ABSTRACT

Xiong, Yin. Investigation of A Spark Ignition Flame Kernel Interacting with A Laminar Vortex Toroid. (under the instruction of Dr. W. L. Roberts)

Chemistry-turbulence interactions play a critical role in most practical combustion environments. In order to reduce cycle-to-cycle variations in SI-IC engines, knowledge of early flame kernel growth in a turbulent flow field is required. Understanding the interaction between a flame kernel and a vortex is an important fundamental step towards this goal.

This dissertation presents high-speed movies of combustion luminosity during the interaction of a laminar vortex toroid with a spark-generated premixed flame kernel in a quiescent combustion chamber. The resulting time evolution of the perturbed flame kernel shows that laminar vortices of various sizes and vortex strengths can increase the kernel growth rate by at least a factor of 3 and significantly increase combustion reaction rates by involving additional highly curved and stretched flame fronts.

This dissertation also describes experiments that were conducted on a premixed, spark-generated flame-kernel interacting with a laminar vortex toroid in different fuel/air mixtures to study the Lewis number effect on the interaction. These experiments were designed to further the fundamental understanding of the role of thermo-diffusive stability in these highly curved and strained kernels. The influence of a time varying strain rate on kernel growth was investigated by studying both lean methane-air (thermo-
diffusively unstable) and lean propane-air (thermo-diffusively stable) flame kernels. Two
tests cases are presented, using natural CH* and OH emission image sequences acquired
by a high-speed intensified camera, to show details of the disturbed flame kernel growth.
In addition to these natural emission images, OH PLIF was employed to determine the
true two-dimensional nature of the interaction. Significant differences are observed in
the highly curved regions on the backside of the invading vortex in the two different
mixtures. Although not measured, the strain rates are expected to be very similar for the
two fuels because the vortex dynamics are the same. Therefore, any differences between
the two fuels in areas of low curvature will be due to the Lewis number dependant
response of the chemistry to strain rate. Lewis number effects on local burning rate
variations, flame front wrinkling, and pocket formation are reported, and in general, the
results are in agreement with predictions from asymptotic theory assuming low stretch
rates.

Charge stratification by direct local injection has been actively studied as a technology
for spark ignited lean burn engines. Local mixture enrichment by direct injection in the
vicinity of the spark plug at the time of ignition can affect flame kernel development and
extend the lean limit of flammability of a fuel/air mixture. Flame kernel-vortex
interactions also can be used to study the overall effect of local injection with different
gas mixtures. In the third set of the experiments, flame kernels were ignited in a lean
premixed CH4/air mixture with an equivalence ratio of 0.6, while CH4/air mixtures at six
different equivalence ratios ranging from 0 to infinity were used to generate the vortex.
Chemiluminescence images of kernel-vortex interactions have been captured using both a
single shot ICCD camera and a high-speed intensified camera. Details about flame
kernel-vortex interactions of the six test cases are presented and discussed by comparing
image sequences for different cases. When the vortex fluid is leaner than the
flammability limit, the vortex burning inside the kernel is very weak, but
chemiluminescence images indicate there is still combustion occurring. For very rich
vortices, there is a near stoichiometric region around the vortex entrance region where
combustion is very vigorous.
Investigation of a Spark Ignition Flame Kernel Interacting with a Laminar Vortex Toroid

By

Yin Xiong

A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

Mechanical Engineering

Raleigh

2001

APPROVED BY:

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Investigation of a Spark Ignition Flame Kernel Interacting with a Laminar Vortex Toroid

By

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A dissertation submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy (Mechanical Engineering) in The North Carolina State University Raleigh, 2001

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**BIOGRAPHY**

Yin Xiong received his Bachelor of Engineering degree in Thermal Physics Engineering from the Department of Engineering Mechanics of Tsinghua University, Beijing, China, in 1992. At the same year, he entered the Department of Thermal Engineering of University of Science & Technology, Beijing, and obtained his Master of Science degree in Thermal Engineering in April 1995. At the end of 1995, he went to Canada for higher degree study. He worked as a research assistant in the Department of Mechanical Engineering of the University of New Brunswick, Fredericton, New Brunswick, Canada. His research work involved numerical simulation and analysis of fire protection techniques, under the direction of Dr. Venart, who was the director of Fire Science Center of the University of New Brunswick. In August of 1997, he stopped his study in Canada and came to America, to continue his pursue of PhD degree in the Department of Mechanical & Aerospace Engineering in the North Carolina State University, Raleigh, North Carolina. He worked as a research assistant in Applied Energy Research Centre, under the direction of Dr. Roberts. His research efforts there were mainly focused on a NSF-sponsored project, aiming the better understanding of some fundamental issues in turbulent combustion. He co-authored several journal papers, conference papers in China, Canada and America.

Yin Xiong’s research interests include fundamental issues of thermal/fluid science, combustion, and advanced laser diagnostic techniques.
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Chapter 1. Introduction, Literature Review, and Research

Objectives

§1.1 Introduction

1. Research Background

Flame/vortex interactions constitute a fundamental problem in combustion theory. This problem is generic as it typifies the more complex situations found in turbulent reactive flows, involving the interaction between the hydrodynamics of the turbulent flow field and the chemical kinetics in the combustion reaction zone. This is an extremely complex interaction and must be simplified considerably if any insight is to be gained.

The turbulence, indicated by much experimental evidence, may be described as an organized motion at the largest scale superposed on a fine grain random background of fluctuations in the small scales. It has been suggested and confirmed by experiments that turbulent combustion could be viewed as a process dominated by the continuous distortion, extension, production and dissipation of the flame surface by vortices of different scales. This conceptual description has given rise to a variety of “flamelet” models for turbulent combustion (Peters, 1986): the turbulent flame can be thought of an ensemble of stretched laminar flamelets. The elementary interaction between a vortex and a flame thus appears as a key process in the description of
turbulent reactive flows. The flame/vortex interaction problem has been investigated most extensively as it allows basic studies of flame structure, quenching and ignition conditions, effects of strain on reaction rates, flame responses and dynamics, etc. Flames submitted to constant or variable strain rate provide remarkably rich examples of the effect of flow non-uniformity on the kinetics.

The flame kernel, the transitory period between ignition and fully developed, self-sustaining flame, is especially sensitive to the hydrodynamic strain exerted by the turbulent vortices and heat loss effects at the point in time when the voltage that is applied across the spark gas is removed. The spark-generated kernel is typically cylindrical to begin with and transforms into a sphere on the order of one cm in diameter. Due to this geometry, the high degree of reaction zone curvature can have a large effect on the ability of the kernel to grow into a fully developed flame front, depending upon the ratio of the thermal diffusivity to the molecular diffusivity of the deficient reactant, defined as the non-dimensional Lewis number. Considerable research has been conducted in studying the fundamental physics for spark ignition in quiescent environments, and much work has been done in specially modified IC engines. However, more research aimed at studying the ignition process with the fluid mechanics simplified down to a single turbulent eddy is needed.

2. **Industrial Applications**
Besides the importance to fundamental turbulent combustion theory, the studies of flame/vortex interaction mechanisms also benefit combustion engineering in industrial applications, where the flame propagation, stability, energy efficiency and emission control are always of major concern.

Most practical combustion devices such as gas/oil burners and furnaces rely on the greatly increased heat release rates generated by turbulent flow fields to operate effectively. At low to moderate turbulence levels, there is a marked increase in the burning rate and an extension in the flammability limits of the premixed reactants. However, as the turbulence intensity increases, and the length scales of the turbulent eddies become small compared to the reaction zone thickness, and this trend reverses as the eddies are able to locally quench the flame front. Better understanding of the flame-turbulence interaction is therefore of great importance for the design of practical combustion devices.

A continuing challenge in designing a more efficient and less polluting spark-ignited (SI) internal combustion (IC) engine is to increase the consistency of the process leading from spark generation to fully developed flame. Previous studies have shown that variations in the initial growth of the flame kernel contribute significantly to cycle-to-cycle variation in engine performance and emissions (Bianco, et al., 1991). The spark ignition event and subsequent flame kernel growth are a result of the complex interaction between the spark-generated plasma and the turbulent flow field in the engine. Large-scale flow structures are created in IC engines by the intake and
exhaust processes. These large-scale motions create vortices of a range of sizes and strengths superimposed on more random background fluctuations on the finer scales. The resulting turbulent flow has high cycle-to-cycle variability (Reuss, 1993) and has substantial effects on the ignition and early kernel development through the time-varying local strain rate. The ability of the spark-generated kernel to continue to grow into a fully developed, self-sustaining flame depends upon the energy deposited in the spark plasma, the hydrodynamics of the local strain field, the rate of heat loss to the electrodes, and the chemical kinetics of high-molecular-weight, multi-component hydrocarbon combustion (Reuss, 1993). For unstrained or lightly strained kernels without heat loss, the combustion wave continues to propagate until all reactants are consumed. As the hydrodynamic strain rate is increased, the flame front may be quenched with the reactant consumption rate falling to zero. This quenching may occur locally, allowing the kernel to recover and consume the reactants, or if the strain rate is high enough, the entire kernel may quench, resulting in a misfire. This is one of the reasons for studying the interaction between a spark-ignited flame kernel in premixed fuel/air mixtures and a well-defined laminar vortex.

To satisfy the requirements of the latest emission standards for the automobile engine, the development of effective combustion process to ensure the operation of spark ignition IC engines operating with very lean fuel/air mixtures is very important. Conventional ignition systems typically result in slow flame propagation speeds when used under ultra-lean conditions. Thus only a partial burns takes place with a consequent high fuel consumption and exhaust emissions. Many enhanced ignition
devices for ultra-lean conditions have been proposed and investigated. These include plasma jet ignition, ultra short pulse ignition and stratified charge engines.

The lean-burn combustion system with charge stratification introduced by direct local injection, which combines the advantages of both a premix combustion system and a Diesel combustion system, has been actively studied as a technology for improving fuel economy and exhaust gas emission. As a prerequisite for charge stratification, a readily ignitable fuel mixture in the vicinity of the spark plug must be provided. The concept of local injection includes the presumption that spatial and temporal variations of velocity and fuel concentration close to and at the instant of ignition cannot be controlled accurately by port injection of the engine, so that a desired stratification requires a combination of a homogeneous lean charge from the port and local injection of a richer fuel/air mixture. This local injection can be expected to have two effects, one associated with velocity characteristics and the other with fuel/air mixture. Local mixture enrichment by direct local injection in the vicinity of the spark plug at the time of ignition can affect flame kernel developments and engine cyclic variability. Better understanding of lean premixed flame kernel growth under the disturbance of local injection of different mixture ratios is of great importance for the development of charge stratification lean-burn technology.

3. Laser diagnostics in combustion research
Laser-based optical diagnostic techniques supply the combustion researcher with the capability for remote, non-intrusive, in-situ, spatially and temporally precise measurements of important chemical parameters. Spatially precise, instantaneous measurements at high rates permit the combustion process to be frozen and tracked with high frequency response. Measurements at many locations simultaneously along a line, over a plane or several planes permit spatial correlations to be obtained providing new phenomenological insight into fundamental combustion behavior. Atoms and molecules difficult to detect by any other means become amenable to interrogation. Furthermore, the various internal energy states can be detected permitting state-specific studies and examination of non-equilibrium phenomena.

Laser diagnostic techniques permit accurate interrogation in easily perturbed regions such as recirculation zones, boundary layers, flame fronts and supersonic steams.

Laser-induced fluorescence spectroscopy (LIF) depends on the absorption of a photon to a real molecular state, and is therefore a much more sensitive technique, capable of detection of sub-part-per-billion concentrations. Thus, this is a very suitable technique for measurement of those minor species that are the transient intermediates in the combustion reaction network. Many of the important transient species, such as CO, CH and OH, etc., have band systems which are suitably located for application of LIF probing. The ability to sensitively detect transitions originating from electronically as well as vibrationally excited levels of a number of molecules offers the possibility of inquiring into the participation of non-equilibrium chemistry in combustion process.
The hydroxyl radical (OH) is frequently used as a tracer in planar-LIF (PLIF) measurements because it is a naturally occurring species that marks the reaction and the burnt-gas zones of many combusting flows, and is well characterized spectroscopically, absorbs strongly at wavelengths that are accessible with excimer and tunable dye lasers, and exhibits high fluorescence yield. These properties allow for imaging of concentration, temperature, and velocity, as well as the visualization of turbulent or transient combustion phenomena.
§1.2 Literature Review

1. Flame propagation under the vortex disturbance

Many experimental and computational studies of turbulence effects on combustion have been reported Renard, et al., (2000) using a laminar vortex interacting with a laminar propagating flame front. Isihzuka et al. (1998) measured the maximum tangential velocities of large diameter vortex rings, and found a linear relationship between the flame speeds along the vortex axis and the maximum tangential velocities for lean, stoichiometric and rich methane/air mixtures, and the slope is quite close to unity. Sinibaldi et al. (1998) studied the local flame propagation speeds along the wrinkled, stretched and unsteady interfaces between lean hydrocarbon/air mixture flames and an invading vortex ring. They noticed that the measured local flame speed was much more sensitive to changes in the curvature of the flame than expected and could not be predicted using steady-state theory of stretched flames. Louch and Bray (1998) numerically investigated the dynamics of the vorticity field in a vortex pair-flame interaction configuration with different imposed mean pressure gradients under moderately low turbulence intensity. Three vorticity regimes (vorticity break-through, break-up and transitional) were identified, and baroclinic torque was determined to play an important role in each of these regimes.
Local and global flame extinction as a result of the vortex interaction is of great importance for both theoretical and practical reasons. Local quenching during a flame-vortex interaction in a lean methane/air mixture was first studied experimentally by Roberts, et al. (1992). Patnaik and Kailasanath (1998), found that both sufficiently high strain and heat losses are simultaneously required for local quenching, and there is a minimum interaction time required for quenching. Katta, et al. (1998) reported an experimental and numerical investigation using a unique counterflow diffusion flame with an embedded vortex generator in an attempt to understand the local quenching process associated with the vortex-flame interaction in methane diffusion flames. They found that large increases in CH$_3$ radicals in the strained flame zone depleted the radical pool and, hence, quenched the flame locally. This quenching process is different from that observed in steady counterflow flames, in which quenching occurs as a result of a gradual reduction in temperature with increasing strain rate. Thevenin, et al. (1998) and Renard, et al. (1998) also used a non-premixed flame interacting with a vortex to provide detailed experimental and numerical results to gain a better understanding of the local extinction processes. The influences of global mixture ratio and vortex velocity on changes in the flame surface were investigated. Their study proved that straining effects are responsible for the extinction of the non-premixed flame front, and that the degree of mixing actually increases at the end of the extinction process. Renard, et al. (1999) used OH PLIF to visualize the flame front of a non-premixed flame interacting with a vortex for investigations of heat release, extinction and time evolution of the flame surface.
Their results show that global intensification or extinction of the flame is characterized by an increase or decrease in flame surface area due to straining.

Fuel pocket formation, evolution and consumption is another important phenomenon observed during flame-vortex interactions. Pocket formation was first observed experimentally in flame-vortex interactions by Roberts and Driscoll (1991). Renard et al. (Renard, et al., 1998) used a novel configuration to study the interaction between a vortex ring and a double premixed counterflow flame. They observed three of the four well-known types of premixed flame-vortex interactions, and the primary features in fuel pocket formation (heat losses, thermo-diffusive effects, curvature and viscosity) were all analyzed. Sun and Law (Sun, et al., 1998, 2000) analytically and computationally studied the extinction mechanisms of fuel pockets and the nonlinear response of stretched premixed flames through flame-vortex interaction. Their results showed that Lewis number played a very important role. On either side of unity Lewis number, stretched spherical flame fronts have different mechanisms of extinction.

2. Lewis number effect on the disturbed flame surface

Application of unsteady strain rates on a flame by the introduction of a vortex result in changes in the local flame temperature, laminar burning velocity, heat release rates, and area of reaction zone. How the flame responds to the vortex-induced strain and curvature is a function of Lewis number. The Lewis number (Strehlow,
1979), $Le$, is defined as the ratio of the thermal diffusivity of the unburnt mixture, $\alpha$, to the mass diffusivity of the deficient reactant, $D$, $Le=\alpha/D$. In lean hydrocarbon-air mixtures, $\alpha$ is essentially the thermal diffusivity of the diluents ($N_2$ in this study) and $D$ is the binary diffusion coefficient between the parent fuel molecule and the diluents. Hence, different Lewis numbers may be obtained by using different fuels and/or diluents with different mixture ratios.

As reported by Clavin, (1985) and Williams (1985), the Lewis number controls flame stability and there is a critical value $Le_c$ of order 1, and for $Le<Le_c$, the flames become unstable and develops cellular structures; for $Le>Le_c$, flames suppress these instabilities. As a consequence, in a turbulent flow field, flames with lower values of $Le$ are more wrinkled than flames with higher $Le$ (Haworth and Poinso, 1992; Rutland and Trouve, 1993; Goix and Shepherd, 1993; Lee, et al. 1993). In their experimental and numerical studies, Samaniego (1999) and Mantel (1999) observed that the decrease of heat release and reaction rates are more pronounced in the interfaces during flame-vortex interactions for higher Lewis number flames. For flames with $Le>1$, the effects of unsteadiness are very strong and the unsteady interaction cannot be considered as a succession of quasi-steady states of the flame. In the computational work by Sun and Law (1998, 2000), two different quasi-steady propagation and extinction mechanisms have been identified. For lean flames with $Le<1$, flames become progressively weaker and extinction is stretch induced; while for rich, $Le>1$ flames, flames are enhanced by stretch and extinction is caused by the depletion of the reactant ahead of the flame.
The G-equation, developed by Markstein (1964), describes the dynamics and geometry of the flame surface G (termed as a premixed flamelet) in the flow field. Asymptotic theory is derived from the solution of the G-equation, coupled with the governing equations in hydrodynamic regions, to represent the interaction between the flame front and the outer hydrodynamic flow: the outer flow convects the flame front while the front affects the outer flow through thermal expansion. Some experimental and computational studies (Law, et al., 2000) have been published to evaluate the flame response prediction based on the asymptotic theory, determining such properties as: flame temperature, burning rate, cusp formation, and wrinkling and pocket formation on the flame surface. It has been found that the asymptotic theory resulting from the linear solution of the coupled G-equations is limited to low strain rates. When the strain rate is high enough, burning intensity for both Le>1 and Le<1 flames will decrease, and this decrease at high strain rates is attributed to a decrease of flame residence time which translates into incomplete combustion.

