Effect of the mixture initial temperature on the velocity field in the swirling flame

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Abstract. The paper presents the results of an experimental study of the flow structure of a turbulent swirling flame of a methane-air and syngas-air mixture at elevated temperature using modern optical methods PIV (Particle Image Velocimetry) and PLIF (Planar Laser-Induced Fluorescence). A comparison of the averaged flow characteristics of a high-swirl flame with an equivalence ratio $\Phi = 0.45$ for syngas-air and $\Phi = 0.7$ for methane-air mixture are performed with preheating the mixture to a temperature of 300, 400 and 500 K. The distribution of the fluorescence signal showed that the longitudinal size of the region of hot combustion products decreases significantly with increasing temperature of the mixture for both syngas-air and methane-air flames. For the flame of a mixture of methane-air and syngas-air heated to a temperature of 500 K, the size of the recirculation zone and velocity pulsation distribution are very similar, in contrast to a methane flame at lower preheating temperatures of the mixture.

1. Introduction

Syngas is a promising alternative renewable fuel with its potential to be used in internal combustion engines, industrial furnaces, and land-based gas turbines. The primary sources of synthetic gas (syngas) are coal and biomass. Subsequent purification and conditioning of syngas will help in the efficient use of these fuels in the production of electric power (using land-based gas turbines). Land-based gas turbines that work on the gasification and subsequent conversion of energy from the derived syngas to electric power are termed as Integrated Gasification and Combined Cycle (IGCC) power plant [1-3].

Lean premixed combustion is technology applied in stationary gas turbines for highly efficient, low-emission power generation using natural gas. 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 gas-turbine plant combustion chambers. Experimental data obtained under standard conditions are not sufficient for appropriate verification of numerical models, and it is necessary to develop experimental databases under conditions of high pressure, high flow temperature, high Reynolds number, or high flow swirling number. Thus, the aim of this work was an experimental study of the flow structure of a turbulent swirling flame of a methane-air and syngas-
air mixture at elevated temperature using modern optical methods PIV (Particle Image Velocimetry) and PLIF (Planar Laser Induced Fluorescence).

2. Experimental setup

Sketch of the experimental setup and photos of examples of methane and syngas flames are 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 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 $Re$ (based on $d$, the bulk velocity of the air flow at the nozzle exit $U_0 = 5$ m/s, and viscosity of the air) was 5000 at mixture temperature of 300 K. At a temperature of 400 and 500 K, the bulk air velocity $U_0 = 6.7$ and 8.5 m/s and $Re = 3900$ and 3300, respectively.

![Figure 1. Scheme of the experimental setup and photos of examples of methane and syngas flames.](image_url)
via a bypass system to the main air path. The temperature of the mixture was controlled by a thermocouple (Type K) near the nozzle exit. The instantaneous velocity field was measured by (PIV) in stereoscopic configuration. The stereoscopic PIV system consisted of two combined pulsed Nd: YAG lasers (Beamtech, Vlité 200, 200 mJ per pulse at a wavelength of 532 nm) and a pair of 4 Mpix CCD cameras (ImperX-B2020M). To reduce the background signal of flame chemiluminescence, a narrow-band filter with a bandwidth of 10 nm at a wavelength of 532 nm was installed on the camera lenses. 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 OH radical in a reacting flow, the PLIF was used. In the PLIF registration system, a tunable Sirah Precision Scan dye laser (with a wavelength of ~ 283 nm, 12 mJ) with a pump laser Nd: YAG, QuantaRay (532 nm, 1 J, ~ 10 ns) was used as a radiation source. The OH* excitation occurred at the transition Q1(8) (v' = 1 ← v''= 0, A2∑+ ← X2Π), 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 (multalkali). After amplification, the phosphor coating of the intensifier illuminated a hybrid CCD-CMOS matrix (Imager sCMOS) 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. To take into account spatial nonuniformity of the energy distribution in the laser sheet and energy pulse-to-pulse fluctuations a part of the laser radiation (approximately 5 %) was reflected using a quartz plate into a quartz cuvette filled with a solution of rhodamine 6G. The processing of the fluorescence signal consisted of the following steps: background subtraction, 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 velocity and intensity of the fluorescence signal was carried out over 1500 images.

