Investigation of the effects of quarl and initial conditions on swirling non-premixed methane flames:

Flow field, temperature, and species distributions

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Abstract

Detailed measurements are presented of the turbulent flow field, gas species concentrations and temperature field in a non-premixed methane swirl flame. Attention is given to the effect of the quarl geometry on the flame structure and emission characteristics due to its importance in gas turbine and industrial burner applications. Two different quarls were fitted to the burner exit, one a straight quarl and the other a diverging quarl of 15° half cone angle. Stereoscopic Particle Image Velocimetry (SPIV) was applied to obtain the three components of the instantaneous velocity on a vertical plane immediately downstream of the quarl exit. Temperature and gaseous species measurements were made both inside and downstream of the quarls, using a fine wire thermocouple and sampling probe respectively. This work provides experimental verification by complementary techniques that, although the main flame structures were governed by the swirl motion imparted to the air stream, the quarl geometry, fuel loading and air loading also had a significant effect on the flow pattern, turbulence intensity, mixture formation, temperature distribution, emissions and flame stabilization. Particularly, in the case of the straight quarl flame, the flow pattern leads to strong, rapid mixing and reduces the residence time for NO formation within the internal recirculation zone IRZ. However, for the diverging quarl flames, the recirculation zone is shifted radially outward, the turbulent interaction between the central fuel jet and the internal recirculation zone IRZ induces another small vortex between these two flow features. Less mixing near the diverging quarl exit is observed, with a higher concentration

of NO and CO in the post-combustion zone. The instantaneous flow field for both flames showed the existence of small scale vortical structure near the shear layers which were not apparent in the time averaged flow field. These structures, along with high levels of turbulence present in the shear layer, result in the enhancement of the mixing, especially with straight quarl. The main goals of this article are to outline results that yield deeper insight into the combustion of swirling flames stabilized within the quarl and to establish an experimental data base for modelers.

1. Introduction

Swirl flows have been widely investigated because of their extensive use in a wide range of practical combustion systems, including gas turbine combustion, industrial burners, and furnaces [1-2]. Although a quarl is commonly used in gas turbine and industrial burners with swirling flames, there have been few studies on the effect of the qural geometry on the combustion characteristics. Many free or confined swirl diffusion flame studies have been performed using burners with a straight exit burner (*i.e.*, no quarl). Experimental results have established the general characteristics of swirl flows and revealed important effects of swirl on promoting flame stability and increasing combustion efficiency [3-7].

Measurements of the concentrations of gas species, temperature and emissions of pollutants in non-premixed swirling flames are presented in [8-10]. Two typical flame configurations arise according to the primary air ratio in non-premixed propane swirling flames. In the first type of flame, the fuel burns at near stoichiometric conditions to form a ring flame around the recirculation zone. In the second type, the fuel layer is diluted by mixing with surrounding air. The second flame type showed a lower NO_x emission relative to the first one but with a higher concentration of unburned hydrocarbons [8]. The effect of fuel-air mixing on the flame structure and NO_x emissions in swirling methane jet flames was experimentally studied [9]. Two modes of

combustion effected the emissions: type 1 was fuel jet dominated combustion and type 2 was strongly recirculating combustion. In strongly recirculating flames, a uniform mixture is formed in the recirculation zone that helps to reduce the NO_x emissions relative to the fuel jet dominated combustion mode. The NO_x emission level can further be reduced by using an annular fuel injector with a significant decrease in CO concentration due to enhanced mixing. In-flame measurements of flow field, temperature, and gas concentration were conducted to clarify the mechanism of NO formation [10] in these two types of combustion.

Laser-based diagnostic techniques offer the ability to yield two-dimensional fields of velocity and scalars with high temporal and spatial resolution. These techniques were employed in [11] to measure the flow field, structure, temperature, and species distributions of a swirl flame in a laboratory-scale gas turbine. Three flames with thermal powers between 7.6 and 34.9 KW were investigated. These flames were observed to behave differently with respect to combustion instabilities. In addition, the near-field flow structure of isothermal swirling flows and reacting non-premixed swirling flames was measured in a straight exit laboratory burner without swirl by [12]. Two fuel injection geometries, co-axial and radial, leading to different mixing mechanisms were investigated and characterized. Their study indicated that, although the main flame structure and mixing process are governed by the swirl motion, the fuel injectors play an important role in flame stabilization. Simultaneous planar laser induced fluorescence (PLIF) on OH radical and particle image velocimetry (PIV) measurements in a gas turbine model combustor were used to investigate the influence of turbulence on local flame characteristics [13]. These measurements revealed the formation of reaction zones in regions where hot burned gas from the recirculation zones mixed with the fresh fuel/air mixture at the nozzle exit.

The effects of the swirling flow on the spray characteristics with straight exit burner has been examined by Presser *et al.* [14]. Under non-burning and burning conditions, the fuel-air interaction in a kerosene spray swirling flames was examined, and provided qualitative details and quantitative measurements of the induced spray. The effects of the physical properties of four different fuels on the swirl spray flames was addressed by these researchers in [15]. They concluded that the fuel viscosity effected the mean droplet size and spray velocity distribution, with a negligible effect of the surface tension. The flame structures were seen to be influenced by the fuel volatility and with increasing carbon to hydrogen fuel ratio, the flame luminosity was observed to increase. Straight exit, double swirl burners have been proposed as a method to develop air staging to reduce NO_x burner [16-17]. They showed that the radial distribution of species and temperature differs significantly in the air staged flames, for which some interpretations have been suggested. The most important parameter was the air distribution, which can lead to air staging along the flame length and reductions of NO_x to one third of that the flames without staging [16]. The details of the swirl effects on the combustion characteristics of premixed swirling flames issued from a double concentric swirl burner was examined by Gupta *et al.* [18] and Marshall and Gupta [19]. The temperature (mean and fluctuations) field of two co-swirl and counter-swirl flames has been investigated. The symmetry of the flame and NO_x emissions were found to be greatly influenced by the swirl direction. Most of these studies investigated swirling flames with a straight exit into a free environment [8, 9, 12, 14-19] and/or in a gas turbine model combustor [11, 13].

