Structure of a reacting flow of a turbulent swirling jet during combustion of a syngas–air mixture

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Abstract. The paper presents the results of an experimental study of the flow structure and features of combustion in a turbulent swirling lean pre-mixed syngas flame using modern planar optical laser-based methods. The measurement of the instantaneous velocity field was carried out using the particle image velocimetry (PIV), and location of the OH radicals in the jet were determined by the method of laser-induced fluorescence (PLIF). A comparison of the averaged flow characteristics of a high-swirl flame with an equivalence ratio $\Phi = 0.45$ for syngas and $\Phi = 0.7$ for methane are performed. Presence of a recirculation zone in the jet core is typical of both cases, however, the size of the central recirculation zone for the methane flame are approximately 1.5 times larger than that for the synthesis gas flame in both dimensions. The average distributions of the intensity of fluorescence signal of the OH radical shows a good coincidence of the position of the flame front in both cases, and lower fluorescence signal intensity for the synthesis gas flame.

1. Introduction

A promising technology for reducing the level of polluting emissions into the atmosphere is purification and further combustion of synthesis gas in gas turbines. Synthesis gas is the result of gasification of fossil fuels, biofuels, and some types of off-cuts. In particular, a promising direction of development in the field of electricity generation based on the use of solid fuel is the development of combined-cycle plants with intra-cycle gasification of solid fuels [1, 2]. Reducing the existing gap in energy efficiency between gas-turbine plants on syngas and natural gas with comparable environmental indicators is a pressing scientific and technical problem for the introduction of such technology. One of the most difficult tasks is organization of the combustion of synthesis gas in the combustion chamber, which ensures high efficiency and low emission of pollutants [3].

Optimization of physicochemical processes in combustion chambers of gas turbines using real devices is difficult due to the obvious limitations on the measurement capabilities and the high cost of launches. Physical simulation of synthesis gas combustion is relevant because it shows the main dynamic processes (flame extinction and blow-off, unsteady dynamics of swirling flows, etc.) and permits the use of modern optical methods for study velocity, concentration and temperature distributions [4]. Detailed experimental data are needed for the development and verification of mathematical modeling methods that adequately predict transfer processes and take into account the main paths of chemical reactions in GTP combustion chambers.
The aim of this work was to study the physics and chemistry of combustion of synthesis gas under conditions of stationary gas turbines, to obtain experimental data using the most modern optical methods for diagnosing fluxes PIV (Particle Image Velocimetry) and PLIF (Planar Laser Induced Fluorescence).

2. Experimental setup

Sketch of the experimental setup is shown in figure 1. The measurements were carried out using a combustion rig consisted of a swirl burner, flow seeding device, premixing pipe and section for the air and fuel flow rate control. The burner was a contraction nozzle (with the exit diameter \( d = 15 \text{ mm} \)) with a vane swirler inside. Swirl of the flow (the ratio between the angular and axial jet momentum fluxes) was organized by using swirlers with inclination angles \( \phi = 55^{\circ} \) corresponding to the swirl ratio \( S = 1 \).

The Reynolds number \( \text{Re}_{\text{air}} \) (based on \( d \), the bulk velocity of the air flow at the nozzle exit \( U_0 = 5 \text{ m/s} \), and viscosity of the air) was 5 000.

Flowmeters were used to measure the volumetric flow rates of gases (Bronkhorst High-Tech). In the experiment using methane, the flow rate of the mixture was: air – 52.8 l/min, \( \text{CH}_4 \) – 3.86 l/min (equivalence ratio \( \Phi = 0.7 \)). In the experiment using synthesis gas, the flow rate of the mixture was: air – 52.8 l/min, \( \text{H}_2 \) – 4.89 l/min, \( \text{CO} \) – 4.89 l/min (equivalence ratio \( \Phi = 0.45 \)). The flow was seeded with \( \text{TiO}_2 \) particles (with the average size of 0.5 \( \mu \text{m} \)). The seeding device was a vessel filled by particles with a mechanical blender inside, connected via a bypass system to the main air path.

The instantaneous velocity field was measured by particle image velocimetry (PIV) in stereoscopic configuration. The stereoscopic PIV system consisted of two combined pulsed Nd: YAG lasers (Quantel, Ever Green 200) (200 mJ per pulse at a wavelength of 532 nm) and a pair of 4 Mpix CCD cameras (ImperX-B2020M). A narrow-band filter with a bandwidth of 10 nm at a laser wavelength of 532 nm was installed on the lenses of the cameras, which reduce the background signal of its own glow of flame. The calculation of the instantaneous velocity field based on the displacement of the tracers was performed using the in-house developed software ActualFlow.

