ABSTRACT

DANBY, SEAN JAMES DENNISON. Experimental Quantification of Transient Stretch Effects from Vortices Interacting with Premixed Flames. (Under the direction of Dr William Roberts.)

The understanding of complex premixed combustion reactions is paramount to the development of new concepts and devices used to increase the overall usefulness and capabilities of current technology. The complex interactions which occur within any modern practical combustion device were studied by isolating a single turbulent scale of the turbulence-chemistry interaction. Methane-air flame equivalence ratios ($\phi = 0.64$, 0.90, and 1.13) were chosen to observe the mild affects of thermo-diffusive stability on the methane-air flame. Nitrogen was used as a diluent to retard the flame speeds of the $\phi = 0.90$, and 1.13 mixtures so that the undisturbed outwardly propagating spherical flame kernel propagation rates, $dr_f/dt$, were approximately equal. Five primary propane equivalence ratios were utilized for investigation: $\phi = 0.69$, 0.87, 1.08, 1.32, and 1.49. The choice of equivalence ratio was strategically made so that the $\phi = 0.69/1.49$ and $\phi = 0.87/1.32$ mixtures have the same undiluted flame propagation rate, $dr_f/dt$. Therefore, in the undiluted case, there are three flame speeds (in laboratory coordinates, not to be confused with burning velocity) represented by these mixtures. Three vortices were selected to be used in this investigation. The vortex rotational velocities were measured to be 77 cm/s, 266 cm/s and 398 cm/s for the “weak”, “medium” and “strong” vortices, respectively. Ignition of the flame occurred in two ways: (1) spark-ignition or (2) laser ignition using an Nd:YAG laser at its second harmonic ($\lambda = 532$ nm) in order to quantify the effect of electrode interference.
Accompanying high-speed chemiluminescence imaging measurements, instantaneous pressure measurements were obtained to give a more detailed understanding of the effect of vortex strength on the overall flame speed and heat release rate over an extended time scale and to explore the use of a simple measurement to describe turbulent mixing. Further local flame-vortex interface analysis was conducted using non-invasive laser diagnostics, such as particle image velocimetry and planer laser induced fluorescence of the OH radical. The dependence of heat release rate on temperature provides an estimation of the strain rate dependence of the reaction rate.

Findings include a direct effect of stretch rate on temperature along the flame reaction zone; however the trend depends on thermo-diffusive stability. For both fuels at a thermo-diffusively unstable mixture, by increasing the vortex strength, the stretch rate increases, while the temperature decreases. The thermo-diffusively stable flames (propane with $\phi < 1.08$) generally show an opposite trend to the unstable flames. By increasing the vortex strength, the thermo-diffusively stable flames tend to have a reduction in stretch rate, which allows an increase in temperature along the flame-vortex interface. Overall, an increase in stretch rate causes all flames to reduce the average reaction zone temperature regardless of thermo-diffusive stability. The formation of surface structure corrugation in thermo-diffusively unstable flames requires an external (to the flame) perturbation. This perturbation is generally in the form heat loss due to either a high stretch rate from an aerodynamic perturbation (vortex) or a localized thermodynamic heat sink (electrodes).
Experimental Quantification of Transient Stretch Effects from Vortices Interacting with Premixed Flames

by

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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

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APPROVED BY:

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William Roberts    Tarek Echekki
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________________________  ________________________
Jack Edwards     Richard Gould
Dedicated to my parents, whose unwavering support throughout the years has provided me with the moral and spiritual fortitude necessary to accomplish anything.
Biography

Born in Lakenheath, England in 1978, Sean was the son of an Air Force pilot and at the age of only three months, took his first trip in an airplane; specifically a C-130 military transport, to Ramstein AFB in Germany. After two years in Germany, Sean was brought to where he considers home; Alamogordo, New Mexico. As he matured, he developed an interest in aircraft, evident by the large number of plastic models hanging from the ceiling in his room. Also as a young child, Sean was fascinated by fire and thanks to an ingenious remedy by his parents where he was allowed to conduct a supervised pyromaniac release, had his fire-loving tendencies subdued before significant damage could be done to people or property.

Throughout high school, Sean developed an interest in science and math. His biology teacher, Kevin Blackstone presented a fascinating microcosm, where concentration gradients and surface tension rule. Sean enjoyed this topic so much, he decided to pursue it further in college, however the allure of machines had not been satisfied and within one month of attending his undergraduate institution, he changed his major to mechanical engineering.

Graduating from New Mexico Tech within four years, (a full year and a half above the average) Sean decided to pursue further education. Accepted to North Carolina State University in the Fall of 2002, the challenges of graduate school became evident on the first day of class with Dr Hassan Hassan’s fluid mechanics course. Though it was a challenge, Sean’s successful completion of this course showed him the significant differences between his undergraduate and his graduate educations. During the same semester, Dr Tarek Echekki’s combustion class caught his attention and in the Spring of 2003, Sean decided to
pursue a thesis in computational combustion. He successfully completed his Master’s degree with Dr Tarek Echekki in the fall of 2004 in mechanical engineering with a minor in mathematics.

Congruently when completing his master’s degree in the Fall of 2004, Sean started research on his PhD work with Dr William Roberts. Fortunate to have Dr Stephen Marley willing to assist him in the preparatory stages of his research, Sean was able to progress relatively quickly to assemble the complex task at hand. Plagued by uncooperative equipment, much of the research was forced in unplanned directions. Thanks to the dedication of Dr Roberts and Dr Tiegang Fang, Sean’s research was able to continue and culminate into the work you see here.
Acknowledgements

This work would not have been possible without the help of a large number of people. First I’d like to thank my committee for being a part of this procedure and taking time out of their busy schedules to oversee this process in such a professional manner. I would like to specifically thank Dr Tarek Echekki for the extensive guidance during my master’s program at State and the continued advice through my PhD. I would also like to thank Dr William Roberts for providing an excellent project and being a very capable researcher with immense knowledge, which he would never hesitate to share with me. Finally I would like to thank Dr Drake and Dr Fansler from GM R&D for their extensive knowledge and assistance through advice and equipment.

I would also like to thank my colleagues at the AERL. First, the extensive help of Dr Stephen Marley, who patently took time out of his last semester to help explain the intricacies of this experimental process and without whom I would have spent significantly more time learning. Also, I would like to thank Dr Tiffany Yelverton for always bringing a sense of humor to the lab and making work a lot of fun. Furthermore I would like to thank Ranjith Kumar Abhinavam Kailasan for bringing an excellent world perspective to my life and allowing me to see things differently.

Finally, I would like to thank the multitude of people outside of my work, who have brought me here. First, my parents (all four of them) without whom I would not be the person I am today and to whom I owe everything. Thank you for being so kind, helpful and understanding. Next, I’d like to thank my friends, Noah, Jared and Mike for always lending an ear when I was in need and providing the necessary distractions when I was sick of
working. I’d also like to thank Dawn for pushing me to pursue this degree and to whom I wish the very best in the future. Finally, I want to thank Meg for being there for me at all times of the day or night with an open heart and an open mind. Thank you for all you have done for me during this uncertain and chaotic time and thank you for your immense patience toward the end of this phase of my life and the start of ours.
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1 Introduction

1.1 Background and Review

The understanding of complex premixed combustion reactions is paramount to the development of new concepts and devices used to increase the overall usefulness and capabilities of current technology. The evolution from laminar spherically propagating flames to turbulent chemistry is a logical and necessary process to study the complex interactions which occur within any modern practical combustion device [1]. Due to its non-laminar behavior, fully turbulent combustion is difficult to reproduce experimentally with the accuracy required to quantify the multi-scale nature of the flow. Analysis of kernel-vortex interactions using laminar flows to represent the turbulent stretching induced upon onset of high curvature has become a well respected answer to this problem.

As previously implied, experimental research involving turbulent chemistry requires choosing a repeatable representation of turbulence. Kernel-vortex interactions have been studied in detail and continue to be an area of interest for combustion researchers [2]. Many past experiments have focused on steady combustion using a variety of burner types [3, 6]. Previous research into freely propagating flame kernels interacting with a vortex has shown the high sensitivity to curvature expressed by the flame’s propagation rate [2]. Further analysis into the flame geometry and vortex effectiveness, performed by Roberts et al [7, 8] found a clear separation between wrinkled and pocketed flames. Their continued research
found a dependence on the vortex characteristics and time of interaction. A disturbed flame could exist in both the flamelet regime and distributed reaction zone regime [8].

Several other investigations have considered premixed flame-vortex interactions. Bell et al. performed numerical simulations of flat, nitrogen-diluted premixed methane-air flames interacting with a vortex pair of similar characteristics as experimentally investigated by Nguyen and Paul, whose work considered a rich methane-air flame and indicated dramatic changes in CH and OH concentrations as a result of the interaction [9, 10]. The results of Bell et al. agree with Nguyen and Paul with respect to the marked decrease in CH concentration. Therefore, a strong coupling between the flow field and chemistry was observed [11], suggesting the need for more detailed analysis of the effect of unsteady stretch on flame propagation, especially for incorporation into future numerical models. More recently, Sinibaldi et al. tested the theory of flame stretch, which relates laminar flame speed to flame stretch rate, during unsteady wrinkling of methane-air and propane-air flames [12]. They chose to investigate the interaction of a flat laminar flame with a vortex toroid of varying strength. Spatially and temporally resolved stretch rate measurements were made along the flame surface using a simultaneous PIV/OH-PLIF diagnostic in conjunction with high-speed shadowgraph imaging. The experimental trends support the well established theory of flame stretch, although measurements of the Markstein number support the postulation that separate Markstein numbers should be identified for the individual strain and curvature contributions to stretch rate [12-14].

The research described up to this point has focused on interactions between a vortex and a planar flamefront that does not impose its own time-varying curvature along the flame
surface. In internal combustion engines [15-17], spark-ignition and the growth of the resulting flame kernel introduces another time-varying flame stretch as the small flame kernel radius expands. This early stage of flame development just after ignition is when the flame is most susceptible to stretch rates imposed by the turbulent flowfields, resulting in flame speed enhancement or local or global quenching [16]. Maximizing the repeatability of the ignition process and enhancing the rate of early flame kernel growth is important in minimizing misfires and partial burn cycles in IC engines, especially at the high levels of charge dilution that are desirable to minimize pumping losses in homogeneous-charge SI engines and to minimize NO production in stratified-charge SI engines. Flame kernel-vortex interactions provide the opportunity to study flame stretch effects in a simplified, repeatable laminar configuration. The transient stretch of the expanding flame kernel can be varied with flame kernel size, composition, and flame speed. Each vortex size and strength can simulate a specific length and velocity scale of the continuum of scales that comprise a turbulent flow field.

The effects of transient stretch on “young” spark-ignited flame kernels during the transition period between ignition and fully developed flames have been analyzed experimentally by the interaction of spherical flame kernels with laminar vortices (primarily by Roberts and coworkers [8, 18, 19]). Their results highlight the added complexity of flame kernel-vortex interactions over the earlier planar flame-vortex configuration. The first flame kernel-vortex interactions were observed using OH-PLIF to determine the degree of flame wrinkling and the ability of vortices of varying size and strength to globally quench combustion in a lean atmospheric pressure methane-air flame kernel [18]. Depending on the
vortex size and strength and the time of the initial flame-vortex interaction, the disturbed
flame existed in either the flamelet regime (continuous reaction zone) or distributed reaction
zone regime (co-existence of reactants and products). Global extinction of the flame kernel
was observed with large vortex sizes interacting with small flame kernels. Localized
flamefront extinction occurred for a range of vortex sizes and strengths and a range of flame
kernel sizes. Xiong et al. [18, 19] investigated the two-dimensional structure of the vortex
interactions with spark-ignited lean methane-air and lean propane-air mixtures at atmospheric
pressure using high-speed imaging of CH* and OH* emission, as well as single-shot OH-
PLIF diagnostics. Augmentation of kernel growth rates, including Lewis number effects,
were studied using four characteristic vortex sizes and three different vortex strengths for
each of the four sizes. Charge stratification was also studied with a lean ($\Phi = 0.6$) methane-
air kernel interacting with vortices composed of reactants ranging from pure air to pure fuel.
This mimics local enrichment conditions near the spark electrode in direct injection lean burn
engines. Charge stratification suppressed combustion with very lean vortices (outside the
flammability limit) but enhanced combustion with fuel-rich vortices as expected [19].

Detailed modeling of flame kernel-vortex interactions (2-D direct numerical simulations
and detailed H₂-air chemical kinetics) by Kolera-Gokula and Echekki [20] found
qualitatively similar results when compared to prior experiments. Depending upon the flame
kernel size and the vortex size and strength, two regimes were identified: 1) enhancement of
flame surface area and volumetric fuel consumption and, 2) global flame kernel extinction.
Direct model-experiment comparisons are not possible in this study, due to the differences in
fuels and conditions.
1.2 Specific Aim

With the insights gained from previous experiments, a wider array of the effect of unsteady stretch is desired, specifically with the aero-thermodynamic response of an externally perturbed thermo-diffusively stable or unstable premixed flame. The objective of this work is to obtain a quantitative classification of the effect of unsteady stretch on premixed combustion augmentation. The aerodynamic and thermodynamic threshold between combustion augmentation and global extinction is of particular interest, due to the direction application possible with practical combustion devices. Also of interest is a pressure dependent classification of the effect of thermo-diffusivity and increased stretch rate. Presented below, the experimental combustion device, fuel mixtures and vortex generation are described, followed by three main chapters describing the varied experiments: development of the necessary parameter space through high-speed imaging, and analysis of vortex effects with effective radius measurements and calculated pressure-dependent reactant consumption rate; local measurements from laser diagnostics for the quantification of stretch effects; and the quantification of physical flame perturbation from ignition electrodes through the study of laser ignition.

1.3 Combustion Chamber and Vortex Generator

For all the experiments described in the following chapters, the combustion chamber, vortex generator and flow controllers remained constant. The combustion chamber was identical to that used by Marley and Roberts [21] (Figure 1.1a). As seen in Fig. 1.1b, the kernel was ignited and allowed to propagate for a specific duration before the top of the
kernel was subjected to the vortex. Four large solenoid exhaust valves located at the bottom of the chamber sealed the vessel during the preparatory stage of each experimental run. The exhaust valves opened approximately 850 ms prior to ignition to allow vortex development and to ensure the burned-gas pressures did not exceed the operational limitations of the equipment. The reactant mixture was metered with calibrated mass flow controllers which provided accuracies of +/- 0.3% for the fuel flow rate (methane, 99.0% purity) and +/- 1.1% for the air and diluent (nitrogen) flow rates. In order to achieve a homogeneous reactant mixture, the combustion chamber was purged with ten chamber volumes of fresh reactants before closing the exhaust valves and allowing any motion to dissipate prior to initiating the experiment. This procedure was proven to provide very repeatable flame propagation rates which are crucial for this highly transient flame [21].

Ignition of the flame occurred in two ways: (1) spark-ignition or (2) laser ignition using an Nd:YAG laser at its second harmonic ($\lambda = 532$ nm). The spark ignition system utilized inductive discharge and interfaced with a computer to easily change the spark energy (~100 mJ) and arc duration (nominally 2 ms). The laser ignition will be discussed in detail in Section 4.2.

The generation of the vortex utilized an Animatics Smart Motor coupled to a linear actuator, which displaced fluid in an aluminum piston in a stainless steel cylinder sealed with iron piston rings. The opening of the cylinder was comprised of a sharp edged orifice with a diameter of 10 mm to allow detachment of the vorticity generated from the displacement of the piston, which was completely controlled through the Animatics software. In each case, the displacement was held constant 1.0 mm while the velocity was varied to observe a range
of vortex strengths. The distance from the orifice to the ignition site was held constant at 100 mm, resulting in an approximately 25% increase in vortex core-to-core diameter during propagation.

1.4 Flame Properties

Undiluted methane-air flame equivalence ratios ($\phi = 0.64, 0.90, \text{ and } 1.13$) were chosen to observe the mild affects of thermo-diffusive stability on the methane-air flame. These equivalence ratios, however, have very different laminar burning velocities ($S_L$) and flame thickness ($\delta_D$). Therefore, nitrogen was used as a diluent to retard the flame speeds of the $\phi = 0.90, \text{ and } 1.13$ mixtures so that the undisturbed outwardly propagating spherical flame kernel propagation rates, $dr/dt$, were approximately equal. The associated flame and mixture properties utilized in this work for methane are listed in Table 1.1. Calculation of the unstretched laminar burning velocity, $S_{L,\infty}$, was accomplished using linear regression of the flame propagation rate versus flame stretch rate ($K$) extrapolated to zero stretch ($K = 0$) [21, [27-29].

The flame response to stretch using a heavier hydrocarbon fuel (relative to methane) was also desired since it is more closely related to fuels primarily used in practical applications. As a result, propane was chosen as the “heavy” hydrocarbon fuel for investigation using flame kernel-vortex interactions. The mixture conditions for the propane-air flames were chosen so that the effects of chemistry could be studied independent of flame speed. Five primary equivalence ratios were utilized for investigation: $\phi = 0.69, 0.87, 1.08, 1.32, \text{ and } 1.49$. The choice of equivalence ratio was strategically made so that the $\phi = 0.69/1.49$ and $\phi =$
0.87/1.32 mixtures have the same undiluted flame propagation rate, \( \text{dr}/\text{dt} \). Therefore, in the undiluted case, there are three flame speeds (in laboratory coordinates, not to be confused with burning velocity) represented by these mixtures. This investigation focused on two of those flame speeds with these five mixtures, labeled “low” and “high.” To achieve the low flame speed, nitrogen was used as a diluent to retard the flame speeds of the \( \phi = 0.87/1.08/1.32 \) mixtures so that the flame propagation rates equal that of \( \phi = 0.69/1.49 \) for the case of an undisturbed outwardly propagating spherical flame kernel. For the high flame speed, which excludes \( \phi = 0.69/1.49 \) since it was not desired to use an oxidizer mixture with more than 21% O\(_2\), the \( \phi = 0.87/1.32 \) mixtures were used undiluted, and the \( \phi = 1.08 \) mixture was diluted to match this flame propagation rate. The relevant flame and mixture properties for the low and high flame speeds are given in Table 1.2 and Table 1.3, respectively.

The flame propagation rates used to obtain proper dilution levels for both fuels were compared using well established spherical flame kernels and therefore were not subject to ignition effects which will be different for each mixture composition. Values for the Markstein number, \( \text{Ma} \), and density ratio, \( \rho_u/\rho_b \), were measured in the same apparatus utilizing the method presented by Marley and Roberts [21], with the results in good agreement with recent literature [22-27].