2. The effect of local injection on the early growth of lean premixed flame kernel

Studies show the local mixture enrichment by direct local injection in the spark plug vicinity at the time of ignition can affect flame kernel developments and engine cyclic variability (Herwerg, et al., 1990; Hravichik, et al. 1995; and Berckmueller, et al., 1997). An important benefit of a controlled locally rich mixture is its ability to extend the lean limit of flammability of a fuel/air mixture (Green, et al., 1992). For
example, results of Arcoumanis et al. (1994) show that a stable and consistent flame kernel could be formed after ignition with small quantity of rich mixture injected near the spark gap. This allowed flame propagation through a very lean mixture with an overall equivalence ratio as low as 0.39. Their work also indicated that the average flame speed could be increased by local injection at all equivalence ratios (Arcoumanis, et al., 1997). It was also shown that the fluid dynamic effect alone caused over stretching of the flame for the ultra-lean homogeneous conditions, while rich local stratification in the vicinity of the spark allowed the suppression of this effect and a reduction of the drivability limit (Arcoumanis, et al., 1999).
§1.3 Research Objectives

In contrast to the many studies discussed above of turbulence-combustion effects using vortices interacting with fully established flames, only one study (Eichenberger and Roberts, 1999) has been reported on turbulence-spark kernel effects using a laminar vortex interacting with a spark-ignited premixed flame kernel. This situation adds two important new features – (1) the chemistry of ignition and transition from spark to fully propagating flame and (2) the time-varying curvature of the expanding flame kernel. Eichenberger and Roberts investigated spark ignition of a lean methane mixture interacting with individual eddies of varying characteristic length and velocity scales. Spark-ignited kernel growth was observed in both the flamelet regime and the distributed reaction zone regime. Global quenching of the growing flame kernel was observed with sufficiently large strong vortices.

The present research extends the previous study (Eichenberger and Roberts, 1999) by using a more robust combustor for greater repeatability and high-pressure operation, smaller vortex sizes of the order of the flame kernel, different fuel/air mixtures, different radicals for PLIF diagnostics, and a high-speed camera to temporally-resolve individual kernel-vortex interactions directly, instead of piecing together many individual images at different times after ignition from repeated kernel-vortex experiments. There are three related research objectives for this research work:
First objective is to get general view of premixed flame kernel/laminar vortex interaction. High-speed camera is used to collect the natural CH/OH emission images during the interaction. Various test conditions are used: on the flame kernel side, kernels with different fuel/air equivalence ratios and maturities are used; on the vortex side, vortices with different sizes, strengths are involved. Research is focused on the overall kernel growth, time evolution of overall reaction intensity of disturbed kernels subjected to different vortex conditions. Local flame front intensity profiles are also studied to get information about local effect of vortex disturbance. With this study, the following questions are to be answered: 1) What are the typical procedures for different flame kernel/vortex interaction? 2) What is the overall effect of the vortex disturbance on the overall growth of the disturbed kernels? 3) Which characteristic parameter of the laminar vortex is more important for the effect of disturbance?

The second objective is to study the Lewis number effect on the disturbed flame surface. Both lean methane/air mixture (Le<1) and propane/air mixture (Le>1) are tested under the similar vortex disturbance for the comparison of Lewis number effect. OH PLIF technique is used to get local and inside information on the interface of flame kernel/vortex interaction. Test results are drawn both quantitatively and qualitatively, and numerical image processing is used to correlate the local curved flame surface curvature and the local burning intensity. The asymptotic theory based on G-equation is used as the theoretic prediction. With this study, the Lewis number effect, combined with different flame surface curvatures, on the local burning rate will be cleared.
The third objective is to observe and study the early growth of a lean premixed flamer kernel under the disturbance of local injection with different equivalence ratios. Both lean side and the rich side fuel/air mixture will be used to generate the injected vortex, including extreme cases such as pure air ($\phi=0.0$) and pure fuel ($\phi=\infty$).
§2.1 Main Combustion Chamber

A large stainless steel combustion chamber (25.4 cm inside diameter, 50.5 cm height, and total volume of 30.6 litter) with its supporting platform was built for pressurized and non-pressurized combustion tests (Fig. 1). Four side-arms (15 cm inside diameter and 10 cm in length) were welded to the chamber. 13 mm thick quartz windows are mounted on these side arms for flame image acquisition and laser diagnostics. An opposing pair of electrodes is inserted into the chamber from two side arms, and the spark gap can be located along the vertical centerline for typical kernel-vortex interactions, or translated radially to look at kernel ignition within the vortex itself. The distance between the tips of the electrodes is continuously adjustable to investigate the influence on ignition energy. Four large solenoid valves (normally open), located at the bottom of the primary chamber, are used to control the on/off of four exhaust ports, which are opened just prior to ignition. This allows the early stages of the ignition process to precede isobarrically.
Fig. 1 Primary Combustion Chamber

- Linear stepping motor
- Vortex generation cylinder
- Primary Combustion
- Windowed side
- Sharp-edged orifice
- Electrodes
§2.2 Vortex Generation Facility

To generate a single, well-defined vortex toroid, a stainless steel cylinder is inserted into the combustion chamber right from the top (see Fig. 1). At the bottom of this inner cylinder, there is a sharp-edged orifice. (Fig. 2). A piston translates inside of this cylinder, and is driven by a digitally controlled, high thrust, high resolution linear stepping motor which is mounted on the top of the combustion chamber. A vortex toroid is generated by pushing the gas mixture (same mixture as in the primary chamber) out through the orifice by the downward displacement of the piston inside the cylinder. Based on the vortex dynamics described in previous study (Roberts and Driscoll, 1991), a well-defined vortex with known length scale, translational velocity and strength (determined by its circulation, or rotational velocity) can be generated by correctly
choosing the cylinder size (inner diameter), orifice diameter, motor speed and piston displacement. The distance between the orifice and the ignition point can also be adjusted, and is maintained at 10-orifice diameter to make sure that all generated vortex rings are self-similar, keeping the decay and entrainment self-similar.

§2.3 Spark Ignition Circuit

A digital distributorless ignition system was built with a high energy, transistor-based ignition circuit (MC3334 and MJ10012 silicon power darlington transistor) and traditional ignition coil (Fig.3). This ignition system, with microsecond level response

![Spark Ignition System Diagram]

**Fig. 3 Spark Ignition System.**
time, can build up to 35,000 V transient voltage difference between the tips of the electrodes, with the appropriate distance. The spark intensity also depends upon the pulse width of the triggering signal to the ignition circuit, which can be digitally controlled. In those tests currently conducted, the gap between the electrodes is kept at 2~3 mm, and the pulse width for triggering signal is set to be 2 ms, which is the shortest duration for generating repeatable sparks in the tested lean fuel/air mixtures. The electrical energy for ignition is approximately 90 mJ (Eichenberger and Roberts, 1999). The electrodes are made of stainless steel, and are coated by ceramic insulation tubes. The electrodes neck down to a diameter of 0.4 mm to minimize heat loss and flow disturbance.

§2.4 Image Recording and Storage System

In order to investigate the kernel-vortex interaction in detail, images of the disturbed flame kernel reaction zone have been captured by placing a camera normal to the electrodes and recording natural CH and OH emissions during the interactions. Two types of camera have been used, one is a single shot Princeton Instrument intensified CCD camera, controlled by a PG-200 pulse generator, the other is an intensified Kodak-4550 high-speed camera which can acquire images with frame rate up to 4500 full frame/s, and two PG-535 pulse generators were used to synchronize the camera and its intensifier. Band pass filters were used to selectively collect chemiluminescence from excited CH and OH radicals.
§2.5 Control and Coordination System

A PC-based digital system has been built to drive, control and coordinate the entire flame-vortex apparatus (Fig. 4). The digital system is based on LabView software and uses data acquisition boards from National Instruments (PC-TIO-10 and AT-MIO-16E). This system can be used as the front control panel and interactive interface for the apparatus. It includes triggering the spark ignition system, driving the linear actuator, triggering the camera, synchronizing the laser, timing and energizing the solenoid valves, and measuring the pressure inside the combustion chamber during tests. The sync pulse from the Nd:Yag is used as the external clock, and the clock pulse AND the command pulse from computer form the master trigger to everything else in the system.
Fig. 4 Electrical control and coordination system.
§2.6 Test Procedure and Timing Sequence

Before the actual flame kernel-vortex interaction begins, the main combustion chamber is filled with gas/air mixture homogeneously at specified mixing ratio. This is done by flushing the gas/air mixture through the chamber for several minutes (equivalent to approximately 10 chamber volumes) before closing all the inlet and outlet valves of the chamber. The combustible mixture is then allowed to settle in the closed chamber for another several minutes to dissipate any motion.

The operations for actual flame kernel-vortex interaction test includes: opening the outlet valves of the chamber about 500 ms before the spark ignition so that the test is conducted isobarically; driving the linear motor to generate the vortex; triggering the spark ignition circuit; and triggering the camera for image acquisition. These operations are centrally controlled and/or synchronized by the digital control system described above, and the timing sequence of the TTL control signals is shown in Fig. 5. The most critical preset delay is the time between vortex generation and the spark ignition, and the determination of its duration requires very good vortex temporal repeatability (up to millisecond level), precise traveling time and velocity measurement of the vortex. Another delay between spark ignition and camera triggering is also important when the single-shot PI camera is used to capture interaction images of various stages of kernel growth.
After the test, the piston inside the vortex generation cylinder will be driven to the bottom of the cylinder to push the exhaust gas out to the main chamber, and the chamber is flushed with air for several minutes before the next test.

Fig. 5  Timing sequence for test operations.
§2.7 Optical Setups for PLIF diagnostic

The laser diagnostic system for PLIF is shown in Fig. 6. A frequency-doubled dye laser (Lambda Physik FL3002), pumped by 532-nm laser beam from a Q-switched Nd:Yag laser (Contiuum SLIII), was used to excite the $Q_1(5)$ transition in $A^3\Sigma^+\rightarrow X^3\Pi$ band near 282 nm. About 100 mJ/pulse of the 532-nm beam were used to pump the dye laser and

*Fig. 6 OH-PLIF laser diagnostic and image acquisition setups.*
the power for UV beam put into the combustion chamber is about 8 mJ/pulse. This UV-beam pulse was spread into a sheet of 50 mm high and about 0.2 mm thick at the focal plane of a long focal length spherical lens, which follows a cylindrical lens. The UV laser sheet crossed the center of the growing and perturbed flame kernel to visualize the flame front of the cross-section. OH PLIF images were captured at a specific instant during the kernel-vortex interaction with a single-shot, intensified CCD camera, coupled with band-pass filters (UG11 and WG305) and UV lenses (105 m Nikkor UV lenses with f/4.5).

§2.8 Image Processing Algorithm and Procedures

Most of the test results are 8-bit or 14-bit digital images captured via Kodak high-speed intensified camera or the single-shot ICCD camera respectively. Image processing is very important to get quantitative results from the pictures. Images processing functions and Macro-codes of Scion Image® and MatLab® are used for both image sequence and individual images. (See Appendix)

Intensity, both local and overall averaged intensity, is used as a major indicator of the local reaction rate. Background intensity varies for different images due to different camera gain setting and/or auto-scaling of the intensifiers. For PLIF (planar laser induced fluorescence) images, shot-by-shot variation of laser energy and its non-uniform distribution also cause intensity difference among different images and different parts of a single image. Images have to be processed to normalize or scale the intensity before
any intensity-related image analysis and comparison can be performed. Image scaling is
usually done via the following procedure: first a region is found where the intensity
should be uniform among different images or within a single image, like the background
area far from the kernel, or section of undisturbed flame front with the uniform intensity
laser sheet passing through; second, measure the (one dimensional or two dimensional)
intensity distribution within the selected region or among the image sequence; then
inverse the obtained intensity distribution to get local compensation factors; the last step
is to apply these local compensation factors pixel-by-pixel to scale the whole processed
image or image sequence. MatLab image processing toolbox can be used for this since it
treats images as 2-D numerical matrices.

Taking an intensity profile across an important region such as the flame front or
kernel/vortex interaction interface is an important method to study the local reaction rate
and look for quenching. Profiles are usually taken along paths that cross the interested
region perpendicularly, and the selected path must have a fixed length (in pixel).
Intensities along the path are collected either by taking intensities of pixels that fall on the
path, or by averaging the intensities of immediate neighbor pixels.

Calculating local curvature along the flame front and kernel/vortex interaction interface is
another major image processing issue. The image should first be binarized to
discriminate the areas of fresh gas and hot product; then the outline of the binary image is
taken out for further processing. Local curvature is calculated by using three neighboring
pixels. The selection of these three pixels is based on the overall characteristic diameter
of the studied object.
In this work, the local integrated intensity is used as an indicator of local burning rate for the 2-D OH-PLIF intensity images. The local integrated intensity is defined and computed as the intensity summation of pixels along a straight line normal to the flame surface, 20 pixels long, starting from the pixel on the flame surface where the local curvature is calculated, pointing to the product side of the flame. The 20-pixel length was chosen because it is equal to the largest thickness of the local flame surface found in those OH-PLIF intensity images. Using local integrated intensity along this path instead of the intensity of a single pixel is a better measure of the effect of curvature on the heat release zone.

Three primary quantities have been calculated for some interactions to allow comparison by performing 2-D image processing on the acquired chemiluminescence images. These quantities are: the characteristic radius, the projected reaction-zone area and the integrated overall intensity of the flame kernel. The definitions and the computing methods for these quantities will be introduced in the following chapters.
Chapter 3

Investigation of Premixed Flame-kernel/Vortex Interactions

via High-Speed Imaging
Investigation of Premixed Flame-kernel/Vortex Interactions
via High-Speed Imaging

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Abstract

In order to reduce cycle-to-cycle variations in SI-IC engines, knowledge of early flame kernel growth in a turbulent flow field is required. Understanding the interaction between a flame kernel and a vortex is an important fundamental step towards this goal. This paper presents high-speed movies of combustion luminosity during the interaction of a laminar vortex with a spark-generated premixed flame kernel in a quiescent combustion chamber. The resulting time evolution of the perturbed flame kernel shows that laminar vortices of various sizes and vortex strengths can increase the kernel growth rate by at least a factor of 3 and significantly increase combustion reaction rates by involving additional highly curved and stretched flame fronts.

Introduction

A continuing challenge in designing a more efficient and less polluting spark-ignited (SI) internal combustion (IC) engine is to increase the consistency of the process leading from spark generation to fully developed flame. Previous studies have shown that variations in the initial growth of the flame kernel contribute significantly to cycle-to-cycle variation in engine performance and emissions [1]. The spark ignition event and subsequent flame kernel growth are a result of the complex interaction between the spark-generated plasma and the turbulent flow field in the engine. Large-scale flow structures are created in IC engines by the intake and exhaust processes. These large-scale motions create vortices of
a range of sizes and strengths superimposed on more random background fluctuations on the finer scales. The resulting turbulent flow has high cycle-to-cycle variability [2] and has substantial effects on the ignition and early kernel development through the time-varying local strain rates. The ability of the spark-generated kernel to continue to grow into a fully developed, self-sustaining flame depends upon the energy deposited in the spark plasma, the hydrodynamics of the local strain field, the rate of heat loss to the electrodes, and the chemical kinetics of high-molecular-weight, multi-component hydrocarbon combustion [3]. For unstrained or lightly strained kernels without heat loss, the combustion wave continues to propagate until all reactants are consumed. As the hydrodynamic strain rate is increased, the flame front may be quenched and reactant consumption rate falls to zero. This quenching may occur locally, allowing the kernel to recover and consume the reactants, or if the strain rate is high enough, the entire kernel may quench resulting in a misfire. Generally, the complexity of the turbulent flows in the engine and the cycle-to-cycle variability in the turbulent engine flows near the spark gap make measurements and modeling of spark ignition and early flame development difficult or impossible in the engine. However, measurements and modeling in simpler combustion chambers can be used to isolate different processes and enhance our understanding.

Many experimental and computational studies of turbulence effects on combustion have been reported [4] using a laminar vortex interacting with a laminar propagating flame front. Ishizuka et al. [5] measured the maximum tangential velocities of large diameter vortex rings and found a linear relationship between the flame speeds along the vortex
axis and the maximum tangential velocities for lean, stoichiometric and rich methane/air mixtures, with the slope being quite close to unity. Sinibaldi et al. [6] studied the local flame propagation speeds along the wrinkled, stretched and unsteady interfaces between lean hydrocarbon/air mixture flames and an invading vortex ring. They noticed that the measured local flame speed was much more sensitive to changes in the curvature of the flame and could not be predicted using steady-state theory of stretched flames. Louch and Bray’s work [7] numerically investigated the dynamics of the vorticity field in a vortex pair-flame interaction configuration with different imposed mean pressure gradients under moderately low turbulence intensity. Three vorticity regimes (vorticity break-through, break-up and transitional) were identified, and baroclinic torque was determined to play an important role in each of these regimes.

Local and global flame extinction as a result of the vortex interaction is of great importance for both theoretical and practical reasons. Local quenching during flame-vortex interactions in lean a methane/air mixture was studied by Patnaik and Kailasanath [8], who found that both sufficiently high strain and heat losses are simultaneously required for local quenching, and there is a minimum interaction time required for quenching. Katta et al. [9] reported an experimental and numerical investigation using a unique counterflow diffusion flame with an embedded vortex generator in an attempt to understand the local quenching process associated with the vortex-flame interaction in methane diffusion flames. They found that large increase in CH₃ radicals in the strained flame zone depleted the radical pool (such as OH, H, and O) and, hence, quenched the flame locally. This quenching process is different from that observed in steady
counterflow flames, in which quenching occurs as a result of a gradual reduction in
temperature with increasing strain rate. Thevenin et al. [10] and Renard et al. [11] also
used a non-premixed flame interacting with a vortex to provide detailed experimental and
numerical results to gain a better understanding of the local extinction processes. The
influences of global mixture ratio and vortex velocity on changes in the flame surface
were investigated. Their study proved that straining effects are responsible for the
extinction of the non-premixed flame front, and that the degree of mixing actually
increases at the end of the extinction process.

