Effect of combustion on swirled flow structure after an industrial burner

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Abstract

At this paper results of investigation of combustion influence on swirled flow stricture after an industrial gas turbine burner with a central body are presented. The burner is used for burning partitialy premixed lean mixture. The main part of gaseous fuel is injected into the swirler and the central body played the role of a bluff body with pilot flame. Investigation was performed with using CFD and experimental measurements. Experimental measurements were carried out with using Laser Doppler Anemometry (LDA) for flow velocity measurements and chromatography equipment for concentration of combustion products measurements. Numerical simulation of the flow velocity field was carried out using Large Eddy Simulation (LES) for turbulence modeling and Flamelet Generated Manifold approach for combustion modeling. Time averaged flow velocity, velocity fluctuations and turbulence kinetics energy spectra were compared for reacting and non-reacting flows. It was shown that results of simulation are in a good agreement with experimental data, except intermediate combustion products, for example CO, in the flame front. It was found that combustion changes the shape of the recirculation zone and reduces the gas mass flow rate inside the recirculation zone. In the non reacting case the maximum velocity fluctuations are located downstream of the central body trailing edge due to the separation of the coherent vortex structures. In the reacting case the maximum velocity fluctuations are shifted from central body into the region of the interaction between the recirculation zone and the main swirling flow, as well as interaction of the swirling flow with outlet secondary air.

Introduction

The swirling flow is used in most modern combustors of gas turbine engines to generate a homogeneous air-fuel mixture and flame stabilization in a wide range of engine operation modes. In a strongly swirling flow the central recirculation zone (CRZ) is formed, which appears as an area in space in which the flow velocity is directed against the movement of the basic gas mass (opposite the direct flow). The CRZ is generated in the axial area, and usually has the shape of a rotation body. Because modern low-emission combustors are using the lean-burn technology, the base part of the air is passing through the burners, in this case the CRZ has a significant impact on the performance of the combustor. One of the properties of a swirling jet is the appearance under certain conditions the precessing vortex core (PVC). This vortex core can be a source of pressure fluctuations (pulsations) in the system, which leads to the pulsation combustion. However, several studies have noted that the presence of the combustion or the pilot diffusion flame can suppress the occurrence of the PVC.

Often the study of the structure and the flow processes in the swirling flow is produced for model constructions or simplified analogues of industrial burners. A wide variety of structural performance of the burner combustion chambers of industrial gas turbine engines leads to the difficulties in generalizing of their research results.

The aim of this work is to study the structure of the flow of the combustion chamber burner of the power plant and the comparison of the flow structure in the cold flow and with combustion.

Methods and instruments

Workflow diagram in the burner is shown in Figure 1.

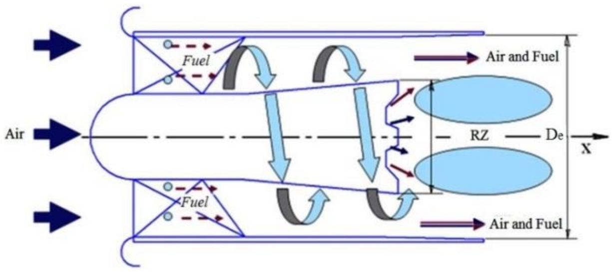

Figure 1 Workflow diagram in the burner

Burner is designed for preparation air-fuel mixture and partially premixed combustion of the gaseous fuel in the gas turbine combustion chamber [1]. The main part of the fuel is injected into the swirler blades passage. The other part of the fuel is supplied through the central body and serves to organize a pilot flame. The fuel is methane.

Experimental measurements of flow velocity were carried out using a Laser Doppler Anemometry LAD-056S of "IOIT" production (Novosibirsk, Russia). For measurements, the solid tracer particles were injected into the flow upstream of the burner. The research was

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conducted as for the reacting and nonreacting flows. The measurement of the chemical composition of the combustion products was produced by chromatographic equipment. All experimental measurements were carried out for open space. Measurements were taken in the longitudinal plane downstream from the exit of the burner. The results of calculation and experiments, as with combustion, and without it, are presented for the four cross-sections from x/D = 0.33 to x/D = 1.33 in the Figure 2. Where D = 60 mm is the diameter at the burner exit.

The inlet temperature is 330 K. The total pressure of the air entering the burner device $\Delta P^* \approx 3{,}3\%$ is greater than atmospheric pressure at the outlet. The Reynolds number was calculated from the diameter of the burner outlet, and the mass-average velocity of the flow at the outlet of the burner calculated from the temperature and flow rate at the inlet of the computational domain, Re≈120000. Fuel consumption to the pilot flame is 11.5% of the total fuel consumption. The total equivalent ratio for the case of mixing equal 0.48, and for combustion case is equal to 0.55. The difference in the equivalence ratio associated with various inlet air mass flow rate, as discussed below.

