Combustion in a High-Swirl Turbulent Jet Undergoing Vortex Breakdown. Investigation by PIV and HCHO PLIF

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1 Introduction

Swirl is often used for stabilization of jet-flames. Formation of spiral vortices, breakdown of the swirling vortex core and formation of the central recirculation zone are typical for jet flows with high swirl [1, 2]. However, effect of such flow features as vortex breakdown and precession of the vortex core on the combustion process is still not completely understood. Particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) are prominent methods to reveal peculiarities of the flow and flame front dynamics. Reacting swirling jets were studied by PIV and PLIF in a number of papers [3-6]. However, role of the large-scale vortex structures (including precessing vortex core) in mechanism of flame stabilization is still a debated issue [6]. Deformations of the flame front and local extinctions affect intensity of heat release. Thus, analysis of flame-vortex interactions in swirl-stabilized combustors is important for better understanding of unsteady combustion regimes.

Formaldehyde (HCHO) is an important combustion intermediate occurring in lower-temperature regions of hydrocarbon-fueled flames. It plays an important role in several combustion processes, including fuel oxidation, auto-ignition, lifted-flame stabilization. It is the initial step of the HCHO→HCO→CO oxidation pathway of conventional hydrocarbons [7]. High concentration of HCHO specify preheat zone of hydrocarbon flames. Photochemical properties of HCHO are well studied [8]. One of the more prevalent strategies for HCHO PLIF measurements is the excitation of 4_0^1 transition by using third harmonic of Nd:YAG laser radiation at 355 nm [9, 10]. Despite of the low intensity of the sideband transition excited near 355 nm, energy of the commercially available pulsed Nd:YAG lasers allows to reach high enough fluorescence signal and allow PLIF measurements without using a specific tunable laser.

The present paper reports on the investigation of combustion regimes in a high-swirl turbulent jet, featured by the vortex breakdown with central recirculation zone and intensive flow precession, by using stereo PIV and HCHO PLIF.

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2 Experimental setup and measurements techniques

Measurements were carried out for swirling flames of methane/air mixture 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 $d = 15$ mm. A vane swirl was installed into the nozzle (see Figure 1 and more details in [12]) 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. Three cases of the equivalence ratio ϕ of methane/air mixture issued from the nozzle were studied 0.7, 1.4 and 2.5. The jet Reynolds number was fixed as 5 000 (bulk velocity U_0= 5 m/s). The layout of the PIV-PLIF setup is shown in Figure 1.

