Effect of hydrodynamic coherent structures on local mixing in a model GT-burner

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Abstract. Turbulent mixing and swirling flow structure in model GT-burner at atmospheric pressure have been investigated (Re = 5000) by using a combination of the particle image velocimetry and planar laser-induced fluorescence methods. Based on the measurements of the velocity fields by a stereo PIV in combination with acetone-PLIF, three-components of turbulence kinetic energy, Reynolds stresses and turbulent fluxes are evaluated. Contribution of large-scale helical vortex structures to the local mixing has been evaluated by snapshot POD method based on singular value decomposition. It was found that helical vortex structures correspond to the vortex core, spiraling around the central recirculation zone. In the case of supply fuel via central channel, the formation of a secondary vortex structure located between the fuel jet and the recirculation zone is observed, contributing to the mixing of fuel with air.

1. Introduction
In modern combustion chambers of gas turbines, the flames are often stabilized by organization of mixing and combustion of fuel and air in swirling flow. On the one hand the flow swirl allows obtaining more compact combustion zone [1, 2] and organizing combustion of fuel-lean mixture to reduce harmful emissions of NOx and CO [3], on the other hand lean combustion can lead to thermo-acoustic oscillations in combustion chambers [4, 5]. High-swirling flows are characterized by the presence of such phenomena as central recirculation zone, vortex breakdown, precessing vortex core and formation of secondary helical vortices [6-8].

Different parameters affect the dynamics and structure of turbulent premixed flames, viz. local velocity and turbulence intensity, large-scale flow structures, strain rate and curvature of the flames. In order to extract information about flame/flow interaction, simultaneous measurements of the velocity field and scalars are required [9]. Particle image velocimetry (PIV) can be used in stereo configuration that allows obtaining three-component velocity fields [10]. Moreover, for extensive studies of turbulent combustion, the stereo-PIV technique is typically combined with planar laser-induced fluorescence (PLIF), which provides information about spatial distribution of a fuel tracer or combustion intermediate species, such as CH or OH [11-14]. However, the combined use of the PIV/PLIF system in the diagnosis of flames must be carried out carefully due to the large velocity gradients in the flame front region and the effect of the chemiluminescence on the recorded signal of the fluorescence.

The present paper focuses on the investigation of influence of large-scale helical vortex structures in model GT-burner on local mixing fuel and main air flows.
2. Experimental setup

To investigate the effect of large scale coherent structures on mixing, a model GT-burner was used. The combustion chamber was connected to a gas cylinder with flammable gas and air-line (pressure in the air-line of up to 2 MPa). The mass flow meters (Bronkhorst El-Flow) were used in order to control the flowrates of gases. The model GT-burner consists of a cylindrical prechamber, model premixer (by geometric analogy with [15]) and combustor with square windows of quartz glass (100×100 with thickness of 4 mm). The combustor width is 180 mm. The premixer includes a radial swirl of flow and central channel for pilot fuel supply. The outlet diameters of the premixer and central channel were 37 mm and 5.8 mm, respectively. The main air flow was supplied through the premixer, in this flow the dioxide titanium particles were added (the average diameter of the particles was 0.5 µm). In the case of investigation of isothermal flows, in order to seed the fuel flow by acetone vapors (with concentration of approximately 3 %) the container with liquid acetone, which was placed in a heated water bath (with temperature of approximately 55°C) to provide thermal stabilization was used. The fuel flow was bubbled through liquid acetone using a bypass scheme. An insignificant part of acetone vapors could condense in supply pipes and hoses.

Investigation of isothermal swirling flows in the model GT-burner at the Reynolds number of 5000 was provided by modern optical techniques such as PIV and PLIF. The photo of the experimental setup is shown in Figure 1. For velocity fields measurements the stereoscopic-PIV system POLIS was used. In this case, the investigation area was illuminated by radiation of the second harmonic of a double-head pulsed Nd:YAG laser (Beamtech Vlite-200, with the pulse energy of 200 mJ, wavelength of 532 nm). The tracer images were captured by two CCD cameras (ImperX IGV-B2820), equipped with Sigma DG 105 mm MACRO lenses (f/2.8) and band-pass optical filters (Edmund Optics, 60 % transmittance at the wavelength 532 ± 5 nm). The resolution of each PIV image was 2048×2048 pixels.

