Investigation of turbulent swirling jet-flames by PIV / OH PLIF / HCHO PLIF

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Abstract. The present paper reports on the investigation of fuel-lean and fuel-rich turbulent combustion in a high-swirl jet. Swirl rate of the flow exceeded a critical value for breakdown of the swirling jet's vortex core and formation of the recirculation zone at the jet axis. The measurements were performed by the stereo PIV, OH PLIF and HCHO PLIF techniques, simultaneously. The Reynolds number based on the flow rate and viscosity of the air was fixed as 5 000 (the bulk velocity was \( U_0 = 5 \text{ m/s} \)). Three cases of the equivalence ratio \( \phi \) of the mixture issuing from the nozzle-burner were considered, viz., 0.7, 1.4 and 2.5. The latter case corresponded to a lifted flame of fuel-rich swirling jet flow, partially premixed with the surrounding air. In all cases the flame front was subjected to deformations due to large-scale vortices, which rolled-up in the inner (around the central recirculation zone) and outer (between the annular jet core and surrounding air) mixing layers.

1. Introduction

Swirl is often used for stabilization of jet-flames. Jet flows with strong swirl are featured by breakdown of the swirling vortex core, formation of the central recirculation zone and presence of spiral/helical vortices [1]. The effect of such flow features as vortex breakdown and precession of the vortex core on the combustion in swirling jets is still not completely understood yet. In particular, impact of the large-scale vortex structures (including precessing vortex core, see [2, 3]) on dynamics and stability of flames in swirling flows is still a debated issue [4]. Thus, analysis of flame-vortex interactions in swirl-stabilized combustors is important for better understanding of unsteady combustion phenomena [5].

The large-scale vortices are known to induce deformations of the flame front, affect the heat release rate and may result in local flame extinction. These features have been recently studied by using the combination of particle image velocimetry and planar-laser induced fluorescence (PLIF) for hydroxyl [6, 7], produced in the flame front and present in the combustion products. Nevertheless, there is a need in a detailed analysis of the reaction zone shape and flame front deformations, including those, which are not induced directly by large-scale flow motions.

The present paper reports on the experimental study of flame stabilisation in a high-swirl jet of methane/air mixture for different equivalence ratios. Three cases of combustion regimes are studied, namely, fuel-lean and fuel-rich premixed flames and fuel-rich partially premixed lifted flame.
2. Experimental setup

Measurements were carried out for the swirling flames of the methane/air mixtures at atmospheric pressure. The flames were organized in an open combustion rig (see details in [2]) by using a contraction axisymmetric nozzle with the exit diameter $d = 15$ mm. A vane swirl was installed inside the nozzle (more details in [8]) to generate high-swirl flow. The swirl rate based on definition in [1] was 1.0, which is well above the critical value of 0.6 for the vortex breakdown in jet flows. Three cases of the equivalence ratio $\phi$ of the methane/air mixture outflowing from the nozzle were studied, namely, $\phi = 0.7$, $\phi = 1.4$ and $\phi = 2.5$. The Reynolds number of the air jet without methane was fixed as 5 000 (bulk velocity $U_0 = 5$ m/s).

A photo of the PIV/PLIF experimental setup is shown in Figure 1. To provide PIV measurements, the flow from the nozzle was seeded by 4 $\mu$m TiO$_2$ particles. The surrounding air was seeded by using a fog generator. A system of two CCD PIV cameras (ImperX IGV-B2020) was oriented horizontally as shown in Figure 1. Each camera captured 4 Mpix images. The cameras were equipped with Sigma AF #50 lenses and band-pass optical filters (60% transmittance at 532 nm and with FWHM of 10 nm). The seeding particles were illuminated by the second harmonic of radiation of a double-head pulsed Nd:YAG laser with 200 mJ energy per each pulse. A system of cylindrical and spherical lenses. Duration of each laser pulse was approximately 10 ns. Time separation between two PIV laser pulses was 35 $\mu$s.

In the case of the OH PLIF measurements a tunable dye laser (Sirah) was used. The tunable laser was pumped by the second harmonic (532 nm) of radiation of a high-energy pulsed Nd:YAG laser (QuantaRay, 1 J per pulse at 532 nm). The output energy of the dye laser pulses was monitored. The average laser pulse energy in the range of 282-284 nm was approximately 5 mJ. Radiation of the third harmonic (355nm) of a Nd:YAG laser (Quantel Brilliant B with 45 mJ energy per pulse) was used for excitation of HCHO fluorescence. The A–X transition was excited. In both cases, the RMS of the laser pulse energy variation was below 5%. Laser beams for OH* and HCHO excitation were combined by using a dichroic mirror. After a collimator optics, the height of PLIF light sheet was 50 mm. The laser
sheet thickness was below 0.8 mm in the measurement region. The sheet illuminated the axial (vertical) plane of the reacting flow.

The fluorescence of OH* was collected by a registration system that consisted of a UV-sensitive image intensifier (LaVision IRO) and sCMOS camera (LaVision, Imager sCMOS, 16 bit images with resolution of 2560×2160 pixels) and was equipped with a UV-lens (100 mm, f# = 2.8). Photocathode (S20 multialkali) of the IRO provided quantum efficiency of about 25% for wavelengths in the range of interest (300-320 nm). The fluorescence of HCHO was collected by a 16-bit ICCD camera (Princeton instruments PI-MAX-4 with GEN II photocathode with quantum efficiency 25% in UV spectral region), equipped with a Sigma AF #50 lens. Appropriate band-pass optical filters were mounted on the lenses to detect OH* and HCHO fluorescence. In both cases the exposure time for each PLIF image was 200 ns.

