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13. ABSTRACT (Maximum 200 words)

This Final Report surveys our results under ARO support in the areas of Spray and Gas-Flame Research. Flame liftoff and blowout is witnessed in spray combustion systems encountered in practical devices. Understanding the governing parameters for flame structure and stability is of fundamental as well as practical importance. Our group has continued an experimental effort in this area of flame stabilization, propagation and extinction in spray flames interacting with an air co-flow. Ph.D. student (Steve Marley) has been the core Ph.D student for the spray flame experimental work. Recently, OH-PLIF measurements have also been performed in our laboratory to visualize the single and double flame structures in such spray flames, along with high-speed visualization of the combustion process of single and double-flame structures. Experiments have also been performed in our laboratory to examine the temporal nature of the spray flame/flow interaction. Much of this work has been presented at conferences and is appearing in the literature in journals. A continuing focus is the effect of entrained air on flame stability and local extinction. These findings are anticipated to be utilized in modeling spray combustion and optimizing spray flame stability parameters.

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(1) Foreword: N/A

(2) Table of Contents

(3) List of Appendixes, Illustrations and Tables

(4) Statement of the problem studied

Understanding the physical phenomena that control spray combustion processes is desirable since many practical combustion/propulsion devices initially introduce fuel as a two-phase flow. Applications such as residential heating, land and air-based transportation or propulsion, and power generation all utilize liquid fuels. This broad range of application necessitates a fundamental understanding of the mechanisms that control spray flame behavior. Issues such as flame structure, stabilization, and extinction are important aspects of spray combustion that are still not well understood for the wide variety of combustors that exist.

Sprays pose significant challenges to applying non-intrusive optical diagnostic techniques in combustion systems due to complicating factors such as attenuation, scattering of the probe beam, and interference from the droplets. Characteristics such as spray pattern, droplet size and velocity distribution, and oxidizer flow field dynamics can play an important role in determining the dominant flame structures. These structures are responsible, ultimately, for determining combustion efficiency and pollutant emissions.

This spray combustion problem studied under ARO support has been cast with the above issues in mind. The intellectual merit of the activity centered on potential for insight gained into the science of spray flame structure, stability and correspondence with well –established gas phase combustion research. Investigations into spray flame structure have helped understand the reaction zone morphology in spray flames. Parallel studies in gaseous flames near blowout have help provide insight into spray flame phenomena.

(5) Summary of the most important results:

Brief List of Topics Investigated and the Results/Contributions

a) Study of the ethanol spray flame using imaging diagnostic techniques. Single and Double Flame structures have been reported. Details of the flame morphologies witnessed are given below.
b) Correspondence between gaseous flame stabilization and spray flame stabilization has been investigated and described.
c) The effect of air co-flow has been characterized and its assistance in preventing local extinction at the flame leading edge has been noted.
d) Air entrainment from the ambient has been shown to be a large factor in dictating leading edge morphology and the presence of local extinction.

Discussion:

One of the most common strategies for producing a fuel spray for combustion applications is with a pressure-swirl nozzle. This method of fuel injection relies upon atomization of the liquid fuel as it flows initially through a swirl chamber (where a thin film is generated) and is discharged from a small orifice that generates a conical sheet [1]. Considerable effort has been placed on characterizing pressure-swirl nozzles for non-reacting sprays. The experimental work of Lefebvre and colleagues [2-4] provides analysis of the effect of nozzle design and flow parameters on important characteristics of the spray such as Sauter mean diameter, droplet size distribution, and cone angle. Theoretical investigations of pressure-swirl nozzles have contributed important formulations for key spray quantities such as Sauter mean diameter [5,6] and initial liquid film thickness within the discharge orifice [6,7]. Modeling

