Flashback and Turbulent Flame Speed Measurements in a Hydrogen and Methane Fired Low-Swirl Injector at Elevated Pressures and Temperatures

David Beerer\textsuperscript{1}, Vince McDonell\textsuperscript{1}, Peter Therkelsen\textsuperscript{2}, Robert Cheng\textsuperscript{2}

\textsuperscript{1}UC Irvine Combustion Lab, Irvine, CA 92697
\textsuperscript{2}Lawrence Berkeley National Lab, Berkeley, CA 94720

This paper reports on flashback limits and turbulent displacement flame speed measurements in a low swirl injector operated at elevated pressures and inlet temperatures with hydrogen and methane based fuels. The goal of this study is to understand the driving physics relating turbulent flame speeds to flashback at conditions relevant to gas turbine engines. Testing was conducted in an optically accessible single nozzle combustor rig at pressures ranging from 1 to 8 atm, inlet temperatures from 290 to 600K, and inlet bulk velocities between 20 and 60 m/s for natural gas and a 90%/10% (by volume) hydrogen/methane blend. Flashback occurred for high-hydrogen flames, but not for natural gas. The firing temperature at flashback was found to be proportional to the bulk velocity and inlet temperature, and inversely proportional to the pressure. Flashback occurred when leading edge of the flame approached the nozzle exit, even in flames which showed attachment near the burner rim. The unburned velocity field was measured using a Laser Doppler Velocimeter (LDV) with water seeding. Turbulent displacement flame speeds were found to be linearly proportional to the root mean square velocity fluctuations about the mean velocity. For identical inlet conditions, high-hydrogen flames had a turbulent flame speed roughly twice that of natural gas flames. Pressure, inlet temperature, flame temperature had surprisingly little effect on turbulent flame speed.

1. Introduction

Interest in synthesis gas from coal gasification has increased in recent years as an alternative fuel to natural gas \cite{i}. Depending upon the source of coal and the process, the hydrogen concentration in the synthesis gas stream can be upwards of 90% by volume \cite{i}. Several studies in past years have outlined the difficulty of stabilizing high-hydrogen flames in lean premixed combustors. The prominent challenge is associated hydrogen’s high reactivity, which makes the flame prone to flashback into the premixer \cite{ii}. Aiding conditions where flashback occurs is of paramount importance to the combustion engineer. Unfortunately, design guides and other tools to help predict the propensity of flashback are in their infancy. The interaction of the turbulent flame propagation rate with the flow aerodynamics is a complex process, which makes it difficult to model. Detailed numerical simulations of hydrogen/air flames have been reported detailing the interaction of wrinkled flames with the flow \cite{iii}. Though the simulations are very time consuming and expensive, which limits their application in engineering design. Turbulent flame speed $S_T$ measurements are also present in the literature, with a handful at elevated pressures and temperatures relevant to gas turbine combustors \cite{iv,v}. Unfortunately, a knowledge gap still exists on how to use such information for the accurate prediction of flashback in lean premixed combustor.

In the present investigation flow field velocimetry measurements and flashback limits are measured and reported in a low-swirl combustor at elevated pressures and inlet temperatures. With this information the relationships between the inlet conditions, flow field, turbulent flame speed, and flashback propensity are established at conditions relevant to gas turbine engines.
2. Background

In a low-swirl combustor stabilization is achieved through a detached or lifted flame that is freely propagating into a divergent turbulent flow field. The flow field is produced with a device known Low-Swirl Injector (LSI), which is statically placed inside the premixer between 1 to 1.5 diameters upstream of the nozzle exit. The LSI consists of an inner channel with a perforated plate, and an outer annulus containing multiple swirl vanes, as shown in Figure 1. The premixed reactants passing through the annulus form a swirling outer region in the combustor, while the reactants passing through the inner channel form a non-swirling inner region. The hole pattern and sizes on the perforated plate control the level of turbulence on the inner flow, and determines the flow split between the two regions. The swirling motion of the outer flow causes it to expand radially outward, which induces a similar divergence on the inner flow as well. The divergence results in a decreasing mean axial velocity along the centerline of the flow field. This velocity gradient is the key to stabilizing the flame. When lit, the turbulent flame will propagate against the velocity gradient at characteristic speed, $S_{T,LD}$, until it reaches a point along the axis where local velocity, $U$, is equal in magnitude, but opposite in direction to $S_{T,LD}$ [vi]. The two velocities will balance, resulting in a stationary but lifted flame. Figure 2 shows a lifted methane/air flame from the current study with the streamlines of the flow field superimposed. Flow is from top to bottom. The distance between the exit plane of the nozzle (defined as $x = 0$) and the leading edge of the flame (denoted as $x_f$) is known as the lift-off height. As will be shown later, $S_{T,LD}$ is primary only a function of the fuel composition and $u'$, the root mean square of the turbulent velocity about the mean. The mean strain from the flow divergence keeps $u'$ fairly constant along the axis from the nozzle exit to the flame front.

