**The Time Evolution of a Vortex-Flame Interaction
Observed via Planar Imaging of CH and OH**

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Abstract

PLIF imaging diagnostics of OH and CH are used to examine a premixed laminar flame subjected to a strong line-vortex pair. Results are reported for a fuel-rich laminar CH₄-air-N₂ rod-stabilized flame. The flow studied was highly reproducible, which enabled the use of phase-sampled imaging to provide time-resolved image sequences. Image sequences are shown for a condition sufficient to produce localized extinction of the primary flame. The results indicate that a breakage in the CH front is not preceded by any distinct change in the OH front. The structure of the CH and OH profiles during the transient leading up to, and through the breakage of the CH front do not appear to be consistent with the concept of a strained laminar flame.

Introduction

The interaction of an isolated vortex with a laminar flame is a 'building block' in any model of turbulence-chemistry interaction because it introduces the effects of strain, curvature, and unsteadiness. The relative importance of these effects is a key issue in turbulent combustion models which utilize the laminar flamelet concept. Hence, the vortex-flame interaction is of considerable interest to combustion theorists, modelers and experimentalists alike. The importance of the flamelet concept is evidenced by the numerous turbulent combustion models, examples of which, can be found in the review by Peters [1, and references therein].

Direct numerical simulation (DNS) studies of the vortex-flame interaction using simplified chemical kinetic mechanisms have been performed by Poinso *et al.* [2], and Ashurst [3] as a basis to test the validity of the different models. Hilka *et al.* [4] extended the DNS modeling works by including detailed chemistry. Experimental investigations of the interaction of toroidal vortices with fuel-lean laminar flames include the works of Roberts and Driscoll [5], Roberts *et al.* [6], and Rolon *et al.* [7]. 2-D line-vortex pairs interacting with a fuel-lean V-flame were examined by Samaniego [8]. A central theme in these works is the concept of ‘quenching’ of a laminar flame by the vortex (the ‘thin flame limit’). Flame ‘quenching’ is of interest because it delimits the regime in which a laminar flamelet approach is valid.

In this paper, we examine the ‘quenching’ or disruption of the standard hydrocarbon reaction pathways in stoichiometric and fuel-rich laminar CH_4 -air- N_2 V-flames by an intense 2-D counter-rotating vortex pair. Here, the term disruption is used to refer to a process in the flame, whereas the term quenching is reserved to refer to collisional non-radiative molecular energy transfer. We combine OH and CH planar laser-induced fluorescence (PLIF) imaging as the diagnostic tool. From an image interpretation viewpoint, an OH image represents the distribution of a chemically long-lived product of combustion. A CH image on the other hand, represents the distribution of a very short-lived combustion intermediate that can unambiguously be interpreted as the primary flame front itself.

Dibble *et al.* [9] suggest that a positive identification of the flame front location is best obtained through images of short-lived, transient species. The argument being that species with a very large ratio of concentration in the flame front to that in the product or

reactants (e.g. CH or C₂), provide a direct identification of a surface (i.e., such images can be easily skeletonized). In contrast the longer lived species (e.g. O, H or OH) have noticeable concentrations well into the reactants or products, hence processing of the images to extract a 'flame front' must be based on absolute signal levels or on gradients. PLIF images of radicals in flames tend to have signal-to-noise ratios of less than 10:1. Such noise-in-signal produces false structures when a surface is defined by an iso-signal contour or by taking gradients. Images of CH (or C₂) also provide direct information as to the status of the chemical pathways when the surface is seen to break as well as providing fundamental information about the chemistry involved in prompt-NO_x formation.

The methane-air reaction pathway [10] can be simplified to hydrogen abstraction giving CH₃ followed by either a C₍₁₎ chemistry path (which branches to singlet CH₂ or formaldehyde the later proceeding through formyl radical to CO) or a C₍₂₎ chemistry path (which branches to triplet and singlet CH₂). The singlet CH₂ is removed at gas kinetic rates by collisional quenching to the triplet or by reactions leading to CO. The resulting triplet CH₂ may be reduced (by H) to produce CH or may be oxidized (by O, O₂ or OH) to produce CO directly or via formaldehyde. The rate coefficients involved in the progression from singlet and triplet CH₂ through CH and to its reaction products are near gas dynamic. Thus a break in the CH surface is most likely the result of disrupting those reactions producing CH₂. This requires a disruption of the C₍₂₎ chemistry as well as all processes leading to singlet CH₂, the only remaining hydrocarbon pathway would be that through formaldehyde. Images of CH

provide both a well defined reaction surface and direct information as to the status of the fast reactions within the flame front.