### 1.5 Vortex Strength and Interaction Time

The classification of interaction time, based on when the vortex first affects flame propagation, is accomplished by assigning three regimes of interaction: early, medium, and late [18]. An early interaction occurs when the ratio of the kernel diameter to vortex diameter
is <1 at the time of first visible interaction. A late interaction is defined when this first interaction occurs for a kernel to vortex diameter ratio >2. Any case falling in between these definitions (1< kernel-vortex ratio <2) is labeled a medium interaction.

PIV measurements were carried out over a wide range of vortex strengths, and three vortices were selected to be used in the flame kernel-vortex investigation. The “weak” vortex rotational and translational velocities were measured to be 77 cm/s and 85 cm/s, respectively. Similar analyses performed with the “medium” and “strong” vortex cases revealed rotational/translational velocities of 266/255 cm/s and 398/351 cm/s, respectively. The rotational velocity is termed the vortex strength since it will determine the stretch rate imposed upon the flame surface [30].

In order to provide a common measure of the vortex effect on any flame front [31], the rotational velocity, $U_{\theta}$, was non-dimensionalized by the unstretched laminar burning velocity, $S_{L,\infty}$, while a characteristic vortex length scale (cylinder exit diameter), $d_o$, was non-dimensionalized by the characteristic flame thickness, $\delta_D$. Figure 1.2 indicates the non-dimensional vortex strengths and sizes for the vortices and reactant mixtures investigated.
Table 1.1: Properties for CH₄-O₂-N₂ flames at 300K and 1 atm.

<table>
<thead>
<tr>
<th>Property</th>
<th>φ = 0.64</th>
<th>φ = 0.90</th>
<th>φ = 1.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Fuel</td>
<td>6.30</td>
<td>6.68</td>
<td>8.00</td>
</tr>
<tr>
<td>O₂/(O₂+N₂)</td>
<td>0.21</td>
<td>0.159</td>
<td>0.154</td>
</tr>
<tr>
<td>Molecular Diffusivity of CH₄-N₂, Dₜ</td>
<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>[cm²/s]</td>
<td></td>
<td></td>
<td>0.21 (O₂-N₂)</td>
</tr>
<tr>
<td>Thermal Diffusivity, α</td>
<td>0.225</td>
<td>0.225</td>
<td>0.225</td>
</tr>
<tr>
<td>[cm²/s]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lewis Number, Le</td>
<td>0.98</td>
<td>0.98</td>
<td>1.07</td>
</tr>
<tr>
<td>Unstretched Laminar Burning Velocity, Sₜ,∞</td>
<td>9.38</td>
<td>10.32</td>
<td>13.34</td>
</tr>
<tr>
<td>[cm/s]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density Ratio, ρu/ρb</td>
<td>4.51</td>
<td>5.57</td>
<td>5.48</td>
</tr>
<tr>
<td>Markstein Number, Ma</td>
<td>-0.10</td>
<td>0.385</td>
<td>1.31</td>
</tr>
<tr>
<td>Flame Thickness, δD=Du/Sₜ,∞</td>
<td>0.245</td>
<td>0.223</td>
<td>0.172</td>
</tr>
<tr>
<td>[mm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalence Ratio, $\phi$</td>
<td>0.69</td>
<td>0.87</td>
<td>1.08</td>
</tr>
<tr>
<td>-------------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>% Fuel</td>
<td>2.82</td>
<td>2.97</td>
<td>3.34</td>
</tr>
<tr>
<td>$O_2/(O_2+N_2)$</td>
<td>0.21</td>
<td>0.176</td>
<td>0.160</td>
</tr>
<tr>
<td>Molecular Diffusivity $C_3H_8-N_2$, $D_u$ [cm$^2$/s]</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Molecular Diffusivity $O_2-N_2$ [cm$^2$/s]</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Thermal Diffusivity, $a$ [cm$^2$/s]</td>
<td>0.210</td>
<td>0.209</td>
<td>0.208</td>
</tr>
<tr>
<td>Lewis Number, $Le$</td>
<td>1.91</td>
<td>1.90</td>
<td>0.99</td>
</tr>
<tr>
<td>Laminar Burning Velocity, $S_{L,\infty}$ [cm/s]</td>
<td>21.47</td>
<td>18.85</td>
<td>18.34</td>
</tr>
<tr>
<td>Markstein Number, $Ma$</td>
<td>4.52</td>
<td>3.48</td>
<td>2.66</td>
</tr>
<tr>
<td>Flame Thickness, $D=Du/S_{L,\infty}$ [mm]</td>
<td>0.0512</td>
<td>0.0584</td>
<td>0.0600</td>
</tr>
</tbody>
</table>
### Table 1.3: Properties for “high” flame speed C<sub>3</sub>H<sub>8</sub>-O<sub>2</sub>-N<sub>2</sub> flames at 300K and 1 atm.

<table>
<thead>
<tr>
<th>Property</th>
<th>Equivalence Ratio, φ</th>
<th>0.87</th>
<th>1.08</th>
<th>1.32</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Fuel</td>
<td>0.87</td>
<td>3.53</td>
<td>3.98</td>
<td>5.25</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt;/(O&lt;sub&gt;2&lt;/sub&gt;+N&lt;sub&gt;2&lt;/sub&gt;)</td>
<td>1.08</td>
<td>0.21</td>
<td>0.192</td>
<td>0.21</td>
</tr>
<tr>
<td>Molecular Diffusivity C&lt;sub&gt;3&lt;/sub&gt;H&lt;sub&gt;8&lt;/sub&gt;-N&lt;sub&gt;2&lt;/sub&gt;, D&lt;sub&gt;u&lt;/sub&gt; [cm&lt;sup&gt;2&lt;/sup&gt;/s]</td>
<td>1.32</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Molecular Diffusivity O&lt;sub&gt;2&lt;/sub&gt;-N&lt;sub&gt;2&lt;/sub&gt; [cm&lt;sup&gt;2&lt;/sup&gt;/s]</td>
<td></td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Thermal Diffusivity, α [cm&lt;sup&gt;2&lt;/sup&gt;/s]</td>
<td></td>
<td>0.207</td>
<td>0.205</td>
<td>0.199</td>
</tr>
<tr>
<td>Lewis Number, Le</td>
<td></td>
<td>1.88</td>
<td>0.98</td>
<td>0.95</td>
</tr>
<tr>
<td>Laminar Burning Velocity, S&lt;sub&gt;L,∞&lt;/sub&gt; [cm/s]</td>
<td></td>
<td>32.39</td>
<td>31.00</td>
<td>29.60</td>
</tr>
<tr>
<td>Markstein Number, Ma</td>
<td></td>
<td>3.73</td>
<td>2.90</td>
<td>0.26</td>
</tr>
<tr>
<td>Flame Thickness, δ&lt;sub&gt;D=Du/SL,∞&lt;/sub&gt; [mm]</td>
<td></td>
<td>0.0340</td>
<td>0.0355</td>
<td>0.0372</td>
</tr>
</tbody>
</table>
Figure 1.1: Drawings of experimental configuration, showing (a) a 3D isometric cutout of the combustion chamber with optical access, (b) the piston-cylinder and (c) the orientation of the kernel-vortex interaction. Note: Ignition electrodes were removed for the laser ignition experiment (see Chapter 4).
Figure 1.2: Non-dimensional vortex strength versus size (Borghi diagram) for the C₃H₈-O₂-N₂ and CH₄-O₂-N₂ flames and vortices investigated.
2 Transient Stretch Effects on Flame Speed and Reactant Consumption Rate through High-Speed Imaging and Pressure Measurements

2.1 Introduction

High-speed chemiluminescence imaging was used to visualize each interaction, allowing measurement of instantaneous flame kernel radius and identifying regions of intensified combustion or local extinction during the interaction with a vortex. Simultaneously, the chamber pressure was measured and used to calculate the laminar flame speed (relative to the undisturbed flame kernel) at times where the kernel size exceeded the imaging field of view. It is desirable to be able to categorize the affect of turbulence on a premixed flame using a readily available diagnostic. Pressure measurements provide global information which may contain sufficient variation to indicate flame augmentation.

Determination of the laminar burning velocity for each flame was accomplished as follows. Assuming the wall effects of the combustion chamber were negligible at times near ignition and the combustion chamber was a closed sphere, the flame speed can be expressed in terms of the rate of pressure increase as [28]:

\[
S_b(P) = R \left[ 3\gamma \left( 1 - \frac{\rho_b}{\rho_u} \right)^{1/3} \left( \frac{p}{p_0} \right)^{1+1/\gamma} \left( 1 - \frac{p}{p_0} \right)^{-1/\gamma} \right]^{2/3} \frac{d(p/p_0)}{dt},
\]

where \( R \) is the chamber radius, \( p \) is the chamber pressure, \( \rho \) is the gas density, \( \gamma \) is the polytropic exponent and the subscripts \( u, b \) and \( o \) denote unburned, burned and initial
conditions respectively. Likewise, the effective radius determined from chemiluminescence images can be used to calculate the flame speed using the following differential:

\[ S_f(r_f) = \frac{dr_f}{dt} \]  \hspace{1cm} (2.2)

Using equations 2.1 or 2.2, the laminar burning velocity is then calculated using [28, 29, 32]:

\[ S_L = S_b / (\rho_u / \rho_b) \]  \hspace{1cm} (2.3)

In order to quantify the effects of stretch on the undisturbed kernel, the laminar burning velocity, calculated from a vortex-affected kernel was normalized by that of the undisturbed kernel at the same equivalence ratio and dilution level. This comparison between experimental conditions is considered the relative increase in reactant consumption rate.

Particular focus has been placed on extending the results of past experimental work in flame kernel-vortex interactions to include stronger vortices [8, 18, 19]. For example, the weakest vortex in this investigation corresponded to the strongest vortex studied by Xiong et al. [8, 18, 19]. Therefore, the present work probes new interactions with stronger vortices while isolating chemistry effects by controlling the characteristic flame propagation rates through \( \text{N}_2 \) dilution.

### 2.2 Experimental Setup

Shown in Figure 2.1, the experimental setup for this investigation required the use of a high-speed camera, pressure transducers and a multitude of data acquisition systems. The ignition system, combustion chamber, vortex generator and array of reactant mixtures
remained constant for this experiment. Primary control of the timing and initiation of the experiment was conducted with a custom-designed LabVIEW program.

2.2.1 High-Speed Imaging

Spark-ignited flame kernel-vortex interactions have been investigated using broadband high-speed chemiluminescence imaging primarily of CO2*/CH*/OH* emission. A Kodak EKTAPRO model 4540 high-speed camera was lens-coupled to an Imco ILS-3 intensifier with a 105 mm UV-Nikkor lens to facilitate imaging at framing rates up to 4,500 frames per second over a 95.7 mm wide by 100 mm high field of view.

An isodata thresholding algorithm was applied to each image to outline the flame boundary. The projected area of the flame kernel was measured and an effective kernel radius, $r_e$, was then calculated assuming spherical symmetry. During many interactions the disturbed flame surface was non-spherical, but since the effective radius simply scales with the projected area, it provides a basis for comparison between cases and to previous work [8, 18, 19]. This combination of high-speed imaging and flame front tracking allows the flame’s response to stretch to be analyzed during the early vortex flame interaction when they are within the camera field of view.

2.2.2 Pressure Measurements

Accompanying the imaging measurements, instantaneous pressure measurements were obtained to give a more detailed understanding of the effect of vortex strength on the overall reactant consumption rate over an extended time scale. Although the actual experimental chamber is not closed, the mass lost has been determined to be less than 3% of the total mass
of the system between 200 and 250 ms after spark ignition. Therefore the system is approximately isochoric. The measurements were obtained using two Kulite Semiconductor pressure transducers, one calibrated to a maximum of 35 kPa-gauge and the other to 690 kPa-absolute, which allowed simultaneous observation of small-scale and large-scale global variations in pressure. The voltage signals were filtered using a third order Butterworth digital filter in LabVIEW. By observing a minimum of five undisturbed kernels for each equivalence ratio studied, the relative error of the global pressure was found to be within 2.5%, while the relative error of the small-scale measurements was found to be within 10% for times less than 150 ms for the methane and 100 ms for the propane.

2.3 Results

2.3.1 Undisturbed Flame Kernels

Since the methane $\phi = 0.90$ and $\phi = 1.13$ flames were diluted with nitrogen to provide the same flame speed as the $\phi = 0.64$ case, the undisturbed chemiluminescence flame kernel sequences are necessarily nearly identical, showing very little difference between lean and rich flames, as seen in Figure 2.2. Given the relatively slow flame speeds of the methane flame, the effect of buoyancy is present, causing the propagation rate of the upper hemisphere to be as much as 30% higher than the lower half of the kernel by the time the kernel has reached the edge of the field of view as seen in Figure 2.3 (corresponding to a diameter of approximately 96 mm). Also, flow disturbance and heat loss due to the electrodes introduces a dimple on both sides of the flame, resulting in a local sign change in the curvature, defined to be positive when the flame is concave to the hot products. The
average methane flame propagation rates, measured from ignition until the flame reaches the image edge, for the $\phi = 0.64$, 0.90, and 1.13 undisturbed cases were 55.7 cm/s, 58.7 cm/s, and 61.4 cm/s, respectively.

Contrary to methane, the undisturbed propane flames show variations in the structure of the flame as the mixture is changed from lean to rich. From Table 1.2, it is seen that the $\phi = 1.32$ and $\phi = 1.49$ mixtures are thermo-diffusively unstable, determined by a negative Markstein number, and therefore will have the propensity to form wrinkled or cellular flame structures under any perturbation. The other mixtures, thermo-diffusively stable, are able to dampen out flame surface disturbances but will do so to a lesser degree as the Markstein number decreases, which is observed with increasing equivalence ratio [33]. To illustrate this point, Figure 2.4 shows chemiluminescence images of both a fuel-lean ($\phi = 0.87$, stable) and a fuel-rich ($\phi = 1.32$, unstable) undisturbed outwardly propagating propane flame kernel diluted to the slow flame speed. The stable flame possesses a very smooth flame surface, while the unstable flame quickly forms wrinkles which will grow and then multiply to eventually form a cellular flame.

Unstretched laminar burning velocity ($S_{L,\infty}$) was calculated using the methods of Marley and Roberts [21] for both flames and used to normalize the undisturbed but stretched laminar burning velocity ($S_{L,u}$). Figure 2.5a shows the effect of stretch on the methane flame through the normalization of the undisturbed laminar burning velocity by the unstretched laminar burning velocity calculated from effective radius (Eqns. 2.2 & 2.3). The asymptotic trend of each equivalence ratio shows the flames progression from highly curved to nearly planar. According to Table 1.1, the Markstein number undergoes a sign change as the equivalence
ratio increases above unity, indicating a change from thermo-diffusively unstable to thermo-diffusively stable flames. The slight increase in burning velocity shown by the $\phi = 0.64$ flame at times shortly after ignition and the subsequent decrease in burning velocity as the equivalence ratio is increased can be attributed to this thermo-diffusive stability change, quantifying the methane flame’s moderate sensitivity to stretch. The evaluation of the pressure-derived burning velocity includes the time rate of change of pressure which, at early times, is minimal and induces a large amount of error. The pressure trace, shown in Fig. 2.5b, expresses the effectiveness at selecting the appropriate dilution to equate the flame speeds of each equivalence ratio.

The time history of undisturbed propane effective kernel radius for two of the five mixtures investigated is plotted in Figure 2.6a, as well as the simultaneously obtained pressure measurements (Fig. 2.6b) to show a comparison between the fast and slow flame speeds. Due to similarities in the results, the $\phi = 0.87$ and $\phi = 1.32$ flames represent the thermo-diffusively stable and unstable flames respectively. Figure 2.6a shows the monotonic increase of the unstable flames, while the stable flames are initially larger but still propagate at the desired rate. It is interesting to note that the initial kernel size increases with decreasing thermo-diffusive stability. Therefore, the initial propane kernels are larger as the equivalence ratio increases, while the opposite trend is true for methane, which behaves similar to a hydrogen-air flame. Also consistent with methane, the unstable propane flames exhibit a linear dependence of effective kernel radius with time, while the stable flames initially lag behind and then eventually recover, yielding a slightly nonlinear trend. Therefore, the dilution levels were chosen to give the best overall match in $dr_e/dt$ for all cases over the range
of kernel sizes investigated with the kernel-vortex interactions. The average flame propagation rates \( S_b \), measured from ignition until the flame reaches the image edge, ranged from 105 to 115 cm/s for the “low” flame speed diluted mixtures and 219 to 230 cm/s for the “high” speed mixtures.

Figures 2.7a and 2.7b show the effect of the spherical geometry on the propane flame for both the slow and fast flame speeds respectively. Figure 2.7a shows the similarity in flame propagation characteristics of the three stable flames, while the unstable flames display an augmented propagation rate. Figure 2.7b shows the similarity of the three flames tested at the fast flame speed. These flames exhibit stable characteristics and therefore show a reduction in burning velocity, even though the \( \phi = 1.32 \) result for the slow flame speed is considered an unstable flame. As the Markstein number approaches zero with increasing equivalence ratio, and subsequently passes it, the increased curvature and cellular structure of the undisturbed flame causes an augmentation of the laminar burning velocity. The subsequent normalization of the disturbed kernels by the undisturbed kernel effectively removes the under-prediction and over-prediction prevalent in the pressure-derived burning velocity, as seen in the following sections.

The following sections explore in detail the effect a vortex has on the spatial flame propagation, with supporting results from the pressure-derived flame speed of the kernels through a comparison to the undisturbed case. As an example, measurements of an undisturbed \( \phi = 0.64 \) methane flame kernel vortex, compared to the same flame kernel interacting with different strength vortices, are shown in Fig. 2.8. The chemiluminescence images show substantial distortion of the flame kernel by the vortex at 30 ms, but differences
are barely discernable in the pressure traces. At later times, the pressure changes are significant, with higher rates of pressure rise with increasing vortex strength. Comparison of pressure measurements between 60 ms and 200 ms for methane and 30 ms and 100 ms for propane are used to determine the relative average and maximum burning velocities for a range of equivalence ratios, vortex strengths, and vortex-kernel interaction times. Methane results are summarized in Table 2.1 and propane results can be found in Table 2.2.