Figure 1: Low Swirl Injector, back view (left) and front view (right).

Unlike high swirl burners, the LSI does not impart enough swirl to form a vortex breakdown or central recirculation zone within the vicinity of the flame [vi]. As a result, the simpler aerodynamics of this flow lends itself to very straightforward analytical models of the turbulent flame process and flame position [vi]. Additionally, the lifted flame avoids the complexities of flame/wall interactions, and also minimizes the heat transfer to the nozzle [vii]. The flame also is more accessible for interrogation with optical or laser diagnostics [vi].

The low-swirl concept was initially developed as a convenient means of studying fundamental turbulent flame properties in a laboratory setting, [viii]. Experience has found that this flame can stabilize a number of fuels over a wide range of conditions, while maintaining low emissions [ix]. Low-swirl burners have, subsequently, been developed for atmospheric pressure applications such as industrial furnaces, boilers, and heaters of various sizes and power outputs [x].

Recently, interest has begun in developing this technology for fuel flexible gas turbines; however, this requires knowledge of the flame’s performance and properties at elevated pressures and temperatures. So far, only a handful of studies have been conducted with the LSI at elevated conditions. Solar Turbines® for instance performed single nozzle rig tests with natural gas at pressures, $P_o$, inlet temperatures, $T_o$, and bulk velocities, $U_o$, of up to 13 atm, 700K and 48 m/s, respectively. Emissions and blow out limits were reported in Johnson et al. [xi] and Nazeer et al. [xii]. The National Energy Technology Lab (NETL) also studied the LSI in their optically accessible SimVal combustor test rig at similar conditions with fuel mixtures of methane and hydrogen. Flame imaging, emissions and limited flashback measurements were reported in Cheng et al. [xiii]. Finally, Georgia Tech has conducted experiments with several syngas compositions at elevated conditions. Flames images and LBO measurements were reported in Littlejohn et al. [xiv].

The most challenging class of fuel reported in these studies are those containing high concentrations of hydrogen. Cheng and Littlejohn [xv] have reported that at equivalence ratios, $\varphi$, above 0.3 hydrogen, flames have a
tendency to begin burning in the shear layer. When this occurs the flames fold back and attaches to the burner rim; though, the inner region of the flame still remains lifted. NETL also reported experiencing flashback for flames with hydrogen fuel concentrations above 80% [xiii]. Their limited data indicates that increasing hydrogen concentration increases the propensity for flashback; however the influence of \( P_0, T_0 \) and \( U_0 \) is unclear. It is also uncertain if the flame flashes back through the inner region or the outer shear and boundary layer. The former is more common for high-swirl flames, while latter is more common for jet flames [xvi, xvii].

Figure 2: Low-swirl methane flame with streamlines superimposed. Flow direction is top to bottom

3. Experiment

The experiments in this study were performed in an optically accessible pressure vessel at the high-pressure test facility at the University California Irvine Combustion Laboratory (UCICL). A photograph of the facility is shown in Figure 3 and full details are given in Beerer et al. [xviii, xix]. The facility is fed by three air compressors, and electric resistance heaters raise the temperature of the air. A back pressure valve regulates the test section pressure. The pressure, inlet temperature, air and fuel flows are all independently adjusted and controlled through proportional integral derivative (PID) feedback control loops.

A cross-sectional image of the high pressure vessel can be seen in Figure 4. The vessel itself is made from a 16” schedule-40 crome-moly steel pipe with 16”-300 lb flange ends. The vessel contains two pairs of window ports. One pair is for 15.3 cm (6”) in diameter circular windows, while the other is for 20 cm by 15.5 cm (8” x 6”) oblong windows. Each window is made from 5 cm (2”) thick fused quartz.

Within the pressure vessel is a single nozzle combustor. The test section consists of a quartz tube 15 cm (6”) in diameter, 3mm thick, and 23 cm (9”) in length. The tube is compressed between two stainless steel plates that are rigidly held into place with four posts. Graphite gaskets are used to produce an air-tight fit between the quartz tube and the metal, even at the high flame temperatures. Springs are located at the end of each post to allow the combustor to grow from thermal expansion.

