ABSTRACT

MARLEY, STEPHEN KISER. Experimental Investigations of Fluid-Chemistry Interactions. (Under the direction of Kevin M. Lyons and William L. Roberts.)

Investigations into the complex interaction between combustion chemistry and the hydrodynamic flow field have been performed in both laminar and turbulent flames. Lifted turbulent spray flames were studied to gain insight into the role of oxidizer entrainment and mixing in the development of double flame structures in polydisperse ethanol sprays. OH Planar Laser-Induced Fluorescence (PLIF) has been used to demarcate reaction zone contours, while smoke visualization illuminates the dynamics between entrained oxidizer and the evaporating fuel spray. Results show that the double flame structure consists of an outer diffusion flame with an inner structure that transitions from mixing controlled to partially premixed combustion downstream of the leading edge. Without air co-flow, the inner branch of the double structure burns intermittently with large regions of local extinction often observed, resulting from a high droplet flux and possibly high strain/scalar dissipation rates. Addition of 0.29 m/s co-flow lifts the flame base enough to increase air entrainment and enhance inner zone combustion. The inner zone burns continuously, with no apparent local extinction, due to turbulent mixing between entrained oxidizer and fuel vapor generated by easily vaporized droplets present in the recirculations along the shear layer. The polydisperse spray distribution yields larger droplets which are able to cross the inner reaction zone and vaporize in the hot region bounded by the double flame structure. This region serves as a fuel source to feed both the stable outer diffusion flame and the diffusive structures of the inner zone. In both cases, the flame leading edge stabilizes in the low-speed flow just outside the
periphery of the spray cone, where flame propagation against the incoming flow is possible.

The second phase of the research analyzed the response of laminar hydrocarbon-air flames to unsteady stretch via flame kernel-vortex interactions. A spark-ignited laminar premixed flame kernel, interacting with a single axisymmetric vortex toroid of variable strength, was investigated to quantify the transient coupling of flame chemistry and stretch rate. High-speed (4500 frames/second) broadband chemiluminescence imaging of natural CH*/OH* flame emission was utilized to map the available parameter space and probe both flame-flow and flame-flame interactions. Both methane and propane fuels were used with nitrogen diluent to carefully control flame speed. Methane flames were studied at equivalence ratios ranging from 0.64 to 1.13, with all flames diluted to the $\Phi = 0.64$ flame propagation rate observed in the absence of the vortex. Emphasis was placed on propane-air flames since the heavier hydrocarbon fuel is considered more suited to fundamental studies related to internal combustion engine applications. Therefore, the equivalence ratios investigated with propane range from 0.69 to 1.49 with dilution levels controlled to allow the observation of three flame propagation rates, corresponding to the undiluted displacement speeds for $\Phi = 0.69, 0.87, 1.00$. Detailed discussion of the flame kernel-vortex results is provided only for the cases at the $\Phi = 0.69$ flame propagation rate, although measurements of unstretched laminar burning velocity and Markstein number are provided for all mixtures. Characterization of the invading vortex ring was performed using Particle Image Velocimetry (PIV) under cold flow conditions. Three vortex strengths, corresponding to different rotational velocities, were chosen to interact with the growing spherical flame. In the weakest flames, the
The strongest vortex has the ability to penetrate completely through the flame kernel and initiate a second propagating flame that connects to the original flame surface. The added ability to control the timing of spark ignition relative to vortex generation facilitates a multitude of different interactions to be observed for a given set of experimental parameters. The CH₄-O₂-N₂ flames exhibited a weak Lewis number dependence in most cases, while the C₃H₈-O₂-N₂ flame structures transitioned from thermo-diffusively stable to unstable behavior as the equivalence ratio was increased above unity. These cases of thermo-diffusive instability, characterized by cellular flame structures, are especially intriguing given the dramatic response of the kernel combustion to the perturbation of the vortex. The effect of unsteady stretch, induced by a vortex toroid, has been shown to greatly augment flame propagation in many of these laminar premixed flames, while both local and global extinction are possible under certain conditions.
EXPERIMENTAL INVESTIGATIONS OF FLUID-CHEMISTRY INTERACTIONS

by

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Herbert M. Eckerlin
Dedicated to Amanda Jolie, an angel to my eyes and a companion to my soul
Stephen Marley was born, raised, and educated in Raleigh, North Carolina. In 1995, he began his engineering education at North Carolina State University. Due to his intense fascination with horsepower and racing, he decided to major in mechanical engineering, and received a B.S. degree from N.C. State in 1999. Deciding to pursue a career in motorsports engine development, he went to graduate school at N.C. State, receiving a M.S. degree in 2000, and then began his Ph.D. program performing experimental research in combustion. In addition to his academic training, he also has worked as both an automotive mechanic and an engine builder, working on some of the fastest Fords in the country, hoping to merge theory with application. His future as a world renown motorsports engineer may be in question, but one piece of drag racing advice will always hold true: “Run what ya brung and hope ya brung enough.”

The primary focus in Stephen’s life is his relationship with his Lord and Savior, Jesus Christ. Regardless of any success or hardship that may befall upon him, he takes comfort in knowing that God sent his only begotten Son to die for his sins, purchasing his life with His blood, so that he may live forever in the presence of God. Stephen continues to develop into a mature follower of Christ, trying not to let his humanity overshadow his Christianity, and desiring to live his life such that it may reflect the glory of God.

“Stop fooling yourselves. If you think you are wise by this world’s standards, you will have to become a fool so you can become wise by God’s standards. For the wisdom of this world is foolishness to God. As the Scriptures say, ‘God catches those who think they are wise in their own cleverness.’ And again, ‘The Lord knows the thoughts of the wise, that they are worthless.’”

1 Corinthians 3:18-20

“Now we see things imperfectly as in a poor mirror, but then we will see everything with perfect clarity. All that I know now is partial and incomplete, but then I will know everything completely, just as God knows me now.”

1 Corinthians 13:12

“Then he said, ‘I assure you, unless you turn from your sins and become as little children, you will never get into the Kingdom of Heaven. Therefore, anyone who becomes as humble as this little child is the greatest in the Kingdom of Heaven.’”

Matthew 18:3-4
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Dr. Kevin Lyons served as one of the co-chairs on the Ph.D. advisory committee, and was the professor with whom I started my Ph.D. program. I would like to sincerely thank Dr. Lyons for persuading me to start working with him on his spray combustion research in 2001. Dr. Lyons is always a great individual to both discuss complicated research problems or just small talk about things such as fly fishing or why his Jeep is in the shop. Dr. Lyons kept me focused on the big picture when I was lost in the details, and he helped me mature into a productive graduate student.
Dr. William Roberts also served as a co-chair on the Ph.D. advisory committee, and supervised the second phase of my Ph.D. program. I would like to thank Dr. Roberts for allowing me to take on his flame kernel-vortex research. I gained invaluable research experience working on a project that is a fundamental link to the operation of spark-ignition engines. This project was ideal since it gave me the best chance of securing a position in the automotive industry. In addition, the complexity of the experimental setup served as an excellent learning experience. Dr. Roberts possesses a tenacious work ethic and an equally impressive breadth of knowledge in the thermal sciences. He is always willing to roll up his sleeves and get dirty in the lab, even at the expense of his personal time. In addition, Dr. Roberts always expected 100% from me, yet was appreciative when I was working around the clock and sleeping on an air mattress in the lab for six weeks. I won’t miss that, but I can truly say I have earned my degree.

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Scattering images using incense smoke for the three vortices investigated: (a) laminar, (b) transitional, and (c) turbulent vortex. In all three cases, the piston displacement and orifice diameter are held constant at 1 mm and 10 mm, respectively. The field of view in each image is 30 mm wide x 30 mm high.

Raw PIV velocity field for the weak vortex case, corresponding to the following vortex generation parameters: $d_o = 10$ mm, piston speed= 36 mm/s, piston displacement= 1.0 mm. The resulting rotational and translational velocities were 77 cm/s and 85 cm/s, respectively. The velocity field represents an approximately 27 mm wide x 22 mm high processing region centered on the vortex.

Non-dimensional vortex strength versus size for the C$_3$H$_8$-O$_2$-N$_2$ and CH$_4$-O$_2$-N$_2$ flames and vortices investigated.

High-speed flame emission images of undisturbed outwardly propagating C$_3$H$_8$-O$_2$-N$_2$ flame kernels for $\Phi = 0.87$ (top row) and $\Phi = 1.32$ (bottom row). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.

Flame radius history for C$_3$H$_8$-O$_2$-N$_2$ flames freely propagating without vortex interaction. N$_2$ dilution levels for the $\Phi = 0.87$, 1.08, and 1.32 cases were...
chosen to match (as closely as possible) the $\Phi=0.69/1.49$ flame propagation rate.

8 10 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=0.69$, weak vortex ($U_0=77 \text{ cm/s}$, $U_\theta/S_{L,\infty}=3.59$, $d_\theta/\delta_D=195.3$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.

8 11 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=0.87$, weak vortex ($U_0=77 \text{ cm/s}$, $U_\theta/S_{L,\infty}=4.09$, $d_\theta/\delta_D=171.2$), and “low” flame propagation rate.

8 12 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=1.08$, weak vortex ($U_0=77 \text{ cm/s}$, $U_\theta/S_{L,\infty}=4.20$, $d_\theta/\delta_D=166.7$), and “low” flame propagation rate.

8 13 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=1.32$, weak vortex ($U_0=77 \text{ cm/s}$, $U_\theta/S_{L,\infty}=4.90$, $d_\theta/\delta_D=143.1$), and “low” flame propagation rate.

8 14 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=1.49$, weak vortex ($U_0=77 \text{ cm/s}$, $U_\theta/S_{L,\infty}=5.53$, $d_\theta/\delta_D=126.6$), and “low” flame propagation rate.

8 15 Flame radius history for $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flames undergoing a late kernel-vortex interaction with the weak vortex ($U_0=77 \text{ cm/s}$) at the “low” flame propagation rate.

8 16 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=0.69$, strong vortex ($U_0=398 \text{ cm/s}$, $U_\theta/S_{L,\infty}=18.54$, $d_\theta/\delta_D=195.3$), and “low” flame propagation rate.

8 17 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=0.87$, strong vortex ($U_0=398 \text{ cm/s}$, $U_\theta/S_{L,\infty}=21.11$, $d_\theta/\delta_D=171.2$), and “low” flame propagation rate.

8 18 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=1.08$, strong vortex ($U_0=398 \text{ cm/s}$, $U_\theta/S_{L,\infty}=21.70$, $d_\theta/\delta_D=166.7$), and “low” flame propagation rate.

8 19 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=1.32$, strong vortex ($U_0=398 \text{ cm/s}$, $U_\theta/S_{L,\infty}=25.30$, $d_\theta/\delta_D=143.1$), and “low” flame propagation rate.

8 20 High-speed $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ flame emission images of late kernel-vortex interaction for $\Phi=1.49$, strong vortex
(U₀= 398 cm/s, U₀/S₁,∞= 28.57, d₀/δ_D= 126.6), and “low” flame propagation rate.

8 21 Flame radius history for C₃H₈-O₂-N₂ flames undergoing a late kernel-vortex interaction with the strong vortex (U₀= 398 cm/s) at the “low” flame propagation rate.

8 22 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 0.69, weak vortex (U₀= 77 cm/s, U₀/S₁,∞= 3.59, d₀/δ_D= 195.3), and “low” flame propagation rate.

8 23 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 0.87, weak vortex (U₀= 77 cm/s, U₀/S₁,∞= 4.09, d₀/δ_D= 171.2), and “low” flame propagation rate.

8 24 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 1.08, weak vortex (U₀= 77 cm/s, U₀/S₁,∞= 4.20, d₀/δ_D= 166.7), and “low” flame propagation rate.

8 25 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 1.32, weak vortex (U₀= 77 cm/s, U₀/S₁,∞= 4.90, d₀/δ_D= 143.1), and “low” flame propagation rate.

8 26 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 1.49, weak vortex (U₀= 77 cm/s, U₀/S₁,∞= 5.53, d₀/δ_D= 126.6), and “low” flame propagation rate.

8 27 Flame radius history for C₃H₈-O₂-N₂ flames undergoing an early kernel-vortex interaction with the weak vortex (U₀= 77 cm/s) at the “low” flame propagation rate.

8 28 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 0.69, strong vortex (U₀= 398 cm/s, U₀/S₁,∞= 18.54, d₀/δ_D= 195.3), and “low” flame propagation rate.

8 29 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 0.87, strong vortex (U₀= 398 cm/s, U₀/S₁,∞= 21.11, d₀/δ_D= 171.2), and “low” flame propagation rate.

8 30 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 1.08, strong vortex (U₀= 398 cm/s, U₀/S₁,∞= 21.70, d₀/δ_D= 166.7), and “low” flame propagation rate.

8 31 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 1.32, strong vortex (U₀= 398 cm/s, U₀/S₁,∞= 25.30, d₀/δ_D= 143.1), and “low” flame propagation rate.
8 32 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ = 1.49, strong vortex (Uₒ= 398 cm/s, Uₒ/SL∞ = 28.57, dₒ/δₒ = 126.6), and “low” flame propagation rate.

8 33 Flame radius history for C₃H₈-O₂-N₂ flames undergoing an early kernel-vortex interaction with the strong vortex (Uₒ= 398 cm/s) at the “low” flame propagation rate.
1. Introduction

1.1 Spray Combustion Background

Description and quantification of the physical phenomena that control spray combustion processes are of great interest, as most practical combustion devices initially introduce the fuel as a two-phase flow. Applications such as residential heating, land and air-based transportation or propulsion, and power generation all benefit from the combustion of 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 can play an important role in determining how the flame structures will exist.

One of the most common strategies for producing a spray for combustion, and the type chosen for analysis in this study, is with a pressure-swirl nozzle. This method of fuel injection relies upon pressure 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 (Lefebvre, 1989). Considerable effort has been
placed on characterizing pressure-swirl nozzles for non-reacting sprays. The experimental work of Lefebvre and colleagues (Wang and Lefebvre, 1987; Chen et al., 1990; Chen et al., 1992) 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 (Couto et al., 1997; Nonnenmacher and Piesche, 2000) and initial liquid film thickness within the discharge orifice (Nonnenmacher and Piesche, 2000; Rizk and Lefebvre, 1985). Modeling approaches for calculating drop size distributions of generalized sprays, including maximum entropy, discrete probability function, and empirical methods have been developed, and their predictive capabilities are thoroughly reviewed by Babinsky and Sojka (2002).

The spray may be characterized as a hollow or solid cone, with the solid cone exhibiting higher droplet counts towards the spray centerline, especially at locations well downstream of the nozzle orifice. The extent to which a pressure-swirl nozzle produces a “solid” cone depends on the specific design, and the nozzles often used in combustion applications (Delavan Spray Technologies, 1998) (e.g. Delavan WDB) perform similarly to their hollow cone counterparts (Delavan WDA). Experimental data is available in the literature for both types of Delavan oil burning nozzles for non-reacting cases. Drallmeier and Peters (1994) measured radial distributions of droplet Sauter mean diameter, velocity, and liquid volume flux at three axial locations (50, 150, 250 mm) for an evaporating iso-octane solid cone spray from a WDB nozzle (30° cone angle, 412 kPa pressure drop, 1.37 g/s flow rate) in a low-speed air co-flow. Herpfer and Jeng (1997)
used a streaked particle image velocimetry and sizing technique to provide radial drop size profiles as well as point-wise size and velocity distributions at a 152 mm axial location for solid cone water sprays generated from a WDB nozzle (45°, 689 kPa, 19.2 g/s) subjected to a 0.25 m/s air downdraft in the same flow direction as the spray. The results from these experiments can be compared to the data acquired for WDA hollow cone nozzles. Okamoto et al. (1998) studied the water spray from a small WDA atomizer (60°, 686 kPa, 0.1 g/s) surrounded by a 3.5 m/s co-axial air stream. They utilized the phase-Doppler technique to measure size distributions as well as radial profiles of droplet size and velocity at axial locations of 15, 30, and 50 mm. One of the few detailed combusting spray studies of a WDA nozzle has been performed by Friedman and Renksizbulut (1999), who burned liquid methanol in air at atmospheric pressure. The WDA nozzle generated an evaporating hollow cone fuel spray (60°, 600 kPa, 0.42 g/s), with volumetric air co-flow rates of 0, 4.77, and 9.52 liters per second. Aside from OH-PLIF imaging of the reaction zone structures, they measured radial profiles of Sauter mean diameter and droplet volume flux at locations 25, 60, and 100 mm downstream of the nozzle, in addition to providing both gas phase and large droplet (>30 µm) velocity fields (Friedman and Renksizbulut, 1999).

The data from these experimental investigations indicate that the sprays generated by Delavan solid cone nozzles actually exhibit similar global trends as the hollow cone nozzles, with the effect of the initial sheet on radial distributions of droplet size and liquid volume flux clearly evident. Thus, both sprays can be characterized by a thin conical sheet at the nozzle orifice, and the analyses presented by Lefebvre (1989) for near-field behavior of pressure-swirl nozzles (such as Reynolds number) can be applied. Other
related studies using Delavan pressure-swirl nozzles include laser sheet drop sizing techniques for rapid characterization of dense sprays (Le Gal et al., 1999; Sankar et al., 1999) and an investigation of the effect of fuel injection pressure on fuel spatial distribution and spray cone geometry (Zhang and Ngendakumana, 1992). True solid cone sprays generated from pressure-swirl nozzles, where the exit orifice is fully flooded and the peak droplet mass flux occurs at the spray centerline, have received relatively little attention. Yule et al. (2000) have contributed much needed droplet size, velocity, and liquid mass flux measurements of a solid cone water spray utilizing a turbulence generating nozzle insert that prevents the formation of a conical sheet. It is important to note that this type of nozzle is generally suited for industrial cooling and cleaning operations, where uniform droplet coverage is desired, and is not designed to be used in spray combustion systems (Yule et al., 2000).

These research efforts have characterized the performance of oil burning pressure-swirl nozzles and set the groundwork for experimental studies in spray flames. Although far-field behavior of non-reacting sprays will differ from that observed in a turbulent lifted spray flame, the near-field characteristics of the spray cone below the flame leading edge and along the cool spray core will be similar. Therefore, the extensive results for pressure-swirl sprays are useful in elucidating the flame-flow phenomena that exist in a reacting spray environment.

Early experimental work in spray flames (Onuma et al., 1974; Onuma and Ogasawara, 1975), utilizing an air-atomized spray jet, indicated that the spray flame burns in a similar manner as turbulent gaseous diffusion flames. These results were based on a piloted kerosene flame in which the droplets evaporated close to the atomizing
nozzle and provided fuel vapor for combustion. More recent experiments in turbulent spray flames (Friedman and Renksizbulut, 1999; Cessou and Stepowski, 1996; Cessou et al., 1999; Allen et al., 1995) 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 nature of the flame and its effect on flame stabilization. The experimental results of Cessou and Stepowski (1996) and Cessou et al. (1999), 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 reaction zone. The fuel droplets traverse this inner zone to be vaporized in the hot viscous region, bounded by the double flame, which serves as a fuel vapor source to feed both reaction zones. These conclusions are supported by the numerical work of Continillo and Sirignano (1990), who modeled laminar counterflow spray flames in which a monodisperse \( n \)-octane spray was present in one of two impinging air streams. Their study predicted the dual diffusion flame zones for several strain rates and initial droplet sizes (55-500 s\(^{-1}\); 10-100 µm investigated, respectively).

The theoretical investigations of Greenberg and Sarig (1996; 1997) also indicate the possibility of multiple reaction zones in the laminar counterflow spray combustion 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 a premixed flame may develop in addition to the two diffusion flames observed in the previous studies (Cessou and Stepowski, 1996; Cessou et al., 1999; Continillo and Sirignano, 1990). This triple flame
scenario is possible only in a slightly oxidizer rich mixture prior to the premixed flame front. A fuel vapor rich (including stoichiometric) or very oxidizer rich mixture results in a double flame (premixed/diffusion pair) or a single premixed flame, respectively. These analytical investigations provide details on spray flame behavior that can give insight into the characteristics observed in turbulent spray flames.

Experimental studies of turbulent reacting sprays, and most practical combustors, usually utilize polydisperse sprays that possess 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 follow the gas phase flow well and therefore have increased residence times in turbulent eddies, will vaporize easily and generate fuel vapor prior to reaching a reaction zone. This scenario supports the notion of partially premixed combustion. The smaller droplets provide fuel vapor for premixed combustion at the primary flame front while the larger droplets can burn either individually or vaporize to be consumed in one of the other possible homogeneous diffusion flames, depending on the local stoichiometry. This issue motivates the work presented in this dissertation. In light of the flame structure observations made in the air blast spray configuration (Cessou and Stepowski, 1996; Cessou et al., 1999), turbulent spray flames produced by pressure-swirl nozzles, both hollow (WDA) and solid (WDB) cone, have been investigated using OH Planar 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 the spray. The atmospheric ethanol spray flame presented here is used to gain an increased understanding of spray flame structure in an environment for which investigations are sparse. The experimental results of
Friedman and Renksizbulut (1999) and Allen *et al.* (1995) both indicate that reacting sprays generated from pressure-swirl nozzles can exhibit the double flame structure, but no discussion on the modes of combustion is given. In addition, both works utilized a bluff body around the fuel nozzle to induce recirculation zones for flame stabilization. A co-flowing air stream was also provided at the periphery of the bluff body. The present study does not utilize such a stabilization device, and instead utilizes a low-speed air co-flow that interacts directly with the flame base to study the effects of air entrainment and flame-flow interaction on flame stabilization and the double reaction zone structure.

1.2 Flame Kernel-Vortex Background

Understanding the physical processes governing turbulent combustion is a classical problem that remains the focus of many experimental, numerical, and theoretical investigations. Most research efforts attempt to treat the turbulent flame in a simplified manner, hoping to use fundamental concepts to create the building blocks of turbulent combustion theory. The complex coupling between the flow field and the flame must be considered over a wide range of length and time scales. Experimental data has shown that turbulent combustion can be viewed as the interaction of the flame surface with vortices of varying characteristic scales. These vortices have the ability to locally affect flame front propagation by altering the flame shape (at large scales) and transport properties (at small scales) of the reaction zone. These effects, which are strongly dependent upon the fuel-oxidizer characteristics, include flame wrinkling, intensification/inhibition of the chemical kinetics, local quenching, and even global extinction in some cases. In order to quantify the flame-vortex interaction, a parameter
termed the flame stretch rate has been identified. Flame stretch, in the most basic sense, represents the fractional time rate of change of the area of a Lagrangian flame surface. Specifically, flame stretch rate takes into account the contributions of both hydrodynamic strain rate and flame curvature. The strain exerted upon the flame results from velocity gradients tangential to the flame surface and therefore controls convective transport. Flame curvature contributes to flame stretch since it dictates the gradients of scalars, such as species concentration and temperature, which are directly related to the transport of species and heat. The flame’s response to the stretch rate depends upon the thermo-diffusive properties of the reactant mixture, represented by both the Lewis (Le) and Markstein (Ma) numbers. These non-dimensional quantities indicate if a mixture is thermo-diffusively stable or unstable. Thermo-diffusively stable mixtures (Le>1, Ma>0) are characterized by reduced laminar burning velocities (relative to the unstretched value) for a positive stretch rate and enhanced burning velocities for negative stretch rates. Thermo-diffusively unstable mixtures (Le<1, Ma<0) simply have the opposite response.

The vortices present in a turbulent flame represent a spectrum of length and time, or velocity, scales. Unfortunately, these scales are coupled in actual turbulent flames and the independent contributions of these scales to flame stretch can not be easily quantified. However, simplification of the physical processes in turbulent flames to the interaction of a laminar flame with a single vortex of known length and velocity scales makes this independent quantification possible. Past work initially studied the interaction of a laminar vortex toroid with a spark-ignited flat laminar flame. Roberts (1992) pioneered the study of these premixed flame-vortex interactions which sparked many subsequent research efforts throughout the 1990’s. Renard et al. (2000) provide a comprehensive
literature review and discussion of flame-vortex interactions, with their work encompassing theoretical, numerical, and experimental investigations (premixed and non-premixed) performed during this time period. In addition, they describe the various configurations utilized in flame-vortex studies, including an extensive background of non-reacting vortex flows.

Since the review of Renard and co-workers, several other investigations have considered premixed flame-vortex interactions. Bell et al. (2000) performed numerical simulations of flat, nitrogen-diluted premixed methane-air flames interacting with a vortex pair of similar characteristics as experimentally investigated by Nguyen and Paul (1996), whose work considered a rich methane-air flame and indicated dramatic changes in CH and OH concentrations as a result of the interaction. Interestingly, the results of Bell et al. (2000) agree with Nguyen and Paul (1996) with respect to the marked decrease in CH concentration, but do not corroborate the increased OH signal observed experimentally. This phenomenon was further investigated by Vagelopoulos and Frank (2002), who probed the transient response of OH-PLIF signals to varying flow geometries and mixture conditions in premixed methane-air flame-vortex interactions. They compared results from two burner geometries consisting of V-flames and axisymmetric counterflow flames. The V-flame interacted with a line-vortex pair in the same configuration as used by Nguyen and Paul (1996), while the counterflow flame experienced unsteady stretch imposed by a vortex toroid. Results of Vagelopoulos and Frank (2002) indicate a different response of the flame to stretch between the two flame-vortex geometries. The V-flame exhibited the OH burst observed by Nguyen and Paul (1996) for nitrogen-diluted stoichiometric and fuel-rich flames. The counterflow flame
did not exhibit this OH burst early in the interaction, but the fuel-rich counterflow flames did have increased OH signal along the sides and trailing edge of the vortex at later times, likely due to curvature effects and flame-flame interactions. Therefore, a strong coupling between the flow field and chemistry was observed (Vagelopoulos and Frank, 2002), suggesting the need for more detailed analysis of the effect of unsteady stretch on flame propagation, especially for incorporation into future numerical models. More recently, Sinibaldi et al. (2003) tested the theory of flame stretch, which relates laminar flame speed to flame stretch rate, during unsteady wrinkling of methane-air and propane-air flames. They chose to investigate the interaction of a flat laminar flame with a vortex toroid of varying strength. Spatially and temporally resolved stretch rate measurements were made along the flame surface using a simultaneous PIV/OH-PLIF diagnostic in conjunction with high-speed shadowgraph imaging. The experimental trends support the well established theory of flame stretch, although measurements of the Markstein number support the postulation (Bradley et al., 1996; Poinsot et al., 1992) that separate Markstein numbers should be identified for the individual strain and curvature contributions to stretch rate (Sinibaldi et al., 2003).