Fuel pocket formation, evolution and consumption is another important phenomenon
observed during flame-vortex interactions. Renard et al. [11] used a novel configuration
to study the interaction between a vortex ring and a double premixed counter flow flame.
They observed three different types of premixed flame-vortex interactions, and the
primary features in fuel pocket formation (heat losses, thermo-diffusive effects, curvature
and viscosity) were all analyzed. Sun and Law [12,13] analytically and computationally
studied the extinction mechanisms of fuel pockets and the nonlinear response of stretched
premixed flames through flame-vortex interaction. Their results showed that Lewis
number played a very important role. The mechanism responsible for extinction of
stretched spherical flamefront was shown to depend upon the Lewis number.

Recent comprehensive studies of flame-vortex interaction have also involved advanced
laser diagnostic techniques, such as planar laser-induced fluorescence (PLIF). Renard et
al. [14] used OH PLIF to visualize the flame front of a non-premixed flame interacting
with a vortex for investigations of heat release, extinction and time evolution of the flame
surface. Their results show that global intensification or extinction of the flame is
characterized by an increase or decrease in flame surface area due to straining.

Samaniego and Mantel [15,16] studied the fundamental mechanisms in premixed
turbulent flame propagation via flame-vortex interactions, both experimentally (using a
$\text{CO}_2^*$ emission imaging technique) and computationally. The influence of both Lewis
and Damköhler number on flame heat release rate and unsteadiness were carefully
studied.

In contrast to the many studies discussed above of turbulence-combustion effects using
vortices interacting with fully established flames, only one study (viz., Eichenberger and
Roberts [17]) has been reported on turbulence-spark kernel effects using a laminar vortex
interacting with a spark-ignited premixed flame kernel. This situation adds two
important new features – (1) the chemistry of ignition and transition from spark to fully
propagating flame and (2) the time-varying curvature of the expanding flame kernel.

Eichenberger and Roberts [17] investigated spark ignition of a lean methane mixture
interacting with individual eddies of varying characteristic length and velocity scales.
Spark-ignited kernel growth was observed in both the flamelet regime and the distributed
reaction zone regime. Global quenching of the growing flame kernel was observed with
sufficiently large strong vortices.

The present research extends the previous study [17] by using a more robust combustor
for greater repeatability, smaller vortex sizes on the order of the flame kernel, and a high-
speed camera to temporally-resolve individual kernel-vortex interactions directly, rather than piecing together many individual images at different times after ignition from repeated kernel-vortex experiments.

**Experimental Methods and Apparatus**

**Experimental design and setups**

A large stainless steel combustion chamber (25.4 cm in inside diameter and 51 cm in height) was built for both pressurized and atmospheric-pressure combustion tests and is shown in Fig. 1. Four side-arms (15 cm inside diameter) were welded to the chamber, with three of the arms housing quartz windows for flame image acquisition and laser diagnostics. An opposing pair of electrodes is inserted into the chamber from two side arms, and the spark gap can be located along the vertical centerline for typical kernel-vortex interactions, or translated radially to permit kernel ignition within the vortex itself. The distance between the tips of the electrodes is continuously adjustable to investigate the influence of ignition energy. Four large solenoid valves (normally open), located at the bottom of the primary chamber, are used to control the four exhaust ports, which are opened just prior to ignition. This allows the early stages of the ignition process to proceed at constant pressure.

A digital distributorless ignition system was built with a high-energy, transistor-based ignition circuit and traditional ignition coil. This ignition system, with microsecond level response time, can build up to 35,000 V transient voltage difference between the tips of the electrodes, with the appropriate distance. The spark intensity also depends upon the
pulse width of the trigger signal to the ignition circuit, which can be digitally controlled. The electrodes are made of stainless steel, and are coated by ceramic insulation tubes. The electrodes neck down to a diameter of 0.4 mm to minimize heat loss and flow disturbance.

To generate a single, well-defined toroidal vortex, a stainless steel cylinder is inserted into the combustion chamber right from the top (see Fig.1). At the bottom of this inner cylinder, there is a sharp-edged orifice. (Fig.2). A piston translates inside this cylinder, and is driven by a digitally controlled, high-thrust, high-resolution linear stepping motor that is mounted on the top of the combustion chamber. A toroidal vortex is generated by pushing the gas mixture (same mixture as in the primary chamber) out through the orifice by the downward displacement of the piston inside the cylinder. Based on the vortex dynamics described in [19], a well-defined vortex with known length scale, translational velocity and strength (determined by its circulation, or rotational velocity) can be generated by correctly choosing the cylinder size (inner diameter), orifice diameter, motor speed and piston displacement. The distance between the orifice and the ignition point can also be adjusted, and is maintained at 10 orifice diameters to make sure that all generated vortex rings are self-similar, keeping the decay and entrainment self-similar.

In order to investigate the kernel-vortex interaction in detail, images of the disturbed flame kernel reaction zone have been captured by placing a camera normal to the electrodes and recording chemiluminescence from CH* and OH radicals during the interactions. Two types of cameras have been used: one is a single-shot Princeton
Instruments intensified CCD camera; the other is an intensified (IMCO ILS-3 lens-coupled intensifier) Kodak 4540 high-speed video camera which can acquire images with frame rates up to 4500 full frame/s (256 gray scale, $256 \times 256$ pixels / frame). A band pass filter (Schott UG-11) was used with the single-shot ICCD camera to selectively collect chemiluminescence from OH radicals. The kernel–vortex experiment (including spark ignition, vortex generation, and camera data acquisition) was computer-controlled with Labview software.

Unless stated otherwise, all the results presented in this paper were obtained using a very lean ($\phi=0.6$) methane-air mixture under atmospheric pressure conditions. These conditions produce a relatively slow flame kernel growth rate in order to maximize the influence of the vortex on the kernel growth. The kernel growth rate is very sensitive to the equivalence ratio, especially near this lean limit. In order to assure accurate and repeatable mixtures, the methane and air were metered through mass flow meters and then allowed to flow into the chamber until at least ten chamber volumes had been replaced with the fuel-air mixture. By measuring the kernel growth rate for a few sequential runs, the variability in mixture ratio could be minimized and the overall experiment made highly repeatable. In order to generate a sufficiently strong spark to ignite the kernel in this lean mixture, the gap between the tips of the two electrodes was fixed at 2 mm, a spark duration of $\sim 1.5$ ms, resulting in a spark energy of $\sim 90$ mJ.

**Vortex Characteristics**
The criterion for a laminar vortex is $\text{Re} < 600$ [20]. The length scale of the vortex is determined by the diameter of the orifice through which the gas mixture is forced out. This diameter determines the core-to-core diameter at the onset of vortex formation. The vortex will grow in size as it propagates through the reactants due to entrainment, but by keeping the vortex travel distance the same, in a non-dimensional sense, for all orifices used, the entrainment is the same. Four different sized orifices were used: 2, 5, 10, and 20 mm. The cylinder sizes (inner diameters) were kept between 6.5 and 7 times the orifice diameters, and for vortices of different length scales, the distances between the orifice and the ignition point were normalized to 10 times the orifice diameters.

As derived in [18] and confirmed in [19], the vortex translation velocity $U_T$ and rotation velocity $U_\theta$ are measures of the vortex strength. They are of the same order, and can be estimated by

$$U_T - U_\theta \propto \frac{\Delta V^2}{td_o^5}$$  \hspace{1cm} (1)

where $\Delta V$ is the volume of the gas displaced by the piston in the cylinder, $t$ is the displacement time of the piston, and $d_o$ is the diameter of the orifice. In the vortex generation apparatus described earlier in this paper,

$$\Delta V = lA_t$$  \hspace{1cm} (2)

and
\[ t = l / v \]  (3)

where \( l \) is the motor-driven piston displacement, \( A_c \) is the cross-section area of the cylinder, and \( v \) is the average linear speed of the piston. Therefore:

\[ U_T - U_\theta \propto l A_c \frac{v^2}{d^3} \]  (4)

The vortex translational and rotational velocities are thus proportional to the product of the piston speed and displacement, which can be expressed in terms of the linear motor speed and total number of motor steps (0.03 mm per motor step). With fixed orifice size and cylinder inner diameter, vortices with different strengths were generated by precisely manipulating the linear motor speed and motor steps with the help of digital motion control hardware and software, described earlier in this paper. For the results discussed, most vortices were generated by driving the piston 25 motor steps (~0.75 mm) downward at three different motor speeds: 1200 steps/s (36 mm/s), 900 steps/s (27 mm/s), and 600 steps/s (18 mm/s). These motor steps and speeds were chosen because they provided repeatable laminar vortices and were within the stepping motor’s speed-thrust limit. Local translational velocities of these vortices at the ignition point were carefully measured by hot-wire anemometry under cold-flow conditions. The measured vortex velocities ranged from 20 to 80 cm/s, depending upon the orifice diameter and the motor speed chosen.
As indicated in Eq.(4), the vortex strength is proportional to the square of the cross-sectional area $A_c$ of the vortex generation cylinder. As mentioned earlier, the ratio $d_c/d_o$ is held nearly constant (6.5~7.0) for all the orifices used in this study, where $d_c$ is the inner diameter of the cylinder. Thus, Eq.(4) can be rewritten as:

$$U_T \sim U_\theta \propto \frac{vl}{d_o} \left(\frac{d_c}{d_o}\right)^4 = \frac{vl}{d_o} C^4 \quad (5)$$

Thus, the strength of the vortex is proportional to $l/d_o$ when the product of the piston translation distance (motor step number) and piston speed (motor speed) is fixed. The vortex size will scale directly with orifice diameter, as mentioned earlier. Therefore, for the same combination of piston displacement and speed, larger vortices will be weaker according to Eq.(5).

Figure 3 shows a cross sectional view of a typical undisturbed vortex ring propagating down the chamber for $d_c = 5.08$ cm, and $U_\theta = 50$ cm/s. The vortex was photographed with a 35 mm camera using light scattered from a laser sheet by sub-micron oil drops seeded into the gas in the vortex-generation cylinder. This vortex image and others like it were used to determine that a highly repeatable laminar vortex of known size and strength could be created and that its arrival time at the spark electrodes could be controlled. The vortex core-to-core distance is about $1.2d_o$ at this downstream location, which is consistent with previous vortex studies [21].

**Summary of the test conditions**

The summary of the test conditions is presented in the following table. There are many combinations of these test conditions and only dozens of these combinations are tested.
In this paper, investigation is focused on the disturbed kernel growth with different ages (kernel maturity) and vortex disturbance with different sizes and strengths.

**Table 1: Summary of the test conditions**

<table>
<thead>
<tr>
<th>Fuel/air mixtures</th>
<th>CH₄/air at φ=0.6, C₃H₈/air at φ=0.67, CH₄/air at φ=0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orifice diameter (determine the size of the generated laminar vortex)</td>
<td>2 mm, 5 mm, 10 mm, 20 mm</td>
</tr>
<tr>
<td>Ratio of the cylinder diameter to orifice diameter (determine the vortex strength)</td>
<td>6.5, 7.0</td>
</tr>
<tr>
<td>Piston speed (determine the vortex strength)</td>
<td>18 mm/s, 27 mm/s, 36 mm/s</td>
</tr>
<tr>
<td>Piston translation distance (determine the vortex strength)</td>
<td>0.15 mm, 0.75 mm</td>
</tr>
<tr>
<td>Distance between the orifice and ignition point</td>
<td>10 times of the orifice diameter</td>
</tr>
<tr>
<td>The gap between the ignition electrodes</td>
<td>2~3 mm</td>
</tr>
<tr>
<td>The duration of the ignition spark</td>
<td>~ 2 ms</td>
</tr>
</tbody>
</table>

**Results and Discussion**

**Examples of Chemiluminescence Images and Intensity Profiles**

For the flames studied here, chemiluminescence comes predominantly from the flamefront, and the location of the flame surface is indicated by peak values of the
chemiluminescence. Furthermore, changes in chemiluminescence intensities can provide evidence for changes in local flamefront reaction rates [22,23]. This was proved by discovering a strong correlation between the overall flame brightness obtained by UV emission imaging system and the effective heat release rate, which represents the overall combustion rate. In particular, very low chemiluminescence intensity suggests local flame quenching. In the present study, relative chemiluminescence intensities in the images suggest that the vortex can strongly perturb the local reaction rate of the flame kernel, presumably by changing the local curvature and strain rate. This effect can be seen most dramatically when the local intensity is compared to a region of the reaction zone that is undisturbed by the vortex. Although not discussed here, the entire flame kernel can be extinguished (global quenching) by large, strong vortices [19]. Global quenching was not observed with the smaller and weaker vortices used in the present study.

Proper interpretation of the chemiluminescence images must recognize that these are not two-dimensional cross sectional images. Instead, the chemiluminescence intensity is integrated in the third dimension along the line-of-sight of the camera collection optics, which can complicate analysis of these complex three-dimensional kernel–vortex interactions.

Fig.4 shows a typical sequence of chemiluminescence images of a growing undisturbed, premixed flame kernel from a lean (\(\phi = 0.6\)) methane-air mixture, recorded by the intensified high-speed camera system at 4500 frames/s. Only a few representative
images are shown in Figure 4 (with the time after spark shown at the bottom of the image). The measured field of view of each image is $89 \times 89 \text{ mm}^2$. The horizontally oriented fine-wire electrodes can be seen, especially in the later images. The “dimples” in the sides of the kernel are caused by the horizontal shape of the initial spark as well as the slower flame propagation along the thin wire electrodes due to heat loss from the flamefront to the electrodes. The size and growth rate of the undisturbed flame kernel is easily quantifiable by the location and movement of the peak chemiluminescence intensity around the edge of the kernel that marks the flamefront. The top part of the kernel has a radius 10 – 20% larger than the bottom, presumably due to buoyancy.

The profiles of chemiluminescence intensity are shown in Fig.4-b, measured from images in Fig.4-a. All intensity profiles were measured along straight lines normal to the local flame surfaces, with the positive direction taken from the fresh-gas side to the hot-product side inside the flame kernel. One typical profile path is shown as an arrow in the 28.78 ms image of Fig.4-a. In any one image in Fig.4-a, the intensity profiles along such paths were similar, indicating uniform burning in the nearly spherical flame kernels. Profiles in images taken at different times after ignition also have qualitatively the same shape, as shown in Fig.4-b. Very low intensity is observed in the unburned gas regions ahead of the flame. Maximum chemiluminescence intensity occurs at the edge of the kernel where the flamefront is oriented parallel to the line-of-sight of the camera. These maximums increase with time after ignition, primarily because the integration lengths of the side of the kernel increase as the kernel gets larger. Profile e has nearly the same peak intensity as profile d, due to camera saturation. The uniform intensity inside the
kernel is caused by chemiluminescence from the front and back flamefronts that surround the kernel. This intensity remains relatively constant at ~100 counts, suggesting that the chemiluminescence intensity, and hence the reaction rate, is nearly constant as the kernel grows.

In subsequent experiments, these laminar flame kernels are disturbed by interaction with a downward-propagating vortex at various time delays between the flame ignition and the generation of the vortex. All the kernel-vortex interaction tests were categorized into three groups (early, late and medium) based upon the ratio of kernel diameter to the vortex diameter at the onset of the kernel-vortex interaction. For an “early interaction” (ratio of kernel diameter at the first interaction to vortex diameter < 1), the traveling vortex arrives at a very early stage of the kernel growth or even before the kernel is ignited. For the “late interaction” (kernel-vortex diameter ratio larger than 2), the influence of the vortex is not seen until the kernel is well established, with a kernel diameter considerably larger than the invading vortex.

Figure 5-a shows a typical sequence of images for a late kernel-vortex interaction in a lean methane-air mixture ($\phi = 0.6$) interacting with a 10 mm vortex with an average translational velocity of 85 cm/s. The measured field of view of each image is $56 \times 56$ mm$^2$. As in the undisturbed kernel images in Fig. 4, images were obtained every 2.2 ms, but only a selected few are presented. The first two images shown in Fig. 5-a were taken 3.3 ms and 7.7 ms after spark ignition and show an undisturbed and symmetric flame kernel. The third image in this sequence, at 14.8 ms after ignition, provides the first
evidence of the presence of the downwardly propagating vortex as it flattens the top of the kernel. In the next few images, the kernel continues to expand, as the vortex continues to propagate downward. By 25.5 ms, the vortex is completely inside the kernel and has a diameter of ~18 mm. The vorticity pulls the reaction zone around the vortex toroid, resulting in a trailing wake behind the vortex. The trailing wake continues to decrease in size due to flame propagation normal to the wake surface. By 41.5 ms after ignition, the vortex breaks up into many smaller pockets and detaches from the wake. By 45 ms after ignition, the last remnants of the vortex are completely consumed, and the wake continues to burn away.

Figure 5-b shows measured intensity profiles through flame surfaces during a late kernel–vortex interaction, as determined from the images in Fig. 5-a. Profile (a) was measured along the centerline at the bottom of the growing kernel from the image obtained 16.2 ms after ignition. This undisturbed flame profile is very similar to those in Fig. 4-b. Profile (b) is measured from the same image as profile (a) through the top of the flamefront as the vortex just begins to press down the top of the kernel. The higher peak intensity and wider peak curve may indicate intensified local reaction rates and thicker flame surface, although geometric effects due to flattening of the flamefront also contribute. It is not possible to separate these two effects from the present images. The flat top of this profile is due to camera saturation. Profiles (c)–(f) were also measured across the kernel–vortex interaction interface and are plotted so that their peaks occur at the same relative location. As seen in these plots, the intensity in the reactants is approximately 10 counts (curves a and b from 0 to 5 mm), due primarily to camera dark counts. When integrating through
two reaction zones [curves (a)–(f) from 8 to 12 mm], the intensity is ~ 80 counts in the post-interaction zones of all six profiles. In the flame–vortex interaction zones, one is typically integrating through 4 reaction zones with intensity of ~ 160 counts [curves (b)–(f) at 2 to 5 mm]. Some changes in local reaction rate can be inferred from the profiles. For example, compare profiles (d)–(f) in Fig.5-b. For profile (d) at 24.2 ms after ignition, the peak intensity is close to the saturated maximum of 230 counts. By 30.8 ms after ignition, profile (e) shows that the intensity increase across the interface is essentially zero, indicating that the flamefront is locally quenched by the combined effects of vortex-induced stretch and heat loss to the electrodes. As the vortex continues to propagate downward and away from the electrodes, the reaction interface is seen to increase in intensity again [profile (f)], suggesting that the leading edge has been reignited by the hotter regions close to the undisturbed parts of the kernel.

