Conical quarl swirl stabilized non-premixed flames: flame and flow field interaction

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Abstract

The flame-flow field interaction is studied in non-premixed methane swirl flames stabilized in quartz quarl via simultaneous measurements of the flow field using a stereo PIV and OH-PLIF at 5 KHz repetition rate. Under the same swirl intensity, two flames with different fuel jet velocity were investigated. The time-averaged flow field shows a unique flow pattern at the quarl exit, where two recirculation vortices are formed; a strong recirculation zone formed far from the quarl exit and a larger recirculation zone extending inside the quarl. However, the instantaneous images show that, the flow pattern near the quarl exit plays a vital role in the spatial location and structure of the reaction zone. In the low fuel jet velocity flame, a pair of vortical structures, located precisely at the corners of the quarl exit, cause the flame to roll up into the central region of low speed flow, where the flame sheet then tracks the axial velocity fluctuations. The vorticity field reveals a vortical structure surrounding the reaction zones, which reside on a layer of low compressive strain adjacent to that vortical structure. In the high fuel jet velocity flame, initially a laminar flame sheet resides at the inner shear layer of the main jet, along the interface between incoming fresh gas and high temperature recirculating gas. Further downstream, vortex breakdown alters the flame sheet path toward the central flame region. The lower reaction zones show good correlation to the regions of maximum vorticity and track the regions of low compressive strain associated with the inner shear layer of the jet flow. In both flames the reactions zones conform the passage of the large structure while remaining inside the low speed regions or at the inner shear layer.
**Keywords:** Conical swirl stabilized; non-premixed flames; PIV/OH-PLIF

1. **Introduction**

Non-premixed swirling flames are used extensively in practical combustion systems, particularly gas turbines, furnaces and boilers [1-2]. The quarl geometry has significant effects on the swirling flame structure and emission characteristics. Different aspects of swirling combustion have been studied, including the swirling flow features [3-4], flame stability and enhancement of flame blowout limits by the use of swirl [5-6], and flow field and emission pollutants, in particularly nitrogen oxide [7-8]. Although most of these studies have been conducted on burners using a diverging quarl, there is little information on the effect of the quarl on the flame-flow interaction.

In contrast to the diverging quarl swirling flame, many free or confined swirl flame studies have been conducted using straight-exit burners. For example, using intrusive measuring techniques, detailed measurements of gas species and temperature in a non-premixed swirling flame are presented in [9]. Also, the effect of the fuel injection pattern and fuel–air mixing on NOx formation in swirling non-premixed flame were investigated [10]. The effect of fuel injection pattern on near flow field of a confined swirl flame was investigated in [11]. They observed intermittent fuel penetration into the recirculated hot products with a central sooting luminous plume in the case of axial fuel injection, whereas this phenomenon was totally absent in the case of radial injection.

Laser based diagnostics have been employed in the swirling flame of a gas turbine model combustor [12-15] without attention to the effects of the quarl geometry on the flame structure. Using OH-PLIF measurements, under pressures ranging from 2 to 6 bar, the general features of the reaction zone of a gas turbine model combustor were reported [12]. The application of the simultaneous PIV and OH-PLIF measurements on this model yielded physical insight into various relevant combustion phenomena, such as the presence of a helical precessing vortex core (PVC) in the inner shear layer of the swirling jet [13]. The coupling between the PVC and the thermo-acoustic pulsation in a noisy swirling flame have been
addressed by analyzing OH-PLIF/PIV measurements [14]. Recently, the interaction of flow, fuel-air mixing and reaction in a turbulent swirling flame have been investigated using simultaneous PIV and acetone/OH-PLIF measurements [15]. A periodic changes in the composition of the unburned mixture between pure air and well-mixed fuel-air is induced at the flame root by the formation of PVC have been addressed [15].