The premixing chamber consists of a 1¼ -inch stainless steel pipe, 30 cm (12”) in length with three fuel spokes positioned perpendicular to the flow near the inlet (top) of the tube. Two sets of thermocouples are used for flashback detection. One set is mounted flush within the walls of the nozzle, while the other set are located in the premixer just downstream of the fuel injection spokes. Additionally, pressure ports in the premixer and combustor allow for measurements of the pressure drop across the LSI and flame during testing, which is also useful for flashback detection.

The LSI used in the present study is shown in Figure 1. The outer and inner channel radii \( (R_o, R_i) \) are 19mm and 13mm, respectively. The LSI has 16 aerofoil shaped swirl vanes with a discharge angle of 37° relative to the incoming flow. The perforated plate consists of 25 holes about 2.6 mm in diameter arranged in a concentric.
This LSI design is a scaled down version of the one used by NETL [xiii] and more recently by Therkelsen et al. [xx]. The same LSI is used throughout this study, but with two different perforate plates. The first plate (LSI-P1) has a thickness of 1.5 mm, while the second plate (LSI-P2) has a thickness of 1.3 mm. The two plates achieve different flow splits through the LSI, and will be discussed in more detail later.

Figure 3: High pressure vessel and facility.

Figure 4: Cross sectional image of pressure vessel and combustor test section.
A closed loop water circuit quenches the hot exhaust products as they exit the combustor test section. Adjacent to the test chamber is a separate control room for personnel. Two computers in the control room collect and record all pertinent data using National Instruments Labview® software.

Fuel flow is controlled either manually or through a dual-fuel mixing station. Two Alicat® mass flow controllers in parallel meter the fuel flow rate. By adjusting the flow rate of each gas, binary mixtures of the constituent fuels can be achieved and tested in the rig. Natural gas (~97% CH₄, 1% C₂H₆, 2% CO₂ and N₂) is supplied from a gas compressor outside the building, and other gases are supplied from high-pressure cylinders. Maximum flow rates of natural gas and H₂ are 15 g/s and 3.5 g/s, respectively. The air flow is measured with a FCI® ST98-L thermal mass flow meters, which has a roughly 2% measurement uncertainty. The fuel flow is also measured through two Micromotions® CMF010 Coriolis meters, each with a 0.5% uncertainty. The stated equivalence ratio and firing temperature are therefore known to within about 3% and the stated inlet pressure and temperature are known to within about 0.1 atm and 5K, respectively. Ignition is accomplished non-intrusively from focusing the beam from a pulsed Nd:YAG laser into the central vicinity of the test section. The laser can be seen in the background of Figure 3 and uses one of the circular quartz windows for access into the combustor.

Flow field measurements are made with a two color Laser Doppler Velocimeter (LDV) and water droplets for seeding. The tracer particles are formed by injecting water through a small BETE® Model PJ8 fogging nozzle mounted above the premixer. The droplets average (Dₐ) 10 microns in diameter and are entrained within the air. Based on air and water flow rates, the water mass fraction to air is usually less than 1%. A Coherent I-90C 4-Watt Argon Ion Laser is used to generate the laser beam which is sent to a TSI® FBL-2 multi-color beam generator, which separates the beam into green (514.5 nm wavelength) and violet (476.5 nm) beams. The beams pass through a fiber optic cable to a TSI® TR-260 transceiver mounted on a two-direction traverse adjacent to one of the oblong quartz windows. The transceiver is shown in the foreground in Figure 3. The beams are focused in the test section using a 500 mm focal length lens in the transceiver. The green beams are used to measure the vertical (axial) velocity, and the violet beams measure the horizontal (transverse) velocity. The back-scattered collected in the same transceiver and sent to a TSI® PDM-1000 photomultiplier module. The analog signal is filtered and digitized in a TSI® FSA-4000 signal processor and recorded on a computer.

4. Results

Non-Reacting Flow Field

The experimental results are reported here in terms of the inlet pressure, \(P_o\), inlet mixture temperature \(T_o\), bulk velocity, \(U_o\), and adiabatic flame temperature \((AFT)\). \(U_o\) is calculated by dividing the volumetric flow rate of air and fuel through the premixer by its cross sectional area, 11.4 cm². \(T_o\) is calculated from an energy balance based on the inlet temperatures and flow rates of the air and fuel. \(AFT\) is calculated based on \(P_o, T_o, fuel\) composition and equivalence ratio, \(\phi\), using the equilibrium module in Reaction Design’s CHEMKIN® software.