Figure 6-a shows a typical sequence of images for an early kernel-vortex interaction again in a lean methane-air mixture (φ = 0.6) with a 10 mm vortex. The kernel is actually ignited as the vortex passes over the electrodes. While the vortex is causing extensive changes in the lower half of the flame kernel, the upper half of the kernel continues to grow apparently unaffected. The first image, which is acquired 1.9 ms after ignition, shows that the initial kernel is severely stretched and elongated by the passing vortex. The vortex translational velocity is greater than the flame propagation speed, so the vortex continues to distort the growing kernel (as seen in the images from 1.9 ms to 12.6 ms). At 12.6 ms, the kernel begins to be convected upward and around the vortex at the lower edges of the flame kernel. The bottom of the kernel continues to grow rapidly
outward with time. It is not clear what causes the secondary leading edge, which appears to start near the electrodes at 5.9 ms and propagates downward from 8.2 to 19.3 ms.

Figure 6-b shows the resulting profiles of chemiluminescence intensity for the early kernel–vortex interaction as imaged in Fig.6-a. Profile (d) for the undisturbed flame surface was measured across the top of the flame kernel where no disturbance by the vortex was observed. (See image at 21.5 ms in Fig.6-a.). This profile is nearly identical to profile (d) in Fig.4-b for completely undisturbed kernel growth. Profiles (a), (b) and (c) in Fig.6-b correspond to the flame surface at the vortex interaction interface measured at the very bottom of the kernel where the vortex stretches the kernel downward. The peak intensities at the local inner flame front are quite close for profiles (b) and (c). However, they are significantly higher than the peak in profile (a), indicating “flame recovery” from early stage disturbance as the flame front was pushed downwards into the fresh mixture. Since the radius of curvature is essentially the same in these early images, the geometric effects are small, and the increase in chemiluminescence intensity is due to increased local reaction rates.

**Image Analysis for flame radius, area, and integrated reaction rate**

Image processing techniques (e.g., thresholding and integration) are used to further analyze the chemiluminescence images. Three primary quantities have been calculated for each interaction to allow comparison by performing 2-D image processing on the acquired chemiluminescence images. The first quantity calculated is the *characteristic*
\textit{radius of the flame kernel}, with or without disturbance from the vortex. This is a spatially averaged scale that is evaluated by measuring the overall area of the disturbed kernel and assuming that the kernel is spherically symmetric. This characteristic radius indicates the overall kernel growth rate under the influences of different vortex sizes and strengths.

The second quantity calculated for each image series is the \textit{projected reaction-zone area} of the kernel. This was obtained by thresholding the emission images at the average intensity of the hot-product zone to exclude the hot product inside the disturbed kernel and then counting the number of pixels with higher intensities in the bright projected reaction zone around the flame kernel. The thresholding process is illustrated by the images in Fig.7. The projected reaction-zone area calculated in this way provides information on both flame surface area and the thickness of the flamefront, but it is not identical to the actual flame surface area since it represents the projection of a three-dimensional object onto a plane.

The third image-processing quantity is the \textit{integrated intensity of the flame kernel}. This quantity is calculated by summing the intensity values (0 for black through 255 for white) of all pixels within the kernel, and thus it contains information about both the overall size and reaction intensity of the disturbed kernel. The image-intensifier gain, which was varied over a substantial range to optimize the image quality from test to test, is an important factor in this intensity-related image processing. To compare intensities between images recorded with different intensifier gains, the following approach is used.
Corresponding images showing the flame kernel at the same stage of growth are selected from two image sequences that were acquired under exactly the same test conditions except for different intensifier gains. Corresponding undisturbed regions of the flame kernels which include both hot product inside the kernel and a section of bright flame zone in each image (usually the very bottom of the studied kernel) are identified. The ratio of the average intensities within these selected regions is then used to adjust the images for the different intensifier gains. Some error is introduced by this correction process, but this procedure is considered adequate for the semi-quantitative analysis in this paper.

Figure 8 shows the premixed undisturbed kernel radius evolution for three different fuel/air mixtures: CH₄/air at φ=0.6, C₃H₈/air at φ=0.67, and CH₄/air at φ=0.8. For CH₄/air flames, the flame kernel grows linearly with time, with a faster rate for the mixture closer to stoichiometric. For the C₃H₈/air flame, nonlinear kernel growth in the first 10 ms is followed by linear growth thereafter. The measured kernel radius growth rates (dr/dt) are 175 cm/s for CH₄/air at φ=0.8, 133 cm/s for C₃H₈/air at φ=0.67, and 60 cm/s for CH₄/air at φ=0.6. Based on data from [23], the laminar burning velocities $S_L$ for these three fuel/air mixtures are 27 cm/s, 21 cm/s and 11 cm/s, respectively. For steady-state flame propagation under adiabatic laminar conditions, the relation between the burning velocity and the kernel radius growth rate should be [25]

$$S_L = \left( \frac{dr}{dt} \right) \left( \frac{T_0}{T_f} \right)$$

(6)
where \( T_0 \) is the initial temperature (300 K in these tests) and \( T_f \) is the final combustion temperature. The spherical flame front propagation rate, \( dr/dt \), normalized by the unstretched laminar burning velocity, \( S_L \), varies between 5.5 and 6.5. The resulting calculated \( T_f \) values of 1850K, 1820K, and 1600K are very reasonable flame temperatures for these lean flames, comparing with the adiabatic flame temperatures of these three cases: 1996K, 1976K, and 1664K, determined assuming chemical equilibrium [26].

Figures 9-a, -b and -c show the evolution of the characteristic kernel radius, the projected reaction-zone area and the integrated intensity of the kernel, respectively, for early, medium, late, and no vortex interaction. All the tests for this figure were conducted in CH\(_4\)/air mixture with equivalence ratio of 0.6. The undisturbed results were obtained by analysis of the images in Fig.4-a. As expected for the undisturbed flame kernels without an imposed vortex, the kernel radius increases linearly with time \( t \) after ignition. The projected cross sectional flamefront area and the total heat release rate (as indicated by the total chemiluminescence intensity) increase faster. For the kernels disturbed by a vortex in Fig.9, a 10 mm orifice was used and the distance between the orifice and the ignition point was kept at 100 mm. The vortex translational velocity is about 85 cm/s.

In Fig.9-a, it can be seen that for most of the time after spark ignition, the kernels grow linearly for both the disturbed and undisturbed cases. The differences in kernel radius and growth rate between the three disturbed cases and the single undisturbed case are quite obvious, but the growth rates for the three disturbed kernels all approach the same
value at later times after ignition. The average growth rate for the undisturbed kernel is approximately 60 cm/s, while for the three disturbed kernels it is approximately 75 cm/s, with peak growth rates of over 100 cm/s early in the interaction. It can also be seen that the undisturbed kernel and the late-interaction kernel both grow linearly with time after ignition. For the early and medium interaction cases, however, the kernels grow in three distinct stages: an undisturbed initial growth stage, an intermediate stage where the kernel experiences the largest contortions, and a recovery stage where the kernel again grows similarly to an undisturbed kernel, but at an accelerated rate. It can therefore be cautiously concluded based on this figure that for the vortex sizes and strengths studied here the vortex increases the overall growth rate of the premixed flame kernel during the time of interaction. At later times, the vortex is burned up, and the final kernel growth rates are approximately the same in all cases.

This conclusion is further supported by the results shown in Fig.9-b, which show the projected reaction-zone areas as a function of time for the three interactions of Fig.9-a. From this figure, it is clear the evolution of reaction zone area for kernels with early, medium, later interaction and non-interaction follow the trends similar to those seen in the characteristic kernel radius shown in Fig.9-a, although the reaction zone area does not increase linearly with time. For the early and medium interaction cases, there are also similar inflection points showing the sharp increase of reaction zone area when the vortex first affects the growing kernel. The intensity evolutions in Fig.9-c tell the same story. Since the integrated intensity contains both kernel size and reaction intensity information, these curves distinguish the four cases better than the projected reaction zone area in Fig.
9-b. Based on these figures, it can be concluded that vortex interaction increases the reaction zone area of a growing flame kernel quite significantly, and the earlier the vortex arrives relative to kernel ignition, the larger the increase in reaction zone area and total intensity. This is to be expected, as the penetrating vortex brings in fresh reactants into contact with the reaction zone and forms new highly curved reaction zone surfaces inside the kernel.

Figures 10-a, -b and -c show the kernel growth, projected reaction zone area and the integrated intensity for kernels disturbed by vortices of the same size but different strengths. The flame kernels were ignited in premixed CH₄/air mixture at an equivalence ratio of 0.6. The 2 mm orifice was used for vortex generation, and all vortices disturbed the kernel at very early stages of growth to maximize the kernel-vortex interaction. The vortex strength is determined by the combination of piston translation distance (number of motor steps) and speed (motor speed). Interactions with three different strengths vortices (strong with \( U_T \sim 105 \text{ cm/s} \), medium with \( U_T \sim 75 \text{ cm/s} \), weak with \( U_T \sim 15 \text{ cm/s} \)) have been compared in these three figures. Figures 10-a, -b, and –c all show that vortex interactions increase the radius and projected reaction-zone area of the kernel. Generally, the higher the vortex strength, the larger the effective kernel size and reaction zone area. The integrated intensity (Fig.10-c) curves for \( U_T = 15 \) and 75 cm/s are very similar to each other.

Figures 11-a, -b and -c shows the time evolution of the characteristic kernel radius, the projected reaction zone area and the integrated intensity for flame kernels disturbed by
vortices of different sizes. The orifice diameters are 2 mm, 5 mm and 10 mm, while the distance between the orifice and the ignition point was kept at 10d_o. All kernels are ignited in a CH_4/air mixture with equivalence ratio of 0.6, and all the interactions are take place at the very early stages of kernel growth. Both the size of the vortices and the velocity at the time of interaction are varied, with the velocity measured at the point of ignition using hot-wire anemometry. The trends in Fig.11 are the same as in Fig.10. Vortex interactions increase kernel growth rates, and the higher the vortex intensity, the higher the increase in kernel growth rate and reaction zone area. Vortex strength is seen to be more important than vortex size in influencing kernel growth, at least under the present experimental conditions.

Conclusions

1) High-speed imaging (4500 frame/s) of combustion luminosity in spark-ignited flame kernels of lean CH_4/air mixtures without an imposed vortex show that the kernel radius increases linearly with time t after ignition. The projected cross sectional flamefront area and the total heat release rate (as measured by the total chemiluminescence intensity) increase nonlinearly with t. Flame kernels of lean C_3H_8/air mixtures are somewhat slower to develop for the first 10 ms after ignition. However, at later times, the propane/air kernels have similar growth rates as the CH_4/air kernels. The measured kernel growth rates dr/dt for flame kernels are consistent with established laminar burning velocities for these mixtures.
2) Interactions with a vortex can enhance significantly the laminar kernel growth rate. For example, for a 10 mm diameter vortex interacting with the $\phi=0.6$ CH$_4$/air kernel, the kernel radius is increased by a factor of ~1.5; the projected reaction zone area increased by ~2.3; and the burn rate increased by a factor of ~3, when compared with an undisturbed kernel.

3) Previously, we have established that large vortices can totally quench flame kernels [17]. However, for the vortex sizes and strengths investigated in this paper, only a small part of the flame kernel is extinguished and only in regions of maximum stretch (i.e., the leading edge of the imposed vortex as it interacts with the kernel).

4) A vortex enhances the kernel growth most when it interacts with a small flame kernel (i.e., early kernel interaction). Again for the 10 mm diameter vortex interacting with the $\phi=0.6$ CH$_4$/air kernel, the increase in burning rate at 35 ms after time of spark is a factor of 2.65, 2.05, and 1.35 for an early, middle and later interaction, respectively.

5) Vortex strength ($U_T$) has a greater influence on kernel growth than vortex size ($d_0$).

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References:


Fig. 1 Primary Combustion Chamber

Fig. 2 Vortex generation: cylinder, piston and orifice
Fig. 3 Mie Scattering Tomography of a Vortex
Fig. 4-a. Images for time evolution of undisturbed flame kernel
(CH₄/air, φ=0.6, size for each image is 89x89mm², and the value under
every image is the time after spark ignition.)
Fig. 4-b Chemiluminescence intensity profiles across the flame surfaces of images in Fig. 4-a. (The profiles have been shifted so that the peak values occur at zero distance. A negative distance is outside the kernel, and a positive distance is inside the kernel)
Fig. 5-a. Images for time evolution of late kernel-vortex interaction (CH₄/air, \(\phi=0.6\), \(d_0=10\) mm, \(U_T=85\) cm/s, size for each image is 56x56mm², and the value under every image is the time after spark ignition. The arrows in 19.5 ms image show the directions for the intensity profiles in Fig. 5-b.)
Fig. 6-a. Images for time evolution of early kernel-vortex interaction (CH₄/air, φ=0.6, d₀ =10 mm, U_T~50 cm/s, size for each image is 56x56mm², and the value under every image is the time after spark ignition. The arrows in the 11.5 ms image show directions for the intensity profiles in Fig. 6-b.)
**Fig. 5-b** Chemiluminescence intensity profiles across the flame surfaces of images in Fig. 5-a. (The profiles have been shifted so that the peak values occur at zero distance. A negative distance is outside the kernel, and a positive distance is inside the kernel)

**Fig. 6-b** Chemiluminescence intensity profiles across the flame surfaces of images in Fig. 5-b. (The profiles have been shifted so that the peak values occur at zero distance. A negative distance is outside the kernel, and a positive distance is inside the kernel)
Figure 7. (a) A typical kernel-vortex interaction image. (b) The resulting thresholded image used to evaluate the projected reaction area. The intensity threshold is selected as the mean intensity of the hot product inside the kernel.
Fig. 8 Undisturbed flame kernel growth in different fuel/air mixtures

Fig. 9-a Time evolution of radius of undisturbed and disturbed flame kernels interacting with vortex at different growth maturities. (CH₄/air mixture, φ=0.6, d₀ = 10 mm, Uₜ~105cm/s.)
Fig. 9-b Projected reaction zone area of kernels disturbed and undisturbed by invading vortex at different growth maturities. (Same test set as those in Fig 9-a.)

Fig. 9-c Integrated intensity within the disturbed flame kernel. (Same test set as in Fig. 9-a, the data for late interaction have been corrected due to the difference in intensifier gain.)
Fig. 10-a Flame kernel growth under the disturbance of vortices with various strength. (CH$_4$/air mixture, $\phi=0.6$, for all vortices $d_0 = 2$ mm, Different vortex translational velocities are generated by varying piston translation and speed.)

Fig. 10-b Area of projected reaction zone for flame kernel disturbed by the vortices with various strength. (Same test set as in Fig. 10-a.)
**Fig. 10-c** Integrated intensity within the disturbed flame kernel. (Same test set as in Fig. 10-a. The data for vortex \( U_T \sim 105 \text{cm/s} \) have been corrected for a change in intensifier gain.)

**Fig. 11-a** Flame kernel growth under the disturbance of vortices of various sizes. (CH\(_4\)/air mixture, \( \phi = 0.6 \), piston translate \( \sim 0.75 \text{mm} \) at 36 \( \text{mm/s} \), all tests are early k-v interactions.)
Fig. 11-b Area of the projected reaction zone of the kernels disturbed by vortices with different sizes. (Same test set as in Fig. 11-a.)

Fig. 11-c Integrated intensity within the disturbed kernel. (Same test set as in Fig. 11-a)
Chapter 4

Lewis Number Effect on Premixed Flame-Kernel/Vortex Interactions
Lewis Number Effect on Premixed Flame-Kernel/Vortex Interactions

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Abstract

Chemistry-turbulence interactions play a critical role in most practical combustion environments. This paper describes experiments that were conducted on a premixed, spark-generated flame-kernel interacting with a laminar vortex in different fuel/air mixtures. These experiments were designed to further the fundamental understanding of the role of thermo-diffusive stability in these highly curved and strained kernels. The influence of a time varying strain rate on kernel growth was investigated by studying both lean methane-air (thermo-diffusively unstable) and lean propane-air (thermo-diffusively stable) flame kernels. Two test cases are presented, using natural CH and OH emission image sequences acquired by a high-speed intensified camera, to show the details of the disturbed flame kernel growth. These details include invading vortex evolution inside the kernel including local quenching, flame pocket formation, breaking-up of the vortex inside the kernel, and burns-off. In addition to these natural emission images, OH PLIF was employed to determine the true two-dimensional nature of the interaction. Significant differences are observed in the highly curved regions on the backside of the invading vortex in the two different mixtures. Although not measured, the strain rates are expected to be very similar for the two fuels because the vortex dynamics are the same. Therefore, any differences between the two fuels in areas of low curvature will be due to the Lewis number dependant response of the chemistry to strain rate. Lewis number effects on local burning rate variations, flame front wrinkling, and pocket formation are reported, and in general, the results are in agreement with predictions from asymptotic theory assuming low stretch rates.
**Introduction**

Different types of flame/vortex interactions have been intensively studied, both computationally and experimentally, for a better understanding of the fundamental mechanisms governing the turbulence-combustion interaction [1~7]. These works have investigated the flame structure, quenching criteria and stability of the flame front distorted by local flow field. Application of unsteady strain rates on a flame by the introduction of a vortex result in changes in the local flame temperature, laminar burning velocity, heat release rates, and area of reaction zone. How the flame responds to the vortex-induced strain and curvature is a function of Lewis number. The Lewis number [8], $\text{Le}$, is defined as the ratio of the thermal diffusivity of the unburnt mixture, $\alpha$, to the mass diffusivity of the deficient reactant, $D$, $\text{Le}=\alpha/D$. In lean hydrocarbon-air mixtures, $\alpha$ is essentially the thermal diffusivity of the diluents ($N_2$ in this study) and $D$ is the binary diffusion coefficient between the parent fuel molecule and the diluents. Hence, different Lewis numbers may be obtained by using different fuels and/or diluents with different mixture ratios.

As reported in [9,10], the Lewis number controls flame stability and there is a critical value $\text{Le}_c$ of order 1, such that for $\text{Le}<\text{Le}_c$, the flames become unstable and develop cellular structures; for $\text{Le}>\text{Le}_c$, flames suppress these instabilities. As a consequence, in a turbulent flow field, flames with lower values of Le are more wrinkled than flames with higher Le [11~14]. In their experimental and numerical studies [15,16], Samaniego and Mantel observed that the decrease of heat release and reaction rates are more pronounced
in the interfaces during flame-vortex interactions for higher Lewis number flames. For flames with Le>1.0, the effects of unsteadiness are very strong and the unsteady interaction cannot be considered as a succession of quasi-steady states of the flame. In the computational work by Sun and Law [17,18], two different quasi-steady propagation and extinction mechanisms have been identified. For lean flames with Le<1, flames become progressively weaker and extinction is stretch-induced; while for rich, Le>1 flames, flames are enhanced by stretch and extinction is caused by the depletion of the reactant ahead of the flame.