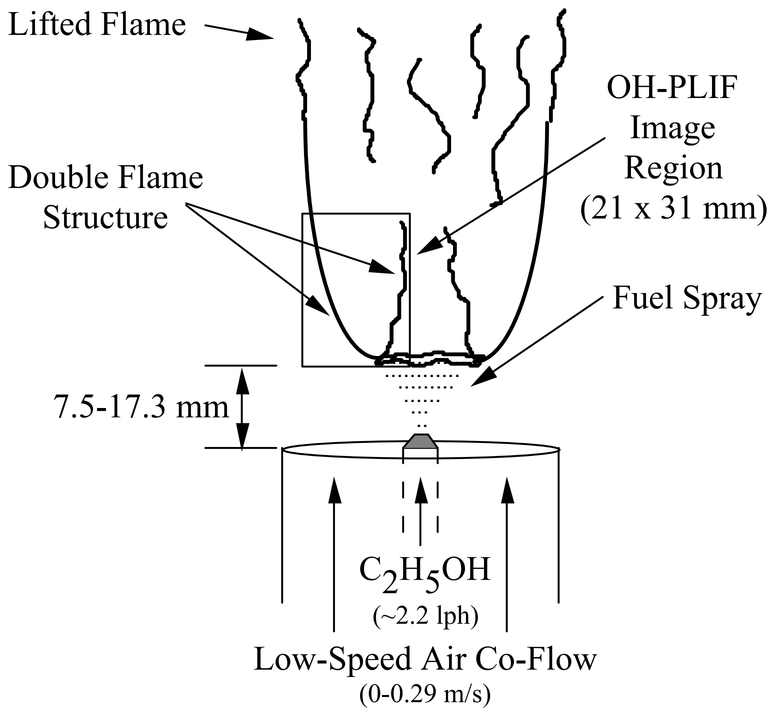
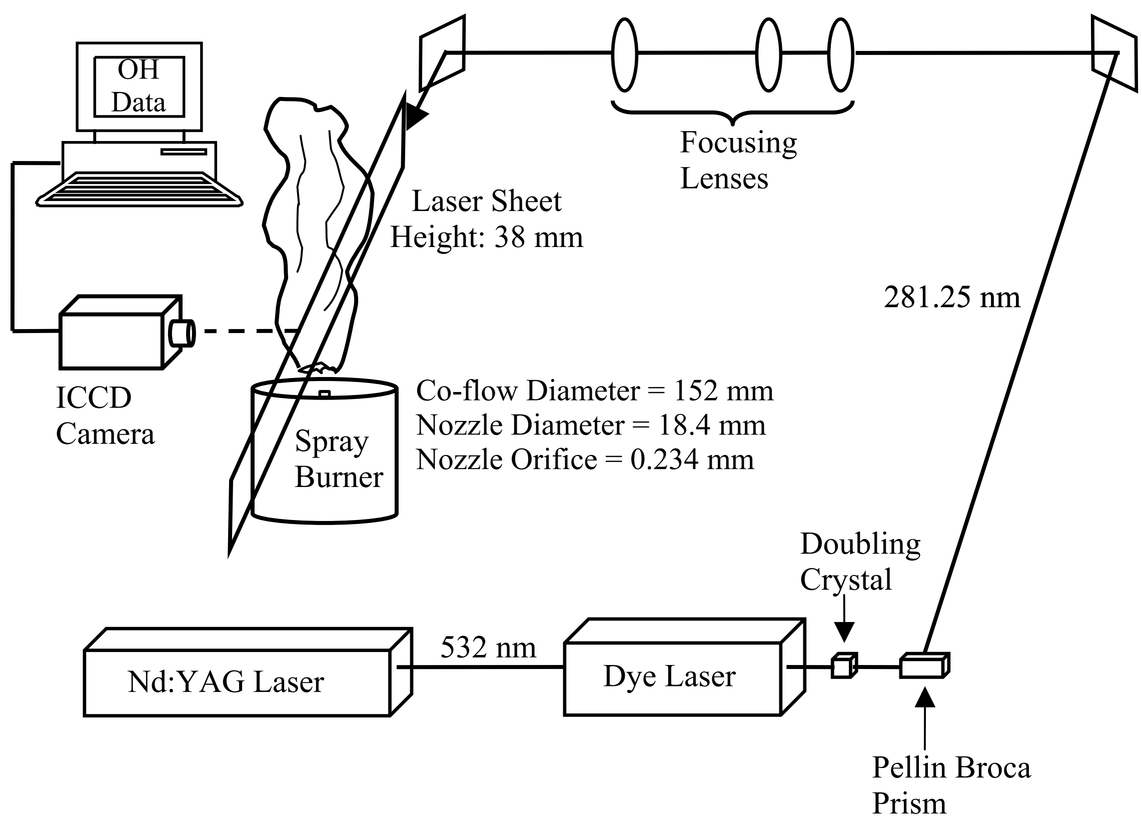


Figure 1a: Burner and Flame Schematic shown above

Figure 1b: OH-PLIF Experimental Set-up at NCSU displayed below



approaches for calculating drop size distributions of generalized sprays have been developed, and their predictive capabilities are thoroughly reviewed by Babinsky and Sojka [8].

These considerable research [9-16] efforts have characterized the general performance of pressure-swirl nozzles and set the groundwork for extending the research into facets of reacting sprays. Early experimental work in piloted kerosene spray flames [17,18], utilizing an air-atomized spray jet, suggested that the spray flame burns in a manner similar to turbulent gaseous diffusion flames. More recent experiments in turbulent spray flames [13,19-21, 29, 35] have reported that the flame can exhibit a double structure, originating at the leading edge, that diverges with increasing downstream location. This double flame structure is of interest with respect to both the characteristics of the flame and its effect on flame stabilization. The experimental results of Cessou and Stepowski [19] and Cessou *et al.* [20], which utilized an air blast injector fed with liquid methanol, suggest that both the inner and outer reaction zones burn in a diffusion mode with minimal droplet vaporization occurring prior to the inner zone. These conclusions are supported by the numerical work of Continillo and Sirignano [22], who modeled laminar counterflow spray flames in which a monodisperse *n*-octane spray was present in one of two impinging air streams resulting in the dual diffusion flame structures. The theoretical investigations of Greenberg and Sarig [23,24] also indicate the possibility of multiple reaction zones in the laminar counterflow arrangement. In their model, a stream containing a quasi-monodisperse fuel spray, fuel vapor, oxidizer, and inert gas impinges on an air jet. The presence of the fuel vapor in one stream allows partial premixing to occur such that, in an initially slightly oxidizer rich mixture, a premixed flame may develop in addition to the dual diffusion flames observed in previous studies [19,20,22].

Experimental studies of turbulent reacting sprays, in addition to practical combustors, usually utilize polydisperse sprays that posses complex droplet size distributions and flow fields due to interactions with the turbulent host gas. As a result of these interactions, it is likely that the smaller droplets, which have a smaller Stokes number and therefore follow the gas phase flow better, will have increased residence times in turbulent eddies. This process leads to enhanced vaporization and the generation of fuel vapor prior to reaching a reaction zone, increasing the likelihood of partially premixed combustion.