Non-reacting radial profiles of the axial velocities for LSI-P1 and LSI-P2 are shown in Figure 5 and Figure 6, respectively. These measurements are made just downstream of the nozzle exit, at \(x = 6 \text{ mm}\); laser access for \(x < 6 \text{ mm}\) is prevented by interference with the exit plane. The profiles are normalized by \(U_o\) and \(R_o\). Qualitatively, the flow profiles are similar to those measured by Cheng et al. [vi] at atmospheric pressures. The mean velocity \(U/U_o\) in the inner region \((r/R_o < 0.6)\) is less than velocity through the outer region \((r/R_o > 0.6)\). The turbulence intensity \(u'/U_o\) is relatively uniform in the inner region, around 10%, but increases to 40% around \(r/R_o=1\), indicating the presence of a shear layer at the burner rim [xxi].

The filled-in symbols in the two plots have the same inlet conditions \((P_o=4 \text{ atm}, T_o=450K, U_o = 47 \text{ m/s})\), in order to compare any differences in the flow field between LS1-P1 and LS1-P2. The LS1-P1 mean velocity profile is parabolic in shape, with \(U/U_o=0.3\) at the centerline. LS1-P2 has a much flatter inner region profile, with lower a velocity at the centerline, \(U/U_o=0.6\). Conversely, the peak velocity in the outer region for LS1-P1 is higher, \(U/U_o=1.4\) compared to LS1-P2 with a peak \(U/U_o = 1.2\). These results indicate that LS1-P2, with the thinner perforated plate, has a higher fraction of air passing through the inner channel.

Comparison of the flow fields at different operating pressures (filled-in versus open symbols in each respective plot) indicates that \(U/U_o\) at the centerline decreases with increasing pressure. Subsequently, the mean velocities in the outer region increases with pressure. This indicates that the flow split is slightly dependent upon the pressure. Curiously, \(u'/U_o\) however does not show a pressure a dependency. Unfortunately, due to temperature limitations with the water seed droplets, the effect of \(T_o\) on flow split could not determined. Measurements at higher bulk velocities indicated that \(U/U_o\) and \(u'/U_o\) are invariant with flow rate. This is consistent with the self-similar flow properties that Cheng et al. [vi] reported at atmospheric conditions.
Figure 5: Non-reacting radial profiles of normalized mean and r.m.s axial velocities for LSI-P1

Figure 6: Non-reacting radial profiles of normalized mean and r.m.s axial velocities for LSI-P2

Flame Shape

Figure 7 compares images of the flames generated using both LSI configurations with the 90%/10% H₂/CH₄ fuel blend. LSI-P1 has a corresponding parabolic shaped flame while LSI-P2 flame is more flat in the inner region. The LSI-P1 flame anchors closer to the nozzle rim (i.e. a smaller $x_f$) due to the lower $U/U_o$ at the centerline compared to LSI-P2. The higher mean velocity in outer region of LSI-P1 pushes the edge of the flame back, resulting in only a small amount of burning in the shear layer. Conversely, the lower mean velocity in the outer region of LSI-P2 leads to a more prominent flame in the shear layer. As will be seen in the next section, the flame shape and position have a major influence on the flashback propensity for both configurations.

Figure 7: Images of 90%/10% hydrogen/methane flames from LSI-P1 and LSI-P2 at similar inlet conditions.
Testing was conducted at different inlet and firing conditions \((P_o, T_o, U_o \text{ and } AFT)\) to see how each parameter affected the flame front position, \(x_f\). When increasing either \(P_o\) or \(AFT\), while keeping the other variables fixed, decreased \(x_f\). Conversely, increasing either \(T_o\) or \(U_o\) correspondingly increased \(x_f\). Photographs of flames these trends are not shown here for brevity, but can be found in Beerer [xix].