The G-equation, developed in [19], describes the dynamics and geometry of the flame surface G (termed as a premixed flamelet) in the flow field. Asymptotic theory is derived from the solution of the G-equation, coupled with the governing equations in hydrodynamic regions, to represent the interaction between the flame front and the outer hydrodynamic flow: the outer flow convects the flame front while the front affects the outer flow through thermal expansion. Some experimental and computational studies [20] have been published to evaluate the flame response prediction based on the asymptotic theory, determining such properties as: flame temperature, burning rate, cusp formation, wrinkling and pocket formation on the flame surface. It has been found that the asymptotic theory resulting from the linear solution of the coupled G-equations is limited to low strain rates. When the strain rate is high enough, burning intensity for both Le>1 and Le<1 flames will decrease, and this decrease at high strain rates is attributed to a decrease of flame residence time, which translates into incomplete combustion.
This paper is a continuation of the lean premixed flame-vortex interaction study introduced in [21] where laminar vortices were studied and the vortex strength for global kernel quenching was quantified. Previous results [22] show that vortex disturbance improves flame kernel growth by involving additional area of highly curved and stretched reaction zone and by increasing the effective kernel size and growth rate. Vortex strength, vortex size, and kernel maturity at which the interaction begins are all contributing factors. In this paper, the acquired images of interactions between a well-defined vortex ring with the same known size, strength and velocity scale, and a mature premixed flame kernel ignited in two different fuel/air mixtures (thermo-diffusively stable and unstable) are studied and compared. Both 3-D projection images of natural CH/OH emission and 2-D images of OH PLIF of the perturbed flame kernels are used to quantify the Lewis number effect on the flame surface.

**Experimental Apparatus and Method**

Figure 1 shows the main stainless steel combustion chamber, 25.4 cm in inside diameter and 50.5 cm in height. For a more detailed description of the apparatus and methods, see [22]. Electrodes are inserted into the chamber from two side arms in opposing directions, and the spark can be generated at the center point of the chamber between the gap of the electrodes. The gap between the two electrodes is kept at 2 mm, and the spark pulse width is digitally set at 2 ms for the tests discussed within this paper to ensure that equal amounts of energy (~120 mJ) were deposited for all cases. To generate a single, well-defined vortex toroid, a stainless steel cylinder is inserted into the combustion chamber from the top (see Fig.1). A sharp-edged orifice exists at the bottom of this inner cylinder.
A piston translates inside this cylinder and is driven by a digitally controlled, high thrust, high-resolution linear stepping motor. A vortex toroid is generated by pushing the gas mixture with the same composition as that in the primary chamber out through the orifice by the downward displacement of the piston inside the cylinder.

The length scale of the generated vortex is governed by the diameter of the orifice through which the gas mixture is expelled. This diameter determines the core-to-core diameter at the onset of vortex formation. For the results presented in this paper, only the 10 mm diameter orifice was used. The vortex will grow in size as it propagates through the reactants due to entrainment; over the ten vortex diameters traveled (100 mm), the vortex characteristic length grows approximately 20%.

The criterion for a laminar vortex is $Re < 600$ [23]. As described in [24], the vortex translation velocity $U_T$ and rotation velocity $U_\theta$ are measures of the vortex strength and scale linearly with each other, proportional to the product of the piston speed and displacement. For the results discussed here, all vortices were generated with the same piston displacement of ~0.75 mm and speed of 36 mm/s because these conditions provided repeatable and laminar vortices and were within the stepping motor's speed-thrust limit. Local translational velocity of these generated vortices was measured to be 85 cm/s at the ignition point using hot-wire anemometry in cold flow tests.

An intensified Kodak-4540 high-speed video camera was used to capture natural, broadband CH and OH emission images for the first 50~80 ms of the perturbed kernel
growth. These 3-D projection images give a qualitative record of the processes occurring during these kernel/vortex interactions. In order to get more quantitative information, instantaneous images of the 2-D flame front were captured using OH PLIF at specific instants during the kernel/vortex interaction. A slow scan ICCD camera, coupled with band-pass filters and a UV lens, was used to acquire the OH PLIF signals. A frequency-doubled Nd:YAG pumped dye laser was used to excite the Q₁(5) transition in A²Σ⁺⁻X²Π band near 282 nm. The UV beam was formed into a sheet approximately 50 mm high and 0.2 mm thick at the focal plane and centered at the electrode gap. The laser diagnostic and image acquisition setups are shown in Fig. 2.

**Flame-Kernel/Vortex Interactions**

Before providing a detailed description and discussion of the flame-kernel/vortex interaction, definitions of some qualitative features will be given. Fig. 3 is a typical OH PLIF image of the kernel/vortex interaction with prominent features identified. The nomenclature adopted is from [25] for fully-developed flame/vortex interactions. As seen in this image, the invading vortex forms an upside-down mushroom-like reactant pocket (or bulb) inside the fairly mature flame kernel, with its foot open to the perimeter of the growing kernel. The “mushroom” consists of “hat”, “root”, and its base points (connecting points with the outer rim of the kernel). The “mushroom hat” is caused by the downward moving and counter-rotating vortex ring; because of the counter-rotation, the reaction zone on the “hat brim” will be stretched and wrapped up into the “hat,” forming a reaction zone inside the “hat.” This inner reaction zone is called the “mushroom ring.” As defined in [18], the flame front curvature is negative (positive)
when the flame is concave (convex) toward the burned mixtures. Positive and negative stretch regions along the reaction zone are identified in Fig. 3.

Two test cases are presented and compared in this paper, the primary difference is the fuel/air mixtures (lean methane/air and lean propane/air) used and hence the unstretched laminar burning velocity, $S_L$, the flame thickness, $\delta_F$, and the $Le$. Details of the resulting flame properties are shown in Table 1. The vortex size, $d_0$, and strength, $U_\theta$, non-dimensionalized by $\delta_F$ and $S_L$ are also listed respectively.

### Table 1: Flame-vortex properties for the two test cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Mixture</th>
<th>$\phi$</th>
<th>Le</th>
<th>$S_L$ (cm/s)</th>
<th>$\delta_F$ (mm)</th>
<th>$T_{F,ad}$ (K)</th>
<th>$d_0/\delta_F$</th>
<th>$U_\theta S_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH$_4$/air</td>
<td>0.60</td>
<td>0.96</td>
<td>11</td>
<td>1.02</td>
<td>1600</td>
<td>9.80</td>
<td>7.73</td>
</tr>
<tr>
<td>2</td>
<td>C$_3$H$_8$/air</td>
<td>0.51</td>
<td>1.86</td>
<td>21</td>
<td>0.97</td>
<td>1820</td>
<td>10.31</td>
<td>4.05</td>
</tr>
</tbody>
</table>

Natural CH and OH emission images of the interaction for these two cases that were acquired by high-speed camera are shown as time resolved sequences in Figs. 4 (lean methane) and 5 (lean propane). The time under each image is the time that image was acquired relative to spark ignition and the physical field of view of all images is $56 \times 56$ mm$^2$. As seen in both of these figures, the kernel is approximately 10 ms ‘old’ when the vortex toroid approaches from above. In a previous study [22], the effect of kernel ‘age’ upon arrival of the vortex was discussed, with the primary result being that the earlier the arrival, the more influence the vortex has on augmenting the effective kernel growth rate.
It should be noted that the kernel could be globally quenched with a moderately strong vortex, such as those used in this study, if the arrival time is very early [21].

The kernel/vortex interaction for both these cases follows a similar course: first, the vortex head presses down from the top of the kernel, flattening the top of the nearly spherical kernel. As the well-structured vortex continues to penetrate into the growing flame kernel, it forms an upside-down, mushroom-like pocket, with its own hat and foot, outlined by very bright, thin reaction zone. Then, because of the counter-rotational motion of the vortex core inside the mushroom hat, part of the hat brim is wrapped in and forms the “mushroom ring.” This transforms the mushroom hat into a closed pocket (in 3-D projection) of fresh reactant with an inwardly propagating hat brim. The final phase of the vortex evolution inside the kernel includes the shrinking and disconnection of the mushroom foot and hat. The main closed pocket (hat) may break up into several smaller pockets, or may stay together, before it is finally consumed inside the kernel.

Figure 6 shows the time-evolutions of the characteristic kernel radius for those two test cases in Fig. 4 and 5. Generally, both methane and propane kernels grow bi-linearly with different but constant growth rates before and after the vortex disturbance begin. The dashed lines that are shown along with the solid curves for kernel radius indicate the changes of kernel growth rates. For the methane kernel, the growth rate slightly increases (from 70 cm/s to 90 cm/s) after ignition, and this change occurs immediately after the vortex disturbance on the growing kernel is visible (see Fig. 4). For the propane kernel, the growth rate increases slightly (from 130 cm/s to 150 cm/s) around 11 ms after
ignition, and this change occurs slightly before the vortex disturbance is first seen in Fig. 5 (~12 ms). There is significant disturbance in the kernel growth around 11 ms due to the vortex invasion. For the similar undisturbed flame kernels observed previously in [22], the growth rate for the methane kernel is ~60 cm/s and ~130 cm/s for the propane kernel. From Fig. 6, it is quite obvious that the vortex disturbance increases the flame kernel growth for both methane and propane flame kernel, but the relative percentage of increase in growth rate is larger for methane (from 60~70 cm/s to 90 cm/s) than that for propane kernels (from ~130 cm/s to ~150 cm/s).

**Asymptotic Theory: stretch, curvature and Lewis number effect on flame surface**

Influences on the laminar burning velocity and peak flame temperature attributable to flow non-uniformity, flame curvature, and flame/flow unsteadiness can be collectively described by a single parameter: the stretch rate. A general definition of stretch [20] at any point on the flame surface is the Lagrangian time derivative of the logarithm of the area A of an infinitesimal element of the surface:

\[ k = \frac{1}{A} \left( \frac{dA}{dt} \right), \text{ with unit of } s^{-1}. \]  

(1)

There are three factors that contribute to the stretch-induced effects: aerodynamic straining, flame curvature, and flame motion. For a non-stationary spherical flame, as the flame propagates, the stretch effects become weaker for an outwardly propagating flame and stronger for an inwardly propagating flame; the stretch rate k can be described as:
\[ k = \frac{2}{R_f} \left( \frac{d R_f}{d t} \right), \]

where \( R_f \) is the instantaneous flame radius.

The flame’s response to stretch has been found to be particularly strong for mixtures with unequal diffusivities because the flame temperature is directly affected. One approach to solving the G-equation coupled with governing equations of the flow field is in the limit of low strain rate. This asymptotic solution predicts that local flame temperature \( T_b \) and burning intensity deviates from the adiabatic flame temperature \( T_{ad} \) and burning intensity only in the simultaneous presence of stretch (\( k \neq 0 \)) and nonequidiffusion (\( Le \neq 1 \))[20]:

- \( T_b > T_{ad} \) and \( S_L > S_{L,u} \) for \((k>0, Le<1)\) or \((k<0, Le>1)\);
- \( T_b < T_{ad} \) and \( S_L < S_{L,u} \) for \((k>0, Le>1)\) or \((k<0, Le<1)\).

where \( S_L \) is the laminar burning velocity and \( S_{L,u} \) is for the unstretched case.

For nonplanar flame surfaces, pure curvature effects play an important role in upstream flame speed modification. For a curved flame surface with positive curvature, as defined in [18], its concave nature towards the fresh mixtures focuses the heat ahead of the flame, and therefore tends to raise the temperature of the flame to a value above the adiabatic flame temperature \( T_{ad} \). On the other hand, this curvature has a defocusing effect on the concentrations of the reactants approaching the flame, and therefore tends to reduce the flame temperature. Thus the temperature of the flame region again depends on the relative ratio of heat and mass diffusion. For \( Le > 1 \), the tip of the flame will burn more
intensely; while for Le<1, the burning is less intense and, with sufficient curvature, can lead to local extinction.

In this paper, the perturbed and growing flame kernel (Fig. 3) can be studied as an outward-propagating spherical flame, and the flame surface is positively stretched and negatively curved, except the waist part where the surface is concave inwardly because of the heat loss to the electrodes. The focus of this study will be on the flame-vortex interaction interfaces, the "bulb" formed by the invasion of the vortex. This traveling, shrinking "bulb" can be seen as an inwardly propagating flame pocket. The leading edge of this spherical surface is negatively stretched and positively curved. On this interaction interface, hydrodynamic strain rate, flame curvature and movement will all have an effect on the temperature and laminar burning velocity.

**Planar OH imaging**

Useful information such as the local burning intensity on the disturbed flame front cannot be derived by analyzing the CH and OH natural emission images like those shown in Fig. 4 and 5, because they are 3-D projections along the direction normal to the image plane. Stretch and curvature effects can be studied more accurately by visualizing a 2-D slice through the disturbed flame front. Lewis number effects on the perturbed flame front with different stretch and curvature can be analyzed by comparison of the OH PLIF images of lean methane/air flame kernels (Le<1, thermo-diffusively unstable) and lean propane/air flame kernels (Le>1, thermo-diffusively stable). The OH radical is commonly used as a marker for visualizing the instantaneous, product-side flame front.
Under certain conditions, the OH fluorescence signal may be considered to be proportional to the concentration of OH radicals. Thus, OH can be used as an approximate tracer of the integrated heat release rate and, consequently of the reaction zone [25]. The local burning rate of the flame front can be related to OH fluorescence intensity, although this relationship can be difficult to quantify [26].

Images of natural CH and OH emission and OH PLIF taken nearly simultaneously from a disturbed flame kernel, 30 ms old and growing in a methane/air mixture, are shown in Figs. 7-a and -b. These images were captured by two ICCD cameras from opposite sides of the kernel (the natural emission image has been horizontally flipped for ease of comparison). The exposure time is 30 μs, and the two images are captured 100 μs apart during the flame-kernel/vortex interaction. These images, and all the images following, have a resolution of 578×384 pixels, 256 gray levels, and a field of view of 63 mm × 42 mm. Fig. 7-a is the 3-D projection image of natural CH and OH emission, and Fig. 7-b is the 2-D OH PLIF image. The OH-PLIF images have been corrected for any non-uniformity in laser sheet intensity. It can be seen that 3-D integration effect is quite obvious in Fig. 7-a and is eliminated in the 2-D OH PLIF image in Fig. 7-b. As expected, all regions of high fluorescence intensity are on the product side of the flame surface.

Two OH PLIF images of slightly curved methane/air and propane/air kernels are presented in Fig. 8 and Fig. 9. These two flame kernels are about the same size and age, and the downward traveling vortex is just beginning to press down the top of the kernel. For the top part of the flame kernel, the surface is positively curved down, while the sign
of stretch is ambiguous. The local flow field at the leading edge of the invading vortex will positively stretch the flame surface due to the counter-rotating vortex pair (in two dimensions) at this local stagnation plane. Based on Eqn. (1), the sign of the stretch is determined by the direction of change of the flame surface area. For the undisturbed flame kernel, the surface is positively stretched and negatively curved due to its continuous growth. For the slightly disturbed top part of the kernel, it is seen (from image sequences in Fig. 4 and 5) that the area first decreases as the approaching vortex “flattens” the upper surface of the kernel. As the vortex continues to propagate into the growing kernel, the area is seen to increase again. Therefore, a change in the sign of the stretch during the very early stages of the interaction is expected. At the upper surface of the kernel in Fig. 8 and Fig. 9, it is most probable that the stretch is positive. Based on the asymptotic theory for this positively stretched flame, the lean methane/air flame (Fig. 8) should be intensified and lean propane/air flame (Fig. 9) should be weakened. By carefully comparing the flame surface OH fluorescence intensity in these two images, it is seen that the intensity is relatively uniform along the kernel/vortex interface in both kernels. Without knowing the local velocity, it is not possible to determine the local strain rate. Based on reference [27], the maximum local stretch rate $K_{\text{max}}$ can be estimated by:

$$K_{\text{max}} = c_1 \left( \frac{U_{\theta}}{d_c} \right)$$  \hspace{1cm} (3)

$U_{\theta}$ is the rotational velocity of the vortex ring, which can be estimated by measuring the downward translational velocity [24], which in the present test, is around 85 cm/s. $d_c$ is the core diameter of the vortex and is approximately 3 mm. The constant $c_1$ in the
experiment is 0.24. Therefore the maximum local stretch rate $K_{\text{max}}$ is about 68 s$^{-1}$ in the tests, which is much higher than the measured value of 42 s$^{-1}$ that is required to quench a steady, planar counterflow flame of methane/air with equivalence ratio of 0.55 [28].

An interesting phenomenon is observed at the top of propane kernel; the flame surface at the interaction interface stretches out tangentially from both sides of the kernel into the fresh gas mixture. This is most likely due to the counter-rotational movement of the vortex toroid and the high viscosity due to the high temperature. This phenomenon was observed several times during OH PLIF tests, but only in lean propane/air kernels, and it never appeared in the lean methane/air kernels or the CH/OH natural emission images. It is unclear why this phenomenon should only be observed in the propane/air kernels.

By looking at later times in the interaction, the ambiguity of the sign of the stretch can be resolved. Fig. 10-a and 10–b show a methane/air kernel and propane/air kernel at 30 ms into the interaction. The leading edge of the invading vortex is positively curved and positively stretched. Normalized intensity profiles are obtained across the kernel-vortex interaction interfaces (the leading edge of the invading vortex) in Fig. 10-a and 10-b respectively. Fig. 10-a and 10-b show the paths of the profiles: crossing the leading edge of the vortex, from the fresh gas side inside the vortex, to the product side in the kernel. The intensities are normalized by the average intensity in the product area of each picture, so that they can be overlapped for comparison. The resulting profiles are shown in Fig. 10-c. The profiles are shifted horizontally so that the peak values, which indicate the flame front, occur at zero on the X-axis. The negative distance indicates the fresh
mixture region inside the vortex pocket, and the positive distance indicates the hot product region outside the vortex. It can be seen that peak intensity of the lean methane flame is about 25% higher than that of the lean propane flame. This result is in agreement with the asymptotic theory which predicts that the combustion will be intensified on the leading edge of the vortex in lean methane/air flame and diminished in lean propane/air flame.