To record the spatial distribution of the \( \text{OH} \) radical in a reacting flow, the planar laser-induced fluorescence method (PLIF) was used. In the planar registration system PLIF of the \( \text{OH} \) radical, a tunable Sirah Precision Scan dye laser (with a wavelength of \( \sim 283 \text{ nm} \)) with a pump laser Nd: YAG, QuantaRay laser (532 nm, 1 J, \( \sim 10 \text{ ns} \)) was used as a radiation source. The \( \text{OH}^* \) excitation occurred at the transition \( Q1(8) \ (v^\prime = 1 \leftrightarrow v^\prime = 0, \ A^2\Sigma^+ \leftrightarrow X^2\Pi) \), which has a weak dependence on temperature. The fluorescence intensity in the flow was recorded using an image intensifier with a multichannel amplifier (LaVision IRO) with a S20 photocathode (multialkali). After amplification, the phosphor coating of the intensifier illuminated a hybrid CCD-CMOS matrix (ImagersCMOS) of a 16-bit...
camera (resolution: 2560 × 2160 pixels, pixel size: 6.5 × 6.5 μm). A quartz lens (LaVision 100 mm) and an optical filter transmitting radiation in the range of 310 ± 10 nm were mounted on the camera (Figure 2). The processing of the fluorescence signal consisted of the following steps: background deduction, laser sheet correction, image reconstruction (using a calibration target, ActualFlow software and spatial data obtained from the velocity fields), averaging over cells equal to the cell size for each velocity vector taking into account the overlap of 50% [5]. The averaging of the fields of speed and intensity of the fluorescence signal was carried out over 1500 images.

![Figure 2. Photo of experimental setup.](image)

3. Results

Experimentally studied synthesis gas and methane combustion regimes were selected as a result of simulation using the GRI-Mech 3.0 mechanism. For methane-air mixture, a lean flame (equivalence ratio Φ = 0.7) was chosen, which is relatively close to the lean blow off limit. For synthesis gas with a 1:1 ratio of hydrogen and carbon monoxide in the fuel mixture, the regime with Φ = 0.45 was selected since the flame front propagation velocity was close to the velocity in a methane flame and was approximately 19 cm/s. For a mixture under the conditions T₀ = 300 K and p = 1 atm, the adiabatic temperature of the methane flame is 1839 K, and syngas flame is 1594 K.

Figure 3 shows the time-averaged velocity fields and the spatial distributions of the OH radical in the flame of synthesis gas and methane with a high swirl, as well as photographs of these regimes. The intensity of the fluorescence signal OH radical (the signal is normalized to the maximum value of the fluorescence signal). The coordinates along the X and Y axis are normalized to the nozzle diameter (15 mm). The photograph shows that the flame has the shape of an inverted cone and looks very similar for both gas mixtures. It is also noticeable that the flame front is stabilized on the centerbody supporting the vanes inside the swirler. For high-swirl flows the vortex core breakdown with the formation of a central recirculation zone is typical. From the velocity fields of figure 3 (c) (d) it can be seen that the size of the central recirculation zone for the methane flame are approximately 1.5 times larger than that for the synthesis gas flame in both dimensions. It should also be noted that despite the difference in the size of the recirculation zone, the jet angle for both flames are the same. The average distributions of the intensity of the fluorescence signal of the OH radical shows a good coincidence of the position of the flame front, if evaluated by the outer boundary of the region of high signal intensity (Figure 3 (e), (f)). In addition, for the synthesis gas flame a lower fluorescence signal intensity is observed in the whole experimental region.
Figure 3. The left column – synthesis gas, the right column – methane. (a) and (b) are the photographs, (c) and (d) are the average velocity fields (the red line is the zero axial velocity), (e) and (f) are the average distributions of the fluorescence signal of OH radicals.

The presence of incorrect vectors in instantaneous fields of velocity (Figure 4 (a), (b)) is due to insufficient local seeding of the surrounding air stream. The vortex structures are present in the synthesis gas flame in the inner and outer shear layer in the same manner as for the methane flame. The instantaneous distribution of the fluorescence signal intensity of the OH radical demonstrates a significant deformation of the flame front in the regions of passing the vortices in the outer shear layer.
A lower signal intensity is observed as well as for average distributions of the fluorescence signal. The difference in the intensity of the fluorescence signal can be explained by the significant difference in the temperature of the combustion products contained in the inner shear layer and the recirculation zone. For a lower temperature of the combustion products in the synthesis gas flame, a lower equilibrium concentration of the radical OH corresponds.

![Figure 4](imageURL)

**Figure 4.** The left column – synthesis gas, the right column – methane. (a) and (b) is the instantaneous velocity fields, (c) and (d) is the instantaneous distribution of the fluorescence signal of OH radicals.

**Conclusion**

In this work, the visualization of two characteristic regimes of combustion of a pre-mixed swirling flame of methane and synthesis gas was carried out. Using the method PIV in stereoscopic configuration, the average and instantaneous velocity fields for the Reynolds number 5000 were obtained, and the average and instantaneous distributions of the fluorescence signal of the OH radical were obtained using the PLIF method. Presence of a recirculation zone in the jet core is typical of both cases, however, the size of the central recirculation zone for the methane flame are approximately 1.5 times larger than that for the synthesis gas flame in both dimensions. The average distributions of the fluorescence signal intensity of the OH radical shows a good coincidence of the position of the flame front in both cases, and a lower fluorescence signal intensity for the synthesis gas flame. These differences in the structure of the flow and distribution of the OH radical between the methane and synthesis gas flames can be explained primarily by a lower temperature of the combustion products in
the latter case. Lower temperatures lead to a decrease of the buoyancy forces and a decrease in the equilibrium concentration of the OH radical in hot combustion products.

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