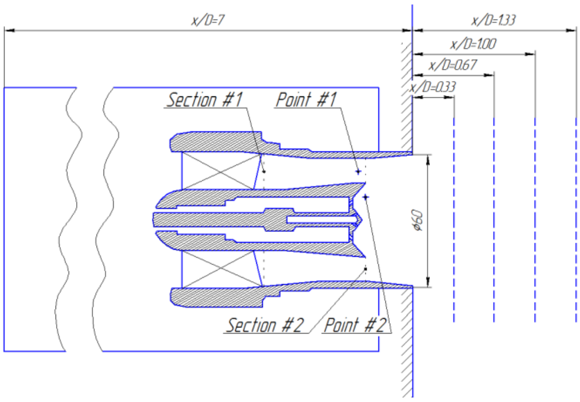


Figure 2 Longitudinal plane scheme of the burner and location of the measurement sections

Computational methods were used to investigate three cases: two of them repeated the experimental conditions and third one had further investigation of the case with fuel supply, but without burning. The calculation was performed in the Ansys Fluent 15.0 software package. For the calculation approach used LES. Subgrid model - a dynamic Smagorinsky-Lilly model [2]. Spatial discretization scheme used in LES is the second order central difference. The calculation of combustion processes was carried out using Flamelet Generated Manifold approach [3], implemented in Ansys Fluent. As the kinetic mechanism of chemical reactions the GRI 3.0 mechanism was accepted [4]. Parameters were set at the flow input as a uniform distribution over the cross section. The time step is equal to 0.00001 s., and the maximum value of the Courant number is 5. The initial conditions for LES calculation were based on the RANS results. To eliminate the influence of the initial conditions before the averaging, the calculation of 3 flows through the burner (flow times through the entire combustion chamber at the bulk velocity) was performed. Then for averaging for three more flows another calculation was performed. The calculation was performed on a supercomputer, "Sergei Korolev" [5] using 256 cores.

Calculated area includes part of the the air supply device plot before the burner, the fuel gas supply channels in the swirler vanes and the central body, also the air channels inside the burner and the atmosphere for it.

The finite element mesh is unstructured. Milling of the mesh was made at the exit of the holes and at the fuel supply downstream of the central body. The total number of items was - 6.5 million units. The finite element mesh on the walls of the central body and the swirler vanes is shown at Figure 3.

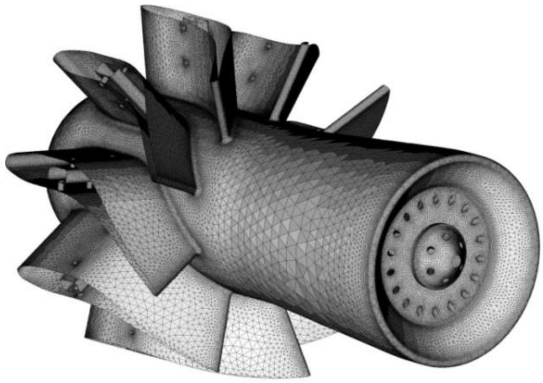


Figure 3 The mesh with the total number of elements is 6.5 million units

Results and consideration

As a result of the calculation, it was found that the swirl number at the outlet of the swirler blades (section №1, Figure 2) for all of the cases, is Sn = 1.07 and at the outlet of the annular channel (section №2, Figure 2) Sn = 0.74. This demonstrates the kinetic energy dissipation of the circumferential flow in the annular channel of the burner.

The Figure 4 shows changes in the axial flow velocity along the radius. Without combustion the axial flow velocity near the burner substantially linearly varies from stream axis to r = 30 mm, which corresponds to the radius of the burner outlet. The flow velocity in the CRZ first increases and then decreases. When increasing the distance from the burner the redistribution of axial velocity of a swirling jet in free flow and smoothing the profile of axial velocity take place. Also it should be noted that the supply of fuel gas has no substantial influence on the distribution of axial velocity in the swirling stream. When combustion the maximum axial flow speed is higher than without combustion. At a distance of 40 mm from the burner, the axial flow velocity in the CRZ does not change as in the radial and the length of the CRZ. It is worth noting that the opening angle of the swirling jet in combustion is lower than without combustion.