The research described up to this point has focused on interactions between a vortex and a flame that does not impose its own time-varying curvature along the flame surface. In other words, these studies have used either stationary flames or well established flat, propagating flame fronts. In order to probe the effects of stretch on “young” spark-ignited flames during the transitory period between ignition and fully developed flames, some experimental research has analyzed the interaction of laminar vortex toroids with spherical flame kernels, introducing the time varying curvature of the
flame front, further enhancing the unsteady stretch dynamics experienced during this flame-flow interaction (Eichenberger and Roberts, 1999; Xiong, 2001). The first flame kernel-vortex interactions were observed using OH-PLIF to determine the degree of flame wrinkling and the ability of vortices of varying size and strength to globally quench combustion in lean methane-air flames (equivalence ratio of 0.55) at atmospheric pressure (Eichenberger and Roberts, 1999). The authors found that, depending on the vortex characteristics and time of interaction, the disturbed flame existed in both the flamelet regime (continuous reaction zone) and distributed reaction zone regime (coexistence of reactants and products). In addition, the results indicate that larger vortices require lower vortex strengths to incur global extinction of the flame kernel, but smaller vortices could continue to quench more mature kernels than larger vortices at their respective vortex strengths (required for extinction of the smallest kernel). A second experimental effort conducted by Xiong (2001) expanded the scope of the flame kernel-vortex interactions by investigating spark-ignited lean methane-air and lean propane-air mixtures at atmospheric pressure using high-speed imaging of CH* and OH* emission, as well as a single-shot OH-PLIF diagnostic to detail the two-dimensional structure of the interaction. Four characteristic vortex sizes were considered, as well as three vortex strengths for each size class. Augmentation of kernel growth rates due to the vortex disturbance, as well as Lewis number effects, were primary objectives of the research. Additionally, the effect of local mixture conditions on flame kernel growth was assessed by utilizing charge stratification, where a methane-air kernel with an equivalence ratio of 0.6 interacted with vortices ranging from pure air to pure fuel. Charge stratification, which simulates local enrichment conditions near the spark
electrode in direct injection lean burn engines, was shown to suppress combustion when very lean vortices (outside flammability limit) were generated but enhanced the combustion intensity with fuel-rich vortices as expected (Xiong, 2001).

It is important to emphasize that the existing literature concerning experimental flame kernel-vortex interactions has restricted the test conditions to fuel-lean hydrocarbon-air reactant mixtures at atmospheric pressure. Therefore, the resulting reaction zones did not exhibit any flame instability, or cellularity, due to the preferential diffusion of species versus heat. Since methane is only slightly unstable in atmospheric fuel-lean mixtures, these flame surfaces remain smooth until perturbed by the invading vortex, whereas the lean propane-air flames are thermo-diffusively stable and also remain smooth prior to the interaction. Cellular structures begin as cracks along the flame surface, which propagate in all directions to form individual cells. These cracks occur in regions of negative stretch (concave to reactants) in thermo-diffusively unstable flames, and the burning velocity can decrease to the point of quenching (Bradley et al., 2000). As each cell grows due to flame expansion, the local stretch rate decreases due to decreasing curvature and causes the cell to destabilize and divide into multiple cells. These new cells, initially stable due to increased curvature, or positive stretch, will repeat the process of expansion and division. Eventually, this cycle will result in the flame becoming turbulent. Several groups have studied flame instabilities recently in outwardly propagating spherical flames, with the onset and propagation of these cellular structures characterized for several fuels and mixture conditions. Bradley et al. (1998; 2000) observed the evolution of thermo-diffusive instabilities in iso-octane-air mixtures at atmospheric and elevated pressures. These results have important implications for actual
engine combustion, since these cellular structures will significantly enhance reactant consumption rates due to increased flame surface area. In addition, local quenching along the cracks on the flame surface may also negatively affect engine emissions. In order to provide comparison with “light” hydrocarbon fuels, Gu et al. (2000) extended the work of Bradley et al. (1998) using methane-air flame kernels over a range of equivalence ratios and pressures. The spherical flames exhibited cellular instabilities at the higher pressures, and interestingly were characterized by acceleration rates similar to those of iso-octane. In addition, Gu et al. (2000) were able to correlate the dependence of the critical radius for the onset of flame instability with the Markstein number. Other research has focused on controlling, or retarding, the transition to cellular flames. Law et al. (2004) analyzed the effect of propane addition to hydrogen-air flames. This approach stems from the need to control the relatively high intensity of hydrogen combustion for possible use in internal combustion engines. Both experimental and theoretical techniques were utilized, and the results showed that the mixing of hydrogen with a heavy hydrocarbon such as propane does delay the onset of instability, raising the possibility of blending fuels for future practical applications (Law et al., 2004). Several other related studies include calculations of critical Lewis numbers of several common fuels indicating the threshold for thermo-diffusive stability (Clarke, 2002) and consideration of cellular instabilities in large-scale premixed explosions (Bradley, 1999; Bradley et al., 2001).

In light of the past work using both well established flames and flame kernels, the current research seeks to investigate flame kernel-vortex interactions over a much larger parameter space than previously possible. Of particular emphasis has been the
occurrence of both local and global extinction as a result of these interactions, requiring vortices of sufficient velocity (and vorticity). In addition, the thermo-diffusive response of the flame to stretch is probed by utilizing both methane and propane fuels over a range of equivalence ratios. Methane-air mixtures are thermo-diffusively unstable in fuel-lean flames and gradually stabilize with increasing equivalence ratio. In contrast, propane-air mixtures are stable in fuel-lean flames and de-stabilize in fuel-rich environments. Although methane-air flames exhibit a weak Lewis number dependence, the unstable rich propane-air flames are characterized by cellular instabilities without the interaction with the vortex, and the addition of unsteady stretch induced by the invading vortex invokes a vigorous flame response. In order to isolate flame speed from the chemistry, nitrogen dilution is used to control the flame propagation rates for all equivalence ratios investigated through reduction in peak flame temperature. This approach allows all the mixtures to be analyzed at common flame speeds so that the kernel-vortex interaction proceeds in a similar manner for each case. Characterization of each mixture is attained through determination of the unstretched laminar burning velocity and Markstein number. The primary diagnostic tool for the flame kernel-vortex interactions is high-speed broadband chemiluminescence imaging of the flame front. In addition, flow visualization and Particle Image Velocimetry (PIV) is utilized to characterize the dynamics of the vortices investigated.
2. Experimental Configurations, Conditions, and Procedures

2.1 Spray Combustion Experiments

The experimental setup for the spray combustion research was designed to facilitate turbulent spray flame characterization and the comparison of these characteristics to those specifically found in the lifted turbulent gaseous diffusion flames of Watson (2002). Particular focus of the diagnostic techniques was the investigation of the combustion structures found near the flame leading edge, or stabilization point, and the morphology of those structures resulting from air entrainment at various liftoff heights due to air co-flow. General description of the experiments is given here, with specific details discussed in the following chapters.

2.1.1 Spray Burner Configuration

The spray burner utilizes a central spray nozzle surrounded by an annular air co-flow. The design of the burner provides a 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 (0 to 0.29 m/s) to influence the flow field, promote entrainment, and modify the flame structure. Delavan pressure-swirl oil burning nozzles were chosen to supply the desired polydisperse fuel spray and can provide a variety of spray characteristics including cone angle (30-60 degrees), cone type (hollow or solid), and flow rate (0.864-2.21 liters per hour). Each of these parameters influences the resulting
drop size and velocity distributions, therefore affecting the flame structures that will exist. As stated earlier, the region of interest in the spray flame was near the stabilization point, and Fig. 2.1 provides an image of this region with the appropriate structures labeled. The continuous fuel spray is generated using a Bosch automotive fuel pump and an Aeromotive fuel pressure regulator, providing a 482 kPa (70 psi) injection pressure differential across the nozzle orifice. This choice of hardware necessitates a 12 volt DC power supply and switch. Co-flow air was provided either by compressor or a centrifugal fan, and the air velocity at the co-flow exit was measured with a TSI Velocicalc air velocimeter.

2.1.2 Optical Diagnostics

Both OH Planar Laser-Induced Fluorescence (OH-PLIF) and smoke visualization were performed in the stabilization region of the flame. 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 (Cessou and Stepowski, 1996; Donbar et al., 2000). 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 (Kelman and Masri, 1997; Tanoff et al., 1996). The OH-PLIF diagnostic, shown in Fig. 2.2, utilizes a frequency doubled Nd:YAG laser (Continuum Surelite III) pumping a dye laser (Lambda...
Physik FL3002) with an output wavelength of 562.50 nm. The beam is frequency doubled to 281.25 nm to excite the R1(8) transition of the A^2Σ<->X^2Π(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 (Dieke and Crosswhite, 1962). A Pellin Broca prism segregates the UV beam, which is then reflected to a series of lenses (f= -75 mm spherical, f= 500 mm spherical, f= 1.2 m cylindrical) to provide a 38 mm high laser sheet that passes through the centerline of the burner with an energy of approximately 3 mJ per pulse. A Princeton Instruments ICCD camera positioned normal to the laser sheet captures the OH fluorescence on a 576 x 384 pixel array with a 105 mm f/4.5 UV-Nikkor lens and a detection gate width of 200 nanoseconds. WG-305 and UG-11 filters reduce the elastic scattering signal from fuel droplets, although some scattering is still observed from the largest drops.

Smoke visualization is facilitated by utilizing a continuous-wave Ar⁺ laser sheet (514.5 nm) formed with a -40 mm focal length cylindrical lens (Fig. 2.3). The diverging sheet passes through the centerline of the burner illuminating a 100 mm high region above the spray nozzle. Incense smoke injected into the co-flow annulus within the plane of the laser sheet supplies smoke to the air co-flow providing highly visible light scattering. A digital camera placed normal to the visible sheet then records the signal as single-shot (4.3 megapixel color digital camera) or high-speed digital video (Redlake MotionScope, up to 2,000 frames per second) images with sufficiently fast exposure times to freeze the flow. The smoke streams are visualized to observe both entrainment of the co-flow air and the subsequent mixing of the turbulent flow along the shear layer within the flame’s spray core (the non-burning region of the spray encapsulated by the
innermost reaction zone). Comparisons can be made regarding the strength of ambient air entrainment and the effect on reaction zone structure with regard to co-flow velocity, spray characteristics, and flame liftoff height. This visualization serves as complementary data to support the results from the OH-PLIF measurements.

### 2.2 Flame Kernel-Vortex Experiments

Flame kernel-vortex interactions, due to their transient nature, require an experimental setup that is very repeatable and easily controlled so that a wide parameter space may be investigated over many experimental runs. In particular, this research effort utilizes the following five independent variables to probe this parameter space and gain a better understanding of the effect of unsteady flame stretch rate on flame propagation: fuel type (propane/methane), equivalence ratio (fuel lean -> rich), flame speed (%N₂ dilution), vortex strength (laminar -> turbulent), and time of flame kernel-vortex interaction (early/medium/late). This section describes the hardware configuration, conditions, and procedures associated with the execution of the experiments.

#### 2.2.1 Burner Assembly

The experimental setup used to generate the flame kernel-vortex interactions, illustrated in Fig. 2.4 and pictured in Fig. 2.5, consists of three major components: combustion chamber, vortex generation apparatus, and ignition system. The stainless steel combustion chamber, constructed during a previous investigation of flame kernel-vortex interactions (Xiong, 2001), has been upgraded to increase both repeatability and
the available parameter space for the current research. The combustion chamber has a large volume of 32.7 liters, much larger than the volume occupied by the flame during data acquisition, so that there is no effect of the chamber surfaces on flame propagation and the experiment can proceed isobarically during the time of interest. In addition, four solenoid exhaust valves located at the bottom of the chamber (see Fig. 2.6) are opened just prior to ignition and remain open during the experiment to further ensure isobaric conditions at atmospheric pressure.

Optical access for imaging the flame-flow interaction is provided via two 5 inch quartz windows (0.5 inches thick) which allow image acquisition in the ultraviolet and visible spectrum, particularly important in combustion diagnostics. Orthogonal to these windows are two smaller quartz windows (one on each side of burner) which provide laser access to the chamber for full characterization of the fluid-chemistry dynamics using diagnostics such as Laser-Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV). Adjacent to these laser access windows are ignition electrodes, which enter from opposing sides of the burner and are oriented horizontally to provide central spark ignition of the reactant mixture. The stainless steel electrodes, initially covered by insulating ceramic tubing, transition to 0.4 mm diameter in the chamber to minimize flow disturbance and heat loss from the flame, both of which can significantly affect flame propagation. One electrode is mounted on a translating mechanism, shown in Fig. 2.7, to provide fine adjustment of the spark gap, nominally 2-3 mm, which may be used to investigate the influence of ignition energy on flame development as a result of varying the breakdown voltage across the gap (increasing voltage as gap is increased).
The vortex generation device is located at the top of the combustion chamber as shown in Figs. 2.4 and 2.5. The vortex apparatus consists of the linear actuator, piston/ring package, and stainless steel cylinder with a sharp-edged orifice located at the bottom. The relative orientation of these components is illustrated in Fig. 2.8. This device is used to generate axisymmetric three-dimensional vortex rings, or toroids, that propagate downward towards the ignition electrodes and interact with the expanding spherical flame kernels. The linear actuator, pictured in Fig. 2.9, utilizes a high-thrust computer-controlled servo motor coupled to a ball screw (8 turns per inch) through a 2:1 gear reduction. This design delivers linear motion with peak thrust of 440 pounds at a velocity of 5 inches per second. The output of the linear actuator is coupled to an aluminum shaft which drives the piston/ring assembly within the cylinder. Piston displacement, slew velocity, and acceleration are easily programmed (serial communication between computer and motor) and feedback controlled via an incremental encoder (internal to the servo motor) with a position accuracy of 2000 counts per revolution. This configuration gives the user complete control of the piston dynamics within the performance constraints of the actuator. The aluminum piston was designed to hold two cast iron rings to prevent leakage of reactant mixture past the piston and infiltration of ambient air into the cylinder. Vorticity is generated by the sharp-edged orifice at the bottom of the cylinder, which will develop into a translating vortex toroid, once the piston impulsively displaces a specified volume, thereby ejecting rotational fluid out of the orifice. Carefully controlled piston dynamics result in well defined and repeatable vortex characteristics, providing a distinct advantage compared to using the stepper motor/screw and open-loop driver assembly utilized in previous research efforts.
During experimentation, the piston displacement is set at 1.0 mm for all cases, but the piston velocity is changed so that various vortex rotational velocities (or strengths) may be investigated. The diameter of the orifice is 10 mm, and the distance from the orifice to the electrode tips is 100 mm, resulting in an approximately 25% increase in vortex core-to-core diameter during propagation.

Spark ignition of the fuel-air mixture is accomplished using an inductive discharge ignition system shown in Fig. 2.10. This system, comprised of a DC power supply (~13.8 volts), ignition control module, and coil, is fully programmable and interfaces with the host computer via serial communication. Ignition energy is easily controlled through software, resulting in adjustable arc durations of ~1-3 ms, with 2 ms being the nominal value chosen for this experimental work. Since the ignition system is designed to work with internal combustion engines, the user must provide a set of surrogate flywheel tooth and TDC (top dead center) TTL pulse trains emulating engine operation. In order to only generate a single spark for the experiment, the ignition system must receive three sets of these pulse trains, resembling the first three engine revolutions during the initial startup of an engine. The first “revolution” initializes the ignition module and alerts it of an engine trying to start. A second set of pulse trains is labeled as the “confirm” cycle. The third, and final, set of pulse trains serves as the “fire” command which results in a spark event coincident with the rising edge of the third TDC signal (the ignition timing advance is set to zero in the software). Any additional pulse trains will result in an additional spark every cycle at TDC. Monitoring of the spark output is accomplished by recording the voltage trace on an oscilloscope using a 10:1 attenuator probe. Figure 2.11 gives a voltage trace of a typical ignition spark provided by this
ignition system. All three phases of the spark event are observed: ionization, arc discharge, and glow discharge. The arc discharge is responsible for transferring most of the energy into the flame kernel and therefore defines the arc duration, which is approximately 2 ms for the voltage trace in Fig. 2.11. Erosion of the electrode tips must also be monitored to maintain the desired spark gap.

2.2.2 Operation of Burner Apparatus

The hardware control and coordination for the burner assembly is handled by two personal computers. The “primary” computer utilizes LabView 6.1 software and a National Instruments PCI-6602 board providing eight 32-bit counter/timers and up to 32 digital I/O lines. Therefore, this computer handles all of the timing and triggering signals required to operate the burner for flame kernel-vortex interactions and subsequent data acquisition. The “secondary” computer simply controls the transfer of the necessary programs to the linear actuator for the generation of various vortex characteristics. All of the hardware is configured to accept standard TTL inputs, except the exhaust valves, which require a digital output (high) signal on a DC-AC relay to provide AC current to the solenoids. A schematic of the hardware and associated connections is given if Fig. 2.12.

When the operator starts the LabView program to initiate an experimental run, assuming the desired reactant mixture has been achieved and the inlet valve has been closed, the exhaust valves close and seal the chamber to allow the mixture to settle to a quiescent state (usually a few minutes). Then, a button on the LabView front panel labeled “START” is clicked, which immediately opens the exhaust valves. After a 10 ms
delay, a master trigger pulse is internally generated which serves as the signal from which all other triggers are referenced. This approach provides highly repeatable burner operation. The only delay that requires adjustment is the TTL signal triggering vortex generation, since different vortex strengths have correspondingly different translational velocities and different interaction times between the kernel/vortex are desired. Figure 2.13 graphs the timing sequence during burner operation for a flame kernel-vortex interaction.

2.2.3 Vortex Characterization

The vortices utilized in this experiment were characterized based on vortex rotational velocity $U_\theta$, defined as the tangential velocity at the edge of the vortex core. This characteristic velocity, also termed vortex strength, indicates the degree of stretch the vortex will exert on a given flame surface. This convention is based on the Rankine vortex, which assumes a linear relationship of the tangential velocity as a function of radius within the core (solid body rotation), and therefore reaches its peak value at the outer edge. Outside of the vortex core, viscosity leads to ambient gas entrainment while instabilities can lead to shedding of vorticity and eventually vortex breakdown. The vortex strength has been shown to be a function of the experimental parameters involved in vortex generation (Roberts, 1992):

$$U_\theta \sim \frac{\Delta V^2}{td_o}$$

(1)
where $\Delta V$ is the displaced volume due to the piston movement, $t$ is the time required to displace the volume, while $d_o$ is the orifice diameter, which determines the vortex core-to-core diameter and is therefore the characteristic length scale of the vortex. Equation 1 may be further simplified in terms of the piston dynamics so that these parameters can be directly controlled to achieve vortices of desired strength:

$$U_0 \sim (vl/d_o) \cdot C^4$$

where $v$ is the piston speed, $l$ is the piston displacement, and the constant $C$ represents the fixed ratio of cylinder diameter, $d_c$, to orifice diameter, $d_o$ (Xiong et al., 2001).

Particle Image Velocimetry (PIV) was utilized to measure the two-dimensional cold flow velocity field of each vortex studied. The main objective of the PIV measurements was to quantify both the vortex rotational and translational velocities, which have been shown to be approximately equal (Roberts, 1992), and to determine if the vortex is laminar, transitional, or turbulent. It is important to note that the classification of a turbulent vortex is not necessarily the same as the classical view of turbulent flow. A turbulent vortex, which may exhibit significant shedding of vorticity and some disorganization along the trailing edge, can have a well defined leading edge structure and is generated with a specific length and velocity scale. The range of vortices chosen for investigation include those in this turbulent regime, but have been measured (discussed in later chapters) to remain well organized along the leading edge and therefore are able to stretch the flame according to their size and strength. A Continuum Minilite PIV system was used to provide the two 532 nm laser beams that were formed
into spatially overlapped sheets using two spherical lenses \((f= -50 \text{ mm and } f= 600 \text{ mm})\) and one cylindrical \((f= 1.2 \text{ m})\) focusing lens, as shown in Fig. 2.14. Two Stanford Research Systems DG535 digital delay generators controlled both the flashlamp and Q-switch operation of the two Nd:YAG lasers. As a result, the time separation between laser pulses was varied between 30 and 100 microseconds, depending on the time scales of the flow. Incense smoke was chosen to seed the vortex and provide scattering images both for the PIV analysis and to observe the overall vortex structure. The two light scattering images were imaged with a Redlake Megaplus ES1.0 interline CCD camera with a 1008 x 1018 pixel array coupled to a Sigma EX 50 mm f2.8 macro lens. This configuration resulted in a resolution of 33.5 pixels/mm, or an approximately 30 mm square field of view. Figure 2.15 is a scattering image of a laminar vortex showing the two-dimensional slice created by the laser sheet passing through the vortex centerline.

Due to the transient nature of the vortex, accurate timing was required so that the acquisition of particle images would occur when the leading edge of the vortex was near the electrodes. LabView software, interfacing with a National Instruments counter/timer board, controlled the triggering of the camera and the vortex generation relative to the PIV laser pulses firing at 10 Hz. Once particle image pairs were acquired, PIV processing was performed using a cross-correlation algorithm with a final interrogation region size of 32 x 32 pixels and 50\% overlap, yielding approximately 0.48 mm between velocity vectors.

2.2.4 High-Speed Chemiluminescence Imaging
The flame kernel-vortex interactions have been investigated using broadband high-speed chemiluminescence imaging primarily of CH*/OH* emission, providing spatially integrated profiles of mean reaction rate and flame front location (or extinction). A Kodak EKTAPRO model 4540 high-speed camera was lens-coupled to an Imco ILS-3 intensifier with a 105 mm UV-Nikkor lens (see Fig. 2.16) to facilitate imaging at framing rates up to 4,500 frames per second over a 95.7 mm wide by 100 mm high field of view (256 grayscale intensity counts, 256 x 256 pixel array). Data acquisition, gated around the burner operation by triggering off of the rising edge of the first TDC ignition trigger pulse, was controlled by LabView software, a counter/timer board, and two SRS DG535 delay generators, initiating the camera and intensifier just after ignition. Figure 2.17 is a wiring schematic of the hardware configuration for the chemiluminescence imaging. Oscilloscope traces of the ignition voltage and intensifier sync signal were recorded (Fig. 2.18), allowing the time between spark ignition and image collection to be measured, thus generating an accurate time history of flame propagation.

Procedures involved in performing high-speed chemiluminescence imaging of flame kernel-vortex interactions were established to yield repeatable data under well-controlled conditions. After several iterations, a set of operating procedures were finalized and rigorously followed throughout the experiment. These steps were grouped into preliminary tasks and tasks that were performed for each run. The preliminary tasks included powering up all hardware, loading applicable software, checking pertinent parameter values or states, and preparing the gas supply for fuel-air-diluent mixtures. After this initial setup, a detailed set of steps were followed to execute the experiment, the most important of which are briefly discussed here. The full set of operating
procedures for the experiment is listed in Fig. 2.19. The first step in this process is to purge any residual gases out of the vortex generation device by displacing the piston to the bottom of the cylinder. Then mass flow controllers are used to meter the appropriate amount of fuel, air, and nitrogen into the chamber to displace ten chamber volumes, ensuring a homogeneous mixture of known equivalence ratio and dilution level. The total flow rate of the reactant mixture was chosen so that this chamber purging process required about ten minutes. While the chamber continues to purge, the linear motor delay is set for proper timing of vortex generation, and the camera is prepared for data acquisition. After the gas flow requirement has been achieved, the LabView control program is started and the exhaust valves close. The piston within the vortex apparatus is returned to its home position, thereby pulling in fresh reactants with the same equivalence ratio and dilution as the chamber. Another several minutes are allowed to elapse so that the reactants may settle to a quiescent state. The next step in the procedure is to arm the camera, intensifier, and vortex apparatus before pressing “START” in LabView and initiating the experiment. Finally, the images are downloaded to the primary computer and digitized for subsequent analysis. Figure 2.20 shows a picture of the “workstation” constructed to efficiently perform these tasks for each run.

