High-repetition rate stereoscopic PIV investigation of stratified swirl flame flashback at atmospheric and elevated pressures

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ABSTRACT

Boundary layer flashback in lean stratified methane-air swirl flames was investigated at atmospheric and elevated pressure conditions (3 atm). The average axial velocity was kept at 2.5 m/s for all experiments. Non reacting flow experiments were performed to establish the nature of stratification in the mixing tube. The distribution of equivalence ratio in the plane of visualization was measured by performing planar laser-induced fluorescence (PLIF) imaging of acetone vapor injected through the fuel ports in the swirl vanes. For the non-reacting 1-atm ensemble-averaged measurements, strong stratification is observed in the radial direction, with richer mixtures present near the mixing tube outer wall. The instantaneous PLIF measurements show the presence of fuel-rich structures in the mixing tube at the globally lean conditions (\(\phi = 0.63\)). For the reacting flow experiments, simultaneous chemiluminescence imaging and three-component PIV are applied to study the physics behind the flame-flow interaction in stratified conditions. During upstream propagation of the flame, a large flame tongue swirls around the center body while propagating upstream. At a certain upstream location, the flame stops moving upstream and swirls around the center body. The radial spread of the stratified flames is found to be larger than that of the fully premixed cases. At elevated pressure the acetone-PLIF images show that pockets of varying local equivalence ratio increases the curvature of the flame. The elevated pressure flashback experiments are conducted at 3 atm at a higher global equivalence ratio (\(\phi = 0.85\)). The upstream propagation of the flame exhibits similar features of flame-flow interaction as that of atmospheric pressure cases. The high-pressure flame was highly wrinkled due to the presence of turbulence and small scale variation in equivalence ratio. Intermittently, the flame skirt was observed to spread in radial direction.

1. Introduction

Stringent conditions on emissions from gas turbines have made the partially premixed or stratified globally-lean flame configurations widely employed in industrial applications. In stratified flows, the equivalence ratio varies spatially, and all equivalence ratios are potentially flammable (Kang et al., 2009) Stratification enables stable operation at a wide range of conditions, even when the combustion is globally lean. It should be noted that the flames are considered partially-premixed if the pre-mixtures are not flammable. Fuel stratification has also been shown to affect local and global flame structures as it leads to higher flames speeds and
broader reactions zones (Sweeney et al., 2012). Flux of excess heat and radicals in the case of rich to lean propagation adds to resistance to extinction (Masri, 2015).

Flashback in premixed flames is a well-known issue in combustion, and occurs when the flame propagates upstream into the fuel-air premixing zone and may cause mechanical damage to the gas turbine (Huang et al., 2009). Some investigations on flashback have focused on studying the flashback propensity and come up with engineering guidelines for gas combustor design (Beerer et al., 2014; Daniele et al., 2010), whereas other studies have looked into upstream propagation of the flame into the mixing tube (Ebi & Clemens, 2016; Eichler et al., 2010). Computational efforts to simulate the upstream propagation have also been employed for hydrogen-air pre-mixtures (Gruber et al., 2012). Recently, Karimi et al. (2015) have developed a theoretical model to predict the flame propagation characteristics in laminar flames. Very limited studies exist on the flashback at elevated pressures (Mayer et al., 2012). Even though it is imperative for gas-turbine manufacturers to understand the effect of pressure on flashback, such studies are rare owing to their difficulty. Furthermore, the effect of stratification on flashback has seen little attention. For example, Sommerer et al. (2004) conducted a joint experimental and numerical study using LES to predict the flame propagation in a mixing tube. The measurements made (time-resolved chemi-luminescence imaging), were mainly used for the purpose of validation of the simulations.

In the current work, we aim to understand flame-flow interaction in a confined stratified swirl flow at pressures ranging from 1 to 3 atm. A model swirl combustor with an axial swirler and a center body is being used to study the upstream propagation of the flame (Ebi & Clemens, 2016). Stratification was achieved by introducing the fuel through radially-outermost ports on the swirl vanes. Pure methane or acetone-seeded methane was injected into the swirling air flow. Various degrees of stratification can be achieved by varying the equivalence ratios in the main swirl flow and in the swirl-vane injection ports.