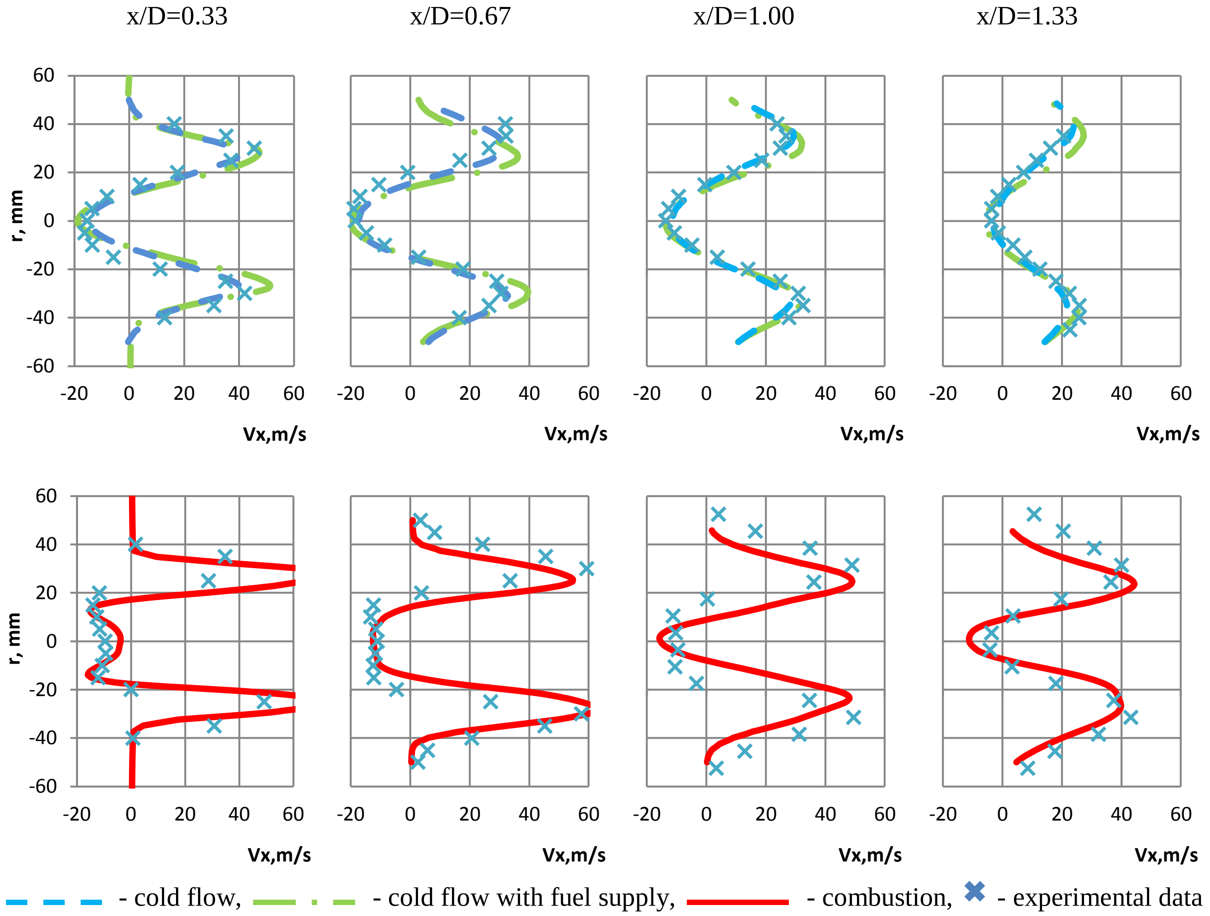


Figure 4 Axial flow velocity

The CRZ contains hot gases with high viscosity (Figure 5) which acts as a damper for the occurrence of the precessing vortex core as shown later.

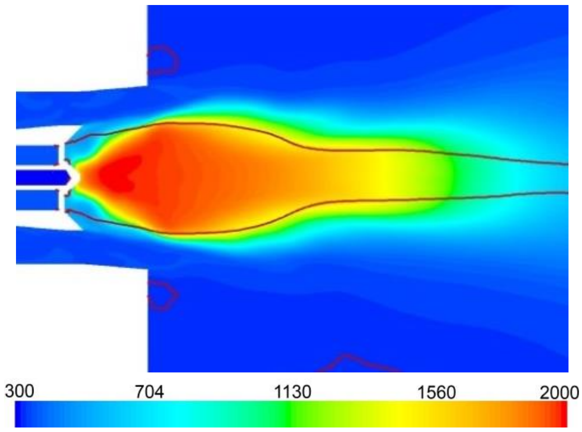


Figure 5 Flow temperature contours and CRZ boundary

Tangential flow velocity is shown at Figure 6. Without burning the tangential flow velocity distribution corresponds to the shape of the combined Rankine vortex: an area with a constant angular velocity (forced vortex) near the axis (up to r≈20mm), and the area with a constant twist flow (free vortex) at the periphery. When increasing the distance from the burner the maximum tangential velocity is decreasing and its displacement in position relatively the axis. As in the case with the axial velocity, the fuel supply does not significantly affect the profile of the tangential flow velocity. In case of combustion, the flow at a constant tangential velocity occupies a smaller area (r≤5 ... 10 mm). In the near wake of the burner there is an area with a constant tangential velocity (5 ... 10≤r≤20 ... 25 mm). It should be mentioned that during combustion the tangential flow velocity in the axial area (r≤5 ... 10 mm) is equal to the tangential velocity flow conditions without burning. Furthermore, this area does not change with distance from the burner substantially the length of CRZ. At a distance from the burner more than 60 mm the tangential velocity distribution, is close to the distribution in the Rankine vortex. In general, the calculation results are in good agreement with the experimental data, except for the area near the border zone of the CRZ in combustion for x/D = 0.67 and x/D = 1.00, where the calculation overestimates the value of the circumferential velocity component.