Considering the complex interplay between flow field, chemical reactions, and quarl geometry, the necessity to delineate the role of the quarl on the flame–flow field interaction specifically, and to contribute to a better understanding of the combustion process in the swirl quarl stabilized flames in general, is clear. Simultaneous high speed OH-PLIF/PIV imaging was applied to non-premixed swirling flames stabilized in a diverging quarl at a 5 KHz repetition rate to gain this understanding

2. Experimental apparatus

Figure 1a shows a sketch of the burner. The swirling flow around a central fuel tube (d_f = 4.4 mm) was generated via four tangential air inlets to the outer air tube (d_A =27 mm). The tangential air streams mixed with axial air upstream of the burner. The swirling flame was stabilized in a quartz quarl of a half cone angle of 15° and a length of 40 mm. The exit planes of the two concentric tubes, fuel (methane) and air, was located at the inlet plane of the quarl (Z = 0 mm). The geometrical swirl number, \( S_g = \frac{(\pi r_o d_A/2A_t)/ [m_\theta/ (m_\theta + m_A)]^2 }{m_\theta} \), is used to define the swirl intensity [5], where m_\theta and m_A are the tangential and axial air flow rates respectively, A_t is the total area of the four tangential air inlets, d_A is the diameter of the air tube, and r_o is the air tube radius at the location of the tangent inputs. At S_g= 12, two flames with different fuel jet velocity (V_f) were studied, namely flame F_A with V_f = 4.4 m/s and flame F_B with V_f = 8.8 m/s. Simultaneous PIV/OH-PLIF measurements were conducted for the region just above the quarl exit at 5 KHz repetition rate. However, the field of view for OH measurements was extended to
cover the entire quarl region, ending at the same height as the PIV field of view, see Fig. 1a for the respective field of views.

Fig. 1. Schematic of: (a) quarl swirl burner, (b) measuring arrangements.

A schematic of the measuring techniques used for the simultaneous stereoscopic PIV and OH-PLIF is shown in Fig. 1b. Two counter propagating laser beams were formed into overlapping sheets and crossed the vertical plan of the burner. The stereoscopic PIV system consisted of a dual cavity, diode-pumped, solid-state Nd:YLF laser (LDY 300 Series) and two high-speed CMOS cameras (LaVision, Image Pro HS 4M, HSS5) with 105 mm/f4 objective lens (Nikon UV Micro-Nikkor) equipped with a 527 nm band pass filter. The two cameras were located at both sides of the OH-PLIF ICCD camera at an angle of ± 15° to acquire the stereoscopic particle images. The laser was capable of producing 35 W per head at 10 KHz with a 9 ns pulse width. The double-pulsed beams were formed into a sheet along the flame central plan using three cylindrical lenses. Mie scattering images were recoded with a resolution of 528×692 pixels at 5000 frames/s. Perspective distortion was corrected using a dual plane, three-dimensional imaging target. Vector fields were computed from particle image spatial cross correlations using the LaVision Davis 8.1 software. An adaptive multi-pass vector evaluation technique was used, with interrogation boxes ranging from 128 pixels to 16 pixels. The laser sheet had a nearly1-mm waist and the size of the interrogation windows was 16×16 pixels with 50% overlap, yielding a spatial
resolution of approximately 1.2 mm × 1.2 mm × 1mm. Both the swirling air and fuel jets were seeded with titanium dioxide (TiO$_2$) particles with a nominal diameter of 0.5 μm.

A frequency-doubled high-speed dye laser (Sirah, Cerdo-Dye) pumped with a frequency-doubled, diode-pumped solid state INNOSLAB laser (Edgewave IS16II-E) was used to generate the necessary UV light for OH-PLIF. The OH signal was acquired via CMOS ICCD camera (LaVision IRO), equipped with Nikkor UV lenses (f/4.5, f = 105 mm) and appropriate filters. OH radicals were exited through the Q$_1$(6) transition of near 283 nm (1, 0) in the band of the $A^2Σ \leftarrow X^2Π$ (1, 0) OH system. Good discrimination of the OH excitation frequency was achieved using a transmission band-pass interference filter (> 80% at 310 nm Laser-Components GmbH). Each OH-PLIF image was processed to remove (a) laser sheet inhomogeneity and (b) background noise from shot-to-shot laser fluctuations. The laser sheet’s profile correction was determined using an ensemble average of 10,000 individual images of the laser sheet passing through a cuvette filled with acetone placed in the center of the field of view.