Processing of the high-speed data begins with breaking the videos up into individual images and applying an isodata thresholding algorithm to outline the flame boundary in each image. Then, the projected area of the flame kernel is measured and an effective kernel radius, \( r_f \), is calculated assuming spherical symmetry. During many interactions the disturbed flame surface is non-spherical, but since the effective radius simply scales with the projected area, it provides a basis for comparison between cases.
and to previous work (Xiong, 2001). This combination of high-speed imaging and flame front tracking allows the flame’s response to stretch to be analyzed and conclusions drawn concerning issues relevant to premixed combustion.
Figure 2.1 Photographs of ethanol spray flame, illustrating the interesting features of the near-field flame zones. The flame characteristics near the stabilization point were the main focus of the spray combustion experiments. Inset image shows entire flame length for reference.
Figure 2.2 Optical setup for single-shot OH-PLIF imaging of ethanol spray flames.
Figure 2.3 Experimental setup for smoke visualization of air entrainment in ethanol spray flames, utilizing high-speed and single-shot digital imaging.
Figure 2.4 Combustion chamber schematic.
Figure 2.5 Combustion chamber image.
Figure 2.6 Plumbing of the four exhaust valves at bottom of combustion chamber.
Figure 2.7 Translation mechanism to adjust electrode spark gap, nominally 2-3 mm.
Figure 2.8  Vortex generation apparatus.
Figure 2.9 Linear actuator used for vortex generation.
Figure 2.10  Inductive discharge ignition system comprised of DC power supply (~13.8 V), ignition module, and coil. Arc duration is programmable between ~1-3 ms.
Figure 2.11  Voltage trace of inductive discharge spark ignition system using 10:1 attenuator probe. Notice that the arc duration is approximately 2 ms, which is the value used during experimentation, but is adjustable from 1-3 ms.
Figure 2.12  Experimental hardware configuration and control schematic for burner operation.
**Figure 2.13** Timing diagram of trigger events during burner operation.
Figure 2.14 Optical setup for vortex PIV measurements.
Figure 2.15 Light scattering image of laminar vortex toroid using incense smoke. This image was acquired using the vortex PIV experimental setup.
Figure 2.16 High-speed camera and intensifier setup for chemiluminescence imaging.
Figure 2.17  Wiring schematic of hardware for high-speed chemiluminescence experiment, in addition to burner equipment shown in Fig. 2.12. The physical orientation of devices is not shown in this figure (camera is lens-coupled to intensifier, etc.).
Figure 2.18  Oscilloscope traces of both the ignition voltage and the intensifier firing during the high-speed chemiluminescence experiment. This data was used to determine the time from spark initiation until the first image was acquired for each run, providing an accurate time history of flame propagation.
**Preliminary Tasks**

1. Make sure lens cap is on intensifier
2. Turn on all power supplies: primary computer, secondary computer, apparatus power, exhaust valves, mass flow controllers
3. Power on all devices, load LabView program, vortex generation software, and intensifier terminal (ILS.TRM)
4. Check exhaust valve logic in LabView program to ensure low state during run
5. If ignition energy is to be changed, connect ignition box RS232, load WinHost software, and change ignition energy within 50-150%, default is 100% (2 ms)
6. Connect desired signals to oscilloscope channels
7. Check delays on both DG535 boxes
8. Send ILS_KV file to the intensifier with desired delay (from DG535 trigger), gate width, and gain
9. Turn on fuel, combustion air, and nitrogen bottles and check pressure
10. Check electrode gap and orientation
11. Turn ON exhaust fan

**Tasks During Run**

1. Run Purge program to push residual gases out of vortex generation cylinder
2. Load Home Position program for piston
3. Meter appropriate flow of fuel, air, and nitrogen dilution into the chamber for at least 10 volume changes
4. Start Timer
5. Check electrodes
6. Set linear motor delay in LabView for the particular case
7. At about 7 minutes, turn off lights
8. With lens cap on and at 4500 Hz, perform Aux Mem on camera keypad
9. Remove lens cap
10. When at least 10 volume changes have occurred, run LabView program to close exhaust valves, turn off all gas flow into the chamber
11. Run Home Position program, load Impulse program for vortex generation
12. Wait a few minutes for the chamber gas to become quiescent
13. Choose RANDOM READY on camera keypad
14. Arm intensifier by pressing GO
15. Run Impulse program
16. Press START in LabView
17. Stop intensifier
18. Push camera mode back to START
19. Replace lens cap on intensifier
20. Download images using IMAQ or GPIB interface, remember:
   
   Figure 2.19 List of operating procedures for high-speed chemiluminescence imaging.
Figure 2.20 Workstation for performing high-speed chemiluminescence imaging of flame kernel-vortex interactions. All equipment was configured to efficiently execute the established operating procedures.
Chapter 3

Combustion Structures in Lifted Ethanol Spray Flames

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Combustion Structures in Lifted Ethanol Spray Flames

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Abstract

The development of a double flame structure in lifted ethanol spray flames is visualized using OH Planar Laser-Induced Fluorescence (PLIF). While the OH images indicate a single reaction zone exists without co-flow, the addition of low-speed co-flow facilitates the formation of a double flame structure that consists of two diverging flame fronts originating at the leading edge of the reaction zone. The outer reaction zone burns steadily in a diffusion mode, and the strained inner flame structure is characterized by both diffusion and partially premixed combustion exhibiting local extinction and re-ignition events.
Introduction

Reaction zones in spray flames are of fundamental and industrial interest. Since many practical devices, including gas turbines, introduce fuel as a spray, an understanding of spray combustion structures may facilitate the design of combustors with increased stability, efficiency, and reduced emissions. While lifted gaseous flames have been studied extensively [1], experimental research on reaction zones in lifted spray flames is sparse. Early studies of sprays suggested a structure similar to that of a corresponding gas diffusion flame, since most of the droplets evaporate close to the fuel nozzle and only a single reaction zone is present [2,3]. More recent investigations have reported that the flame can exhibit a double structure, originating at the leading edge, that diverges with increasing downstream location [4-6]. This multi- branched reaction zone structure is of general interest regarding the nature of the leading edge of double and triple flames. Triple flames are the subject of intense experimental and numerical investigations related to their fundamental role in flame stabilization and propagation [7]. Related spray studies utilized either air-blast injection of the fuel spray with no other external oxidizer flow [5,6], or a pressure-swirl nozzle surrounded by a large bluff body with co-flow supplied by a thin annular ring [4], and have not addressed the role of air entrainment to any degree. The double flame structure, specifically from pressure-swirl nozzles in co-flow, is a focus of this paper. Visualizing reaction zones, diffusion or partially premixed, and assessing the effect of air entrainment on the leading edge of these zones is a novel aspect of this technical brief. In addition, the OH-PLIF results from this work provide a basis for comparison between lifted spray flames and the characteristics of lifted gaseous jet diffusion flames with similar co-flow.
Experimental Setup

The burner used in this study is illustrated in Fig. 1 and is composed of a central spray nozzle surrounded by an annular air co-flow. A 45° solid cone pressure-swirl nozzle supplies the desired ethanol fuel spray with a manufacturer specified overall Sauter mean diameter of 75 microns at 482 kPa injection pressure differential across the nozzle orifice and a flow rate of 0.864 liters per hour. The Reynolds number of the spray, based on the initial sheet thickness of the spray cone [8], is calculated to be 1600 at the injector exit. Rizk and Lefebvre [9] give an expression for the determination of the film thickness inside the nozzle orifice. This method of computing a characteristic Reynolds number, which is usually applicable for hollow cone pressure-swirl nozzles, is validated by the results of Drallmeier and Peters [10]. The solid cone pressure-swirl nozzle used in their investigation, of the same design utilized in this study, possesses characteristics similar to those seen in hollow cone nozzles, with the effect of the initial sheet on droplet size and liquid volume flux clearly evident. Thus, the spray presented here can also be characterized as a thin conical sheet at the nozzle orifice. Compressed air delivers the co-flow at variable flow rates (0 to 0.29 m/s) via six ports located at the base of the burner (one ten-mesh and three twenty-mesh stainless steel screens produce a uniform velocity profile across the co-flow).

OH-PLIF was employed to obtain instantaneous planar images of the reaction zones in the spray flame. OH is a good marker of the fuel-lean side of reaction zones in diffusion flames, but signals are generally broader in premixed flames because of the long-lived presence of OH molecules in the hot combustion products [5,11]. OH fluorescence in diffusion flames appears as a thin band, since the reactions are occurring
along the stoichiometric contour between the fuel and oxidizer flows. Partially premixed combustion zones exhibit “broad” regions of OH, thicker than seen in pure diffusion flames, and have been observed previously in both initially non-premixed and partially premixed flames [12,13]. The output of a frequency doubled Nd:YAG pumped dye laser is used to excite the hydroxyl (OH) radical. The dye laser output of 562.50 nm is doubled to 281.25 nm which excites the R 1(8) transition of the $A^2\Sigma - X^2\Pi(1,0)$ band. Fluorescence is then collected from the (0,0) and (1,1) bands ($\lambda \approx 306-312$ nm) [14]. A Pellin-Broca prism provides UV beam separation, and a series of focusing lenses produce a 38 mm high laser sheet. Positioned at 90° to the laser sheet is an ICCD camera with a detection gate width of 200 nanoseconds (576x384 array with a 105 mm UV-Nikkor lens; WG-305 and UG-11 filters capture fluorescence and reduce elastic scattering signal from droplets).

Results and Discussion

With respect to the results of past work without air co-flow [4], terminology is introduced 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 [15]. 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 [16] 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. This result is in contrast to the images obtained by Friedman and Renksizbulut [4], where a well developed double reaction zone structure was observed without co-flow. The hollow cone pressure-swirl nozzle used in their study has a 50% higher nominal fuel flow rate (at 861 kPa pressure differential) and a wider 60° cone angle, resulting in increased momentum and jet spread providing conditions favorable to air entrainment and the formation of an inner reaction zone even without co-flow. 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 [15], [17]). This observation explains why no cusp is observed in Fig. 2a. Kelman et al. [18] 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 [6].

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). Small pockets of OH are also noticeable at locations downstream of the inner reaction zone in some images. These isolated regions of combustion are likely pinched off of the lower inner reaction zone due to excessive strain rates that quench local combustion. The OH profile of the inner zone is noticeably thinner than the outer zone as a result of increased local strain at the flame front [18]. 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 [13,19]. 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.

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 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 the entrainment of air due to large
scale vortices [20]. 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 [19]. The oxidizer for the inner zone diffuses into the flame from the spray side of the flame front.

**Conclusions**

The structure of a lifted ethanol spray flame has been investigated using OH-PLIF. Overall, the morphology of the flame is primarily controlled by both the air co-flow velocity and the droplet distribution. Without co-flow, the flame exhibits a single flame structure similar to that observed in lifted gaseous jet diffusion flames. The addition of low-speed co-flow lifts the flame and permits increased entrainment of air. The presence of oxidizer within the fuel spray creates a unique scenario that is not seen in non-premixed gas flames. A double flame structure develops that originates at the leading edge and diverges with increased downstream location. The inner reaction zone burns in both a diffusion and a partially premixed mode. Future work is aimed at obtaining quantitative data, especially drop size and velocity distributions, to validate models of evaporation and combustion. Also of interest is the investigation of spray flames under pressure and with co-flow swirl (to enhance the flame stability), conditions typically found in gas turbines.
Acknowledgments

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References


Figure Captions

Figure 1. Layout of the burner and optical setup for acquisition of OH-PLIF images.

Figure 2. Instantaneous OH-PLIF images and photograph of spray flame at increasing liftoff heights.
Figure 1
S.K. Marley
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Figure 2
S.K. Marley
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Chapter 4

Leading-Edge Reaction Zones in Lifted-Jet Gas and Spray Flames

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Leading-Edge Reaction Zones in Lifted-Jet Gas and Spray Flames

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Abstract

An investigation of the leading edge characteristics in lifted turbulent methane-air (gaseous) and ethanol-air (spray) diffusion flames is presented. Both combustion systems consist of a central nonpremixed fuel jet surrounded by low-speed air co-flow. Non-intrusive laser-based diagnostic techniques have been applied to each system to provide information regarding the behavior of the combustion structures and turbulent flow field in the regions of flame stabilization. Simultaneous sequential CH-PLIF/particle image velocimetry and CH-PLIF/Rayleigh scattering measurements are presented for the lifted gaseous flame. The CH-PLIF data for the lifted gas flame reveals the role that “leading-edge” combustion plays as the stabilization mechanism in gaseous diffusion flames. This phenomenon, characterized by a fuel-lean premixed flame branch protruding radially outward at the flame base, permits partially premixed flame propagation against the incoming flow field. In contrast, the leading edge of the ethanol spray flame, examined using single-shot OH-PLIF imaging and smoke-based flow visualization, does not exhibit the same variety of leading-edge combustion structure, but instead develops a dual reaction zone structure as the liftoff height increases. This dual structure is a result of the partial evaporation (hence partial premixing) of the polydisperse spray and the enhanced rate of air entrainment with increased liftoff height (due to co-flow). The flame stabilizes in a region of the spray, near the edge, occupied by small fuel droplets and characterized by intense mixing due to the presence of turbulent structures.
Introduction

Many lifted flame stabilization studies have shifted their focus to approaches that lie between the fully premixed argument introduced by Vanquickenborne and Van Tiggelen [35] and the diffusion flame quenching arguments proposed by Peters and Williams [28]. In particular, partially premixed flame propagation and, more specifically, triple flame arguments have received considerable attention and Peters [29] 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 (Fig. 1). In theory, the premixed wings allow for flame propagation against the incoming unburned flow while stabilizing the trailing diffusion flame. There have been several computational triple flame studies [30,36] as well as experimental evidence in laminar jet flames [5,17,20]; however, conclusive evidence of triple flames in turbulent flows is lacking. Watson et al. [37] provide experimental evidence for “leading-edge flames” in lifted turbulent methane/air jet flames, where an outward (i.e., air-side) radial projection in CH fluorescence is seen at the base of the trailing diffusion flame. It remains unclear whether the leading-edge flame results from modification of the idealized triple flame by the flow field dynamics.

The purpose of this paper is to describe the concepts regarding the leading-edge flame observed through CH fluorescence in lifted gaseous flames and relate this structure to features observed through OH planar laser-induced fluorescence (PLIF) in lifted spray flames. The study of spray flame stabilization, in comparison to the work performed in lifted gaseous diffusion flames, is a developing area of research in which experimental results are relatively sparse. The presence of the dispersed phase adds additional
complexity to the analysis of the turbulent flow field, and the resulting reaction zone structures are strongly dependent on both the burner design and the method of fuel injection. For this investigation, the fuel spray is generated by a Delavan pressure-swirl nozzle for combustion applications. These oil burning nozzles have been studied and characterized in the published literature, with experimental data providing measurements for drop size, liquid volume flux, and velocity distributions [10,14]. Friedman and Renksizbulut [11] measured radial profiles of Sauter mean diameter, droplet volume flux, and provided both gas phase and large droplet (>30 micron) velocity fields in a reacting spray generated by a Delavan pressure-swirl nozzle. Other spray characterization work with these pressure-swirl atomizers provides laser sheet drop sizing data [19,31] and discussion on the effect of fuel injection pressure on fuel spatial distribution and spray cone geometry [42]. These experimental results provide a solid foundation of pressure-swirl spray characterization upon which the study of reacting sprays can be extended. It is important to note that the highest velocities and droplet fluxes (thus momentum) occur at the spray periphery, and the edge of this spray “cone” serves as a region of high shear and mixing. The spray can be characterized as a thin conical sheet emerging from the nozzle orifice with droplet atomization and evaporation occurring as the liquid phase interacts with the turbulent host gas.

Early studies of burning sprays [26,27] suggest a flame structure similar to that of a corresponding gas diffusion flame, since most of the droplets evaporate close to the fuel nozzle and only a single reaction zone is present. Recent experimental diagnostic research [1,4,11,24] has reported that spray flames can exhibit a double structure which originates at the leading edge and diverges with increasing downstream location. This
multi-branched reaction zone structure is of interest regarding the nature of the leading edge and its effect on spray flame stabilization. Numerical [6] and theoretical [12,13] investigations have predicted multiple reaction zones in laminar counterflow spray flames and provide insight describing the mechanisms governing spray flame behavior.

Visualization of the development of these double structures has been performed utilizing OH-PLIF in the stabilization region of a burning ethanol spray. Supplementary flow visualization, using smoke as a tracer, has also been applied to illuminate features regarding air entrainment and mixing along the shear layer in the spray. Focus has been placed on the nature of the reaction zones and the effect that oxidizer entrainment has on the overall flame morphology. These characteristics provide a basis for comparison to the mechanisms that govern the behavior of lifted gaseous flames.

**Experimental Details**

The axisymmetric gaseous flame burner consists of a 5-mm i.d. fuel jet surrounded by a concentric 150-mm co-flow tube. Methane is delivered through the fuel jet, while low-speed air (∼ 0.1 m/s) passes through the co-flow annulus. Three flow conditions were examined, resulting in three different liftoff heights. The methane jet-exit velocity for each case was 15.8, 21.2, and 27.5 m/s, corresponding to jet-exit Reynolds numbers of 4800, 6400, and 8300, respectively. Both sides of the lifted flame were imaged during the two lower flow rates (Fig. 2a), while the wider stabilization region resulting from jet spread during the highest flow rate limited these images to one side of the flame.
In order to provide a meaningful comparison between lifted gaseous and spray flames, the burner used for the spray combustion imaging utilizes a similar 152-mm co-flow with a central spray nozzle. The adjustable air co-flow provided airflow velocities ranging from 0 to 0.29 m/s, and a series of stainless steel mesh screens create a uniform velocity profile across the low-speed co-flow. A pressure-swirl oil-burning nozzle (45°, solid cone) supplies the polydisperse ethanol spray at a regulated injection pressure differential of 482 kPa (across the nozzle orifice) and a flow rate of 0.864 liters per hour, corresponding to a manufacturer specified overall Sauter mean diameter of 75 microns. The experimental setup allowed the left half of the flame base to be imaged with OH-PLIF (Fig. 2b), while the entire flame base is imaged with smoke visualization in the reacting spray.

Results from two sets of simultaneous experiments are presented for the gaseous flame case, each of which includes CH-PLIF. For this reason, the details of the CH-PLIF experimental arrangement are described below, while readers are referred to other sources regarding the other techniques. Specifically, details of the simultaneous CH-PLIF/Rayleigh scattering experiment are included in Watson et al. [39] while the joint sequential CH-PLIF/particle image velocimetry (PIV) experiment is described in Watson et al. [40].

The CH-PLIF portion includes a Nd:YAG-pumped dye laser which excites the Q_1(7.5) transition of the B^2 Σ^+→X^2 Π(0,0) band of CH (λ = 390.30 nm, pulse energy ~ 15 mJ). Fluorescence from the A-X(1,1), (0,0), and B-X(0,1) bands between λ = 420 and 440 nm was recorded by a Princeton Instruments ICCD camera [2,9]. Specifically, the fluorescence profiles were imaged onto the 576 x 384 pixel array of the ICCD detector,
which was binned by three \((192 \times 128\) pixels) to improve the relatively low signal of the CH fluorescence. The rectangular CH-PLIF images represent an approximately 37-mm-wide x 25-mm-high region of the flow including the base of the fluctuating flame.

For the spray flame, both OH-PLIF and smoke visualization were performed in the stabilization region. Planar imaging of OH fluorescence in the spray flame serves to mark the 2-D reaction zone contours in the flame and allow 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 and care must be taken in the analysis of such data [3,8]. 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 [15,34]. The OH-PLIF diagnostic, shown in Fig. 3a, 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 [7]. A Pellin Broca prism segregates the UV beam, which is then reflected to a series of lenses to provide a laser sheet that passes through the centerline of the burner. An ICCD camera positioned 90° to the laser sheet captures the OH fluorescence on a 576 x 384 pixel array, corresponding to a 40-mm-high x 21-mm-wide image region. WG-305 and UG-11 filters reduce the signal due to elastic scattering from large fuel droplets.
Smoke visualization is facilitated by utilizing a continuous-wave Ar\textsuperscript{+} laser sheet formed with a -40-mm focal length cylindrical lens (Fig. 3b). The diverging sheet passes through the centerline of the burner illuminating a 100-mm-high region above the spray nozzle. Incense sticks placed in the plane of the laser sheet supply smoke to the air co-flow providing highly visible light scattering. The signal is then recorded by both a high-speed digital camera (up to 2000 frames per second) and a color digital camera placed 90° to the visible sheet. The smoke streams are visualized to observe both entrainment of the co-flow air and the subsequent mixing of the turbulent flows along the shear layer within the flame’s spray core. Comparisons can be made regarding the strength of ambient air entrainment and the effect on reaction zone structure with regard to co-flow velocity, spray characteristics, and flame liftoff height. This visualization serves as complementary data to support the results from the OH-PLIF measurements.

**Results**

*Lifted Methane-Air Gaseous Flame*

An ensemble of simultaneous two-shot CH-PLIF/PIV images and CH-PLIF/Rayleigh scattering images were captured during each of the three gaseous flow conditions and Fig. 4 is a scatter plot of the stabilization point locations. Larger fluctuations in the liftoff height and a widening of the flame base are evident as Re\textsubscript{d} is increased (groupings of Re = 4800, 6400, and 8300). With these fluctuations, the flame spends a certain amount of time propagating upstream *against* the flow and a certain amount of time dropping back downstream *with* the flow – a trend that is simply
observed as the flame fluctuates about some average liftoff height [16]. Moreover, one can envision the upstream propagation representing the stable portion of the flame’s oscillation “cycle,” while the downstream movement characterizes the unstable portion, with flame blowout corresponding to the most extreme unstable case. One possible explanation of the phenomena is that the difference between the stable and unstable modes coincides with the local presence (and absence) of the leading-edge flame [37]. Several CH-PLIF images illustrating the leading-edge flame are shown in Fig. 5, and upon comparison with the idealized triple flame (Fig. 1), it is apparent that two of the three structures are witnessed. It is conceivable that the leading-edge flame 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 [36]. Alternatively, the air-side branch may survive since it exists in a low-speed region where the velocity is approximately 1.0 m/s as determined through PIV [25,38].

Reasons for the intermittent appearance (~ 30% of the images) of the leading-edge structure have been discussed previously [37]. Namely, it is believed that the structure does not have to exist around the entire circumference of the flame base; rather, it is only necessary along a portion of the flame base in order to stabilize the entire flame, and due to the limitations in applying a planar sheet-imaging technique to an inherently three-dimensional flow [21,32], the leading-edge structure is not “caught” within the 2-D image plane during all images. Incidentally, flame radical chemiluminescence [33] has also produced intermittent leading-edge structures [22]. With regard to this reasoning, three possibilities exist and during only one will the leading-edge structure be observable. These include the following, as summarized in Fig. 6: (a) the flame is stable (i.e.,
propagating upstream) and a portion of the leading-edge structure exists within the laser sheet, (b) the flame is stable and any leading-edge structure lies beyond the laser sheet, and (c) the flame is temporarily unstable (i.e., dropping downstream) and no leading-edge structure exists at any location around the entire flame base.

Conclusions regarding the relationship between lifted flame stability/propagation and the appearance of the leading-edge are drawn from both the sequential CH-PLIF and the simultaneous CH-PLIF/Rayleigh scattering experiments. Watson et al. [39] report that during instances when the leading-edge structure is apparent in the CH-PLIF images, the axial gradient in the Rayleigh signal across the flame zone into the unburned mixture is much steeper than during cases with no leading-edge structure (Fig. 7a vs. Fig. 7b). Based on this result, it is possible that the leading-edge structure facilitates the propagation of the flame into the unburned mixture and is thereby indicative of upstream propagation. The diffuse gradient accompanying cases with no leading-edge structure indicates that the CH zones existed further upstream during the time immediately prior (i.e., the flame is moving downstream in the direction of the flow). It is theorized that this unstable phase of downstream movement continues until a location is reached where the stoichiometry allows the leading-edge structure to return and the flame resumes its stable upstream propagation.

Recent sequential CH-PLIF images [41] provide supporting results. Specifically, image pairs are presented that illustrate the appearance of the leading edge from the first to the second CH-PLIF image while the flame has propagated upstream, while others show no leading-edge structure while the CH zones have dropped downstream from the first to the second image.
Lifted Ethanol-Air Spray Flame

The two diagnostic techniques applied to the spray flame, OH-PLIF and smoke visualization, allow the leading edge combustion structures and local flow dynamics to be analyzed qualitatively. The two cases described, no co-flow and 0.29 m/s co-flow, provide a satisfactory range of conditions wherein the flame undergoes a significant change in structure and behavior. The relationship between this flame morphology and flame stabilization is of primary importance, especially since the lifted gaseous jet flames do not undergo such drastic changes.

For the case of no co-flow, the spray flame is stabilized close to the spray nozzle, as seen from the OH images in Figs. 8a-b (pertaining to the setup shown in Fig. 3a). The combustion event is characterized by a single diffusion flame structure, similar in a basic respect, to the structure observed in lifted gaseous diffusion flames [38]. The OH images show a stable and smooth contour that is largely free from the effects of large-scale turbulence and strain downstream of the stabilization point. The stoichiometric contour in the near field of the spray flame is dictated by the droplet trajectories and evaporation rate of the fuel evident by the well-defined diverging flame boundary. Large droplets are also witnessed, from both elastic and possibly spontaneous Raman scattering, penetrating the combustion zone and continuing into the ambient air. The leading edge exhibits small fluctuations which result from slight axial oscillations of the flame base. As the flame oscillates about an average liftoff height of 7.8 mm above the spray nozzle, the leading edge changes from an abrupt absence of combustion at the most upstream OH signal location (Fig. 8a) to possessing a small cusp that projects radially inward toward
the fuel spray (Fig. 8b). This cusp at the flame leading edge marks the onset of the formation of the double flame structure and signifies the development of a flammable mixture inward of the stable diffusion flame. In order to sustain an inner reaction zone there must be sufficient entrainment of oxidizer into the spray for combustion. MacGregor [23] has shown that sprays are generally less efficient than gas jets at entraining ambient air. This lack of entrainment efficiency means that, at lower flame liftoff heights, there is insufficient momentum transfer to entrain the required air for sustaining an inner reaction zone. Large-scale mixing structures near the stabilization point, however, have the ability to stretch the reaction zone at the leading edge around vortices (see Fig. 9 in Ref. 38). Furthermore, Kelman et al. [16] have observed the entrainment of ambient fluid around the base of a methane jet flame. Therefore, when these large-scale turbulent structures exist at the leading edge of the spray flame, they can form the cusp that is often observed in the OH images without co-flow. It is important to note that these areas of flow recirculation near the stabilization point, which contain small droplets that follow the gas motion and are vaporized easily for mixing and combustion, play an integral part in lifted spray flame stabilization [4].

These results obtained from the OH images are further supported by smoke visualization of the spray under the same flow conditions. Entrainment of ambient air is very weak without co-flow (comparing Fig. 9 later to Fig. 10), where the incense smoke injected below the spray nozzle wafts around the outer flame boundary and only occasionally enters the flame base. Figure 9 shows both single-shot color photographs and a digital video sequence of the smoke visualization as streams of smoke pass through the laser sheet. The smoke follows the random motion of the ambient air unless it flows
in close proximity to the exposed spray beneath the flame resulting in momentum transfer and entrainment. There is no distinct pattern of gas flow into the flame except in the vicinity immediately adjacent to the spray edge. As shown in Fig. 9a, one region of a large patch of smoke is weakly drawn into the flame base, while the rest of the smoke follows the chaotic motion of the ambient air. The time sequence in Fig. 9c shows similar entrainment of a slow moving smoke streak as it flows down the edge of the flame until it comes in communication with the fuel spray. Most images do not show smoke entrainment, but do indicate the large-scale motion of the air, which is visualized in Fig. 9b. This is not to say that entrainment is intermittent. The spray is continuous and therefore continuously transfers momentum from the fuel droplets and vapor to the surrounding air mass. These images are presented to reveal the relative inability of the fuel spray to entrain oxidizer at low liftoff heights, thereby only allowing a single reaction zone to exist, occasionally with a cusp at the leading edge. This observation becomes significant when compared to the spray flame in co-flow as described next.