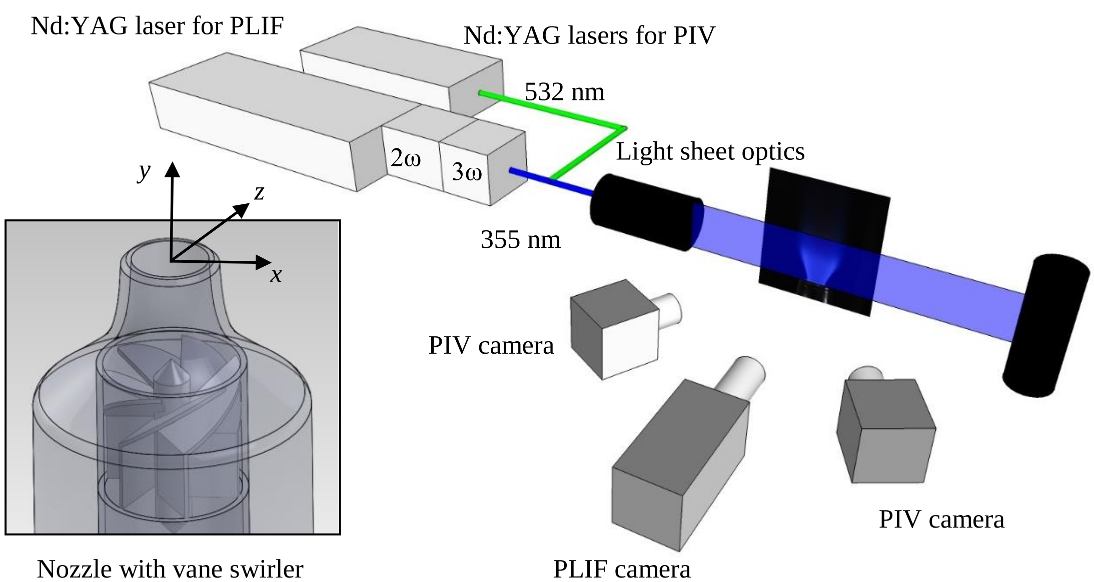

Figure 1. Sketch of the PIV-PLIF setup

To provide PIV measurements the flow issuing from the nozzle was seeded by 4 μm Al_2O_3 particles. The used stereo PIV system consisted of two cameras (ImperX IGV-B2020). The cameras were equipped with Sigma AF #50 lenses and band-pass optical filters (60% transmittance at 532 nm and full width of 10 nm at the half maximum). The seeding particles were illuminated by the second harmonic of the double-head Nd:YAG laser with 200 mJ energy per each pulse. A beam was converted into the laser sheet using a system of cylindrical and spherical lenses. Each PIV camera captured 4 Mpix images. 2000 instantaneous three-component velocity fields were obtained for each flow case. The velocity fields were calculated by an iterative cross-correlation algorithm with image deformation, the final size of the computational domain was equal to 32 × 32 pixels, and 50% overlapping. 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 this domain was not calculated).

The third harmonic (355nm) radiation of the Nd:YAG laser (Quantel Brilliant B, energy per each pulse was 45 mJ) has been used for excitation of HCHO fluorescence. The A-X 4^1_0 transition was excited. RMS of the energy variation was below 5%. After the collimator optics, the height of the light sheets was 50 mm. Their thickness was below 0.8 mm in the measurement region. Both sheets illuminated the central (vertical) plane of the reacting flow. The fluorescence of HCHO was collected by registration system (LaVision) consisted of a 16-bit sCMOS Imager Pro X camera with IRO Image Intensifier equipped with a LaVision UV Lens f#2.8 and HCHO PLIF optical filter. The exposure time for each image was 200 ns. The raw PLIF image data contain several systematic and random errors. The systematic errors were caused by spatially non-uniform laser sheet intensity, non-uniform pixel sensitivity, background and dark signal. The sequence employed for correcting systematic errors was as follows: background subtraction, laser sheet correction, white sheet correction and laser shot-to-shot fluctuation correction.

3 Results

Figure 2 shows the flame images and examples of the HCHO PLIF data, providing information about preheat zone. The spatial coordinates are normalized by the nozzle inner diameter. The intensity scale is the same for all images.