3. Results and discussion

3.1. Mean flame characterizes

The time-averaged flow fields of 2500 PIV recordings for flames $F_A$ and $F_B$ in the vertical plane are shown in Fig. 2a-2b, respectively. Streamlines and velocity vectors are superimposed on the azimuthal velocity component plotted in gray scale contours. The main features show a round methane fuel jet penetrating into swirling flow confined with a quarl. The flow field shows a unique feature downstream of the quarl which consists of a cone-shaped stream flow at the quarl exit, characterized by a high velocity inflow region and referred to hereafter as the jet. Within the quarl radius, a pair of recirculation zones are formed, called RZ1 and RZ2, which are separated by a shear layer, SL2. The recirculation zone, RZ1, is the typical recirculation zone formed due to the axial adverse pressure gradient associated with the vortex breakdown. Strong velocity gradients occur in shear layer (SL1) between RZ1 and the inflow jet. The second recirculation zone, RZ2, is located close to the quarl exit and dominates a large
portion of the quarl radius and extends inside the quarl. The RZ2 is confined by the shear layer SL2 and the central jet. Through this shear layer, SL2, hot burned gas from downstream mixes with the fresh fuel/air mixture. The flow field reveals high swirling velocities near the quarl exit and near the exhaust at the contraction of the swirling jet. Increasing the fuel jet velocity, $V_f$, (flame $F_B$, Fig. 2b) is observed to shift RZ1 further downstream.

Figures 2c-2d show the time averaged OH-PLIF images of flames $F_A$ and $F_B$, respectively, where OH serves as a marker for the reaction zone and hot burned gases. As shown, with the existence of the quarl at the burner exit, a conical thin laminar flame confining a dark cold region of swirling flow within the quarl. As shown the presence of OH near the quarl corners in flame $F_A$. Downstream the quarl in flame $F_A$, the OH signal is much more widely spread, covering RZ1, RZ2, and some OH signal within the central region. However in $F_B$, the OH signal is very thin and localized at SL1 and at RZ1 regions.

Fig. 2. Average vectors and streamlines overlaid the azimuthal velocity (gray scale contours), (a) flame $F_A$, (b) flame $F_B$, and the corresponding average OH images in (c) and (d).
3.2. Instantaneous flame structure

Figure 3 shows a typical example of the instantaneous flow field superimposed the OH-PLIF image of flames \( F_A \) and \( F_B \). For clarity, alternate vectors have been removed. This figure shows the existence of small-scale vortical structures at the inner shear layer of the swirling jet and at the central flame region, which are not visible in the time-averaged images. Inside the quarl, a thin conical OH layer surrounds a central region of unburned mixture and/or heated gases, indicating the formation of a laminar flame near the quarl walls.

Fig. 3. Instantaneous simultaneous PIV and OH-PLIF measurments: (a) flame \( F_A \), (b) Flame \( F_B \), plots to the right are zoomed windows.
The existence of this OH layer away from the fuel nozzle tip indicates that the fuel begins mixing with the swirling air immediately at the fuel nozzle exit, and illustrates the role of RZ2 in enhancing the mixing of fresh reactants with the burned gas. With the low $V_f$, flame $F_A$, the measurements reveal a pair of vortices formed at each corner of the quarl, as shown in the zoomed windows of Fig. 3a. This flow field is composed of two counter rotating vortices, one lying closer to the shear layer of the jet flow (vortices 3 and 4, see Fig. 3a.) and the other located near the central flame region (vortices 1 and 2). Both unburned gas coming from the central region and hot burned gas are present in the region around vortices 1 and 2. Also observed that the upper two vortices (3 and 4) corrugate the flame sheet towards the lower vortices. The flame sheet is wrinkled in the neighborhood around these vortices, leading to enhanced flame area, and thus strong convective mixing between burned and unburned gas. One can notice the formation of the stagnation point closer to the center region (shown by white dots). Through the mutual interaction between these two vortices, the flame moves into regions of low flow speed. With increasing the fuel jet velocity, the flow field near the quarl corners is altered and thereby the flame structure. The thin flame sheet originates from inside the quarl and follows the inner shear layer of the jet flow conforming the passage of the high jet velocity. As shown in Fig. 3b, the outer vortex is displaced far downstream and radially outward. This causes a reduction in the strength of the lower vortex (see the zoomed windows). These vortical structures in the inner shear layer of the jet flow along with the high turbulence intensity present in the shear layer result in intense mixing between cold fresh gas and hot burned gas and it increases the heat release around the vortex. This structure plays a vital role in stabilizing the flame in the regions of high flow velocity.