The addition of a 0.29 m/s co-flowing air stream incurs a distinct change in the spray flame structure and fluid dynamics. There is a transition from the single reaction zone observed without co-flow, to the development of a dual reaction zone structure as seen in the OH images of Figs. 8c-f. Turbulent fluctuations in the flow field likely cause the leading edge to oscillate in liftoff height (as high as 15.7 mm). The OH images reveal the evolution of the inner reaction zone as the flame liftoff height increases. The low-speed co-flow convects the flame base far enough downstream to significantly increase the entrainment rate of air into the spray due to a larger region of the spray cone being exposed for momentum transfer with the surrounding air. Initially, combustion at the
leading edge intensifies and a short, thin diffusion flame branch of the inner zone is evident (Fig. 8c), with some images showing isolated patches of OH fluorescence downstream resulting from local extinction along the turbulent shear layer (Fig. 8d). These “patches” of OH fluorescence indicate the possibility of partially premixed combustion due to extinction and re-ignition events in lifted spray flames. When the flame lifts to the highest axial locations, air entrainment is further increased and allows a flammable mixture to exist well into the core of the spray. Figure 8e shows a fully developed inner reaction zone, burning in a diffusion mode and extending downstream with local extinction occurring at an upstream position near the leading edge. In some cases, as in Fig. 8f, the inner reaction zone is continuous with flame extinction only occurring at higher axial locations as the reaction zone penetrates closer to the spray centerline. It is interesting to note that the leading edge spreads out, or widens, as the liftoff height increases and the dual flame structure develops. This observation, concurrent with the outward radial movement of the flame base, indicates a larger area that is favorable for combustion as the flame burns in a location of the spray that contains a broader region of small droplets (providing fuel vapor) due to evaporation and atomization effects. Also important is the relative thickness of the OH signal when comparing the inner and outer combustion structures near the leading edge. The inner reaction zone is noticeably thinner and more wrinkled than the stable outer diffusion flame. The thinning of the OH contour as the reaction zone curves around the leading edge towards the inner zone is indicative of combustion occurring in a region of increased strain [16]. This result is reasonable since the inner reaction zone is visibly more turbulent along the shear layer, and experiences regions of local extinction.
Further analysis of the reacting spray in co-flow is provided by flow visualization. Figure 10 contains images of the smoke visualization from the spray flame with co-flow (0.29 m/s co-flow velocity). In contrast to the results depicted in Fig. 9 (without co-flow), the entrainment of smoke, and therefore ambient air, is increased markedly in the presence of a co-flowing air stream. This indicates that the air currents induced by the spray in co-flow strongly increase the rate of ambient air entrainment to support combustion at the inner reaction zone. Figure 10a clearly shows the well-defined flow field beneath the leading edge. The streamlines of smoke are visualized as the air is entrained into the spray as it flows past the nozzle. The entrained air possesses significant radial movement before being redirected axially by the momentum of the dense spray core. The smoke can further be traced inside the spray as it travels downstream adjacent to the blue luminescence of the inner reaction zone. This region of high velocity indicates that the inner reaction zone exists along or near the shear layer created between the low-speed gas flow and the momentum-dominated region of the spray. The shear, or mixing, layer provides a region in the spray which is characterized by intense mixing due to high levels of turbulence and recirculation. Although the turbulence intensity can significantly increase local strain and scalar dissipation rates, it also provides a region populated by small droplets within a polydisperse spray and aids in the entrainment of air due to large-scale structures [18]. Therefore, the increased air entrainment, in conjunction with enhanced mixing between oxidizer and fuel vapor resulting from easily vaporized ethanol droplets, creates a scenario that permits a strained inner reaction zone.
Some images, such as Fig. 10b, show dispersion of smoke around the leading edge. In this image, the smoke being pulled towards the spray is both entrained into the spray and directed around the outer edge of the flame base. This visualization gives an indication of how the flow field divides as it approaches the flame front. The digital video sequence in Fig. 10c further visualizes the typical entrainment of co-flow air. Figure 10c also indicates how the fluid adjacent to the leading edge interacts with the flame base as the outer region of the smoke is directed downstream along the outer reaction zone while the smoke directly beneath the stabilization point gets pulled into the spray and eventually merges with the upstream entrained flow. It is interesting to note that the time scale of Fig. 10c is much shorter than that of Fig. 9c due to the much different characteristics of the ambient flow between the two cases. The presence of co-flow decreases the residence time of the gas flow near the leading edge. Although not obvious in the sequence of individual images, recirculation of the flow is observed in the videos as the smoke enters the spray.

**Leading Edge: Gaseous vs. Spray Flame**

As a result of the experimental data obtained in both the lifted gaseous and spray flames, valuable comparisons can be made regarding the characteristics of the leading edge. The turbulent gaseous flame exhibits “leading-edge” combustion structures witnessed in the CH images that serve to stabilize the flame in a region of relatively low-speed flammable gas. The argument for partially premixed flame propagation, as a primary flame stabilization mechanism [29], is a key point in the characterization of turbulent gas flames. In contrast, the OH images of the spray flame do not indicate the
same variety of premixed flame branches extending from the base of the flame. The spray flame does, however, exhibit the formation of a cusp at the stabilization point that extends inward towards the spray centerline. This region marks the point in the flow field where a second flammable layer begins to form, which extends from the base of the stable diffusion flame towards the mixing layer. This scenario is due to the polydisperse spray distribution that is created from practical pressure-swirl spray nozzles. As mixing and evaporation rates are enhanced with increased co-flow due to air entrainment, the leading edge serves as a thermal energy source to ignite the turbulent mixture possessing large numbers of small droplets with high evaporation rates residing along the shear layer. The larger droplets with ballistic trajectories simply cross the thin reaction zone to vaporize in the hot region between the two flame structures, thereby providing fuel primarily for the outer diffusion flame. This statement is supported by the observation that the outer diffusion flame is unaffected by the formation of the inner reaction zone. The inner reaction zone does experience regions of local extinction as the reactions are quenched during periods of excessive strain or scalar dissipation rates. The leading edge demarcates the location where the strain rates begin to increase dramatically, as seen by the thinning of the OH zone.

The gas flame undergoes more fluctuations in liftoff height than the spray flame (compare Fig. 4 to an average fluctuation of ~5 mm for the spray flame in co-flow), further indicating the role that the droplets play in spray flame stabilization. The fully developed turbulent flow in the gas jet, and the associated vortices, controls the behavior of the leading edge in gas flames whereas the interaction between both large-scale structures and the droplet dynamics is responsible for the characteristics and stabilization
of the spray flame leading edge. It is apparent that a time scale for vaporization in sprays must be considered in addition to the mixing and chemical times in order for the leading edge to form a secondary inner reaction zone [4]. This additional parameter introduces an extra level of complexity in the analysis of spray combustion systems. A monodisperse spray in which the dispersed phase is highly atomized and exhibits high fuel vapor production rates would likely provide similar results to those seen in lifted gaseous diffusion flames.

Conclusions

Observations of the leading edge characteristics in turbulent lifted gaseous and spray flames have been provided to compare and distinguish the mechanisms that govern the flame structure and stabilization in each respective combustion system. In the methane flame, CH-PLIF has been performed simultaneously with both particle image velocimetry and Rayleigh scattering in two independent experiments. Single-shot OH-PLIF and flow visualization was performed in the ethanol spray flame. Each flame stabilizes in a zone of high mixing due to large-scale structures in the turbulent flow field. The leading edge of the lifted gaseous diffusion flame has been shown to oscillate between modes of stable upstream propagation and unstable downstream recession. The flame finds stability in regions of low-speed flow that are within the flammability limits. This so-called “leading-edge” combustion process is accomplished due to the fuel-lean premixed branch of the leading edge stabilizing the trailing diffusion flame through premixed flame propagation. The spray flame leading edge does not indicate the same variety of “leading-edge” combustion structure, but does develop a dual reaction zone. It
is offered that flame stabilization in reacting sprays occurs where small droplets are available (to readily provide a mixable fuel vapor) and large-scale structures exist (which mix the fuel vapor with entrained air). The inner reaction zone develops along the turbulent shear layer. These main points compare and contrast flames stabilized in single and two-phase reacting flows. The authors believe these observations are timely, especially regarding the current emphasis of the combustion community on partially premixed combustion and triple flame structures [29]. In addition, these results are pertinent in applications where a liquid or gaseous fuel may be considered for use in a practical device, and the best choice of fuel may depend upon the flame characteristics and stability desired. Future work includes modifying the spray dynamics in order to clarify how fuel properties (e.g., viscosity, surface tension, density), droplet size and velocity distribution, and oxidizer flow field affect leading edge combustion and stabilization. These research tasks will require diagnostic techniques that provide quantitative characterization of the turbulent flow field and reaction zones, such as with PIV or multiple-shot PLIF, and discriminate between different droplet size classes and liquid and gas phases.

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Figure Captions

Fig. 1: Idealized triple flame.

Fig. 2: Test conditions and measurement locations for (a) methane/air gaseous flame \((Re_d = 4800)\), and (b) ethanol/air spray flame.

Fig. 3: Experimental setup for spray flame: (a) single shot OH-PLIF, and (b) smoke visualization with high-speed and single shot digital imaging.

Fig. 4: Scatter plot of the gaseous flame stabilization point locations for the three flow conditions. The horizontal and vertical lines through the data represent the average axial and radial locations, respectively.

Fig. 5: CH-PLIF images showing the leading-edge flame structure observed as the air-side projection at the base of the trailing diffusion flame.

Fig. 6: Three cases illustrating the intermittent appearance of the leading-edge structure (in both time and circumferential location) and the limitations of planar sheet-imaging techniques in representing three-dimensional flow.

Fig. 7: Simultaneous Rayleigh scattering (left) and CH fluorescence (right) images contrasting the (a) sharp vs. (b) diffuse Rayleigh signal gradient in the axial direction across the hot zone and its relationship to the presence and absence of the leading-edge CH-PLIF structure.

Fig. 8: OH-PLIF images of the left half of the flame base for the lifted ethanol spray flame showing the development of the inner reaction zone: (a) – (b) are for no co-flow while (c) – (f) are for 0.29 m/s co-flow.

Fig. 9: Smoke visualization in spray flame with no co-flow showing color digital photographs of (a) wafting smoke entrainment at flame base, (b) large-scale ambient air motion, and (c) digital video sequence of slow moving fluid flow as a smoke streak traverses upstream along the high temperature boundary of the flame until being entrained at the leading edge.

Fig. 10: Smoke visualization in spray flame with 0.29 m/s co-flow showing color digital photographs of (a) steady entrainment of smoke into spray, (b) dispersion of ambient gas flow into and around flame base, especially left side, and (c) high speed digital video sequence of strong smoke entrainment and flow of smoke around the left flame leading edge.
Figure 1
Figure 2

(a) CH$_4$ (15.8 m/s) Low-Speed Air Co-Flow (0.13 m/s)

(b) C$_2$H$_5$OH (0.864 lph) Low-Speed Air Co-Flow (0-0.29 m/s)

Simultaneous Image Region (37.4 x 24.9 mm)

Fuel Spray

Stabilization Point

Unburned Fuel

Lifted Flame

Image Region (21.0 x 39.5 mm)

5.79 mm

22.9 mm
Figure 3

Nd:YAG Laser
Dye Laser
Doubling Crystal
Pellin Broca Prism

ICCD Camera
Spray Burner
Laser Sheet
Focusing Lenses

Co-flow Diameter = 152 mm
Nozzle Diameter = 18.4 mm
Nozzle Orifice = 0.21 mm

532 nm

Laser Sheet

281.25 nm

a)

b)

Ar\textsuperscript{+} Laser
Incense Smoke
Mesh Screens

-40 mm Lens

514 nm

High-speed Digital Camera (or single-shot digital camera)

Figure 3
Stabilization Point Locations

Re_d = 8300

37.4 x 24.9 mm Image Regions

Re_d = 6400

Re_d = 4800

Axial Location (mm)

Radial Location (mm)

Figure 4
Figure 5

(a) $Re_d = 4800$

(b) $Re_d = 6400$

(c) $Re_d = 8300$

(d) $Re_d = 8300$

$\uparrow \text{CH}_4$
Figure 6
Figure 7

(a) Sharp Rayleigh Signal Gradient / Leading-Edge CH-PLIF Structure

(b) Diffuse Rayleigh Signal Gradient / No Leading-Edge CH-PLIF Structure
Figure 8:

(a) (b) (c) (d) (e) (f)
Figure 9

(a) 0.0 m/s co-flow
45° cone angle
0.864 lph

(b) f/4.8
1/500 s

(c) 0 ms
50 ms
150 ms
212 ms
349 ms
387 ms
Figure 10
Chapter 5

Effects of Leading Edge Entrainment on the Double Flame Structure in Lifted Ethanol Spray Flames

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Effects of leading edge entrainment on the double flame structure in lifted ethanol spray flames

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Abstract

OH planar laser-induced fluorescence and smoke visualization have been performed in the near field of a turbulent ethanol spray flame to investigate reaction zone structure and the effects of air entrainment on combustion. Annular air co-flow surrounds an axisymmetric spray injector utilizing a pressure-swirl atomizer to supply a hollow cone fuel spray. OH fluorescence demarcates reaction zone contours while smoke visualization indicates ambient air entrainment and turbulent mixing within the spray. A double flame structure is observed, appearing as two diverging flame fronts originating at the stabilization point, and consists of an outer diffusion flame with an inner structure that transitions from mixing controlled to partially premixed combustion downstream of the leading edge. Without co-flow, the inner branch of the double structure burns intermittently with large regions of local extinction often observed, resulting from a high droplet flux and possibly high strain/scalar dissipation rates. Addition of 0.29 m/s co-flow lifts the flame base enough to increase air entrainment and enhance inner zone combustion. The inner zone burns continuously, with no apparent local extinction, due to turbulent mixing between entrained oxidizer and fuel vapor generated by easily vaporized droplets present in the recirculations along the shear layer. The polydisperse spray distribution yields larger droplets which are able to cross the inner reaction zone and then vaporize in the hot region bounded by the double flame structure. This region serves as a fuel source to feed both the stable outer diffusion flame and the diffusive structures of the inner zone. In both cases, the flame leading edge stabilizes in the low-speed flow just outside the periphery of the spray cone, where flame propagation against the incoming flow is possible.
Keywords: spray combustion; OH-PLIF; flow visualization; double flame structure; flame stabilization; liftoff; extinction

1. Introduction

Understanding the physical phenomena that control spray combustion processes is desirable, as most practical combustion devices initially introduce the 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 can play an important role in determining the dominant flame structures. These structures are responsible, ultimately, for determining combustion efficiency and pollutant emissions.

One of the most common strategies for producing a spray for combustion is with a pressure-swirl nozzle. This method of fuel injection relies upon pressure 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 approaches for calculating drop size distributions of generalized sprays have been developed, and their predictive capabilities are thoroughly reviewed by Babinsky and Sojka [8].

The spray may be characterized as a hollow or solid cone, and the type often used in combustion applications (e.g. Delavan WDA/WDB) [9] perform similarly. Experimental data for drop size, liquid volume flux, and velocity distributions is available in the literature for both solid cone (WDB) [10,11] and hollow cone (WDA) [12] Delavan oil burning nozzles for non-reacting cases. One of the few detailed reacting spray studies of a Delavan WDA nozzle has been performed by Friedman and Renksizbulut [13], who burned liquid methanol in air at atmospheric pressure. This nozzle generates an evaporating hollow cone fuel spray (60° cone angle), and [13] investigated volumetric air co-flow rates of 0, 4.77, and 9.52 liters per second. Aside from OH-PLIF imaging of the reaction zone structures, they measured radial profiles of Sauter mean diameter and droplet volume flux in addition to providing both gas phase and large droplet (>30 µm) velocity fields [13]. Other related studies using Delavan pressure-swirl nozzles include laser sheet drop sizing techniques for rapid characterization of dense sprays [14,15] and
an investigation of the effect of fuel injection pressure on fuel spatial distribution and spray cone geometry [16].

These considerable research efforts have characterized the general performance of pressure-swirl nozzles and set the groundwork for extending the research to 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] 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 possess 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. It is this issue that motivates the work presented in this paper. In light of the observations made in the air blast spray configuration [19,20], in addition to the limited flame structure results available for reacting pressure-swirl sprays exhibiting the dual structure [13,21], turbulent spray flames produced by a hollow cone (WDA) pressure-swirl nozzle in co-flow have been investigated using OH planar 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 the spray.

2. Experimental setup

2.1. Burner configuration

The burner used in this study utilizes a central spray nozzle surrounded by an annular air co-flow as illustrated in Fig. 1. The burner was designed to provide a 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 (0 to 0.29 m/s) to influence the flow field, promote entrainment, and modify the flame structure. The 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 at a 482 kPa injection pressure differential across the nozzle orifice. This injection condition corresponds to a fuel flow rate of 2.2 liters/hour. In addition, 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]).

2.2. Optical diagnostics

Both OH-PLIF and smoke visualization were 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. 1), while the entire flame base is imaged with smoke visualization. The exact axial location of the OH imaging region varied slightly between cases in order to capture the fluctuating flame base and associated flame structures for both co-flow rates (i.e. liftoff heights). 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, shown in Fig. 2a, 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 droplets, although some scattering is still observed from the largest drops.

Smoke visualization is facilitated by utilizing a continuous-wave Ar$^+$ laser sheet (514.5 nm) formed with a -40 mm focal length cylindrical lens (Fig. 2b). The diverging sheet passes through the centerline of the burner illuminating a 100 mm high region above the spray nozzle. Incense smoke injected into the co-flow annulus within the plane of the laser sheet supplies smoke to the air co-flow providing highly visible light scattering. A color digital camera placed 90° to the visible sheet then records the signal as single-shot images with sufficiently fast exposure times to freeze the flow (1/1000s-1/250s). The smoke streams are visualized to observe both entrainment of the co-flow air and the subsequent mixing of the turbulent flow along the shear layer within the flame’s spray core (the non-burning region of the spray encapsulated by the innermost reaction zone). Comparisons can be made regarding the strength of ambient air entrainment and the effect on reaction zone structure with regard to co-flow velocity, spray characteristics,
and flame liftoff height. This visualization serves as complementary data to support the results from the OH-PLIF measurements.

3. Results and discussion

The hollow cone nozzle is well suited to provide a finely atomized fuel spray for combustion applications. Description of the near-field spray flame structures is also of fundamental interest, especially in making comparisons to the characteristics of the well-studied turbulent gaseous diffusion flames [29]. The two co-flow conditions presented here, no co-flow and 0.29 m/s co-flow, provide distinct flame behavior that results from changes in the oxidizer flow field.

The double reaction zone witnessed 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. The double reaction zone is easily observable due to the bright blue luminescence present at the flame base. Due to viscous effects, a shear layer is created at the interface between the spray cone and the surrounding gas flow. Shear layers augment transport and mixing in turbulent flows, and aid in the formation of a flammable mixture to support the inner reaction zone. Photographs of the spray flames discussed here, exhibiting the double structure, are presented in Fig. 3 for both co-flow cases. The double reaction zones are evident and the co-flow acts to stabilize the flame farther downstream (increased liftoff height) at larger radii.
3.1. Flame without co-flow

The spray combustion system was initially operated without any co-flowing air stream, and representative OH and smoke visualization images are shown in Fig. 4. The flame base oscillates around an average liftoff height of 12.4 mm (+/- 25% fluctuation around average) as the flame responds to the turbulent fluctuations of the flow field. The OH images indicate that the flame exhibits the double reaction zone structure, with local extinction occurring at upstream positions of the inner reaction zone. These regions of extinction appear in roughly 55% of the OH images. 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. From the images it is reasoned that the smallest droplets, which possess high vaporization rates, are able to feed the inner reaction zone while the large droplet population can vaporize between the reaction zone structures to supply fuel vapor primarily to the outer diffusion flame. 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. 4a (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. 4b-d). The results of MacGregor [30] indicate that sprays typically are less efficient than gas jets at entraining ambient fluid.
This entrainment inefficiency, a result of poor momentum transfer, makes it difficult to sustain an inner flame structure due to minimal oxidizer availability. In addition, this upstream region coincides with the spray cone boundary, contributing a high droplet mass flux, which can incur extinction as a result of quenching by droplets or possibly high strain/scalar dissipation rates, but quantitative measurements would be needed to support the latter possibility. Therefore, isolated pockets of combustion characterize the inner zone with continuous but diffuse regions of combustion occurring farther downstream. The broad “patches” of OH fluorescence suggest partial premixing of reactants along the wrinkled inner reaction zone. This wrinkled OH contour provides evidence that the inner reaction zone resides along the shear layer created between the momentum-dominated region of the spray and the entrained gas flow. As a result, it is reasoned that the inner zone burns in either a mixing-controlled mode, usually at the upstream locations when there is no local extinction (thin OH signal), or in a partially premixed mode downstream where there is sufficient time for partial premixing of reactants. It is important to note that the hot region bounded by the inner and outer reaction zones serves as a fuel vapor source to feed the stable outer diffusion flame and also supply fuel to the diffusive structures of the inner zone.

The smoke visualization images further support the results obtained from the OH fluorescence data. Without co-flow, the smoke is injected only on one side of the flame beneath the spray nozzle. The ambient air tends to waft around outside of the flame boundary with no distinct pattern of gas flow (Fig. 4e) except around the base of the flame where the spray is in direct communication with the ambient air. The exposed spray cone is able to entrain some air into the flame as a result of momentum transfer to
the air as in Fig. 4f. The intermittent smoke entrainment is not to say that air entrainment is intermittent. The spray is continuous and therefore continuously entrains surrounding air, but the strength of entrainment is weak and only air that flows immediately adjacent to the spray edge is pulled into the spray. The smoke can be traced well into the core of the spray and flows just radially inside the inner reaction zone boundary (Fig. 4f). These streams of oxidizer within the flame demarcate the shear layer justifying the results from OH-PLIF and clearly indicating that these areas of mixing control the location (and appearance) of the inner reaction zone in conjunction with the polydisperse spray characteristics. Another interesting feature of the flow visualization is observed near the injector tip. The strong elastic scattering from the droplets, appearing as a V-shaped structure originating at the nozzle orifice, illuminates how the droplets are distributed as a hollow cone with the highest droplet counts occurring at the spray periphery. This result is important as each luminous branch of scattering intersects the base of the inner reaction zone just inside the leading edge, further indicating the contribution of the spray cone to local extinction due to a high drop flux. The flame leading edge is always positioned on the air side of the spray edge, where small droplets and fuel vapor populate recirculation zones created at the spray-air interface. These regions of recirculation create a combustible mixture ideally suited for flame stabilization and have been discussed previously in spray combustion studies [20].

3.2. Flame with 0.29 m/s co-flow

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. 5. The flame stabilizes at an average liftoff height of 21.3 mm, which is roughly 72% farther downstream than for the no co-flow case. As a result, the flame base is located in a different region of the spray and more of the spray cone is exposed for subsequent air entrainment. The OH images in Figs. 5a-d indicate that the double reaction zone is now continuous and no longer experiences regions of local extinction. The inner reaction zone is still wrinkled and shows characteristics of partially premixed combustion due to turbulent mixing at downstream locations. The upstream combustion structure of the inner zone burns in a diffusion mode and is somewhat thinner than the outer diffusion flame, suggesting that the inner zone experiences relatively high strain rates compared to the outer zone which burns in the low-speed gas flow well isolated from the flow turbulence. Another characteristic of the flame with co-flow is that the leading edge appears wider (via OH imaging) and is more rounded than in the flames without co-flow, which exhibit a cusp structure. This observation can be explained by the realization that the flame base is stabilized downstream in a region of the spray that has had time to spread and evaporate more than in the no co-flow case, therefore creating a wider region favorable to combustion.

Flow visualization of the flame with co-flow provides further insight into the flame structures observed. Figures 5e and 5f, 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. 5f. 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. Their results are expected, since the reduced velocity difference between the jet and co-flow air results in less momentum transfer and less shear-generated recirculation which tends to “engulf” and entrain surrounding air. 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. The streamlines of smoke are visualized as the air is entrained into the spray as it flows past the nozzle. The entrained air possesses significant radial movement before being redirected axially by the momentum of the dense spray core (see Figs. 5e-f). The smoke can further be traced inside the spray as it travels downstream adjacent to the blue luminescence of the inner reaction zone. This region of high velocity indicates that the inner reaction zone exists along or near the shear layer created between the low-speed gas flow and the momentum-dominated region of the spray. The shear layer provides a region in the spray that is characterized by intense mixing due to high levels of turbulence and recirculation. The smoke visualization images in Fig. 5 capture the mixing structures as the entrained smoke flows along the spray core before being consumed by the inner reaction zone. These “branch-like structures” are indicative of vortical motions that enhance mixing between
fuel vapor and entrained oxidizer [32]. Equally important, these vortical structures in shear layers have been shown to preferentially distribute droplets, with the turbulent eddies being populated by the smaller, easily vaporized droplets while the larger drops are centrifuged out into the surrounding flow [32,33]. This scenario favors partially premixed combustion at the downstream locations of the inner reaction zone, further supporting the analysis of the OH images. 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.

It is important to note that the flame characteristics that are observed in these spray flames are highly dependent upon both the oxidizer flow field and the nozzle characteristics. As a final comparison, Fig. 6 shows OH images for a WDB 0.50-60 pressure-swirl nozzle subjected to no co-flow (Fig. 6a, 9.4 mm liftoff height), 0.29 m/s co-flow (Fig. 6b, 11.7 mm liftoff height), and a relatively high 0.43 m/s co-flow velocity (Fig. 6c, 13.7 mm liftoff height). This nozzle flows 1.6 liters/hour at the same fuel injection conditions as those used for the WDA 0.75-60 nozzle analyzed in this paper, which is about 73% of the capacity of the larger nozzle but with the same 60° cone angle. The images are taken of the full width of the flame stabilization region as indicated in the Fig. 6 photograph. Interestingly, even at the highest co-flow rate of 0.43 m/s, the flame liftoff height is lower than for the WDA 0.75-60 nozzle at a 0.29 m/s co-flow velocity (13.7 mm vs. 21.3 mm). As a result, the entrainment of air is weaker limiting oxidizer availability, resulting in a segmented OH profile along the inner reaction zone even at high co-flow rates, in addition to regions of partially premixed combustion. These results
emphasize the strong dependence of the inner reaction zone upon entrainment and the interaction between the fuel spray, fuel vapor, and surrounding air flow.