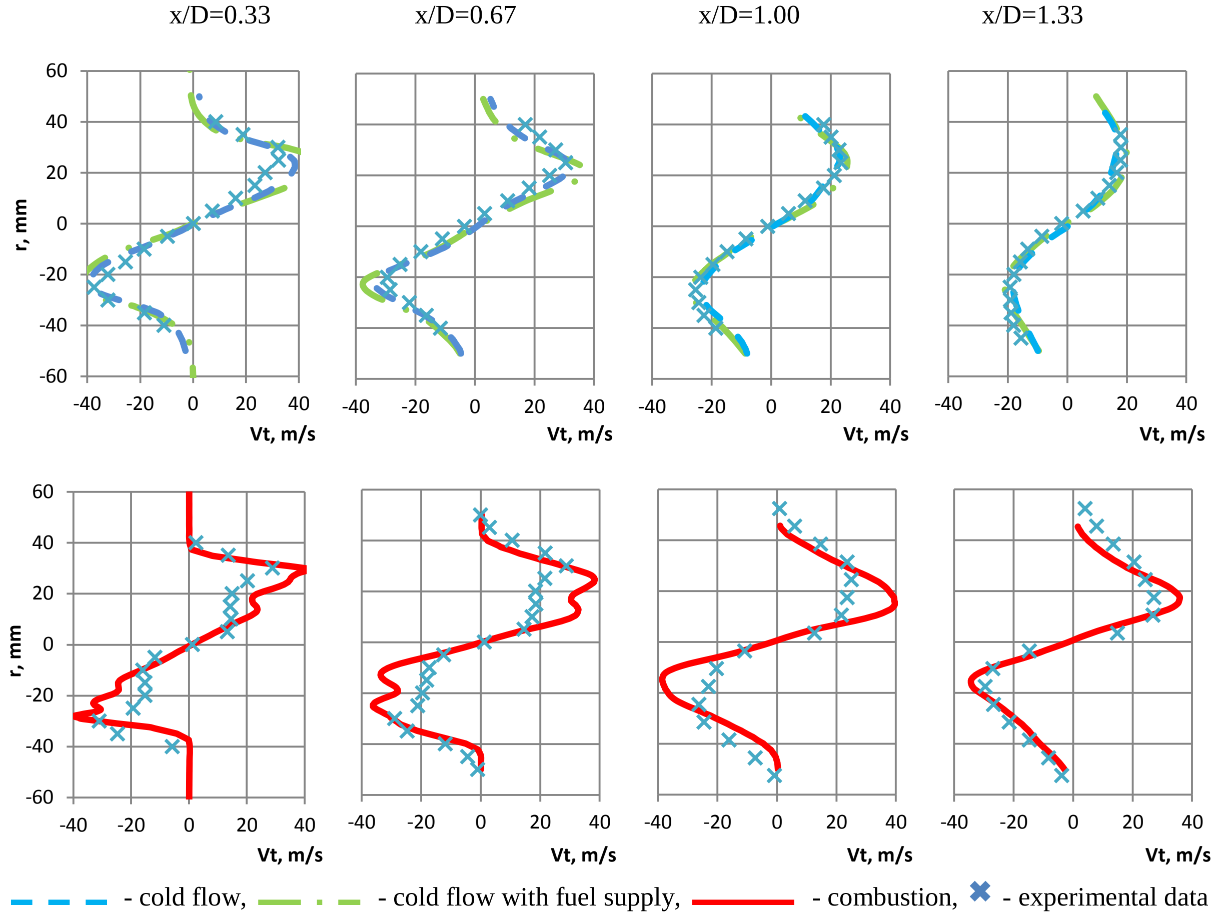


Figure 6 Tangential speed of the flow

The figures 7 and 8 show the graphs of RMS of axial and tangential flow velocity changes. The results are compared with the experimental measurements in part of the RMS LES flow velocity. Without combustion the maximum value of the axial velocity pulsations, correspond to the position of the highest time-averaged gradient of the axial velocity. At combustion case the axial velocity pulsations in CRZ are practically constant along the radius. The total level of pulsations is lower than in the case of cold flow. At the edge of the CRZ the RMS of axial velocity for the case with combustion is maximum. Overall, the results of calculation of the axial flow velocity pulsations are in good agreement with the experimental data, except for the area within the case inside the reverse flow zone in the near wake of the burner (with x/D = 0.33-0.67), where the calculation overestimates the RMS axial velocity value.

As the axial flow velocity pulsations, the pulsation of the tangential flow velocity when burning are lower than without burning. Fuel supply slightly increased the RMS of the tangential flow speed compared with a cold flow without fuel. It is also should be mentioned that in the test section area the average value of RMS both the tangential and axial speeds of the flow when increasing distance from the burner in the case of combustion is increasing, while in the case without combustion is decreasing.