![Figure 1](image.png)

**Figure 1.** Photograph of the experimental setup. The geometry of the nozzle is presented by inset.
For excitation of acetone fluorescence, radiation of a tunable dye laser (Sirah PrecisionScan) at wavelength of 283.55 nm was used. The tunable dye laser was pumped by second harmonic of Nd:YAG solid-state laser (QuantaRay with 800 mJ per 7 ns pulse at 532 nm). To remove residual laser radiation in the PLIF optical system the spectral separation of laser harmonics was implemented by a dichroic mirror. Acetone vapor fluorescence was captured by an image intensifier (quantum efficiency of 25 %), which was connected to LaVision ImagerPro sCMOS camera (2560×2160 pixel, 16 bits) and equipped with a quartz lens (f/#2.8, 100 mm) with a set of optical filters (Multi-Notch filter which removed the harmonics of Nd:YAG-laser and the interference band-pass filter). The exposure time for PLIF images was 200 ns.

The laser beam of the PLIF system was converted to a collimated laser sheet with approximately 50 mm width and 0.8 mm thickness in the region of interest. The PLIF pulse was shot between a pair of the PIV laser pulses. The laser beam of PIV system was converted into a diverging laser sheet (with 0.8 mm thickness) by spherical and cylindrical lenses. A laser sensitive paper was used to ensure that the laser sheets of PIV and PLIF systems coincide well. The PLIF camera was calibrated in the same way as the PIV cameras. For post-processing of raw PLIF images a set of mathematical algorithms were used. The processing algorithms including removal of the background, dark-current and reflections, also take into account spatial non-uniformity of the laser-sheets and sensitivity of camera, fluctuations of laser energy from pulse to pulse. To take into account non-uniformity of the energy distribution in the laser sheet and fluctuations of laser energy from pulse to pulse, part of the laser beam (approximately 5 % of energy) was reflected by a quartz plate into a quartz cuvette with solution of rhodamine 6G in a water. The spatial distribution of the fluorescence signal inside the cuvette was recorded using a camera with a CCD sensor (ImperX Bobcat IGV-B4820, 16 Mpix, 12 bit). The velocity fields were evaluated by an iteration cross-correlation algorithm with continuous image shift and deformation of interrogation area between iterations. The finite size of interrogation area was 32×32 pixels with overlapping of 50 %. The obtained PLIF intensity was spatially sampled to the same spatial grid as the PIV data with the same resolution.

To reveal coherent structures, the PIV was processed by snapshot POD method [16], based on singular value decomposition [17]. POD provides the coherent part of the velocity fluctuations in the framework of triple decomposition via conditional sampling of the instantaneous fields [18, 19]. In general, each POD mode can be expressed as the linear combination of the instantaneous velocity fields. Therefore, the passive scalar fluctuations can be also conditionally sampled based on the temporal coefficients of the velocity POD modes (similar to [20]).

3. Results and discussions
Specifications of two cases considered here are summarized in Table 1. So, in Case 1 the air was supplied only through premixer. Whereas in Case 2 the additional air flow modeling a fuel was supplied via the central channel.

| Case   | $Q_{air}$, [l/min] | $U_0$, [m/s] | $Q_{fuel}$, [l/min] | $U_{fuel}$, [m/s] | $Re$, [-] |
|--------|--------------------|--------------|---------------------|------------------|----------|
| Case1  | 133.15             | 2.17         | 0                   | 0                | 5000     |
| Case2  | 133.15             | 2.17         | 9.2                 | 6.12             | 5000     |

The results of flow hydrodynamic structure investigation by PIV show that in Case 1 there is a pronounced recirculation zone. In the area outside the opening angle of the jet, the stagnation zone is formed. Based on instantaneous velocity fields (2000 image pairs) spatial distributions of velocity fluctuations and Reynolds stresses are evaluated. The velocity fluctuations and their derivatives have been calculated by determination of deviation at each grid node of instantaneous value velocity from the
average value. The fluctuations of the radial and axial velocity in the central region of the flow are small and have maximum in the area where air flows from the premixer. At the same time, in absolute values, velocity fluctuations reach magnitude of up to 40% of the bulk velocity. The Reynolds stresses demonstrate the presence of mixing layers between the recirculation zone, the flow of the main air and the stagnation area, reaching magnitude of up to 10% of the bulk velocity. The examples of spatial distribution of three-component average velocity, radial and axial component of turbulence kinetic energy and Reynolds stresses are shown in Figure 2.