Experimental

In the limit of weak excitation and of strong collisional quenching, the fluorescence signals (OH or CH) are directly proportional to the mole fraction of the absorbing species and a Boltzmann fraction (a non-linear function of temperature) as divided by the rate coefficient for collisional quenching. In order to interpret the fluorescence signals we consider a set of 1-D CH₄-air-N₂ flame calculations at each of our flame conditions [11]. These results (species and temperature variations) are used to simulate the spatial variation in the fluorescence signal across the flame front. In the case of OH, collisional electronic energy transfer in the *A*-state is well understood [12] and there is a relatively comprehensive data base at elevated temperatures. Our calculations indicate that the PLIF images of OH (when pumping $6.5 \leq J \leq 8.5$) essentially represent images of OH mole fraction to within 10% variation. OH radicals are mostly present in hot combustion products and to that extent, are an indicator of elevated temperatures. Thus an image of OH also shows the boundary of the hot products with the cold reactants of the vortex core.

A similar argument cannot be quantified for quenching of the CH *A*- or *B*-states, since there is not a model for the CH quenching process and only limited quenching data exists for elevated temperatures. The experimental data does show [13, 14] that there is a weak dependence on collision partner for all of the major-species found in the flames considered here. This suggests that quenching in CH will be relatively insensitive to the composition of the collisional bath in particular because CH is found in a relatively narrow range of flame

conditions. It is expected that the cross-sections at elevated temperatures will scale as $T^{-1/3}$ making the quenching rate coefficient a weak function of temperature. Thus PLIF images of CH (using excitation of $J \approx 4.5$ to the A - or B -state) in an atmospheric pressure hydrocarbon flame appear to primarily reflect CH mole fraction.

High speed (kHz rate) PLIF time-sequence images of a single vortex-flame interaction are beyond the reach of conventional dye lasers and cameras. However, these systems can be used to phase-sample a highly repeatable sequence which then provides the same time-resolved information. Thus, the design of the flow facility was guided by the need for a highly repeatable, 2-D vortex-flame interaction. Figure 1 shows a schematic of the flow facility which consist of a laminar V-flame burner, a vortex generator, and a test section fitted with quartz windows for PLIF imaging diagnostics. The laser sheet enters the test section from the left, making a perpendicular cut with the symmetry planes of the V-flame and vortex-pair. The PLIF image is collected perpendicular to the laser sheet. The design of the burner is similar to the one used by Samaniego [8]. The laminar V-flame is attached to a heated NiCr wire suspended across the top of the burner. The burner (63.5 mm square) is packed with glass beads followed by honeycomb and wire screen flow straighteners. The line-vortex pair is generated by an impulse from a speaker (86 mm dia.), mounted to an adjoining chamber (89 mm square x 100 mm long). The vortex-pair issues from a 2-D contoured nozzle (3 mm throat) which spans the entire width of the test section. The gas in the vortex generator has the same fuel-air- N_2 mixture as in the test section. Water condensation in the test section is prevented by cooling both the test section and the vortex

generator with circulating water maintained at 55 C. Pressure regulated orifice flow meters supply a controlled CH₄-air-N₂ mixture to the burner assembly. We dilute the CH₄-air mixture with N₂ to reduce the flame temperature and hence the flame speed. This permits us to stabilize propane- or methane-air flames over a wide range of fuel-lean ($\phi = 0.55$) to fuel-rich ($\phi = 1.19$) conditions in a V-configuration. Previous experimental studies of vortex-flame interactions have used only fuel-lean flames.

Timing is controlled by a master oscillator in the camera system, operating at 3 Hz. A digital delay generator provides the variable time delays between the vortex generator and PLIF diagnostics for the phase sampling measurements. The driving function for the vortex generator is created using a waveform synthesizer which provides a smooth asymmetric pulse (1 ms rise time and 8 ms fall time) that is DC amplified to drive the speaker voice-coil. In the results to follow, the amplitude was set to produce a 1.07 mm deflection of the voice-coil.

The OH and CH PLIF measurements were performed separately. For the OH excitation, the output of a XeCl excimer-pumped dye laser was frequency-doubled to produce laser pulses with energies of approximately 5 mJ at a wavelength of $\lambda = 283.02$ nm, with a linewidth of 0.16 cm^{-1} FWHM. The laser was tuned to excite the Q₁(6.5) transition of the (1,0) band in the OH *A-X* system. The non-resonant fluorescence was collected by a f/1.2 cassegrain lens (98 mm) and filtered with 2 mm of Schott WG305 colored glass prior to being imaged onto the photocathode of an image intensified-fibercoupled-CCD video camera. For the CH excitation, a XeCl excimer-pumped dye laser running a UV dye (Exalite 389) was used to directly generate laser pulses with approximately 20 mJ of energy at a

wavelength of $\lambda = 389.48 \text{ nm}$, 0.08 cm^{-1} FWHM. The laser was tuned to excite the $Q_1(4.5)$ transition of the (0,0) band in the CH $B-X$ system. Non-resonant fluorescence from $B-X$ (0,1) as well as $A-X$ (0,0) and (1,1) (produced by internal $B \Rightarrow A$ conversion) was collected with an $f/1.2$ camera lens (50 mm) and filtered with 2 mm of Schott GG 420 colored glass before being imaged onto the photocathode of the image intensifier. This means of detection is similar to the technique used by Paul and Dec [15], who employed $A-X$ (1,0) excitation. The camera lens used for the CH measurements provides an enhanced spatial resolution compared to the cassegrain (i.e., the camera lens displays much better contrast transfer at high spatial frequencies than the cassegrain), which is a critical requirement when imaging CH due to its thin profile in a flame.