**Flashback**

Flashback limits for both LSI configurations were measured using the fuel blend of 90%/10% H\(_2\)/CH\(_4\), by volume. The flashback limit was determined for each test by first establishing a relatively low flame temperature \((AFT \approx 1200K)\) in the combustor; then while keeping \(P_o\), \(T_o\) and \(U_o\) constant, the equivalence ratio (and \(AFT\)) was gradually increased until the flame flashed back. At this point the fuel flow was terminated. Test conditions ranged from: \(3 \text{ atm} < P_o < 8 \text{ atm}, 290 < T_o < 600\text{K}, 20 \text{ m/s} < U_o < 60 \text{ m/s}\). Under these same conditions natural gas flames were never observed to flashback. As \(AFT\) increased, the flame drew closer to the nozzle, \(x_f \rightarrow 0\). Flashback occurred once the leading edge of the flame reached the nozzle \((x_f = 0)\) for both configurations. Figure 8 shows a sequence of photographs from a flashback using LSI-P1. From studying these images and those from other tests, it appears that flashback occurs via flame propagation through the inner region of the flow, even at conditions where a flame appeared in the shear layer. In the second photograph, for instance, the flame core is well within the nozzle, but a gap still exists between the flame and the rim. This suggests the flame did not propagate through the shear layer/ boundary layer. Only in the final photograph when the flame is fully flashed back does the flame also encompass the boundary layer region.

![Figure 8: Sequential images of a flashback event](image)

Flashback could be observed visually, and fuel flow was often terminated manually. As expected, thermocouples mounted in the nozzle and premixer wall measured a temperature rise after flashback, but their response time was fairly slow (on the order of seconds). The pressure drop measured between the premixer and combustor also registered a sudden increase (within tenths of second) after flashback, as shown in Figure 9. Because of the faster response time, the LabView\textsuperscript{®} controller was programmed to automatically terminate the fuel flow when the pressure drop value increased by a factor of two over the steady value, i.e.:

\[
\Delta p_{\text{flashback}} > 2 \cdot \Delta p_{\text{non-reacting}}
\]

This method proved to be a reliable means of sensing flashback and terminating fuel flow before the flame damaged the LSI, and was also used in several tests besides the manual shut-off.

![Figure 9: Pressure drop and axial velocity measurements during a flashback event](image)
Figure 9 also shows the corresponding axial velocity in the combustor during a flashback event. The velocity measurements were made using the LDV system at $x = 15\, mm$ along the combustor centerline downstream of the sudden expansion. The mean velocity is steady until flashback, at which point it rapidly increases. Upon termination of the fuel, the velocity drops back to its nominal pre-flashback range. The velocity remains positive during the entire event, at no time is there a velocity dip or flow reversal. This indicates that no recirculation bubble or vortex break down proceeds flashback. Therefore, this suggests that the combustion induced vortex break (CIVB) flashback mechanism, which is common for high-swirl burners [xvi], does not contribute to flashback in a low-swirl burner. The lack of any pressure or velocity oscillations also negates the possibility of a combustion instability induced flashback. Inspections of the LSI after flashback have found discoloration on the downstream face of the perforated plate, which indicates that upon flashback the flame attaches to the LSI. Once this occurs, the flow through the nozzle is mostly hot combustion products, rather than unburned reactants. The hot combustion products have a lower density and, subsequently, a higher velocity, which would explain the observed velocity increase and pressure drop surge in Figure 9 during flashback.

Figure 10 shows the flashback results from this study for LSI-P1 using the 90%/10% H$_2$/CH$_4$ blend at $T_o = 400K$. The symbols represent the AFT where the flashback occurred for a given $P_o$ and $U_o$. Tests at common pressures are connected with a line. Below each line represents the region where a stable flame can be successfully stabilized; above the line the flame is propane to flashback. The results indicate that for a constant $T_o$ and $P_o$, increasing $U_o$ increases the AFT at flashback. At higher pressures, this $U_o$ dependencies (slope) decreases. For a constant $T_o$ and $U_o$, increasing $P_o$ decreases the AFT at flashback. This flashback dependency on $U_o$ and $P_o$ is similar to that observed in high-swirl and jet burners [xxii,xvi,xvii].

![Fig 10: Flashback results for LSI-P1 for $T_o=400K$](image)

Figure 11 compares the flashback limit of LSI-P1 for varying inlet temperatures. For a constant $U_o$ and $P_o$, increasing $T_o$ increases the AFT at flashback. This is rather surprising because studies with high-swirl and jet burners report that increasing $T_o$ decreases the flashback limit [xxii, Error! Bookmark not defined.]. This is an important finding because it indicates that in a simple-cycle gas turbine, where $T_o$ increases with pressure ratio, the detrimental effect of the increase in $P_o$ has on the flashback limits will be in part counter balanced by the beneficial effect of increasing $T_o$. As a result, the flashback limits for the LSI should be higher than high-swirl or jet burners for engines with large pressure ratios.