The main effects of turbulence on non-unity Lewis number flames are to wrinkle the reactive layer, to generate additional flame surface area, and to slightly increase the mean burning rate per unit surface area through flow straining effects. For flames with sub-unity Lewis number, positive stretch will act to increase the flame displacement speed $S_L$ by locally increasing the flame temperature, and negative stretch will decrease the displacement speed. This mechanism leads to an increase in the fluctuation of $S_L$ along the flame front for wrinkled flames, where the stretch is continuously changing between positive and negative values. Thus, lean methane/air kernels tend to promote the elongation action of the invading vortex, and there will be more wrinkling of the flame front than lean propane/air flames, which tend to smooth the wrinkles. Figures 11-a and 11-b compare the interaction interfaces for lean methane/air and lean propane/air kernels for an interaction which is further along in time. It can be seen that the vortex toroid (mushroom head) is just crossing the electrodes (indicated by the black line) in both figures. It is clear in these figures that the flame surface of lean methane/air kernel is much more wrinkled than the lean propane/air kernel.
The formation and consumption of the inwardly propagated flame pocket is an important phenomenon along the disturbed flame surface. For flames with $\text{Le}>1$, thermo-diffusive effects are stabilizing and thus tend to inhibit the formation of pockets. For flames with $\text{Le}<1$, the amplification of wrinkles along the flame front will eventually break up the continuous flame front and thus promote the formation of smaller flame pockets. Observations of the final stages of the burning vortex inside the flame kernel support this prediction. As seen in Fig. 4 u–y, the mushroom head of the invading vortex breaks up into small pockets inside the lean methane/air flame kernels before it burns away. In contrast, for the vortex in lean propane kernels, the mushroom head stays in one piece (Fig. 5 v–y) for most of the time before it finally burns away. OH PLIF images support this conclusion. In Fig. 12-a, vortex toroid in a lean methane/air kernel breaks up into three pieces of highly curved pockets. In Fig. 12-b, the vortex toroid detaches from its tail, staying in one main piece with relatively smooth flame front and intensified burning rate.

The burning rate or the flame temperature response to the different curvatures is also observed and studied. Fig. 13 show a lean propane/air kernel. The leading edge of the invading vortex is positively stretched and positively curved, while the leading edge of the growing kernel is mostly positively stretched and negatively curved. There is a continuous region at the top of the kernel where the curvature changes from positive to negative very sharply. These turning points: cusps (in 2-D), although barely seen in Fig. 13, have near-zero curvature at the positive sections (vortex surface), and high negative curvature at the negative sections. It is quite clear in this figure, that with decreasing
positive curvature, and thereby decreasing positive stretch along the interaction interface from the very bottom of the leading edge to the turning point with near-zero curvature, the burning intensity decreases for lean propane/air flame. The reduction in the flame temperature can be so severe that local extinction may occur on the way to the cusps (see the intensity discontinuity along the leading edge in Fig. 13). Similar interaction images were also captured for lean methane/air flame, but the intensity is relatively uniform along the interaction interface and no local extinction was observed. This may be explained by the fact that the lean methane kernels having Lewis numbers close to unity.

**Quantitative study on local curvature and local burning rate**

As mentioned earlier, the local strain rate on the flame surface is determined by three factors: local flame front curvature, motion of flame surface, and the non-uniformity of the external flow field. During the late or final stages of the kernel-vortex interaction, the inwardly propagating flame pocket formed by the invading vortex is almost motionless, and the vorticity induced by the vortex is very small due to the high viscosity in the hot product region; therefore the main source of the strain rate comes from the flame front curvature. The time evolution of the overall curvature (averaged absolute curvature) has been measured and quantified using the natural emission image sequences, allowing the coordination of the local burning rate with the local flame curvature in OH-PLIF images for methane and propane flames. The reason for computing absolute curvature is to avoid cancelling of positive and negative curvatures on wrinkled flame surfaces.
The local curvature has been calculated along the flame front for both natural CH and OH emission images and OH-PLIF images. Images captured with the high-speed camera have been pre-processed to outline the flamefront for curvature calculations. Fig. 15-a and –b show the effect of this pre-process. Local curvatures are computed by sampling three neighboring points on the flamefronts. The averaged absolute value of these local curvatures is used as the index for the overall curvature of a processed kernel image. The time evolution of the overall curvature for a growing, disturbed flame kernel can be obtained by calculating the rms of curvature for every image of the sequence.

Figure 15-a shows the time evolution of averaged absolute curvature for undisturbed methane (\(\phi=0.6\)) and propane (\(\phi=0.8\)) flame kernels. In this figure, as the flame kernel grows, its curvature rms decreases sharply for the first 10~15 ms after ignition, as expected, and then the rate of curvature change slows and gradually approaches zero curvature as is expected since the flamefront becomes more planar. Curvature of the methane flame is always higher than the propane flame at any given instant, since it grows more slowly. As it is shown in the previous study [22], the undisturbed flame kernel grows linearly (radius vs. time) for most stages of its growth, and the propane flame kernel grows much faster than the methane flame kernel. The undisturbed flame kernel looks like a flame ball, thus the averaged absolute value of the curvature should be quite close to the inverse of the characteristic radius of the kernel. The time evolutions of the characteristic radius were measured with the same image sequences used in Fig. 15-a, using the method described in reference [22]. The results are shown in Fig. 15-b along with the inverse of curvature rms data in Fig. 15-a for comparison. From Fig. 15-b, it can
be seen that the radius computed from the inverse of the measured curvature compare favorably with the measured characteristic kernel radius quite closely, especially for methane flame kernel. It should be noted that the two image processing algorithms used in Fig. 15-b for radius and curvature are independent of each other and are based on different assumptions. Obtaining results with negligible differences with the same image sequence indicates that these two algorithms are reliable.

Fig. 16 shows the time evolution of averaged absolute curvature for disturbed flame kernels. The data were obtained from the image sequences shown in Fig. 4 and 5. It can be seen that for the first ~10 ms, both methane and propane flame kernel curvature drops sharply during the undisturbed growth stage, as expected. After that, as the invading vortex begins to press down into the kernel, the overall averaged absolute curvature of the kernel continues to drop, but less sharply for both methane and propane kernels. Despite the effect of globally increasing the kernel growth [22], the vortex pressing down locally decreases the curvature as the vortex head “curved” into and flattened the top of the growing kernel. As the vortex continues to enter the kernel, the overall curvature begins to increase. There are several factors that effect the averaged absolute curvature. The first is the overall size of the vortex “bulb”, the inwardly propagating, open-tail flame pocket. This pocket first expands when it is entering the kernel, then shrinks. The second factor is the different burn-off processes for methane and propane kernels. The third is the final stage of the vortex evolution: whether the vortex breaks into many smaller pockets or remains a single pocket until it is completely consumed. All these factors contribute to the oscillation and the relatively slow increase of the averaged
absolute curvature. From Fig. 16, it can be seen that during the final phase of vortex-kernel interaction (t>25 ms), the rms curvature of the methane kernel is significantly higher than that of the propane kernel, indicating the bulb is more wrinkled and more inclined to break up, which in this case, is due to the different Lewis numbers. This figure quantitatively proves the conclusion made earlier in this paper based on qualitative image analysis.

There are many reports on the relationship between local flame surface curvature and local burning rate for premixed flames with different Lewis numbers [18,20]. In this work, the local integrated intensity is used as an indicator of local burning rate for the 2-D OH-PLIF intensity images. The local integrated intensity is defined and computed as the intensity summation of pixels along a straight line normal to the flame surface, 20 pixels long, starting from the pixel on the flame surface where the local curvature is calculated, pointing to the product side of the flame. The 20-pixel length was chosen because it is equal to the largest thickness of the local flame surface found in those OH-PLIF intensity images. Using local integrated intensity along this path instead of the intensity of a single pixel is a better measure of the effect of curvature on the heat release zone. These curvature and intensity integration algorithms have been applied to several OH-PLIF images to obtain a correlation between local curvature and intensity, and the results are shown in Fig. 17 and 18. Fig. 7-b has been used for methane flame image processing, and Fig. 11-b for propane flame. Both kernels are approximately the same size, and the vortices are at approximately the same location: passing the electrodes. Over 200 points on the disturbed flame surface in these images have been sampled for
each of these two correlation curves. The original data points are quite scattered. Fig. 17 and Fig. 18 were the results of averaging over both intensity and curvature axes. The averaging method is proceeded as follows: first divide the I-C (Intensity-Curvature) plane into small square cells of $\Delta i$-by-$\Delta c$. Next determine the mass center of those sample points in each cell and use the coordinates of this center $(i, c)$ to represent all the points in that cell. The local intensity has been normalized to the value at the region of zero curvature. The data was then fit with a 3$^{\text{rd}}$-order polynomial, which is shown in these figures. From these two figures, opposite trends for the intensity-curvature relationship are quite clear: for the lean methane flame with Lewis number less than 1, the integrated OH intensity, and presumably the local burning rate, increases with the increasing curvature, from the negative side to the positive side; for the lean propane flame with Lewis number larger than 1, the local burning rate decreases as the curvature value crossing zero from negative to positive. Although there are not enough data points to estimate the intensity with local curvature values above 1, the current results clearly indicate the local curvature effect on local burning rate with different Lewis numbers. The trends in Fig. 17 and 18 are in agreement with the prediction of asymptotic theory, in the limit of very low strain rates. Also by carefully comparing Fig. 17 and 18, it can be found that the slop that the propane flame intensity drops is slightly greater than that slope with which the methane flame intensity increases. This difference may be explained by the departure from unity Lewis number for each mixture: methane flame has a Lewis number of 0.96 while the Lewis number for propane flame is about 1.86.
Summary and Conclusion

1. Experiments were conducted on premixed, spark-generated flame-kernel/laminar vortex interactions with different fuel/air mixtures to study the fundamental role of chemistry-turbulence interactions in combustion. Both lean methane/air (thermo-diffusively unstable) and lean propane/air (thermo-diffusively stable) flame kernels were studied. Two test cases are presented with natural CH and OH emission image time sequences acquired by a high-speed intensified camera, showing many details of the disturbed flame kernel growth.

2. OH PLIF was employed to determine the true two-dimensional nature of the interaction. Local OH fluorescence intensity along the kernel/vortex interaction interfaces, which is an indicator of the stretched local burning rate and flame temperature, have been carefully studied and compared for both lean methane/air kernels and lean propane/air kernels at similar kernel growth stages and with similar vortex strengths and length scales. The results have been compared with the estimated flame response to stretch based on asymptotic theory.

3. The experimental results show that on the leading edge of the invading vortex, which is positively curved and stretched, the combustion is intensified for methane/air kernel with sub-unity Lewis number and diminished in propane/air kernel with Lewis number greater than one.
4. The test results also show that low Lewis number flames tend to intensify the fluctuation of flame speed along the disturbed flame front, thus wrinkling and eventually breaking the vortex into several flame pockets, while the high Lewis number flames tend to smooth the disturbed flame front and inhibit multiple pocket formation.

5. Quantitative study on the local/overall flame front curvature and local burning rates has been conducted. The time evolution of the averaged absolute flame surface curvature for different fuel/air mixtures have been presented. The relation between an indicator of the local burning rates and the local flame curvature has been shown, and the trend lines fits of the test data meet the expectation from asymptotic theory with low strain rate.

6. Distinct differences between methane flame and propane flame have been observed. Propane flame has whisps and regions of very low OH intensity.

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Reference:


22. Xiong, Y., Roberts, W., Drake, M. C., Fansler, T. D., accepted to *Combust. Flame*.
Fig. 1 Primary Combustion Chamber
Fig. 2 OH-PLIF laser diagnostic and image acquisition setups. (The high-speed video camera was used without laser)
Fig. 3 Definitions of some qualitative features in flame-vortex interactions and signs of curvature along the interaction interface.
Fig. 4 Image sequence for Case 1—CH₄/air, φ=0.6, late interaction.
Fig. 5 Image sequence for Case 2—\( \text{C}_3\text{H}_8/\text{air}, \phi=0.67 \), late interaction.
Fig. 6 Time evolution of the characteristic kernel radius for case 1 and 2. (the dashed lines indicate the different growth rates in different phases of growth)
Fig. 7-a Natural CH/OH image of kernel-vortex interaction in lean methane/air flame kernel ($\phi=0.6$, field view is $63\times42\text{mm}^2$).

Fig. 7-b OH PLIF image of kernel-vortex interaction in lean methane/air flame kernel ($\phi=0.6$, field view is $63\times42\text{mm}^2$).
Fig. 8 OH PLIF image of kernel-vortex interaction in lean methane/air flame kernel ($\phi=0.6$, field view is $63\times42\text{mm}^2$).

Fig. 9 OH PLIF image of kernel-vortex interaction in lean propane/air flame kernel ($\phi=0.5$, field view is $63\times42\text{mm}^2$).
Fig. 10-a OH PLIF image of kernel-vortex interaction in lean methane/air flame kernel (φ=0.6, field view is 63x42mm²).

Fig. 10-b OH PLIF image of kernel-vortex interaction in lean propane/air flame kernel (φ=0.5, field view is 63x42mm²).
Fig. 10-c Normalized intensity profiles across the kernel-vortex interaction interfaces in Fig. 10-a and b.
Fig. 11-a OH PLIF image of kernel-vortex interaction in lean methane/air flame kernel ($\phi=0.6$, field view is $63\times42\text{mm}^2$).

Fig. 11-b OH PLIF image of kernel-vortex interaction in lean propane/air flame kernel ($\phi=0.5$, field view is $63\times42\text{mm}^2$).
Fig. 12-a OH PLIF image of kernel-vortex interaction in lean methane/air flame kernel ($\phi=0.6$, field view is 63x42mm$^2$).

Fig. 12-b OH PLIF image of kernel-vortex interaction in lean propane/air flame kernel ($\phi=0.6$, field view is 63x42mm$^2$).
Fig. 13 OH PLIF image of kernel-vortex interaction in lean propane/air flame kernel ($\phi=0.5$, field view is 63x42mm$^2$).

Fig. 14 Effect of image pre-processing to outline the flamefront for curvature calculation. (a. the original image, b. the resulting image)
Fig. 15-a Time evolution of the averaged absolute curvature for undisturbed flame kernel

Fig. 15-b Comparison of measured characteristic kernel radius and the calculated value from the inverse of the overall averaged absolute curvature.
Fig. 16 The averaged absolute curvature vs. time for the disturbed kernels with late interaction.
Fig. 17 Local integrated intensity vs. Local signed curvature on the flame surface of methane flame kernel.

Fig. 18 Local integrated intensity vs. Local signed curvature on the flame surface of propane flame kernel.
Chapter 5

Interaction Between a Lean Premixed Flame Kernel and a Laminar Vortex of Different Mixture Ratio
Interaction Between a Lean Premixed Flame Kernel and a Laminar Vortex of Different Mixture Ratio

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This manuscript is being submitted for consideration as a full-length paper
Abstract

Charge stratification by direct local injection has been actively studied as a technology for spark ignited lean burn engines. Local mixture enrichment by direct injection in the vicinity of the spark plug at the time of ignition can significantly affect flame kernel development and extend the lean limit of flammability of a fuel/air mixture. The interaction between a lean premixed spark-ignited flame kernel and a laminar vortex toroid containing a different fuel/air mixture was experimentally investigated to gain an understanding of the effect of ‘turbulent’ bulk transport of material into the growing flame kernel. Flame kernels were ignited in lean premixed methane/air mixture with equivalence ratio of 0.6, while the equivalence ratio of the vortex core fluid was varied between 0 and infinity. Chemiluminescence images of the kernel-vortex interaction were captured using either a single shot ICCD camera or a high-speed intensified camera. Details regarding flame kernel-vortex interactions for six test cases are presented and discussed. It was observed that vortices composed of fluid outside the traditional flammability limits were completely consumed inside the growing flame kernel.

Introduction

To increase fuel economy and satisfy increasingly stringent tailpipe emission standards for spark ignited internal combustion automobile engines, it is important to develop an effective combustion process to allow consistent and reliable operation of these engines using very lean fuel/air mixtures. There exists a great potential to improve the fuel economy and reduce the CO and NOx emission of the internal combustion engine with the development of a lean burn engine [1]. Conventional ignition systems typically result in slow flame propagation speeds when used under ultra-lean conditions [2]. Thus only a partial burn takes place with a consequent higher fuel consumption rate and increased exhaust emissions. Many enhanced ignition devices for ultra-lean conditions have been proposed and investigated [3]. These include plasma jet ignition, ultra short pulse ignition and stratified charge engines.
The stratified charge combustion system, which combines the advantages of both a premix combustion system and a Diesel combustion system, has been actively studied as a technology for improving fuel economy and reducing exhaust gas emission [4~7]. As a prerequisite for charge stratification, a readily ignitable fuel mixture in the vicinity of the spark plug must be provided. This can be achieved by a number of different means, such as port injection [8], use of a pre-chamber to create a “torch” jet into the lean mixture [9], and direct local injection [10]. The concept of local injection includes the presumption that spatial and temporal variations of velocity and fuel concentration close to and at the instant of ignition can not be controlled accurately by port injection of the engine, so that a desired stratification requires a combination of a homogeneous lean charge from the port and local injection of a richer fuel/air mixture [11]. This local injection can be expected to have two effects, one associated with velocity characteristics and the other with fuel/air mixture.

Studies show the local mixture enrichment by direct local injection in the vicinity of the spark plug at the time of ignition can affect flame kernel developments and engine cyclic variability [12~14]. An important benefit of a controlled locally rich mixture is its ability to extend the lean limit of flammability of a fuel/air mixture [15]. For example, the results of Arcoumanis, et al. [11] show that a stable and consistent flame kernel can be formed after ignition with small quantity of rich mixture injected near the spark gap. This allowed flame propagation through a very lean mixture with an overall equivalence ratio as low as 0.39. Their work also indicates that the average flame speed could be increased by local injection at all equivalence ratios [16]. It was also shown that the fluid dynamic effect alone caused over stretching of the flame for the ultra-lean homogeneous conditions, while rich local stratification in the vicinity of the spark allowed the suppression of this effect and a reduction of the drivability limit [17].