2. Experimental set up
2.1 Swirl combustor and Pressure chamber
Flashback experiments were conducted in a model high-swirl burner (swirl number ~ 0.9). The burner consisted of a plenum, quartz mixing tube and combustion chamber as shown in Fig. 1(a). The inner diameter of the mixing tube was 52 mm, and the combustion chamber had an internal diameter and height of 100 mm and 150 mm, respectively. The main air flow entered the
mixing tube after passing through an axial swirler that consisted of eight vanes whose trailing edges were inclined at 60 degrees relative to the burner axis. The swirl number, i.e., the ratio of axial to azimuthal momentum flux, is 0.9. Fuel ports of diameter 1 mm were located on both sides of each swirl vane, at a radial location of 23.5 mm from the axis of the combustor assembly. The gas composition of both the streams, i.e. main stream and injected stream, could be independently varied. A closed cylindrical center body made of steel was attached to the swirler. The center-body was painted with ultra-flat texture black paint. The upper face of the center body was flush with the mixing tube exit plane.

For high-pressure cases, the swirl burner was mounted inside the high-pressure combustion facility. This facility consisted of a cylindrical stainless steel chamber (internal diameter of 203 mm), which is designed to allow experiments at pressures up to 10 atm (Fig. 1b). Air was supplied through the bottom of the chamber, which was controlled by a control valve (50 mm Hammel Dahl globe valve). Pressurization was achieved by a back pressure regulator (50 mm NLB series, Equilibar), which throttles the flow at the exit. The main premixture was supplied through a dedicated pipe tee in the bottom section of the chamber. The middle section of the chamber enabled optical access to the combustor assembly through three rectangular fused silica windows (25 mm thick, surface quality: 60-40, Esco Optics). The upper section of the chamber housed an access port and an ignition assembly that consists of a silicon nitride surface igniter.
(Honeywell Glowfly). Another fused silica window was installed at the top of the chamber and was aligned along the center line of swirl combustor. Cooling of the pressure chamber walls was achieved by a room-temperature shroud flow that entered from the bottom of the facility. In order to protect the sealing elements of the top window frame, additional cooling air was supplied at the top of the chamber. Further downstream, a water-cooled heat exchanger was used to bring down the exhaust temperature within tolerable limits for the back pressure regulator. Continuous monitoring of temperature and pressure was employed at structurally critical points in the combustion facility.

Flashback experiments were conducted at absolute pressures of 1 atm and 3 atm. The air and methane were supplied to the combustor at room temperature. The flow rates to the combustor were controlled using four mass flow controllers (Alicat MCR series), which were operated remotely using a LabVIEW program. Before starting the flashback experiment, a continuous air co-flow was started to ensure sufficient cooling. Afterwards, the flame was ignited in the combustion chamber at atmospheric pressure. Sudden expansion at the exit of the mixing tube induces a vortex breakdown, which in combination with the wake of the center-body, creates a low axial velocity region. This low-velocity region stabilizes the conical shaped flame in the combustion section. Typically, the varying pressure experiments were conducted at constant volume flow rate, which implies that the Reynolds number increased as the pressure was increased. A step increase in equivalence ratio was provided to trigger flashback. Fuel flow was cut off immediately after flashback to avoid having the flame stabilize for long periods in the mixing tube.

As pointed earlier, the velocity field in the vicinity of the flame front is of primary interest in the current study. High-speed planar Mie scattering of a liquid aerosol served the dual purpose of providing the particle images for PIV and an evaporated interface for flame front detection. Previously, this approach was used successfully to demarcate the flame front is several studies (Lachaux et al. 2005). It should be noted that for correct interpretation of the flame front in a highly three dimensional flow, planar data can be highly ambiguous and so high-speed chemiluminiscence imaging was used to help us to identify the location of the flame relative to the laser sheet.