4. Conclusions

The spray combustion system studied in this experimental investigation serves to both provide fundamental insight into the structure and stabilization of lifted spray flames and to provide qualitative data that is relevant to practical combustion devices. OH-PLIF and smoke visualization have been utilized to visualize combustion structures, air entrainment to support the inner reaction zone, and to develop a better understanding of how the flame-flow interaction is involved in lifted spray flame stabilization. Cases for no co-flow and 0.29 m/s co-flow have been presented to illuminate the response of the double reaction zone to changes in the oxidizer flow field. 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. There are no 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. One key element associated with the double reaction zone, common to both cases presented here, is the
role of turbulent 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 next step in the study of turbulent spray flames is to investigate other configurations that are more directly related to real applications. Spray flames in cross flow and under pressure are of interest, as well as performing similar measurements with other fuels and nozzle parameters. The presence of a two-phase flow introduces complexities that severely limit the type of non-intrusive diagnostics that may be applied, and with advances in these techniques, the scope of future investigations will allow more detailed quantitative measurements to be made which will greatly enhance our understanding of spray combustion.

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References


**Figure Captions**

Fig. 1. Burner schematic illustrating the double flame structure and OH-PLIF imaging region.

Fig. 2. Optical setup for spray flame diagnostics: (a) single-shot OH-PLIF, and (b) smoke visualization with single-shot digital imaging.

Fig. 3. Photographs of the ethanol spray flame for both (a) 0.0 m/s co-flow, and (b) 0.29 m/s co-flow. Notice the double reaction zone structure evident at the flame base (blue luminescence) in both images.

Fig. 4. Images for hollow cone pressure-swirl nozzle without co-flow: (a)-(d) single-shot OH-PLIF, and (e)-(f) smoke visualization photographs.

Fig. 5. Images for hollow cone pressure-swirl nozzle with 0.29 m/s co-flow: (a)-(d) single-shot OH-PLIF, and (e)-(f) smoke visualization photographs.

Fig. 6. 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.
Lifted Flame
7.5-17.3 mm
C$_2$H$_5$OH (~2.2 lph)
Low-Speed Air Co-Flow (0-0.29 m/s)

Double Flame Structure

OH-PLIF Image Region (21 x 31 mm)
Fuel Spray

7.5-17.3 mm

C$_2$H$_5$OH (~2.2 lph)
Figure 2

(a) Nd:YAG Laser

(b) Ar⁺ Laser

Laser Sheet Height: 38 mm
Co-flow Diameter = 152 mm
Nozzle Diameter = 18.4 mm
Nozzle Orifice = 0.234 mm

Dye Laser

Pellin Broca Prism

Incense Smoke

Mesh Screens

Digital Camera
Figure 4
Figure 5
Figure 6
Chapter 6

Measurements of Laminar Burning Velocity and Markstein Number Using High-Speed Chemiluminescence Imaging

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Measurements of Laminar Burning Velocity and Markstein Number Using High-Speed Chemiluminescence Imaging

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Introduction

The laminar burning velocity of premixed hydrocarbon-air flames is a key parameter of both fundamental and practical significance. Accurate measurement of unstretched laminar burning velocity, especially for the heavier hydrocarbon fuels typically used in internal combustion engine applications, is necessary for assessing combustion theories and the validation of numerical models. Since the early 1990’s, experimental investigations have utilized a variety of flame configurations, including both isobaric [1-8] and non-isobaric [9,10] outwardly propagating spherical flames, flat counterflow flames [11,12], and flat adiabatic flames stabilized above a perforated plate burner to achieve nearly stretch-free conditions [13]. The stagnation flow of Vagelopoulos and Egolfopoulos [14] facilitates direct measurements of unstretched burning velocities, therefore eliminating the extrapolation to zero stretch rate required by other methods. Although numerous investigations have provided measurements of laminar burning velocity for various fuels and mixture conditions, discrepancies still exist in the published data. The objective of this work is to demonstrate the use of high-speed chemiluminescence imaging to measure unstretched laminar burning velocity, utilizing unconstrained spherical propane-air flames over a range of fuel-lean and rich equivalence ratios. In addition, the non-dimensional Markstein number, Ma, which indicates both the response of the laminar burning velocity to flame stretch and the thermo-diffusive stability of the reaction zone, is determined for each reactant mixture. These results are
then compared to the available literature to assess the validity of this technique in characterizing hydrocarbon-air flames.

The flame stretch rate, \( K \), proposed by Williams [15] defines flame stretch as the fractional time rate of change of a flame surface element of area \( A \):

\[
K = \frac{1}{A} \frac{dA}{dt} \tag{1}
\]

This general expression for flame stretch rate can be simplified for the case of unconstrained spherical flames propagating outward at constant pressure from a point ignition source [1]:

\[
K = \frac{2}{r_f} \frac{dr_f}{dt} \tag{2}
\]

Equation 2 gives a concise definition of flame stretch rate that requires only a time history of the flame radius, \( r_f \). Due to the symmetry of spherical flames, the burned gas has negligible motion, and therefore the flame propagation rate, \( \frac{dr_f}{dt} \), equals the burned gas burning velocity, \( S_b \). The flame speed can be related to flame stretch rate through the linear relationship given by Clavin [16], and has been recently applied in measurements of hydrocarbon-air flames [6,7]:

\[
S_b = S_{b,\infty} - L_b K \tag{3}
\]
where \( S_{b,\infty} \) is the unstretched (\( K=0 \)) flame propagation rate and \( L_b \) is the burned gas Markstein length. Therefore, once an accurate time record of flame radius has been obtained, \( S_b \) can be plotted against the flame stretch rate \( K \), from which a linear regression yields the unstretched flame propagation rate \( S_{b,\infty} \) as the intercept at \( K=0 \), with the slope of the regression line corresponding to \(-L_b\). The laminar burning velocity based on the unburned gas properties, \( S_L \), is related to \( S_b \) by considering mass continuity at the unstretched flame condition:

\[
S_{L,\infty} = S_{b,\infty}/(\rho_u/\rho_b)
\]  

(4)

where \( \rho_u/\rho_b \) is the ratio of the unburned and burned gas densities assuming adiabatic combustion at constant pressure.

The analysis of Faeth and co-workers [1-5] can be utilized to non-dimensionally investigate the flame response to stretch, including the determination of the Markstein number, \( Ma = L/\delta_D \), where \( L \) is the Markstein length and \( \delta_D \) is the characteristic flame thickness, both based on the unburned gas properties:

\[
S_{L,\infty}/S_L = 1 + MaKa
\]  

(5)

The Karlovitz number, \( Ka = KD_u/S_L^2 \), is a non-dimensional measure of the stretch rate and \( D_u \) is the mass diffusivity of the fuel in the unburned gas [1]. It is important to note the difference between \( L_b \) from Eq. 3, based on the burned gas properties, and the
Markstein length used here, L. Either parameter may be used for characterizing the flame response to stretch, but unburned gas Markstein length, and therefore Ma, is typically used by convention. The linear dependence of \( S_{L,\infty}/S_L \) on \( K_a \) facilitates linear regression of Eq. 5, resulting in evaluation of Ma as the slope of the regression line. It is emphasized that both Eq. 3 and Eq. 5 provide similar analyses of the flame response to stretch rate. The advantage of using Eq. 3 to determine \( S_{L,\infty} \) (through Eq. 4) is that measured flame propagation rates are directly used in the extrapolation to zero stretch rate, without necessitating the use of a single gas density ratio to represent all flame stretch conditions. The analysis of Eq. 5 does utilize this single density ratio to relate flame speed to \( S_L \) at each stretch rate, but has been shown to provide reliable results and is therefore chosen here for consistency in the evaluation of Ma so that comparisons may be made to previous results [1,2,4,17].

**Experimental Method**

Unconstrained spark-ignited propane-air flames have been investigated at atmospheric pressure over a range of equivalence ratios, \( \Phi = 0.69-1.49 \). The burner consists of a 32.7 liter cylindrical stainless steel combustion chamber with optical access provided by two quartz windows. Two opposed 0.4 mm diameter electrodes are oriented horizontally within the chamber to provide spark ignition of controllable spark gap (~2 mm) and arc duration (~2 ms) from an inductive discharge ignition system. Four solenoid exhaust valves are opened approximately 860 ms prior to spark ignition to ensure the combustion process during the data acquisition period proceeds isobarically (pressure rise less than
Metering of proper quantities of fuel (CP grade, minimum 99.0% purity) and air is obtained using calibrated mass flow controllers with an accuracy of +/- 0.3% for the fuel stream and +/- 1.1% for the air stream. The chamber is purged by flowing the reactant mixture through the chamber for ten volume changes and then allowed to settle to a quiescent state once the exhaust valves have been closed.

High-speed imaging of broadband chemiluminescence signal (primarily from CH*) has been used to obtain time-resolved measurements of flame radius and overall flame morphology. This technique inherently demarcates the reaction zone, thereby facilitating accurate tracking of the flame front, and providing a unique advantage over schlieren techniques which only identify the location of maximum density gradient. A Kodak Ektapro Model 4540 high-speed camera, operating at 4500 frames per second, is lens-coupled to an Imco ILS-3 intensifier with a 105 mm UV-Nikkor lens to provide videos of flame propagation from ignition until the reaction zone reaches the full field of view (95.7 mm wide x 100 mm high). This configuration allows the spherical flames to be observed over an order of magnitude of stretch rates (564 - 46 s\(^{-1}\)) similar to past studies. Synchronization of the burner operation and image acquisition is controlled by LabView software interfacing with a National Instruments counter/timer board.

Once the flame propagation videos are acquired, the data reduction scheme begins by outlining the flame luminosity against the dark background using an isodata thresholding algorithm applied frame by frame to each video. Measurements of the projected flame area can then be made with an uncertainty less than 4%, from which the flame radius is
calculated assuming spherical symmetry. The technique of using projected flame area to determine flame radius has been applied before [17], with results showing good agreement to the manual measurement of a specific flame radius or diameter. The time derivative of flame radius, $dr_f/dt$, represents the laminar burning velocity of the burned gas, $S_b$, and is used in Eq. 2 to calculate stretch rate and in Eq. 3 by plotting $S_b$ versus $K$ to obtain $S_{b,\infty}$ at $K=0$ in the manner described above. The value of $S_{L,\infty}$ is then found using Eq. 4, with the gas density ratio for each mixture calculated using a chemical equilibrium code incorporating the Chemkin and STANJAN packages. Values for $Ma$ are obtained by first tabulating $S_L$ and $K_a$ for each data point and then plotting $S_{L,\infty}/S_L$ versus $K_a$ such that linear regression of the data yields $Ma$ from the relationship in Eq. 5.

The value of mass diffusivity for these propane-air flames is $D_\alpha = 11.5$ mm$^2$/s according to the recently published value given by Hassan et al. [4].

**Results**

The range of equivalence ratios investigated encompasses both thermo-diffusively stable and unstable flame conditions. Thermo-diffusive instabilities arising from the preferential diffusion of reactants with respect to thermal transport can lead to cellular flame structures that augment flame propagation through an increase in flame surface area. These cellular structures originate as wrinkles or cracks along the flame surface, which grow and divide to form cells of smaller length scales. Images of flame chemiluminescence for both stable and marginally stable conditions are shown in Fig. 1 for representative cases analyzed in this study. Since measurements of flame radius were
restricted to less than 45 mm, effects of flame cellularity were not observed in the experimental data. In addition, data processing was only performed for flames with a radius of at least 5 mm, therefore eliminating ignition energy effects on flame propagation rates [4].

The measurements of unstretched laminar burning velocity, $S_{L,\infty}$, for atmospheric propane-air flames at 298 K initial reactant temperature are compared to the results of other experimental investigations in Fig. 2 as a function of equivalence ratio. The agreement is quite good, with only the richest case, $\Phi = 1.49$, showing deviation from the published values. This comparison is important, since the work of Hassan et al. [4] and Jomaas et al. [8] used shadowgraph and schlieren imaging techniques, respectively, to make measurements of flame radius in their analyses of outwardly propagating spherical flames. Interestingly, this result suggests that the reaction zone is thin enough to make the determination of flame radius less sensitive to measurement technique than previously thought. In addition, the close agreement to the nearly stretch-free measurements of Bosschaart and de Goey [13] and Vagelopoulos and Egolfopoulos [14] indicates that the use of chemiluminescence as an indicator of flame radius is valid for laminar burning velocity measurements.

The flame response to stretch is represented in Fig. 3 as plots of $S_{L,\infty}/S_L$ versus $K_a$ for several equivalence ratios. The linear relationship between burning velocity and stretch rate is clearly seen, although the scatter of data increases for the $\Phi = 1.49$ case. Positive slopes indicate thermo-diffusively stable mixtures (positive $Ma$), while negative slopes
represent unstable flame propagation (negative Ma) and the propensity for flame cellularity. The data for the Φ= 1.32 case show that the mixture is only marginally stable, and therefore would be susceptible to the wrinkling effects of perturbations or hydrodynamic instabilities, as indicated by the chemiluminescence image shown in Fig. 1b. Markstein numbers are plotted in Fig. 4 to show the transition from thermo-diffusively stable to unstable mixtures as the equivalence ratio increases. The behavior of propane is consistent with that of heavier hydrocarbons, in contrast to methane-air and hydrogen-air flames which become thermo-diffusively stable with increasing equivalence ratio [2,3,5,7,18-20]. The results of several other studies [2,4,17] of propane-air flames are given for comparison. Interestingly, there is a large amount of scatter between the published results. It should be noted that the results of Palm-Leis and Strehlow [17] may be erroneously shifted towards higher values of equivalence ratio due to problems in calculating Φ, as discussed by Kwon et al. [1]. The measurements of Ma for the present study fall well within the range of values for each mixture. Linearly interpolating between data points, the transition from positive to negative Ma occurs approximately at Φ= 1.34. These results indicate that the experimental procedure can be used to accurately measure the flame response to stretch and its associated thermo-diffusive stability.

In conclusion, the use of high-speed broadband chemiluminescence imaging has been demonstrated to provide reliable characterization of laminar premixed propane-air flames, including measurements of unstretched laminar burning velocity and Markstein number, both of which are fundamental parameters in general combustion theory and laminar/turbulent flame models.
Acknowledgments

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References


List of Figure Captions

Figure 1. Flame chemiluminescence images for atmospheric propane-air flames at thermo-diffusively (a) stable (Φ= 1.00), and (b) marginally stable (Φ= 1.32) conditions. The field of view for both images is 95.7 mm (width) x 100 mm (height).

Figure 2. Comparison of measured unstretched laminar burning velocities, $S_{L,\infty}$, as a function of equivalence ratio for propane-air flames at standard temperature and pressure.

Figure 3. Measured response of laminar burning velocity as a function of Karlovitz number, $K_a$, for both thermo-diffusively stable and unstable propane-air mixtures.

Figure 4. Comparison of measured Markstein numbers, $M_a$, as a function of equivalence ratio for propane-air flames at standard temperature and pressure.
Figure 2
Figure 3
Figure 4
7. Observations on CH₄-O₂-N₂ Flame Kernel-Vortex Interactions

7.1 Introduction

Flame-vortex interactions serve as the building blocks for understanding premixed turbulent combustion. Each vortex represents a specific length and velocity scale of the continuum of scales that comprise turbulence. Ideally, the researcher can use flame-vortex interactions to probe these length/time/velocity scales to identify optimal operating conditions for practical applications, such as internal combustion engines. For example, the engine designer can tailor the intake path (consisting of the intake manifold runner, cylinder head port and bowl, valves) and combustion chamber design to promote these optimal turbulence scales for increased combustion efficiency and/or reduced pollutant emissions.

When a laminar flame kernel instead of a flat flame is utilized, the time-varying curvature of the flame front becomes an additional consideration in the flame response to the local stretch rate. Flame kernel-vortex interactions provide the opportunity to study flame stretch effects in an environment applicable to the early stages of flame development just after ignition, when the flame is most susceptible to local or global quenching. As a result, the viability of the flame kernel dictates if the reaction zone will continue to propagate and consume the reactants in the combustion chamber, or misfire and contribute to increased engine emissions, reduced performance, and poor fuel economy. This chapter investigates flame kernel-vortex interactions using methane-air
mixtures with nitrogen diluent to control flame speed. Methane behaves similar to hydrogen with respect to thermo-diffusive stability and is considered a “light” hydrocarbon fuel. The scope of the experimental investigation included variably timed interactions of fuel-lean and rich CH₄-O₂-N₂ flames with vortex toroids of different strengths, or rotational velocities. Particular emphasis was placed on observing conditions of local or global extinction and the result of quenching on the overall propagation of the flame kernel.

7.2 Experimental Details

7.2.1 Experimental Apparatus

The combustion chamber, illustrated in Fig. 7.1, used for the flame kernel-vortex interactions consists of a 32.7 liter stainless steel pressure vessel with optical access via two 5 inch quartz windows for image acquisition. Laser access is provided orthogonal to the quartz windows and facilitates diagnostics such as Laser-Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV). Two electrodes, which reduce to 0.4 mm diameter to minimize the effect on flame propagation, enter from opposing sides of the burner and are oriented horizontally to provide central spark ignition of the reactant mixture. One electrode is mounted on an adjustable mechanism to allow fine adjustment of the spark gap (2-3 mm). The ignition system utilizes inductive discharge and interfaces with a computer to easily change the spark energy and arc duration (nominally 2 ms). Four large solenoid exhaust valves located at the bottom of the chamber seal the vessel during the preparatory stage of each experimental run. The exhaust valves open approximately 860 ms prior to ignition to ensure that the combustion process occurs.
isobarically at atmospheric pressure, with a maximum pressure rise less than 2%. The reactant mixture is metered with calibrated mass flow controllers which provide accuracies of +/- 0.3% for the fuel flow rate (methane, 99.0% purity) and +/- 1.1% for the air and diluent (nitrogen) flow rates. In order to achieve a homogeneous reactant mixture, the combustion chamber is purged with ten chamber volumes of fresh reactants before closing the exhaust valves and allowing the gases to settle prior to initiating the experiment. This procedure has proven to provide very repeatable data which is crucial for this highly transient flame.

The vortex generation device is located at the top of the combustion chamber. A schematic showing the design and orientation of the vortex apparatus is shown in Fig. 7.2. This device is used to generate axisymmetric three-dimensional vortex rings, or toroids, that propagate downward towards the ignition electrodes and interact with the outwardly propagating flame kernels. A linear actuator, coupled to a software-controlled servo motor, is used to drive an aluminum piston located within a stainless steel cylinder. Two cast iron piston rings prevent leakage of reactant mixture past the piston and infiltration of ambient air into the cylinder. A sharp-edged orifice is located at the bottom of the cylinder to create vorticity, which will develop into a translating vortex toroid, once the piston impulsively displaces a specified volume within cylinder, thereby ejecting rotational fluid out of the orifice. The dynamics of the actuator are carefully controlled so that the characteristics of the resulting vortex are well defined. In all cases, the piston displacement is set at 1.0 mm, but the piston velocity is varied so that multiple vortex rotational velocities (or strengths) may be investigated. The diameter of the sharp-edged orifice is 10 mm, and the distance from the orifice to the electrode tips is 100 mm,
resulting in an approximately 25% increase in vortex core-to-core diameter during propagation due to entrainment. In this work, all vortices are generated using a reactant mixture identical to that of the main combustion chamber.

7.2.2 Vortex Characterization

The vortices utilized in this experiment were characterized based on vortex rotational velocity, $U_\theta$, defined as the tangential velocity at the edge of the vortex core. This characteristic velocity, also termed vortex strength, is used to indicate the degree of stretch the vortex will exert on a given flame surface. This convention is based on the Rankine vortex, which assumes a linear relationship of the tangential velocity as a function of radius within the core, and therefore reaches its peak value at the outer edge. Outside of the vortex core, viscosity leads to ambient gas entrainment while instabilities can lead to shedding of vorticity and eventually vortex breakdown. The vortex strength has been shown to be a function of the experimental parameters involved in vortex generation (Roberts, 1992):

$$U_\theta \sim \frac{\Delta V^2}{t d_o^5}$$

(1)

where $\Delta V$ is the displaced volume due to the piston movement, $t$ is the time required to displace the volume, while $d_o$ is the orifice diameter, which determines the vortex core-to-core diameter and is therefore the characteristic length scale of the vortex. Equation 1 may be further simplified in terms of the piston dynamics so that these parameters can be directly controlled to achieve vortices of desired strength:
\[ U_0 \sim (v l / d_o) C^4 \]  

(2)

where \( v \) is the piston speed, \( l \) is the piston displacement, and the constant \( C \) represents the fixed ratio of cylinder diameter, \( d_c \), to orifice diameter, \( d_o \) (Xiong et al., 2001).

Particle Image Velocimetry (PIV) was utilized to measure the two-dimensional cold flow velocity field of each vortex studied. The main objective of the PIV measurements was to quantify both the vortex rotational and translational velocities, which have been shown to be approximately equal (Roberts, 1992), and to determine if the vortex is laminar, transitional, or turbulent. A Continuum Minilite PIV system was used to provide the two 532 nm laser beams that were formed into spatially overlapped sheets using two spherical lenses (\( f = -50 \) mm and \( f = 600 \) mm) and one cylindrical (\( f = 1.2 \) m) focusing lens. Two Stanford Research Systems DG535 digital delay generators controlled both the flashlamp and Q-switch operation of the two Nd:YAG lasers. As a result, the time separation between laser pulses was varied between 30 and 100 microseconds, depending on the time scales of the flow. Incense smoke was chosen to seed the vortex and provide scattering images both for the PIV analysis and to observe the overall vortex structure. The two light scattering images were imaged with a Redlake Megaplus ES1.0 interline CCD camera (1008 x 1018 pixels), resulting in a resolution of 33.5 pixels/mm, or an approximately 30 mm square field of view.

Due to the transient nature of the vortex, accurate timing was required so that the acquisition of particle images would occur when the leading edge of the vortex was near the electrodes. LabView software, interfacing with a National Instruments counter/timer
board, controlled the triggering of the camera and the vortex generation relative to the PIV laser pulses firing at 10 Hz. Once particle image pairs were acquired, PIV processing was performed using a cross-correlation algorithm with a final interrogation region size of 32 x 32 pixels and 50% overlap, yielding approximately 0.48 mm between velocity vectors.

7.2.3 High-Speed Imaging

The flame kernel-vortex interactions have been investigated using broadband high-speed chemiluminescence imaging primarily of CH*/OH* emission. A Kodak EKTAPRO model 4540 high-speed camera was lens-coupled to an Imco ILS-3 intensifier with a 105 mm UV-Nikkor lens to facilitate imaging at framing rates up to 4,500 frames per second over a 95.7 mm wide by 100 mm high field of view. Data acquisition was gated relative to burner operation, controlled using LabView, a counter/timer board, and two SRS DG535 delay generators, initiating the camera and intensifier just after ignition. Oscilloscope traces of the ignition voltage and intensifier sync signal allowed the time between spark and image collection to be measured.

An isodata thresholding algorithm was applied to each image to outline the flame boundary. The projected area of the flame kernel was measured and an effective kernel radius, \( r_e \), was then calculated assuming spherical symmetry. During many interactions the disturbed flame surface was non-spherical, but since the effective radius simply scales with the projected area, it provides a basis for comparison between cases and to previous work (Xiong, 2001). This combination of high-speed imaging and flame front tracking
allows the flame’s response to stretch to be analyzed and conclusions drawn concerning issues relevant to premixed combustion.

### 7.2.4 Flame Properties

The mixture conditions for the methane-air flames were chosen so that the effects of chemistry could be studied independent of flame speed. Three equivalence ratios were chosen for investigation: \( \Phi = 0.64, 0.90, 1.13 \). These mixtures have very different laminar burning velocities when the fuel is oxidized by undiluted air. Therefore, nitrogen was used as a diluent to retard the flame speeds of the \( \Phi = 0.90 \) and \( \Phi = 1.13 \) mixtures so that the flame propagation rates of these mixtures, \( \frac{dr}{dt} \), were equal to that of the \( \Phi = 0.64 \) case of an undisturbed outwardly propagating spherical flame kernel. These flame propagation rates were compared using well established spherical flame kernels and therefore were not subjected to ignition effects which will be different for each mixture composition. The associated flame and mixture properties utilized in the experiment are listed in Table 7.1. Values for the unstretched laminar burning velocity, \( S_{L,\infty} \), and the Markstein number, \( Ma \), were measured in the same apparatus utilizing the method presented by Marley and Roberts (2005), with the results in good agreement to the recent literature for undiluted methane-air flames (Aung et al., 1995; Bosschaart and de Goey, 2004; Gu et al., 2000; Hassan et al., 1998) as shown in Fig. 7.3.

<table>
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<tr>
<th>Equivalence Ratio, ( \Phi )</th>
<th>0.64</th>
<th>0.90</th>
<th>1.13</th>
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<tr>
<td>% Fuel</td>
<td>6.30</td>
<td>6.68</td>
<td>8.00</td>
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### Table

<table>
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<th></th>
<th>O₂/(O₂+N₂)</th>
<th>Molecular Diffusivity of CH₄-N₂, Dₚ [cm²/s]</th>
<th>Thermal Diffusivity, α [cm²/s]</th>
<th>Lewis Number, Le</th>
<th>Laminar Burning Velocity, Sₗ,∞ [cm/s]</th>
<th>Markstein Number, Ma</th>
<th>Flame Thickness, δₓ= Dₚ/Sₗ,∞ [mm]</th>
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<td>0.98</td>
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</tbody>
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#### 7.3 Results and Discussion

#### 7.3.1 Vortex Strength

The PIV measurements were carried out over a wide range of vortex strengths, but only three vortices were selected to be used in the flame kernel-vortex investigation. The three vortex cases studied represent laminar, transitional, and “turbulent” vortices, therefore facilitating a thorough analysis of the flame response to unsteady stretch. The piston displacement for all three cases remained constant at 1.0 mm, while the peak piston speeds were 36 mm/s, 110 mm/s, and 180 mm/s, corresponding to “weak,” “medium,” and “strong” vortices, respectively. The PIV scattering images also served to visualize the vortex structure as shown in Fig. 7.4. Each velocity field generated from the PIV data provides a two-dimensional slice through the vortex center and reveals the axisymmetric character of the three-dimensional toroid. Figure 7.5 shows the raw velocity field for the “weak” vortex from which the rotational and translational velocities were measured to be 77 cm/s and 85 cm/s, respectively. Similar analyses performed with
the “medium” and “strong” vortex cases revealed rotational/translational velocities of 266/255 cm/s and 398/351 cm/s, respectively. As stated earlier, the rotational velocity is termed the vortex strength since it will determine the stretch rate imposed upon the flame surface.