Research Results in Spray Flames at NCSU

Laser-induced fluorescence for reaction zone imaging and smoke visualization to observe the entrainment of ambient air and subsequent mixing along the shear layer in spray flames has been performed by our group using the facilities at North Carolina State University. The burner used in these studies utilizes a central spray nozzle surrounded by an annular air co-flow as illustrated in Fig. 1a. The burner is designed to provide flat air velocity profile at the exit of the co-flow region, and the large cross-sectional area (152 mm diameter) allows the use of low-speed co-flow air to influence the flow field, promote entrainment, and modify the flame structure. A Delavan hollow cone nozzle (WDA 0.75-60), characterized by a 60° cone angle and 0.234 mm orifice, was used to supply the desired ethanol fuel spray. The Reynolds number of the spray, based on the initial sheet thickness of the spray cone [1], is calculated to be approximately 2,050 at the injector exit using the work of Rizk and Lefebvre [7], who give an expression for the determination of the film thickness inside the nozzle orifice (which is directly related to the sheet thickness [1]). Both OH-PLIF and smoke visualization were been performed in the stabilization region of the flame. The experimental setup allowed the left half of the flame base to be imaged with OH-PLIF (see Fig. 1a). Planar imaging of OH fluorescence in the spray flame serves to mark the 2-D reaction zone contours and allows qualitative analysis of these flame structures. This technique is considered to be a satisfactory marker of the fuel-lean side of diffusion flames, but the signal is broadened in premixed flames due to the presence of OH radicals in the hot combustion products [19,25]. While the OH signal in diffusion flames appears as a thin band along the stoichiometric contour, OH fluorescence in premixed or partially premixed flames exhibits "broad" regions of OH, and has been observed in initially non-premixed and partially premixed combustion [26,27]. The OH-PLIF diagnostic utilizes a frequency doubled Nd:YAG laser pumping a dye laser with an output wavelength of 562.50 nm. The beam is doubled down to 281.25 nm to excite the $R_1(8)$ transition of the $A^2\Sigma$-$X^2\Pi(1,0)$ band of OH. The shifted fluorescence is detected by the (0,0) and (1,1) bands corresponding to wavelengths of 306-312 nm [28]. A Pellin Broca prism segregates the UV beam, which is then reflected to a series of lenses to provide a 38 mm high laser sheet that passes through the centerline of the burner with an energy of 3 mJ per pulse. An ICCD camera positioned 90° to the laser sheet captures the OH fluorescence on a 576 x 384 pixel array (binned by two), corresponding to a 31 mm high by 21 mm wide image region. WG-305 and UG-11 filters reduce the elastic scattering signal from fuel