2.2 Laser diagnostics set up
Time-resolved chemi-luminescence of the flame during flashback was recorded with a high-speed CMOS camera (Photron Fastcam APX) in conjunction with high-speed intensified relay optics module (HiCatt 25, Lambert Instruments). These images were captured at 4 kHz, with a resolution of 512 x 512 pixels. The camera was fitted with a Nikkor 105mm lens operated with an f/5.6 aperture. To achieve simultaneity between chemi-luminescence images and Mie scattering images, the trigger and gain gate duration to the intensifier was timed to avoid the exposure during laser pulses by capturing the images in between the pulses. The field-of-view was perpendicular to the laser sheet as indicated in Fig. 2b. The flow was seeded with olive oil droplets of approximately 1 µm in diameter using a six-jet atomizer (TSI Inc.). These oil droplets were illuminated with two high-repetition rate diode-pumped, frequency-double 527 nm Nd:YLF lasers (Coherent Evolution-90) operated at a repetition rate of 4 kHz. A combination of a negative and a positive cylindrical lens was used to form a collimated laser sheet that entered the mixing tube from the top window in the r-z plane and was aligned along the diametric plane of the mixing tube axis, as shown in Fig. 2.
Two high-speed CMOS cameras (FASTCAM-ultima APX) were operated in forward scattering mode at a framing rate of 8 kHz and a resolution of 256 x 512 pixels. The cameras were fitted with Scheimpflug adapters and Nikkor 105 mm lenses operated with an f/5.6 aperture. The angle between cameras and light-sheet normal was 27°. The field-of-view was 13.5 x 27 mm² with a pixel resolution of 50 μm. The top edge of the field-of-view was located at z = -55 mm, meaning 55 mm upstream of the mixing tube exit plane. Calibration data were obtained by translating a 10 mm wide calibration target -- with a dot spacing of 1 mm and a dot diameter of 0.25 mm -- through the laser sheet. The Mie scattering images were de-warped on the basis of a 3rd order polynomial mapping function obtained by calibration. The light sheet setup and camera positioning enabled us to obtain valid particle images up to 0.5 mm away from the center body. Bringing the light sheet from the top window helped in reducing the scattering off the center body.

To quantify the stratification in the flow, acetone PLIF images were captured at 10 Hz using a 14 bit CCD camera with quantum efficiency of near 60% (PCO 1400). Exposure duration for the camera sensor was kept at 1 μs to minimize the background luminosity from the flame. A blue band-pass filter (BG25) and an IR filter were mounted in front of the camera lens to filter out non-fluorescent light. A set of 600 fluorescence images were captured per non-reacting experimental run with resolution of 696 x 520 pixels to determine the equivalence-ratio statistics along the length of mixing tube covering an axial length of 25 mm. The camera was fitted with a 12 mm extension tube and a 50 mm f/1.4 Nikon lens. The 266 nm laser pulse (20 mJ) with repetition rate of 10 Hz was generated by frequency-doubling a high energy pulse of 532 nm light from an Nd: YAG laser (Continuum Powerlite 9010). The 266 nm beam was expanded into a sheet that overlapped the 527 nm laser sheet generated for PIV. There are two possible directions from which the laser sheet could enter the field of view: from the top and from the side. Laser entry from the top offers a high-fluence beam entry and reduced reflections from the center-body...
surface; however, the beam steering during flashback experiments led to a striated non-uniform laser sheet, which isn’t ideal for equivalence ratio distribution measurement. Hence, the laser sheet entered through the side, going in the mixing tube radially and falling normally on the center-body’s surface. It should be noted that the PLIF and PIV images were not captured simultaneously since the purpose of the PLIF imaging was to get the equivalence ratio statistics in the plane of the velocity measurements, whereas the PIV was employed for investigating the flashback dynamics. The flow through the fuel ports (stream 2) was seeded with acetone by passing the flow through a 1.1 m long acetone bubbler.

3. Image Processing

The three-component planar velocity field was calculated on the basis of two subsequent Mie scattering images taken at 8 kHz using the LaVision DaVis software package. The interrogation window size was 16x16 pixels corresponding to 0.8 x 0.8 mm² in physical space. A 75% overlap was chosen to get a larger number of vectors in the vicinity of the flame front (based on vaporized droplets). The distance between the wall and the first velocity vector in the radial direction was about 0.5 mm. The calibration process included correcting the images for geometrical distortion induced by the curvature of the mixing tube walls. For the current experiment, a fused-silica tube with high optical homogeneity (i.e., no lengthwise striations) was used to minimize optical defects.