The imaged areas are shown schematically in Fig. 1, these areas correspond to a magnification that provided a resolution of approximately 12 pixels/mm for both the OH and CH measurements. In both measurements, the pump laser beams were formed into sheets measuring approximately 4 cm high in the test section using a combination of cylindrical and spherical quartz lenses. The laser sheet thickness was approximately 200 μm , however, this is not a limitation in imaging 2-D flows. Nonetheless, finite depth of field, aberration in the lenses, and finite pixel size result in an ultimate resolution of 160 μm (based on a Nyquist criterion).

The images from the video camera were acquired synchronously and digitized with an 8-bit video frame-grabber installed in a PC-AT computer. Data reduction was performed using the KHORUS image processing package running on a workstation. Laser sheet profile

intensities for the OH images were corrected by normalizing the images with a profile obtained from a PLIF image of homogeneous, saturated acetone vapor in the cold test section. The acetone images were obtained using the OH pumping laser and the same lens and filter (acetone absorbs well at 283 nm and fluoresces in the blue visible). The CH images were manually corrected for variations in sheet intensities by assuming that the CH fluorescence along an undisturbed V-flame front is a constant. Due to the highly repeatable flame-vortex interactions, the signal-to-noise ratio of the images was improved by acquiring and averaging 30 single-shot images at each time-sequence frame.

Results

Figure 2 shows a phase-sampled series of CH images taken at $\phi = 1.19$ and a cold flow burner face velocity of 39.5 cm/s (CH_4 - air - N_2 at mole fractions of 0.075 - 0.6 - 0.325). The first 8 frames are in 1 ms steps, starting with an initial deformation of the flame through its breakage. The thickness of the undisturbed CH surface in the images is measured to be 0.25 mm (full width at half max.). Taking into account the finite resolution of the imaging system (including pixel size, lens blur, intensifier blur and sheet thickness) suggest that the thickness of the actual CH surface is less than 0.2 mm.

The initial deformation of the flame surface appears relatively symmetric about the vortex centerline. The tangential velocity component along the flame surface creates an inherently asymmetric flow geometry producing an unequal torque on the vortex pair during the initial interaction. With increasing delay the unequal torque deviates the vortex trajectory and the point of initial CH breakage is seen slightly below the vortex centerline. At 5 ms, the

CH signal (hence the CH mole fraction) where the surface is broken, is more than 100 times below that measured in the undisturbed surface. The ratio of the undisturbed flame speed to the apparent vortex velocity is approximately 0.1 (a vortex velocity of 100 cm/s was measured from the differential deflection of the CH surface prior to breakage of the flame). Taking this velocity ratio, assuming a flame thickness of 0.2 mm and measuring the vortex diameter from the images to be 8 mm gives a Damkohler number of 4. This classifies the flow as a 'distributed reaction zone'.

Kee et al. [16] have observed that increasing but steady strain yields little or no change in flame internal structure; profiles tend to thin slightly but absolute concentrations remain strikingly constant. The image data is noticeably different. The breakage of the CH front appears to be preceded by a 2- to 3-fold decrease in CH concentration whereas the thickness perpendicular to the surface remains near constant. Figure 3 shows two sets of OH LIF profiles aligned perpendicular to the flame surface. One set of profiles is taken just prior to and the other set is taken just after breakage of the CH front. Each set includes a profile from an undisturbed region of the flow and a profile from the centerline of the vortex pair. The two profiles from the undisturbed region of the flow are essentially identical, attesting to the reproducibility of the flowfield and the pointing stability of the laser sheet. The profile from the vortex core prior to breakage of the front has a similar shape to that in the undisturbed flow but shows a slight decrease in peak OH concentration. The profile from the vortex core after breakage of the front show a 4-fold increase in OH signal as well as the penetration of OH into the vortex core. A similar analysis of images taken at the same vortex

strength but for a stoichiometric flame (not shown here) reveals a different behavior: The OH profile from the vortex core prior to breakage shows the same peak OH value as in the undisturbed flow and significant penetration of OH into the vortex core. This profile remains essentially unchanged through breakage of the CH front. It is evident that OH and by inference, other radicals as well as flame enthalpy penetrate well into to vortex core (reactants) during the buildup prior to breakage of the CH front. The evolution of the OH profile does not appear to change up to breakage of the CH front. Whereas the behavior after breakage appears to be very sensitive to local stoichiometry.

