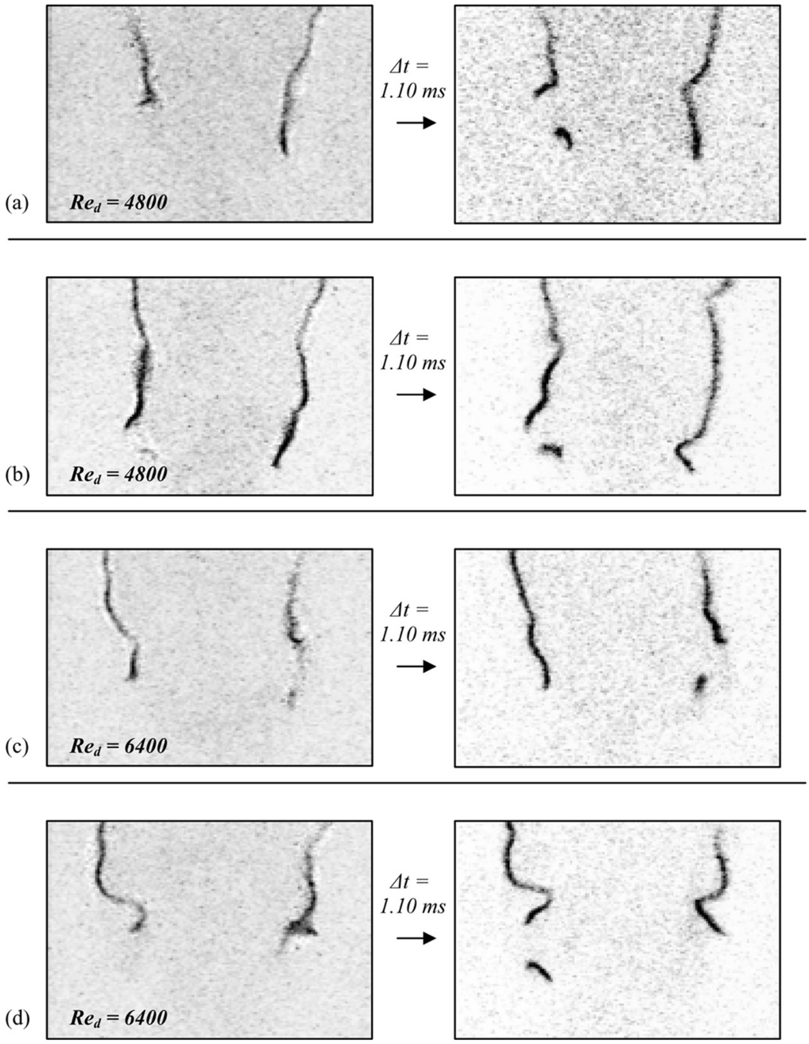

Figure 2. Sequential CH-PLIF images showing flame fragments, or islands, upstream of the flame base and towards the jet centerline. The sequential CH-PLIF shows the temporal development of these fragmented zones. Whether they are centers of ignition or merely appearing due to azimuthal activity has not been determined.

phenomenon. This data is obtained by sequentially acquiring CH-PLIF images near the leading edge of the reaction zone. In each image pair, fragments are observed below and slightly inward from the flame base in the second CH image after not being witnessed in the first. Upatnieks et al. (2002) have observed somewhat corresponding islands of low seeding density through a cinema PIV (CPIV) technique capable of recording 8000 images per second; specifically, isolated islands of low seed density are observed upstream of the flame base, and over time, the islands grow in the downstream direction before merging with the trailing diffusion flame structure that exists downstream. Shown in Figure 2 (a) and (b) are cases for $Re = 4800$ and in 2 (c) and (d) for $Re = 6400$, all with 1.10 ms separation between two essentially instantaneous images.

