Comparison between premixed and partially premixed combustion in swirling jet from PIV, OH PLIF and HCHO PLIF measurements

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Abstract. The present paper reports on the investigation of fuel-rich and fuel-lean turbulent combustion in a high-swirl jet. The jet flow was featured by a breakdown of the vortex core, presence of the central recirculation zone and intensive precession of the flow. The measurements were performed by the stereo PIV, OH PLIF and HCHO PLIF techniques, simultaneously. Fluorescence of OH$^*$ in the flame and combustion products was excited via transition in the (1,0) vibrational band of the $A^2\Sigma^+ – X^2\Pi$ electronic system. The fluorescence was detected in the spectral range of 305-320 nm. In the case of HCHO PLIF measurements the A-X $4\sigma_0^*$ transition was excited. The jet Reynolds number was fixed as 5 000 (the bulk velocity was $U_0 = 5$ m/s). Three cases of the equivalence ratio $\phi$ of methane/air mixture issued from the nozzle were considered 0.7, 1.4 and 2.5. 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

Currently, swirling jet flows are often used to stabilize flames in gas turbines and furnaces, since the swirl provides efficient and compact combustion with good ignition and stability characteristics for a wide range of operating parameters [1,2]. Structure of turbulent jet flows with swirl and combustion has been investigated in a number of works [3-5]. Structure and dynamics of swirling jet flows is complex due to such effects as formation of spiral/helical vortices, precession of the swirling jet’s vortex core, breakdown of the vortex core and formation of the central recirculation zone [1-6].

Planar laser-induced fluorescence (PLIF) is widely used for diagnostics of flows with combustion. It provides information on local flame front deformation and extinctions and local temperature and heat release [7, 8]. Experimental data on the temperature fields and concentration of reactants (such as OH, CH, and NO) is necessary for better understanding of combustion processes, development of theoretical models and verification of numerical codes.

Particle image velocimetry (PIV) method has become a standard tool for velocity measurements in non-reacting flows [9] and often used for diagnostics of flows with combustion [10]. The advantages of PIV method for reacting flows diagnostics are that it is almost non-intrusive and provides
estimation of planar velocity fields. The latter feature allows to detect coherent structures in flows, such as large-scale vortices.

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 [11]) by using a contraction axisymmetric nozzle with the exit diameter of \( d = 15 \text{ mm} \). A vane swirl was installed inside the nozzle (more details in [6]) to generate high-swirl flows. 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 issued 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 \( U_0 = 5 \text{ m/s} \)).

A photo of the PIV/PLIF experimental setup is shown in Figure 1. To provide PIV measurements, the flow issued from the nozzle was seeded by 4 \( \mu \text{m} \) TiO\(_2\) particles. The surrounding air was seeded by using a fog generator. A system of two CCD PIV cameras (ImperX IGV-B2020) were 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 the radiation of a double-head pulsed Nd:YAG laser with 200 mJ energy per each pulse. A beam was converted into a laser sheet by using 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 \( \mu \text{s} \).

![Figure 1. Photo of the PIV/PLIF experimental setup](image-url)
To have a sufficient amount of statistical data for each flow case, a set of 1 000 instantaneous three-component velocity fields were measured via two independent runs. The velocity fields were evaluated by an iterative cross-correlation algorithm with image deformation. The final size of the interrogation area was equal to 32 × 32 pixels. Spatial overlap rate between neighbour interrogation areas was 50%. To take into account possible non-uniformity of flow seeding, the used cross-correlation algorithm accounted for the number of particles in each computational domain. If the number of particles was less than five, the velocity vector in the domain was not calculated. The processing algorithms were described in previous studies [6, 12].

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 the radiation of a high-energy pulsed Nd:YAG laser (QuantaRay, 1 J per pulse for 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. The RMS of the energy variation was below 5%. The third harmonic (355 nm) radiation of a pulsed Nd:YAG laser (Quantel Brilliant B, 90 mJ per each pulse for 355 nm) was used for excitation of the HCHO fluorescence. The RMS of the energy variation was also below 5%. Laser beams for OH and HCHO fluorescence 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 flows.

The fluorescence of OH* was collected by a registration system 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 equipped with a UV-lens (100 mm, f# = 2.8). Photocathode (S20 multialkali) of the IRO provided quantum efficiency 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.

For calibration of the dye laser wavelength, excitation spectrum of OH* fluorescence was measured. The tunable laser wavelength was varied for the spectral range of 282-284 nm with the step of 2 pm. The excitation spectrum of OH radicals was compared to the spectrum calculated by using the LifBase software [13]. The raw PLIF images contain 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 image 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 negligible cross-talk between the 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. Figure 3 shows flame photographs and examples of the stereo PIV, OH PLIF and HCHO PLIF snapshots which are captured simultaneously. Intensity of HCHO fluorescence provides information about preheat zones, whereas OH fluorescence is in the flame front and hot combustion products.

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 corresponds to an annular swirling jet surrounding the central recirculation zone with weakly turbulent slow reverse flow. The HCHO snapshots show that the methane combustion took place in the inner mixing layer between the central recirculation zone and the annular swirling jet. The OH PLIF data shows that the hot combustion products concentrated inside the recirculation zone. The main difference between OH PLIF intensity for the fuel-lean ($\phi = 0.7$) and fuel-rich ($\phi = 1.4$) is that in the latter case OH 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, issuing from the nozzle and entraining the surrounding air, near the nozzle exit. Hot combustion products with OH$^*$ are concentrated inside the recirculation zone and also observed in the outer mixing layer. According to HCHO PLIF, the hydrocarbon combustion occurs both in the inner and outer mixing layers. Fuel preheat takes place during mixing of the hot gases inside the recirculation zone with the jet issuing 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 first two cases, the flame front was located in the inner mixing layer between low-speed recirculation zone and annular swirling jet. For the fuel-rich flame the fuel burned in the outer mixing layer after being preheated by the recirculating at the jet axis hot gases and mixed with the surrounding air.
Acknowledgments

The research is supported by Russian Science Foundation (grant № 16-19-10566). The authors are grateful to Professor Kemal Hanjalic and Dmitry Markovich for fruitful discussions and recommendations.

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