Figure 4 shows a series of phase-sampled OH images. Note that the region shown in the OH images is larger than that shown in the CH images. At early times, the deformation seen in the OH image matches that seen in the CH image. After breakage of the CH surface, the OH image shows the vortex moving well into the postflame gases. The ‘burnout’ of the vortex is initiated by closure of the stem (when the two sides of the channel reattach at approximately 16 to 18 ms) leaving the vortex as an isolated pocket (at 20 ms). A similar event was noted by Roberts *et al.* [6]. Single-pulse images show that the closure of the vortex stem is unstable on a microsecond timescale, likely due to slight variations in initial conditions through the inherent time-jitter in the process of moving the speaker voice coil. Following this initial closure the OH field propagates rapidly to fill in the remaining stem.

Roberts *et al.* [6] noted a marked decrease in the peak OH LIF signal in profiles taken across the vortex flame front boundary (they studied the interaction of a toroidal vortex with a lean methane air flame, $\phi = 0.55$). We observe a similar effect under comparable vortex-

flame conditions. They argued that a substantial decrease in this signal could be used as an indicator of flame ‘quenching’. However, in considering a stoichiometric or slightly fuel-rich vortex-flame interaction, the OH profile in the products is seen to remain near constant up to breakage of the CH surface.

The observed increase in the OH LIF signal immediately around the vortex in the fuel-rich case is too large to be explained solely on the basis of changes in temperature and collisional bath. This OH signal increase must be related to a local increase in OH mole fraction. Hence, the response of the stoichiometric to slightly fuel-rich postflame gases to the introduction of fresh reactants by the vortex, appears as a local increase in OH production. In the later frames of Fig. 4, the remnant of this OH production is observed on either side of the closed-off vortex stem. The closure of this stem may be more like a CO-hydrogen flame. The OH left behind is finally removed by relatively slow diffusion and chemical reactions.

The initial break in the CH surface appears as a hole several flame thicknesses in size. This breakage process is slow enough to be frozen by the pulsed-laser PLIF technique, but appears unsteady on a microsecond timescale, again due to slight time-jitter in the initial conditions. Within a fraction of a ms from this initial break, the CH surface surrounding the vortex disappears leaving only a small penetration corresponding to the stem left in the wake of the vortex. A corresponding event is not seen in the OH images even when looking at scalar contours, image time-series differences (phase velocity images of the OH front), or images of OH scalar dissipation (as derived from the 2-D OH images).

The last four frames in Figure 2 are taken at longer delays and show the initial closure of the broken flame surface. As seen in the OH images, the vortex actually penetrates well into the products before it decays. However no CH LIF signals were detected in the post flame front gases associated with the reactions leading the final consumption of the vortex or the channel from the flame surface to the vortex. It would appear that the normal chemistry of a steady laminar flame is required to establish a CH population.

Conclusions

PLIF imaging diagnostics of OH and CH were used to examine a laminar flame subjected to a strong line-vortex pair. Planar images of these radicals provide distinctly different information, the OH being a marker of a long-lived combustion generated intermediates, and the CH providing an unambiguous marker of the primary reaction zone. The flow studied was highly reproducible, which enabled the use of phase-sampled imaging to provide time-resolved image sequences. Work is in progress to extend the measurements to include PLIF images of NO and CO as well velocity images using PIV.

The results show that events leading up to a breakage in the CH front are not associated with any distinct change in the OH front. This suggests that OH images may not be the best indicator of flame front structure. The OH field does respond to the presence of the vortex. This appears to occur after the breakage of the CH front, and may increase or decrease the peak OH concentration depending on the flame stoichiometry. The structure of the CH and OH profiles during the transient leading up to the breakage of the CH front do not appear to be consistent with the concept of a strained laminar flame. Thus, it is difficult to

reconcile the measured response of the flame to an isolated vortex pair in terms of strained laminar flames or flamelets. A clearer understanding must await a simulation of a flame-vortex interaction that includes the full effects of unsteadiness and detailed chemistry.

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Figure Captions

Figure 1. Schematic of the flow field showing the fields imaged for CH and OH.

Figure 2. Phase-sampled CH PLIF image sequence. The frames are numbered in ms of additional delay from the upper left image. The region shown is 27.2 x 23 mm (see Figure 1).

Figure 3. OH LIF profiles perpendicular to the flame front (actual locations demarked in Fig. 4).

Figure 4. Phase-sampled OH PLIF image sequence. The frames are numbered in ms of additional delay from the upper left image in Fig. 2. The region shown is 38.8 x 32.8 mm.

Nguyen and Paul Figure 2