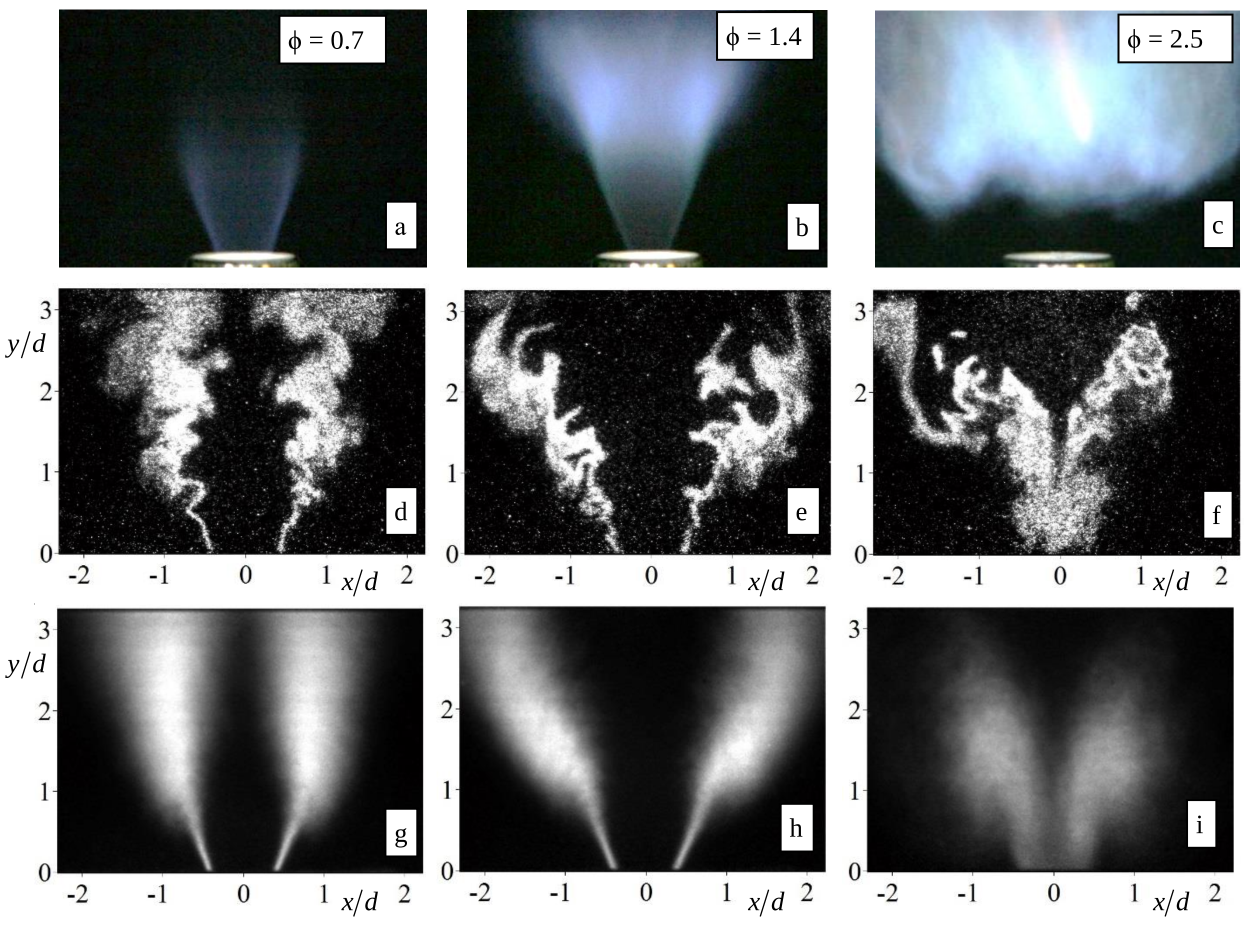

Figure 2. Direct images (a-c) and HCHO PLIF intensity (d-f) instantaneous (g-i) ensemble averaged

Large-scale deformations of the flame front in turbulent swirling flow were detected for all three investigated equivalence ratios. Ensemble averaged patterns were significantly different from the instantaneous realizations. For the case of lean mixture at $\phi = 0.7$ and rich mixture at $\phi = 1.4$ the flame had a shape of inverted cone. A little more opening angle of the flame front could be seen for the rich flame. The flame front was subjected to sufficient deformations that could be observed for these two cases due to azimuthal instability modes in the inner and outer mixing layer of the jet. Moreover separated flame islands could be recognized for instantaneous patterns. This could be described by two different situations: the out of plane closing of the flame to the simply connected region or the combustion in the separate flow region trapped by the large-scale vortex. The flame front in the case of lifted flame (stabilized at some distance from the nozzle rim) of rich (ϕ = 2.5) mixture was significantly different from the two previous cases. As could be clearly seen the principal difference for the rich lifted flame is the presence of HCHO fluorescence region in the central core of the flow.