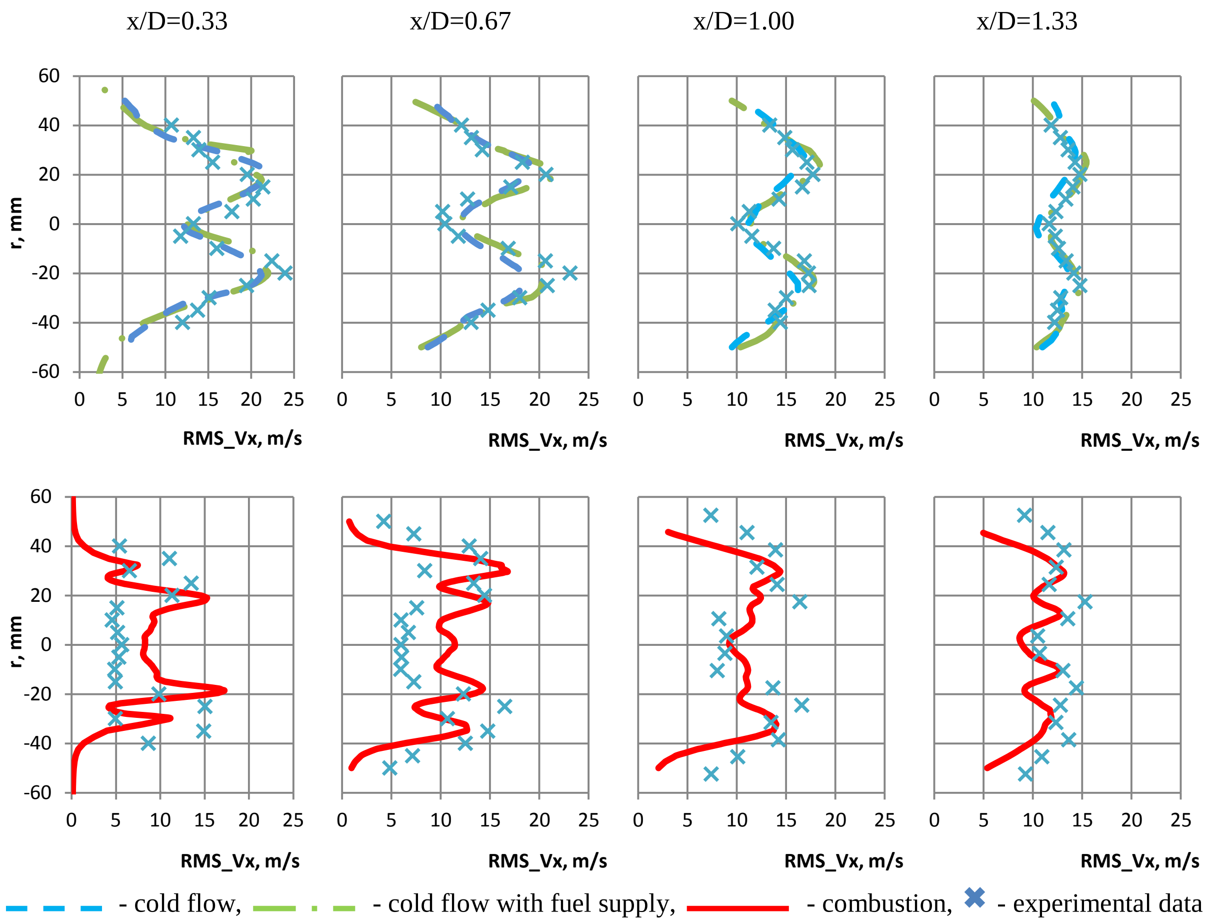


Figure 7 Axial flow velocity pulsations

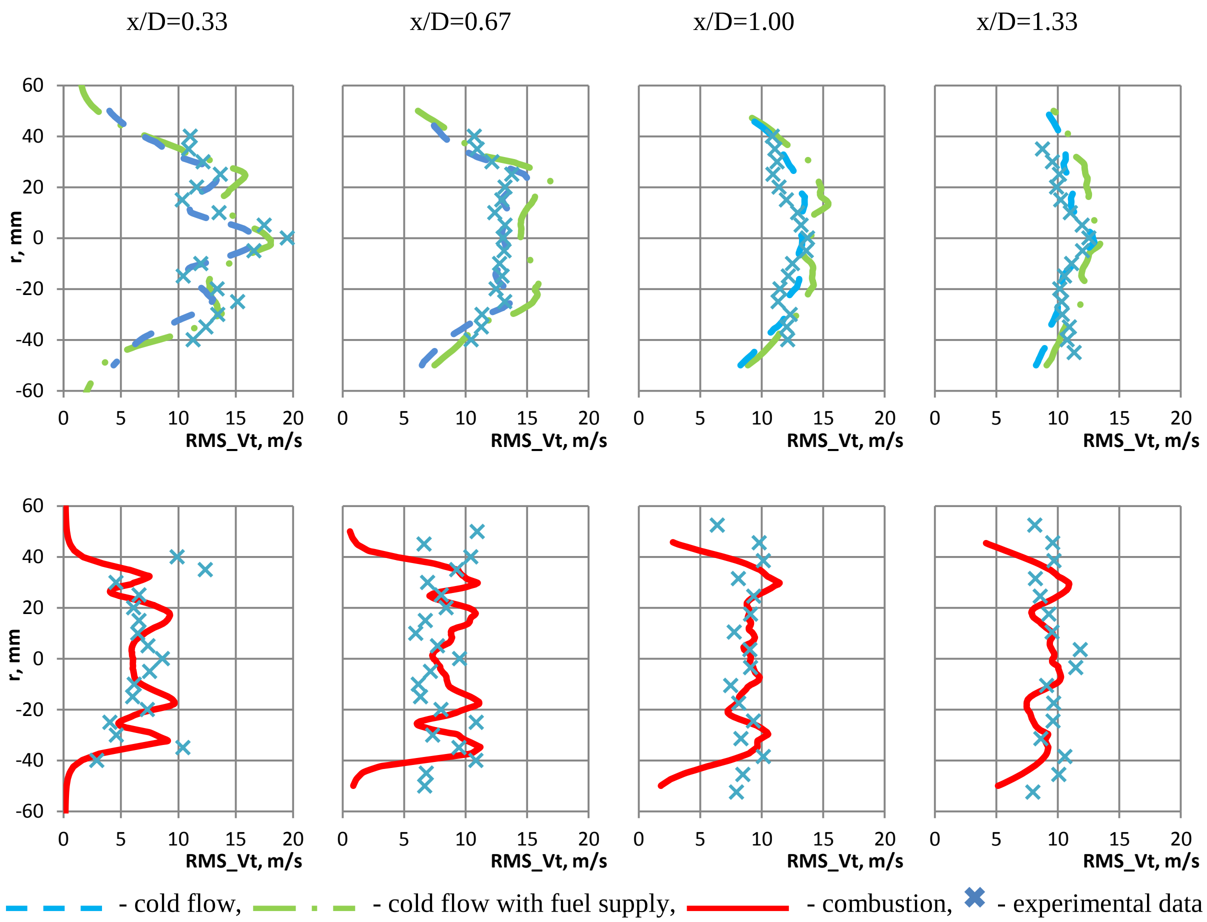


Figure 8 Circumferential flow velocity pulsations

The figure 9 shows a comparison of the calculated results with the experimental data on the chemical composition of the working fluid. A comparison was made for mixture fraction (**f**), CO and CO2. Experimental measurement of the **f** was produced only for the case with combustion. The results show that the mixture fraction stay practically unchanged in the area of the CRZ. Mixture in the CRZ without burning becomes poorer when the distance from the burner increasing. In general, the backflow zone during the combustion is richer in composition than without burning. As shown below, this is due to the fact that the combustion zone in the backflow zone involved minimal amount of the main stream gas mixture than when cold flow. Also it should be mentioned that there is a good agreement between the results of mixture fraction calculation with the experimental data, which indicates the adequacy of the mathematical model used to predict the processes of mixing fuel with air.

Comparison of carbon monoxide shows that the position of the maximum CO concentration is modeled correctly, but the absolute value is less than the value that was obtained experimentally, especially in the near wake of the burner (x/D = 0.33 ... 0.67). Because the concentration of the final combustion products, such as CO2, which were obtained by calculation are in good agreement with the experimental data, it is possible that it can be a difference due to the special aspects of CO used the kinetic mechanism of chemical reactions in the calculation of intermediate components.