Based on the dependency of the flashback limit on the inlet conditions, the data for LSI-P1 was regressed into an expression for equivalence ratio, or $\phi$, at flashback as function of $U_o T_o / P_o$:

$$\phi_{\text{flashback}} = A \cdot \left( \frac{U_o [m/s] T_o [K]}{P_o [\text{atm}]} \right) + B$$

For LSI-P1, $A = 6.51 \times 10^{-5}$ and $B = 0.336$. Figure 12 shows the flashback results collapse quite well with the correlation; the average error between the actual to predicted values are $\pm 3\%$. The data correlated better with $\phi$ than AFT, which is why $\phi$ was used in the correlation. For an engine designer, by plugging in the $U_o$, $T_o$ and
\( P_o \) for his/her engine, the \( \varphi \) at flashback can be easily calculated. The \( AFT \) for the 90%/10% H\(_2\)/CH\(_4\) blend under lean conditions can then be calculated using the empirical formula:

\[
AFT = C \cdot T_o^{[K]} + D
\]

where

\[
C = -0.343 \varphi + 0.978
\]

and

\[
D = -1007 \varphi^2 + 3132 \varphi + 38.9
\]

This formula is accurate to within \( \pm 5K \) compared to temperatures calculated in CHEMKIN\textsuperscript{®} for \( 1200 \text{K} < AFT < 1900 \text{K} \) at any pressure.

In addition to the data from the current study, two of the conditions where NETL encountered flashback are also plotted Figure 12. In NETL’s tests, the hydrogen concentration in the fuel was increased while holding \( P_o, T_o, U_o \) and \( \varphi \) constant until flashback occurred. The two points represent conditions where flashback occurred with hydrogen concentrations of roughly 90%. NETL’s two points fall onto the correlation line from this study, which again used a similar LSI design. This indicates that flashback conditions are repeatable in different combustors.

NETL also reported that for a fixed inlet conditions, increasing the hydrogen concentration decreased the flashback limit. Therefore, it should be emphasized that the correlation in Figure 12 is strictly for the 90%/10% H\(_2\)/CH\(_4\) blend. Unfortunately, time and cost did not permit a full study on the effect of fuel composition effect on flashback.

Comparison of the NETL data with the correlation from this study indicated that for 100% H\(_2\), flashback occurs at an \( AFT \) roughly 350K lower than with a 90%/10% H\(_2\)/CH\(_4\) blend. Most likely the dependency of flashback on \( P_o, T_o \) and \( U_o \) observed in this study also holds for varying levels of hydrogen concentration.

The video evidence presented earlier shows that flashback occurs when the leading edge of the flame ingresses into the nozzle, or \( x_f \rightarrow 0 \). This would suggest that if the lift-off height could be increased, then the flashback resistance of the burner would be improved. This was tested by measuring the flashback limits of LSI-P2, which from Figure 7 is seen to have a larger lift-off height due to the higher fraction of flow through the inner channel. A handful of tests were conducted with LSI-P2 and are plotted in Figure 12. On average LSI-P2 could stabilize flames at an \( AFT \) of about 300K higher than LSI-P1. A correlation of the same form was developed for LSI-P2, with \( A = 1.55 \times 10^{-4} \) and \( B = 0.391 \). In spite the greater burning intensity in the shear layer, the results support the hypothesis that flashback is controlled by the flame position in the inner region alone, and is not influenced by the flame attachment at the burner rim.

The flashback results with LSI-P2 might at first suggest that it is preferable design over LSI-P1. While the LSI-P2 does provide better flashback resistance, it had difficulty stabilizing natural gas flames. As seen in Figure 2, the lift-off height for the methane flames with LSI-P1 is nominally around \( x_f \approx 5 \text{mm} \) at typical operating conditions from this study. For LSI-P2, \( x_f \approx 50 \text{mm} \) for the natural gas flames at similar inlet conditions due to the higher velocities in the inner region. At a distance that far downstream of the nozzle, the shear layer has mixed with the inner region, which raises the turbulence intensity and disrupts the flow divergence. Natural gas flames with LSI-P2 were observed to fluctuate around the mean lift-off height wildly, leading to severe pressure oscillations. In
short, while the LSI-P2 design is optimized for high-hydrogen operation, LSI-P1 is more fuel-flexible. The ideal configuration for an engine would likely fall in between these two designs.