![Figure 2. Scheme of temporal synchronization between PIV, OH PLIF and HCHO PLIF systems](image)

For calibration of the dye laser wavelength, excitation spectrum of OH* fluorescence was measured. The excitation spectrum of OH* was compared with the spectrum, calculated by using the LifBase software [9]. The raw PLIF images contained different types of systematic and random error. The systematic errors were caused by spatially non-uniform laser sheet intensity, non-uniform spatial sensitivity of the photocathode and CCD, background signal and dark current. The sequence employed for correcting systematic errors is as follows: background subtraction, laser sheet correction, white sheet correction and laser shot-to-shot fluctuation correction.

To make sure that PIV and PLIF measurement planes coincided, prior to each run a photo-sensitive paper was placed into the measurement volume and exposed to a single shot of each laser. This test was performed to ensure that laser sheet planes were well aligned. Synchronization between PIV, OH and HCHO PLIF systems (see scheme in Fig. 2) was provided by combination of an 8-channel synchronizer (BNC, model 575), LaVision processing timing unit and by an in-house programmable synchronizing processor. The entire measuring system was operated at a repetition rate of three acquisitions per two seconds. The OH* and HCHO images were registered between the first and second pulses of the PIV laser, with a delay after the first pulse of 10 μs and 20 μs, respectively. The time delay between laser pulses of the PIV and PLIF lasers and short PLIF exposure provided a negligible cross-talk between different systems.
3. Results

Based on 2D stereo PIV and 2D PLIF measurements, flame front stabilization in the high-swirl flow is analyzed for three considered combustion regimes. The focus is placed on the flow pattern, large-scale flow features (e.g., recirculation zone, flow precession) and shape of the reaction zones. Intensity of HCHO fluorescence provides information about spatial structure of preheat zones, whereas OH* fluorescence is in the flame front and hot combustion products. Pixel-by-pixel multiplication of OH* and HCHO fluorescence signals allows estimating the heat release zone of the flame front. Figure 3 shows flame photographs and examples of the stereo PIV, OH PLIF and HCHO PLIF snapshots which are captured simultaneously. Figure 4 shows an average velocity fields and cross-sections for a high-swirl flow with combustion.

Figure 3. Photographs of three considered combustion regimes (a-c) and examples of the simultaneously instantaneous captured snapshots. Velocity fields and distribution of OH* (d,e,f), velocity fields and distribution of HCHO (g,h,i), velocity fields and region of maximum heat release (j,k,l) for the axial plane of methane/air swirling flames for (a,d,g,j) \( \phi = 0.7 \), (b,e,h,k) \( \phi = 1.4 \), (c,f,i,l) \( \phi = 2.5 \)
Figure 4. Average velocity fields for different equivalence ratios (a,b,c) and profiles (d,e,f) for the axial plane of the methane/air swirling. For the velocity field, the color shows the normal-to-plane velocity component and the solid line shows the region when the axial velocity component is negative. The dotted lines correspond to cross-section ($y/d=1$).

An analysis of experimental data shows that for the premixed combustion of fuel-lean ($\phi = 0.7$) and fuel-rich ($\phi = 1.4$) methane/air swirling jets, the flame front has a shape of inverted cone, penetrating inside the nozzle. According to the PIV data, these combustion regimes correspond to an annular swirling jet surrounding the central recirculation zone with weakly turbulent slow reverse flow. The OH PLIF data shows that the hot combustion products concentrate inside the recirculation zone. Pixel-by-pixel multiplication of OH* and HCHO fluorescence signals shows that the methane combustion took place in the inner mixing layer between the central recirculation zone and the annular swirling jet. In addition, in the case of combustion of fuel-rich ($\phi = 1.4$) mixture, the maximum of heat release zone presents downstream the recirculation zone, during unburnt hydrocarbons mixing and reacting with the surrounding air.

Combustion of the fuel-rich mixture with $\phi = 2.5$, viz., when the fuel concentration is above the flammability limit for the homogenous mixture, occurs after the jet mixing with surrounding air. Thus, the flame burns at a certain distance downstream the nozzle exit. The PIV data shows, that the annular swirling jet surrounds the central recirculation zone with unsteady reverse flow. The OH PLIF data shows that there is no OH* in the swirling jet, outflowing from the nozzle and entraining the surrounding air, near the nozzle exit. Hot combustion products with OH* are concentrated inside the recirculation zone and are observed in the outer mixing layer. Simultaneously measurements and multiplication of OH* and HCHO fluorescence signals show that the hydrocarbon combustion occurs both in the inner and outer mixing layers. Fuel preheat takes place during hot gases mixing inside the recirculation zone with the jet outflowing from the nozzle and it burns in the low-speed regions of the mixing layer after mixing with the surrounding air.
4. Conclusions

The present work reports on the combined PLIF/PIV measurements for investigation of premixed and partially premixed combustion of methane in a swirling jet with vortex breakdown and central recirculation zone. The stereo PIV measurements were carried out simultaneously with OH PLIF and HCHO PLIF. Analysis of the reacting zones shapes in the high-swirl flow was carried out for three different conditions, viz., fuel-lean and fuel-rich flames with the flame shape like an inverted cone and lifted flame fuel-rich jet mixing with the surrounding air. For the premixed combustion of fuel-lean ($\phi = 0.7$) and fuel-rich ($\phi = 1.4$) methane/air swirling jets, the flame front was located in the inner mixing layer between the low-speed recirculation zone and annular swirling jet. For the fuel-rich lifted flame ($\phi = 2.5$) the fuel burned in the outer mixing layer after being preheated by the hot gases, recirculating at the jet axis, and mixed with the surrounding air.

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