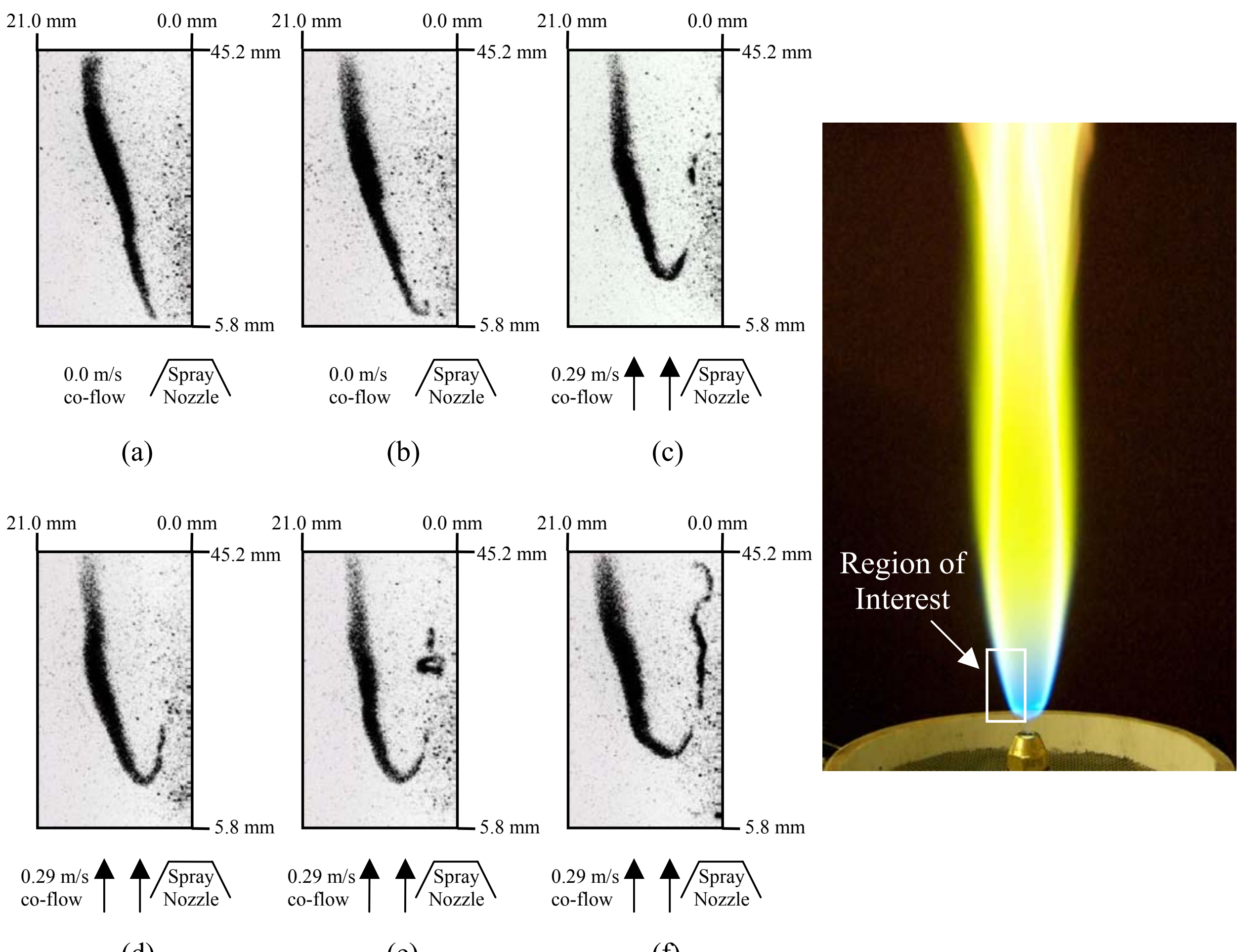


Figure 2. OH-PLIF images and photograph of spray flame at increasing liftoff heights. Note the formation of the inner OH structures as the flame is lifted farther from the nozzle

droplets, although some scattering is still observed from the largest drops.

It is useful to introduce some terminology to simplify the discussion of the 2-D planar images. The double reaction zone consists of two diverging flame fronts on each side of the spray centerline that join together at the flame base, or leading edge. These two flame structures may be labeled the inner and outer reaction zones, depending on their radial positions relative to the axis of symmetry. Due to viscous effects, a shear (or mixing) layer is created at the interface between the spray cone and the surrounding gas flow. Shear layers contribute to transport and mixing in turbulent flows, and aid in the formation of a flammable mixture to support the inner reaction zone. Description of the spray flame structure is facilitated by the representative OH images shown in Fig. 2 along with a photograph of the flame. Figures 2a and 2b (zero co-flow) show the leading edge of the reaction zone stabilized near the fuel nozzle (7.8 mm downstream). These images portray a single branch structure similar to that witnessed in lifted gaseous jet diffusion flames [34]. Since the leading edge of the flame is located close to the tip of the fuel nozzle both axially and radially, there is insufficient entrainment of ambient air to support an inner reaction zone. MacGregor [30] showed that spray jets are not as efficient as gaseous jets at entraining ambient air, and in this case there is not enough time for significant momentum transfer, thus entrainment, to occur before the reaction zone develops. Figure 2b, without co-flow, shows a small cusp at the leading edge as the reaction zone wraps around the stabilization point. This cusp is thought to exist as a result of transient large scale mixing structures, interacting intermittently with the flame base, that can stretch the reaction zone around the leading edge as they rotate (see Fig. 9 in [26], [34]). This observation explains why no cusp is observed in Fig. 2a for the flame stabilized close to the burner (not enough time for entrainmentto be accomplished). Kelman et al. [26] also observed roll-up of the flame base around large-scale fuel eddies of lifted methane jet flames, resulting in air entrainment around the leading edge. These recirculation zones in burning sprays contain small droplets that follow the gas flow near the spray edge and vaporize easily for subsequent burning near the flame leading edge, which is critical in lifted spray flame stabilization [20].

The addition of low-speed (0.29 m/s) air co-flow induces a transition from a single to a dual reaction zone as seen from the images in Fig. 2c-2f. It is important to note that the data presented for these co-flow cases represent the same experimental conditions. The interaction of local flow turbulence with the flame base results in an oscillating liftoff height. As this process occurs, the double reaction zone undergoes a series of progressive changes that give insight into the characteristics of turbulent spray flames. The annular co-flow convects the flame downstream allowing sufficient air entrainment to support a secondary reaction zone along the mixing layer. Initially, the OH at the stabilization point becomes more pronounced and an inner reaction zone is only present near the leading edge (Fig. 2c and 2d). Figure 2e shows a detached inner reaction zone structure illustrating flame and product fragments as "patches" of OH radicals. Extinction and re-ignition processes allow adequate time for local partial premixing to occur. The level of induced strain (at the inner zone interface) prevents the existence of segregated diffusion and premixed components of the partially premixed structure, thus a single merged reacting layer exists [27,22]. Finally, in Fig. 2f, the flame has lifted to its most downstream location (15.7 mm liftoff height). In this case, the flame has a fully developed inner reaction zone with areas of local extinction. The inner OH structure is again significantly thinner than the outer reaction zone due to strain. Also, the inner zone is wrinkled but does not have the large OH blotches, indicative of local premixing, that were observed in the previous case (Fig. 2e). **Therefore, the inner reaction zone burns in a predominately diffusion mode**. <u>It is clear that co-flow and its effect on air entrainment needs more study in light of these observations. Desired are comprehensive and dedicated studies akin to the triple flame imaging studies in gaseous flames that have involved many groups from around the world.</u>