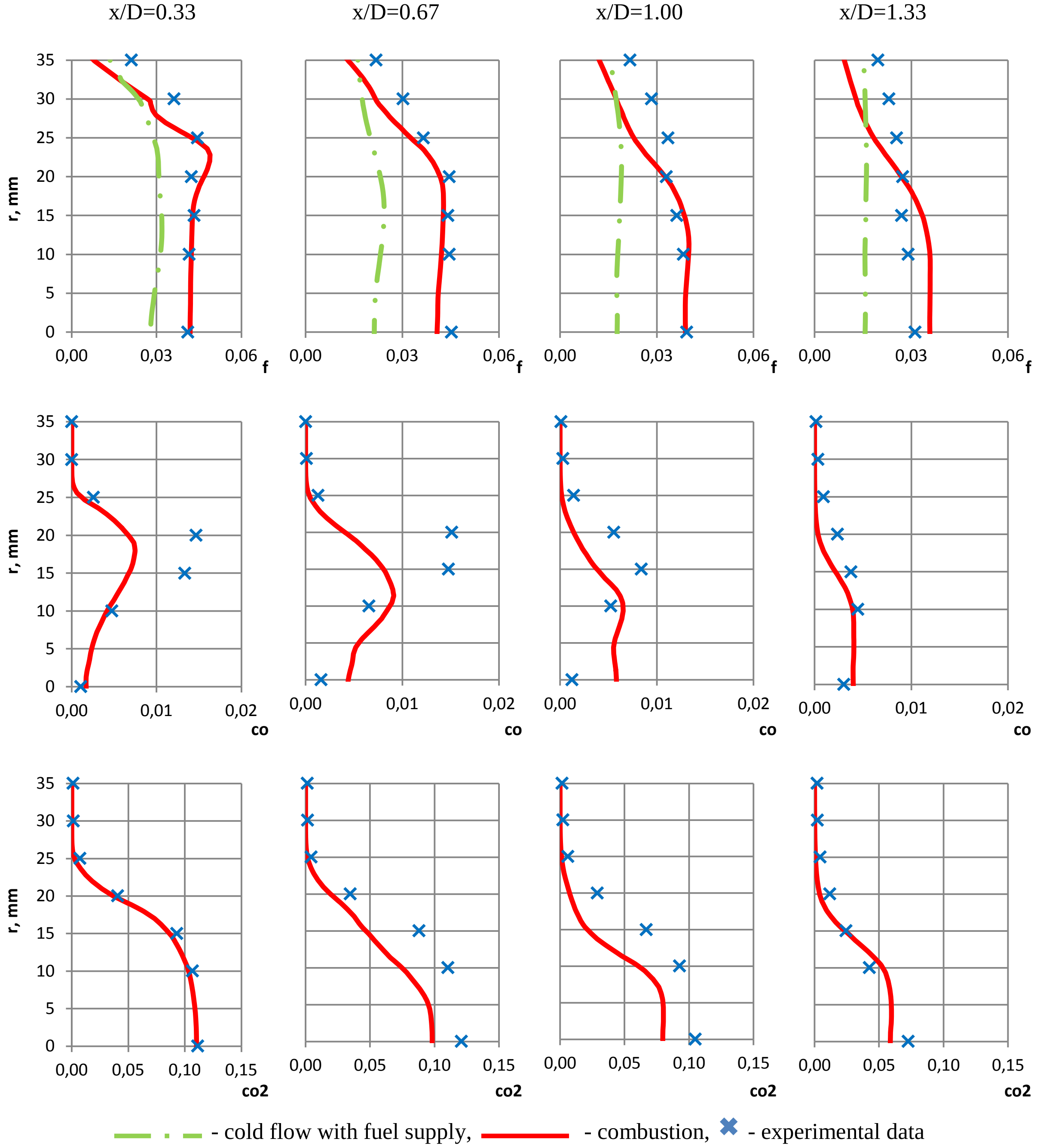


Figure 9 Gas chemical composition

The Figure 10 shows the information which is the calculation result of CRZ: changes of the relative mass flow of the gas G, the relative volumetric flow rate Q and backflow zone radius R along its length. Flows relative values were modified to the parameters in the inlet. Fuel supply slightly affects the gas flow rate and the shape of the CRZ, it is more influenced by combustion processes. The relative mass flow during combustion is about 3 times less than in the cold flow and is maximum 2% of the total flow through the burner. Along with this the volume flow during combustion is half higher than cold blow, which is aligned with a higher temperature during combustion. Combustion also changes the shape of the CRZ and increases its volume. During the cold flow, the CRZ had two indicative "humps", one directly behind the central body, and the other in an open area of the burner. When burning a form of the CRZ becomes more oval, and there is only one "hump" directly from the burner outlet.

The Figure 11 shows the spectra of pressure fluctuations at two points (point # 1 and point # 2 Figure 2). It was found that the Strouhal number is equal to 0.74 for cold cases without fuel and is equal to 0.77 with the fuel supply.