2.3.2 Disturbed Flame Kernels: Methane

The first flame kernel-vortex interactions considered are identified as late interactions. A late interaction is defined by the non-dimensionalized size of the flame kernel (kernel diameter/ vortex diameter) being greater than two at the onset of interaction with the vortex. The weakest vortex interactions proceed similarly to those shown in Xiong et al. [18]. A typical interaction is shown in Figure 2.9 for a \( \phi = 0.90 \) flame. Examining the flame kernel just after ignition, it is interesting to note that the flame sensitivity to heat loss to the electrodes increases as the nitrogen dilution is increased. This thermo-diffusive effect results in the flame developing slightly faster in the vertical direction, exhibiting an elongated shape during the early stages of flame development. At the onset of interaction (after \(~50 \text{ ms}\) in Fig. 2.9), the propagating vortex pushes the flame surface downward, reducing the local flame curvature while simultaneously exerting positive strain: two opposing terms in the determination of flame stretch. The weak vortex does not quench the leading edge of the vortex, nor does the vortex propagate through to the bottom of the flame kernel.
The first interaction of the strong vortex (\(U_0 = 398\) cm/s) and rich flame kernel (\(\phi = 1.13\)) occurs at 40 ms after ignition and by 46 ms, the vortex leading edge is clearly extinguished as shown in Figure 2.10. This indicates the positive stretch exerted on this thermo-diffusively stable mixture exceeds the quenching stretch rate in this region. At approximately 50 ms after ignition, the trailing edge of the burning vortex becomes wrinkled as a result of instabilities responsible for vorticity shedding. The leading edge of the strong vortex has enough momentum to push through the bottom of the expanding flame kernel by 55 ms. At still later times (not shown), the vortex convects further, burning as a highly distorted flame (significantly increasing the flame surface area) connected by a narrow neck to the original flame kernel.

For all three equivalence ratios investigated (some cases not shown), the coherent leading edge of the strong vortex appears to be able to locally quench the flame by 45 ms after ignition. As the vortex propagates into the kernel and approaches the electrodes, the trailing wake narrows, and the \(\phi = 0.64\) and \(0.90\) cases exhibit a higher degree of flame wrinkling at the vortex trailing edge than the \(\phi = 1.13\) case. This observation is indicative of increased thermo-diffusive stability as the equivalence ratio increases, consistent with an increasing Markstein number (see Table 1.1). Re-ignition of the vortex fluids occurs in the lower flame kernel hemisphere, with the \(\phi = 1.13\) flame being the slowest to respond. The vortex is strong enough to punch through the lower flame kernel surface, with possible mutual flame annihilation evident from the fragmented reaction zones visible in each case. Final consumption of the remaining vortex core fluid occurs via multiple pocket formation for all three cases, just beneath the bottom of the initial flame kernel. Only the rich (\(\phi = 23\)
1.13) case has a second expanding flame kernel connected to the original kernel (Fig. 2.10, last three frames).

Pressure measurements quantify the longer term (> 70 ms) effects of the vortex on the kernel. Late interactions with a weak vortex (in Figure 2.11a) show small effects on burning velocity for all three equivalence ratios investigated. Late interactions with a strong vortex (in Fig. 2.11b) show enhancement in both average and maximum normalized flame speeds, with the largest enhancement for the leanest flames. The average and maximum normalized flame speeds for the $\phi = 0.64$, 0.90, and 1.13 cases are 1.16/1.32, 1.09/1.20 and 1.02/1.20 respectively.

Manipulating the experiment timing such that the vortex arrives sooner after spark ignition maximizes the effect the vortex has on flame propagation. A typical weak vortex interaction, which occurs soon after ignition (approx. 10 ms) when the flame kernel is still small (~5 mm radius) as seen in Xiong et al. [18] is shown in Figure 2.12. The images in Fig. 2.12 are also similar to direct numerical simulations of flame kernel vortex interactions (e.g. Fig. 2 in [20]), even though the computations were for premixed H$_2$ rather than methane. In Fig. 2.12, as the weak vortex traverses the electrodes, the leading edge flame dims for all three cases, but does not locally extinguish as in the late interactions discussed earlier. During the separation of the trailing wake flame from the vortex flame, multiple pockets are formed occur as seen in the $\phi = 0.64$ mixture (for times longer than 16 ms after ignition) while the $\phi = 0.90$ and $\phi = 1.13$ cases exhibit a clean break between the two regions. In addition, the top of the disturbed kernel for the $\phi = 1.13$ case is less wrinkled than the fuel-
lean cases: another indicator of increased thermo-diffusive stability with increasing equivalence ratio. During final vortex consumption (at 44.3 ms) near the bottom of the flame kernel, the remaining momentum from the vortex is able to slightly dimple the kernel bottom. This increases the reaction zone curvature and therefore generates marginally elevated stretch rates, but the effects are not measurable in either the chemiluminescence signal intensity or the effective kernel radius.

Early interactions with a strong vortex are shown in Figures 2.13 and 2.14 or lean (ϕ = 0.64) and rich kernels, respectively, while the ϕ = 0.90 case is not shown because of its close similarity to the ϕ = 0.64 case. In Fig. 2.13, the interaction begins at 9.0 ms after ignition. The strong vortex is able to severely wrinkle the flame kernel, push through the flame kernel, and induce local extinction at the kernel bottom (t = 19.7 ms). At 25.0 ms and later, the vortex momentum facilitates strong downward flame propagation as the reaction zone follows in the vortex wake. The wrinkling induced by the strong vortex is significant enough to initiate a cellular structure in the ϕ = 0.64 flame surface, an indication that the reaction zone has developed instabilities.

The ϕ = 1.13 case (Figure 2.14) is unique in that the strong vortex is able to globally quench the flame kernel. Images in Fig. 2.14 are qualitatively similar to direct numerical simulations of a vortex induced flame kernel quenching (e.g. Fig. 4 in [19]). In Fig. 2.14, by 11.6 ms, chemiluminescence from the flame boundary has diminished, and the kernel has broken up into several flame fragments. Concurrently, the pressure results show no noticeable deviation from barometric pressure for this case, therefore the majority of the reactant mixture remains unburned. The results of the three early interactions with the strong
vortex support the notion of increased susceptibility to flame quenching with increased dilution, especially for positively stretched, thermo-diffusively stable reaction zones [18].

Pressure measurements shown in Figs. 2.11c and 2.11d also indicate much stronger effects on average and peak normalized flame speeds for the early vortex arrival. The $\phi = 0.64$ and $\phi = 0.90$ cases show strong enhancement of normalized flame speeds (by as much as 50% for the $\phi = 0.64$ case). The $\phi = 1.13$ with a weak vortex case has a reduction in normalized flame speeds throughout the time recorded, while the strong vortex totally extinguishes the flame kernel.

The effects of flame kernel interactions on flame speeds at short times after the interaction are best quantified using changes in the slope of effective flame kernel radius vs. time measured from the high speed chemiluminescence images (as shown in Figures 2.15 and 2.16). The slope is linear (i.e. constant flame speed) for the undisturbed lean methane flame kernels (Fig. 2.15). Flame propagation is enhanced for the $\phi = 0.64$ flame kernel immediately after the kernel-vortex is observed in the chemiluminescence images. The average flame burning velocity (based on effective kernel radius) is increased by a factor of 1.3 by the early interaction with a weak vortex. The effect becomes less pronounced as the timing of the vortex arrival is delayed.

The effect of vortex strength is quantified in Figure 2.16a for $\phi = 0.64$ and the early interaction, resulting in a nearly 90% increase in the average flame speed ($S_b$) for the strongest vortex. Not only is there a step change in kernel growth soon after the interaction due to transient stretch effects (Fig. 2.16a), there is a longer term effect on relative burning
velocity due to flame wrinkling and an increase in effective flame area. Results for the $\phi = 0.90$ kernels (not shown) are similar.

As expected from combustion theory including thermo-diffusive effects, rich ($\phi = 1.13$) methane-air flame kernels and kernel-vortex interactions have quite a different behavior (as summarized in Fig. 2.16b) when compared to lean methane-air flame kernels. The growth in the undisturbed flame kernel is not linear. At early times when the kernel radius is small and the curvature large, the effective burning velocity is reduced by the high stretch. Early vortex interaction with the rich flame kernel further increases the local stretch and reduces the relative burning velocity immediately following the initial kernel-vortex interaction. The stronger the vortex, the stronger the effect on early flame kernel growth. For the strongest vortex, the entire flame kernel is quickly extinguished. For the weak and medium vortices, the relative burning velocities start to increase due to flame front wrinkling by the vortex later in the interaction (20 – 60 ms after ignition in Fig. 2.16b). After 35 ms in the weak vortex and 55 ms in the strong vortex cases, the effective kernel radius has increased due to interactions with the vortex (even though the initial vortex had a negative effect).

Because the flames grow too large to be in the field of view for the chemiluminescence imaging, at significantly long times after the interaction, the effects of flame kernel interactions on burning velocities are best quantified by chamber pressure measurements (summarized in Table 2.1). As just described, the early interaction with the strongest vortex causes kernel extinction for the rich flame kernel due to excessive stretch effects. For all other cases studied, the average normalized reactant consumption rates at these late times are always greater than 1 (i.e., enhanced flame growth) due to transient stretching for lean flame.
kernels and due to flame front wrinkling for all nonextinction cases. The amount of
enhancement is largest for early vortex interactions (the smallest flame kernels), for lean vs.
rich flame kernels, and for strong vs. weak vortex strengths.

2.3.3 Disturbed Flame Kernels: “Slow” Propane

The first flame kernel-vortex interactions discussed for these mixtures at the slow flame
propagation rate are late interactions with the weak vortex. Figure 2.17 shows
chemiluminescence images for each equivalence ratio at certain times during the interaction.
As the vortex first interacts with the kernel for all cases, the flame is strong enough to
actually push the imposing vortex upwards, reversing the propagation direction (in laboratory
coordinates), until the vortex moves into the kernel and resumes its downward travel. As the
vortex bubble is formed within the kernel (at 41 ms), the laminar reaction zone is observed to
be well-defined around the vortex and connects to the outer kernel surface via the trailing
wake. As the vortex continues to propagate, the trailing wake of the $\phi = 1.32$ and $\phi = 1.49$
cases develops a complex structure due to wrinkling, while the stable cases exhibit
symmetric wake flames. As the wake flame detaches and vortex consumption occurs, the $\phi = 0.69, 0.87, 1.08$ cases show a well-defined reaction zone around both the trailing wake and
remaining vortex reactants, which are completely consumed just above the electrodes. In
comparison, for the $\phi = 1.32$ and $\phi = 1.49$ cases, both the vortex and wake reaction zones
become diffuse during the final stages of the interaction, and the chemiluminescence signal
gradually fades away with no distinct flame boundary between reactant and products. This
scenario suggests that the combustion may be incomplete and is in the distributed reaction
zone regime since reactants and products could co-exist. From Figure 2.18a, it is observed that the flames exhibit burning velocity characteristics similar to the undisturbed kernels, indicating the minimal effect of the weak vortex on the overall growth of the well established flame kernels. The only mixture with an appreciable increase in flame propagation was $\phi = 1.49$, with the average burning velocity increasing by 24%.

Presented next is the investigation into the effect of the strong vortex on late propane kernel-vortex interactions. Although not shown, contrary to the late interactions with the weak vortex, the strong vortex exhibits little or no attenuation as its leading edge interacts with the expanding flame kernel. Similar to the weak vortex interaction however, for $\phi = 1.49$ it appears that stretch-induced intensification occurs at the connecting region between the vortex trailing edge and the outer flame kernel. Of course, this elevated intensity may be due to wrinkling or area generation. Continued propagation of the vortex into the kernel leads to the generation of a turbulent wake flame, especially for the thermo-diffusively unstable cases ($\phi = 1.32$ and $\phi = 1.49$) which show a very wide and intense wake reaction zone. As the vortex traverses the electrodes, the thermo-diffusively stable cases undergo quenching along the vortex flame, leaving a vigorous reaction zone along the trailing edge, and then re-igniting below the electrodes. For the $\phi = 1.32$ mixture, no quenching occurs, but heat losses incur a less defined reaction zone that is less intense but deformed due to flow disturbance from the electrodes. The vortex leading edge reaction zone for the $\phi = 1.49$ case only locally loses intensity at the electrodes before becoming very intense as turbulent trailing edge combustion consumes the vortex. The normalized flame burning velocity, plotted in Fig. 2.18b, shows a very moderate increase in the flame burning velocity. As with
the results from the late interactions with the weak vortex, only marginal variations in the average flame burning velocity are observed, with peak values ranging from 10% to 42% increase.

Chemiluminescence image sequences of propane, shown in Figure 2.19, present early interactions with weak vortices at the slow flame speed. As the early interaction proceeds in the $\phi = 0.69$ case, the vortex leading edge flame wrinkles and develops into an intense pocket of combustion as the vortex is consumed. In the $\phi = 0.69, 0.87, 1.08$ cases, the trailing edge of the flame narrows quickly due to vorticity and exposes the remaining pocket of reactants in the vortex cores to the encroaching hot products, but the leading edge vortex reaction zone is not as intense for the $\phi = 0.87$ and $\phi = 1.08$ cases in comparison to the $\phi = 0.69$ flame, even though the flame structure is similar. In addition, for the $\phi = 0.69$ and $\phi = 0.87$ flames, the disturbed reaction zone is well defined by the chemiluminescence signal, whereas the $\phi = 1.08$ case exhibits a more diffuse signal along the reaction zone. For all three mixtures, the vortex and wake continue to burn and eventually separate before the vortex is finally consumed. During this process, the diffuse reaction zone for the $\phi = 1.08$ case becomes very evident inside the flame kernel. As the vortex enters the kernel for the $\phi = 1.32$ mixture, flame wrinkling occurs and the intensity along the vortex flame surface varies locally. Also, the flame kernel shows signs of wrinkling along its outer surface. The intensity of the leading edge of the vortex flame dims as it passes over the electrodes and never recovers. Further progression of the interaction leads to the narrowing of the wake at the trailing edge of the vortex, while the remaining vortex flame possesses fluctuations and discontinuities in signal
intensity, suggesting incomplete combustion. During final vortex consumption, the vortex flame gradually fades away, a process much different than the well-defined reaction zones observed in the fuel-lean cases. The receding wake has a diffuse reaction zone with no clear boundary, suggesting that the combustion may occur in the distributed reaction zone regime. The remaining flame kernel continues to expand as cellular flame structures develop. The most unstable mixture considered, $\phi = 1.49$, exhibits fluctuating intensities around the vortex as vorticity wraps the flame to the trailing edge. Figure 2.18c illustrates the effect of the early interactions with the weak vortex on the burning velocity for each of the equivalence ratios studied. The enhanced flame propagation for the $\phi = 1.32$ is evident compared to the late interactions, although the increase in flame propagation rate is not significantly larger. The maximum flame propagation rates vary from 10% to 20% augmentation.

The final cases considered for the “slow” flame speed are early interactions with a strong vortex which provide the most dramatic responses to flame stretch observed in this investigation. The image sequences of the kernel-vortex interactions are shown in Figure 2.20 for all five mixtures. Since the interaction begins when the flame kernel is very small, the vortex strength is high enough to compress the kernel into a U-shaped flame for all mixtures, although flame propagation and intensification increases with increasing $\phi$. For the $\phi = 0.69$ and $\phi = 0.87$ mixtures, the vortex leading edge stretches the flame and merges the top and bottom kernel surfaces, leading to local extinction at the bottom flame boundary which has also been found in the computational results of this study [20]. This event is followed by trailing edge combustion, highly wrinkled due to vorticity, propagating down through the “tube” of reactants recently entrained, and into the vortex wake. In the $\phi = 1.08$
flame, the reaction zones merge but the apparent quenching is not as obvious. Local extinction appears to occur from the images, though, as the trailing edge combustion is observed to propagate through the kernel bottom. The flame kernel-vortex interactions proceed differently for the unstable mixtures corresponding to $\phi = 1.32$ and $\phi = 1.49$. The unstable flames exhibit no local extinction as a result of the vortex-induced stretch and flame-flame interaction. The vortex flame becomes very wrinkled and intense for both rich mixtures. In addition, the vortex momentum stretches the kernel bottom and significantly increases the flame surface area. Another characteristic of the unstable flames is that a well-defined wake does not form. Instead, a heavily contorted wake flame breaks up into pockets and the reaction zones become diffuse as they are consumed. Cellular instabilities then develop, especially at the wrinkled kernel upper surface. The unstable flames clearly exhibit augmented flame propagation due to the early interaction with the strong vortex as indicated by the flame burning velocity in Fig. 2.18d. The local extinction events that occur for the thermo-diffusively stable mixtures inhibit flame growth, especially for the fuel-lean mixtures. Average flame propagation rates increase with increasing equivalence ratio and range from -2% to 77%.

2.3.4 Disturbed Flame Kernels: “Fast” Propane

In order to observe the effects of flame speed on turbulent chemistry, a “fast” flame speed kernel is subjected to identical vortex conditions as the “slow” flame speed kernel. Initial observations of the chemiluminescence images show similar results to the slow flame speed in nearly all the cases, except at an obviously faster rate. There are significant
differences however. The attenuation observed when the vortex initially intersects the kernel during the slow interactions is nearly non-existent for all the fast cases. This may be attributed to the increased chemical reactivity resulting in increased flame speed. Also there appears to be a disturbance on the right side of the kernel in each of the cases, which can be attributed to electrode interference, which was largely absent in the slower flame images.

Presented first are images for the late vortex for both weak and strong propagation velocities (Figure 2.21a) at each of the equivalence ratios at various times of interest. Flame structure follows similarly to the slow flame speed, where the less thermo-diffusively stable flame ($\phi = 1.32$) tends to produce a cellular flame structure, however these chemical effects on the physical structure of the flame are reduced due to the increased burning velocity, reducing the time allowed for formation. The initial interaction of the vortex with the kernel shows a significant reduction in the propagation of the vortex flame front into the kernel, much more so than the slow flame speed. Instead of propagating into the kernel, the vortex is engulfed by the flame front as it progresses around the toroid. The consumption of the vortex is also augmented by this increase in flame burning velocity. Aside from surface structure, very little difference can be observed between the differing equivalence ratios. The quantitative results of burning velocity give a more exact comparison between the experiments and are shown in Figure 2.22a. From this figure, it can be seen there is high fluctuation between the disturbed and undisturbed kernels. This may be due to the sensitivity of the burning velocity calculations to the time rate of change of the pressure measurements. However the results can still be compared, as the separation found in the undisturbed case between equivalence ratio continues to be exhibited with richest case displaying the highest
burning velocity. Average burning velocities for this interaction show decreases of as much as 64% however, the maximum burning velocities consistently show an increase, ranging from 43% to 86%.

Much like the late weak interactions, the late strong interactions show little difference from the slow speed combustion results (Fig. 2.21b). A significant difference is the rate of consumption and propagation of the vortex. Since the vortex contains significantly more momentum it is able to overcome the expansion forces of the kernel. The vortex is able to propagate just past the electrodes before the entrained reactants are completely consumed. Contrasting with the weak vortex, the strong interaction shows significantly more wrinkling and a near saturation of the chemiluminescence signal indicating possible increased combustion rate. Variations in stoichiometry are evident at 16 ms for the $\phi = 1.08$ and $\phi = 1.32$ cases. At this time the kernel appears to be augmented more than the $\phi = 0.87$ kernel, showing more evidence of increased reactant consumption. This trend is continued for these cases until the vortex is completely consumed, which occurs sooner than the lean flame.