Relevant swirling flame work with a quarl, includes a study of the stability maps of a swirl-stabilized, nonpremixed natural gas burner with three quarls and three fuel nozzle arrangements by Milosavljevic *et al.* [20]. The quarl half-angles were 20 ° and 25°, the ratios of length to

through diameter were $L/D = 1$ and 1.9 , and the maximum swirl number was 1.8 . They concluded that the leanest flames were found in the 20° , $L/D = 1$ quarl, and the poorest stability was provided by the 25° , $L/D = 1.9$ quarl. In a different study, the flow field and flame structure of a turbulent non-premixed swirl flame with a straight exit burner (no quarl) was measured by Shen *et al.* [21] and results were compared with existing data on a diverging quarl flame in [22] to provide further insight into the effect of the burner geometry on the flame structure. The flow field of their study was determined using the isothermal equivalent to the swirling flames via a laser Doppler velocimeter.

It is clear that the effects of a quarl on the flow field and combustion of reacting swirling flames have not been adequately investigated. In addition, no measurements of gaseous concentration, temperature, and velocity inside the quarl are available, although such measurements are important for establishing real boundary conditions. Here, the influence of the initial conditions (both fuel and air loading) on the structure of a free turbulent swirl diffusion flame with either a straight or diverging quarl is experimentally investigated. Comprehensive measurements of turbulent near flow field and just above the quarl exit using stereoscopic PIV and in-flame measurements of temperature and chemical species concentration inside of and downstream from the quarl are reported.

2. Experimental setup and measurement techniques

A schematic of the swirl-stabilized flame apparatus is shown in Fig. 1a. The burner consisted of two concentric tubes with an annulus that supplied swirled air and a central pipe delivering the fuel (methane). The swirl was generated via four tangential air inlets that mixed the tangential air with axial air upstream of the burner. The swirling coaxial airflow surrounded the central fuel tube with an inner diameter, d_f , of 4.4 mm and outer diameter, d_{fo} , of 6.3 mm. The air tube

diameter, d_A , at the throat ($Z = 0$ mm) indicated in Fig.1a, was 27 mm. The flame was established in a quarl downstream from the exit of the air tube. Two different quarls were fixed at the exit of the burner, namely a straight quarl (shown in Fig. 1a) and a diverging quarl with a half cone angle of 15° as shown in Fig. 1b. The length, L , of both quarls was the same, 40 mm. This burner was specifically designed to facilitate accessibility to radial and axial measuring probes inside the quarl for gas species concentration and temperature measurements. These measurements were done inside the quarl via four vertically aligned holes that were 3 mm in diameter on one side of the quarl. Only one measuring hole was used at a time with the other three holes sealed, such that no air could be entrained into the upstream region of the flame through these holes.

As shown in Fig. 1c, the stereoscopic PIV system consisted of a dual cavity, diode-pumped, solid-state Nd:YLF laser (LDY 300 Series) and a pair of CMOS cameras (LaVision, Image Pro HS 4M, HSS5, with a maximum resolution of 2016×2016 pixel). The laser produced 3.5 mJ / pulse at a repetition rate up to 10 kHz, with 9 ns pulse duration. Pulses were formed into a sheet with a 0.5-mm waist along the flame centerline using three cylindrical lenses. Both the air and fuel jets were seeded with titanium dioxide (TiO_2) particles with a nominal diameter of 0.5 μm via two seeding units (Particle Blaster 100- LaVision). The PB 100 seeding unit consists of a cylinder with a variable speed magnetic stirrer and plate with six nozzles to introduce the carrier flow inside the cylinder (the cylinder is partially filled with the seeding powder). The magnetic stirring bar inside the housing actuates the particles; by the changing the speed of rotation, agglomeration of the seeding particles could be prevented. In addition, the seeding unit incorporates a heating unit to remove any humidity from the seeding powder. The cut-off frequency in the turbulent flow field of the seeding particles is estimated to be 60 KHz, based on

the interpolation formulae: $f_{\text{cut-off}} \approx \nu/\pi (\varepsilon_{\text{cut-off}}/a)^2$ as suggested by Mei [23], where a is the seeding particle radius, ν is the kinematic viscosity, and $\varepsilon_{\text{cut-off}}$ is a function in the density ratio ρ , defined as the ratio between the seeding particle and fluid density and estimated as: $(\varepsilon_{\text{cut-off}} \approx [((3/2(\rho)^{0.5})^\gamma + (0.932/(\rho - 1.621)^\gamma)^{1/\gamma})]$. The cameras were mounted equidistant from the centerline of the burner with an angle of separation of 35° . Mie-scattered light from the particle-laden flow was collected using a 105 mm, f/4 objective lens (Nikon UV Micro-Nikkor) equipped with a 527 nm band pass filter. The cameras were operated in two-frame burst mode at 500 fps. Image-blur due to off-axis defocusing was corrected using Scheimpflug adaptors between the objectives and the cameras. Perspective distortion was corrected using a dual plane, three-dimensional imaging target (LaVision Type 22). Image de-warping between the two camera images was corrected using the image correction and distortion function. Also, with the self-calibration function, the coordinate system and the camera calibration of this stereoscopic PIV setup were adjusted so that the $Y = 0$ mm plane (see Fig. 1a. for coordinates) was adjusted exactly in the middle of the laser light sheet. Vector fields were computed from particle image spatial cross correlations using the La Vision Davis 8.1 software package. An adaptive multi-pass vector evaluation technique was used, with interrogation boxes ranging from 128 pixels to 16 pixels, with 50% overlap resulting in spatial resolution and vector spacing of approximately 0.5×0.5 mm and 0.25 mm, respectively. The final velocity vector fields were smoothed with a 3×3 vector moving average filter for subsequent analysis.