Strouhal number was determined as:

$$St = \frac{fD}{u_b}$$

where D –is the burner exit diameter, 0.06 mm,

f_{cold} – characteristic frequency in case of cold flow at, 468 Hz,

f_{mixing} – characteristic frequency with fuel supply at 482 Hz,

u_b – mass average velocity at burner exit, 38 m/s.

Pulsation component of the static pressure with the frequency 468 Hz at the point №1 during the cold blow without fuel is 63% of the total pulse and at the point №2 is 41%, besides the pulsation amplitude at this frequency increased by 2.4 times. For the case with cold fuel delivery, the static pressure pulsation component with the frequency of 482 Hz at the point №1 is 47% of the total pulse component and at the point №2 is 36%, whereas the amplitude of pulsation increased in 2.1 times.

At the points of the characteristic frequencies during combustion the pressure pulsations were not found. Under combustion conditions a PVC was founded under isothermal conditions was suppressed. Flame front area surrounds the CRZ, which encompasses the hot gases. The position of the flame front relatively to the CRZ is shown on the Figure 12.

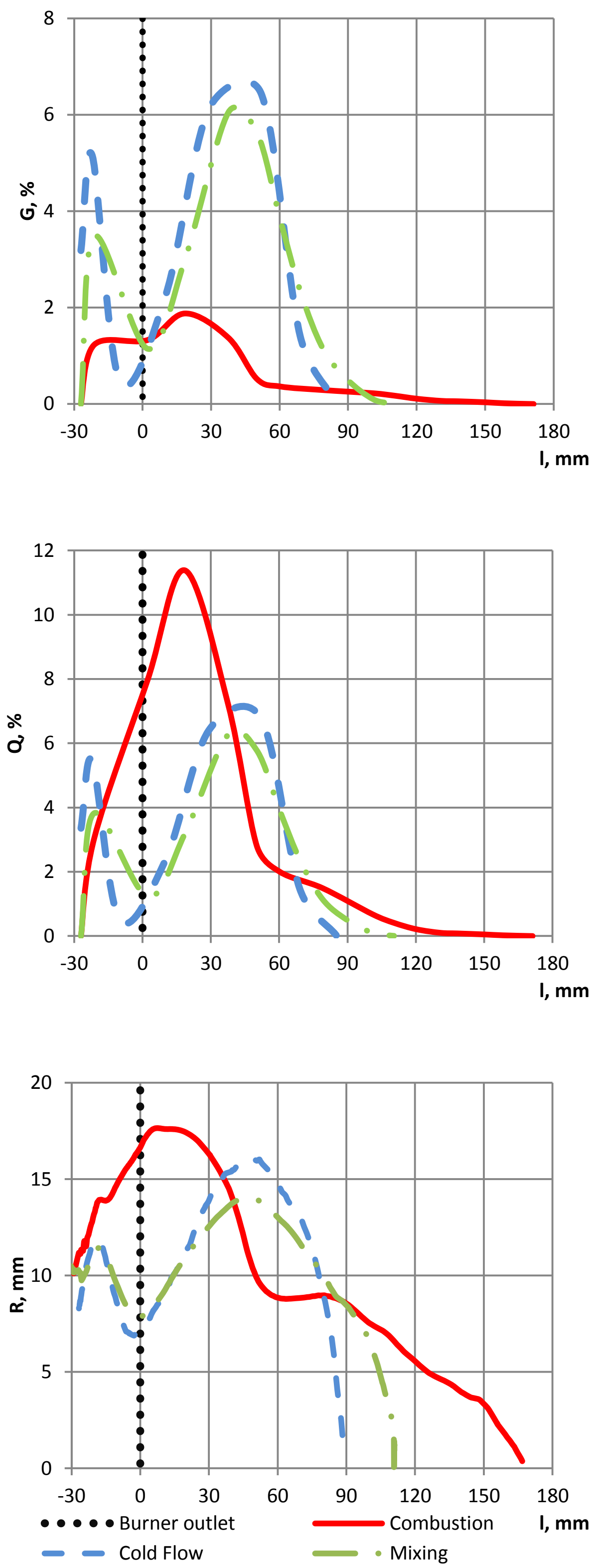
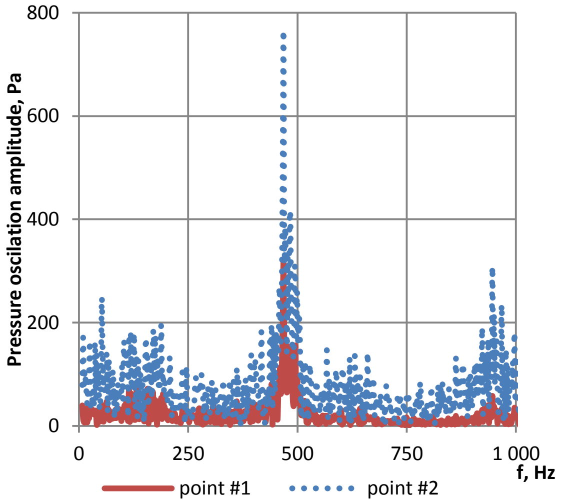