Figure 2.22b shows the normalized reactant consumption rate for the strong-late interactions. Similar to the weak vortex interaction, there appears to be a significant deviation from the undisturbed results. However, unlike the weak interaction, the strong vortex causes a much more significant augmentation of the kernel, with peak increases of 38%, 41% and 110% for the $\phi = 0.87$, $\phi = 1.08$ and $\phi = 1.32$ kernels respectively.

The results from the early interactions of the weak vortex for the fast flame speed are presented in Figure 2.23a. These select images show initial variations in kernel size and structure, which is to be expected due to their varying Markstein numbers. Following the
sequence of images, it appears as though the vortex propagation has been completely counter-balanced by the kernel expansion. This is a much more dramatic effect than the “slow” speed combustion results, where the vortex is able to survive through the majority of the kernel propagation. Here, the vortex is stopped and consumed without producing a significant flame structure within the kernel. The weak vortex burning velocities are similar to previous conditions, however there is a more significant increase in maximum burning velocity when compared to the late interaction (Fig. 2.22c). Peak increases of 34% to 102% are observed.

Final observations are the early strong vortex interacting with the “fast” flame speed kernel presented in Fig. 2.23b. From this figure it is clear that there is a significant difference between the early-weak vortex and the early-strong vortex. There is more entrainment of unburned reactants from the strong vortex due to an increased vorticity which is evident by the increased chemiluminescence signal indicating an increased burning rate. The consumption of the vortex occurs quicker than the weak vortex yet the effect of the vortex on the kernel is more significant evidenced by the expansion rate. The results from the strong vortex show an appreciable increase in flame propagation rate (Fig. 2.22d). A maximum increase of 45%, 54% and 107% are observed for the equivalence ratios of 0.87, 1.08 and 1.32 respectively.

2.4 Summary

To gain both fundamental and practical insight into the effects of transient stretch on spark-ignited flame kernel growth, a well-characterized vortex was generated and allowed to
interact with a flame kernel at various stages of growth. To quantify chemical effects, CH₄-O₂-N₂ flames at three different equivalence ratios, \( \phi = 0.64, 0.90, \) and 1.13 have been compared, using nitrogen dilution to equalize the flame speed \( (S_b) \) in the absence of vortex interaction. Furthermore to observe complex hydrocarbon and thermo-diffusive effects, propane was analyzed for five reactant mixtures, ranging in equivalence ratio from 0.69 to 1.49. Nitrogen dilution was also added to the appropriate propane mixtures so the flame kernels could be categorized at two flame speeds (“slow” or “fast”). The “slow” flame speed had the same undisturbed flame propagation rate as the \( \phi = 0.69/1.49 \) cases and the “fast” flame speed had the same undisturbed propagation rate as the \( \phi = 0.87/1.32 \) cases. Three vortex strengths, covering the laminar to transitional regimes, were studied to provide a wide range of imposed stretch rates. Additionally, kernel response to the vortex-induced stretch was investigated as a function of the maturity of the kernel by varying the initial interaction time. High-speed chemiluminescence imaging was used to visualize each interaction, allowing measurement of instantaneous flame kernel radius and identifying regions of intensified combustion or local extinction during the interaction with a vortex. Simultaneously, instantaneous pressure was measured and used to calculate the laminar flame speed at times where the kernel size exceeded the imaging field of view.

The use of global pressure measurements to directly measure burning velocity has been shown to provide results which contain a complex combination of reaction consumption rate and kernel propagation, which cannot be decoupled without additional information. The normalization of the disturbed kernel by the undisturbed kernel provides the necessary
separation of these two parameters in order to observe the effect of flame stretching. Trends observed are discussed below:

(1) During the early stages of the flame-vortex interaction, the transient stretch effects were dominated by methane’s weak dependence on Markstein number, with lean methane-air flames showing an initial augmentation of burning velocity while rich methane-air flames showed an initial suppression of burning velocity. This is in agreement with steady stretched flame theory. However, at later stages of the interaction, the effect of increased flame surface area due to flame corrugations, all kernels show a relatively modest increase in reactant consumption rate, regardless of equivalence ratio.

(2) Methane imaging results show that many unique flame-flow and flame-flame interactions occurred. With sufficiently strong vortices, an interaction was shown to occur at both the top and bottom surfaces of the flame kernel. These bottom interactions can result in local extinction and the initiation of a secondary expanding flame front connected to the primary kernel. Very early interactions have been shown to break the small kernel into multiple pockets, from which the flame may recover or globally extinguish, depending on the fuel, vortex strength and equivalence ratio. Several cases, characterized by extinction events or greatly reduced mean reaction rates, deviated from the norm but occur at conditions that are at the limit of the probed parameter space (methane, $\phi = 1.13$, early interaction, medium/strong vortex).
Propane Lewis number effects are evident even without the vortex interaction, since the initial kernel size increased with increasing equivalence ratio, or decreasing thermo-diffusive stability. Although the weak vortex has a minimal effect on flame propagation during late interactions, the $\phi = 1.49$ flame-flow interaction does cause local intensification of chemiluminescence signal in regions of high positive stretch rate due to increased burning intensity. Also, the thermo-diffusively unstable flames exhibit diffuse reaction zones that indicate the possibility of incomplete combustion within the distributed reaction zone regime, a result that is observed throughout the investigation for these mixtures. The introduction of a strong vortex allows the vortex to survive for longer time within the kernel for the late interactions, and the thermo-diffusively stable flames exhibit extinction and re-ignition of the vortex fluid as the vortex traverses the ignition electrodes. The flame speeds are high enough that late interactions with the weak vortex temporarily reversed the propagation direction of the vortex leading edge for each speed studied.
Table 2.1: Average/maximum normalized reactant consumption rate of the methane flame between 60 ms and 200 ms.

<table>
<thead>
<tr>
<th>Equivalence Ratio $\phi$</th>
<th>0.64</th>
<th>0.90</th>
<th>1.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Interaction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Weak” Vortex</td>
<td>1.05/1.26</td>
<td>1.06/1.20</td>
<td>1.00/1.12</td>
</tr>
<tr>
<td>“Strong” Vortex</td>
<td>1.16/1.32</td>
<td>1.09/1.20</td>
<td>1.02/1.20</td>
</tr>
<tr>
<td>Early Interaction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Weak” Vortex</td>
<td>1.15/1.54</td>
<td>1.08/1.29</td>
<td>1.00/1.18</td>
</tr>
<tr>
<td>“Strong” Vortex</td>
<td>1.21/1.74</td>
<td>1.09/1.22</td>
<td>Global Quenching</td>
</tr>
</tbody>
</table>

Table 2.2: Average/maximum normalized reactant consumption rate for the propane flames studied at the (a) slow flame speed and (b) fast flame speed.

<table>
<thead>
<tr>
<th>Strength</th>
<th>Slow (a)</th>
<th>Fast (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.69</td>
<td>0.87</td>
</tr>
<tr>
<td>Late Interaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weak</td>
<td>0.94/1.13</td>
<td>0.94/1.04</td>
</tr>
<tr>
<td>Strong</td>
<td>0.96/1.24</td>
<td>0.88/1.12</td>
</tr>
<tr>
<td>Early Interaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weak</td>
<td>0.96/1.20</td>
<td>0.93/1.10</td>
</tr>
<tr>
<td>Strong</td>
<td>1.04/1.25</td>
<td>0.98/1.12</td>
</tr>
</tbody>
</table>
Figure 2.1: Wiring diagram for the spark-ignited CH₄-O₂-N₂ and C₃H₈-O₂-N₂ flames to measure flame speed using a high-speed camera and global pressure measurements.
Figure 2.2: High-speed flame emission images of undisturbed outwardly propagating flame kernel for $\Phi = 0.90$ and $O_2/(O_2+N_2) = 0.159$. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.

Figure 2.3: Undisturbed effective radius of the methane flames studied. Equivalence ratios above 0.64 have been diluted with nitrogen to match the lean flame speed.
Figure 2.4: High-speed flame emission images of undisturbed outwardly propagating C$_3$H$_8$-O$_2$-N$_2$ flame kernels for $\phi = 0.87$ (top row) and $\phi = 1.32$ (bottom row). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.5: (a) Methane flame’s response to stretch, for each of the equivalence ratios studied calculated from effective radius. (b) Undisturbed pressure traces for each flame mixture (different N₂ dilution levels are used to make pressure rise similar for all cases). Time is relative to spark ignition.
Figure 2.6: (a) Flame radius history for propane flames freely propagating without vortex interaction. \( N_2 \) dilution levels for the “slow” flames were chosen to match (as closely as possible) the \( \phi = 0.69/1.49 \) flame propagation rate. (b) Global pressure measurements for undisturbed, \( \phi = 0.69, 0.87, 1.08, 1.32 \) and 1.49, kernels. \( \phi = 0.87, 1.08 \) and 1.32 flames are diluted to approximate the 0.69/1.49 flame speed for the “low” flame speed results and are shown on the primary y-axis, while the “high” 1.08 flame is nitrogen diluted to approximate the 0.87 flame speed and are shown on the secondary y-axis. All times are relative to spark ignition.
Figure 2.7: Effective radius derived undisturbed laminar propane burning velocity normalized by the unstretched laminar burning velocity for the (a) slow flame speed and the (b) fast flame speed for each equivalence ratio studied. Time is after ignition.

Figure 2.8: Low-limit (34 kPa max) pressure trace for the $\phi = 0.64$ flame kernel, and the corresponding chemiluminescence images at 30 ms for the undisturbed flame and for interactions with different strength vortices. Time is relative to spark ignition.
Figure 2.9: High-speed flame emission images of late kernel-vortex interaction for $\phi = 0.90$ and weak vortex ($U_0 = 77$ cm/s, $U_0/S_{1\infty} = 7.46$, $d_o/\delta_D = 44.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.10: High-speed flame emission images of late kernel-vortex interaction for $\phi = 1.13$ and strong vortex ($U_0 = 398 \text{ cm/s}, U_0/S_{L,\infty} = 29.8, d_0/\delta_D = 58.1$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.11: Effect of vortex strength on flame speed for the methane-air flame at the three equivalence ratios studied for: the late interactions of the (a) weak vortex ($U_θ = 77 \text{ cm/s}$) and (b) the strong vortex ($U_θ = 398 \text{ cm/s}$); and the early interactions of the (c) weak vortex and (d) strong vortex ($\phi = 1.13$ undergoes global extinction). Shown are the disturbed flames normalized by the undisturbed flames ($S_{L,d}/S_{L,m}$). All times are relative to spark ignition.
Figure 2.12: High-speed flame emission images of early kernel-vortex interaction for the spark-ignited, $\Phi = 0.64$ methane flame and weak vortex ($U_0 = 77 \text{ cm/s}, U_0/S_{Lc} = 8.21, d_o/\delta_p = 40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.13 High-speed flame emission images of early kernel-vortex interaction for the spark-ignited, $\Phi = 0.64$ methane flame and strong vortex ($U_0 = 398$ cm/s, $U_0/S_{Lx} = 42.4$, $d_o/\delta_D = 40.8$). All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.14: High-speed flame emission images of early kernel-vortex interaction for the spark-ignited, $\Phi = 1.13$ methane flame and strong vortex ($U_\theta = 398$ cm/s, $U_\theta / S_{L,\infty} = 29.8$, $d_\circ / \delta_D = 58.1$). Image edges are artificially enhanced through thresholding to emphasize the flame boundary during the quenching process. The time separation between frames is short to capture the extinction event. All times listed are relative to spark ignition.
Figure 2.15: Effect of interaction time on flame propagation for the spark-ignited $\phi = 0.64$ CH$_4$-O$_2$-N$_2$ flame interacting with the weak vortex ($U_\theta=77$ cm/s). Vertical lines indicate the start of the vortex interaction; early interaction first followed sequentially by the later interactions.
Figure 2.16: Effect of vortex strength on flame propagation for the spark-ignited (a) $\phi = 0.64$ flame and (b) the $\phi = 1.13$ flame undergoing early kernel-vortex interactions. Solid triangles are extrapolated from a second-order polynomial fit to the last 20 ms. Time is relative to spark ignition. Vortex is approximately 1.25 cm (core-to-core) and interacts at approximately 5ms after ignition.
Figure 2.17: High-speed spark-ignited C₃H₈-O₂-N₂ flame emission images of late kernel-vortex interaction for $\phi = 0.69, 0.87, 1.08, 1.32$ and $1.49$, weak vortex ($U_\theta = 77 \text{ cm/s}$, $U_\theta/S_{L,\infty} = 3.59$, $d_0/\delta_D = 195.3$), and “slow” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.18: Effect of vortex strength on flame speed for the spark-ignited propane-air flame at each equivalence ratio studied at the slow propagation rate for: the weak vortex \( (U_\theta = 77 \text{ cm/s}) \) at the (a) late interaction, and (b) early interaction; and the strong vortex \( (U_\theta = 398 \text{ cm/s}) \) at the (c) late interaction and (d) early interaction. Shown are the disturbed flames normalized by the undisturbed flames \( \left( S_{L,d} / S_{L,u} \right) \). All times are relative to spark ignition.
Figure 2.19: High-speed spark-ignited C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for $\phi = 0.69, 0.87, 1.08, 1.32$ and $1.49$, weak vortex ($U_0 = 77$ cm/s, $U_0/S_{L,\infty} = 3.59$, $d_0/\delta_D = 195.3$), and slow flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.20: High-speed spark-ignited C₃H₈-O₂-N₂ flame emission images of early kernel-vortex interaction for \( \phi = 0.69, 0.87, 1.08, 1.32 \) and 1.49, strong vortex (\( U_\theta = 398 \text{ cm/s}, U_\theta/S_{L,\infty} = 25.30, d_\theta/\delta_D = 143.1 \)), and slow flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 95.7 mm wide x 100.0 mm high.
Figure 2.21: High-speed spark-ignited C₃H₈-O₂-N₂ flame emission images of late kernel-vortex interaction for $\phi = 0.87$, 1.08, and 1.32, with (a) weak vortex ($U_\theta = 77$ cm/s, $U_\theta/S_{L,\infty} = 3.59, d_\theta/\delta_D = 195.3$), and (b) strong vortex ($U_\theta = 398$ cm/s, $U_\theta/S_{L,\infty} = 25.30, d_\theta/\delta_D = 58$).
= 143.1), at the fast flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 73.2 mm wide x 75.8 mm high.

Figure 2.22: Effect of vortex strength on flame speed for the spark-ignited propane-air flame at each equivalence ratio studied at the fast propagation rate for: the weak vortex ($U_0 = 77 \text{ cm/s}$) at the (a) late interaction, and (b) early interaction; and the strong vortex ($U_0 = 398 \text{ cm/s}$) at the (c) late interaction and (d) early interaction. Shown are the disturbed flames normalized by the undisturbed flames ($S_{L,i}/S_{L,0}$). All times are relative to spark ignition.
Figure 2.23: High-speed spark-ignited C$_3$H$_8$-O$_2$-N$_2$ flame emission images of *early* kernel-vortex interaction for $\phi = 0.87$, 1.08, and 1.32, with (a) weak vortex ($U_0 = 77$ cm/s, $U_0/S_{L,\infty} = 3.59$, $d_0/\delta_D = 195.3$), and (b) strong vortex ($U_0 = 398$ cm/s, $U_0/S_{L,\infty} = 25.30$, $d_0/\delta_D = 143.1$), at the “fast” flame propagation rate. All times listed are relative to spark ignition. The field of view in each image is 73.2 mm wide x 75.8 mm high.
3 Local Flame-Vortex Effects, Measured Using Non-invasive Laser Diagnostics

3.1 Introduction

While the high-speed imaging and pressure measurements provided a sufficient understanding of the global effect of a highly transient stretch event on a flame, the subtle variations within specific flame regions were not measurable without further diagnostics. In order to precisely measure key attributes of the flame-vortex interaction while simultaneously maintaining the undisturbed aero-thermodynamic structure of the spark-ignited flame, laser based diagnostics were chosen.

The inclusion of laser diagnostics to accurately determine the location of the flame front and radical species has become a common practice among experimental combustion researchers. Cattolica and Vosen have used Laser Induced Fluorescence (LIF) of the hydroxyl radical (OH) coupled with schlieren photography to accurately map the chemical structure of a methane-air flame as it is disturbed by a vortex [34]. Congruently, Kaminski, et al. used Planar Laser Induced Fluorescence (PLIF) to measure the degree of flame wrinkling. They were able to evaluate LES results to show the effectiveness of such techniques for time-resolved comparisons [35].

Since this technique has been used extensively for radical mapping, and more specifically has been used to determine flame temperature, the local flame boundaries, [36-37] as well as heat release rate [38], laser diagnostics were chosen to provide a detailed measurement of the flame structure as well instantaneous temperature within the flame.
kernel. The following subsections will include an abbreviated description of the fluorescence technique and theory, as described almost exclusively by Eckbreth [39].

3.1.1 Laser Induced Fluorescence (LIF)

The process of fluorescence is initialized by the excitation of a molecule from a ground state to an excited state, which requires a very specific quantum of energy. Typically, the use of a tunable dye laser allows for the production of the photons at the specified wavelength necessary to excite the specific energy mode of the target molecule. Normally occurring spontaneously, the molecule will then return to a lower state. This state is not, however, the original ground state resulting in the emission of a Stokes-shifted photon, relative to the incoming wavelength. This can be advantageous since detection of the incoming light is not desirable. A set of optical filters can then be used to more accurately detect the re-emitted light (see Section 3.2.1). Often prior to re-emission, the excited molecule undergoes a form of quenching. One of the most common forms of quenching is called collisional energy transfer (CET), where the molecule is returned to a lower state prior to fluorescence due to collisions with the ambient gases [40].

In order to accurately predict the fluorescence energy, molecular spectroscopy requires the comprehension of a wide variety of quantum mechanical processes. Due to the increased complexity of the energy states of diatomic molecules compared to the states associated with atomic spectroscopy, each excitation mode must be understood and accounted for. The three modes, rotational, vibrational and electronic, decoupled, carry specific energy defined by quantum mechanics. These modes however, are not decoupled during an actual event and require a more complex representation of the energy associated with excitation. Once fully
understood, the selection criteria provide the specific energy levels allowed for spectroscopy. The complete fluorescence energy expected for a specific molecule undergoing absorption and reemission is [41]:

\[ F = h \nu \frac{\Omega}{4\pi} \cdot l \cdot A \cdot N_1^0 \cdot B_{12} \cdot I_\nu \frac{A_{21}}{A_{21} + Q_{21}} \]  

3.1

Where, \( h \) is Planck’s constant, \( \nu \) is the frequency of the incident photon, \( \Omega \) is the collection solid angle, \( l \) is the axial extent along the beam from which the fluorescence is observed, \( A \) is the focal area of the beam, \( N_1^0 \) is the initial undisturbed ground state population, \( B_{12} \) is the Einstein coefficient for a transition between states 1 and 2, \( I_\nu \) is the incident laser irradiance per unit frequency interval, \( A_{21} \) is the spontaneous emission rate constant and \( Q_{12} \) is the collisional quenching rate. Equation 3.1 requires a priori knowledge of a large number of parameters pertaining to the instantaneous properties of the molecule and the environment surrounding it, making LIF a difficult method for direct species measurements. This technique, however is greatly simplified when a ratio of fluorescence signals is taken as a number of the parameters in equation 3.1 are identical for the two fluorescence lines [42].