A 3-D positioning mechanism was used to move the measuring probes for temperature and gas concentration measurements in all three spatial dimensions with a resolution of 0.1 mm. The temperature distribution of the flame was measured using a 12- μ m wire diameter uncoated type-S (Pt-Pt-13%Rh) thermocouple. The thermocouple (TC) signal was digitized and recorded by a

PC using an AD Lab Card (model NI PCI-6020, 16-bit, maximum sampling rate 200 KHz). Due to the relatively small wire diameter of the thermocouple, the temperature measurements in this work were uncorrected for radiation [24]. The maximum error in temperature measurements, neglecting the influence of radiation, was estimated to be ± 50 K. A water-cooled sampling probe with an inner diameter of 1 mm and a 2.5 mm-diameter outer cooling tube were used to collect gas samples for both in-flame and post-combustion measurements. The tip of the outer cooling tube was tapered to an inner diameter of 1 mm, such that the disturbance to the flow was minimized. The gas sample was cooled down to 60 °C to yield water vapor condensation and the concentrations of O₂, CO and NO were measured using a LANCOM series II gas analyzer. The uncertainty in the gas species concentrations were $\pm 0.1\%$ in O₂, ± 1 ppm for NO, and ± 50 ppm in CO concentrations.

The swirl number in this study is defined as the geometrical swirl number and calculated by measuring the mass flow rates of the axial air (m_A) and tangential air (m_θ), which is defined as [25]:

$$S_g = \frac{\pi r_o d_A}{2 A_t} \left(\frac{m_\theta}{m_\theta + m_A} \right)^2 ,$$

where S_g is the geometric swirl number, A_t is the total area of the four tangential air inlets, with $d_t = 4.4$ mm, r_o is the radius of the air tube ($d_A - d_t$), and d_A is the inner diameter of the air tube, $d_A = 27.2$ mm. In this work, the swirl number was 10.25.

3. Results and Discussion

3.1. Flame stability and appearance

With a fixed geometrical swirl number, S_g , of 10.25, the flame stability limits were measured with two quarls, a straight and diverging quarl, fitted to the burner exit. These stability results are presented as the relation between the axial air velocity, V_a (calculated based on the axial flow rate and the annulus area), and the fuel jet velocity at blow off, $V_{f_{\text{blow-off}}}$. The stability point was reached by gradually reducing the fuel flow rate while keeping the axial and tangential air flow rates constant until the flame was extinguished. As illustrated in Fig. 2, the fuel velocity at extinction, $V_{f_{\text{blow-off}}}$, generally increases with increasing axial air velocity. The flames with the straight quarl were more stable than those with the diverging quarl, and this effect was more pronounced at high axial air velocities. The possible physical mechanism leading to this difference is the zero axial velocity contour in the straight quarl, where the strain rates are relatively low, substantially improving the stability limits. This hypothesized mechanism is confirmed by the in-flame measurements.

By decreasing the fuel jet velocity in the straight quarl, the effect of the internal recirculation zone, IRZ, through the backflow becomes dominant, which moves the forward stagnation point further upstream towards the fuel tube. This leads to more fuel/air mixing with hot combustion products continuously mixed with the fresh fuel/ air mixture and to a higher probability that the instantaneous flammable region overlaps the zero axial velocity contours. Contrary to this, in the diverging quarl, the IRZ is shifted radially away from the fuel jet, which means that there is less of an interaction between the fuel jet and the vortex in the early axial zone of the flame. With this shifted IRZ, less mixing and more unheated recirculated gases are pushed toward the fuel jet shear layer. Therefore, when the flame approaches extinction by decreasing the fuel jet velocity, which increases the percentage of unheated recirculated gases relative to the fuel jet, which in turn, leads to the sudden blow off of the flame in the diverging qual.

Based on the stability plot, in-flame measurements were conducted on five selected flames. The main parameters of these selected flames and the corresponding flame designations are listed in Table 1, and their locations on the stability curves are shown in Fig. 2. Two sets of experiments with a straight quarl were conducted. In the first set, the axial air velocity was 2.7, 4, or 6 m/s, while the jet fuel velocity, V_f , was kept constant at 5.8 m/s. In the second set, with a constant axial air velocity, V_a , of 4 m/s, the fuel jet velocity was 3.5, 5.8, or 7.3 m/s. One flame condition ($V_f = 5.8$ m/s and $V_a = 4$ m/s) with the diverging quarl and same swirl number, was investigated. As indicated in Table 1, among the five conditions in the flame appearance investigation, four flames were selected for Stereo PIV and temperature/gas species measurements.