These events may be explained by flame movement in the out-of-sheet direction and this motion could conceivably play a role in stabilizing the flame in a global sense. As mentioned in previous studies by the authors (Watson et al., 1999a), the leading-edge CH-PLIF structures observed as air-side radial extensions have been observed in approximately 30% of the images from lifted flames similar to those examined in the current investigation. The authors argue that this structure may only have to exist along a portion of the entire flame base in order to stabilize the entire flame, reasoning that images that do not exhibit any leading-edge structure may simply be cases where the structure lies beyond the scope of the 2-D images. In view of this theory, it is conceivable that instances showing flame fragments in the second CH image after not being present in the first (Fig. 2) represent cases where more stable portions of the flame base (i.e., portions that exhibit leading-edge structure) have influenced the image region thereby contributing to the propagation of the entire lifted flame. In this fashion, circulation of burnt gases upstream of the bulk-flame leading edge may need to be considered. Su et al. (2006) also describe findings on flame stabilization with both helical and axisymmetric large scale structures that may be clarified by knowledge of phenomena upstream of the bulk flame (rather than simply assuming that the flame does not impact the upstream fluid).

While the sequential CH-PLIF images show the evolution of the main CH profile and fragments, there is no direct indication of where the regions of hot gases associated with the bulk combustion are located. Imaging of Rayleigh scattering can be used to visualize the high and low density regions (corresponding to low- and high-temperature regions). In order to visualize the thermal characteristics, images are shown from joint Rayleigh/CH-PLIF measurements and the details of these types of measurement techniques are discussed elsewhere (Watson et al., 2000). Figure 3 (medium flow $Re_d = 6400$) shows four instantaneous image pairs of the CH radical distribution on the left and a corresponding Rayleigh image on the right. The dark zones are indicative of high

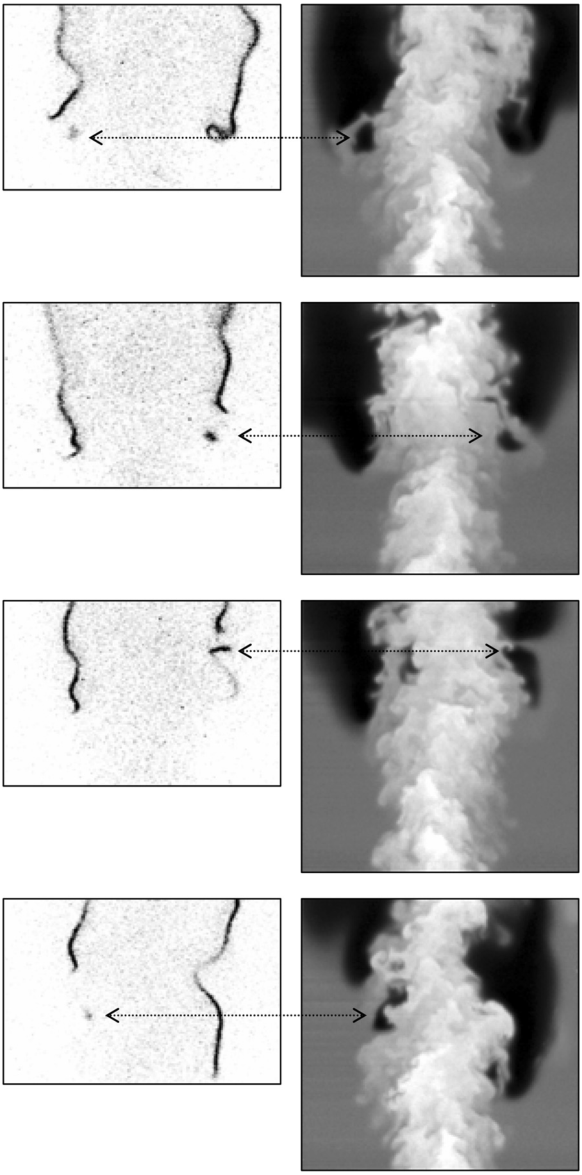

Figure 3. Joint Rayleigh/CH-PLIF images displaying the persistence of combustion for the $Re_d = 6400$ case. The CH radical image is on the left and the morphology of the high-temperature zones is on the right. Flame islands are witnessed that are larger than those seen in the $Re_d = 8300$ case.