Entrainment has been shown to have a significant impact on both the structure and stabilization of spray flames. Axisymmetric co-flows used in sprays are able to lift the flame base into downstream regimes of the spray (droplets, fuel vapor, and air) and permit significant air entrainment near the shear layer. This entrainment, along with the atomization characteristics of the polydisperse spray, allows an inner reaction zone to form. This fact explains the widening of the leading edge as the liftoff height increases. The spray spreads out as it propagates, further atomizing the droplets and providing a wider region favorable to reaction zone stabilization. One

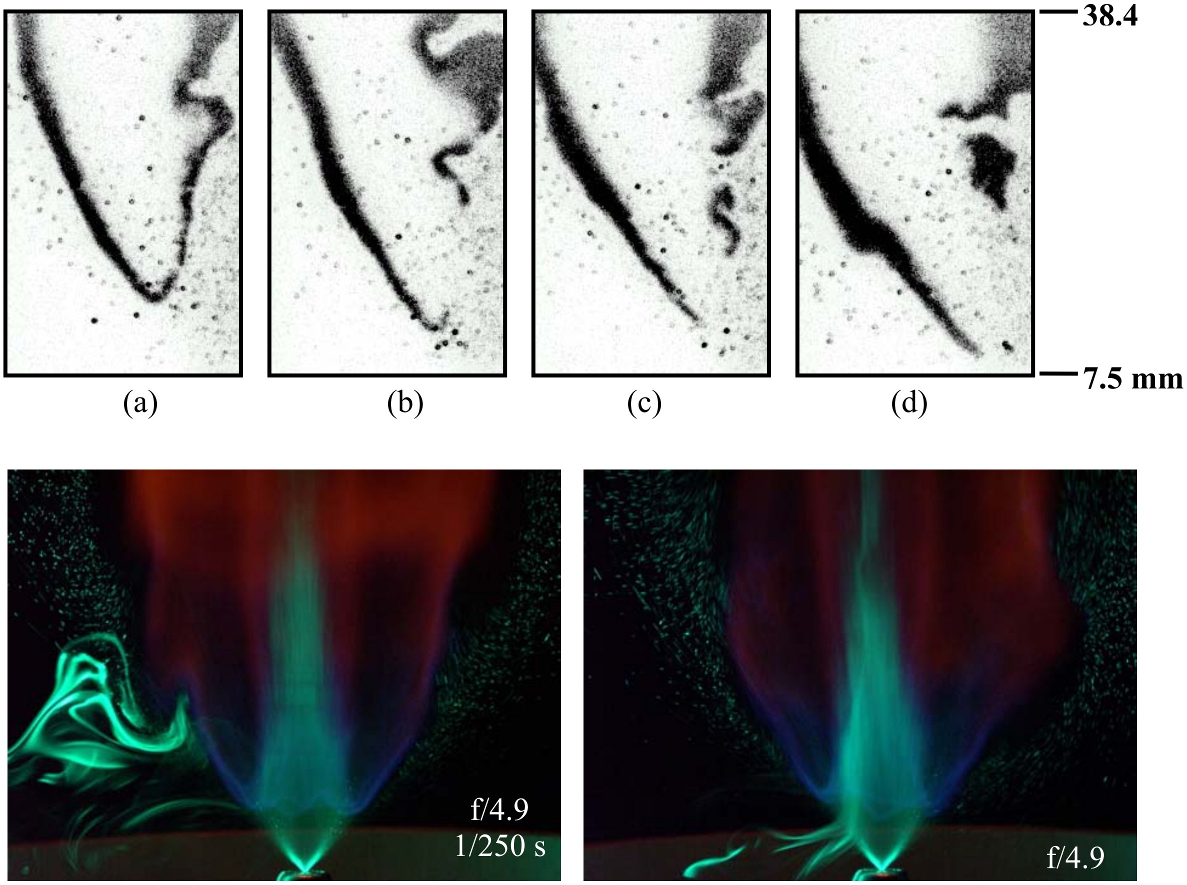


Fig. 3. Images for hollow cone pressure-swirl nozzle WITHOUT co-flow: (a)-(d) single-shot OH-PLIF, and (e)-(f) smoke visualization photographs.

common theme is the role of turbulent mixing in leading edge behavior and inner flame structure. The flame is stabilized at the edge of the spray where the smallest droplets are rapidly vaporized and mixed, independent of the larger ballistic droplets which cross the inner reaction zone and feed the outer diffusion flame and bulk combustion downstream. As seen from the OH images (Fig. 2f), lifting the base of the flame far enough downstream allows the oxidizer to penetrate the fuel spray and form a wrinkled inner diffusion flame with the exception of cases exhibiting isolated blotches of OH which involve partial premixing. The thin, wrinkled nature of the inner zone, when compared to the smooth boundary of the outer structure, indicates that inner zone combustion exists along the shear layer created between the momentum-dominated region of the spray and entrained gases. The shear layer provides a region of enhanced mixing and aids in theentrainment of air due to large-scale vortices [33]. It is important to note that, when a fully developed inner zone exists, the hot region between the two reaction zones, laden with droplets, is primarily responsible for diffusion of fuel vapor to feed both flame structures [22]. The oxidizer for the inner zone diffuses into the flame from the spray side of the flame front.