Photographs with exposure time of 1/30 s of the swirling methane flames with $Sg = 10.25$ for the three different V_a of 2.7, 4, and 6 m/s are shown in the first row of Fig. 3. At low axial velocity (left photo), a blue bubble-like recirculation zone appeared at the flame base at the quarl exit. The flame was long and its highly luminous yellow jet flame fully penetrated the recirculation zone, indicating insufficient mixing. Increasing the axial air velocity to 4 m/s shortened the flame length and a more compact blue flame was formed, indicating the formation of a strong internal recirculation zone that enhanced fuel-air mixing. As the axial air velocity was further increased (third photo), the flame became blue, indicating high and uniform temperature distribution. Moreover, the flame was acoustically noisy, resulting from the violent interaction of the central jet and recirculation vortex and/or vortex breakdown. The first three photos of the second row show the effect of increasing the fuel jet velocity on flame appearance when Sg and axial velocity were kept constant (see Table 1). With increasing fuel velocity, the internal recirculation zone, IRZ, was seen to intermittently penetrate the flame and a yellow plume appeared (Flame

Fs5) and the yellow plume appears as a result of penetration of the fuel jet to the IRZ and increases as the fuel jet increases. This luminosity indicated the formation of soot that was confined to the central region, likely due to the intermittent formation of a large concentration of fuel in the high temperature regions of the flame, see flames Fs1 and Fs5. Also, as shown in the last photo in the second row, the diverging quarl had a significant effect on the flame appearance (flame Fd2). In this case, the diverging quarl led to the fuel being able penetrate through the IRZ, which was not the case with the straight quarl under the same operating conditions (flame Fs2). With a diverging quarl, the IRZ shifted radially outward, which reduced the momentum exerted from the reverse flow on the central fuel jet at locations low in the flame.

3.2. Flow field features

Figure 4 shows ensemble averaged images of 500 stereo PIV recordings for swirling flames Fs2, Fs3, Fs4, and Fd2. Only half of the PIV measurements are presented due to symmetry. These images were recorded over the entire region of the flame above the quarl exit. The flow swirled counter-clockwise about the vertical axis (as viewed from above) and the highest flow velocities were seen in the conically shaped inflow of fresh gases. The velocity vector values in the measurement plane are indicated by the arrows and are superimposed with streamlines; the out-of-plane component (W) is discussed in the next section. Typical features of the flow field of a swirling flame accompanied by a straight quarl (Fs2) are shown in Fig. 4a. The flow field is characterized by an inner recirculation zone, IRZ. The eye of this IRZ appears immediately at the quarl exit ($-15 < r < -5$ mm), and, as indicated, the IRZ extends down inside the quarl. The negative axial velocity in the near field around the flame's central region indicates that the backflow and the fuel jet formed a stagnation point inside the quarl. This IRZ is flanked by a velocity peak (at nearly $r = -16$ mm) associated with the faster flow through the annular swirling

jet. A shear layer exists between the inflow swirling jet and IRZ. In this shear layer, hot combustion products are continuously mixed with the fresh fuel-air mixture, and combustion is stabilized such that the flame resides here. Further downstream, the inward flow toward the central region disappears. As shown in Fig. 4b, increasing the axial air velocity leads to more outward radial expansion of the swirling jet. This toroidal recirculation zone increases with axial air velocity. Moreover, the radial expansion and the higher axial velocity leads to the downstream movement of the center of the IRZ, while its radial location remains nearly fixed. Contrary to this behavior, decreasing the fuel jet velocity of flame Fs3 (Fig. 4c) causes the center of the IRZ to move upstream, closer to the quarl exit.

The flow field for the diverging quarl (Fd2, Fig. 4d) exhibits different flow field features compared with those of flame Fs2. In the near field close to the quarl exit, three different flow regions are observed: a positive velocity vector around the flame's centerline due to the fuel jet; an outer recirculation zone located far from the flame's centerline; and an inner vortex generated between the fuel jet and this outer recirculation zone. This inner vortex is generated at the shear layers of these two large features and this inner vortex is responsible for the mixing between the fuel jet and the main swirling jet at locations near the fuel tube's exit. With the diverging quarl, the swirling jet expands radially, leading to the creation of an inner vortex far away from the flame's centerline (see Fig. 4-d). This in turn allows the central fuel jet to penetrate through the recirculation backflow, leading to less mixing between the fuel and air and resulting in soot formation within the central region of that flame that was observed in the flame appearance. Figures (4e-4f) illustrate the average velocity vectors superimposed the strain rate ($\partial v / \partial z$, where v is the vertical velocity component and z is the vertical axial distance) at the lower part of flames Fs2 and Fd2. As shown close to the burner exit, the zero velocity line of the IRZ for

flame Fs2 is localized within a region of relatively low strain rate. However, in the flame Fd2, the recirculation zone is shifted radially, with the flame residing in a region of relatively high strain rate where the flame is reside there.

While the ensemble-averaged flow field provides insights into the flame's stabilization mechanisms, instantaneous flow structures play a more critical role in determining combustion stability, mixing enhancement, and flame blow off. Instantaneous structures of the flow field are shown in Fig. 5 with two examples of the velocity vectors and a streamline plot from a time series of the straight and diverging quarls under F2 conditions. It is immediately clear that the instantaneous flow field looks dramatically different from the mean flow field and that strong temporal fluctuations of the structures occur. In contrast to only a single internal recirculation zone observed in the mean velocity field, the instantaneous PIV images indicate the existence of multiple small-scale vortical structures in regions close to the shear layers and at further axial distances from the central region of the flame, see Fig. 5 which shows two examples of consecutive flow field plots at 500 fps. These small vortices form and dissipate continuously in the shear layer. Along with the high turbulence intensity present in the shear layer, these vortices result in intense mixing between the cold fresh gas and hot burned gases coming from IRZ in flame Fs2. However in flame Fd2, the intensity of the mixing is reduced due to the radial expansion of the swirling jet flow. Figures 5c- 5d illustrate the mutual interaction between the central fuel jet and the swirling main jet in the shear layers of the inner vortex. In addition, in both flames, the instantaneous velocity fields are much larger than those in the ensemble averaged fields shown in Fig. 4. Furthermore, at some locations, sudden increases in velocity occur within the instantaneous field of flow, and these increases are averaged out in the mean flow field. According to mass conservation requirements, strong swirling flow components

normal to the measurement plane are needed to support such increases or decrease. Fig. 5e shows an example of these increases, where the planner velocity vectors are overlaid with the swirling velocity in a typical instantaneous velocity image. The locations where the velocity suddenly increases are associated with a lower tangential velocity and vice versa.