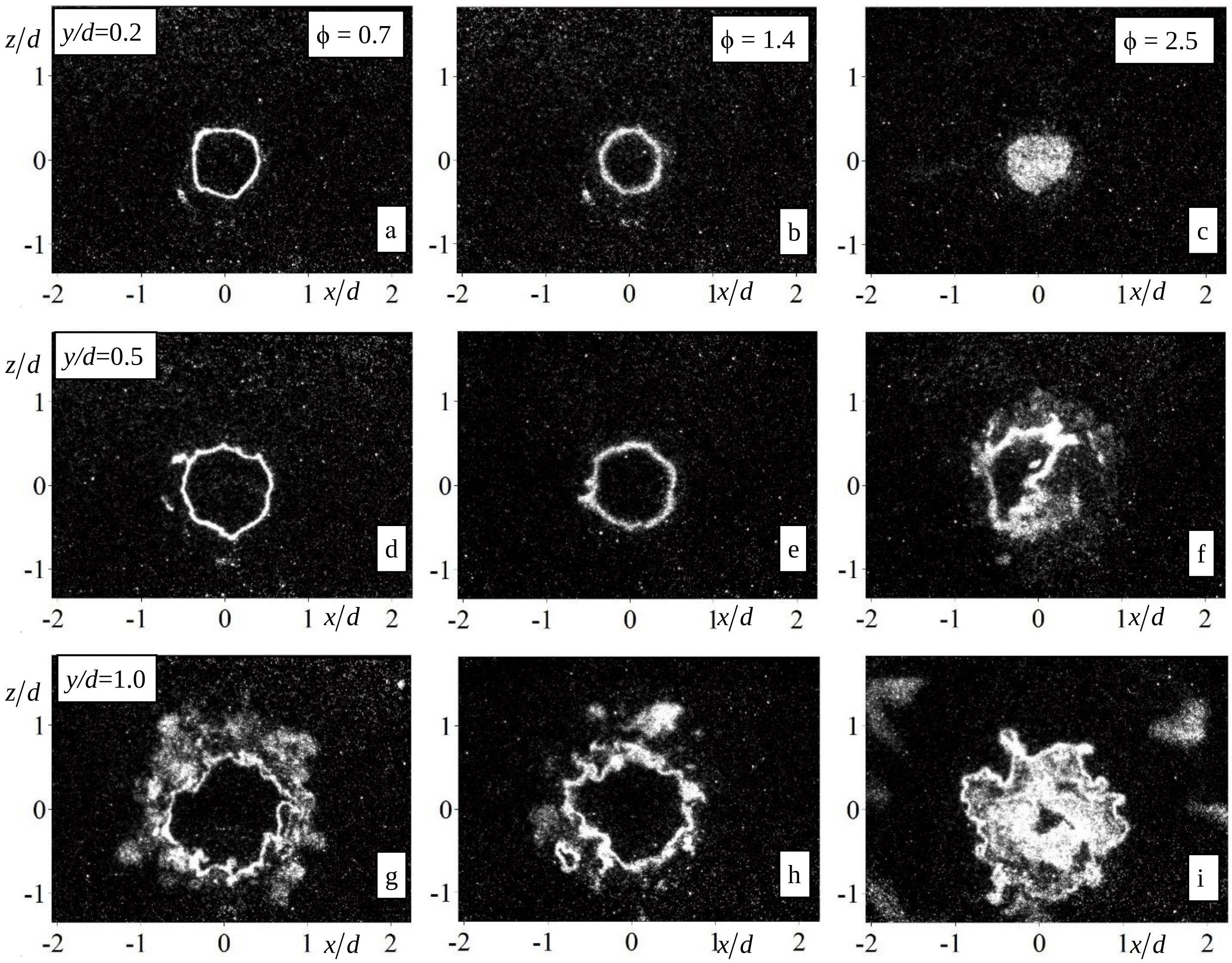

Figure 3 HCHO PLIF intensity in horizontal cross-sections: examples of the instantaneous snapshots

An additional series of HCHO PLIF measurements at several distances from the nozzle exit was accomplished in horizontal cross-section of the flow (see Figure 3) that confirms formation of HCHO in the jet core for the case ϕ = 2.5. The flame front deformation was observed for the distances started from 0.2d from the nozzle exit. That was expected due to azimuthal instabilities induced in the inner and outer shear layer of the swirling flow.