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 \( T_0 = 300 \) K and \( p = 1 \) atm, the adiabatic temperature of the methane flame was 1839 K, and syngas flame was 1594 K [6].

Figures 2-4 show distributions of the time-averaged velocity, axial and radial velocity pulsations and intensity of the OH radical fluorescence signal (the signal is normalized to the maximum value of the fluorescence signal) in a turbulent swirling flame of a mixture of methane-air and syngas-air with different initial temperatures of the mixture. The coordinates along the X and Y axis are normalized to the nozzle diameter (15 mm). The obtained velocity distributions show that the flow structure corresponds to a swirling annular jet enveloping the central recirculation zone containing combustion products. There are two mixing layers in the flow: between the jet and the surrounding air and between the jet and the recirculation zone. The intensity of OH* fluorescence is a marker of regions containing hot combustion products. According to the obtained distribution of the OH* fluorescence intensity, the flame front is stabilized in the inner mixing layer between the recirculation zone and the swirling jet. The recirculation zone during the combustion of the syngas-air mixture is approximately 1.5 times more compact than in the case of a methane-air flame. From the OH PLIF figure 2-4 (c, f) experimental data, it can be seen that the longitudinal size of the region of hot combustion products decreases significantly with increasing temperature of the mixture for both syngas-air and methane-air flames.
Figure 2. The left column – synthesis gas, the right column – methane. (a) and (b) are the average velocity fields (the solid line is the zero-axial velocity, the color shows the tangential component of the velocity), (c) and (d) are the axial and radial velocity pulsations, (e) and (f) are the average distributions of the fluorescence signal of OH radicals. The temperature of the mixture is 300K.
Figure 3. The left column – synthesis gas, the right column – methane. (a) and (b) are the average velocity fields (the solid line is the zero-axial velocity, the color shows the tangential component of the velocity), (c) and (d) are the axial and radial velocity pulsations, (e) and (f) are the average distributions of the fluorescence signal of OH radicals. The temperature of the mixture is 400K.
Figure 4. The left column – synthesis gas, the right column – methane. (a) and (b) are the average velocity fields (the solid line is the zero-axial velocity, the color shows the tangential component of the velocity), (c) and (d) are the axial and radial velocity pulsations, (e) and (f) are the average distributions of the fluorescence signal of OH radicals. The temperature of the mixture is 500K.

From the presented velocity distributions, it can be seen that with an increase in the temperature of mixture, there is a decrease in the size of the central recirculation zone for both methane-air and syngas-
air flames. There is also a significant increase (up to two times) in the axial and tangential velocity due to the temperature expansion of the heated mixture. Despite the increase in the bulk velocity, heating the mixture leads to a decrease in the Reynolds number to 3300 at a temperature of 500 K. In the case of syngas combustion, the maximum level of velocity pulsations, both axial and radial, is observed near the nozzle on the jet axis under the lower part of the central recirculation zone. With increasing temperature, following the Reynolds number, the value of the velocity pulsations (normalized to the bulk velocity) also decreases. In the case of methane flames the most intensive pulsations, unlike syngas, is located in the inner and outer mixing layer and also decreases with the heating of the flow. It should be noted for the flame of a mixture of methane-air and syngas-air heated to a temperature of 500 K, the size of the recirculation zone and velocity pulsation distribution are very similar, in contrast to a methane flame at lower preheating temperatures of the mixture.

Conclusions
Visualization and experimental study of two characteristic regimes of combustion of a premixed swirling flame of methane and synthesis gas at elevated temperature using modern optical methods PIV (Particle Image Velocimetry) and PLIF (Planar Laser-Induced Fluorescence) were carried out. The distribution of the fluorescence signal showed that the longitudinal size of the region of hot combustion products decreases significantly with increasing temperature of the mixture for both syngas-air and methane-air flames. For the flame of a mixture of methane-air and syngas-air heated to a temperature of 500 K, the size of the recirculation zone and velocity pulsations distribution are very similar, in contrast to a methane flame at lower preheating temperatures of the mixture. These experimental results can be used for the verification of numerical models of preheated swirling turbulent flows with combustion. In order to obtain an extensive experimental database of turbulent swirling flow with lean premixed syngas combustion at the gas turbine relevant conditions the next stage of work should be experimental studies under conditions of high temperature, pressure, and high Reynolds numbers.

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