Entry of the PIV laser sheet from the top of the mixing tube ensured that PIV measurements could be made near the center-body surface with a minimum of scattering. Reducing the scattering is more important with PIV than with PLIF since the laser light and scattered light are at the same frequency and so cannot be distinguished. This orientation of the laser sheet worked well at atmospheric pressure, but at higher pressure, striations in intensity appeared in the particle scattering images. These intensity striations were random in nature, and were caused by the sheet passing through the swirl flame and exhaust gases. This effect increased at higher pressures owing to the larger gradients associated with the higher Reynolds numbers. Example striations in the particle scattering images are shown in Fig 3(a). The resulting striated particle fields are problematic for PIV since they cause the cross-correlation peaks to have a two dimensional character. Figure 3(a) shows a sample cross correlation map calculated at a location with striations, and exemplifies the elongated cross-correlation function. To mitigate this effect, the intensity profile was corrected by first filtering the vertical sliding background of size 16 pixels and then applying min-max normalization filter. The resulting image had a relatively
uniform particle image. A sample correlation maps for a sheet-corrected image is shown in Fig. 3. The corrected image shows axisymmetric correlation peaks, as is expected for round particle images. This operation greatly improves the quality of the resulting PIV data, as shown in Fig 3(b).

![Correlation Maps](image)

**Figure 3** Striated Mie scattering image captured at 3 atm and corresponding correlation map

(a) Before sheet correction (b) After sheet correction

The uncertainty bias in the velocity calculation for atmospheric pressure experiments is measured to be less than 0.1 m/s, whereas the stereo-reconstruction error is found to be less than 0.3 at all points in the field-of-view. For elevated pressure measurements, the maximum uncertainty bias and the stereo-reconstruction error was found to be 0.2 m/s and 0.6.

The flame front is detected in the particle images by detecting the low scattering signal region. A MATLAB code was used to extract the flame front on the basis of threshold intensity in 8x8 px windows with 75% overlap. For the particle images captured at 3 atm, striations were filtered out as described earlier. Then, a smoothing spatial filter was applied to get rid of high-frequency signals due to the discrete nature of the particle images. Afterwards, the image was binarized on the basis of a cut off intensity. Then, an edge detection routine was applied to get the flame front location. It should be noted that the filtering also averages out the sub-millimeter flame structures which might exist in highly turbulent flames.
In order to process PLIF images, a set of 100 background images were captured for each run in the absence of the acetone and averaged. This average background image was then subtracted from the PLIF signal images. Spatial intensity variation of the laser sheet was corrected by filling the mixing tube using very small flow rates of acetone-saturated-air through the fuel ports (stream 2) and keeping the main air supply (stream 1) closed. The sheet corrected images were converted to equivalence ratio by normalizing them by the pure state that issued from the swirl jets.

4. Results and Discussion

The current set of experiments is focused on investigating flashback in stratified swirl methane-air flames at 1 atm and 3 atm. The average axial velocity has been kept at 2.5 m/s for both the cases, which implies the mass flow rate and Reynolds number are three times higher for the elevated-pressure case. Flashback is triggered by providing a step increase in the fuel flow rate, thereby increasing the global equivalence ratio. The global equivalence ratios during flashback at atmospheric and elevated pressure experiments are 0.63 and 0.85, respectively. The Reynolds numbers, based on the hydraulic diameter of the annulus, corresponding to the 1 atm and 3 atm cases, are 6100 and 18700, respectively. To assess the mixing of fuel and air, acetone was seeded into the fuel stream, and the acetone concentration was imaged using the PLIF technique. Time resolved chemiluminescence images were taken to gain insight into the global behavior of the flame propagation. Simultaneous stereoscopic PIV results provided planar information on flame-flow interaction.

4.1 Atmospheric pressure experiments

4.1.1 Non-Reacting Mixing Studies (1 atm)

To assess the equivalence ratio distribution through the mixing tube, non-reacting mixing studies were conducted using acetone PLIF to visualize the distribution of “fuel”. In these experiments acetone-seeded air was flowed through the fuel-injection ports in the swirl vanes, and the acetone was visualized using PLIF. These air-acetone jets issue perpendicularly from the swirl vane surface. The field of view for the acetone PLIF is 55 mm to 80 mm upstream of the mixing tube exit plane. This region corresponds to 45 to 70 fuel jet diameters downstream of trailing edge of the swirl vanes. The acetone PLIF images were calibrated to enable determination of the equivalence ratio at each imaged point. Calibration was achieved by adding a uniform saturated
acetone mixture to the mixing tube and them capturing images. To create the uniform mixture the mixing tube was plugged with a concentric Teflon plug, and the mixing tube was then filled with air seeded with saturated acetone. The saturated acetone signal level was used as the reference to map each pixel to quantitative acetone concentration. These calibration images also serve the purpose of providing the laser sheet correction.

