Investigation of unsteady combustion of methane-air flame in a model combustion chamber with swirling flow

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Abstract. The present paper reports on the investigation of unsteady combustion of a methane-air mixture, including combustion at increased pressure in the combustion chamber and increased temperature of mixture heating for a model gas-turbine swirl burner based on a design by Turbomeca. To measure the velocity and OH fluorescence fields in the flows a combination of stereoscopic PIV and acetone PLIF systems is used. In all cases, the flow dynamics is associated with the movement of large-scale vortex structures in the inner and outer mixing layers and the flow structure corresponds to a swirling jet with a central recirculation zone containing combustion products. An increase in the heating temperature of the mixture and pressure in the combustion chamber leads to a periodic partial separation of the flame from the model swirl nozzle. However, the flow of fuel through the central channel will stabilize the flame.

1. Introduction
An impressive number of works have been devoted to investigation of the thermogasdynamic structure of flows in vortex combustion chambers, in particular, a number of monographs [1-5] and reviews [6-8]. A swirler is placed in front of the combustion chamber. The flow swirl provides a stable combustion in a compact volume in a wide range of flow rates and fuel-air ratios. The dynamics and structure of the swirling flow are complex due to a number of effects viz. the formation of a region of reduced pressure in the center of the vortex core, shear instability velocity in the outer mixing layer and intensification of longitudinal instability modes, formation of a central recirculation zone, swirl flow precession and intense heat and mass transfer.

The influence of the precessing vortex core on the mechanisms of flame stabilization in swirling jets with combustion has been extensively studied in the literature. The development of the PIV method in a stereoscopic configuration has led to numerous experimental studies of the effect of combustion on the velocity field in a swirling jet [9-13] and in combustion chambers with swirling flow [14-16]. The combination of PIV measurements simultaneously with the use of the PLIF method allows the detailed study of the conditions of flame stabilization in a turbulent swirling flow and the study of the influence of large-scale coherent structures on this process [17-19].

The work focuses on experimental studies of the combustion of a methane-air mixture under non-stationary conditions, including combustion at increased pressure in the combustion chamber and increased temperature of mixture heating for a model gas-turbine swirl burner based on a design by Turbomeca. The investigation was carried out with the combined use of PIV and PLIF methods.
2. Experimental setup
A model combustion chamber of a gas turbine burner consisted of a cylindrical plenum chamber, model swirl nozzle (by geometric analogy with [20]), combustion chamber with viewing windows made of fused silica (for observation 100 × 100 mm with a thickness of 10 mm and for flame illumination 100 × 25 mm with 10 mm thick) and confusor with an outlet nozzle. The outlet diameter D of the nozzle was 37 mm. To heat the air, a 4 kW heating element with an industrial temperature controller Termodat-13KT5 was used. The heater was installed downstream of the perforated plate after the main air inlets in the cylindrical preliminary chamber. The air temperature behind the heater and the heater surface was controlled by using thermocouples (Type K).

![Diagram of experimental setup](image)

Figure 1. Scheme of the experimental setup

The OH PLIF system consisted of a pulsed tunable dye laser (Sirah Precision Scan), a pulsed Nd: YAG pump laser (QuantaRay), and UV-sensitive intensified sCMOS camera. The laser beam was converted into a laser sheet using a collimator (LaVision). A tunable dye laser excited OH fluorescence at the wavelength of the Q_{1}(8) transition. Selection of the wavelength was conditioned by OH fluorescence measurements made for the same experimental setup under reacting flow conditions [21]. The average pulse energy at 283 nm was approximately 12 mJ. To take into account the spatial non-uniformity of energy distribution in the laser sheet and the change in the energy of each laser pulse, a part of the laser radiation (approximately 5%) was directed into a calibration cuvette containing rhodamine 6G. The spatial distribution of the fluorescence signal inside the cuvette was recorded using a CCD camera (ImperX Bobcat IGV-B4820, 16 Mpix, 12 bit). The intensity of the OH fluorescence signal was recorded using a sCMOS camera (LaVision Imager sCMOS, 16 bit images with 2560×2160 pixels) equipped with an UV-sensitive image intensifier (LaVision IRO). The image intensifier was also equipped with a UV-lens and a bandpass filter (310 ± 10 nm). The exposure time of the PLIF images was 200 ns.