3.3. Time sequence measurements:

Due to the super equilibrium OH within the reaction zone, Sadanandan et al. [16] showed that the reaction zone may be identified by the regions of highest gradient of the OH-PLIF signal. In this work, we used a Sobel gradient filter, which takes the derivative in the one direction and smoothed in the
orthogonal direction, to detect the reaction zone. The largest gradients most likely correspond to reaction zones, the smallest gradients to boundary layers between hot and cold gases. Figure 4 shows an example of a raw OH-PLIF image and after applying the gradient filter.

![Sample of OH-PLIF image and OH gradient](image)

**Fig. 4** (a) Sample of OH-PLIF image, (b) OH gradient.

A sample time sequence of the reaction zone overlaid with different flow parameters is presented and discussed for flame F_A. The images are cropped to the regions above the quarl (from t = 0, 0.2, 0.4, 0.6 and 3.4 ms). Figures 5a-5b show the reaction zones overlaid with the velocity vectors on the top of the contours of axial velocity (v) and swirling velocity (w), respectively.

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into SL1 through the large vortex, which leads to flame wrinkling (shown by arrows in Fig. 5a). Further downstream, \( Z \approx 75 \text{ mm} \), with the contraction of the jet flow toward the flame centerline, the two branches of the reaction zones tend to elongate at the central flame region.

![Fig. 5. Reaction zones and velocity vectors overlaid against (a) contours of the axial velocity (v), (b) swirling velocity (w).](image)

Figure 5b, shows the time sequences of the reaction zone overlaid against the contours of the swirling velocity. There appears to be less sensitivity between the spatial location of the reaction zone and the swirling velocity components, where the reaction zones tend to be located at the boundaries of high swirling velocity pockets; see for example the reaction zone location relative to the left high swirling pockets identified by the arrows in the plots. This reduced sensitivity relative to the high sensitivity to the axial components is attributed to the smaller fluctuations of the swirling velocity.

Figure 6a, shows the same sequences overlaid against the corresponding instantaneous vorticity field. In general, the results show that the reaction zone is confined from the outside by long vortical structures corresponding to the swirling flow jet. As mentioned previously, the reaction zone remains in the low axial velocity regions, where the spatial location of the flame sheet depends on the flow structure. In general, less correlation is seen between the reaction zone and the confining high vorticity.
flow, and the reaction zone does not pass through these regions of high vorticity. Occasionally, the wrinkled reaction zones match the inner boundaries of the outer maximum vorticity (identified with arrows). As shown, the left reaction zone indicates a greater inward shift toward the central region with the appearance of localized regions of high vorticity. This leads to an increase in the flame area and hence the reaction rates at this location.

Fig. 6. Flame F_A reaction zones overlaid against: (a) vorticity contours, (b) minimum principle normal strain.

Fig. 6b shows this series superimposed on plots of minimum principle strain rates. In these plots, the magnitude and direction of the strain rate are indicated by line segments oriented in the direction of the strain axis and the length of each segment is directly proportional to the magnitude of the strain. As noted before, the reaction zones are oriented towards, and reside in, regions of low swirling velocity, the flame sheet in these regions is very thin and it is more likely associated with correct principle (2D) strain rates. In a normal diffusion flames, the thinnest reaction zones are oriented perpendicular to the axis of the principle compressive strain rates [17]. By considering Fig. 5a and strain plots in Fig. 6b, it is clear that regions of high compressive strain result from high axial velocity, and two high compressive strain
rates regions are associated with each vortical structure (identified by arrows). Another region of higher principle compressive strain is generated by the lower left vorticity, where the back flow and forward flow merge inside the vortex. The axial location of the flame sheet is dictated by the large magnitude axial velocity fluctuations, and thus, the reaction zone is seen to persist in the regions of the low strain rate and follows the passages of minimum strain around the periphery of the smaller vortices (see lower left reaction zone of the flames from frame 1 to 6). It is remarkable that the wrinkled flame sheets are oriented perpendicular to the axis of compressive strain rates at the SL1 of the swirling jet.