Figure 4(a-c) shows the instantaneous equivalence ratio distributions in the mixing tube for the non-reacting, 1 atm case. Figure 4(d) shows the 200-frame average equivalence ratio distribution for the same field of view. The average image shows that the equivalence ratio distribution is not uniform, and the flow is highly stratified with a rich mixture ($\phi \approx 0.7$) near the outer wall and for $-80 \text{ mm} < z < -65 \text{ mm}$. Leaner mixtures, with $\phi$ ranging from 0.2 to 0.5, is present radially inward and near the top of the field of view. It should be noted that below $z = -65 \text{ mm}$, the radial gradient in equivalence ratio is approximately twice that of the rest of the locations. Instantaneous distributions show the presence of rich “fuel”-air pockets in the lower half of the area of visualization. Above $z = -65 \text{ mm}$, the instantaneous equivalence ratio distribution is seen to be relatively uniform, as a weak radial gradient is observed. This uniformity shows that the radial stratification, observed in the mean, does not always hold in an instantaneous sense. The equivalence ratio in the mixing tube lies within the flammability limits of a methane-air mixture ($0.45 < \phi < 1.4$).

Since the mixing of the fuel jets in the swirl flow evolves azimuthally as well as axially and radially, the possibility of strong azimuthal equivalence ratio gradients exist. To investigate this possibility, the swirl combustor was rotated about its axis in increments of $\pi / 32$ radians, and the PLIF imaging was repeated for each angle. Five different increments were used to obtain a total angular change of $\pi / 8$. These mean images showed that the radial stratification seen in Fig. 4(d) holds for all of the planes; i.e., the azimuthal variation in the average equivalence ratio distribution was found to be small as compared to the radial variations.
4.1.2 Reacting Flows Studies

For the reacting cases pure methane was issued from the ports in the swirl vanes. For the purposes of this study, we assume that the stratification upstream of the flame is similar to that of the non-reacting cases, even though the densities are different. For the non-reacting cases, the jet to air density ratio is 1.3, and for the reacting cases the jet to air density ratio is 0.53. As stated above, flashback is initiated by first establishing a stable swirl flame in the combustion section and then increasing the equivalence ratio until flashback occurs. The high-speed luminosity imaging shows that the stratified-flame flashback starts in a similar fashion to that in the fully-premixed case that we have studied extensively in the past (Ebi & Clemens (2016)). The similarity to the fully-premixed case is expected as the fuel-air mixture is well mixed at the end of the mixing tube, as seen in Fig. 1. As the flame progresses upstream, spatial changes in $\phi$ begin to affect the flame structure.

Figure 5 shows chemiluminescence images for comparable instances during flashback for fully premixed (taken from Ebi & Clemens, 2016) and stratified flashback (current study). Even though the global behavior of the flame is similar for both these cases, the local flame structure for the stratified flame is different. A comparison of Fig. 5(a) with 5(c) shows that the leading edge of the flame is smoother in the fully premixed case. The trailing edge of the premixed flame (Fig. 5(b)) shows multiple small flame bulges that are aligned along the swirl flow streamlines. This behavior was attributed by Ebi & Clemens (2016) as similar to flashback in a 2D channel and the bulges likely coincide with low-momentum structures in the incoming boundary layer.
For the stratified case, the trailing edge (Fig. 2(d)) shows a gradual variation in luminosity between two far-spaced flame tongues. The flame tongue in the front is also a part of a locally bright flame structure, which is something that this characteristic of the stratified cases – the flame luminosity exhibits greater variation than in the fully premixed case. The radial spread of the flame is also larger and the flame surface also exhibits greater curvature.

As the flame propagates upstream, the flame leaves the region of relatively uniformly mixed fluid and enters the stratified flow regime. Something that is typically observed from the luminosity movies is that the propagation of the flame along the center body slows down and eventually stops at a point where the flammable mixture in the boundary layer isn’t sufficient to allow further propagation. Later, the flame stops progressing upstream and keeps revolving around the center body. At this time, as well as during propagation, the high φ pockets of fuel-air mixture that are convected downstream might offer the flammable mixture to the flame surface. This flame-flow interaction may play a role in larger radial spread of the flame as well as much more curved flame surface.

![Figure 5](image)

**Figure 5.** Comparison of propagating flame structure for fully-premixed (top row) and stratified mixture (bottom row). Each row shows the leading and trailing edges of the flame tongue swirling around the center body. The red arrow shows the movement of the flame tongue while the grey arrow shows the direction of swirl flow. These images are captured for flashback at Re = 6100.