The centerline profiles of the mean axial velocity, V , and the central turbulence intensity characterized by the root mean squared rms of the axial velocity, V_{rms} , are shown in Fig. 6. As illustrated in Fig. 6a, the three flames with the straight quarl all show a negative centerline velocity across the IRZ. Further downstream, these profiles show a progressive velocity increase until reaching the boundary of the IRZ. Downstream of the IRZ, the centerline velocity profiles show a nearly linear centerline increase, with the highest centerline velocity for flame Fs2 and the lowest centerline velocity for flame Fs4, due to the lower thermal input of flame Fs4. The corresponding mean centerline temperature distributions for these flames are shown in Fig. 7. The data indicate that there is a gradual centerline temperature increase with the diverging quarl compared to a steep temperature increase with the straight quarl. Beyond the peak temperature, flame Fs4 experiences a linear decline in temperature; flame Fs3 experiences a significant decrease in temperature around the boundaries of IRZ. However in the near field, due to the penetration of the fuel jet into the IRZ (Fig. 6a.), the centerline velocity of flame Fd2 experiences a gradual decrease, reaching a minimum value at $Z = 80$ mm. This decrease is due the fuel jet-vortex interaction. Downstream of this location, the centerline velocity recovers, exhibiting a higher centerline velocity in comparison with Fs2.

Two factors lead to this behavior: the first is a reduced effect from the IRZ on the early fuel jet for flame Fd2, and the second is the delay of mixing, which increases the flame's centerline temperature in the post-combustion flame region (see Fig. 7). Axial profiles of the vertical

velocity rms, V_{rms} , are shown in Fig. 6b. The data show similar profiles for all flames with straight quarls, where V_{rms} is lower in the near field with a steep increase, reaching a peak at the boundary of the IRZ. For flames with diverging quarls, a remarkably high and constant V_{rms} at the quarl exit exists for a short distance (attributed to the central fuel jet) and is followed by a steep increase in V_{rms} , reaching a peak at the axial location of minimum V . In general, the V_{rms} of the diverging quarl exhibits higher velocity fluctuations relative to the flames with the straight quarl due to the vigorous fuel jet-vortex interaction downstream of the quarl exit plane. In addition, the early mixing of straight quarl flames leads to regions of higher temperature regions in the lower parts of flame, and hence more damping of the velocity fluctuations.

The mean swirling velocity component, W , was investigated by the ensemble average of 500 stereo PIV recordings of flames Fs2 and Fd2, with the contours of the mean swirling velocity shown in Fig. 8. One can see that, in both flames, the maximum swirling velocity components are located downstream from the quarl exits. In addition, with the radial expansion of the swirling jet associated with the diverging quarl, these flow conditions conserve the tangential velocity for a longer distance further downstream from the quarl, while pushing the location of the maximum swirling velocity downstream. This may help explain the penetration of the fuel jet into the IRZ with the diverging quarl. The contours shown in Fig. 8 and the radial profiles of the swirling velocity and the swirling velocity fluctuations at $Z = 80$ mm shown in Fig. 9 indicate that over the entire region of both flames, no mean tangential component exists at the flame centerline. However, high tangential velocity fluctuations (W_{rms}) occupy the flame core, with higher fluctuations measured for Fd2.

Although the average velocity vectors show a negative axial velocity for flame Fs2 and a positive axial velocity for flame Fd2 at low axial distances. For example, at an axial distance of

$Z = 60$ mm, the axial velocity histograms (Fig. 10) indicate that both negative and positive values exist. With the large velocity fluctuations at the flame's centerline for flame Fd2, the histogram shows a broader velocity band than that of flame Fs2, with the average shifted toward the positive velocity. These velocity fluctuations give an indication of the motion of the stagnation point for flame Fs2, and the higher velocity fluctuations associated with the central penetrated jet of flame Fd2.

3.3. Temperature field and gas concentrations

The mean temperature contours for flames Fs2, Fs3, Fs4 and Fd2 are presented in Fig. 11, where these contours result from measurements inside and downstream from the quarl. With the formation of the IRZ at the quarl exit of flame Fs2, it can be seen in Fig. 11a, the highest temperatures were obtained in the main reaction zone, located at the boundary of the IRZ and extending down inside the quarl. In the IRZ close to the axis, where burnt out gases mainly prevail, low heat loss leads to higher temperatures. Further downstream from the IRZ, a narrow annular tail of peak temperature surrounds a relatively low temperature central flame region. With increasing axial air velocity at the same swirling number of flame Fs3, a large IRZ is formed at the quarl exit, leading to stronger inner backflow and resulting in a broader high temperature zone inside the quarl. With increasing axial velocity, the engulfment of the cold mixture in the central region reduces the temperature level immediately downstream of the IRZ. By decreasing the velocity of the fuel jet (flame Fs4), the overall mean gas temperature across the entire flame is reduced (Fig. 11c). The temperature contours of the diverging quarl shown in Fig. 11d indicate a very different temperature distribution. The peak temperature occurs much further downstream and is confined to a narrow region about the centerline, in line with the flow field pattern of the diverging quarl flame. An example of the radial temperature distribution at an