**Figure 12: Correlation for flashback limit of LSI-P1**

**Turbulent Flame Speed**

In low swirl flames, the local displacement turbulent flame speed, $S_{T,LD}$, is the most relevant turbulent flame speed for investigation [i,vi]. This is the speed at which the leading edge of the flame propagates into the flow. By measuring the velocity at the leading edge of the flame, the turbulent flame speed can be deduced, $U|_{x=x_f} = S_{T,LD}$ per the definition given by Cheng et al [vi]. Additionally, the velocimetry measurements throughout the entire flow field will help establish the controlling aerodynamics that are responsible for the flame behavior.

The velocity in the reacting flows just was measured along the centerline ($\tau = 0$) of the combustor. LSI-P1 was used for the natural gas flames because of their good stability; while LSI-P2 was used for the high-hydrogen flames to take advantage of the larger lift-off height. Because water droplets are used for seeding, which evaporate upon crossing the flame front, these are *conditioned* velocimetry measurements [xxiii]. This means that these are the velocities of just the (unburned) reactants, both upstream and through the flame brush. Figure 13 presents the axial profile of the normalized mean and the r.m.s. fluctuating velocity components for a reacting flow. $U/U_o$ initially decreases linearly from the nozzle exit ($x = 0$) to the flame front, $x_f$; it then increases through the flame brush. While not shown, the signal rate upstream of $x_f$ is relatively constant, but decreases rapidly upon entering the flame brush. The axial and transverse r.m.s. velocities, $u'$ and $v'$, increase by about 5% from $x = 0$ to $x_f$. The magnitude of $v'$ is roughly half that of $u'$. Overall, these profiles are very similar to the reacting profiles observed by Cheng et al. [vi] atmospheric pressure.

**Figure 13: Axial profiles of normalized mean, r.m.s axial and r.m.s. radial velocities for a high-hydrogen flame with LSI-P2**
Turbulent displacement flame speeds, $S_{T,LD}$ were deduced for natural gas, 90/10 H$_2$/CH$_4$ blend, and pure hydrogen flames from the axial profile measurements over a range of inlet conditions: 3 atm < $P_o$ < 8 atm, 290 < $T_o$ < 420K, 20 m/s < $U_o$ < 60 m/s. For this rig, these conditions correspond to flames with thermal power outputs from 190 to 390 kW. The $AFT$ for the natural gas and high-hydrogen flames ranged from 1780K to 1950K and 1350 to 1770K, respectively. The full details of the conditions for each burn test are listed in Table 11. The firing temperatures ranges were mostly limited by the lean blow out and flashback limits.

The $S_{T,LD}$ results are shown in Figure 14 as a function of $u'$ measured at $x_f$. The measurements from the current study are shown as circles, while the results from Cheng et al. [ii,xv] at standard atmospheric conditions are displayed as diamonds. The estimated error from this study are ±2% for the $S_{T,LD}$ and ±10% for $u'$ based on a 95% confidence level. Typically 2000 to 3000 velocity samples were taken for each test point.

Cheng et al. (2008) reports that $S_{T,LD}$ scales linearly with $u'$. The measurements from this study indicate that this linear relation continues to hold at elevated pressures, temperatures, and turbulence intensities as well. The entire set of data correlates well with the relation:

$$S_{T,LD} = K \cdot u'$$

where $K_{H_2/CH_4(90/10)} = 4.2$, and $K_{CH_4} = 2.1$. This simple relation is rather remarkable given the wide range of inlet conditions and firing temperatures in this study. The lack of any pressure, inlet temperature, equivalence ratio/firing temperature implies that the only two parameters that control $S_{T,LD}$ are the fuel composition and the turbulence level. If any dependency on pressure or temperature does exist, they are within the experimental uncertainty of the data. A single test was also conducted with pure hydrogen in this study. This point (in orange) has a $S_{T,LD}$ measured for this test was about 14% higher than the $S_{T,LD}$ for the 90/10 blend at similar inlet conditions.

![Figure 14: $S_{T,LD}$ as a function of $u'$](image)

The faster turbulent flame speed for high-hydrogen blends over methane base fuels are expected given hydrogen’s higher propensity to flashback. However, the lack of pressure and inlet temperature dependence at first may be rather unexpected because of the strong influence that $P_o$ and $T_o$ have on the flashback limits. This puzzling result can be explained though by the effect the inlet conditions have on the flow field upstream of the flame. Figure 15 plots the normalized mean velocity near nozzle exit ($x=6$ mm) versus $P_o$ for reacting high-hydrogen and non-reacting LDV tests (from Figure 6). $U/U_o$ is seen to decrease with pressure for both reacting and non-reacting flows. In the case of reacting flows, this decrease in mean velocity allows the flame to anchor closer to the nozzle rim. This is consistent with the observations mentioned earlier. Comparison of the value of $U/U_o$ and the rate of decrease with $P_o$ between the reacting and non-reacting flows show the two cases to be the same. This indicating that this velocity dependence on pressure is not result of flame/flow interactions. The turbulence intensity $u'/U_o$ does not show any change with $P_o$ which would indicate that $S_{T,LD}$ would remain constant for a given bulk velocity, and this also consistent with the turbulent flame speed measurements.