In order to provide a common measure of the vortex effect on any flame front, the rotational velocity, \(U_\theta\), is non-dimensionalized by the unstretched laminar burning velocity, \(S_{L,\infty}\), while the characteristic length scale, \(d_o\), is non-dimensionalized by the characteristic flame thickness, \(\delta_D\). Figure 7.6 indicates the non-dimensional vortex strengths and sizes for the vortices and reactant mixtures investigated. It is important to note that, although the burning velocity and flame thickness differ between the three mixtures, the flame propagation speeds for the undisturbed kernels are nearly equal.

7.3.2 Undisturbed Flame Kernels

A high-speed image sequence for a freely propagating flame kernel is shown in Fig. 7.7. Since the \(\Phi = 0.90\) and \(\Phi = 1.13\) flames were diluted with nitrogen to provide flame propagation rates as close to the \(\Phi = 0.64\) case as possible, the undisturbed flame kernel sequences are nearly identical. Several key characteristics of the flame kernel are worth noting from Fig. 7.7. Given the relatively slow flame speeds, the effect of buoyancy is present, causing the propagation rate of the upper hemisphere to be as much as 30% higher than the lower half of the kernel by the time the kernel has reached the edge of the field of view. Also, flow disturbance and heat loss due to the electrodes incurs a dimple on both sides of the flame, resulting in a sign change in the curvature, defined to be positive when the flame is concave to the hot products. Nevertheless, the
flame kernel remains mostly spherical once established and is very repeatable. A comparison of the flame propagation, represented by effective kernel radius, is given in Fig. 7.8 for all three equivalence ratios. From the plots, it is observed that all three undisturbed flames have similar flame propagation rates. The undiluted $\Phi = 0.64$ flame maintains a constant propagation rate as evidenced by the linear change of flame radius with time. As the nitrogen dilution level is increased with equivalence ratio, the flame propagation becomes increasingly nonlinear, appearing to lag behind the undiluted flame near ignition and then exceeding it once the flame is well established. Therefore, the dilution levels were chosen to give the best overall match in $\frac{dr}{dt}$ for all cases over the range of kernel sizes investigated with the kernel-vortex interactions. The average flame propagation rates, measured from ignition until the flame reaches the image edge, for the $\Phi = 0.64$, $\Phi = 0.90$, and $\Phi = 1.13$ undisturbed cases were 55.7 cm/s, 58.7 cm/s, and 61.4 cm/s, respectively.

7.3.3 Late Kernel-Vortex Interactions

The flame kernel-vortex interactions can be classified according to the time when the vortex first affects flame propagation. This classification is accomplished by assigning three regimes of interaction: early, medium, and late (Xiong, 2001). An early interaction occurs when the ratio of the kernel diameter to vortex diameter is $\leq 1$ at the time of first visible interaction in the high-speed chemiluminescence videos. A late interaction is defined when this first interaction occurs for a kernel to vortex diameter ratio $> 2$. Any case falling in between these definitions ($1 < \text{kernel-vortex ratio} < 2$) is labeled a medium interaction. All three interactions have been investigated, but only
early and late interactions are discussed in detail. The late interactions are discussed first, with the results of the early interactions presented in the following section.

Particular focus has been placed on extending the results of past experimental work in flame kernel-vortex interactions, including the analysis of extinction events, both local and global (Eichenberger and Roberts, 1999; Xiong et al., 2001). The strongest vortex studied by Xiong et al. (2001) using the $d_o = 10$ mm orifice size in a similar experimental apparatus had a translational speed of 85 cm/s, corresponding to the weakest vortex in this investigation. Therefore, this work probes new interactions with stronger vortices while isolating chemistry effects by controlling the characteristic flame propagation rates through addition of a diluent. The first flame kernel-vortex interactions considered are late interactions with the weak, laminar vortex. Figures 7.9-7.11 are image sequences of the late interactions with the weak vortex for the three reactant mixtures. Examining the flame kernel just after ignition, it is interesting to note that the flame sensitivity to heat loss (to the electrodes) increases as the nitrogen dilution is increased to inhibit the $\Phi = 0.90$ and $\Phi = 1.13$ flames. This sensitivity, a thermo-diffusive (or Lewis number) effect, results in the flame developing slightly faster in the vertical direction, exhibiting an elongated shape during the early stages of flame development. The vortex begins to interact with the top of the flame kernel approximately 39 ms after ignition and well after the flame has become established. At this point, the propagating vortex pushes the flame surface downward, reducing the local flame curvature while simultaneously exerting positive strain, two opposing terms in the determination of flame stretch. As the vortex continues to invade the flame kernel, a trailing wake of reactants is left behind the vortex. Vorticity pulls the flame surface around the vortex toroid,
wrapping the flame behind the trailing edge of the vortex, and inducing wrinkling of the flame, characterized by vigorous combustion and increased luminosity. The vorticity also pinches the trailing wake and will eventually lead to the vortex flame (defined as reaction zone surrounding vortex fluid) separating from the trailing wake flame as this region is consumed. As the vortex approaches the electrodes, the trailing wake continues to narrow, and it becomes apparent that the $\Phi=0.64$ and $\Phi=0.90$ cases exhibit a higher degree of flame wrinkling at the vortex trailing edge than the $\Phi=1.13$ case. This observation is indicative of increased thermo-diffusive stability as the equivalence ratio increases, consistent with an increasing Markstein number (see Table 7.1 above). In addition, the wrinkled reaction zone generates flame surface area which increases the consumption rate of reactants, resulting in the vortex consumption occurring predominately from the trailing edge towards the leading edge, and from the centerline radially outwards. The inhibitive effect of nitrogen dilution is again observed when the vortex leading edge comes in close proximity to the electrodes. By 70 ms after ignition, local extinction, as indicated by lack of CH* and OH* chemiluminescence, has already occurred along the leading edge of the vortex flame for the $\Phi=1.13$ case, whereas the $\Phi=0.64$ and $\Phi=0.90$ flames are still intact at the same point in the interaction. As the vortex traverses the electrodes, the situation changes and all three cases exhibit local extinction of the leading edge. The $\Phi=1.13$ is still the more extreme case since the moderately wrinkled trailing edge is all that remains of the vortex flame. Interestingly, the two fuel-lean cases undergo re-ignition of the vortex fluid once it is below the electrodes and in contact with hot combustion products, but the fuel-rich case remains locally quenched. During this process, the wake flame detaches from the vortex flame and gradually is
consumed as it burns back towards the top of the kernel. Final consumption of the remaining vortex core fluid occurs via multiple pocket formation for all three cases, just beneath the electrodes. The plots of effective kernel radius versus time are similar to the curves of Fig. 7.8 for the undisturbed case, indicating this vortex strength does not significantly augment flame propagation for the late interaction, and therefore are not shown. The average flame speeds (laboratory reference frame) for the $\Phi=0.64$, $\Phi=0.90$, and $\Phi=1.13$ cases over the available measurement area are 57.3 cm/s, 60.2 cm/s, and 62.4 cm/s, respectively.

The images of flame chemiluminescence during interaction with a medium strength vortex ($U_{\theta}=266$ cm/s) are shown in Figs. 7.12-7.14. As before, vertical elongation of the initial kernel is observed as the nitrogen dilution level increases. Once the vortex has entered the flame kernel, approximately 44-45 ms after ignition, the effect of increased vortex strength is immediately evident. The flame surrounding the vortex has a thicker chemiluminescence signal in all three mixtures compared to the well defined reaction zone seen during the late interaction with the weak vortex. This broadening of the spatially integrated signal indicates three-dimensional structure of the vortex flame. As the interaction proceeds farther into the upper hemisphere of the kernel, the reaction zone appears to become quite wrinkled, or corrugated, for all cases. The leading edge of the vortex flame is locally extinguished 46 ms into the interaction for $\Phi=1.13$, whereas the two fuel-lean flames exhibit a continuous reaction zone at this time. Also, in all three cases the trailing wake flame appears to transition to a turbulent reaction zone and is significantly wider than seen with the weak vortex. Heat losses near the electrodes again cause extinction of the vortex flame for the fuel-lean cases (fuel-rich
case already extinguished), while the turbulent trailing edge and wake continue to consume reactants. All three vortex flames undergo a re-ignition process in the lower kernel hemisphere, resulting in highly wrinkled flames. The $\Phi = 1.13$ case is slower to re-develop during this ignition process indicated by decreased luminosity compared to the fuel-lean cases. During the vortex flame re-ignition, the trailing wake in each case detaches from the vortex with small flame pocket formation. Consumption of the remaining vortex fluid intensifies greatly, even saturating the camera detector, near the kernel bottom as the vortex encounters hot combustion products. As the vortex flame begins to interact with the lower kernel reaction zone, the vortex combustion is very intense and positively stretches the flame kernel.

A very interesting observation is made at the onset of this flame-flame interaction. Comparing the 59.56 ms, 59.71 ms, and 61.45 ms images for the $\Phi = 0.64$, 0.90, and 1.13 cases, respectively, it is observed that thermo-diffusive effects become important at the flame-flame interface. The fuel-lean images during this condition show that the reaction zone continues to burn normally with no loss of chemiluminescence signal along the stretched flame kernel surface. The $\Phi = 1.13$ case, however, actually exhibits greatly reduced luminosity, possibly local extinction, resulting from reduced burning velocities associated with positive stretch for a thermo-diffusively stable flame.

As the interaction proceeds, the vortex reactants are consumed while continuing to stretch the kernel bottom. At this time, about 69 ms after ignition, all three cases show decreased intensity along the very bottom of the stretched flame surface suggesting reduced mean reaction rates, although the effect is more pronounced with increasing equivalence ratio, as expected. One final result of this reduced combustion intensity is
that the remaining vortex momentum in the $\Phi = 1.13$ flame is able to affect a larger region of the lower flame kernel surface (compared to the fuel-lean cases) before the vortex is completely attenuated and normal flame propagation resumes along the deformed kernel. Similar to the late interaction with the weak vortex, the plots of effective kernel radius as a function of time remain similar to the undisturbed case, but it is important to remember that the interaction between the vortex and the kernel bottom is not included in the flame radius calculations since the upper kernel surface has exited the field of view when the secondary interaction occurs.

The final cases considered for the late kernel-vortex interactions involve the flame’s response to the strong vortex ($U_\theta = 398$ cm/s). Figures 7.15-7.17 provide the high-speed images for the three mixtures starting just prior to the interaction, since the early undisturbed flame kernel growth is the same as shown in the previous figures. The coherent leading edge of the turbulent vortex is apparent in all three cases as the vortex first forms the typical “bubble” flame around 43-44 ms into the interaction. Soon thereafter, the trailing edge of the vortex flame becomes wrinkled as a result of instabilities responsible for vorticity shedding. Similar to the late interaction with the medium strength vortex, the vortex flame leading edge for the $\Phi = 1.13$ case is extinguished 46 ms into the interaction, indicating that the positive stretch exerted on this thermo-diffusively stable, diluted mixture exceeds the quenching stretch rate in this region of reduced burning velocity and temperature.

Consistent with the data from the previous cases, the vortex flame leading edge is extinguished in all three mixtures as it passes over the electrodes. Also, the trailing wake of the $\Phi = 1.13$ flame is less wrinkled than the two fuel-lean flames, a supportive indicator
of thermo-diffusive stability. Re-ignition of the vortex reactants occurs in the lower flame kernel hemisphere, with the $\Phi = 1.13$ flame being the slowest to respond and all three vortex flames exhibiting turbulent combustion. The flame-flame interaction as the intense, turbulent flame ball reaches the kernel bottom is especially interesting for the cases investigated. As the vortex flame impacts the kernel flame, the vortex strength is large enough to punch through the kernel surface, with mutual flame annihilation evident from the fragmented reaction zones visible in each case. The $\Phi = 0.64$ and $\Phi = 0.90$ cases exhibit partial survival of the vortex flame leading edge, while only the sides and trailing edge of the $\Phi = 1.13$ vortex flame are sustained as a result of the bottom interaction for the same reasons already discussed. The sustained combustion as the vortex momentum continues through the flame kernel is due to the turbulent reaction zone at the vortex trailing edge and wake. This process leads to the initiation of essentially a second expanding flame kernel that is connected to the original kernel. The trailing wake can be seen to extend from the bottom of this new kernel all the way up to the top of the primary kernel as shown in the 57.12 ms, 55.16 ms, and 58.15 ms frames from Figs. 7.15, 7.16, and 7.17, respectively. The trailing wake observed 58.15 ms after ignition in Fig. 7.17 ($\Phi = 1.13$) is intriguing in that it suggests that a reactant core can exist over the entire diameter of this double flame kernel arrangement, without being enclosed by a flame front. By the next frame in Fig. 7.17, the wake flame has separated just beneath the electrodes, and both reactant cores burn in opposite directions towards the flame kernel surface. One final observation concerns the interface between the two kernels after the vortex reactants have been consumed. The two expanding kernels are directly adjoined along their respective flame surfaces for the fuel-lean cases, whereas in the fuel-rich case,
the secondary kernel has a “neck” which connects to the original kernel. This connecting region is most visible from 59.93 ms to 67.93 ms after ignition in Fig. 7.17, and is the result of the dramatic local extinction event and slow flame recovery associated with this diluted mixture. At later times, the two flame surfaces adjoin in a similar fashion to the fuel-lean cases, and flame propagation resumes without perturbation.

The plots of effective kernel radius versus time are shown in Fig. 7.18 for late interactions with the strong vortex. Due to the relatively large kernel size when these late interactions occur, the flame radius profiles do not indicate dramatic changes in flame propagation rates, from which the average values are only incrementally higher than the undisturbed cases (61.4 cm/s vs. 55.7 cm/s, 62.7 cm/s vs. 58.7 cm/s, and 62.7 cm/s vs. 61.4 cm/s for the \( \Phi = 0.64 \), \( \Phi = 0.90 \), and \( \Phi = 1.13 \) mixtures, respectively). A change in slope is visible during the initial interaction of the vortex and flame kernel, with peak flame speed achieved as the kernel surface is pulled around the outer diameter of the vortex, which has its velocity component vertically upward and therefore maximizes flame area generation. The peak flame propagation rates associated with this flame-flow interaction are 76.3 cm/s, 78.0 cm/s, and 87.8 cm/s for the \( \Phi = 0.64 \), \( \Phi = 0.90 \), and \( \Phi = 1.13 \) mixtures, respectively.

### 7.3.4 Early Kernel-Vortex Interactions

In order to maximize the effect of the invading vortex on flame propagation, early flame kernel-vortex interactions were studied. These interactions occur soon after ignition, when the flame kernel is much smaller than the vortex, and therefore has a more dramatic response to stretch than observed in the late interactions. Figures 7.19-7.21
show the time sequence of CH*/OH* images of an early interaction for the same mixtures already discussed. As the vortex traverses the electrodes, the leading edge flame dims for all three cases, but does not locally extinguish as in the late interactions. During the separation of the trailing wake flame from the vortex flame, multiple pocket formation occurs for the \( \Phi = 0.64 \) mixture while the \( \Phi = 0.90 \) and \( \Phi = 1.13 \) cases exhibit a clean break between the two regions. In addition, the top of the disturbed kernel for the \( \Phi = 1.13 \) case is less wrinkled than the fuel-lean cases, another indicator of increased thermo-diffusive stability with increasing equivalence ratio. During final vortex consumption near the bottom of the flame kernel, the remaining momentum from the vortex is able to slightly dimple the kernel bottom, increasing the reaction zone curvature and therefore generating marginally increased stretch rates, although the effects are not observed in either the chemiluminescence signal intensity or the plots of effective kernel radius, shown in Fig. 7.22. The inhibitive effect of the nitrogen dilution on the \( \Phi = 1.13 \) flame is clearly seen in the plot, as the flame development lags behind the fuel-lean flames. The average/maximum flame propagation rates for the \( \Phi = 0.64 \), \( \Phi = 0.90 \), and \( \Phi = 1.13 \) mixtures are, in order: 73.9/95.5 cm/s, 73.1/96.2 cm/s, and 71.6/87.8 cm/s.

As the vortex strength is increased, the flame response to stretch is further enhanced. Figures 7.23-7.25 highlight the early interactions with the medium vortex strength. Just after ignition, the vortex hits the kernel and strongly suppresses combustion. The \( \Phi = 0.64 \) flame exhibits the highest signal strength, with the \( \Phi = 0.90 \) and \( \Phi = 1.13 \) kernels showing greatly reduced chemiluminescence. It is important to note that the initial size of the flame kernel initiated by the spark plasma generally decreases with increasing equivalence ratio for these diluted methane-air flames. As a result, when
investigating these very early kernel-vortex interactions, the leaner flames will be slightly more developed and less likely to be quenched. Due to the relatively large size of the vortex, the vortex dynamics become very important in the observed flame propagation. For example, in the 6.78 ms image of Fig. 7.23 (Φ = 0.64), the flame wraps around the edges of the vortex due to vorticity. The flame continues to propagate around the vortex and consumes the reactants as the kernel expands, without any obvious breaks in the flame front indicative of local extinction. This interaction is much different than what occurs in the other two mixtures. The Φ = 0.90 kernel, shown in Fig. 7.24, actually breaks up into several flame pockets just below the electrodes due to the vortex interaction. The individual flame pockets continue to grow, merging by 11.82 ms, and then form a wrinkled expanding flame without any remaining vortex fluid to be consumed within the kernel. Once the equivalence ratio is increased to 1.13, the flame responds differently than the first two fuel-lean cases. Instead of breaking up into multiple flame pockets, the small kernel remains one entity, but is almost globally extinguished as shown in Fig. 7.25. The flame follows the imposed flow field of the vortex and is then advected down into the trailing wake created by the momentum of unburned vortex fluid. This process reveals a vertically elongated tube-like flame that eventually begins to expand outwards as the convective currents decay and flame propagation recovers. As all three flames continue to expand (not shown in figures), the flame surfaces become increasingly smooth as the equivalence ratio increases, an expected characteristic of increasing thermo-diffusive stability. The time history of effective kernel radius, seen in Fig. 7.26, shows a rather wide range of flame behavior due to the interaction of the vortex with very young kernels. Although the local
extinction events occurring in the $\Phi = 0.90$ flame definitely inhibit flame development, the near global extinction of the $\Phi = 1.13$ flame is responsible for greatly reduced flame propagation rates. The $\Phi = 0.90$ flame does recover quickly, and the highly wrinkled reaction zone ends up having a higher average flame speed, 94.0 cm/s, compared to those of the $\Phi = 0.64$ (81.7 cm/s) and $\Phi = 1.13$ (51.0 cm/s) flames.

The final cases to be considered are the early interactions with the strong vortex. It is important to mention that these early interactions occur slightly later than those with the medium strength vortex, otherwise global extinction would likely occur for all three mixtures. Figures 7.27-7.29 illustrate these early interactions for the same three reactant mixture conditions. As the interactions first begin for the $\Phi = 0.64$ and $\Phi = 0.90$ cases, the turbulent vortex is able to heavily wrinkle the flame kernel and incur local extinction at the kernel bottom since the vortex is strong enough to push through the reaction zone. Specifically, for the $\Phi = 0.64$ case, the flame at the vortex leading edge only partially extinguishes, mutually with the kernel bottom, and then the wrinkled flame at the trailing edge propagates into the premixed vortex fluid. The vortex momentum facilitates strong downward flame propagation as the reaction zone follows in the vortex wake. The wrinkling incurred by the strong vortex is significant enough to initiate a cellular structure in the $\Phi = 0.64$ flame surface, an indication that the reaction zone has developed instabilities. Local extinction occurs in a similar fashion for the $\Phi = 0.90$ flame, but extinguishes over most of the leading edge. Again, the vorticity intensifies combustion at the trailing edge and advects the turbulent flame through the kernel bottom while the vortex fluid is consumed. As the remaining vortex momentum dissipates, normal flame propagation resumes, with the observation that the $\Phi = 0.90$ flame does not develop
cellular instabilities. The $\Phi=1.13$ case is unique, in that the strong vortex is able to globally quench the flame kernel. By 11.60 ms, the chemiluminescence signal has become very weak, and the kernel has broken up into several flame fragments. These patches gradually extinguish, with no visible signal seen after 16 ms. The results of the three early interactions with the strong vortex support the notion of increased susceptibility for flame quenching with increased dilution, especially for positively stretched, thermo-diffusively stable reaction zones. Figure 7.30 serves as complementary data to show how local extinction affects flame propagation during these early interactions.

7.3.5 Trends in Flame Propagation

The preceding sections compare effects of mixture composition on flame kernel-vortex interactions. Several general trends emerge during these interactions, with a few exceptions. First, flame propagation is enhanced with earlier interaction times, clearly shown in Fig. 7.31 for the $\Phi=0.64$ flame and weak vortex. The late interaction deviates little from undisturbed flame kernel growth, while the early interaction increases the average flame propagation rate (based on effective kernel radius) by a factor of 1.3. Second, increasing the vortex strength incurs higher stretch rates on the flame kernel, and therefore increases the flame growth rate. The effect of vortex strength is illustrated in Fig. 7.32 for $\Phi=0.64$ and the early interaction, resulting in an 86% increase in the average propagation rate. Deviations from these trends appear when early interactions occur with vortices strong enough to cause local, or even global, extinction of the flame kernel. Given the available parameter space for the current investigation, this scenario
was possible with the diluted fuel-rich mixture (Φ = 1.13). Inhibited flame propagation with earlier interaction time is evident in Fig. 7.33 with the medium strength vortex. The chemiluminescence images for this interaction (Fig. 7.25) show the flame kernel almost globally extinguish before recovering in the vortex wake. The effective flame radius fluctuates during this process compared to the smooth curve of the late interaction under the same conditions. Reduced flame propagation with increased vortex strength is observed for early interactions in the fuel-rich mixture. The curves in Fig. 7.34 demonstrate how progression from no extinction, to local, then global, as the Φ = 1.13 kernel interacts with vortices of increasing strength, impedes flame growth in these diluted mixtures which have been shown to be susceptible to quenching.