3.1.2 2-\( \lambda \) OH Fluorescence and Boltzmann for Thermometry

Thermometry from fluorescence requires the detection of two separate yet compatible lines. Typically the initial ground state is identical but the excited states are different, allowing a comparison between the two values. According to equation 7.56 from Eckbreth [39], the temperature is evaluated from:
\[ T = \frac{\hbar (E_1 - E_2)}{\ln \left( \frac{F_{31} I_{13}}{F_{32} I_{23}} \right) k^{\lambda_{31}^{2}}} \] (3.2)

Where \( F_{ij} \) is the fluorescence signal due to emission from \( i \to j \) and \( I_{ij} \) is the irradiance.

Since the OH radical is an important marker for the combustion process, and since the OH molecule has a very well-understood fluorescence spectrum [43], it is often chosen as the detection species. The specific quanta chosen for this study excited two rotational lines from the \( X^2\Pi (v''=0) \) level to the \( A^2\Sigma (v'=1) \) state. The transitions chosen were the \( Q_1(5) \) and the \( Q_1(14) \) lines since they have a particularly high probability, are easily discernable from surrounding fluorescence lines, and together they provide high accuracy measurements for a wide range of temperatures. Figure 3.1 shows the theoretical temperature determined from the fluorescence ratio. With the use of a known temperature via other means (i.e. a thermocouple), the measured ratio can be compared to the theoretical value and used to determine a correction factor necessary to predict the temperature of the entire field.

### 3.2 Experimental Setup

As described in chapter 1, the combustion chamber, flow controllers and vortex generator remained unchanged for this experiment. The flame properties and vortex strengths also remained the same for this experiment. There were a number of additional systems added to perform the laser diagnostic however. Figure 3.2 illustrates the optical setup and is described in the following subsections. Although not shown in Fig. 3.2, ignition occurs identically to that of Fig. 2.1.
3.2.1 Optical Equipment

Fluorescence images were obtained using a Princeton Instruments intensified charge coupled device (ICCD) positioned orthogonal to the incoming beams, and opposite to an Andor iStar ICCD. The incoming light was filtered using two optical filters, a UG-11 and a WG-305. Figure 3.3 shows the percent transmittance of these two filters and their combined value. It was desirable to center the observed signal around 330 nm in order to remove noise from the elastically scattered light which occurred during the fluorescence event [44]. The two PIV images were obtained using a Redlake Megaplus ES 1.0 interline CCD camera (1008 x 1018 pixels) positioned parallel to the incoming beam. Due to port constraints, the PIV images and a single OH PLIF image were obtained from a single port, accomplished by using a 45°, 532 nm coated mirror.

The OH molecule was excited by using two Continuum Surelite III Nd:Yag lasers at their second harmonic as pumps to two different dye lasers. A Continuum Jaguar dye laser, was tuned to 572.74 nm then frequency doubled using a BBO crystal to approximate the Q₁(14) transitions of the OH molecule [43]. The desired UV light was separated from the primary through a Pellin Broca prism and the Q₁(14) transition was polarity shifted, by use of a pair of mirrors, to perpendicular (s-polarization). The Nd:Yag laser was used to pump a PDL II dye laser, which was tuned to 565.33 nm. The output of this dye laser was also frequency doubled using a KD*P crystal to approximate the Q₁(5) transition of OH. A Pellin Broca prism was used to separate the desired UV light from the remaining light. Since this beam is naturally p-polarized and since the Q₁(14) beam polarization was rotated to s-polarization, spatial overlap was accomplished using a thin film polarizer.
Prior to entering the pressure vessel, a small portion of the beams (~2% - 4%) was diverted across a porous plug burner, equipped with a thermal couple and a photo multiplier tube (PMT). The light entering the PMT was filtered using the same band-pass setup as that used by the ICCDs. This allowed instantaneous measure of the beams energy at the desired transition. The spatially overlapped beams were then collimated and sent through a long focal length cylindrical lens (f = 1000 mm) to produce the desired laser sheet. The collimated beams delivered approximately 2 mJ of energy for each transition into the pressure vessel.

To obtain flow field data simultaneously with the OH fluorescence images, the incoming premixed gases were further mixed with TiO$_2$ seed particles (nominal diameter of 3-5 $\mu$m) to allow elastic scattering of two PIV lasers. A Continuum Minilite PIV system was used to provide the two 532 nm laser beams. These beams were collimated and sent through a cylindrical lens and then spatially overlapped with the UV beams using a coated mirror prior to entering the pressure vessel.

### 3.2.2 Timing

Due to the transient nature of the kernel, adequate timing accuracy was required to obtain repeatable data. Figure 3.4 shows the timing scheme used to provide repeatable conditions. The variables in the diagram (t, v, and p) were all adjusted to obtain results at a specific time of interest. Each aspect of the experiment was controlled using LabVIEW software coupled to a NI BNC-2121 DAQ board. Triggered by a Stanford Research Systems DG535 delay generator, the software initialized the procedure for ignition based on the delays inherent in the laser firing scheme. The vortex generation, PIV camera gate and ICCD anti-inhibit were all timed from the same LabVIEW DAQ delay generator. The delays
for each of the times of interest can be selected and run in the software with errors on the order of $10^{-9}$ s. The two ICCD cameras were controlled by Princeton instruments PG-10 and PG-200 pulse generators. A Quantum Composer delay generator was used to provide the signals for both the Flashlamp and Q-switch of the Continuum Minilite PIV system, which was subsequently triggered from the original DG535.

3.2.3 Image Post-processing

Due to the highly transient nature of the premixed flame, it was impossible to obtain more than one image per ICCD at any given time. The images, therefore, required a great deal of post-processing, which was accomplished using a custom written code in Matlab (see Appendix).

Prior to acquiring data and for each camera, an image was taken without any signal to provide a background which was subsequently subtracted from each image. This allowed any camera bias to be removed from the result. The $Q_1(14)$ image was then aligned to the $Q_1(5)$ image using a control-point based image alignment tool in Matlab. The control-points were determined from a target mounted to a flat piece of Plexiglas and suspended inside the combustion chamber in such a way that the face was positioned at the focus of the laser sheets. This process was simplified by focusing both ICCDs with the same resolution (~13 pix/mm) and setting the center of the field of view to a central point equidistant from both electrodes.

Since this experiment was designed to utilized unsaturated fluorescence, the images required compensation for the laser sheet intensity variations. This was completed by suspending a dye cuvette, much like the alignment target, at the focus of the laser sheets. A
series of images for each laser were then obtained and the highest signal value measured at each row of pixels where the cuvette was observed. These values were then inverted and used to dampen the areas of unnatural intensity. Due to intensity fluctuations in the maximum value, a series of 20 or more images were taken and the average value along each row was used for the correction.

Once the images were aligned and the raw data corrected for each fluorescence line, the pixel-by-pixel ratio of the signals was obtained and a temperature was calculated. Since the instantaneous fluorescence intensity was recorded, a correction was done to adjust the experimental ratio to match that of the Boltzmann temperature so the remaining ratios would produce the correct temperature. Any outlying noise found on the reactant side of the flame edge was removed using the threshold images as described in the following section. Finally, the temperature field was filtered to express the $87^{th}$ percentile of a 4x4 interrogation window throughout the flame by using the \textit{ordfilt2} command in Matlab. This effectively smoothed the temperature profile to allow the expression of the flame temperature variations. The following sections present the results starting with geometric measurements from thresholding, followed by stretch measurements and concluding with stretch-dependent temperature measurements.

### 3.3 Flame Boundary: Thresholding

Initial PLIF images of the flames showed a clear separation between the unburned reactants and the hot products. The $Q_1(5)$ transition, having the more energetic emission,
was chosen to determine the location of the flame edge. Once determined, the flame area was calculated and compared to the chemiluminescence measurements.

Figure 3.5 shows the threshold images of the $\phi = 0.64$ methane flame. From this figure, the affect of the increase in vortex strength can be seen, especially at the later times. Variations in the initial interaction between the vortex and the kernel do not appear to dramatically change as the vortex increases in strength. At 6 ms after ignition, however there is an obvious advancement of the stronger vortices (> 77 cm/s) into the kernel. At 10 ms after ignition there is a clear separation of vortex strength. The strong vortex compresses the flame further, significantly reducing the flames area, while increasing the flame boundary.

A convenient method for measuring the affect of the vortex is to observe the ratio of flame length (length of the flame edge) to flame cross-sectional area. Figure 3.6 shows the ratio of flame length to flame cross-section for the methane flame at $\phi = 0.64$ undergoing each of the interaction strengths. As seen in the figure, as the vortex strength increases, the flame length approaches and eventually surpasses the flame area. It is at these later times that specific flame properties would be desired, since the flame is more likely to be extinguished due to mutual annihilation.

Since the propane flame has higher thermo-diffusive dependence, the threshold images provide insight into the geometric affect of a varying equivalence ratio. Figures 3.7 through 3.10 show the varying geometry of the weak and strong vortex affecting the propane flames between $\phi = 0.69$ to $\phi = 1.32$. While the weak interactions maintain a similar structure for all equivalence ratios, there is some variation in the overall size of the kernel as the mixture varies from thermo-diffusively stable ($\phi = 0.69$) to thermo-diffusively unstable ($\phi = 1.32$).
The vortex does not appear to penetrate farther for any mixture, however the flame propagation appears to increase with decreased thermo-diffusive stability. The strong vortex interactions for all the equivalence ratios show the flame with a varied response. Like the weak interaction, there is an overall increase in kernel size, however unlike the weak vortex, the strong vortex appears to either be augmented by the increased turbulence and generate more flame area (Figs. 3.9 and 3.10) or show little to no augmentation and nearly extinguish the flame (Figs 3.8 and 3.9).

The affect of vortex strength and interaction time is best observed by taking the ratio of flame length to cross-sectional area and plotting this ratio over the time observed. Figure 3.11a shows the flames geometric response to the weak vortex interaction. As seen in the figure, there is little variation in the flame length to flame area ratio, as expected from the earlier threshold images. With increased vortex strength, however, there is a significant variation, which also deviates from the expected trend provided by the methane flame. As seen in Fig. 3.11b, for the thermo-diffusively stable flames ($\phi = 0.69$ and $\phi = 0.87$), the trend is similar to the methane flame (thermo-diffusively unstable at $\phi = 0.64$), showing an increase in this ratio. The thermo-diffusively unstable flames do not show this trend and due to the significant increase in flame area, display a decrease in the flame length to flame area ratio. This departure from the expected trend is a testament to the large thermo-diffusive dependence of the propane flame.
3.4 Stretch Rate

In order to obtain a quantitative value which can be compared to other stretching events, the velocity field surrounding the flame was measured using PIV. Typically, the stretch rate is used to quantify the influence of an external perturbation on the flame edge.

The increased tangential strain rate caused by increasing the rotational velocity imposed by the vortex (weak to strong) can be measured based on the rate of change of the tangential velocity \( u_t \) along the coordinate which follows the flame edge \( s \), as described by Driscoll, et al [45]:

\[
S_{tt} = \frac{\partial u_t}{\partial s}
\]  

(3.3)

Since the most significant vortex effects are located at the interface between the vortex and the flame, the top third of each of the flames were isolated from the rest of the flame. The tangential velocity along this section is plotted against the tangential coordinate in Figure 3.12. As seen from the figure, the trend of the velocity shows a positive slope when moving from the left of center to the right of center for each of the vortex strengths. Also seen in the figure, as the vortex strength increases, the tangential velocity becomes less linear, yet still monotonically increasing. Since the fluctuation of the strain rate is mostly due to an increase in flame curvature, the linear fit to the velocity was sufficient to describe the tangential strain rate \( S_{tt} \).

While the strain rate is an indication of the external influence the vortex has on the flame chemistry, this does not completely describe the vortex effect. The flame structure and basic
chemical process must be taken into consideration. Driscoll, et al continues to describe a second term which accounts for the rate of area increase from the increased curvature [45]:

\[
\frac{S_{L,\infty}}{R}
\]

(3.4)

where \( R \) is the instantaneous radius of curvature and is positive when convex toward the reactants. If this term is subtracted from the tangential strain rate, the two-dimensional stretch rate (\( K \)) is evaluated:

\[
K = S_{\tau} - \frac{S_{L,\infty}}{R}
\]

(3.5)

Figure 3.13 shows the results of the average stretch rate of the methane flame studied. It can be seen, as the vortex strength increases, the average stretch rate increases. However, as time progresses, the average strain rate tends to decrease for all the vortex strengths studied. This reduction can be attributed to the increase in flame length and the subsequent slowing of the impinging turbulence due to the increasing viscous drag.

In order to observe the effects of increasing thermo-diffusive dependence in a highly transient environment, propane’s response was also observed. Figure 3.14 shows the affect for each of the equivalence ratios studied. By separating each image by equivalence ratio, the general trend of the stretch rate can be seen as a function of time after ignition. As seen in Figures 3.14a, and 3.14b a thermo-diffusively stable flame has an increase in average stretch rate as time increases after ignition when subjected to a strong vortex. This trend begins to reverse as the flame equivalence ratio increase. Figure 3.14c shows a decrease in the average flame stretch rate when the flame is subjected to a strong vortex. This trend continues for the thermo-diffusively unstable flame (Fig. 3.14d). This increase in stretch rate
can be explained by the high rate of curvature developed from the stable flame and the relatively slow unstretched laminar burning velocity, which is normalized by the instantaneous effective radius, according to equation 3.5. The trends remain consistent for a weak vortex, regardless of equivalence ratio, where the average stretch rate decreases as time advances. Also seen in the methane results, this decrease in average stretch rate can be attributed to the overall reduction in velocity from viscous drag produced by the flame front.

Due to the large parameter space studied, it is not practical to explore every interaction at every moment after ignition, therefore only a few of the noteworthy interaction strengths and times will be discussed further.

### 3.5 Thermometry

The affect of hydrodynamic strain on the flame chemistry is best described by the temperature, as it has a direct correlation to the heat release rate. There are limitations, however on the available equivalence ratios which can be used for thermometry. Due to collisional quenching affects, only the very lean methane equivalence ratio provided enough signal to obtain a reliable temperature measurement. By using the known flame boundary to compare the measured signal to the region outside of the flame, an estimation of the signal-to-noise ratio can be obtained. Figure 3.15a shows the average signal-to-noise ratio of the methane flame. If the ratio of the two fluorescence lines is taken, then the decreasing trend in signal quality can be seen. This process can be repeated for propane and displayed for the five equivalence ratios studied. Shown in Fig. 3.15b, the trend line of the ratio can be seen to
drop quickly, recover slightly, then fall to unusable levels. Since the richest case does not provide sufficient signal ratios, this equivalence ratio was not used for this analysis.

Following the post-processing techniques described in section 3.2.3, the temperature of the flame kernel was evaluated. Due to the large number of cases studied and the large amount of space necessary to display them, only a single time was selected to display both methane and propane. Since the propane flame speed was, on average, much higher than the methane flame speed, a time of 7 ms was selected for the methane and a time of 6 ms was selected for the propane in order to provide comparatively similar geometric structure.

Figure 3.16 shows the combined two dimensional field of temperature overlaid with velocity for the weak vortex at 7 ms after ignition. As seen in the figure, there is obvious separation between the areas of high rotation of the vortex, an area nearest to the cores, and the actual flame front. Also, from the figure the flame edge is clearly defined by a higher temperature. This value of ~2300K is near the expected lean adiabatic flame temperature, and is indicative of the flame reaction zone. The values found within the flame boundary are significantly cooler than the flame edge, yet show little variation from the median temperature of 1900K. Due to the proximity in time to the ignition event, the flame has not expanded sufficiently to allow for significant cooling of the centered products, causing a near homogenous temperature profile.

Shown in Figure 3.17, when the methane flame kernel is interacted with a medium strength vortex, the two-dimensional temperature field shows a loss of continuity along the flame edge. The increase in vortex strength is sufficient to stretch the flame, causing a reduction in the chemical process. Like the weak vortex interaction, the center of the flame
remains nearly homogenous. Unlike the weak vortex however, the center shows a high
temperature value. This anomaly is the result of residual spark energy located in the center
of the kernel, which was often seen early in the chemiluminescence images from chapter 2.
This measurement and should be considered false and not a part of the normal flame
structure.

This decrease in flame temperature along the edge becomes more evident when the
vortex strength is increased to “strong”. Figure 3.18 shows the two dimensional temperature
and velocity overlay for the methane flame subjected to a strong vortex. Like the interactions
discussed above, the edge of the flame has a defined reaction zone, though there is less
continuity than the weak flame. In the upper “wings” of the flame found at the highest
extreme of the flame, there is an area of cool products, which may be due to the highly
curved flame front produced from the high velocity found at close proximity to the vortex
cores. Like the medium strength vortex, this case has a large amount of residual spark found
in the center of the flame, causing a significant rise in the calculated temperature, which
should be negated as a real chemical event. Also of note is the large increase in vortex
strength evident from the size of the velocity vectors seen in this figure. Much like the initial
observations of the cold-flow velocity fields produced during the initial preparation stages of
this work (not shown), the strong vortex has well defined vortex cores. But unlike the cold
flow vectors, there is a minor compression of the leading edge of the vortex as it approaches
the kernel.

Analysis was also performed on the propane flame to produce temperature and velocity
fields similar to those presented above for the methane flame. Even though the average
signal-to-noise ratio of the propane mixtures tended to drop as the equivalence ratio increased (Fig. 3.15b), all but the richest cases were examined in order to observe the effects of a flame which exhibits high thermo-diffusive dependence. Since only the most extreme cases were of interest, the medium strength vortex interaction was not studied.

Figure 3.19 shows the propane flame’s response to the weak vortex for equivalence ratios between 0.69 and 1.32 at 6 ms after ignition. Initial observation of the temperature fields shows an overall increase in flame area as equivalence ratio increases, which corresponds to the threshold images presented earlier (Figs. 3.7 through 3.10). Similar to the methane results, there is a clear separation between the flame reaction zone and the hot products for all equivalence ratios. Shown in Fig. 3.19a, the most lean flame ($\phi = 0.69$) appears to have a structure in the upper-left quadrant not found in the other mixtures. This unusual “dip” in the flame curvature is a result of electrode interference for the Q1(14) image and does not reflect a true representation of the flame boundary. According to the image, the “oldest” products found in the central region of the flame have a higher temperature than the products found just after the flame front, especially around the top and bottom of the flame. This trend is found throughout the remaining equivalence ratios and may be a result of the residual spark heating the combustion products remaining near the ignition point.