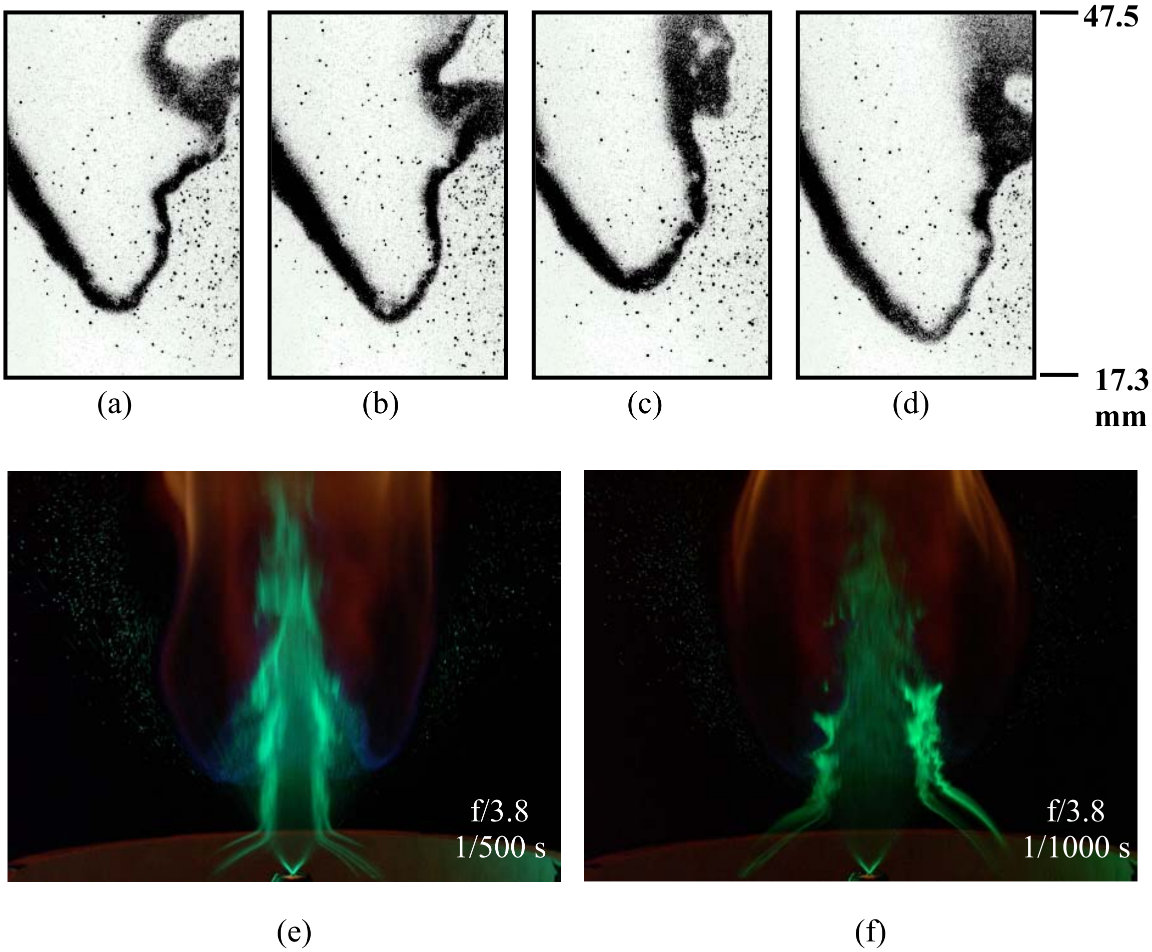


Fig. 4. Images for hollow cone pressure-swirl nozzle WITH co-flow: (a)-(d) single-shot OH-PLIF, and (e)-(f) smoke visualization photographs. The co-flow velocity is .29 m/s

The spray combustion system was initially operated without any co-flowing air stream, and representative OH and smoke visualization images are shown in Fig. 3. The flame base oscillates around an average liftoff height of 12.4 mm (+/- 25% fluctuation about the average) as the flame responds to the turbulent fluctuations of the flow field. The outer reaction zone has a stable and smooth OH contour that is largely free from the effects of large-scale turbulence and strain downstream of the stabilization point. The polydisperse spray distribution facilitates the existence of the double reaction zone. It is interesting to note that, in the images that contain no local extinction of the inner reaction zone, the flame is lifted slightly higher than the average, as in Fig. 3a (14.1 mm liftoff height). This observation is consistent with past work in pressure-swirl spray flames, where increases in liftoff height indicate increased air entrainment, resulting in enhanced inner zone combustion and less tendency to locally extinguish [29]. Generally, the flame without air co-flow exhibits weak entrainment of ambient air and an intermittent inner reaction zone (Figs. 3b-d). The addition of low-speed (0.29 m/s) air co-flow significantly alters both the gas phase flow field and the double flame structure. This particular co-flow velocity was chosen because it provides a well-lifted flame that is a balance between the low-liftoff height flame without co-flow and the highly lifted (~125 mm) flame that is observed at moderate co-flow velocities (~0.50 m/s) without a double structure. OH-PLIF images and smoke visualization for the co-flow case are shown in Fig. 4. The OH images in Figs. 4a-d indicate that the double reaction zone is now continuous and no longer experiences regions of local extinction with the co-flow present. The inner reaction zone is still wrinkled and shows characteristics of partially premixed combustion due to turbulent mixing at downstream locations.

