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EXPERIMENTAL INVESTIGATION OF A TWO-ZONE DRY LOW EMISSION GAS TURBINE COMBUSTOR*

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Abstract

A new design of a two-zone combustor with sequentially located pilot and main zones is described. The pilot zone provides: the required range of stable combustion at leaner conditions, heating and initiation of combustion in the main zone. The main zone provides burnout of the fuel-air mixture at leaner conditions with low emission values. Combustion in both zones is formed by supplying air through the double tangential swirlers with co-rotation in the pilot zone and counter-rotation in the main zone, while the fuel is supplied between the swirlers vanes. It is shown that the investigated combustor ensures the simultaneous minimization of emissions (CO and NO_x) at acceptable values of non-uniformity of the outlet temperature field and a wide range of stable combustion.

Keywords: combustion; emissions; swirl, turbine

1. Introduction

One of the main environmental pollution sources is transport system, in particular, gas turbine engines. Therefore, pollutants reduction in the exhaust gas is a crucial task at the stage of gas turbine combustor development and modernization. Emission standards (nitrogen oxides (NO_X), carbon oxides (CO), unburned hydrocarbons (C_XH_Y) and smoke) for aircraft engines become more stringent over time by International Civil Aviation Organization (ICAO)

The key challenges in the process of creating a low-emission combustor are associated with a simultaneous decrease in CO and NO_X emissions, for which opposite measures are necessary to be mutually conducted. The combustor optimal design should be a

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tradeoff between low concentrations of CO and NO emissions. This can be achieved by: improving the workflow of the primary zone (Lefebvre and Ballal, 2010), intermediate and dilution zone (Inozemtsev and Sandratskiy, 2006), selection of the flame tube volume and the residence time in the combustion chamber (Pchelkin, 1984). Many studies are devoted to the theory and methods of combustor design (Biryuk et al., 2016; Bulysova et al., 2018; Evdokimov et al., 2020; von Langenthal et al., 2019; Salamon et al., 2020; Yousef et al., 2018), in some cases, special types of combustors have to be used, development of which are impossible to achieve on the basis of existing experimental and theoretical approaches.

The aim of this work is to develop a Dry Low Emission Gas Turbine Combustor.

Pollutants reduction is interconnected with other combustor characteristics, for example: the range of stable combustion and the uniform outlet temperature distribution, reason for need, to carry out comprehensive studies in the process of creating a low-emission combustor. Therefore, in this work, it is required to solve the following tasks to investigate the characteristics of the combustor workflow:

i) conduct a combustor outlet temperature measurement to estimates nonuniformity;
ii) determine the range of stable combustion at leaner conditions;
iii) measure the emission (CO and NO_X) at the exit of the combustor in different operation regimes.

2. Materials and methods

2.1. Experimental configuration

Fig. 1 presents setup diagram designed to study the characteristics of the combustor. It consists of the systems: air supply and heating, supply of gas fuel and a system for measuring parameters of air, fuel and combustion products.

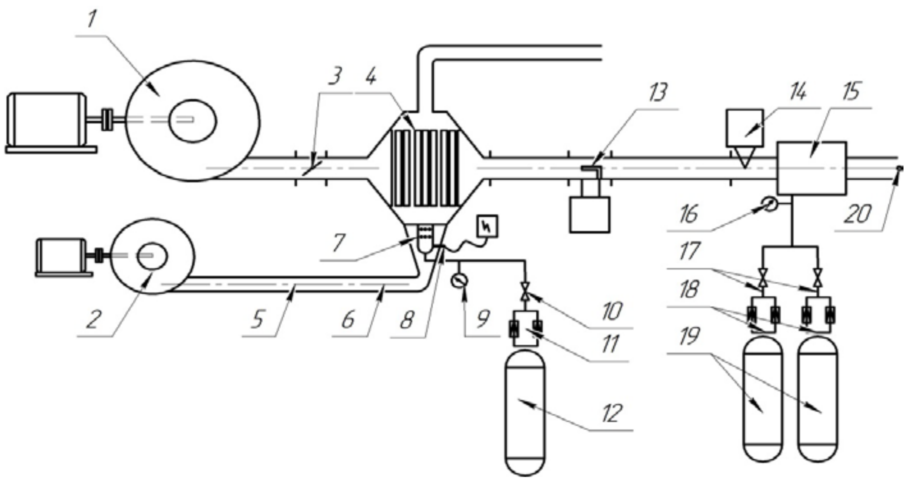

Fig. 1. Schematic of the experimental test rig facility
1 - main blower, 2 – generator chamber blower, 3 – Throttle valve, 4 – heat exchanger, 5 – measuring orifice plate (double diaphragm), 6 – throttle valve, 7 – generator combustor, 8 – spark plug, 9 – pressure gauge, 10 – flow valve, 11 – gas reducer, 12 – LPG bottle, 13 – measuring device, 14 – thermocouple group Chromel-Copel (type L), 15 – test combustor, 16 – pressure gauge, 17 – stopcocks, 18 – gas reducer, 19 – LPG bottle for main combustor, 20 – gas sampling and temperature measurement site.