7.4 Conclusions

The effect of unsteady stretch in CH₄-O₂-N₂ flames has been investigated using flame kernel-vortex interactions. Three equivalence ratios, Φ = 0.64, 0.90, and 1.13 have been compared using nitrogen dilution to equalize the flame propagation rates in the absence of vortex interaction. This scenario facilitates analysis of these different mixtures, including thermo-diffusive stability, even though methane-air flames do not exhibit strong Lewis number effects. Three vortex strengths, covering the laminar to near turbulent regimes, were studied to provide a wide range of experimental conditions, including varied times of interaction. High-speed chemiluminescence imaging was used to visualize each interaction and identify regions of intensified combustion or local extinction. The results showed that many unique flame-flow and flame-flame interactions were possible, with the general trends supporting enhanced flame
propagation with stronger vortices and earlier interactions. With sufficiently strong vortices, an interaction was shown to occur at both the top and bottom surfaces of the flame kernel. These bottom interactions can result in local extinction and the initiation of a secondary expanding flame front connected to the primary kernel. Very early interactions have been shown to break the small kernel into multiple pockets, from which the flame may recover or globally extinguish depending on the vortex strength and equivalence ratio. Several cases, characterized by extinction events or greatly reduced mean reaction rates, showed opposite trends than stated but occur at conditions that are at the limit of the probed parameter space ($\Phi = 1.13$, early interaction, medium/strong vortex).
Figure 7.1 Combustion chamber.
Figure 7.2 Vortex generation apparatus.
Figure 7.3 Comparison of laminar burning velocities for undiluted methane-air mixtures.
Figure 7.4  Scattering images using incense smoke for the three vortices investigated: (a) laminar, (b) transitional, and (c) turbulent vortex. In all three cases, the piston displacement and orifice diameter are held constant at 1 mm and 10 mm, respectively. The field of view in each image is 30 mm wide x 30 mm high.
Figure 7.5 Raw PIV velocity field for the weak vortex case, corresponding to the following vortex generation parameters: $d_o = 10$ mm, piston speed $= 36$ mm/s, $l = 1.0$ mm. The resulting rotational and translational velocities were 77 cm/s and 85 cm/s, respectively. The velocity field represents an approximately 27 mm wide x 22 mm high processing region centered on the vortex.
Figure 7.6 Non-dimensional vortex strength versus size for the CH$_4$-O$_2$-N$_2$ flames and vortices investigated.
Figure 7.7  High-speed flame emission images of undisturbed outwardly propagating flame kernel for $\Phi = 0.90$ and $O_2/(O_2+N_2) = 0.159$. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.8 Flame radius history for CH$_4$-O$_2$-N$_2$ flames freely propagating without vortex interaction. N$_2$ dilution levels for the $\Phi=0.90$ and $\Phi=1.13$ cases were chosen to match (as closely as possible) the $\Phi=0.64$ flame propagation rate.
Figure 7.9  High-speed flame emission images of late kernel-vortex interaction for $\Phi = 0.64$ and weak vortex ($U_0 = 77 \text{ cm/s}$, $U_0/S_{L_c} = 8.21$, $d_o/\delta_D = 40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.10  High-speed flame emission images of late kernel-vortex interaction for $\Phi = 0.90$ and weak vortex ($U_0 = 77$ cm/s, $U_0/S_{L,v} = 7.46$, $d_o/\delta_D = 44.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.11  High-speed flame emission images of late kernel-vortex interaction for $\Phi=1.13$ and weak vortex ($U_0= 77 \text{ cm/s}, U_0/S_{L,in}= 5.77, d_o/\delta_D= 58.1$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.12 High-speed flame emission images of late kernel-vortex interaction for $\Phi=0.64$ and medium vortex ($U_0=266$ cm/s, $U_0/SL_{x}=28.4$, $d_o/\delta_D=40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.13  High-speed flame emission images of late kernel-vortex interaction for \( \Phi = 0.90 \) and medium vortex \((U_\theta = 266 \text{ cm/s}, U_\theta/SL_\infty = 25.8, d_\delta/D = 44.8)\). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.14 High-speed flame emission images of late kernel-vortex interaction for $\Phi = 1.13$ and medium vortex ($U_0 = 266 \text{ cm/s, } U_0/SL_\infty = 19.9, \delta_D/\delta = 58.1$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.15 High-speed flame emission images of late kernel-vortex interaction for $\Phi = 0.64$ and strong vortex ($U_0 = 398$ cm/s, $U_o/S_{L,\infty} = 42.4$, $d_o/\delta_D = 40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.16  High-speed flame emission images of late kernel-vortex interaction for $\Phi=0.90$ and strong vortex ($U_0=398$ cm/s, $U_0/S_{L,\infty}=38.6$, $d_0/\delta_D=44.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.17  High-speed flame emission images of late kernel-vortex interaction for $\Phi=1.13$ and strong vortex ($U_\theta=398$ cm/s, $U_\theta/S_{L_{\infty}}=29.8$, $d_\theta/\delta_D=58.1$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.18 Flame radius history for CH₄-O₂-N₂ flames undergoing a late kernel-vortex interaction with the strong vortex ($U_0=398$ cm/s).
Figure 7.19 High-speed flame emission images of early kernel-vortex interaction for $\Phi = 0.64$ and weak vortex ($U_0 = 77$ cm/s, $U_\theta/U_{L,\infty} = 8.21$, $d_\theta/d_\delta = 40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.20 High-speed flame emission images of early kernel-vortex interaction for $\Phi = 0.90$ and weak vortex ($U_\theta = 77$ cm/s, $U_\theta/S_{L,\infty} = 7.46$, $d_\phi/\delta_D = 44.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.21  High-speed flame emission images of early kernel-vortex interaction for $\Phi = 1.13$ and weak vortex ($U_0 = 77$ cm/s, $U_0/S_{L,\infty} = 5.77$, $d_o/\delta_D = 58.1$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.22 Flame radius history for CH$_4$-O$_2$-N$_2$ flames undergoing an early kernel-vortex interaction with the weak vortex (U$_0$ = 77 cm/s).
Figure 7.23 High-speed flame emission images of early kernel-vortex interaction for $\Phi = 0.64$ and medium vortex ($U_0 = 266$ cm/s, $U_0/S_{L,\infty} = 28.4$, $d_0/\delta_D = 40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.24 High-speed flame emission images of early kernel-vortex interaction for $\Phi = 0.90$ and medium vortex ($U_0 = 266 \text{ cm/s}, U_0/Sl_x = 25.8, d_o/\delta_D = 44.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
**Figure 7.25** High-speed flame emission images of early kernel-vortex interaction for $\Phi = 1.13$ and medium vortex ($U_\theta = 266$ cm/s, $U_\theta/S_{L_{\infty}} = 19.9$, $d_\theta/\delta_D = 58.1$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.26 Flame radius history for CH₄-O₂-N₂ flames undergoing an early kernel-vortex interaction with the medium strength vortex (U₀ = 266 cm/s).
Figure 7.27 High-speed flame emission images of early kernel-vortex interaction for $\Phi=0.64$ and strong vortex ($U_\theta=398$ cm/s, $U_\theta/S_{L,\infty}=42.4$, $d_\omega/\delta_D=40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.28  High-speed flame emission images of early kernel-vortex interaction for $\Phi=0.90$ and strong vortex ($U_\theta=398 \text{ cm/s}, U_\theta/S_{L,\infty}=38.6, d_0/\delta_D=44.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.29 High-speed flame emission images of early kernel-vortex interaction for Φ = 1.13 and strong vortex (U₀ = 398 cm/s, U₀/SL∞ = 29.8, d₀/δ₀ = 58.1). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 7.30 Flame radius history for CH₄-O₂-N₂ flames undergoing an early kernel-vortex interaction with the strong vortex (U₀= 398 cm/s).
Figure 7.31 Effect of interaction time on flame propagation for the $\Phi = 0.64$ CH$_4$-O$_2$-N$_2$ flame interacting with the weak vortex ($U_0 = 77$ cm/s).
Figure 7.32 Effect of vortex strength on flame propagation for the $\Phi=0.64$ CH$_4$-O$_2$-N$_2$ flame undergoing early kernel-vortex interactions.
Figure 7.33 Effect of interaction time on flame propagation for the $\Phi = 1.13$ CH$_4$-O$_2$-N$_2$ flame interacting with the medium strength vortex ($U_\theta = 266$ cm/s).
Figure 7.34 Effect of vortex strength on flame propagation for the $\Phi = 1.13$ CH$_4$-O$_2$-N$_2$ flame undergoing early kernel-vortex interactions.
8. Effects of Flame Stretch and Instability on C₃H₈-O₂-N₂ Flame Kernel-Vortex Interactions

8.1 Introduction

In light of the insight obtained from CH₄-O₂-N₂ flame kernel-vortex interactions, the flame response to stretch using a heavier hydrocarbon fuel is also desired since it is more closely related to fuels primarily used in practical applications. As a result, propane was chosen as the “heavy” hydrocarbon fuel for investigation using flame kernel-vortex interactions. Contrary to methane, which exhibits a weak Lewis number dependence, propane is characterized by a significant change in thermo-diffusive stability as a function of equivalence ratio. These C₃H₈-O₂-N₂ mixtures are thermo-diffusively stable in fuel-lean mixtures and transition to unstable behavior as the equivalence ratio increases above stoichiometric. Instabilities arise as “cracks” along the flame surface which will grow and divide to form cellular structures. This process increases the flame surface area, resulting in enhanced flame propagation rates and reactant consumption. As a cellular flame continues to propagate, the instabilities will eventually cause the flame to undergo a transition from laminar to turbulent. Flame stability is an important aspect of premixed combustion, and failure to account for thermo-diffusive instability (in addition to hydrodynamic instability) can cause unexpected events in real devices, such as an overly rapid pressure rise in a combustion chamber, resulting in undesirable effects such as engine knock.
This chapter discusses the results of \( \text{C}_3\text{H}_8-\text{O}_2-\text{N}_2 \) flame kernel-vortex interactions over a wide range of experimental conditions. Mixtures ranging in equivalence ratio from 0.69 to 1.49 have been investigated, as well as three vortex strengths and various interaction times. Nitrogen dilution was used to control the flame speeds so that the effects of chemistry could be assessed independent of flame propagation rate, particularly advantageous when studying thermo-diffusive stability. Flame morphology over this wide parameter space is of particular interest, including the interaction of vortices with cellular flame structures and stretch-induced regions of local extinction.

8.2 Experimental Details

8.2.1 Experimental Apparatus and Methods

The experimental setup and methods employed for the propane flame kernel-vortex interactions are the same as detailed in Chapter 7 for the methane fuel investigation, and therefore are only briefly discussed in this chapter. The 32.7 liter stainless steel combustion chamber, illustrated in Fig. 8.1, consists of two 5 inch diameter quartz windows for optical access and two smaller windows to facilitate laser sheet propagation for laser-based combustion diagnostics. Central spark ignition is provided by two 0.4 mm diameter stainless steel electrodes inserted horizontally from opposing sides of the chamber, with one electrode mounted on a translation mechanism to accurately control the spark gap (2-3 mm). The ignition system utilizes inductive discharge and is programmable to control the arc duration, nominally 2 ms but can be adjusted from 1-3 ms. Four solenoid valves located at the bottom of the chamber are used to seal the chamber before each run and open 860 ms prior to ignition to allow the
atmospheric combustion to proceed isobarically. Mass flow controllers are used to carefully control fuel, air, and diluent flow rates so that the mixture properties are accurate for each experimental run. In addition, mixture homogeneity is achieved by flowing premixed reactants through the system until the chamber has been purged with ten chamber volumes. After the exhaust valves are closed, the reactants are allowed to settle so that no parasitic gas flow exists during the flame kernel-vortex interaction.

The vortex generation device is located at the top of the combustion chamber. A schematic showing the design and orientation of the vortex apparatus is shown in Fig. 8.2. This device is used to generate axisymmetric three-dimensional vortex rings, or toroids, that propagate downward towards the ignition electrodes and interact with the outwardly propagating flame kernels. A linear actuator, coupled to a software-controlled servo motor, is used to drive an aluminum piston located within a stainless steel cylinder. Two cast iron piston rings prevent leakage of reactant mixture past the piston and infiltration of ambient air into the cylinder. A sharp-edged orifice is located at the bottom of the cylinder to create vorticity, which will develop into a translating vortex toroid, once the piston impulsively displaces a specified volume within cylinder, thereby ejecting rotational fluid out of the orifice. The dynamics of the actuator are carefully controlled so that the characteristics of the resulting vortex are well defined. In all cases, the piston displacement is set at 1.0 mm, but the piston velocity is changed so that various vortex rotational velocities (or strengths) may be investigated. The diameter of the sharp-edged orifice is 10 mm, and the distance from the orifice to the electrode tips is 100 mm, resulting in an approximately 25% increase in vortex core-to-core diameter during
propagation. All vortices are generated using a reactant mixture identical to that of the main combustion chamber.

The vortices utilized in this experiment were characterized based on vortex rotational velocity, $U_0$, defined as the tangential velocity at the edge of the vortex core. This characteristic velocity, also termed vortex strength, is used to indicate the degree of stretch the vortex will exert on a given flame surface. The orifice diameter, $d_o$, determines the vortex core-to-core diameter and is therefore the characteristic length scale of the vortex. Particle Image Velocimetry (PIV) was utilized to measure the two-dimensional cold flow velocity field of each vortex as its leading edge approached the ignition electrodes. The main objective of the PIV measurements was to quantify both the vortex rotational and translational velocities, which have been shown to be approximately equal (Roberts, 1992), and to determine if the vortex is laminar, transitional, or turbulent. Incense smoke was chosen to seed the vortex and provide scattering images both for the PIV analysis and to observe the overall vortex structure.

The flame kernel-vortex interactions have been investigated using broadband high-speed chemiluminescence imaging primarily of CH*/OH* emission. A Kodak EKTAPRO model 4540 high-speed camera was lens-coupled to an Imco ILS-3 intensifier with a 105 mm UV-Nikkor lens to facilitate imaging at framing rates up to 4,500 frames per second over a 95.7 mm wide by 100 mm high field of view. Processing of the high-speed data begins with breaking the videos up into individual images and applying an isodata thresholding algorithm to outline the flame boundary in each image. Then, the projected area of the flame kernel is measured and an effective kernel radius, $r_k$, is calculated assuming spherical symmetry. During many interactions the disturbed flame
surface is non-spherical, but since the effective radius simply scales with the projected area, it provides a basis for comparison between cases and to previous work (Xiong, 2001). This combination of high-speed imaging and flame front tracking allows the flame’s response to stretch to be analyzed and conclusions drawn concerning issues relevant to premixed combustion.

8.2.2 Flame Properties

The mixture conditions for the propane-air flames were chosen so that the effects of chemistry could be studied independent of flame speed. Five primary equivalence ratios were utilized for investigation: \( \Phi = 0.69, 0.87, 1.08, 1.32, \) and 1.49. The choice of equivalence ratio was strategically made so that the \( \Phi = 0.69/1.49 \) and \( \Phi = 0.87/1.32 \) mixtures have the same undiluted flame propagation rate, \( \text{dr}_f/\text{dt} \). Therefore, in the undiluted case, there are three flame speeds (in laboratory coordinates, not to be confused with burning velocity) represented by these mixtures. This investigation focused on two of those flame speeds with these five mixtures, labeled “low” and “high.” To achieve the low flame speed, nitrogen was used as a diluent to retard the flame speeds of the \( \Phi = 0.87/1.08/1.32 \) mixtures so that the flame propagation rates equal that of \( \Phi = 0.69/1.49 \) for the case of an undisturbed outwardly propagating spherical flame kernel. For the high flame speed, which excludes \( \Phi = 0.69/1.49 \) since it was not desired to use an oxidizer mixture with more than 21% \( \text{O}_2 \), the \( \Phi = 0.87/1.32 \) mixtures were used undiluted, and the \( \Phi = 1.08 \) mixture was diluted to match this flame propagation rate. The relevant flame and mixture properties for the low and high flame speeds are given in Tables 8.1 and 8.2, respectively.
It is important to note that the slow flame speed is still higher than the flame speed analyzed in Chapter 7 for methane fuel. In order to provide a more direct comparison between these two fuels, flame kernel-vortex interactions were obtained with a $\Phi = 1.08$ C$_3$H$_8$-O$_2$-N$_2$ mixture that was diluted to the $\Phi = 0.64$ CH$_4$ flame propagation rate. This approach keeps the relative strength of the vortex on each flame kernel similar, since a slower flame will be more influenced by a given vortex than the faster flame speeds. Table 8.3 details the properties for the methane mixtures from Chapter 7 with the highly diluted propane $\Phi = 1.08$ properties specifically chosen to study fuel effects. As a final comparison, undiluted stoichiometric propane-air and methane-air mixtures were investigated, and their properties are listed in Table 8.4. The stoichiometric cases possess the highest flame speeds used in the combustion chamber and therefore represent the upper limit of that parameter. Only the results for the “low” flame speed kernel-vortex interactions are presented in this chapter. The remaining cases will be included in a separate publication, but their flame properties are included here to inform the reader of the scope of this research in addition to providing necessary details for future investigations.

The flame propagation rates used to obtain proper dilution levels were compared using well established spherical flame kernels and therefore were not subject to ignition effects which will be different for each mixture composition. Values for the unstretched laminar burning velocity, $S_{L,\infty}$, and the Markstein number, Ma, given in Tables 8.1-8.4 were measured in the same apparatus utilizing the method presented by Marley and Roberts (2005), with the results in good agreement to the recent literature for undiluted propane-air flames (Bosschaart and de Goey, 2004; Hassan et al., 1998; Jomaas et al.,
2004; Vagelopoulos and Egolfopoulos, 1998) as shown in Fig. 8.3. The unstretched laminar burning velocities for all mixtures investigated with the flame kernel-vortex interactions are plotted in Fig. 8.4. Notice that the values of burning velocity for the “low” and “high” flame speeds actually decrease with increasing equivalence ratio, even though the flame propagation rates are held equal within experimental capabilities.

**Table 8.1** Properties for “low” flame speed C$_3$H$_8$-O$_2$-N$_2$ flames at 300K and 1 atm.

<table>
<thead>
<tr>
<th>Equivalence Ratio, $\Phi$</th>
<th>0.69</th>
<th>0.87</th>
<th>1.08</th>
<th>1.32</th>
<th>1.49</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Fuel</td>
<td>2.82</td>
<td>2.97</td>
<td>3.34</td>
<td>4.49</td>
<td>5.89</td>
</tr>
<tr>
<td>O$_2$/(O$_2$+N$_2$)</td>
<td>0.21</td>
<td>0.176</td>
<td>0.160</td>
<td>0.178</td>
<td>0.21</td>
</tr>
<tr>
<td>Molecular Diffusivity C$_3$H$_8$-N$_2$, $D_u$ [cm$^2$/s]</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Molecular Diffusivity O$_2$-N$_2$ [cm$^2$/s]</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Thermal Diffusivity, $\alpha$ [cm$^2$/s]</td>
<td>0.210</td>
<td>0.209</td>
<td>0.208</td>
<td>0.203</td>
<td>0.197</td>
</tr>
<tr>
<td>Lewis Number, Le</td>
<td>1.91</td>
<td>1.90</td>
<td>0.99</td>
<td>0.97</td>
<td>0.94</td>
</tr>
<tr>
<td>Laminar Burning Velocity, $S_{L,\infty}$ [cm/s]</td>
<td>21.47</td>
<td>18.85</td>
<td>18.34</td>
<td>15.73</td>
<td>13.93</td>
</tr>
<tr>
<td>Markstein Number, Ma</td>
<td>4.52</td>
<td>3.48</td>
<td>2.66</td>
<td>-0.61</td>
<td>-1.92</td>
</tr>
<tr>
<td>Flame Thickness, $\delta_D = D_u/S_{L,\infty}$ [mm]</td>
<td>0.0512</td>
<td>0.0584</td>
<td>0.0600</td>
<td>0.0699</td>
<td>0.0790</td>
</tr>
</tbody>
</table>

**Table 8.2** Properties for “high” flame speed C$_3$H$_8$-O$_2$-N$_2$ flames at 300K and 1 atm.

<table>
<thead>
<tr>
<th>Equivalence Ratio, $\Phi$</th>
<th>0.87</th>
<th>1.08</th>
<th>1.32</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Fuel</td>
<td>3.53</td>
<td>3.98</td>
<td>5.25</td>
</tr>
</tbody>
</table>
Table 8.3  Comparison of properties for CH$_4$-O$_2$-N$_2$ flames and diluted C$_3$H$_8$-O$_2$-N$_2$ flame at 300K and 1 atm.  The C$_3$H$_8$ flame has been diluted with N$_2$ to match the CH$_4$ flame propagation rate.

<table>
<thead>
<tr>
<th>Equivalence Ratio, $\Phi$</th>
<th>$\text{CH}_4$ 0.64</th>
<th>$\text{CH}_4$ 0.90</th>
<th>$\text{CH}_4$ 1.13</th>
<th>$\text{C}_3\text{H}_8$ 1.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Fuel</td>
<td>6.30</td>
<td>6.68</td>
<td>8.00</td>
<td>3.04</td>
</tr>
<tr>
<td>$\text{O}_2/(\text{O}_2+\text{N}_2)$</td>
<td>0.21</td>
<td>0.159</td>
<td>0.154</td>
<td>0.145</td>
</tr>
<tr>
<td>Molecular Diffusivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel-N$_2$, $D_u$ [cm$^2$/s]</td>
<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
<td>0.11</td>
</tr>
<tr>
<td>Molecular Diffusivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{O}_2$-N$_2$ [cm$^2$/s]</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Thermal Diffusivity, $\alpha$ [cm$^2$/s]</td>
<td>0.225</td>
<td>0.225</td>
<td>0.225</td>
<td>0.209</td>
</tr>
<tr>
<td>Lewis Number, $Le$</td>
<td>0.98</td>
<td>0.98</td>
<td>1.07</td>
<td>1.00</td>
</tr>
<tr>
<td>Laminar Burning Velocity, $S_{L,\infty}$ [cm/s]</td>
<td>9.38</td>
<td>10.32</td>
<td>13.34</td>
<td>12.82</td>
</tr>
<tr>
<td>Markstein Number, $Ma$</td>
<td>-0.10</td>
<td>0.385</td>
<td>1.31</td>
<td>2.36</td>
</tr>
<tr>
<td>Flame Thickness, $\delta = \frac{D_u}{S_{L,\infty}}$ [mm]</td>
<td>0.245</td>
<td>0.223</td>
<td>0.172</td>
<td>0.0858</td>
</tr>
</tbody>
</table>

**Table 8.4** Properties for undiluted stoichiometric C\textsubscript{3}H\textsubscript{8}-O\textsubscript{2}-N\textsubscript{2} and CH\textsubscript{4}-O\textsubscript{2}-N\textsubscript{2} flames at 300K and 1 atm.

<table>
<thead>
<tr>
<th>Equivalence Ratio, $\Phi$</th>
<th>C\textsubscript{3}H\textsubscript{8} 1.00</th>
<th>CH\textsubscript{4} 1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Fuel</td>
<td>4.03</td>
<td>9.51</td>
</tr>
<tr>
<td>O\textsubscript{2}/(O\textsubscript{2}+N\textsubscript{2})</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Molecular Diffusivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel-N\textsubscript{2}, $D_u$ [cm\textsuperscript{2}/s]</td>
<td>0.11</td>
<td>0.23</td>
</tr>
<tr>
<td>Molecular Diffusivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O\textsubscript{2}-N\textsubscript{2} [cm\textsuperscript{2}/s]</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Thermal Diffusivity, $\alpha$ [cm\textsuperscript{2}/s]</td>
<td>0.205</td>
<td>0.225</td>
</tr>
<tr>
<td>Laminar Burning Velocity, $S_{L,\infty}$ [cm/s]</td>
<td>38.59</td>
<td>33.90</td>
</tr>
<tr>
<td>Markstein Number, $Ma$</td>
<td>3.56</td>
<td>1.13</td>
</tr>
<tr>
<td>Flame Thickness, $\delta = \frac{D_u}{S_{L,\infty}}$ [mm]</td>
<td>0.0285</td>
<td>0.0678</td>
</tr>
</tbody>
</table>

**8.3 Results and Discussion**

The Results and Discussion section is organized to present a subset of many data cases, all of which can not be included in this chapter. The first subsection discusses the results of the vortex analysis and how these vortex properties characterize the range of kernel-vortex interactions available in the current experimental apparatus. The following subsection then details the results of C\textsubscript{3}H\textsubscript{8}-O\textsubscript{2}-N\textsubscript{2} flames at the prescribed “low” flame propagation rate in order to compare the effects of equivalence ratio, vortex strength, and
interaction time on kernel-vortex interactions. The classification of interaction time, based on when the vortex first affects flame propagation, is accomplished by assigning three regimes of interaction: early, medium, and late (Xiong, 2001). An early interaction occurs when the ratio of the kernel diameter to vortex diameter is $<1$ at the time of first visible interaction in the high-speed chemiluminescence videos. A late interaction is defined when this first interaction occurs for a kernel to vortex diameter ratio $>2$. Any case falling in between these definitions ($1 < \text{kernel-vortex ratio} < 2$) is labeled a medium interaction. All three interactions have been investigated, but only early and late interactions are discussed in detail.

8.3.1 Vortex Strength

The PIV measurements were carried out over a wide range of vortex strengths, but only three vortices were selected to be used in the flame kernel-vortex investigation. The three vortex cases studied represent laminar, transitional, and turbulent vortices, therefore facilitating a thorough analysis of the flame response to unsteady stretch. The piston displacement for all three cases remained constant at 1.0 mm, while the peak piston speeds were 36 mm/s, 110 mm/s, and 180 mm/s, corresponding to “weak,” “medium,” and “strong” vortices, respectively. The PIV scattering images also served to visualize the vortex structure as shown in Fig. 8.5. Each velocity field generated from the PIV data provides a two-dimensional slice through the vortex center and reveals the axisymmetric character of the three-dimensional toroid. Figure 8.6 shows the raw velocity field for the “weak” vortex from which the rotational and translational velocities were measured to be 77 cm/s and 85 cm/s, respectively. Similar analyses performed with
The “medium” and “strong” vortex cases revealed rotational/translational velocities of 266/255 cm/s and 398/351 cm/s, respectively. As stated earlier, the rotational velocity is termed the vortex strength since it will determine the stretch rate imposed upon the flame surface. In order to provide a common measure of the vortex effect on any flame front, the rotational velocity, $U_\theta$, is non-dimensionalized by the unstretched laminar burning velocity, $S_{L,\infty}$, while the characteristic length scale, $d_0$, is non-dimensionalized by the characteristic flame thickness, $\delta_D$. Figure 8.7 indicates the non-dimensional vortex strengths and sizes for the vortices and reactant mixtures investigated. Due to the large amount of data acquired, only kernel-vortex interactions with the weak or strong vortices are further discussed in this chapter.

8.3.2 “Low” Flame Speed

The set of flame kernel-vortex interactions considered are only those at the “low” flame propagation rate. As stated before, the equivalence ratios in this category are $\Phi=0.69$, 0.87, 1.08, 1.32, and 1.49, and the middle three mixtures were diluted so that their undisturbed flame propagation rates matched, as close as possible, the rate of the $\Phi=0.69$ (or 1.49) mixture. From Table 8.1, it is seen that the $\Phi=1.32$ and $\Phi=1.49$ mixtures are thermo-diffusively unstable, determined from a negative Markstein number, and therefore will have the propensity to form wrinkled or cellular flame structures under any perturbation. The other mixtures, thermo-diffusively stable, are able to dampen out any flame surface disturbances but will do so to a lesser degree as the Markstein number decreases, which is observed with increasing equivalence ratio. To illustrate this point, Fig. 8.8 shows images obtained from the high-speed chemiluminescence videos of both a
fuel-lean (Φ = 0.87, stable) and a fuel-rich (Φ = 1.32, unstable) undisturbed outwardly propagating propane flame kernel diluted to the low flame speed. The stable flame possesses a very smooth flame surface, while the unstable flame quickly forms wrinkles which will grow and then multiply to eventually form a cellular flame. Both flame kernels are affected by the intrusive ignition electrodes, which results in locally decreased flame propagation rates due to heat loss and a local change in the sign of the flame curvature, defined as positive when concave to the hot products. The time history of effective kernel radius for these five mixtures is plotted in Fig. 8.9 for undisturbed kernels. The figure shows the three stable flames have very similar flame propagation characteristics, while the unstable flames are initially larger but still propagate at the desired rate. It is interesting to note that the initial kernel size increases with decreasing thermo-diffusive stability. Therefore, the initial propane kernels are larger as the equivalence ratio increases, while the opposite trend is true for methane (see Chapter 7), which behaves similar to a hydrogen-air flame. Also consistent with methane, the unstable propane flames exhibit a linear dependence of effective kernel radius with time, while the stable flames initially lag behind and then eventually recover, yielding a slightly nonlinear trend. Therefore, the dilution levels were chosen to give the best overall match in ∂r_k/∂t for all cases over the range of kernel sizes investigated with the kernel-vortex interactions. The average flame propagation rates, measured from ignition until the flame reaches the image edge, ranged from 105 to 115 cm/s for the low flame speed diluted mixtures.