Figure 7 shows a time-series of the spatial location and structure of the reaction zone versus flow field of flame \( F_B \). Increasing the fuel jet velocity sustains the flow in the forward direction within the central flame region, and therefore there is less penetration of the back flow into the quarl exit. The reaction zone confining the swirling flow inside the quarl continues outside the quarl, but resides primarily in the SL1 along the interface between incoming unburned gas and the high temperature recirculating products. Further downstream, the reaction zone becomes corrugated near the location of vortex breakdown where the vortex rolls up the flame sheet and the reactions zone becomes more fragmented with appearance of isolate OH spots. Roll-up of the reaction zone results in a strong local heat release (see Fig. 3b). This flame-vortex interaction alters the path of the flame sheet from SL1 toward the inner zone (like flame \( F_A \)). In this sequence, the reaction zone follows the passage of the large scale structure, while remaining in the SL1 up to the vortex rolling up the flame.

Fig. 7b shows the same sequence of flame \( F_B \) overlaid on the instantaneous vorticity field. As shown, vortical structures to the left and right of the origin start narrow near the quarl exit and start to increase in width axially. As shown in all frames, the vorticity plots show what appears to be a correlation between high levels of vorticity and the reaction zones. With flame fragmentation around the flame rolling up locations, several isolated flame pockets are observed and the motion of the reaction zone become more complex. One can notice that, contrary to flame \( F_A \) (Fig. 6a), the spatial location of
the reaction zone at the lower part of the flame is located on or just behind the boundary of the vortical structure, whereas in flame \( F_A \), it is confined by vortical structure from outside. Figure 7c shows the compressive strain rate field overlaid the reaction zones of flame \( F_B \). The vortical structure formed two regions of high compressive strain separated by a thin layer of low strain, where the flame sheet is seen to reside (shown by elbows). Further downstream, the reaction zone is seen to track the large magnitude axial velocity fluctuations, while remaining in the low speed regions of the flow, and therefore in most cases, it resides at the boundaries of the high compressive strain rate layers.

Fig. 7. Reaction zones against: (a) velocity vectors and axial velocity contours, (b) vorticity, and (c) minimum principle strain rate field.
4. Conclusions

Simultaneous stereoscopic PIV and OH-PLIF measurements have been applied on two methane non-premixed quarl stabilized swirled flames of different fuel jet velocity ($V_f$), ($F_A$, $F_B$ with $V_f$ = 4.4 and 8.8 m/s, respectively) at a repetition rate of 5 KHz. In both flames, the time averaged flow field downstream the quarl shows a streamlined conical swirling jet surrounding two recirculation zones. One recirculation zone, RZ1, is more intense, located further downstream of the quarl at the inner shear layer of the jet (SL1), while RZ2 is a larger recirculation zone located between RZ1 and the central jet and extends down inside the quarl.

The flow field immediately downstream the quarl exit plays a vital role in the flame-flow interaction. Time sequences of instantaneous measurements show that in both flames a thin laminar flame is formed at the lower part of the flame near the quarl wall. Downstream of the quarl, the location of the reaction zone is altered, where in flame $F_A$ a pair of vortices are formed near the quarl corner and roll up the flame toward the center and away from the inner shear layer. The flame is observed to reside primarily in regions of low axial-velocity and show a high sensitivity to axial velocity fluctuations and the vortex formed within this region. These vortices lead to the wrinkling of the reaction zone and occasionally reside in SL1. The reaction zones in flame $F_B$ are predominantly formed at the inner shear layers of the jet flow. In this shear layer, the hot burned gas from the recirculation zone (RZ1) mixes with the fresh fuel/air mixture. The vortex break down causes a roll-up of the reaction zone toward central region, leading to intense mixing between the hot and cold gases which plays a vital role in stabilizing the flame in regions of high velocity. As the reaction zone is advected by the flow field, the interaction and correlation between the flame sheet and the other flow features, i.e., vorticity field and the compressive strain, changes. Good correlation between the reaction zone and regions of maximum vorticity were observed in flame $F_B$, while the regions of maximum vorticity confined the reaction zones in $F_A$. The reaction zone conformed to regions of low compressive strain, inside the central region and around the
periphery of vortices in flame F_A, while in flame F_B it was seen to lie along regions of minimum strain of the vortical structure and up to the location of vortex breakdown.

References