Most of the research work mentioned above studied the charge stratification techniques using simplified spark ignited gasoline engines. They determined the effect by monitoring engine parameters such as pressure, temperature and concentrations of emission components, etc. Since local enrichment by local injection not only changes the
local equivalence ratio of the mixture, but also disturbs the local quiescent mixture in the vicinity of the spark plug, it is necessary to understand the local effect of this injection disturbance on the early stages of flame kernel growth. Previously, the authors [18, 19] have investigated the interaction between a lean premixed flame kernel-laminar vortex all composed of the same fuel/air mixture using advance image acquisition systems and laser diagnostic techniques. This previous research presented a detailed study on lean flame kernel growth under the influence of a single, laminar vortex of varying characteristic size and strength, and at different kernel maturities. This paper extends the authors previous work by allowing dissimilar equivalence ratios between the ambient kernel fluid and the vortex core fluid. In all the experimental results presented here, the ambient kernel fluid was composed of methane/air at an equivalence ratio of 0.6, while the vortex core fluid was varied from pure air to pure fuel.

**Experimental Apparatus and Test Settings**

The apparatus used for these experiments was the apparatus discussed in detail in references [18,19] with a small modification. The difference was the addition of a separate mixture injection system for the vortex generation piston-cylinder device, shown in Fig. 1. Approximately 60 seconds before spark ignition, while the main combustion chamber was filled with homogeneous and quiescent fuel/air mixture, the gas mixture stored in a small pressurized gas cell is released into the lower part of the vortex generation cylinder, through the thin tube. The pressure and volume of the gas cell were selected to ensure the gas in the vortex generation cylinder was completely displaced by the new mixture from the gas cell. This allowed dissimilar equivalence ratios between the ambient kernel fluid and the vortex core fluid.

The test settings for the results presented are listed in Table 1. The vortex size (nominal core-to-core distance of 10 mm) and strength (translational velocity of 85 cm/s at the ignition point) were held constant for all vortices studied here. Vortices with six different equivalence ratios were used, from pure air to pure methane, as they are listed as six test cases in Table 2. It should be noted here that there is no gas cell release in test case 3.
(\(\phi=0.6\)) because the equivalence ratio of the vortex is the same as the overall ratio in the main combustion chamber. Also in test case 3, a high-speed camera (Kodak-4500) was used, while in other cases, a single shot ICCD camera was used to collect the chemiluminescence images of the growing disturbed flame kernels.

Maxworthy [20] studied the structure and stability of laminar vortex rings, and found that the volume of the vortex has a linear relationship with time due to the entrainment of the ambient fluid after it is generated. In a previous study [18], the core-to-core distance of the vortex ring generated by the 10-mm orifice was measured to increase approximately 20\% by the time it arrived at the ignition point, after travelling the 100 mm through ambient gas. Because the vortex volume scales as the cube of the diameter, the vortex volume at the ignition point can be estimated and a resulting equivalent equivalence ratio can be calculated. Table 2 also lists the resulting average equivalence ratio for each test condition after the vortex has traveled the 100 mm through the lean premixed CH4/air mixture. Of course, the local equivalence ratio will vary as a function of the radial location within the vortex toroid, from 0.6 at the outer edge to that of the initial core fluid at the center. Due to the structure of the vortex toroid, this variation will not be linear. The vortex toroid can be described as a Rankine vortex with exponential velocity decay outside the core [21]. This Rankine core, which makes up approximately one quarter of the volume at ten diameters downstream of vortex generation, should be very similar in composition to the original core fluid.

<table>
<thead>
<tr>
<th>Table 1. Experimental Settings.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel/air mixture in chamber</td>
</tr>
<tr>
<td>Orifice diameter for vortex generation cylinder</td>
</tr>
<tr>
<td>Distance between the orifice and the ignition point</td>
</tr>
<tr>
<td>Translational velocity of the generated vortices</td>
</tr>
<tr>
<td>Gaps between the tips of the ignition electrode</td>
</tr>
<tr>
<td>Duration of the ignition spark</td>
</tr>
</tbody>
</table>
### Table 2. List of Test Cases

<table>
<thead>
<tr>
<th>Test Case number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalence ratio of initial vortex</td>
<td>0</td>
<td>0.3</td>
<td>0.6</td>
<td>1.0</td>
<td>1.5</td>
<td>∞</td>
</tr>
<tr>
<td>Equivalence ratio of the vortex around ignition point</td>
<td>0.25</td>
<td>0.43</td>
<td>0.6</td>
<td>0.81</td>
<td>1.03</td>
<td>4.40</td>
</tr>
</tbody>
</table>

### Test Results and Discussion

Chemiluminescence images of the lean premixed disturbed flame kernel for the six test cases are shown in Fig. 2 to Fig. 7 respectively. In all image sequences, the vortex is propagating from top to bottom. Four images are presented for each case, forming a time sequence to show the evolution of these kernel-vortex interactions: the first image in each figure corresponds to the beginning of the interaction, when the vortex first begins to deform the top of the growing kernel. The second and third image in each figure correspond to intermediate stages of the interaction, showing the vortex approaching and passing the ignition electrodes (indicated by the horizontal dark line in the center of the images). The fourth image in each figure corresponds to the final stages of the kernel-vortex interaction. Images in Fig. 4 for case 3, where the vortex and kernel fluid are the same, were collected by a Kodak 5450 high-speed camera mated with an Imco ILS-3 lens-coupled intensifier during a single test run, with a field of view of 56×56 mm². The images show the interaction between 19 and 40 ms after ignition. Finer temporal detail of this sequence has been published in [18] and is shown here for comparison purposes. Images for all the other cases were collected by a single shot Princeton Instruments ICCD camera during successive test runs, and the field of view is about 38×58 mm². The kernel size is approximately 41 mm in diameter, making these interactions “late”, as defined in [18].

The general characteristics of a late interaction between the lean premixed flame kernel and the laminar vortex with the same equivalence ratio are described and presented in detail in previous studies [18,19]. Figures 2 to 7 show that the six test cases presented
here follow a similar evolution: first, the vortex head presses down from the top of the kernel, flattening the top of the nearly spherical kernel. As the well-structured vortex continues to penetrate into the flame kernel, it forms an upside-down mushroom like pocket, except the one in case 6 (Fig. 7). The final stage of the interaction is the break-up and consumption of the invading vortex inside the flame kernel. As discussed above, the vortex travels 100 mm (ten core diameters) through the ambient gas mixture before it reaches the electrodes. Due to entrainment, even the vortices generated with unignitable fuel/air mixtures such as pure air (case 1, $\phi=0$), pure methane (case 6, $\phi=\infty$) and very-lean mixture (case 2, $\phi=0.3$), there are still a visible flame front around the invading vortex, especially at the leading edge. From the first images in each of these figures, it can be seen that the very early stages of kernel-vortex interaction, when the vortex just begins to penetrate into the top of the flame kernel, are quite similar for all these test cases. The concaved flame fronts on the top of the kernel have a strong chemiluminescence signal, even for those disturbed by unignitable vortices, indicating strong local reaction.

In test cases 1 and 2, pure air and very-lean methane/air mixture with equivalence ratio of 0.3 were used to generate the vortex respectively. The visible chemiluminescence signal surrounding the vortex is due to the entrained combustible mixture, and the signal is seen to be weak compared to the undisturbed portions of the growing kernel. As seen in image D of both of these figures, the vortex retains its size; there is no appreciable inward propagation of the reaction zone followed by consumption of the vortex fluid. At times later then that corresponding to image D, no chemiluminescence is visible inside the kernel, indicating complete quenching of the flame surrounding the vortex. There is little discernable difference between the $\phi = 0$ and the $\phi = 0.3$ conditions other than in the wake region, where the 0.3 case shows slightly more activity.

For cases 3 and 5, vortex core fluid equivalence ratios were 0.6 and 1.5, respectively. These conditions are close to the lean and rich flammability limit for methane and are nearly symmetric around the peak laminar burning velocity [22]. Due to entrainment, the actual equivalence ratio inside the vortex for case 5 is lower than 1.5. As expected, the image sequences (Fig. 4 and 6) for these two cases are quite similar: the well-structured
vortices form well-shaped upside-down mushroom like pocket inside the flame kernel; and the intensity at the kernel-vortex interaction interfaces are quite bright, indicating strong local reaction (see image B’s of Fig. 4 and 6); at late stage of interaction, because of the rotational motion around the vortices cores that wrap up the flame front on the leading edge of the vortices, a closed, inwardly propagated flame pockets are formed at the heads of the vortices (image C’s of Fig. 4 and 6). But these two cases show difference in their final stages of kernel-vortex interactions: in test case 3, the vortex head detached from its trail and break up into several small pockets (Fig. 4-D); while in test case 5, the vortex head also detached from its trail, but kept in on piece before it finally burned off. Similar phenomena were observed previously in the study of the Lewis number effect in kernel-vortex interaction [19]. For lean methane mixture with equivalence ratio of 0.6, the Lewis number is less than 1 (~0.96), which for a rich methane mixture, the Lewis number is larger than 1. It was predicted by asymptotic theory with condition of low strain rate and demonstrated by previous experimental results [19] that for flame with sub-unity Lewis number, positive stretch will make the flame front more wrinkled and ultimately break up the flame surface into small pieces. But for flame with Lewis number larger than 1, the positive stretch will smooth the wrinkles on the flame surface. The difference presented in the final stages of kernel-vortex interactions for case 3 and 5 proves this prediction.

The stoichiometric methane/air mixture is used to generate the vortex for test case 4. This vortex should be consumed the fastest due to the high laminar burning velocity of this core fluid. In the image A of Fig. 5, the high intensity on the kernel-vortex interaction interface indicates very strong local reaction. The evolution of the interaction in test case 4 is very similar to that observed in cases 3 and 5; there forms a upside-down mushroom like pocket, and the intensity (see images B and C of Fig. 5) along the flame front is very similar to the corresponding images in cases 3 and 5. However, comparing the final stages of Figs 5 and 6, it is clear that the vortex in Fig 6 burns away more quickly than in Fig. 5. This is somewhat curious until the effect of entrainment is included. Table 2 shows a calculated average equivalence ratio of case 5 (Fig. 6) of near
unity, while the initially stoichiometric vortex has been diluted by the ambient fluid to
approximately 0.8.

The test case 6 uses pure methane ($\phi=\infty$) to generate the vortex. Except the initial stage
(Fig. 7-A), all other stages of the interaction for this case are quite unique (Fig. 7-B, C, D) when compared with corresponding images for other test cases. The unique features
include the observation that, for the most part, the kernel-vortex interaction interfaces are
far more diffusive than seen in the other cases. The shape and the size of the vortex are
nearly constant as the interaction progresses; this is similar to cases 1 and 2, where the
vortex fluid was also outside the flammability range, even after accounting for
entrainment. However, there are differences between the very lean vortex and the very
rich vortex, such as: there is no mushroom like vortex inside the disturbed flame kernel;
the width of the vortex wake is about the same with the diameter of the vortex head, and
the wake is not observed to burn away. A third unique feature in the pure fuel vortex is
the generation of high intensity areas around the intersection ring formed by the invading
vortex and the flame surface on the top of the kernel. This high intensity area is most
likely a region of near stoichiometric reactions, where pure fuel from the vortex is mixing
with the overall lean ambient fluid. At the final stages of evolution, the
chemiluminescence signal is seen to diminish to near background levels inside the kernel.
There is no evidence of pocket formation (see Fig. 7-D).

**Summary and Conclusions**

Experiments were conducted on interactions between a lean premixed spark-ignited
flame kernel and a laminar vortex of known size and strength containing fluid with a
different fuel/air mixture to study the fundamental role of bulk transport and the
chemistry-turbulence interaction in stratified combustion. Flame kernels were ignited in
lean premixed CH$_4$/air mixture with equivalence ratio of 0.6, and CH$_4$/air mixtures of six
different equivalence ratios ranging from 0 to infinity were used to generate the vortex.
Chemiluminescence images of kernel-vortex interactions were captured using either a
single shot ICCD camera and high-speed intensified camera, to acquire a qualitative
measure of the local reaction rate. For vortices composed of flammable mixtures, the
vortex is completely consumed inside the kernel, with the higher consumption rate occurring with the initially rich vortex. This is due to a leaning out of the vortex as it propagates through the lean ambient fluid. Lewis number is seen to play a role in the final fate of the vortex; for lean mixtures, the vortex is seen to break up into many small pockets before finally being consumed, while for the rich mixture, the vortex is consumed as a single pocket. For vortices composed of inflammable mixtures, the vortex is not consumed and the chemiluminescence signal diminishes almost completely. The pure air and $\phi = 0.3$ cases are quite similar, while the pure fuel case has a number of noticeable differences, including a more diffuse region of signal intensity, an intense ring around the opening formed in the kernel by the vortex, and the wake not burning.

Acknowledgement:

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Reference:

10. Kume, T., Iwamoto, Y., Lida, K., Murakami, M., Akishino, K., and Ando, H., 
   *SAE paper* 960600, 1996.
Fig. 1 Primary Combustion Chamber
Fig. 2 Image sequence for test case 1 (CH₄/air, injection $\phi=0.0$, field of view is 38×58 mm²)
Fig. 3 Image sequence for test case 2 (CH₄/air, injection $\phi=0.3$, field of view is 38×58 mm²)
Fig. 4 Image sequence for test case 3 (CH₄/air, injection $\phi=0.6$, field of view is $56\times56$ mm²)
Fig. 5 Image sequence for test case 4 (CH₄/air, injection φ=1.0, field of view is 38×58 mm²)
Fig. 6 Image sequence for test case 5 (CH₄/air, injection \( \phi = 1.5 \), field of view is 38×58 mm²)
Fig. 7 Image sequence for test case 6 (CH₄/air, injection \( \phi=\infty \), field of view is 38×58 mm²)
Chapter 6. Summary and Conclusions

The research described in this dissertation represents a study of the fundamental building block of turbulent premixed flame ignition: the interaction of laminar premixed kernel with a well-defined toroidal vortex. Both lean methane/air (thermo-diffusively unstable) and lean propane/air (thermo-diffusively stable) flame kernels were studied. Test cases are presented with natural CH and OH emission image time sequences acquired with a high-speed intensified camera, showing many details of the disturbed flame kernel growth as a function of vortex size, strength and kernel maturity at vortex arrival. The effective kernel growth rate was determined from these image sequences. OH PLIF was employed to determine the true two-dimensional nature of the interaction. Local OH fluorescence intensity along the kernel/vortex interaction interfaces, which is an indicator of the stretched local burning rate and flame temperature, have been carefully studied and compared for both lean methane/air kernels and lean propane/air kernels, at similar kernel growth stages and with similar vortex strengths and length scales. The results have been compared with the estimated flame response to stretch based on asymptotic theory. Quantitative study on local/overall flame front curvature and local burning rates has been conducted, the time evolution of the averaged absolute flame surface curvature for different fuel/air mixtures has been presented. Kernel-vortex interactions were also studied where the vortex core fluid was at a different equivalence ratio from the kernel fluid to simulate the stratified charges. The equivalence ratio for the vortex
fluid ranged from 0 to infinity. Conclusions reached from this investigation of ignited kernel-vortex interaction includes:

1) Tests show that the undisturbed kernel radius increases linearly with time $t$ after ignition. The projected cross sectional flamefront area and the total heat release rate (as measured by the total chemiluminescence intensity) increase nonlinearly with $t$. Flame kernels of lean C$_3$H$_8$/air mixtures are somewhat slower to develop for the first 10 ms after ignition. However, at later times, the propane/air kernels have similar growth rates as the CH$_4$/air kernels. The measured kernel growth rates $dr/dt$ for flame kernels are consistent with established laminar burning velocities for these mixtures.

2) Interactions with a vortex can enhance significantly the laminar kernel growth rate. For example, for a 10 mm diameter vortex interacting with the $\phi=0.6$ CH$_4$/air kernel, the kernel radius is increased by a factor of $\sim$1.5; the projected reaction zone area increased by $\sim$2.3; and the burn rate increased by a factor of $\sim$3, when compared with an undisturbed kernel.

3) A vortex enhances the kernel growth most when it interacts with a small flame kernel (i.e., early kernel interaction). Again for the 10 mm diameter vortex interacting with the $\phi=0.6$ CH$_4$/air kernel, the increase in burning rate at 35 ms after time of spark is a factor of 2.65, 2.05, and 1.35 for an early, middle and later interaction, respectively.

4) Vortex strength ($U_T$) has a greater influence on kernel growth than vortex size ($d_0$).
5) On the leading edge of the invading vortex, which is positively curved and stretched, the combustion is intensified for methane/air kernel with sub-unity Lewis number, and diminished in propane/air kernel with Lewis number greater than one.

6) Lewis number flames tend to intensify the fluctuation of flame speed along the disturbed flame front, thus wrinkling and eventually breaking the vortex into several flame pockets, while the high Lewis number flames tend to smooth the disturbed flame front and inhibit multiple pocket formation.

7) Quantitative study on local/overall flame front curvature and local burning rates has shown the relation between an indicator of the local burning rates and the local flame curvature, and the trend lines match the expectation of asymptotic theory with low strain rate.

8) Distinct differences between methane kernel and propane kernel have been observed. Propane kernel has whisps at the vortex interface early in the interaction and regions of very low OH intensity.

9) For vortex core fluid with an equivalence ratio below the flammability limit, combustion of vortex is still observed.

10) For vortex core fluid composed of pure fuel, local region of stoichiometric mixture exists and combustion is observed to be very vigorous.
Bibliography


APPENDICES
**A.** This macro file outputs the area and the characteristic radius of the flame kernel. The images are ordered consecutively.

Macro 'area_measure-1 [a]';
Var
  i,nFiles: integer;
begin
  {ResetCounter;}
  SetOptions('Area,User2');
  nFiles:=GetNumber('Number of files in this folder: ',81,0);
  for i:=1 to 9 do begin
    Import('G:\t103\3_','i:1','.tif');
    SetScale(4.58,'mm',1);
    SetUser1Label('time(ms)');
    SetUser2Label('Radius(mm)');
    Invert;
    AutoThreshold;
    Measure;
    rUser1[i]:=1.0+i/4.5;
    rUser2[i]:=Sqrt(rArea[i]/3.14);
    Dispose;
  end;
  for i:=10 to 99 do begin
    Import('G:\t103\3_','i:2','.tif');
    SetScale(4.58,'mm',1);
    SetUser1Label('time(ms)');
    SetUser2Label('Radius(mm)');
    Invert;
    AutoThreshold;
    Measure;
    rUser1[i]:=1.0+i/4.5;
    rUser2[i]:=Sqrt(rArea[i]/3.14);
    Dispose;
  end;
  for i:=100 to nFiles do begin
    Import('G:\t103\3_','i:3','.tif');
    SetScale(4.58,'mm',1);
    SetUser1Label('time(ms)');
    SetUser2Label('Radius(mm)');
    Invert;
    AutoThreshold;
    Measure;
rUser1[i]:=1.0+i/4.5;
rUser2[i]:=Sqrt(rArea[i]/3.14);
   Dispose;
end;
{ShowResults;}
end
B. This macro file outputs the area of the burning frontline of the flame kernel.