The first flame kernel-vortex interactions discussed for these mixtures at the low flame propagation rate are late interactions with the weak, laminar vortex. Figures 8.10-
8.14 contain images taken from the high-speed videos for each mixture condition. As with the undisturbed cases, the initial kernel both increases in size and is more spherical with increasing equivalence ratio until the Markstein number becomes negative, indicating thermo-diffusive instability. The thermo-diffusively stable cases ($\Phi = 0.69, 0.87, 1.08$) have smooth flame surfaces, while the unstable mixtures ($\Phi = 1.32, 1.49$) quickly develop wrinkles ($\Phi = 1.32$) or cellular instabilities ($\Phi = 1.49$). As the vortex first interacts with the kernel for all cases, the flame is strong enough to actually push the imposing vortex upwards, reversing the propagation direction, before further expansion allows the vortex to resume downward travel. As the vortex bubble is formed within the kernel, the laminar reaction zone is observed to be well-defined around the vortex and connects to the outer kernel surface via the trailing wake. Interestingly, for the $\Phi = 1.49$ case, the positively curved connecting region between the wake and outer flame kernel goes through a phase of intensification when the curvature is maximized before reducing due to kernel expansion and vortex propagation (see 29.93 ms frame in Fig. 8.14). This observation is possibly due to the increased burning velocity resulting from positive stretch, characteristic of thermo-diffusively unstable flames. As the vortex continues to propagate, the trailing wake of the $\Phi = 1.32$ and $\Phi = 1.49$ cases develops three-dimensional structure in the form of wrinkling, while the stable cases exhibit symmetric wake flames. Also, as the vortex is consumed, primarily by trailing edge combustion, the remaining flame pocket is increasingly curved (U-shaped) with increasing equivalence ratio. This behavior may be due to increased wrinkling (as $\Phi$ increases) along the vortex centerline, which favors consumption from the center outwards, instead of uniformly across the vortex surface. As the wake flame detaches and vortex consumption occurs,
the $\Phi = 0.69, 0.87, 1.08$ cases show a well-defined reaction zone around both the trailing wake and remaining vortex reactants, which are completely consumed just above the electrodes. In comparison, for the $\Phi = 1.32$ and $\Phi = 1.49$ cases, both the vortex and wake reaction zones become diffuse during the final stages of the interaction, and the chemiluminescence signal gradually fades away with no distinct flame boundary between reactant and products. This scenario suggests that the combustion may be incomplete and is in the distributed reaction zone regime since reactants and products could co-exist. Finally, as flame kernel expansion proceeds, the thermo-diffusively stable cases remain smooth while the unstable mixtures continue to undergo cellular flame structure growth and reproduction. Figure 8.15 plots the flame radius as a function of time for the five equivalence ratios undergoing the late interactions with the weak vortex. From Fig. 8.15, it is observed that the flames exhibit flame propagation characteristics similar to the undisturbed kernels, indicating the minimal effect of the weak vortex on the overall growth of the well established flame kernels. The only mixture with an appreciable increase in flame propagation was $\Phi = 1.49$, with the average propagation rate increasing by 14%, to a value of 131 cm/s versus the undisturbed value of 115 cm/s.

The next step in the analysis is to investigate the effect of the strong vortex on late kernel-vortex interactions. Figures 8.16-8.20 detail the key events that occur during the interactions for all five mixtures. The first characteristic observed for all cases is that the strong vortex exhibits little or no attenuation as its leading edge interacts with the expanding flame kernel, contrary to the late interactions with the weak vortex. As the vortex bubble forms with the trailing wake, the leading edge is still well-defined while wrinkling at the trailing edge is apparent in all cases. In addition, three-dimensional
structure is seen at the outermost radial positions on the vortex sides. Similar to the weak vortex case, for $\Phi = 1.49$, it appears that stretch-induced intensification occurs at the connecting region between the vortex trailing edge and the outer flame kernel surface (see 22.86 ms image of Fig. 8.20). Of course, this elevated intensity may be due to wrinkling or area generation, and then the intensification would result from spatial integration of the three-dimensional flame surface. Farther propagation of the vortex into the kernel leads to the generation of a turbulent wake flame, especially for the thermo-diffusively unstable cases ($\Phi = 1.32$ and $\Phi = 1.49$) which show a very wide and intense wake reaction zone. As the vortex traverses the electrodes, the thermo-diffusively stable cases undergo quenching along the vortex flame, leaving just the trailing edge combustion, and then re-igniting below the electrodes. For the $\Phi = 1.32$ mixture, no quenching occurs, but heat losses incur a less defined reaction zone that is less intense but deformed due to flow disturbance from the electrodes. The vortex leading edge combustion for the $\Phi = 1.49$ case only locally loses intensity at the electrodes before becoming very intense as turbulent trailing edge combustion consumes the vortex. As the vortex is consumed below the electrodes, all cases are characterized by wrinkled turbulent reaction zones, with the most intense, vigorous combustion occurring in the unstable flames. This intense combustion that is observed in the unstable cases allows the vortex to be more quickly consumed than in the stable cases due to increased flame surface area and reactant consumption rates. As a result, the vortex momentum is less attenuated for the stable cases, allowing flame-flow and flame-flame interactions at the bottom kernel surface. These interactions are characterized by positive stretch and a thinning of the reaction zone as it is pushed downward, creating increased reaction zone
area. Some remaining vortex momentum is able to dimple the bottom kernel surface for the $\Phi= 1.32$ case, while the vortex is consumed well before reaching the kernel bottom for the $\Phi= 1.49$ case and therefore has no observed effect. Similar to the late interactions with the weak vortex, the final consumption of vortex fluid in the unstable cases is diffuse, and the chemiluminescence signal simply fades away without a well-defined reaction zone consuming the remaining reactants. The effective flame radius history, plotted in Fig. 8.21, shows an increase in the slope at the time when the vortex is entering the flame kernel. The peak local flame propagation rates usually occur as the vortex wraps the reaction zone around its outermost radial position at the vortex edge. As with the results from the late interactions with the weak vortex, only marginal increases in the average flame propagation rate are observed, with peak propagation rates ranging from 134 to 143 cm/s. It is important to remember that these average flame speeds only reflect changes in the projected flame kernel area, and therefore do not always capture the varied flame-flow dynamics that occur within the kernel itself. In addition, the measurements can only be made when the entire flame kernel is within the field of view, so any effects that occur after this point can not be included in the calculations.

Early flame kernel-vortex interactions were studied to gain a better understanding of the effect of flame stretch on young flame kernels just after ignition. This scenario maximizes the influence that the invading vortex has on the relatively small flame, resulting in dramatic changes in the flame propagation and reactant consumption. The first cases considered are early interactions with the weak vortex at the low flame propagation rate, with the corresponding chemiluminescence video sequences shown in Figs. 8.22-8.26. As the early interaction proceeds in the $\Phi= 0.69$ case, the vortex leading
edge flame wrinkles and develops into an intense pocket of combustion as the vortex is consumed. In the \( \Phi = 0.69, 0.87, 1.08 \) cases, the trailing edge of the flame narrows quickly due to vorticity and exposes the remaining pocket of reactants in the vortex cores, but the leading edge vortex combustion is not as intense for the \( \Phi = 0.87 \) and \( \Phi = 1.08 \) cases in comparison to the \( \Phi = 0.69 \) flame, even though the flame structure is similar. In addition, for the \( \Phi = 0.69 \) and \( \Phi = 0.87 \) flames, the disturbed reaction zone is well defined by the chemiluminescence signal, whereas the \( \Phi = 1.08 \) case exhibits a more diffuse signal along the perturbed reaction zone. For all three mixtures, the vortex and wake continue to burn and eventually separate as the vortex is finally consumed. During this process, the diffuse reaction zone for the \( \Phi = 1.08 \) case becomes very evident inside the flame kernel. As flame expansion continues for these three thermo-diffusively stable mixtures, the flame surfaces remain smooth with no instabilities formed. Increasing the equivalence ratio to \( \Phi = 1.32 \) introduces thermo-diffusive instability. As the vortex enters the kernel for the \( \Phi = 1.32 \) mixture, flame wrinkling occurs and the intensity along the vortex flame surface varies locally. Also, the flame kernel shows signs of wrinkle formation along its outer surface. The leading edge of the vortex flame dims as it passes the electrodes and never really recovers its original intensity. Further progression of the interaction leads to the narrowing of the wake at the trailing edge of the vortex, while the remaining vortex flame possesses fluctuations and discontinuities in signal intensity, suggesting incomplete combustion. During final vortex consumption, the vortex flame gradually fades away, a process much different than the well-defined reaction zones observed in the fuel-lean cases. The receding wake has a diffuse reaction zone with no clear boundary, suggesting that the combustion may occur in the distributed reaction zone.
regime. The remaining flame kernel continues to expand as cellular flame structures develop. The most unstable mixture considered, Φ = 1.49, exhibits fluctuating intensities around the vortex as vorticity wraps the flame to the trailing edge. Similar to the Φ = 1.32 case, the leading edge flame dims as it passes the electrodes due to heat loss. As the vortex is consumed, discontinuities along the reaction zone suggest either reduced reaction rates or incomplete/quenched combustion. The trailing wake flame and kernel are wrinkled due to instability, and the vortex flame separates from the wake reaction zone but not along defined boundaries such as in the fuel-lean flames. The remaining vortex reactants fade away as the wake retreats, and the flame kernel continues to expand with a highly cellular flame surface. Fig. 8.27 illustrates the effect of the early interactions with the weak vortex on the effective kernel radius. The enhanced flame propagation is evident compared to the late interactions, although the increase in flame propagation rate is not significantly larger. The average flame propagation rates vary from 117 to 136 cm/s, while the peak propagation rates span 145 to 169 cm/s.

The final cases considered, early interactions with the strong vortex, provide the most dramatic responses to flame stretch observed in this investigation. The image sequences of the kernel-vortex interactions are shown in Figs. 8.28-8.32 for all five C₃H₈-O₂-N₂ mixtures. Since the interaction begins when the flame kernel is very small, the vortex strength is high enough to compress the kernel into a U-shaped flame for all mixtures, although flame propagation and intensification increases with increasing Φ. For the Φ = 0.69 and Φ = 0.87 mixtures, the vortex leading edge stretches the flame and merges the top and bottom kernel surfaces, leading to local extinction at the bottom flame boundary. This event is followed by trailing edge combustion, highly wrinkled due to
vorticity, propagating down through the flame hole and into the vortex wake. In the $\Phi=1.08$ flame, the reaction zones merge but the quenching is not as obvious. Local extinction does occur, though, as the trailing edge combustion is observed to propagate through the kernel bottom. As the flame continues to expand, the trailing wake flame is consumed, and the wrinkled reaction zone generated by the turbulent vortex smooths out due to thermo-diffusive stability. It is important to note that the decreasing Markstein number with increasing equivalence ratio is evident by the increased wrinkling of the top kernel flame surface. The flame kernel-vortex interactions proceed differently for the unstable mixtures corresponding to $\Phi=1.32$ and $\Phi=1.49$. The unstable flames exhibit no local extinction as a result of the vortex-induced stretch and flame-flame interaction. The vortex flame becomes very wrinkled and intense for both mixtures. In addition, the vortex momentum, instead of incurring quenching, stretches the kernel bottom and significantly increases the flame surface area. Another characteristic of the unstable flames is that a well-defined wake does not form. Instead, a heavily contorted wake flame breaks up into pockets and the reaction zones become diffuse, not well demarcated as they are consumed. Cellular instabilities then develop, especially at the wrinkled kernel top surface. The unstable flames clearly exhibit augmented flame propagation due to the early interaction with the strong vortex as indicated by the flame radius history for all mixtures in Fig. 8.33. The local extinction events that occur for the thermo-diffusively stable mixtures inhibit flame growth, especially for the fuel-lean mixtures. The $\Phi=1.08$ case shows the largest deviation of flame propagation from the fuel-lean cases in these kernel-vortex interactions compared to the previous scenarios. Average
flame propagation rates increase with increasing equivalence ratio and range from 136 to 153 cm/s.

8.4 Conclusions

The effect of unsteady stretch on C$_3$H$_8$-O$_2$-N$_2$ mixtures has been assessed using flame kernel-vortex interactions. The results for five reactant mixtures, ranging from $\Phi = 0.69$ to $\Phi = 1.49$, were presented to cover the range of thermo-diffusive stability. Nitrogen dilution was added to the appropriate mixtures so that all flame kernels had the same undisturbed flame propagation rate as the $\Phi = 0.69/1.49$ cases, termed the “low” flame speed. Three vortex strengths, corresponding to laminar, transitional, and near turbulent were generated at various times relative to ignition so that several interaction scenarios were possible. Based on initial flame characterization, it was determined that the two richest mixtures, $\Phi = 1.32$ and $\Phi = 1.49$, were thermo-diffusively unstable and would develop cellular structures. Lewis number effects were evident even without the vortex interaction, since the initial kernel size increased with increasing equivalence ratio, or decreasing thermo-diffusive stability. This trend was also observed with the methane-air flames in Chapter 7, although decreasing stability corresponded to decreasing equivalence ratio. The flame speeds were high enough in the propane flames that late interactions with the weak vortex temporarily reversed the propagation direction of the vortex leading edge.

Although the weak vortex had a minimal effect on flame propagation during late interactions, in the $\Phi = 1.49$ flame the flame-flow interaction did cause local intensification of chemiluminescence signal in regions of high positive stretch rate due to
increased burning intensity. Also, the thermo-diffusively unstable flames exhibited diffuse reaction zones that indicated the possibility of incomplete combustion within the distributed reaction zone regime, a result that was observed throughout the investigation for these mixtures. The introduction of the strong vortex allowed the vortex to survive for a longer time within the kernel for the late interactions, and the thermo-diffusively stable cases exhibited extinction and re-ignition of the vortex combustion as the vortex traversed the ignition electrodes. As expected, the most vigorous consumption of the vortex was seen in the unstable cases. The early kernel-vortex interactions provided the most dramatic flame response and increased flame propagation rates. With sufficiently strong vortices, the kernel was locally extinguished in the thermo-diffusively stable flames, while the unstable flames became quickly wrinkled and the cellular structures significantly augmented flame propagation.
Figure 8.1 Combustion chamber.
Figure 8.2 Vortex generation apparatus.
Figure 8.3 Comparison of laminar burning velocities for undiluted propane-air mixtures.
Figure 8.4 Comparison of laminar burning velocities as a function of equivalence ratio for all mixtures investigated.
Figure 8.5  Scattering images using incense smoke for the three vortices investigated: (a) laminar, (b) transitional, and (c) turbulent vortex. In all three cases, the piston displacement and orifice diameter are held constant at 1 mm and 10 mm, respectively. The field of view in each image is 30 mm wide x 30 mm high.
Figure 8.6 Raw PIV velocity field for the weak vortex case, corresponding to the following vortex generation parameters: $d_0 = 10$ mm, piston speed $= 36$ mm/s, piston displacement $= 1.0$ mm. The resulting rotational and translational velocities were 77 cm/s and 85 cm/s, respectively. The velocity field represents an approximately 27 mm wide x 22 mm high processing region centered on the vortex.
Figure 8.7 Non-dimensional vortex strength versus size for the $\text{C}_3\text{H}_8$-$\text{O}_2$-$\text{N}_2$ and $\text{CH}_4$-$\text{O}_2$-$\text{N}_2$ flames and vortices investigated.
Figure 8.8  High-speed flame emission images of undisturbed outwardly propagating C$_3$H$_8$-O$_2$-N$_2$ flame kernels for $\Phi = 0.87$ (top row) and $\Phi = 1.32$ (bottom row). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.9 Flame radius history for C$_3$H$_8$-O$_2$-N$_2$ flames freely propagating without vortex interaction. N$_2$ dilution levels for the $\Phi = 0.87$, 1.08, and 1.32 cases were chosen to match (as closely as possible) the $\Phi = 0.69/1.49$ flame propagation rate.
Figure 8.10  High-speed C₃H₈-O₂-N₂ flame emission images of late kernel-vortex interaction for \( \Phi = 0.69 \), weak vortex (\( U_0 = 77 \text{ cm/s}, \frac{U_0}{S_{L,\infty}} = 3.59, \frac{d_0}{\delta_D} = 195.3 \)), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.11  High-speed C\textsubscript{3}H\textsubscript{8}-O\textsubscript{2}-N\textsubscript{2} flame emission images of late kernel-vortex interaction for Φ= 0.87, weak vortex (U\textsubscript{0}= 77 cm/s, U\textsubscript{0}/S\textsubscript{L,x}= 4.09, d\textsubscript{o}/δ\textsubscript{D}= 171.2), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.12 High-speed C₃H₈-O₂-N₂ flame emission images of late kernel-vortex interaction for $\Phi= 1.08$, weak vortex ($U_0 = 77$ cm/s, $U_0/SL_\infty = 4.20$, $d_0/\delta_D = 166.7$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.13  High-speed C\textsubscript{3}H\textsubscript{8}-O\textsubscript{2}-N\textsubscript{2} flame emission images of late kernel-vortex interaction for Φ= 1.32, weak vortex (U\textsubscript{θ}= 77 cm/s, U\textsubscript{θ}/S\textsubscript{L,∞}= 4.90, d\textsubscript{0}/δ\textsubscript{D}= 143.1), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.14  High-speed C\textsubscript{3}H\textsubscript{8}-O\textsubscript{2}-N\textsubscript{2} flame emission images of late kernel-vortex interaction for $\Phi$= 1.49, weak vortex ($U_0$= 77 cm/s, $U_0/S_{L,\infty}$= 5.53, $d_0/\delta_D$= 126.6), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.15 Flame radius history for C$_3$H$_8$-O$_2$-N$_2$ flames undergoing a late kernel-vortex interaction with the weak vortex ($U_0 = 77$ cm/s) at the “low” flame propagation rate.
Figure 8.16 High-speed C$_3$H$_8$-O$_2$-N$_2$ flame emission images of late kernel-vortex interaction for $\Phi=0.69$, strong vortex ($U_0=398$ cm/s, $U_0/S_{L,\infty}=18.54$, $d_{v}/\delta_D=195.3$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.17  High-speed C₃H₈-O₂-N₂ flame emission images of late kernel-vortex interaction for $\Phi=0.87$, strong vortex ($U_\theta=398$ cm/s, $U_\theta/S_{L,\infty}=21.11$, $d_o/\delta_D=171.2$), and "low" flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.18  High-speed C₃H₈-O₂-N₂ flame emission images of late kernel-vortex interaction for Φ = 1.08, strong vortex (U₀ = 398 cm/s, U₀/S₁,∞ = 21.70, d₀/δ₀ = 166.7), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.19  High-speed C<sub>3</sub>H<sub>8</sub>-O<sub>2</sub>-N<sub>2</sub> flame emission images of late kernel-vortex interaction for Φ = 1.32, strong vortex (U<sub>θ</sub> = 398 cm/s, U<sub>θ</sub>/S<sub>L∞</sub> = 25.30, d<sub>θ</sub>/δ<sub>D</sub> = 143.1), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.20  High-speed C₃H₈-O₂-N₂ flame emission images of late kernel-vortex interaction for Φ = 1.49, strong vortex ($U_0 = 398$ cm/s, $U_0/S_{L,infty} = 28.57$, $d_o/\delta_D = 126.6$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.21 Flame radius history for $\text{C}_3\text{H}_8$-O$_2$-N$_2$ flames undergoing a late kernel-vortex interaction with the strong vortex ($U_0 = 398$ cm/s) at the “low” flame propagation rate.
Figure 8.22  High-speed C$_3$H$_8$-O$_2$-N$_2$ flame emission images of early kernel-vortex interaction for $\Phi = 0.69$, weak vortex ($U_0 = 77$ cm/s, $U_0/S_{L,c} = 3.59$, $d_0/\delta_D = 195.3$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.23  High-speed C$_3$H$_8$-O$_2$-N$_2$ flame emission images of early kernel-vortex interaction for $\Phi = 0.87$, weak vortex ($U_0 = 77$ cm/s, $U_0/S_{Ltr} = 4.09$, $d_0/\delta_D = 171.2$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.24  High-speed C$_3$H$_8$-O$_2$-N$_2$ flame emission images of early kernel-vortex interaction for $\Phi = 1.08$, weak vortex ($U_0 = 77$ cm/s, $U_0/S_{L,v} = 4.20$, $d_o/\delta_D = 166.7$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.25  High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 1.32, weak vortex (U₀= 77 cm/s, U₀/S₁₉,c= 4.90, d₀/δ₀= 143.1), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.26  High-speed \( \text{C}_3\text{H}_8\text{-O}_2\text{-N}_2 \) flame emission images of early kernel-vortex interaction for \( \Phi = 1.49 \), weak vortex \( (U_0 = 77 \text{ cm/s, } U_0/S_{L\infty} = 5.53, d_o/\delta_D = 126.6) \), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.27  Flame radius history for C\textsubscript{3}H\textsubscript{8}-O\textsubscript{2}-N\textsubscript{2} flames undergoing an early kernel-vortex interaction with the weak vortex (U\textsubscript{0} = 77 cm/s) at the “low” flame propagation rate.
Figure 8.28  High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for $\Phi=0.69$, strong vortex ($U_0=398$ cm/s, $U_0/S_{L,\infty}=18.54$, $d_o/\delta_0=195.3$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.29  High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 0.87, strong vortex (U₀= 398 cm/s, U₀/S₁,∞= 21.11, d₀/δ₀= 171.2), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.30 High-speed C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for Φ= 1.08, strong vortex (U₀= 398 cm/s, U₀/S₁∞= 21.70, d₀/δ₀= 166.7), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.31  High-speed C$_3$H$_8$-O$_2$-N$_2$ flame emission images of early kernel-vortex interaction for $\Phi = 1.32$, strong vortex ($U_0 = 398$ cm/s, $U_0/Sv_{\infty} = 25.30$, $d_o/\delta_0 = 143.1$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.32  High-speed C\textsubscript{3}H\textsubscript{8}-O\textsubscript{2}-N\textsubscript{2} flame emission images of early kernel-vortex interaction for $\Phi = 1.49$, strong vortex ($U_0 = 398$ cm/s, $U_\theta/\langle U_{L,\infty} \rangle = 28.57$, $d_0/\delta_0 = 126.6$), and “low” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 8.33  Flame radius history for C₃H₈-O₂-N₂ flames undergoing an early kernel-vortex interaction with the strong vortex (U₀ = 398 cm/s) at the “low” flame propagation rate.
9. Future Work

9.1 Spray Combustion Research

Valuable insights have been obtained as a result of the spray combustion studies performed during this research effort. Unfortunately, spray flames are extraordinarily complex, and much work remains to fully characterize these two-phase reacting flows. Careful quantification of spray flame characteristics, such as droplet size and velocity distributions, gas phase motion and entrainment, mixing, and temperature, need to be performed in the current spray flame apparatus to further describe the observed flame structures. Several studies have detailed diagnostic tools capable of making these measurements in both non-reacting and reacting sprays, and these works will be referenced briefly here to aid in future efforts.

Lee et al. (2001) investigated non-reacting gasoline sprays with a combination of techniques including shadowgraph imaging, phase Doppler anemometry (PDA), and particle image velocimetry (PIV). The shadowgraph images provided a time history of overall spray morphology, while the phase Doppler particle analyzer (PDPA) and PIV system facilitated measurements of mean drop sizes/velocities and instantaneous two-dimensional drop velocity fields, respectively. Another method to characterize fuel sprays is with a technique called planar drop sizing (PDS), which has recently been applied to air-assisted oil sprays by Zimmer and Ikeda (2003). In this method, the fuel is doped with Rhodamine B to serve as a fluorescent tracer of the droplets. A Nd:YAG
laser is then used to generate simultaneous images of droplet fluorescence (a volume effect) and Mie scattering (a surface area effect). With proper calibration against a PDA system, the ratio of the fluorescence image to the scattering image yields an instantaneous two-dimensional measurement of Sauter mean diameter, particularly useful in dense sprays. An additional advantage of the technique applied by Zimmer and Ikeda (2003) was that both sets of images (fluorescence and scattering) could then be analyzed with a cross-correlation algorithm to yield PIV measurements of the spray.

While PIV was used initially to provide simple characterization of the dispersed phase velocity field in non-reacting (Ikeda et al., 1998) and reacting sprays (Ikeda et al., 1999), recent data processing developments have facilitated droplet size-classified analyses which help to elucidate the role of different droplet size classes in turbulent flows (Ikeda et al., 2000; Palero and Ikeda, 2002). Several other PIV diagnostics that have been applied to turbulent spray flames include velocity measurements of the low Stokes flow (Tomimatsu et al., 2003) and stereoscopic PIV, providing three-dimensional droplet velocities (Palero and Ikeda, 2002). Another technique, termed Doppler global velocimetry (DGV), has been shown to provide time-averaged three-component velocity measurements of both the gas and liquid phases in a combusting flow (Schodl et al., 2002). Spray combustion involves the complex interaction of the dispersed phase with a turbulent continuous phase, and other methods are also available to quantify these two-phase flow fields (Grunefeld et al., 2000; Boedec and Simoens, 2001; Rottenkolber et al., 2001; Driscoll et al., 2003). Finally, the recent application of two-color laser-induced fluorescence by Lavieille et al. (2001) to spray flames indicates the feasibility of non-intrusive measurement of droplet temperature.
9.2 Flame Kernel-Vortex Research

The scope of the flame kernel-vortex research has covered a large parameter space and has revealed a wide range of flame-flow phenomena, including dramatic extinction events and cellular flame instabilities. These important interactions need to be investigated further with advanced laser-based diagnostics to quantify the local stretch rate, reaction rate, heat release rate, and temperature. This information will establish a substantial database for integration into numerical models and contribute to the theory of turbulent premixed combustion. Measurement of local stretch rate will require simultaneous OH-PLIF/PIV so that the local flame curvature and hydrodynamic strain rate can be determined. The local flame speed, also required in the calculation of stretch, can be determined using the high-speed chemiluminescence data if the experiment is repeatable. Reaction rate measurements can be made with the simultaneous imaging of OH and CO laser-induced fluorescence (Rehm and Paul, 2000; Frank et al., 2002), while heat release rate is correlated with simultaneous fluorescence measurements of OH and CH$_2$O radicals (Paul and Najm, 1998; Bockle et al., 2000). In order to attain satisfactory formaldehyde LIF signals, the heat release rate measurements will likely be restricted to stoichiometric or fuel-rich flames. Two-dimensional temperature fields will be evaluated with two-line OH-PLIF thermometry using the same approach as Welle (2002).
10. List of References