The stereoscopic PIV system consisted of a pair of CCD cameras (ImperX Bobcat IGV-B2020, 4 Mpix, 8 bit) and a double pulsed Nd: YAG laser (Quantel EverGreen 200, 6 ns pulse duration with an energy of 200 mJ at 532 nm), which was used to illuminate tracer particles. The cameras were equipped with lenses (Sigma 105 mm, DG MACRO) and the narrow bandpass optical filter to suppress the chemiluminescence of the flame (532 ± 5 nm). The laser beam was converted into a divergent laser sheet using a system of cylindrical and spherical lenses. The delay between a pair of PIV laser pulses was 10-40 μs.
3. Results
Photographs of the combustion modes of a methane-air flame at different pressures in the combustion chamber and mixture heating temperature are shown in Figure 2. Three combustion modes were considered: Figure 2a: the pressure in the combustion chamber is 1 bar, the temperature of the mixture is 293 K, Figure 2b: the pressure in the combustion chamber is 2 bar, the temperature of the mixture is 500 K, Figure 2c: the pressure in the combustion chamber is 3.4 bar, the temperature of the mixture is 500 K. Figures 3, 4 and 5 show instantaneous and time-averaged velocity fields and spatial distributions of OH fluorescence measured for different combustion modes.

Figure 2. Photos of the flame in the combustion chamber for different combustion modes.

Figure 3. Spatial distribution of the instantaneous (a) and average (b) velocity field during the combustion of a swirling methane-air flame at atmospheric pressure and at a mixture temperature of 293 K.

Figure 4. Spatial distribution of the instantaneous (a) and average (b) velocity field during the combustion of a swirling methane-air flame at a pressure of 2 bar and at a mixture temperature of 500 K.
Figure 5. Spatial distribution of the instantaneous (a) and average (b) velocity field during the combustion of a swirling methane-air flame at a pressure of 3.4 bar and at a mixture temperature of 500 K.

Time-averaged velocity fields and spatial distributions of OH fluorescence show that the flow structure corresponds to a swirling jet with a central recirculation zone containing combustion products. At distance from the exit of the model swirl nozzle of up to 0.5 D, the influence of the fuel supplied via the central channel on the flow is noticeable. The mixing layers are observed between the central recirculation zone, the flow of the main fuel-air jet and the stagnant zone. An increase in the heating temperature of the mixture and pressure in the combustion chamber leads to a decrease in the radial and axial components of the velocity in the area of the outflow of the fuel-air jet from the swirler and in the size of the central recirculation zone. The OH fluorescence distribution shows that the flame is, on average, stabilized in the inner mixing layer, between the fuel-air jet and the central recirculation zone.

Analysis of instantaneous fields of velocity and fluorescence OH shows that in the case of combustion of the methane-air mixture at atmospheric pressure without mixture heating the swirling flame is stabilized at the exit from the model swirl nozzle. There is a periodic partial separation of the flame from the ring of the model swirl nozzle; however, in this case, stabilization of the flame is supported by the combustion of fuel supplied via the central channel. In the case of combustion of the methane-air mixture at an elevated temperature of mixture heating and a pressure in the combustion chamber of 2 and 3.4 bars, the flame also stabilizes at the exit from the premixer. At the same time, high-speed chemiluminescence shows that conditions, under which the flame is completely detached from the model swirl nozzle, can be realized. However, at a distance of less than one caliber from the premixer exit, the flame is stabilized due to the fuel supplied via the central channel.

4. Conclusions
An experimental study was carried out on an experimental stand for physical modeling of the combustion of a turbulent flame of a methane-air mixture at an increased pressure with heated air using modern optical diagnostics, stereo-PIV and PLIF methods. It was found that, for all combustion modes studied, the flow structure corresponds to a swirling jet with a pronounced central recirculation zone containing combustion products. An increase in the heating temperature of the mixture and pressure in the combustion chamber leads to a decrease in the radial and axial components of the velocity in the region of the flow of the fuel-air jet from the swirler. Also, in these combustion modes, there is a periodic partial separation of the flame from the model swirl nozzle. However, the flow of fuel through the central channel will stabilize the flame.

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