Flow visualization of the flame with co-flow provides further insight into the flame structures observed compared with the no co-flow case. Figures 4e and 4f, which show smoke injected upstream of the nozzle on both sides of the burner (though emanating from different radii in the co-flow), give a qualitative measure of the air entrainment associated with co-flow. The entrainment rate is significantly increased and the spray is able to generate strong air currents beneath the base of the flame, even at a smoke injection radius of 38 mm as in Fig. 4f. The increased entrainment with a co-flowing air stream is in contrast to the experimental study of Han *et al*. [31], who found that increases in co-flow velocity actually reduce entrainment rates in turbulent non-reacting and reacting jets of methane (with nitrogen) stabilized at the nozzle by a hydrogen pilot. The difference in this experiment is that the spray flame is allowed to lift higher with co-flow (not piloted as in [31]), which exposes more of the spray to interact with the air mass thereby increasing entrainment. <u>Overall, the addition of low-speed co-flow convects the flame downstream to significantly increase air entrainment, enhance inner zone combustion, and reduce local extinction.</u>

In the absence of a co-flowing air stream, the flame possesses a double reaction zone with an inner structure that burns intermittently with areas of local extinction occurring often at the most upstream locations near the leading edge. When the inner structure exists as a continuous reaction zone without local extinction, it burns predominately in a diffusion mode just inside the leading edge and transitions to partially premixed combustion farther downstream. The addition of low-speed co-flow increases the liftoff height resulting in higher entrainment rates and enhanced inner zone combustion. This can be seen as summarized in Figure 5. There are few extinction events with co-flow, and the leading edge widens as the flame base stabilizes in a location of the spray where there is a larger region possessing fuel vapor for combustion due to spreading of the spray cone and evaporation of the fuel droplets. <u>One key element associated with the double reaction zone, common to both cases presented here, is the role of turbulent</u>

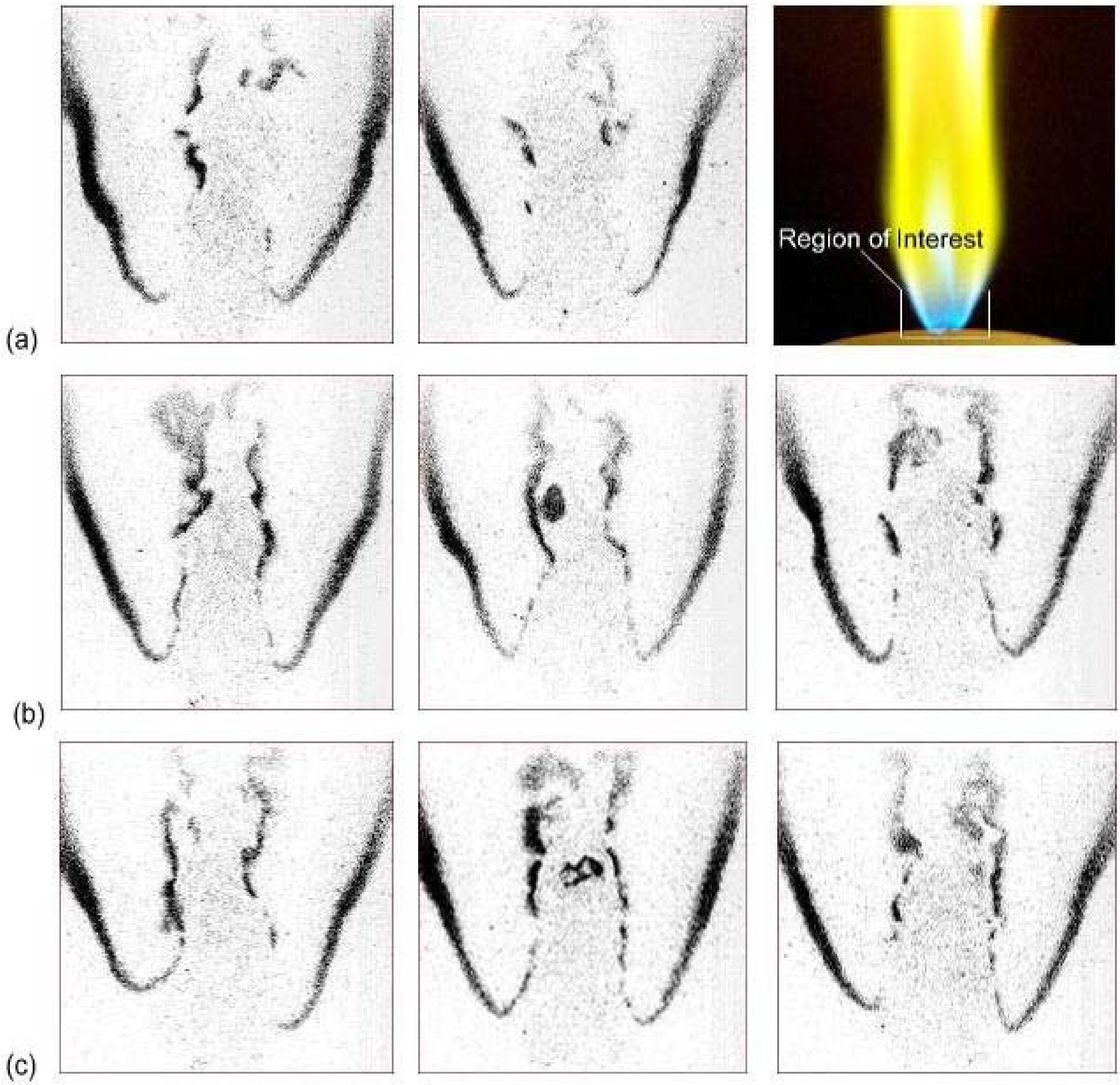


Fig. 5. OH images and photograph of the WDB 0.50-60 pressure-swirl nozzle for (a) 0.0 m/s co-flow, (b) 0.29 m/s co-flow, and (c) 0.43 m/s co-flow.