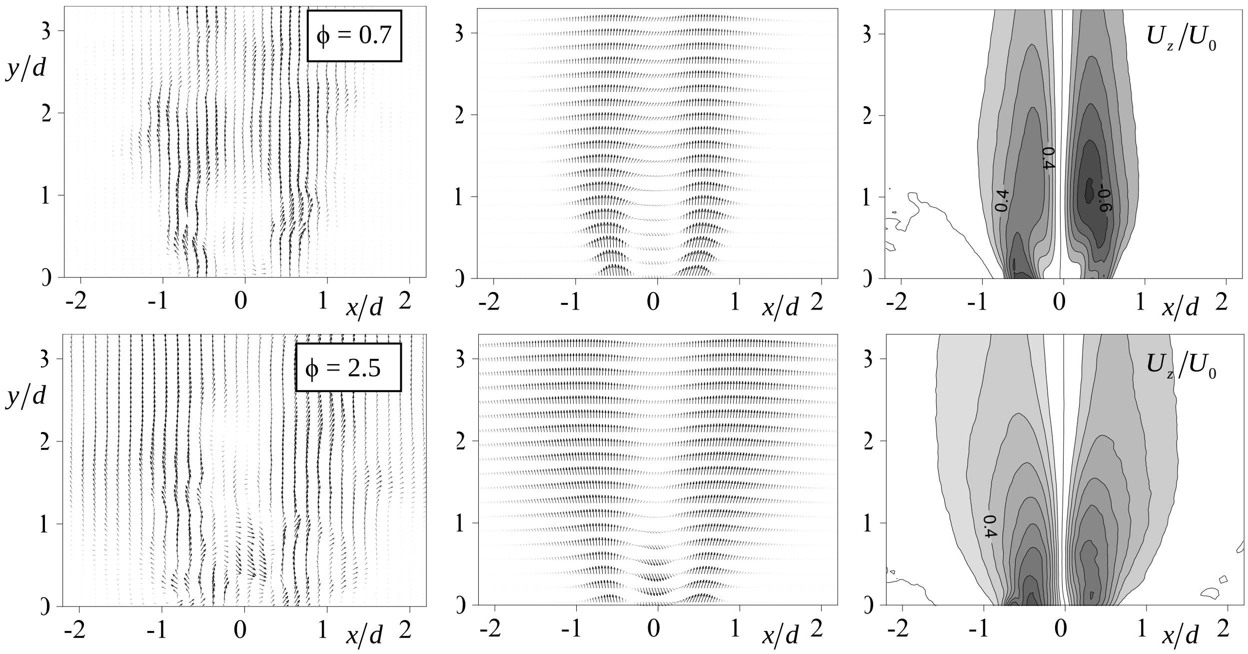

Figure 4 Examples of the instantaneous (left) and averaged (middle and right) PIV data.

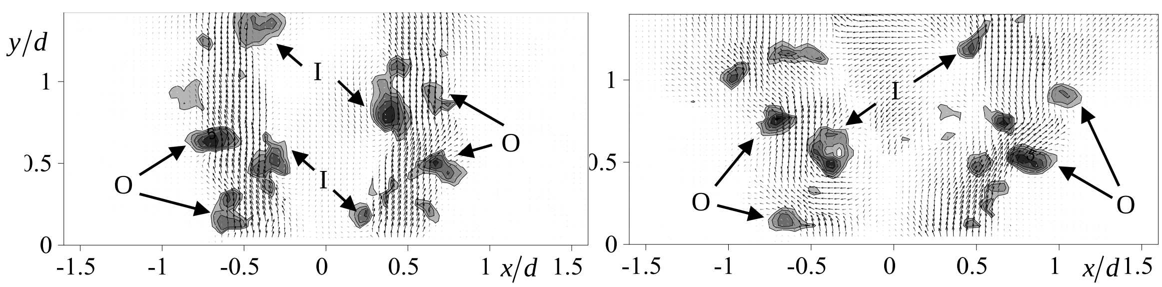

Figure 5 Snapshots of the instantaneous velocity and 2D Q-criterion (see [12]) distribution for flames at ϕ = 0.7 (left) and ϕ = 2.5 (right).

PIV measurements revealed presence of central recirculation zone for the studied high-swirl jets. The mean velocity fields for the fuel-rich lifted flame and fuel-lean inverted flame are shown in Figure 4. The flow pattern includes two mixing layers, viz. one is located between the annular jet and the surrounding air; whereas another one bounds the central recirculation zone. The instantaneous snapshots have shown that the flow is featured by large-scale velocity fluctuations, including unsteady transverse flows, associated with flow precession. The analysis of the instantaneous flow patterns has revealed presence of large-scale vortices in the inner and outer mixing layers (the examples are marked by “I” and “O” symbols in Figure 5, respectively). Based on the previous study [12] these vortex cores were concluded to be parts of helical vortex filaments intersecting the measurement plane.

4 Conclusions

Experimental study of turbulent swirling premixed methane-air flames was carried out using stereo PIV and HCHO PLIF technique. It was shown that for the lifted flame of fuel-rich mixture (ϕ = 2.5) HCHO fluorescence was detected inside the recirculation zone in contrast to the cases of inverted conical flames of the mixtures of ϕ = 0.7 and ϕ = 1.4. For all considered equivalence ratios, the azimuthal disturbances and deformations of the flame front were observed in the PLIF images captured for planes perpendicular to the jet axis. Based on the PIV data it was concluded that large-scale vortex structures present in the inner (around the central recirculation zone) and outer (between the annular jet core and the surrounding air) mixing layers should be also responsible for the observed flame front deformations.

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