Such variation in equivalence ratio also likely affects the spatial distribution of heat release rates and hence the dilatation and the blockage effects of the flame (Masri et al., 2015).
Figure 6: Chemiluminescence and the axial velocity fields at time instants: a. \( t_0 \), b. \( t_0 +3 \), c. \( t_0 +4 \) and d. \( t_0 +5 \) ms. Green line in the chemiluminescence images shows the position of laser sheet. Evolution of a flame structure is marked by yellow circle in successive frames.

Figure 6 shows results of the simultaneous time-resolved PIV and chemiluminescence imaging, with the chemiluminescence at the top and axial velocity field in a radial-axial plane at bottom. Figure 6 (a) shows the instant in which the flame is about to enter the laser sheet. The absence of flame allows the velocity field calculation for the entire field of visualization. For the successive frames Fig 6(b)-(d), the masked region along the center body represents the planar profile of the propagating flame which has entered the laser sheet. The luminosity of the flame shows the gradual growth of flame structure (yellow circle) as it is convected along the main swirl flow. It should be noted that even though the structure moves downstream, a rapid increase in its size aids the propagation of the flame tip. Although not as apparent from these still images, the movie shows that Fig 6(c) is an example of significant deflection of the upstream flow when it encounters the flame. This reversal in local axial velocity is similar to that found in the fully premixed case (Ebi & Clemens, 2016; Eichler et al., 2012).

Another salient feature of the stratified flame is the large-scale wrinkling of the flame surface, which is apparent in the planar profile of the flame. One of the possible reasons for the flame wrinkling is the presence of local pockets of varying stoichiometry, as was observed with the PLIF imaging in the non-reacting flows. However, to investigate this possibility further, a set of PLIF images were captured for the stratified flame flashback with the acetone-seeded methane as
fuel. It should be noted that seeding with acetone alters the parameters such as flame speed and adiabatic flame temperature, hence these measurements, as shown in Fig. 7 are meant for qualitative understanding of the flame wrinkling. The false color image shows the instantaneous normalized PLIF signal during flashback. The flame zone is represented by the low signal region (blue) close to the center body. In Fig. 4(a) a fuel-rich acute-tip pocket (circled in red) in the unburned reactants seems to alter the surface by inducing the negative curvature on the flame surface. In Fig. 4(b), the positively curved flame structure (shown in red ellipse) progresses into the locally lean pocket of the fuel-air stream. These images confirm the role of variations of local equivalence ratio in shaping the flame front. For fuels with non-unity Lewis number e.g. hydrogen, it might have a significant effect in the propagation of flame.

![Figure 7](image)

**Figure 7**: Normalized PLIF signal showing the effect of rich fuel-air pockets on shaping of flame surface. The dark blue zone represents the flame.

### 4.2 Elevated pressure experiments

To study the effect of pressure on stratified flame flashback, experiments are conducted at the same axial velocity as the atmospheric pressure runs. The increase by a factor of 3 in pressure leads to a factor of 3 increase in density and Reynolds number. Note that the laminar flame speed of a methane-air premixture of a given equivalence ratio decreases with an increase in pressure (Lachaux et al. (2005)) Hence, the flashback is triggered at a higher global equivalence ratio ($\phi_g = 0.85$) as compared to atmospheric pressure runs. PLIF images were captured for the non-reacting case to understand the stratification in the plane of visualization. Time resolved
chemiluminescence and PIV measurements were acquired for the reacting cases during flashback.

4.1.1 Non-Reacting Mixing Studies (3 atm)

Figure 8(a-c) shows the instantaneous equivalence ratio distribution for the non-reacting flow at elevated pressure conditions. The ensemble-averaged distribution of 600 images are shown in Fig. 8(d). The horizontal striations are due to an inadequate laser sheet correction. As the 1-atm case, acetone-laden air is injected through the swirl vane injection ports. A notable difference from the lower pressure case is the increase in turbulence as evident by the presence of fine-scale sub-millimeter structures. This is expected owing the higher Reynolds number of the flow. Furthermore, the flow appears to have a similar overall mixing pattern as that at atmospheric pressure, where there is a richer region in the lower right section of the field of view, and the mixture is more uniform near the downstream section; however, there is clearly a larger degree of stratification in the downstream section than at lower pressure. This observation implies reduced mixing of the gas exiting the fuel-injection jets. Another difference is that the equivalence ratios in the rich mixtures are significantly higher than at lower pressure, which is expected for the higher global equivalence ratio, but is also consistent with reduced mixing.