By increasing the equivalence ratio to $\phi = 0.87$, the flame appears to become slightly compressed by the weak vortex, as seen in Fig. 3.19b. Like the previous cases mentioned there is a significant “hot spot” in the center of the flame, which appears to heat the core fluid, yet the edge products cool before reaching the reaction zone, where the obvious high-temperature boundary can be observed. The increase in equivalence ratio appears to provide
a more continuous temperature profile along the flame reaction zone than that of the $\phi = 0.69$
flame. Approaching thermo-diffusive instability, the $\phi = 1.08$ flame shown in Fig. 3.19c
contains a similar structure to the previous flames, with a heated core and a clearly defined
flame boundary. The structure however has increased in size compared to the thermo-
diffusively stable flames at the same time, indicating a significant augmentation in the
reaction rate, which can also be seen in the flame’s increased reaction zone temperature. The
overall core temperature however remains consistent with the other equivalence ratios.

The final equivalence ratio presented here is the most thermo-diffusively unstable flame
studied with these techniques. Shown in Fig. 3.19d, the $\phi = 1.32$ flame presents
thermodynamic qualities closer to the most stable flame ($\phi = 0.69$) with a significant drop in
temperature between the defined reaction zone and the core of the products. A portion of this
central rise in temperature could be attributed to the residual spark energy necessary for
ignition. The drop in temperature seen here however may be due to the increased flame
length produced from the high amount of curvature generated from the flame’s thermo-
diffusive instability, which was also seen in the high-speed chemiluminescence results from
Chapter 2.

The results presented above of the weak propane flame provide only a portion of the
necessary data in order to understand the thermo-diffusive affects present in the flame
chemistry. Figure 3.20 shows the propane flame response to the strong vortex for each
equivalence ratio presented. For all equivalence ratios, the flame is defined by a distinct
reaction zone and a core of hot products. The increase in vortex strength is observed to affect
each equivalence ratio differently however.
Initial observations of Fig. 3.20a, show the most thermo-diffusively stable flame ($\phi = 0.69$) with an average increase in temperature in all areas inside the flame boundary. There is still a reduction in temperature just inside the flame reaction zone, however as seen in the weak vortex interaction of the same flame. The upper edge of the flame also has a more continuous temperature profile to that found in the weak vortex interaction. The results of the $\phi = 0.87$ flame shown in Fig. 3.20b present a similar increase in flame reaction zone continuity as well as a general increase in combustion product temperature. There is also a clearly defined spark residual found in the core of the flame, which would skew an average kernel temperature measurement. Moving to the $\phi = 1.32$ flame in Fig. 3.20c, where the Markstein number indicates a progress toward thermo-diffusive instability (Ma = 2.66), there is a significant difference in the flame structure compared to the stable flames. The top flame front, which interacts directly with the incoming vortex, shows significant compression and progression toward the lower flame front. The temperature along the top flame front appears to be reduced when compared to the weak vortex interaction, especially at an area around the center of the flame. At areas along the “wings” of the flame, however the temperature appears to be higher than the center. This increase may indicate a reduction in stretch rate, as seen with the weak vortex when the same flame undergoes a lower stretch rate.

The final equivalence ratio presents structures not seen in any of the other interactions discussed so far. The high velocity vortex contains enough momentum to entrain new reactants and bring them within a close enough proximity to the hot products to ignite a separate flame kernel. Figure 3.20d shows this structure above the left-hand “wing” of the original flame kernel. The temperature within this structure does not appear to maintain the
homogeneous composition of the weak interactions, suggesting a highly stretched structure, which would coincide with the high velocity of the vortex core. The central structure of the main kernel is comprised of a similar heterogeneous mixture of temperatures, also suggesting a highly stretched flame. The flame reaction zone is poorly defined when compared to the previously discussed flames and vortex strengths. This flame’s inconsistent structure may be due to the poor signal-to-noise ratio found with rich flames, as discussed earlier, however a trend can still be formed to compare the weak vortex interaction with the strong vortex interaction.

3.6 General Trends

From the previous section, the general thermodynamic structure was observed as a function of equivalence ratio and vortex strength. This allowed a direct comparison between thermodynamic and aerodynamic variations in the flame response however more direct observations between flames at specific locations along the flame front are necessary in order to provide a complete characterization of the flame. By selecting the regions near the flame-vortex interface, the thermodynamic response of the flame can be directly measured as a function of stretch rate. As before, the center third of the flame was chosen as the region of interest. This corresponds to a tangential coordinate range of -0.6 cm to 0.6 cm. The area compared, however spanned only the most central region between -0.2 cm and 0.2 cm. This region was selected and an average value of a 2x2 interrogation window surrounding each point was calculated. By displaying the flame temperature along this interface as a function of stretch rate, the direct affect of the increased vortex strength can be observed.
Starting with lean methane, Figure 3.21 shows the relationship between temperature along the flame edge and the imposed stretch rate. As seen in the figure there is significant variation in the weak vortex temperature along the area of interest. This scatter quickly reduces as the vortex strength increases. According to the figure, the average temperature appears to drop as the flame stretch rate is increased. This reduction in temperature is a direct result of the impinging vortex strength and the progression of increasing turbulence causing extinction along the flame-vortex interface. This extreme stretching was seen to cause global extinction of the thermo-diffusively stable methane flame during the high-speed chemiluminescence work discussed previously and it is speculated that a further increase in vortex strength would provide the same result for the thermo-diffusively unstable flame.

Due to the inability to obtain thermo-diffusive trends with methane, similar analyses were performed using propane. Figure 3.22 shows the temperature as a function of stretch rate along the center of the flame-vortex interface (top of the flame) for each of the propane flames investigated. Shown in Fig. 3.22a, the most thermo-diffusively stable propane flame moves from an average temperature of ~1600K to ~1720K with an increased vortex strength. Along the same path, the average stretch rate reduces from a weak vortex interaction to a strong vortex interaction. This trend continues when the equivalence ratio is increased to \( \phi = 0.87 \) (Fig. 3.22b), even though the weak vortex interaction shows nearly the same temperature as the \( \phi = 0.69 \) result. The strong vortex interaction has a much higher average temperature at ~1900K. Moving to \( \phi = 1.08 \), shown in Fig. 3.22c, the trend between interaction strengths begins to deviate from the highly stable flames. Moving from weak to strong, the average stretch rate is shown to increase, rather than decrease as seen previously.
The average temperature also deviates from the previous equivalence ratios, as it remains nearly constant across stretch rate. The thermo-diffusively unstable flame presents the most varying trend when compared to the previous equivalence ratios. Seen in Fig. 3.22d, the $\phi = 1.32$ case shows a completely opposite trend in average temperature to the cases previously presented, except for the methane case, which is also a thermo-diffusively unstable flame. The trend in temperature as a function of thermo-diffusive stability is therefore consistent between fuels. The average stretch rate also follows the methane result, as it increases with vortex strength, resulting in identical characteristics between fuels.

3.7 Summary

As a continuation of previous global measurements, non-invasive laser diagnostics were performed on methane and propane kernels subjected to vortices of varying strengths in order to obtain an accurate two-dimensional measurement of the geometric and aero-thermodynamic response of the flame. Due to experimental and physical limitations, the methane flame was limited to the thermo-diffusively unstable mixture ($\phi = 0.64$), while the propane flame measurements were accurate enough to provide trends in thermo-diffusive stability ($\phi = 0.69$ through $\phi = 1.32$). A number of trends arose from these measurements, which reflect this thermo-diffusive dependence, and are mentioned below:

1. By increasing the impinging vortex strength, the flame length, determined by the edge of the flame boundary, became large compared to the flame cross-sectional area for the methane flame at $\phi = 0.64$. This trend continued for lean propane until the mixture became rich, where the thermo-diffusive effects caused rapid area
The stretch rate, known to be a function of the turbulence imposed upon the flame reaction zone and the flame curvature, increased as the vortex strength increase, as expected. The stretch rate was seen to decrease, however for all flames studied as time progressed after ignition, regardless of vortex strength. Therefore, the effect of the vortex on the flame is diminished with increasing time, since the flame causes a viscous damping of the external influence provided by the vortex.

There is a direct effect of stretch rate on temperature along the flame reaction zone; however the trend depends on thermo-diffusive stability. For both fuels at a thermo-diffusively unstable mixture, by increasing the vortex strength, the stretch rate increases, while the temperature decreases. The increase in stretch rate is expected as the thermo-diffusively unstable flames tend to become more curved than the stable flames. The decrease in temperature suggests the thermo-diffusively unstable flames have a reduction in heat release rate when influenced by a highly stretching vortex. The thermo-diffusively stable flames (propane with $\phi \leq 1.08$) generally show an opposite trend to the unstable flames. By increasing the vortex strength, the thermo-diffusively stable flames tend to have a reduction in stretch rate, which allows an increase in temperature along the flame-vortex interface. This apparently opposite response to increased vortex strength suggests the stable flames lack of increased flame area reduces the effective stretch rate. Overall, an increase
Figure 3.1: Temperature as a function of fluorescence ratio described by equation 3.2.
Figure 3.2: Optical setup for the simultaneous 2-λ OH PLIF and PIV experiment.
Figure 3.3: Optical filters used to remove elastically scattered light for the OH-PLIF image acquisition. The combination of the two filters effectively creates a single band-pass filter centered approximately around 335 nm.
Figure 3.4: Timing diagram of the simultaneous PIV & OH-PLIF experiment. The values for \( p \) and \( v \) varied according to the time of interest \((t)\) after ignition, since they are not triggered from the laser gate.
Figure 3.5: Threshold images of methane with an equivalence ratio of 0.64 showing (a) an undisturbed flame; a flame interacting with (b) a weak vortex, (c) a medium vortex and (d) a strong vortex. Time is relative to ignition. Each image has dimensions 38.5 mm x 25.6 mm.
Figure 3.6: Ratio of flame length to cross-section area for each methane flame-vortex interaction observed. The best-fit lines are second-order polynomials.

Figure 3.7: Threshold images of propane with an equivalence ratio of 0.69 interacted with a (a) weak vortex and (b) strong vortex.
Figure 3.8: Threshold images of propane with an equivalence ratio of 0.87 interacted with a (a) weak vortex and (b) strong vortex.

Figure 3.9: Threshold images of propane with an equivalence ratio of 1.08 interacted with a (a) weak vortex and (b) strong vortex.
Figure 3.10: Threshold images of propane with an equivalence ratio of 1.32 interacted with a (a) weak vortex and (b) strong vortex.

Figure 3.11: Ratio of flame length to cross-section area for propane flames interacting with a (a) weak vortex and (b) a strong vortex. The best-fit lines are second-order polynomials.
Figure 3.12: Tangential velocity as a function of tangential coordinate for the $\phi = 0.64$ methane flame.
Figure 3.13: Average stretch rate across the top of the flame along the center third of the field of view for the $\phi = 0.64$ methane flame for each of the vortex strengths studied.
Figure 3.14: Average stretch rate of propane flames interacting with weak and strong vortices for (a) $\phi = 0.69$, (b) $\phi = 0.87$, (c) $\phi = 1.08$ and (d) $\phi = 1.32$. 

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Figure 3.15: Average signal-to-noise ratio of the (a) methane flame and (b) the propane flame as a function of equivalence ratio. The black line is the ratio of the $Q_{1}(14)$ to $Q_{1}(5)$ signal-to-noise ratio and is plotted on the secondary y-axis.
Figure 3.16: Two-dimensional temperature and velocity field of $\phi = 0.64$ methane undergoing an interaction with a weak vortex ($U_0 = 77$ cm/s) at 7 ms after ignition.
Figure 3.17: Two-dimensional temperature and velocity field of $\phi = 0.64$ methane undergoing an interaction with a medium vortex ($U_0 = 266$ cm/s) at 7 ms after ignition.
Figure 3.18: Two-dimensional temperature and velocity field of $\phi = 0.64$ methane undergoing an interaction with a strong vortex ($U_0 = 398 \text{ cm/s}$) at 7 ms after ignition.
Figure 3.19: Combined thermometry and velocity data for the propane flames (a) $\phi = 0.69$ (b) $\phi = 0.87$ (c) $\phi = 1.08$ (d) $\phi = 1.32$ undergoing a weak interaction.
Figure 3.20: Combined thermometry and velocity data for the propane flames (a) $\phi = 0.69$ (b) $\phi = 0.87$ (c) $\phi = 1.08$ (d) $\phi = 1.32$ undergoing a strong interaction.
Figure 3.21: Lean methane temperature at 7 ms after ignition along the top-center (-0.2 < S < 0.2) of the flame as a function of stretch rate. The black points represent the average of the surrounding values.
Figure 3.22: Temperature as a function of stretch rate for the (a) $\phi = 0.69$ propane flame, the (b) $\phi = 0.87$ propane flame, the (c) $\phi = 1.08$ propane flame and the (d) $\phi = 1.32$ propane flame at 6 ms after ignition along the top-center (-0.2 < S < 0.2) of the flame-vortex interface. The black points represent the average of the surrounding values.
4 Quantification of Electrode Perturbation through Laser Ignition

4.1 Motivation

Previously discussed high-speed chemiluminescence images of the flame-vortex interactions have provided a means by which to reliably quantify the affect of a transient event on the progression and expansion of premixed hydrocarbon flames. Each progression from thermo-diffusively stable flames to thermo-diffusively unstable flames showed a significant increase in flame surface generation, as corrugated structures were observed. These structures were also observed to occur with flames with no vortex interaction, suggesting a purely chemical response. In order to validate this assumption, the flame must be allowed to propagate without any physical interference from either a thermodynamic or aerodynamic perspective. The use of laser ignition has been used in the past to provide a truly non-invasive environment.

The concept of laser ignition has been suggested since the inception of lasers as viable research tools in the 1970’s [46]. More recent research as been directed toward the use of laser ignition as a more efficient means of igniting highly transient flows such as supersonic airstreams and internal combustion engines [47, 48]. Yalin et al. [48] suggests the use of laser ignition in modern internal combustion engines could be practical due to the desirable high-pressure ignition characteristics. A detailed analysis of laser-ignited gasoline for internal combustion engine use by Mullett et al. [49] highlights the combustion cylinder response to laser inconstancies. Their research suggests the development of stable laser
ignition sources could provide more stable combustion events, compared to spark ignited flames, for practical internal combustion systems. Fundamental laser ignition research has also been conducted on a variety of flames; to include hydrogen diffusion flames [50] and premixed methane flames without consideration to the affect on device performance [51].

Discussed below, the thermodynamic losses caused from ignition electrode interference are quantified with respect to the techniques previously employed, such as high-speed chemiluminescence and global pressure measurements. The modifications to the research environment are discussed first, followed by an analysis of the undisturbed and disturbed flame kernels. Finally, an analysis of the effect of laser energy on kernel formation is performed, followed by a brief description of the overall conclusions.

4.2 Experimental Setup

As previously discussed, the combustion chamber, fuel mixture and vortex generator remained unchanged for this experiment. As seen in Figure 4.1, the ignition electrodes were removed and replaced with a single 4-cm AR coated BK-7 lens, mounted within the combustion chamber. Internal mounting was necessary due to the need for a “fast” lens (low f-number) in order to produce a small viable combustion initiation zone. A single Nd:YAG at its second harmonic (λ = 532 nm) was used as the ignition source. Preliminary cold-flow observations showed gaseous ionization of the surrounding air at the ignition site upon initiation.

Timing and ignition was controlled with a similar custom LabVIEW program used in the previous experiments. Channels previously used to initiate the spark ignition were
reprogrammed to externally control the Flashlamp and Q-switch of the laser power supply. This allowed a very precise ignition timing (± 2ns), which was considered sufficiently precise to not require measurement of the ignition event for determination of high-speed camera gate timing. In order to produce more repeatable laser emission energy, the Flashlamp was allowed to fire the maximum number of cycles between initiation and ignition (8 cycles for the necessary 850 ms delay) prior to opening the Q-switch. Emission energy still contained variation however on the order of 10%.

Preliminary observations of the ignition energy requirements, showed the need to increase the laser energy with increasing equivalence ratio, especially for methane. This also resulted in a shift of the initial ignition zone, as evident by the undisturbed results presented below. The location of the ignition zone was held constant for all equivalence ratios and fuels in order to observe the effect of both varying ignition energy and kernel formation.

4.3 Comparison of undisturbed laser-ignited kernels to spark-ignited kernels

Without ignition electrodes to interfere with the flame, the high-speed chemiluminescence images of the undisturbed laser ignited flames show variation from their spark-ignited counterparts. The severity of the deviation depends on the relative thermo-diffusive stability of the mixture. Laser-ignited methane does not present significant thermo-diffusive dependence, which is reflected in the undisturbed laser ignited results. Figure 4.2 contains a few select snapshots of the high-speed chemiluminescence images of the laser ignited methane flames studied. According to the figure, thermo-diffusive effects are non-existent, as the $\phi = 0.64$ flame shows little variation from the remaining equivalence ratios.
At about 52 ms after ignition, there is a slight deviation of the $\phi = 0.90$ flame however, where a small region of the right extreme of the flame begins to progress before the bulk flame front. This variation is most likely due to the close proximity of the flame front to the ignition lens.

A significant departure from the spark-ignited flame, the overall structure of the laser-ignited undisturbed methane flame front is smoother, especially along the top and bottom surfaces. However, a “dimpling” structure remains along the ignition region. This may be due to the cylindrical shape of the flame kernel observed during the initial ignition phase, which is a product of the laser ignition shape.

Though the methane flame presents few differences between spark ignited flame geometry and laser ignited flame geometry, the propane flame shows a more significant departure from the spark-ignited results. The thermo-diffusive effects of the propane flame are nearly non-existent when the flame propagates without the interference from the spark electrodes. Figure 4.3 shows the high-speed chemiluminescence images of the laser ignited propane flames at the extreme equivalence ratios ($\phi = 0.69$, $\phi = 1.08$ and $\phi = 1.49$). Initial observations show almost no variation between thermo-diffusively stable and unstable flames. According to the figure, the intermediate equivalence ratio shows more geometric variation when compared to the richest case, which was not observed during spark ignition.