Macro 'burning-front-1 [b]';
Var
  i,nFiles: integer;
begin
  {ResetCounter;}
  SetOptions('Mean,User1');
  nFiles:=GetNumber('Number of files in this folder:',81,0);
  for i:=1 to 9 do begin
    Import('G:\t103\3_',i:1,'.tif');
    SetUser1Label('burning area');
    Invert;
    AutoThreshold;
    Measure;
    SetThreshold(rMean[i]);
    MakeBinary;
    GetHistogram(0,0,255,255);
    rUser1[i]:=Histogram[255]*0.04767;
    SetPicName('d:\temp-yin\measurements\test_',i:3,'.tif');
    SaveAs;
    Dispose;
  end;
  for i:=10 to nFiles do begin
    Import('G:\t103\3_',i:2,'.tif');
    SetUser1Label('burning area');
    Invert;
    AutoThreshold;
    Measure;
    SetThreshold(rMean[i]);
    MakeBinary;
    GetHistogram(0,0,255,255);
    rUser1[i]:=Histogram[255]*0.04767;
    SetPicName('d:\temp-yin\measurements\test_',i:3,'.tif');
    SaveAs;
    Dispose;
  end;
  for i:=100 to nFiles do begin
    Import('G:\t103\3_',i:3,'.tif');
    SetUser1Label('burning area');
  end;
end;
C. This macro file outputs the products of the mean intensity and the area (in mm²) of the flame kernel as the integrate intensity of the kernel-vortex interaction region. The images are ordered consecutively.

Macro 'intensity-summation-1 [i]';
Var i, nFiles: integer;
begin
  {ResetCounter;}
  SetOptions('Area, Mean, User1');
  nFiles := GetNumber('Number of files in this folder:', 81, 0);
  for i := 1 to 9 do begin
    Import('G:\t103\3_', i:1, '.tif');
    SetUser1Label('intensity');
    SetScale(4.58, 'mm', 1);
    Invert;
    AutoThreshold;
    Measure;
    rUser1[i] := rArea[i] * rMean[i];
    Dispose;
  end;
  for i := 10 to 99 do begin
    Import('G:\t103\3_', i:2, '.tif');
    SetUser1Label('intensity');
    SetScale(4.58, 'mm', 1);
    Invert;
    AutoThreshold;
Measure;
   rUser1[i]:=rArea[i]*rMean[i];
   Dispose;
end;

for i:=100 to nFiles do begin
   Import('G:\t103\3_','i:3','.tif');
   SetUser1Label('intensity');
   SetScale(4.58,'mm',1);
   Invert;
   AutoThreshold;
   Measure;
   rUser1[i]:=rArea[i]*rMean[i];
   Dispose;
end;
{ShowResults;}
end
D.  
% This m-file is for the laser sheet intensity correction along the  
% Y(vertical) direction. The correction function is obtained by manually  
% measuring the OH flourescence intensity along the out rim of the  
% 2-D  
% undisturbed kernel image, and best-fit the vertical distribution.  

clear;

%img=imread('/afs/unity.ncsu.edu/users/y/yxiong/matlab/research/methane/k30-v20-a.tif');
img=imread('/afs/unity.ncsu.edu/users/y/yxiong/matlab/research/methane/k30-v19-a.tif');
%img=imread('/afs/unity.ncsu.edu/users/y/yxiong/matlab/research/propane/k30-v01-c.tif');
img_corr=img;
imshow(img, 65535);

% the following correction factor distribution is for the laser sheet in propane flame.  
for y=1:2,  
  I(y)=1.0;
end

%for y=4:190, % for methane  
for y=3:144,% for methane bak and propane  
  I(y)=1.635-(1.636-1.04)/(144-3)*(y-3); % for propane  
  %I(y)=2.111-(2.111-1.05)/(144-3)*(y-3); % for methane bak  
  % I(y)= 2.738-(2.738-1.00)/(190-4)*(y-4); % for methane  
end

%for y=191:275, % for methane  
%for y=145:200,% for methane bak  
for y=145:247, % for propane  
  %I(y)=1.025;% for methane bak  
  % I(y)=1.014;% for methane  
  I(y)=1.02; % for propane  
end

%for y=276:384, % for methane  
%for y=201:384,% for methane bak  
for y=248:384, % for propane  
  %I(y)=1.10+(1.85-1.10)/(384-201)*(y-201);% for methane bak  
  I(y)=1.012+(1.46-1.012)/(384-248)*(y-248); % for propane
% I(y)=1.025+(1.432-1.025)/(384-276)*(y-276);% for methane
end

for y=308:384,
    % I(y)=1;
end
%plot(I);

for x=1:578,
    for y=1:384,
        %img_corr(y,x)=min(65535, double(img(y,x))*I(y)*0.99);
        img_corr(y,x)=double(img(y,x))*I(y);
    end
end

imshow(img_corr);
% This m-file calculate the local curvature of the flame surface based on the
% input coordinate data

clear;

ohc; % get the corrected image data from the original image
img_corr(y,x)

% set the search path for data and image files
p=path;
p=path('/afs/unity.ncsu.edu/users/y/yxiong/matlab/research/methane/','p');
p=path('/afs/unity.ncsu.edu/users/y/yxiong/matlab/research/propane/','p');

[x1,y1,x0,y0,x2,y2,sign]=textread('propane_vortex.dat','%3d %3d %3d %3d %3d %3d %2d');

%[x1,y1,x0,y0,x2,y2,sign]

N = length(x1); % get the number of data groups
ints=zeros(1,N); % Array for local intensity integration
%ints=double(ints);
curv=zeros(1,N); % Array for local curvature

% Get the intensity integration along the flame front point by point
for i = 1 : N,
    % get the location of the center of the circle based on three-point on the front line
    [xc,yc]=cp(x1(i),y1(i),x0(i),y0(i),x2(i),y2(i));
    R=norm([x0(i),y0(i)]-[xc,yc]); % the radius of the local circle
    curv(i)=sign(i)/R; % the signed local curvature

    for r=1:20, %r is the index and the distance between (x0,y0) and the point for intensity
        % calculate the intensity integration locally
        % the intensity integration is defined as the summation of pixel intensities
        % along the radius( from (x0,y0) to (xc,yc)) for the distance of max(r) pixels width
        if sign(i) ==-1 % negative curvature, then integrate inwardly
            xr=x0(i)+(xc-x0(i))*(r/R);
        end
    end
end

E.
yr=y0(i)+(yc-y0(i))*(r/R); % (xr, yr) is the point for intensity integration
elseif sign(i) == 1 % positive curvature, then integrate outwardly
    xr=x0(i)*(1+r/R)-xc*(r/R);
    yr=y0(i)*(1+r/R)-yc*(r/R); % (xr, yr) is the point for intensity integration
end

% intensity summation
ints(i)=ints(i)+double(img_corr(round(yr),round(xr)));
end
end

plot(curv/0.108,ints/max(ints),'*'); % plot the ints vs. curv(mm^-1)
grid on; title('Local Intensity(normalized) vs. Signed Curvature');
ylabel('Integrated Intensity');
xlabel('Local curvature (mm^-1)');
shrink;

% end of the file
% This m-file is for local curvature calculation along the outline of an object
% within an black/white image. The object is described by black pixels in the
% image. The input images should be pre-processed.

clear;

% Read in the pre-processed image(black/white), and outline the boundary of the
% object
im=imread('testcircle.tif');
imeedge=edge(im); % getting the outline of the image
%imshow(im);
%figure,imshow(imeedge);

% Get the image features about the outline
stats=imfeature(imeedge, 'all');
N_pix=stats.Area; % number of nonzero pixels in the image, and it is pixel number on the outline
% Estimate the radius of the object based on object area and perimeter(stats.area)
R_obj=min(stats.Area/(2*pi),sqrt(stats.ConvexArea/pi));
r=max(floor(R_obj/6),2); % the sampling radius for local curvature calculation

% Curvature calculation on all pixels on the boundary
curv=zeros(1,N_pix); % initiate the array for local curvature;
im_curv=zeros(size(im)); % initiate the image of curvature distribution
n_lc=0; % the counter for number of less than 2 cross points

for i=1:N_pix,
    x0=stats.PixelList(i,1); y0=stats.PixelList(i,2);
    % Studied point on boundary

    % Find the cross points on the edges of the window of (2r+1) by (2r+1)
    n_cross=0; % initialize the total number of points that cross the window
    index_c=1;
    %xc=zeros(1,50); yc=zeros(1,50);
    % initialize the x-,y- coordinates for crossing points(pc
    pc=zeros(50,2); % p(x,y)
    % Note: matrix index is described like: (row, column)
    if i==129
disp('pause');
end
for xp=max(x0-r,1):min(x0+r,256),
    if (imedge(max(y0-r,1),xp)==0) % find one crossing point on
top line
    pc(index_c,1)=xp;pc(index_c,2)=max(y0-r,1);
    n_cross = n_cross+1; index_c = index_c+1;
    end
    if (imedge(min(y0+r,256),xp)==0) % find one crossing point on
bottom line
    pc(index_c,1)=xp;pc(index_c,2)=min(y0+r,256);
    n_cross = n_cross+1; index_c = index_c+1;
    end
end
for yp=max(y0-r+1,1):min(y0+r-1,256),
    if (imedge(yp,max(x0-r,1))==0) % find one crossing point on
left line
    pc(index_c,1)=max(x0-r,1);pc(index_c,2)=yp;
    n_cross = n_cross+1; index_c = index_c+1;
    end
    if (imedge(yp,min(x0+r,256))==0) % find one crossing point on
right line
    pc(index_c,1)=min(x0+r,256);pc(index_c,2)=yp;
    n_cross = n_cross+1; index_c = index_c+1;
    end
end
if n_cross>2 % if there are more than two crossing points
sw_cross=zeros(1,4); % initialize the cross point indicator
% [0,0,0,0] mean no
on four edges
ps=zeros(4,2); % points on the lines after shrinking
% First shrink the points on each window edge into one point
ind=find(pc(:,2)==max(y0-r,1)); % check the points on the top
line
if length(ind)>0 % there are cross points on this line
    sumc=0; % initialize the summation counter
    for j=1:length(ind),
        sumc=sumc+pc(ind(j),1); % add up the x- on this line
        pc(ind(j),:)=[0,0]; % black out this point for not
being recounted
    end
    ps(1,1)=sumc/length(ind); % x- for the shrunked point on
the top
\( \text{ps}(1,2) = \max(y_0 - r, 1) \); % y- for the shrinked point on the top
\( \text{sw}_\text{cross}(1) = \| \text{ps}(1,:) - [x_0, y_0] \| \); % the switch value is the distance to the center
end
ind = find(\text{pc}(:,2) == \min(y_0 + r, 256)); % check the points on the bottom line
if length(ind) > 0 % there are cross points on this line
sumc = 0; % initialize the summation counter
for \( j = 1: \text{length(ind)} \),
    \( \text{sumc} = \text{sumc} + \text{pc}(\text{ind}(j),1) \); % add up the x- on this line
    \( \text{pc}(\text{ind}(j),:) = [0,0] \); % black out this point for not being recounted
end
\( \text{ps}(2,1) = \text{sumc}/\text{length(ind)} \); % x- for the shrinked point on the bottom
\( \text{ps}(2,2) = \min(y_0 + r, 256) \); % y- for the shrinked point on the top
\( \text{sw}_\text{cross}(2) = \| \text{ps}(2,:) - [x_0, y_0] \| \); % the switch value is the distance to the center
end
ind = find(\text{pc}(:,1) == \max(x_0 - r, 1)); % check the points on the left line
if length(ind) > 0 % there are cross points on this line
sumc = 0; % initialize the summation counter
for \( j = 1: \text{length(ind)} \),
    \( \text{sumc} = \text{sumc} + \text{pc}(\text{ind}(j),2) \); % add up the y- on this line
    \( \text{pc}(\text{ind}(j),:) = [0,0] \); % black out this point for not being recounted
end
\( \text{ps}(3,1) = \text{sumc}/\text{length(ind)} \); % y- for the shrinked point on the left side
\( \text{ps}(3,2) = \max(x_0 - r, 1) \); % x- for the shrinked point on the left side
\( \text{sw}_\text{cross}(3) = \| \text{ps}(3,:) - [x_0, y_0] \| \); % the switch value is the distance to the center
end
ind = find(\text{pc}(:,1) == \min(x_0 + r, 256)); % check the points on the right line
if length(ind) > 0 % there are cross points on this line
sumc = 0; % initialize the summation counter
for \( j = 1: \text{length(ind)} \),
    \( \text{sumc} = \text{sumc} + \text{pc}(\text{ind}(j),2) \); % add up the x- on this line
    \( \text{pc}(\text{ind}(j),:) = [0,0] \); % black out this point for not being recounted
end
\begin{verbatim}

ps(4,2) = sumc/length(ind); % y- for the shrunked point on the bottom
ps(4,1) = min(x0+r, 256); % y- for the shrunked point on the bottom

sw_cross(4) = norm(ps(4,:) - [x0, y0]); % the switch value is the distance to the center

end

% find the first two cross points which are farest to the center point
ind = find(sw_cross); % find the index of these crossing points
if length(ind) == 2 % only two shrunked points left
    pc(1,:) = ps(ind(1),:);
    pc(2,:) = ps(ind(2),:); % the first two points of pc are the points for curvature calculation
end

if length(ind) >= 3 % there are more than two crossing points on the four sides of
    % mixing any two points whose distance is less than r/sqrt(2)
    if sw_cross(1) ~= 0 % there is a point on top
        if sw_cross(3) ~= 0 % there is a point on left side
            if norm(ps(1,:) - ps(3,:)) <= r/sqrt(2) % short distance between these two points
                ps(1,:) = mean([ps(1,:); ps(3,:)]); % the first point is the center point

                % between them
                sw_cross(1) = norm(ps(1,:) - [x0, y0]); % update the distance
            end
        end
    end
    if sw_cross(4) ~= 0 % there is a point on right side
        if norm(ps(1,:) - ps(4,:)) <= r/sqrt(2) % short distance between these two points
            ps(1,:) = mean([ps(1,:); ps(4,:)]); % the first point is the center point

            % between them
            sw_cross(1) = norm(ps(1,:) - [x0, y0]); % update the distance
        end
    end

end

end

end

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\end{verbatim}
if sw_cross(2)~=0 % there is a point on bottom
    if sw_cross(3)~=0 % there is a point on left side
        if norm(ps(2,:)-ps(3,:)) <= r/sqrt(2) % short distance between these two points
            ps(2,:)=mean([ps(2,:);ps(3,:)]); % the first point is the center point
        end
    end
end

if sw_cross(4)~=0 % there is a point on right side
    if norm(ps(2,:)-ps(4,:)) <= r/sqrt(2) % short distance between these two points
        ps(2,:)=mean([ps(2,:);ps(4,:)]); % the first point is the center point
    end
end

% window, and I want to delete two which is closest to the center
for j=1:2 % find the first two fairest crossing points to the center
    ind=find(sw_cross==max(sw_cross));
    pc(j,:)=ps(ind(1),:); % point ready for curvature calculation
    sw_cross(ind)=0; % black-out this point in indicator vector
end

if n_cross<2
    n_lc=n_lc+1;
    disp('one cusp found');
end

[x_cp, y_cp]=cp(x0, y0, pc(1,1), pc(1,2), pc(2,1), pc(2,2));
% curv(i)=1/sqrt((x0-x_cp)^2+(y0-y_cp)^2); % this the absolute value of the local curvature
curv(i)=1/norm([x0, y0]-[x_cp, y_cp]);

% Add sign of curvature based on original preprocessed image
if curv(i)~=0
    % xc=mean([pc(1,1), pc(2,1)]);
    % yc=mean([pc(1,2), pc(2,2)]);
    xc=x0+(x_cp-x0)*curv(i)*1;
    yc=y0+(y_cp-y0)*curv(i)*1; % one step (1/R) towards the center
    if im(round(yc), round(xc))==0 % it is black inside the circle
        curv(i)=-1*curv(i);
    end
end
im_curv(y0, x0)=curv(i);
end

sum(abs(curv))/length(curv), 1/R_obj, length(find(curv>0))
E_bending=sum(curv.^2)/length(curv)
% curv=(curv-min(curv))/(max(curv)-min(curv))*255;
for i=1:N_pix,
    % x0=stats.PixelList(i,1); y0=stats.PixelList(i,2);
    % im_curv(y0, x0)=curv(i);
end
im_curv=(im_curv-min(curv))/(max(curv)-min(curv));
figure, imshow(im_curv);
% plot(curv);

G.
% This m-file follows the insv.m to calculate the averaged curvature and local
% intensity relation. It uses the resulting arrayes of insv.m: curv, ints

% get the curvature scan range and step
Cstart=min(curv);
Cstop=max(curv);
Cstep=(Cstop-Cstart)/20; % this is the step pace
for c=cstart:cstep/2:cstop,
i=find(curv<=(c+cstep/2) & curv>(c-cstep/2)); % get the index of points in the subsection
L=length(i);

if L>0 % there are points inside this subsection
    c_avg=0; in_avg=0; % initialize the average value of curvature and intensity
    for j=1:L,
        c_avg=c_avg+curv(i(j))/L; % acumulate and average the curvature within the subsection
        in_avg=in_avg+ints(i(j))/L; % acumulate and average the intensity
    end

    curv_avg=[curv_avg,c_avg]; % append it into an array
    ints_avg=[ints_avg,in_avg];
end

end

figure;
plot(curv_avg/0.108, ints_avg/max(ints_avg),'o');
grid on; title('Local Intensity(normalized) vs. Signed Curvature');
ylabel('Integrated Intensity');
xlabel('Local curvature (mm^-^1)');

% save it in a result file for post-processing
fid = fopen('c_i_propane.dat','w');
fprintf(fid,'%9.6f %8.6f
',
[curv_avg/0.108;ints_avg/max(ints_avg)]);
fclose(fid);

% end of file