axial distance of $Z = 38$ and 50 mm (inside and outside the quarl) is shown in Fig. 12a, where the peak temperature for flame Fs2 occurs at the flame centerline compared to radially shifted temperature peak for flame Fd2 at an axial distance of $Z = 38$ mm. With the aid of the radial axial velocity and radial temperature profiles at an axial distance of $Z = 50$ mm for flames Fs2 and Fd2, shown in Fig. 12b, the main swirling jet at the diverging quarl is shifted outward. In addition, it is clear that at the fuel jet's shear layer, there is a reversed flow region in flame Fd2 and a totally reversed region occupying the central region of flame Fs2. The peak temperature is located in the reversed inner boundaries with the temperature gradually declining toward the main swirling jet in flame Fd2. With the straight quarl, a fairly uniform temperature is observed near the centerline inside the reversed region of flow, with a steeper temperature decline moving radially outward. This indicates that there is less fuel jet swirling in the diverging quarl. In the flow field pattern of the diverging quarl, the fuel jet penetrates the IRZ, and hence a lower temperature is recorded at the flame's centerline inside the quarl, with the formation of the secondary vortex at the shear layer of the fuel jet, leading to a peak temperature located away from the flame's centerline inside the quarl as shown in Fig. 12b. As a consequence, mixing between the fuel and air is postponed to further downstream and a higher temperature is recorded at the flame's tip.

Figures 13 and 14 show the radial gas concentrations and mean temperatures in flames Fs2 and Fd2 at eight different axial locations. The concentrations are plotted on a dry basis. As shown in Fig. 13, the temperature profile of flame Fs2 inside the quarl and near the burner exit at $Z = 28.5$ mm is nearly uniform in the low-temperature region. The concentration measurements indicate a corresponding very low and uniform CO concentration of 60 ppm; the O_2 concentration is nearly constant at 20.9% with a slight decrease at the flame's centerline; and the

NO concentration is nearly zero. The centerline temperature continuously increases with axial distance, and at 48.5 mm it reaches 1200 °C, which is accompanied by a steep CO increase, indicating the mean location of the flame stabilization point. At 63 mm and further from the fuel tube's exit, the peak temperature is nearly constant and the radial extent of this high temperature region spreads with downstream distance, indicating a well-mixed zone within IRZ. This is coupled with a further reduction in the O₂ and CO concentrations and a progressive increase with a shift in the CO peak to the boundaries of the uniform flame temperature. Moreover, the NO profiles show a gradual increase as shown in Fig. 13g, they follow the profiles of temperature and the availability of O₂ species. The maximum NO concentration increases with the maximum flame temperature, indicating that the thermal NO mechanism is the dominant mechanism in these regions of the flame.

At the furthest downstream locations, Z = 113 and 133 mm, the O₂ profiles exhibit relative increases within the central flame region, which are attributed to transport of O₂ from the outer regions of the flame. The CO concentration profiles show a gradual reduction in the downstream direction, due to oxidation to CO₂. At Z = 73 and 83 mm, the NO concentration peaks at the boundaries of the uniform flame temperature region, but with a more uniform temperature profile at further downstream locations, the NO profiles show an attenuated plateau with the peak displaced away from flame centerline.

The radial temperature profiles and concentration profiles for flame Fd2 are shown in Fig. 14. The profiles are seen to qualitatively follow the same trends as those of flame Fs2 (Fig. 13). However, due to the diverging quarl, the following features are noted for flame Fd2. The peak flame temperature is located away from the flame's centerline near the exit of the quarl, due to penetration of the fuel jet into the IRZ, and the formation of small vortices at the fuel jet, as

mentioned earlier. At $Z = 28.5$ and 38.5 mm, a remarkably lower O_2 concentration along the centerline is observed followed by a radially sharp increase in the jet shear layer, indicating less mixing in these regions near the quarl exit. Due to the delayed mixing between the fuel jet and swirling air at this early axial distance, the O_2 concentration at the centerline is seen to slightly increase downstream, reaching a plateau of uniform O_2 concentration, due to the inner vortex located between the fuel jet and the shifted main vortex. At the outer radial boundaries of this plateau, a steep increase in O_2 is observed, indicating strong mixing with the outer swirling flow. The sudden increase in CO concentration for flame Fs2 at the boundaries of the IRZ (Fig. 13e) is absent in these flames; rather, a gradual radial increase with the higher concentrations is located at the central flame region. The NO measurements show a sudden increase in the NO concentration between $Z = 38.5$ and 48.5 mm, with a higher concentration at the central region.

Based on flame appearance and flow field patterns, we conclude that the diverging quarl leads to insufficient fuel/air mixing at the early axial distances, which leads to a lack of oxygen within the central fuel jet. These conditions indicate that the prompt NO mechanism is the dominant NO formation mechanism at these axial locations near the quarl exit, but further downstream, the NO profiles follow the temperature profile (Fig. 14h) with a higher NO emission with the diverging quarl in comparison with the straight quarl and indicating a switch to the thermal mechanism. Due to back flow in the early regions in flame Fs2, leading to shorter residence times in the recirculation zone and higher recirculated burned gas concentrations, the low NO concentration within IRZ of flame Fs2 is observed.

4. Conclusions

The design of a quarl-stabilized swirling flame burner for gas turbines and industrial burners requires careful examination of the role of different operational parameters and geometry to

predict flame stability, flame structure, and emissions. The objective of this work was to obtain better insight into the role played by the quarl's geometry on the structure of free-swirling non-premixed CH₄/air flames. The burner was fitted with straight exit or diverging quarl with a 15° half cone angle. With a fixed geometrical swirl number, the effect of axial air velocity, fuel loading, and quarl geometry on the lean stability limit, flame appearance, turbulent flow field, and major gas concentrations inside the quarl and the near field was measured. Due to the lack of optical access inside the quarls, the turbulent flow field was captured only downstream of the quarl exit, using Stereoscopic PIV. However, both the temperature field and major gaseous species concentrations were measured both inside and outside of the straight and diverging quarls.