![Figure 2](image1.png)

**Figure 2.** Spatial distribution of average velocity (a), radial (b) and axial (c) component of turbulence kinetic energy and Reynolds stresses (d) for the combustor without fuel supply via the central channel.

![Figure 3](image2.png)

**Figure 3.** Spatial distribution of average velocity and fuel concentration (a), radial component of turbulence kinetic energy (b), Reynolds stresses (c) and radial turbulent flux (d) for the combustor with fuel supply via the central channel.

It should be noted that for the convenience of visualization of received investigation results in Case 2, the experimentally measured fuel concentration was normalized to the magnitude of the fuel concentration directly at the outlet from the central channel $C_0$. The jet of fuel flowing from the central channel leads to a significant change in hydrodynamic structure of the flow. The spatial distributions of the radial and axial components of the turbulence kinetic energy and the Reynolds stresses show that the magnitude of the velocity fluctuations is comparable in the central region and in the area where air flows from the premixer. In the last case the velocity fluctuations for axial component reach magnitudes
of up to 60% of the bulk velocity. One can observe the presence of additional mixing layer between the fuel jet and recirculation zone. The examples of spatial distribution of average velocity and fuel concentration, radial component of turbulence kinetic energy, Reynolds stresses and radial turbulent flux are shown in Figure 3. Note that for approximately 5 mm the flow of the central jet core is not resolved by PIV because it was not seeded by the tracer particles (rectangular shaded area in the image).

![Figure 3. Examples of spatial distribution of average velocity and fuel concentration, radial component of turbulence kinetic energy, Reynolds stresses and radial turbulent flux.](image)

**Figure 3.** Examples of spatial distribution of average velocity and fuel concentration, radial component of turbulence kinetic energy, Reynolds stresses and radial turbulent flux.

To identify coherent structures of the flows inside model GT-burner and to analyze their contribution to the mixing, POD is applied to the sets of the measured velocity fields. POD spectra of the velocity fluctuations for the jets are shown in Figure 4. For Case 1, two most energetic modes contain of up to 15% of spatially averaged turbulent kinetic energy. Spatial distributions of the first two POD modes (see Figure 5) show the presence of large-scale vortex structures passing between the recirculation zone, the flow of the main air and the stagnation area. The coherent structure corresponds to the vortex core, spiraling around the central recirculation zone. In Case 2, the formation of a secondary vortex structure located between the fuel jet and the recirculation zone is observed, contributing to the mixing of fuel with air.

![Figure 4. POD spectra of the velocity fluctuations for the combustor with/without the fuel supply via the central channel.](image)

**Figure 4.** POD spectra of the velocity fluctuations for the combustor with/without the fuel supply via the central channel.

![Figure 5. Spatial distributions of the first two POD modes for the combustor without fuel supply (a,b) and with fuel supply (c,d) via the central channel.](image)

**Figure 5.** Spatial distributions of the first two POD modes for the combustor without fuel supply (a,b) and with fuel supply (c,d) via the central channel.
Conclusions
In this work, the swirling flow structure and turbulent mixing in model GT-burner at atmospheric pressure in the absence and presence of fuel supply through the central channel of the premixer have been investigated by using the combination of modern methods of optical diagnostic (PIV/PLIF). It is found that geometry of premixer provides implementation of a pronounced recirculation zone in the investigated flow. The supply of fuel through the central channel leads to a significant change in the flow structure. The fluctuations of velocity on the jet axis are comparable with fluctuations in the main air flow and reach (for axial component) magnitudes of up to 60% of the bulk velocity. The contribution of the coherent velocity fluctuations to the turbulent transport has been evaluated via the SVD-based POD. It is found that first two most energetic coherent velocity fluctuations correspond to the vortex core, spiraling around the central recirculation zone and contain of up to 15% of spatially averaged turbulent kinetic energy. The supply of fuel through the central channel leads to the formation of additional vortices between the fuel jet and the recirculation zone, contributing to the mixing of fuel with air.

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