Comparing the effective radius of the spark-ignited undisturbed methane flame to the laser ignited undisturbed methane flame provides a means to quantify the affect of the electrodes. To ascertain deviations in effective radius, the correlation between the spark-ignited flame and the laser-ignited flame was calculated. If the entire expansion is
considered, the correlation is \( R^2 = 0.9994 \), however, if the first 10 ms are removed, the correlation increases to \( R^2 = 0.99993 \), suggesting a slight deviation in effective radius for the spark-ignited flame. According to Figure 4.4a, the effective radius of each of the equivalence ratios of the methane flame has a more similar propagation rate to that of the spark-ignited flame (see Fig. 2.3) with less deviation at later times after ignition. Though muted when compared to the spark-ignited flame, there are visible thermo-diffusive effects on the effective radius trend. During the initial phase of kernel formation, the thermo-diffusively stable methane flame (\( \phi = 1.13 \)) shows a non-linear decrease in effective radius followed by a recovery to a nearly linear propagation rate; while the thermo-diffusively unstable flame possesses an exceptionally linear relationship (\( R^2 = 0.99996 \)) throughout the entire expansion process.

The laser ignited undisturbed propane flame effective radius shows a similar trend when compared to the methane results. As seen in Fig. 4.4b, the propane effective radius is clustered near a singular line, yet follows the same general trend when compared to the spark ignited results at the same condition (see Fig. 2.6a). The thermo-diffusively stable flames, like the methane, display a drop in effective radius during the initial phases of the kernel propagation. The thermo-diffusively unstable flames deviate from the expected result seen in the methane flame, and tend to increase in effective radius during the initial expansion phase. With sufficient time, all cases return to a near linear expansion, similar to the spark ignition effective radius trend.
4.4 **Comparison of disturbed laser-ignited kernels to spark-ignited kernels**

The addition of a vortex to the laser-ignited kernel presents a variety of different flame responses when compared to a spark-ignited kernel. As in previous experiments, the kernel was subjected to identical vortices of three different strengths in order to gage the flame response. The removal of the spark electrodes allowed observation of a truly unencumbered flame. The interactions will be presented below by strength, starting with the weak vortex interaction. For brevity, the medium strength vortex chemiluminescence results have been omitted.

4.4.1 *Weak vortex interaction of the laser ignited flames*

Observations of the weak vortex interaction with the methane flame presents unique structural variations from the spark ignited results. According to Figure 4.5, initially the vortex interacts with the lean methane flame ($\phi = 0.64$) in a nearly identical manner to that of the spark-ignited flame. As the vortex progresses through the kernel, the structure of the vortex becomes asymmetric and the vortex tail appears to form additional flame surfaces (36 ms). The flame also appears to become corrugated along the top surface of the flame; a structure reminiscent of the thermo-diffusively unstable propane flame (36 ms and 47 ms). This structure was not prevalent in the spark-ignited lean methane flame. This could be attributed to the lack of interference from the electrodes, as the flame chemistry is unencumbered during flame expansion. The ignition site of the laser-ignited flame is also brought further into the background, causing the vortex to interact with the flame at a location which is slightly off-center. This allows the observation of additional flame structures along the initial kernel-vortex interface.
Comparing the thermo-diffusively stable flames (\(\phi = 0.90 \) and \(\phi = 1.13\)), Fig. 4.5 shows a large similarity between the flame properties of these two chemical compositions. The vortex maintains its axisymmetric structure further into the kernel when compared to the lean case. For both stable flames, comparison to the spark-ignited cases at the same mixture reveals a nearly identical structure, except for the vortex continuity. As the vortex passes the electrodes it becomes disturbed, resulting in an earlier consumption than the laser-ignited flames. This trend is continued in the lean case as well (Fig. 2.12), even though the corrugated structure is not as visible.

High-speed chemiluminescence images of laser-ignited propane reveal a significant departure from the results seen during the spark-ignited event. Figure 4.6 shows a very clear separation in structure between the thermo-diffusively stable flames (\(\phi = 0.69\), \(\phi = 0.87\) and \(\phi = 1.08\)) and the thermo-diffusively unstable flames (\(\phi = 1.32\) and \(\phi = 1.49\)). Notably, the \(\phi = 1.32\) flame produces a secondary flame structure along the direction of the incoming laser. This expansion appears to be a result of the initial flame structure, where the central reactants, not consumed during the initial ignition phase, are pushed outward by the expanding flame front. While the structure of the spark-ignited thermo-diffusively unstable flames presents additional corrugation, they do not appear to be augmented to the same degree as the laser-ignited flames. This augmentation of the unstable flames was a result not found in the undisturbed flames of the same mixture (Fig. 4.3), suggesting the necessity for an external perturbation to obtain flame surface corrugation.

Thermo-diffusively stable laser-ignited propane flames appear to have a very similar structure to the corresponding spark-ignited flames. The surface of the flame remains
smooth between ignition types. The vortex symmetry also appears to dissipate at the same rate, since by no later than 26 ms, the vortex begins to show additional surface structures for both ignition types. Deviations from expected trends appear when the relative progression of the laser-ignited kernel is compared to the spark-ignited kernel. According to Figure 4.6, the vortex has not progressed into the laser-ignited kernel to the degree it did in the spark-ignited kernel. This may be attributed to the relative slowing of the propane flame caused from the heat loss to the spark electrodes.

4.4.2 Strong vortex interaction of the laser ignited flames

Further analysis of the effect of ignition on flame expansion requires comparison of a high stretch environment to the previously discussed cases. Select high-speed chemiluminescence images of the laser-ignited methane flame subjected to a strong vortex are shown in Figure 4.7 for all equivalence ratios studied. Comparing the thermo-diffusively unstable laser ignited methane (\( \phi = 0.64 \)) to spark ignited methane (Fig. 2.13) shows a very similar interaction, however the vortex of the laser ignited kernel appears to have progressed farther than the vortex of the spark-ignited kernel (~15 ms). This continues until the flame reaches the image boundary. Likewise, the thermo-diffusively stable, lean flame (\( \phi = 0.90 \)) shows a region of apparent flame-flame annihilation as the vortex flame front approaches the bottom flame front of the original kernel (~15 ms). As the vortex continues, it entrains fresh unburned reactants, causing the formation of a secondary kernel attached to the primary. As with the spark ignition, the rich case (\( \phi = 1.13 \)) undergoes global annihilation and therefore
due to the similarity of this interaction to the spark-ignited kernel (Fig. 2.14) and the lack of sufficient chemiluminescence intensity, it has been omitted.

4.4.3 Effect of ignition type on flame effective radius

Comparison between ignition types requires an observation of the trends in effective radius of the flame-vortex interaction. Figure 4.9a shows the affect of vortex strength on the laser-ignited thermo-diffusively unstable methane flame. When compared to Fig. 2.16a, initial observations indicate nearly identical trends. Variations become obvious, however, when the early times are analyzed. The laser-ignited flame appears to have a much closer effective radius compared to the spark-ignited flame for the first 7 ms. Also, the strong vortex appears to have a more significant effect on the laser-ignited flame than the spark ignited flame; with a separation from the medium strength vortex effective radius approximately 20 ms before the spark-ignited flame.

The remaining laser-ignited interactions show similar trends to the spark-ignited interactions, where an increase in vortex strength causes a corresponding increase in effective radius. According to Fig. 4.9a, the weak vortex initially reduces the effective radius to values below that of the undisturbed kernel as it begins to penetrate the top flame edge of the kernel. This trend is also seen in the spark-ignited flame (Fig. 2.6a), though the radius is quicker to recover past the undisturbed line.

Increasing the equivalence ratio to $\phi = 1.13$, presents more significant deviations between ignition types. The laser-ignited flame shown in Fig. 4.9b presents the same “clustering” effect found in the laser-ignited undisturbed flame. When compared to the
spark-ignited flame, (Fig. 2.6b) there is less of a reduction in effective radius for the weak-vortex interaction at times near ignition. The laser-ignited flame and medium vortex, also appear to progress in a more stable manner than the spark-ignited flame at times near ignition. At approximately 20 ms after ignition, however, the laser-ignited flame shows a reduction in the medium strength effective radius; an affect not seen in the comparable spark-ignited effective radius. As discussed earlier, the strong vortex interaction causes global extinction and therefore the effective radius drops quickly to zero at approximately 6 ms after ignition. Also seen in the spark-ignited results, the laser-ignited flame is apparently completely extinguished 10 ms earlier, suggesting the electrodes help to sustain the thermo-diffusively stable flame.

Analysis of the effective radius of the propane flame requires a comparison to the spark-ignited effective radius, not presented in Chapter 2. This data is therefore presented side-by-side to the spark-ignited results. Figures 4.10 through 4.12 show the effective radius of the laser-ignited and the spark-ignited propane flames for all equivalence ratios studied. These results will be discussed in order of equivalence ratio, moving from lean (thermo-diffusively stable) to rich (thermo-diffusively unstable).

Comparison of thermo-diffusively stable propane spark-ignited flame to the laser-ignited flame shows only a few minor variations (Figs 4.10a and b). The most significant difference appears for the weak vortex, as the spark-ignited flame (Fig. 4.10b) undergoes a flame radius reduction (compared to the undisturbed flame) during the first ~19 ms after ignition. This trend is not observed during the identical laser-ignited event, where the weak-vortex effective radius remains above the undisturbed value for its entire progression. The medium and
strong interactions for both ignition schemes appear nearly identical, but for a few deviations during the initial expansion phase.

Increasing the equivalence ratio to $\phi = 0.87$ does not significantly alter the result of a comparison between ignition schemes (Figs 4.10c and d). Interactions of note are limited to the strong vortex. The strong vortex, apparently unencumbered by the electrodes, expands the effective radius of the spark-ignited kernel beyond that of the medium vortex at times around 8 ms. At times closer to 10 ms, however, the radius reduces to values below the medium strength vortex, from which it does not recover until after 22 ms. The laser-ignited flame at identical conditions shows a more monotonic rise, eventually surpassing the medium strength vortex.

Analysis of the effective radius of the near stoichiometric flame presents the beginning of significant deviation between ignition schemes. Figures 4.11a and b shows the effective radius of the laser-ignited flame and the spark-ignited flame respectfully. Initial observation of the spark-ignited results (Fig. 4.11a) shows a close clustering of effective radii for all vortex strengths (excluding undisturbed) near ignition (~1-5 ms). According to Fig. 4.11b, during the same time, the spark-ignited flames do not share this similarity. The spark-ignited flame shows an almost instant augmentation when affected by both the medium and strong vortices, starting at 4 ms. The weak vortex interaction seen in the spark-ignited figure is the only case which appears to deviate from this trend and decrease to just below the undisturbed values before recovering around 10 ms and surpassing the undisturbed effective radius.

Increasing the equivalence ratio to $\phi = 1.32$, the first of the two thermo-diffusively unstable flames can be analyzed. According to Figs 4.11c and 4.11d, the previous trend of
near instant augmentation for the spark-ignited flame, when compared to the laser-ignited flame, is repeated. The laser-ignited flame however, appears to deviate from the expected strong-vortex-high-effective radius trend seen with the thermo-diffusively unstable methane flame. Also, according to the figures, the undisturbed propagation rate appears to be significantly lower for the laser-ignited flame than the spark-ignited flame.

The final equivalence ratio of $\phi = 1.49$ (Figure 4.12) provides results of the most thermo-diffusively unstable flame. This flame displays the most significant differences between ignition schemes. According to Fig. 4.12b, there is an immediate rise for the strong vortex interaction with the spark-ignited flame at approximately 4 ms, which is not seen in the laser-ignited flame until approximately 8 ms after ignition. Also, there is less of a deviation of the laser-ignited flame between the undisturbed and the strong vortex interaction than the deviation of the spark-ignited flame across the same parameter space.

### 4.4.4 Effect of ignition type on flame burning velocity

In order to quantify the effect of ignition type on the flame chemistry, the burning velocity was calculated and plotted using the same technique as employed in Chapter 2 for the spark-ignited flames. Since the results of that analysis presented complex results, they have been repeated here to provide an instant comparison between ignition schemes. The results from the methane flame are presented first, followed by the propane in order of increasing equivalence ratio.

Figure 4.13 shows the disturbed burning velocity normalized by the undisturbed burning velocity calculated from global pressure measurements for the methane flame across all
equivalence ratios. General trends of the spark-ignited methane flame show the effect of thermo-diffusive stability as the lean methane flame has the most significant augmentation for all vortex strengths, followed by the subsequently increasing equivalence ratio.

Comparing directly the laser-ignited flames to the spark-ignited flames shows an increase in burning velocity at times closer to ignition for all vortex flames and equivalence ratios, suggesting the lack of electrode interference allows the progression of all flames at times near ignition.

Comparing the weak vortex interactions across ignition schemes, (Figs. 4.13a and 4.13b) there is a significant increase in burning velocity in the laser-ignited flame starting near the same time as the spark-ignited flame. The spark-ignited flame however, begins to drop before reaching 200 ms, where the laser-ignited flame does not. For both ignition schemes, the medium strength vortex appears to reduce the burning velocity when compared to the weak vortex (Figs. 4.13c and 4.13d). The strong vortex interactions for both ignition schemes, show significant augmentation for the thermo-diffusively unstable flame, with less, but still significant increase in burning velocity for the $\phi = 0.90$ flame and global extinction for the $\phi = 1.13$ flame.

Thermo-diffusive effects are also visible for the propane flame, though the laser-ignition significantly affects the flame response. According to Figure 4.14, moving from laser-ignited thermo-diffusively stable propane to thermo-diffusively unstable propane causes an increase in burning velocity during times near the ignition event. While still following the expected augmentation trend, the laser-ignited results show only small variations between vortex strengths. Only a few cases are observed to move away from the expected thermo-
diffusive trend. At $\phi = 1.49$ in Fig. 4.14c, the normalized reactant consumption rate appears to decrease when compared to the neighboring value at $\phi = 1.32$. According to Fig 4.14e, the thermo-diffusive trend appears to affect the flame along all times after ignition, unlike the spark-ignited trends which appear to be affected at later times only (Figs. 4.14b, 4.14d and 4.14f).

Information provided by the pressure calculated measurements is best described by comparing the normalized reactant consumption rate as a function of Markstein number as this is a measurement of thermo-diffusivity. Shown in Figure 4.15, there is a definite separation between the laser-ignited flames and the spark-ignited flames. According to the trend of the strong vortex interaction, the thermo-diffusively unstable spark-ignited flames ($\text{Ma} < 0$) appear to show a significant augmentation compared to the laser-ignited flames. Furthermore, the dependence on stretch rate of the normalized reactant consumption rate shows that the global pressure measurement provides information regarding the affective turbulence. Figure 4.16 shows the disturbed burning velocity normalized by the undisturbed burning velocity as a function of the average stretch rate, as calculated from Chapter 3 across the 7 ms range available. According to the figure, as the thermo-diffusivity increases, and the vortex strength increases, the normalized pressure-derived burning velocity also increases.

### 4.5 Effect of increased laser energy on kernel formation

Beyond comparison between spark-ignited and laser-ignited kernels, the highly controllable ignition energy of the laser-ignited system provided additional insight into the
affect ignition energy has on kernel formation. Since the laser-ignition system required the use of a “fast” lens to focus the incoming beam to a small point within a short distance, increasing the energy of the beam should increase the viable ignition area of the fuel. Prior to a chemical analysis, the ignition site itself was analyzed to observe the variation in ignition geometry across laser energy. Analyzed in a similar fashion to the chemiluminescence threshold images, Figure 4.17 shows the effective radius of the high-intensity ignition zone as a function of laser energy. As seen in the figure, there is a trend toward an asymptote of approximately 4.2 cm past 200 mJ. This suggests additional energy beyond 200 mJ would not result in varied flame geometry. In order to validate this theory, the effect of varying ignition energy was observed. Due to its relative chemical simplicity and well-known properties methane was chosen as the fuel to analyze.

Figure 4.18 shows the effect of increasing the ignition energy of the laser-ignited methane flame through a normalization of the laser-ignited undisturbed effective radius by the spark-ignited undisturbed effective radius. Values above 15 ms required a linear interpolation since the largest flame reached the edge of the field of view at this time. Increments of 50 mJ were chosen to provide a consistent trend in ignition energy. Typically, for this setup, lean methane required a minimum of approximately 40 mJ to ignite, so the 10 mJ increase can be seen as a slight increase in the 50 mJ case at times near ignition. As the energy increases, the relative effective radius also increases. According to the figure, this increase is found to be more significant at times near ignition. As the flame kernel expands, the relative radius begins to asymptote to unity for all energies. Also seen in the figure are large fluctuations at times very near ignition (0-3 ms). These are a result of the polynomial
interpolation of the spark-ignited effective radius to $t = 0$, since camera limitations prevented observation of the spark-ignition event. According to the figure, there is a reduction in the effect of increased ignition energy past a value of 200 mJ, which corresponds to the asymptotic limit of the ignition site energy previously discussed.

4.6 Abbreviated Conclusions

Laser ignition of methane and propane flames was accomplished in order to quantify the spark-ignition electrode interference on the flame-vortex propagation rate and calculated burning velocity. The chemical composition of the reactants was chosen to match that of the spark-ignited kernels in order to provide a direct comparison. A majority of trends were observed, summarized below:

1. High-speed chemiluminescence imaging of laser-ignited flames suggests the need to externally perturb a thermo-diffusively unstable flame in order to create a corrugated structure. Even though it has a low thermo-diffusive dependence, methane follows this thermo-diffusive trend, especially when the flame undergoes a strong vortex interaction.

2. According to effective radius measurements, electrode interference can account for a loss in propagation rate of the methane flame. When the electrodes are removed, the propagation rate of the undisturbed flame is unencumbered and the effective radius of each equivalence ratio follows nearly the same linear path.
(3) The affect of the electrodes on burning velocity is significant for both flames. While the methane flame exhibits augmented burning velocities without electrode interference, the propane flame exhibits a relative reduction in burning velocity without the electrodes. This suggests the high thermo-diffusive dependence of propane may require external interference in order to create more significant heat release.

(4) Increasing the laser energy causes an increase in the viable ignition zone for values between 40 mJ and 200 mJ. Increasing further does not significantly increase the viable ignition zone, nor does the flame kernel obtain a significant increase in initial effective radius beyond 200 mJ.
Figure 4.1: Experimental setup modification for laser ignition.
Figure 4.2: High-speed chemiluminescence images of the undisturbed laser ignited methane flame.
Figure 4.3: High-speed chemiluminescence images of the undisturbed laser ignited propane flame. Time is relative to ignition.
Figure 4.4: Undisturbed effective radius of the laser-ignited (a) methane flames and (b) propane flames studied.