The lean stability limits were strongly influenced by the bulk combustion-air velocity for both quarls, where increasing the axial air velocity reduced the stability flame region, with more broaden flame stability in the case of the straight quarl. The mean flow fields showed that the global mixing process and the main flame structure are governed by the swirling motion exerted on the air stream, and the quarl geometry plays an important role in mixing, flow field features, and flame stabilization. With the straight quarl, the mean flow field can be divided into two main regimes: a conically shaped inflow swirling region and an inner recirculation zone region. The recirculation zone extends down inside the straight quarl. The turbulent interaction between the central fuel jet and the backflow generated within the inner recirculation zone enhanced the mixing just inside the quarl. In contrast, in the diverging quarl flame, the flow field near the quarl exit is characterized by three regions: the central fuel jet region, the outer recirculation region, and between these two regions, the inner recirculation zone. This is accompanied by an outward shift of the conical swirling flow. The inner vortex is responsible for the mixing between the

central fuel jet and the outer recirculation zone. With this flow pattern, less mixing near the quarl exit is observed.

The peak swirl velocity is located closer to the straight quarl exit and located farther downstream in the diverging quarl, with a slower rate of decay with axial distance for the diverging quarl. The instantaneous structure of the IRZ consisted of several small vortices mainly located inside the inner shear layer of the swirling jet stream for both quarls. These instantaneous velocity realizations also revealed the existence of small vortices far away from the quarl exit along the flame's central region.

Due to different flow field patterns, both the temperature field and species concentrations inside and outside the quarl were affected. In the straight quarl flame, the temperature measurements showed a significant change when both the fuel jet velocity and the axial air velocity were changed. Strong and rapid mixing in these flames increased the mixture's homogeneity and shortened the residence time for NO formation within IRZ, while higher NO and CO concentrations were measured at the IRZ boundaries. In these flames, thermal NO is the dominant formation mechanism.

However, the peak flame temperature in the diverging quarl was shifted outward near the quarl exit, where prompt NO is the main mechanism and peak concentrations occurred along the centerline. A steep increase in the CO concentration at the IRZ boundaries in the straight quarl flame was not observed; rather, a gradual increase with a relatively high concentration in the flame's central region was seen in the diverging quarl. The diverging quarl flames show a higher concentration of NO and CO in the post-combustion zone.

In conclusion, these experimental measurements provide better understanding of the flow field pattern of swirling flames with quarls and of the effect of this pattern on the flame stability,

temperature fields, and flame structure in terms of major species. These results will be useful in the validation and improvement of numerical simulations. Future work will focus on further investigations inside the quarl using simultaneous OH PLIF/PIV measurements with optical access via a quartz quarl. With this information, a clearer understanding of the turbulence-chemistry interaction in the vicinity of the quarl will be possible. The data will be organized in a usable form and made available, together with information on boundary conditions and estimated measurement accuracies, to model developers.

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References

- [1] Beér JM, Chigier NA. Combustion Aerodynamics, Applied Science Publishers, London, 1972.
- [2] Syred N, Beér JM. Combustion in swirling flows: A review. Combust. Flame. 1974; 23 Issue 2: 143-201.
- [3] Feikema D, Chen RH, Driscoll JF. Enhancement of flame blowout limits by use of swirl. Combust. Flame 1990; 80: 183-195.
- [4] Feikema D, Chen RH, Driscoll JF. Blowout of nonpremixed flames: Maximum coaxial air velocities achievable with and without swirl. Combust. Flame 1991; 86: 347-358.
- [5] Meier W, Weigand P, Duan XR, Thoben RG. Detailed characterization of the dynamics of thermoacoustic pulsations in a lean premixed swirl flame. Combust. Flame 2007; 150: 2-26.
- [6] Meier W, Duan XR, Weigand P. Investigation of swirl flames in a gas turbine model combustor II. Turbulence-chemistry interactions. Combust. Flame 2006; 144: 225-236.
- [7] Faler JH, Leibovich S. Disrupted states of vortex flow and vortex breakdown. Phys. Fluids 1977; 20: 1385-1400.
- [8] Takagi T, Okamoto T. Characteristics of combustion and pollution formation in swirling flames. Combust. Flame 1981; 43: 69-79.
- [9] Schmittl P, Günther B, Lenze B, Leuckel W, Bockhorn. Turbulent swirling flames: Experimental Investigation of the flow fields and formation of nitrogen oxide. Proc. Combustion Inst. 2000; 28: 303-309.
- [10] Cheng TS, Chao YC, Wu DC, Yuan T, Lu CC, Cheng CK, Chang JM. Effects of fuel-air mixing on flame structures and NO_x emissions in swirling methane jet flames. 27th Symposium (International) on Combustion 1998; P1229-1237.
- [11] Weigand P, Meier W, Duan XR, Stricker W, Aigner M. Investigation of swirl flames in a gas turbine model combustor I. Flow field, structures, temperatures, and species distributions. Combust. Flame 2006; 144: 205-224
- [12] Olivani A, Solero G, Cozzi F, Coghe A. Near flow field structure of isothermal swirling flows and reacting non-premixed swirling flames. Experimental Thermal and Fluid science 2007; 31: 427-436.
- [13] Sadanandan R, Stöhr M, Meier W. Simultaneous OH-PLIF and PIV measurements in a gas turbine model combustor. Appl. Phys. B 2008; 90: 609-618.