Figure 10 Central recirculation zone parameters



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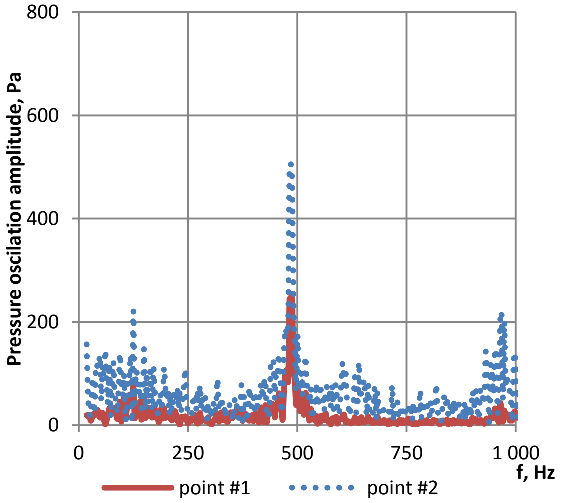
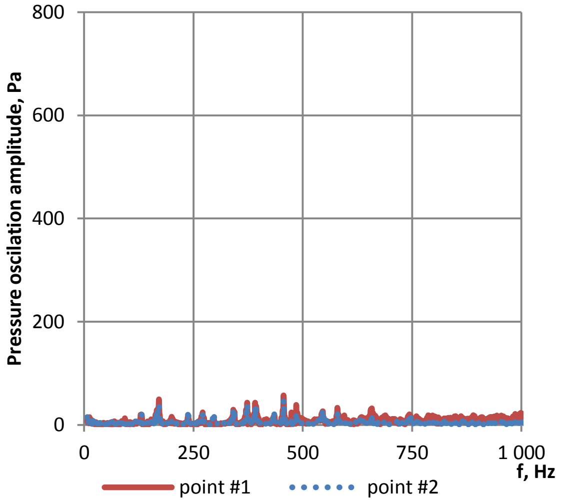


b)



c)

Figure 11 Pressure fluctuations spectrum as the result from the LES: a – cold flow, b – fuel supply, c - combustion

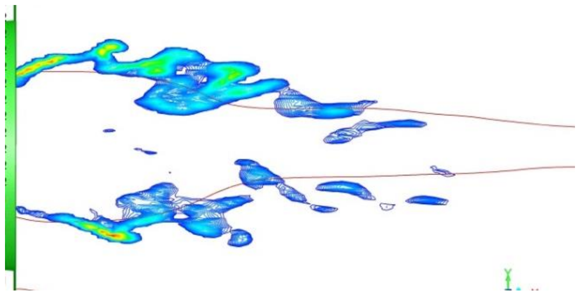


Figure 12 The position of unsteady flame front relatively to the time-averaged position of the CRZ

Conclusions

In this paper we present the results of computational and experimental research of the swirling jet flow after burner for industrial turbine engine. The study was conducted under atmospheric conditions in open space. Experimental measurements were made using LDA as for the cold flow, and for the case with the burning. Composition of the combustion products via sampling also were determine experimentally. The calculation was performed using the LES in conjunction with the model Flamelet Generated Manifolds for simulation of combustion processes. Additionally, the case with fuel supply but without burning was modeled. It is found that the simulation results are in good agreement with experimental data on flow rate, its fluctuating component, as well as chemical composition except for carbon monoxide. Flow structure after the burners was analyzed in detail and characteristics of the CRZ were obtained. It was shown that the fuel supply had insignificant effect on the flow structure. It was found that the combustion process changes the shape of reverse currents, increasing its diameter. Mass flow during combustion is significantly lower than in the cold case. Pressure pulsations associated with the precession of the vortex core, which were discovered during cold blow, were absent when burning.

Acknowledgements

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