mixing along the shear layer where the inner reaction zone resides. The OH-PLIF images and complementary smoke visualization clearly indicate that the inner zone is characterized by intense mixing which preferentially increases the residence time of small droplets in turbulent eddies and provides fuel vapor for partial premixing of reactants.

The results of these ARO-sponsored investigations, along with those of other research groups, provide evidence of the presence of a single- and double-flame structures [33-36] that are surmised to function in a capacity that permits stabilization of the flame. These leading edge flames are often present at the stabilization point of lifted spray investigated by a two-dimensional laser-sheet imaging technique, as has been described earlier. The nature of the flamefront in the stabilization region of the *spray-jet flame* is vibrant topic of research [34-36], along with the corresponding work in gaseous flames [39-47]. Whether all spray flames exhibit "leading edge' flame structures as shown by our group for the gaseous and for some spray cases case is a major question to be addressed by our group in future work. These fundamental flame structure and stability issues are important to understand for fuel/air mixing in combustion systems, injector and air intake design in engines and turbines. More detailed study of spray jet flames is necessary to illuminate the features common to both systems (gas and spray) and show differences in the flame structure and dynamics. The connection of these reaction zones with double and triple flame structures studied in gaseous flame stabilization is incomplete; continued research is warranted and in-progress on these fascinating natural phenomena.

(6) Listing of all publications and technical reports supported under this grant or contract.

(a) Papers published in peer-reviewed journals

S. K. Marley, K. M. Lyons and K. A. Watson. "Leading-Edge Reaction Zones in Lifted-Jet Gas and Spray Flames", Flow, Turbulence and Combustion 72 (1): 29-47(2004).

S.K. Marley, E.J. Welle, K.M. Lyons and W. L. Roberts "Effects of Leading Edge Entrainment on the Double Flame Structure in Lifted Ethanol Spray Flames", To Appear: Experimental Fluid and Thermal Science.

S.K. Marley, E.J. Welle and K.M. Lyons "Combustion Structures in Lifted Ethanol Spray Flames", ASME Journal for the Engineering of Gas Turbines and Power 126 (2): 254-258 (2004).

(b) Papers published in non-peer-reviewed journals or in conference proceedings

S.K. Marley, E.J. Welle, and K.M. Lyons "OH-PLIF of an Ethanol Spray Flame in Annular Air Co-Flow," Fall Meeting of the Western States Section of the Combustion Institute, Salt Lake City, October 2001.

S. D. Terry and K. M. Lyons, "Investigation of Flame Hysteresis Phenomena in Lifted Flames" Central States of the Combustion Institute, Spring Meeting, Austin, March 2004.

(c) Papers presented at meetings, but not published in conference proceedings

S.K. Marley and K.M. Lyons, "Effects of Entrainment on Flame Structure in Spray Flames55th Annual Meeting of the American Physical Society's Division of Fluid Dynamics, Dallas, November 2002.

S.K. Marley, K.A. Watson, and K.M. Lyons, "Image Measurements from Lifted Gaseous and Spray Flames," 20th Annual Gallery of Fluid Motion, 55th Annual Meeting of the American Physical Society's Division of Fluid Dynamics, Dallas, November 2002.

(d) Manuscripts submitted, but not published

(e) Technical reports submitted to ARO

K. M. Lyons, IPR "Stabilization and Blowout of Gaseous- and Spray-Jet Flames", Submitted to ARO in March 2001

K. M. Lyons, "Stabilization and Blowout of Gaseous and Spray Jet Flames" presented at the ARO/AFOSR Contractors' Meeting in Chemical Propulsion, USC, Los Angeles, CA June 2001.

K. M. Lyons, IPR Stabilization and Blowout of Gaseous- and Spray-Jet Flames, Submitted to ARO in March 2002

K. M. Lyons, "Stabilization and Blowout of Gaseous and Spray Jet Flames and their Correspondence" presented at the ARO/AFOSR Contractors' Meeting in Chemical Propulsion, Dayton, OH, June 2002.

K. M. Lyons, IPR Stabilization and Blowout of Gaseous- and Spray-Jet Flames, Submitted to ARO in March 2003

K. M. Lyons, "Experiments in Gaseous and Spray Jet Flame Stabilization" presented at AFOSR/ ARO Contractors' Meeting in Chemical Propulsion, Tucson, AZ, June 2004

(7) List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project

Primary Researcher/Student Supported : Stephen Marley, North Carolina State University (current Ph. D student).

Other Participating Students:

Stephen Terry, North Carolina State University (current Ph. D student)
David Wilson, North Carolina State University (current M. S. student)
Jose Torres, North Carolina State University (M.S thesis In–Progress)
Dr. Kyle Watson, now Asst Prof., University of the Pacific

(8) Report of Inventions: NA

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(10) Appendices: N/A