![Figure 8](image)

**Figure 8:** Instantaneous equivalence ratio distribution for the non-reacting case at 3 atm. (d) The ensemble-averaged distribution.

4.1.2 Reacting Flows Studies (3 atm)

Figure 9(a) and 9(b) shows chemiluminescence snapshots captured during flashback for fully-premixed and stratified conditions at 3 atm. The premixed case is taken from a previous study (Ebi & Clemens, 2016)). An increase in the pressure leads to a decrease in the laminar flame
speed (Lachaux et al. (2005)), thereby reducing the radial spread of the flame. The effect of the turbulence can be seen in the small scale wrinkling of the flow. On the other hand, the stratified flame flashback seems to extend farther into the channel. Even though the laminar flame speed decreases with the pressure, the reduced mixing likely aids flame propagation into the richer mixtures in the stratified case. Wrinkling of the flame surface and bright zones in the chemiluminiscence are also observed.

Figure 9: Leading edge of the flame for (a) fully premixed and (b) stratified cases. $P = 3 \text{ atm, } Re_h = 18700$

Simultaneous axial velocity field and chemiluminescence time-sequenced images are presented in Fig. 10. Owing to scattering from the wall, the PIV could not be measured closer than 1 mm from the center body. Figure 10(d) shows the time at which the flame tip crosses the laser sheet, and we observe the negative axial velocity zone upstream as was observed in the fully premixed case (Ebi & Clemens (2016)). Also seen in Fig 10(d), the flame spreads out radially up to 11 mm into the flow, which suggests the possibility of flame interaction with the outer boundary layer.
Figure 10: Chemiluminescence and the axial velocity fields at time instants: a. $t_o$, b. $t_o +8$, c. $t_o +10$ and d. $t_o +12$ ms. Green line in the chemiluminescence images shows the position of laser sheet.

Conclusions

Flashback experiments were conducted in a model swirl combustor with an axial swirler and a center-body. Fuel was injected perpendicularly into the swirl flow via fuel ports on the swirl vanes. To assess the mixing between fuel and air streams, acetone PLIF imaging was conducted for a set of non-reacting flow experiments with matching flow conditions to that of the reacting cases. Atmospheric pressure experiments were conducted for the average axial velocity of 2.5 m/s. The global equivalence ratio was kept at $\phi = 0.63$. The time-averaged equivalence ratio distribution in the mixing tube shows that the flow is radially stratified. The instantaneous measurements indicate the presence of locally rich fuel-air mixture pockets in the flow.

For the flashback experiments in stratified flow at 1 atm, high-speed chemiluminescence imaging shows that a large flame tongue propagates upstream with a swirling motion around the center body, similar to the fully premixed cases studied previously. However, the flame becomes more wrinkled as it progresses upstream. The upstream propagation of the flame stopped at an intermediate location in the mixing tube and the flame tongue would continue swirling around the center-body. Time resolved PIV measurements show the presence of negative axial velocity zone upstream of the flame tip, in agreement with Ebi & Clemens (2016). The stratified flame exhibits increased wrinkling and larger radial spread as compared to a fully premixed flame at similar flow conditions. Acetone PLIF snapshots were captured during flashback of acetone-seeded methane-air flame. Fuel-rich and fuel-lean pockets in the approach flow were seen to affect the local flame surface curvature, which indicates stratification causes wrinkling of the flame surface.

Non-reacting and reacting flow experiments with matching average axial velocity were conducted at 3 atm. The instantaneous PLIF measurements for non-reacting flow showed even greater stratification than at the low-pressure condition, and pockets of rich mixtures that exceeded the equivalence ratio of the 1-atm case. Both observations are consistent with decreased mixing of the swirl-air and injection gases. The time-resolved chemiluminescence images show that the flame is more wrinkled at the elevated pressure, which is expected due to the increased turbulence. Large scale wrinkling of the flame was also observed suggesting the role of variation in fuel-air ratio in approach flow. The radial spread of the flame was found to be greater than for the fully premixed case. The presence of negative axial velocity zones is observed at the flame tip.
on the center-body, which suggests the role of flow deflection in axial direction on flame propagation.

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