Observations with changes in inlet temperature shows that increasing $T_o$ pushed the flame away from the nozzle. Unfortunately, the LDV testing was not be performed over a wide enough inlet temperatures range (because of seeder limitations), to see if $U/U_o$ is also dependent on inlet temperature. It is conjectured that an opposite effect
would have been observed for increasing in $T_o$. That is, $U/U_o$ would increase with $T_o$, but this remains to be proven. If this were the case, it would explain the dependence of the flashback limit on inlet temperature.

![Figure 15: U/Uo and u'/Uo near the nozzle exit for non-reacting and reacting flows for LSI-P2](image)

While $u'/U_o$ did not show any dependence on $P_o$ or $T_o$ in the high-hydrogen tests, $u'/U_o$ at $x_f$ was found to increase with $AFT$ as shown in Figure 16. The turbulence intensity dependence on flame temperature can be from two possible sources. For one, it is suspected that increasing heat release with $AFT$ creates fluctuations in the flow that generate additional turbulence. Additionally, Johnson et al. [xi] have shown that divergence rate upstream of the flame increases with flame temperature due to the thermal expansion of the reactants upon crossing the flame front. This increase in divergence/strain can supply the flow field with additional turbulent kinetic energy which in turn increases $u'/U_o$. Given that $S_{T,LD}$ is so strongly dependent upon $u'$, this flame generated turbulence will, subsequently, increase $S_{T,LD}$. Therefore it is believed that the observed upstream propagation of the flame with $u'$ observed earlier is a result of the $S_{T,LD}$ indirectly increasing with $AFT$ through $u'$.

![Figure 16: Turbulence intensity at leading edge of flame as a function of AFT](image)
5. Summary

Flow field and flashback measurements were performed with a LSI and a sudden expansion nozzle in an optically accessible test rig using methane and high-hydrogen fuels. Observations were made regarding the flame position on the inlet parameters including, $P_o$, $T_o$, $U_o$, $AFT$ and fuel composition. Flashback measurements were performed and the effect of the inlet parameters on the limits was quantified. Finally velocity field measurements were conducted over the same range of inlet conditions. Through the velocity measurements the effect that inlet conditions have on the interaction between the flow field and turbulent flame speed, which ultimately influence the flashback limits. These results provide insight on how low-swirl flames will behave in the elevated conditions experienced inside power generating gas turbines.

The key findings of this study are:

- Flashback occurred when the leading edge of the lifted flame ingressed within the combustor nozzle.
- Increasing $P_o$ and $AFT$ increase the propensity for flashback, whereas increasing $T_o$ and $U_o$ decrease it.
- The propensity of flashback is dependent upon the proximity of the flame to the nozzle which is itself dependent upon the parameters $P_o$, $T_o$, $AFT$ and $U_o$.
- The turbulent flame speed is only a function of the turbulence intensity and not $AFT$, $T_o$, $P_o$.
- The normalized velocity upstream of the flame decreased with increasing $P_o$ which allows the flame to anchor closer to the nozzle, increasing the flashback propensity.
- The turbulence intensity, $u'/U_o$, increases with $AFT$ which increases the turbulent flame speed. This allows the flame to anchor closer to the nozzle, thus increasing the flashback limit.

6. Acknowledgments

The authors would like to thank the students and staff at the UCICL for their assistance, specifically Adrian Narvaez, Joe Velasco, Kyle Dykman, Adam Silver, Guillermo Gomez, Rich Hack and Scott Samuelsen. The authors also thank David Littlejohn (LBNL) and Bobby Noble (Georgia Tech) for helpful discussions with the experimental set up. Most of the experimental set up was funded under Contract No. 500-08-034 with the California Energy Commission (CEC) under the direction of Marla Mueller. The LDV system was purchased with funding from the Naval Office of Research.
References

i Lieuwen, T., V. Yang, V., Yetter, R., (Eds.), (2009), Synthesis Gas Combustion CRC Press


14