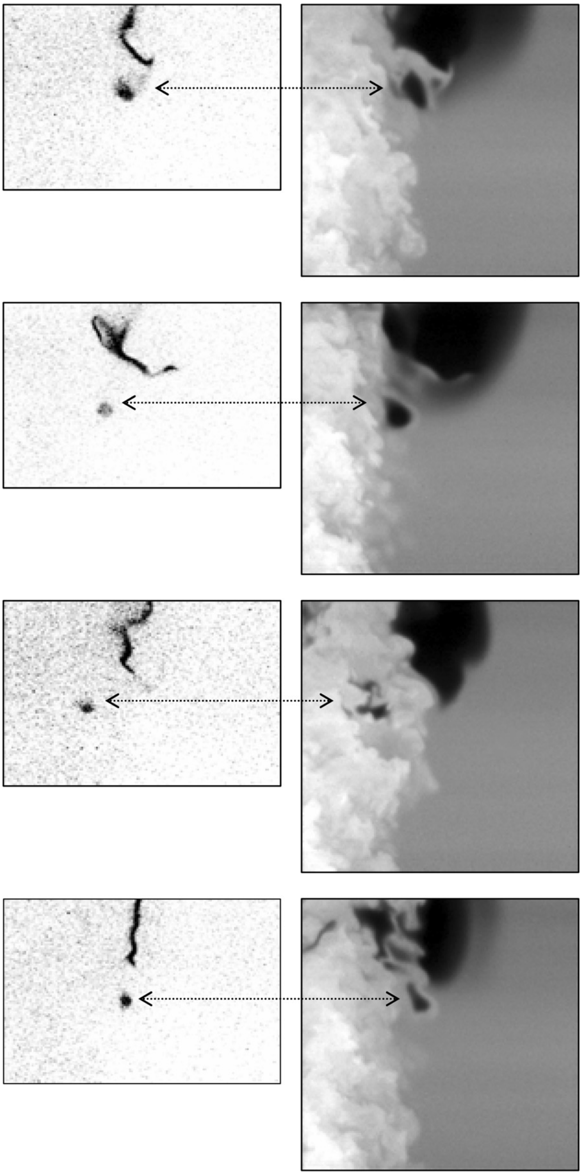

Figure 4. Joint Rayleigh/CH-PLIF images displaying the persistence of combustion for the $Re_d = 8300$ case. The CH radical image is on the left and the morphology of the high-temperature zones is on the right. Flame islands are witnessed that are smaller than those seen in the $Re_d = 6400$ case.

temperature zones in the flame and the jet mixing with the ambient air and subsequently combusting. These images were selected since they show the presence of flame fragments detached from the main flame upstream from the bulk reaction zone. Figure 4 also shows similar phenomena for the $Re_d = 8300$ case. They show the presence of small spots of CH upstream of the flame leading edge. It is difficult to assess if these spots indicate local regions of ignition, or if they are attached to the bulk combustion and related to secondary instabilities (like helical structures or jet filaments) that have been argued to play a role in flame stabilization (Demare and Baillot, 2001). Further experimentation to assess these out-of-plane phenomena is needed with multi-planar or stereo techniques. The effect of radicals produced from these flame islands on bulk flame properties has also yet to be determined.

CONCLUSIONS AND COMMENTS

Islands, or pockets, of combusting gases have been detected upstream of the bulk combustion zone that show instantaneous reactions, rather than merely hot products. These islands may be important for maintaining flame stabilization and may be introduced by out-of-plane activity. They are of important for theories that regard the behavior of fluid upstream of lifted flame reaction zones as being the same as that of a corresponding nonreacting jet.

Experimentation with reaction-rate imaging techniques (Frank et al., 2002) shows promise to shed light on the morphology and roles of reaction zones and islands at the leading edge that PLIF imaging of only single radicals fails to reveal.

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