- [14] Presser C, Gupta AK, Semerjain HG. Aerodynamic characteristics of swirling spray flames: pressure-jet atomizer, *Combust. Flame* 1993; 92:25-44.
- [15] Presser C, Gupta AK, Avedisian CT, Semerjain HG. Fuel property effects on the structure of spray flames, *Twenty-Third Symposium (International) on combustion/The combustion Institute*, 1990; 1391-1367.
- [16] Ballester J, Sanz A, Gonzalez MA, Investigation of the characteristics and stability of air-staged flames, *Experimental thermal and fluid science*, 2008; 32: 776-790.
- [17] Jing J, Li Z, Zhu Q, Chen Z, Wang L, Chen L, influence of the outer secondary air van angle on the gas/particle flow characteristics near the double swirl flow burner, *Energy*, 2011; Vol 36, Issue 1: 258-267.
- [18] Gupta AK, Lewis MJ, Daurer M, Swirl effects on combustion characteristics of premixed flames, *Journal of Engineering for gas turbine and power*, July 2001; 123: 619-626.
- [19] Marshall Aw, Gupta AK. Thermal behavior of coswirling flames, *combust. Sci. and Tech.* 2004; 176: 437-451.
- [20] Milosavljevic VD, Taylor AMKP, Whitelaw JH. The influence of burner geometry and flow rates on the stability and symmetry of swirl-stabilized nonpremixed flames. *Combust. Flame* 1990; 80: 196-208
- [21] Shen D, Most JM, Joulain P. The effect of initial conditions for swirl turbulent diffusion flame with a straight-exit burner. *Combust. Sci. and Tech.* 1994; 100, 203-224
- [22] Tangirala V, Chen RH, Driscoll JF. Effect of heat release and swirl on the recirculation within swirl-stabilized flames. *Combust. Sci. Technol.*, 1987; 51, 75-95.
- [23] Mei R, Velocity fidelity of flow tracer particles, *Experiments in fluids*, 1996; 22: 1-13.
- [24] Lockwood FC, Moneib HA. Fluctuating temperature measurements in turbulent-jet diffusion flame. *Combust. Flame* 1982; 47: 291-314.
- [25] Claypole TC, Syred N. The effect of swirl burner aerodynamics on NO_x formation, *Eighteenth Symposium (International) on Combustion*, The combustion Institute, Pittsburgh 1981; 18 issue 1: 81- 89.

Table1

The main parameters of investigated flames.

Quarl	S _g	Va (m/s)	Vf (m/s)	mom _a /mom _f	flame	measurements			
						appearance	SPIV	Temperature	Gas concentrations
Straight	10.25	2.7	5.8	13.8	Fs1	*			
		4		30.4	Fs2	*	*	*	*
		6		68.4	Fs3	*	*	*	
		4	3.5	83.4	Fs4	*	*	*	
			5.8	30.4	Fs2	*	*	*	
			7.3	19.2	Fs5	*			
Diverging θ = 15 °	10.25	4	5.8	30.4	Fd2	*	*	*	*

mom_a/mom_f: is the axial momentum of the air stream to the axial momentum of the fuel jet.

Fig. 1. Experimental set up, (a) swirling burner with straight quarl, (b) diverging quarl, (c) Stereo PIV set up

Fig. 2. Lean stability limits for straight and diverging quarl swirl stabilized methane non-premixed flame at ($S_g = 10.25$). The stars denote flames far from blow-off which are under investigation.

Fig. 3. Flames appearance, first raw show the effect of increasing the axial air velocity ($S_g = 10.25$, $V_f = 5.8 \text{ m/s}$), and in the second raw, from the first to the third photos indicate the effect of increasing fuel jet velocity ($S_g = 10.25$, $V_a = 4 \text{ m/s}$, for clarity the photo of flame **Fs2** is repeated), the last images “**Fd2**” shows the effect of quarl angle on the flame appearance working the same flow conditions of flame **Fs2**.

Fig. 4. Time average velocity vectors overlaid the averaged stream line plots at the axial plane of the burner: (a) flame Fs2, (b) flame Fs3, (c) flame Fs4, and (d) flame Fd2 (alternate rows of vectors have been removed for clarity), (e) and (f) are the velocity vectors superimposed the average strain rate ($\partial v / \partial z$) of flames Fs2 and Fd2 respectively.

Fig. 5. Two examples of instantaneous velocity vectors and stream lines plot of the flow field at the axial plane: (a), (b) of flame Fs2, (c), (d) of Fd2, and (e) the velocity vector superimposed with the swirling velocity contours for Fd2 (alternate rows of vectors have been removed for clarity).

Fig. 6. Centerline profiles of (a) mean axial velocity, V , and (b) rms of the axial velocity, (V_{rms}) for flames Fs2, Fs3, Fs4, and Fd2

Fig. 7. Mean centerline temperature of flames, Fs2, Fs3, Fs4, and Fd2.

Fig. 8. Time average velocity contours of swirling velocity components of the flow field at the axial plane of the burner: (a) Flame Fs2, (b) Flame Fd2.

589 **Fig. 9.** Radial profiles of swirling velocity component, W , and W_{rms} , of flames Fs2 and Fd2 at axial
590 distance $z = 80$ mm.

Fig. 10. Axial velocity histograms on the burner axis and at an axial location of $Z = 60$ mm, (a) Flame Fs2 and (b) Flame Fd2.

Fig. 11. Mean temperature contours: (a) Flame Fs2, (b) Flame Fs3, (c) Flame Fs4, and (d) Flame Fd2.

Fig. 12. Radial profiles, (a) temperature profile at axial distances at $Z = 28$ and 50 mm of flames Fs2 and Fd2, and (b) Radial axial velocity profiles at $Z = 50$ mm of flames Fs2 and Fd2.

Fig. 13. Radial profiles of species concentration and mean temperature at different axial locations of flame Fs2.

Fig. 14. Radial profiles of species concentration and mean temperature at different axial locations of flame Fd2.