Figure 4.5: Sequence of high-speed chemiluminescence images of the weak vortex interacting with the laser ignited methane flame.
Figure 4.6: Sequence of high-speed chemiluminescence images of the weak vortex interacting with the laser ignited propane flame. Time is relative to ignition.
Figure 4.7: Sequence of high-speed chemiluminescence images of the strong vortex interacting with the laser ignited methane flame.
Figure 4.8: Sequence of high-speed chemiluminescence images of the strong vortex interacting with the laser ignited propane flame.
Figure 4.9: Effective radius measurements of the laser ignited methane flame at (a) $\phi = 0.64$ and (b) $\phi = 1.13$. 
Figure 4.10: Comparison of laser ignition effective radius measurements (a and c) to spark ignited effective radius measurements (b and d) of the propane flame at (a and b) $\phi = 0.69$ and (c and d) $\phi = 0.87$
Figure 4.11: Comparison of (a and c) laser ignition effective radius measurements to (b and d) spark ignited effective radius measurements of the propane flame at (a and b) $\phi = 1.08$ and (c and d) $\phi = 1.32$
Figure 4.12: Comparison of laser ignition effective radius measurements (a) to spark ignited effective radius measurements (b) of the propane flame at $\phi = 1.49$. 
Figure 4.13: Disturbed laminar burning velocity normalized by undisturbed laminar burning velocity for the methane flame. Laser ignition is shown in the left column, while spark ignition is shown in the right column to facilitate comparison of augmentation between ignition types for (a-b) weak vortices, (c-d) medium vortices and (e-f) strong vortices.
Figure 4.14: Disturbed laminar burning velocity normalized by undisturbed laminar burning velocity for the propane flame. Laser ignition is shown in the left column, while spark ignition is shown in the right column to facilitate comparison of augmentation between ignition types for (a-b) weak vortices, (c-d) medium vortices and (e-f) strong vortices.
Figure 4.15: Normalized reactant consumption rate as a function of thermo-diffusivity (Markstein number) for all flames studied. Solid lines are third order fits to the spark-ignited and laser-ignited flames interacting with a strong vortex.

Figure 4.16: Disturbed burning velocity normalized by undisturbed burning velocity as a function of average stretch rate (across all time) for all flames studied.
Figure 4.17: Effective radius of the high-intensity region of the laser ignition site as a function of laser energy. The best-fit line is a second-order polynomial.

Figure 4.18: Effect of laser energy on effective radius of the undisturbed $\phi = 0.64$ methane flame. Filled symbols represent a linear fit to the last 15% of the original effective radius data.
5 Conclusions

A variety of experimental investigations were performed in order to quantify the aerodynamic and thermodynamic variations of a highly transient combustion event from steady flame theory. Previous investigations illustrated the need to expand the experimental parameter space to include a variety of equivalence ratios and stronger vortices. Methane at equivalence ratios of $\phi = 0.64$, $\phi = 0.90$ and $\phi = 1.13$, and propane at equivalence ratios of $\phi = 0.69$, $\phi = 0.87$, $\phi = 1.08$, $\phi = 1.32$ and $\phi = 1.49$ were chosen and nitrogen diluted to the same flame speed to allow a separation of chemical kinetic effects from stretch effects, while maintaining thermo-diffusive trends. High-speed chemiluminescence imaging coupled with global pressure measurements were performed in both spark-ignited and laser-ignited flames, to allow effective radius and relative reactant consumption rate calculations, and to quantify the aero-thermodynamic effect of the ignition electrodes. PIV and OH-PLIF measurements were then performed on key interactions to provide a means to determine the stretch rate dependence of flame dynamics. The overall findings of this investigation are presented below:

1. The thermo-diffusive effects of propane are more prevalent than methane. Undisturbed premixed methane flames near their ignition limit ($\phi = 0.64$), though thermo-diffusively unstable ($Ma = -0.10$), did not present significant variation in surface structure when compared to thermo-diffusively unstable propane ($\phi = 1.32$ and $\phi = 1.49$; $Ma = -0.61$ and $Ma = -1.92$, respectively).
For most flames, a congruent increase in stretch rate (defined by the rotational velocity of the vortex) and an increase in curvature (defined as a reduction in the delay of the vortex interaction with the kernel) causes an increase in the reactant consumption rate. As the vortex strength was increased by approximately 400%, the maximum burning velocity (relative to the undisturbed flame) of the methane flames increased by 2% to 20% depending on the equivalence ratio.

Thermo-diffusive instability is necessary for continued flame propagation if the flame is subjected to a high stretch rate. As seen in the rich methane flame, global extinction occurred during the strong vortex interaction. The lean flame however, displayed a significant augmentation (~ 74% increase in $S_b$) when subjected to a vortex of identical strength.

Using global pressure measurements to determine overall flame augmentation is possible. With a known undisturbed reactant consumption rate, the augmented flame stretch rate can be estimated as either above or below 150 s$^{-1}$. With a known mixture, the instantaneous pressure measurements can be used to categorize the stretch rate as high or low, relative to the undisturbed reactant consumption rate.

The stretch rate imposed on the flame from the impinging vortex diminishes with increasing time, since the flame causes a viscous damping of the external influence provided by the vortex. This suggests the transfer of momentum from the vortex to the flame kernel causes an increase in flame area, while decreasing the tangential (to the flame surface) vortex velocity.
There is a direct effect of stretch rate on temperature along the flame reaction zone which also has a thermo-diffusive trend that varies from steady flame theory. For both fuels with a thermo-diffusively unstable mixture, by increasing the vortex strength, the stretch rate increases, causing a decrease in temperature. The increase in stretch rate is expected as the thermo-diffusively unstable flames tend to become more curved than the stable flames. The decrease in temperature suggests the thermo-diffusively unstable flames have a reduction in heat release rate when influenced by a highly stretching vortex. The thermo-diffusively stable flames (propane with $\phi \leq 1.08$) generally show an opposite trend to the unstable flames, which follows steady flame theory. By increasing the vortex strength, the thermo-diffusively stable flames tend to have a reduction in stretch rate, which allows an increase in temperature along the flame-vortex interface. This apparently opposite response to increased vortex strength suggests the stable flames lack of increased flame area reduces the effective stretch rate. Overall, an increase in stretch rate causes all flames to reduce the average reaction zone temperature across the center of the flame regardless of thermo-diffusive stability, except for the unity Lewis number flames (propane at $\phi = 1.08$). This trend follows the results found for steady flames, except with thermo-diffusively unstable flames. Both unstable methane and propane flames showed a decrease in temperature, which is contrary to the extensive steady flame results found in recent literature.

The formation of surface structure corrugation in thermo-diffusively unstable flames requires an external (to the flame) perturbation. This perturbation is
Increasing the ignition energy associated with laser ignition caused an increase in the initial kernel size. As expected from the undisturbed flame chemistry, this propagation continued asymptotically to the same rate as the flame propagated beyond 25 ms after ignition. The addition of energy into the unburned reactants caused a larger kernel to form initially however, the flame was not continuously augmented.
6 Future Work

As presented, the development of complex turbulence-chemistry interactions requires diligent control of the surrounding conditions. In order to provide insight into practical internal combustion devices, the effect of increased pressure would be a necessary next step.

This process would require a re-design of the combustion chamber in order to provide a near isobaric environment, though at higher pressures than atmospheric. This device would ideally be made spherical to remove any asymmetric affects of the chamber. Great care would have to be taken to consider the combustion volume as well as optical access, which requires a near planar face to reduce the formation of optical aberrations or diagnostic energy loss. Care would also need to be taken to provide the near isobaric conditions necessary to reduce equipment damage and injury. The use of computer controlled needle valves coupled with highly sensitive pressure transducers would be ideal.

Expansion on both the spark-ignited results and the laser-ignited results would be of interest within a new combustion chamber. The variation of modern spark-ignited combustion devices from purely undisturbed flames would be of interest. This could allow the development of more sensitive pressure-derived results, dependent on the overall stretch rate which the flame is undergoing.
7 Literature Citations


8 Appendices
Post processing program to determine stretch rate, temperature, flame boundaries and laser profile (KVProgram.m):

```
act = ['1100'];  % Boolean to drive action (thermometry, vector combo, thresholding, profile)

% Load file...name describes the conditions, % Date, Fuel, Phi, Vortex, Time ie:
% 05_15_08P1.32WE10ms.asc

[fname,pname] = uigetfile('*.asc','Select File'); cd(pname);
dte = datenum(fname(1:8));
phi = str2num(fname(10:13));
vtx = fname(14:15);
tme = str2num(fname(16:17));

% Change vortex alpha notation to numerical notation:
if vtx == ['Ud']
    vtn = 0;
elseif vtx == ['WE'] | vtx == ['WL']
    vtn = 1;
elseif vtx == ['ME'] | vtx == ['ML']
    vtn = 2;
elseif vtx == ['SE'] | vtx == ['SL']
    vtn = 3;
end

% Matlab format data archive:
dta = load('C:\MATLAB_KV\ExperimentLog.txt');
% Search entire parameter space for number of cases where date, phi and vortex strength match:
nc = 0;
for i = 1:length(dta)
    if dta(i,1) == dte & dta(i,2) == phi & dta(i,3) == vtn
        nc = nc + 1;
        tt2(nc) = dta(i,4);
    end
end

% if nothing is found, display error and exit program
if nc == 0
    disp('        !!!Warning!!!
    No matching name found in log file
    Exiting program');
    return
end

% Name structure for input to program:
pnm = fname(1:15);
snm = fname(18:end);

% Waitbar stuff:
if fname(9) == ['M']
    fuel = [' Methane '];
else
    fuel = [' Propane '];
end

% 145
```
% Run the profile program if selected:
% -----------------------------------------------------------------

pnme = ['Q5ProfilePoly.mat'];
if act(4) == [1]
    dir_old = pwd;
    % Run for Q5
    [fname1,pname1] = uigetfile('*.asc','Select Q5 File');
    KVProfile(fname1,pname1,dir_old,fname1(1:end-5));
    % Run for Q14
    [fname1,pname1] = uigetfile('*.asc','Select Q14 File');
    KVProfile(fname1,pname1,dir_old,fname1(1:end-5));
elseif length(dir(pnme)) == 0
    dir_old = pwd;
    % Run for Q5
    [fname1,pname1] = uigetfile('*.asc','Select Q5 File');
    KVProfile(fname1,pname1,dir_old,fname1(1:end-5));
    % Run for Q14
    [fname1,pname1] = uigetfile('*.asc','Select Q14 File');
    KVProfile(fname1,pname1,dir_old,fname1(1:end-5));
end
% -----------------------------------------------------------------
% Run the thresholding program using the input values defined above:
% -----------------------------------------------------------------
n2sve = [fname(1:15),'ThreshImages.mat'];
if act(3) == [1] | length(dir(n2sve)) == 0
    h = waitbar(0,['Running Thresholding Calculations ',fname(10:13),fuel,vtx,' @ ',num2str(tme),' ms']);
    for i = 1:nc
        % Text time variable for loading the correct file:
        if tt2(i) < 10
            tt = ['0',num2str(tt2(i))];
        else
            tt = num2str(tt2(i));
        end
        % Name of file:
        nme = [pnm,tt,'ms.txt']; % file name for Q5 (Mac camera - Highest signal/noise)
    % -----------------------------------------------------------------
    % Run the program:
    % -----------------------------------------------------------------
        [Thresh(:,:,i)] = KVThreshold(nme);
    % -----------------------------------------------------------------
    % -----------------------------------------------------------------
    % -----------------------------------------------------------------
    waitbar(i/nc,h,['Running Thresholding Calculations ',fname(10:13),fuel,vtx,' @ ',num2str(tme), ' ms']);
end
save(n2sve,'Thresh');
close(h);
else
    load(n2sve);
end

% Run the thermometry program using the input values defined above:
% -----------------------------------------------------------------
if act(1) == ['1']
    h = waitbar(0,['Running Thermometry ',fname(10:13),fuel,vtx,' @ ',num2str(tme),' ms'],
    'Position',[300 690 280 50]);
    for i = 3:nc
        % Find the transitions, intensities and temperature measured for
        % the specific experiment stored in the database file:
        % -----------------------------------------------------------------
        for j = 1:length(dta)
            if dta(j,1) == dte & dta(j,2) == phi & dta(j,3) == vtn & dta(j,4) == tt2(i)
                Q14T = dta(j,5); Q5T = dta(j,6); Q14I = dta(j,7); Q5I = dta(j,8); T = dta(j,9);
            end
        end
        % Calculate the thermometry corrector:
        % -----------------------------------------------------------------
        EneTransQ14 = 0.9064;   % Transmittance percentage of energy calculated from Fresnel equations Q14
        EneTransQ5  = 0.9534;   %       "                               "                       "      Q5
        EneRatio    = sqrt(EneTransQ14/EneTransQ5);
        Tmod = (T + 273 + 100);
        Rcalc = -1.2114247734E-16*Tmod^5 + 2.3224815142E-12*Tmod^4 - 1.7449318614E-08*Tmod^3 +
            6.4306598189E-05*Tmod^2 - 1.1732183471E-01*Tmod + 8.7379289677E+01; %Rcalc = 0.0000054167*(T +
            273 + 100)^2 - 0.02697*(T + 273 + 100) + 36.493;  % Ratio calculated from corrected (+100) TC temp
        PR = Q5T/Q14T;              % Ratio of transitions calculated from porus plug
        ER = Q5I/Q14I;              % Ratio of energy signals
        IC = Rcalc - PR;            % Initial corrector
        C  = 0.5 + ER; % + 1/IC; %ER/IC*EneRatio; %ER; %27/IC*EneRatio*ER; % Final Corrector
        fprintf('               IC                    ER                 C   
');
        fprintf(' %20.6f %20.6f %20.6f
',IC,ER,C);
    end
    % Profile
    % -----------------------------------------------------------------
    kc = 0.90;          % Q5  (num)
    kb = 1.00;          % Q14 (denom)
    load('Q5ProfilePoly.mat');
    Poly5 = mean(Poly,2);
    load('Q14ProfilePoly.mat');
    Poly14 = mean(Poly,2);
if tt2(i) < 10
    tt = ['0',num2str(tt2(i))];
else
    tt = num2str(tt2(i));
end

nme1 = [pnm,tt,snm];  % file name for Q14 (PC camera)
nme2 = [pnm,tt,'ms.txt'];  % file name for Q5 (Mac camera)

[Temperature(:,:,i),Q14ImageUC(:,:,i),Q5ImageUC(:,:,i),Q14Image(:,:,i),Q5Image(:,:,i),Tave(i,:),Temp_filt(:,:,i),Thr
esh2(:,:,i)] = ThermProgram(nme1,nme2,Poly14,Poly5,C,Thresh(:,:,i),['1100']);

figure(1000); plot(1:length(Poly5),Poly5,'b-',1:length(Poly14),Poly14,'r-'); set(gcf,'position',[32 735 288 208],'name','Plot of Profiles Used');
close(h);
n2sve = [fname(1:15),'TempData.mat'];
save(n2sve,'Temp_filt');

Avettle = ['Average Temperature of Kernel with ',num2str(max(Tave(:,2)) - min(Tave(:,2)))];
end

% Run the vector program using the input values defined above:
tme = str2num(fname(16:17));
if act(2) == ['1']
    h = waitbar(0,['Loading Vector Data',fname(10:13),fuel,vtx,' @ ',num2str(tme),',',num2str(num2str(str(tme)),' ms')]);

    % Unstretched laminar burning velocity (methane - propane...lean to rich)
    SL_list = [9.38,10.32,13.34,21.47,18.85,18.34,15.73,13.93];

    % Select based upon input parameters:
    if fuel == [' Methane ']
        if phi == 0.64
            SL = SL_list(1);
        elseif phi == 0.90
            SL = SL_list(2);
        elseif phi == 1.13
            SL = SL_list(3);
        else
            disp('Flame speed error');
            break
        end
    elseif fuel == [' Propane ']
        if phi == 0.69
...
SL = SL_list(4);
elif phi == 0.87
    SL = SL_list(5);
elif phi == 1.08
    SL = SL_list(6);
elif phi == 1.32
    SL = SL_list(7);
elif phi == 1.49
    SL = SL_list(8);
else
    disp('Flame speed error');
    break
end
end

Tmp_nme = [pnm,'TempData.mat']; % name for thermometry
Thr_nme = [pnm,'ThreshImages.mat']; % name for threshold images;

load(Tmp_nme); % output variable is 'Temp_filt'
load(Thr_nme); % output variable is 'Thresh'

for i = 3 : nc
    if tt2(i) < 10
        tt = ['0',num2str(tt2(i))];
    else
        tt = num2str(tt2(i));
    end

    % Select ROI size based on vector speed:
    if vtn == 3 % strong vtx
        ROI_height = (60 - 4*i)/100;
    elseif vtn == 1 % weak vtx
        ROI_height = 0.6;
    else
        ROI_height = 1;
    end

    Vnme = [pnm,tt,'msImage1.mat']; % file name for vector file
    [s,K,r,Stt,V,V_fit,Temp,Vec,T_K,Cout] = VectorProgram(Vnme,Temp_filt(:,:,i),Thresh(:,:,i),SL,ROI_height);

    % Save the stretch and strain data:
    if s ~= 0
        %figure; plot(s(1:end-1),K);
        svenme = [pnm,tt,'Stretch&Strain.txt']; % Name of file
        fid = fopen(svenme,'w'); % Open file
        head1 = ['Coordinate        Stretch        Strain        Temp        TanVelocity
Radius \n'];
        % Header for file
fprintf(fid,head1); % Write header to file

% Write data to file:
for k = 1:length(K)
    fprintf(fid,'%12.4e\t%12.4e\t%12.4e\t%12.4e\t%12.4e\t%12.4e
',s(k+1),K(k),Stt(k),T_K(k),V(k+1),r(k));
end
fclose(fid); % Close file
end

% Save the temperature and vector data for techplot:
% -----------------------------------------------------------------
svenme = [pnm,tt,'ThermVec.dat']; % Name of file
fid    = fopen(svenme,'w'); % Open file
if s ~= 0
    head1  = ['VARIABLES= "X-Coordinate (cm)"", "Y-Coordinate (cm)"", "U/Temp", "V/Edge" ZONE T="Velocity", I=71, J=123 \n'];   % Header for file
    fprintf(fid,head1); % Write header to file

    % Write vector data to file:
    for k = 1:length(Vec)
        fprintf(fid,'%12.4e\t%12.4e\t%12.4e\t%12.4e
',Vec(k,1),Vec(k,2),Vec(k,3),Vec(k,4));
    end
    head2  = ['ZONE T="Temperature", I=',num2str(size(Temp_filt,1)),', J=',num2str(size(Temp_filt,2)),' \n'];   % Header for file
    fprintf(fid,head2); % Write header to file

    % Write temperature data to file:
    for k = 1:length(Temp)
        fprintf(fid,'%12.4e\t%12.4e\t%12.4e\t%12.4e
',Temp(k,1),Temp(k,2),Temp(k,3),Temp(k,4));
    end
    fclose(fid); % Close file
end

Stt_mean(i) = mean(Stt);
K_mean(i) = mean(K);

% Update waitbar:
% -----------------------------------------------------------------
waitbar(i/nc,h,['Loading Vector Data',fname(10:13),fuel,vtx,' @ ',tt,' ms']);
end
close(h); end
Image of the labView front panel used in the laser ignition experiment.