The air supply system provides full airflow into the combustor at all operating modes. It consists of the main blower 1 with a power of 32 kW and 200 kW and an auxiliary blower 2 (for heat exchanger 4) with a power of 2.2 kW, a system of air ducts and bypass and throttle valves 3.6.

Air heating system allows increasing the airflow temperature to the combustor up to 180°C. It consists of a blower 2, an air duct system, a throttle valve 6, a heat exchanger 4, a tubular combustor 7, a gas fuel supply system (LPG bottle 12) and an ignition system 9-11. Having a closed system it is possible the prevent the mixing of the combustion products with the heated air.

The fuel supply system consists of containers with gas (propane-butane, natural gas and carbon dioxide) 19, isolation and throttle valves, mixers, measuring sections, pipelines and nozzles. The regulation of the gas supply is carried out by gas reducers 18 and stopcocks 17.

The measurement system allows measuring the flow rate of the air by measuring static pressures, high-speed heads and static temperatures at specific points and sections. An integrated (5-point) cooled sampler is located at the exit of the combustor Fig.2. The composition of gas samples was determined by a gas analyzer polar-T.

2.2. Approach to reduce emissions

The reduction in pollutant emissions of gas turbine engines has been widely discussed in many studies, including (Lefebvre and Ballal, 2010), in which the main ways to reduce emissions are:

- supply a well-mixed air/fuel mixture to the burning zone;
- select equivalence ratio to achieve combustion temperature in the burning zone around 1600…1750 K;
- increase residence time in the combustion zone for complete fuel burning;
- reduce factors affecting the "freezing" of combustion products.

With the tightening of environmental requirements for emissions annually, it is necessary to revise ways to reduce emissions in more detail. In this paper, we consider the improvement of the front-mounted device design, which allows for intensive mixing, a wide range of stable operation and a uniform outlet temperature field.

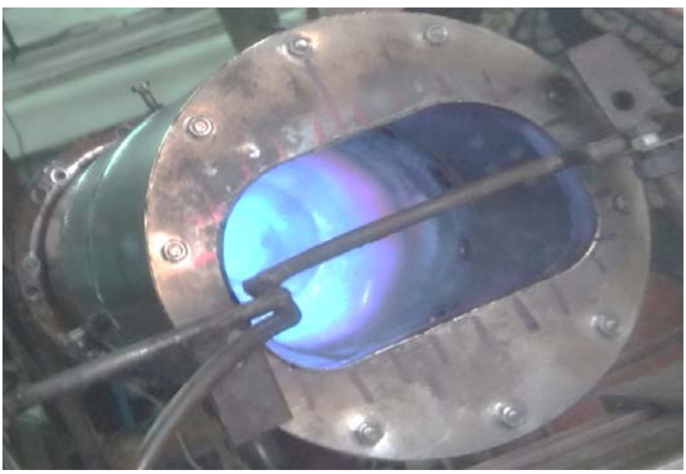

Fig.2. Photo of the combustor for sampling combustion products in the optimal mode.

Therefore, the following approach was applied:

- increase of fuel and air mixing efficiency by supplying fuel between the vanes of double tangential swirlers with counter-rotation and formation of the preparation zone of the mixture before the main combustion zone;
- increase of flow turbulence intensity by using of double radial swirlers with counter-rotation;
- division of the flame tube volume into 3 zones:
    - **pilot zone**, in which the residence time of the mixture is increased (by swirling) and diffusion-type combustion, is formed. Pilot zone provides: a wide range of stable combustion; the initial heating of the mixture in the main zone; initiates the combustion of the main mixture and affects the outlet temperature field
    - **main zone**, in which combustion process is described as homogeneous. Low CO concentration is provided due to the high turbulence intensity and the initial heating of the mixture by mixing it with the products of the pilot zone. Moreover, in the main zone a Lean-Burn Combustor (α_{mz} ≈1.6) is formed with a combustion temperature T_c ≈ 1700-1800 K, which is: the boundary between dissociation and recombination and the boundary of NO_x formation. (Lefebvre and Ballal, 2010).
    - **dilution zone**, in which air is supplied through radial holes and mixed with high-temperature combustion products (main zone) to required average temperatures and uniformity of the outlet temperature field.

3. One dimensional calculation of combustion chambers

To determine combustion chamber geometry and the distribution of the equivalence ratio along the length of the flame tube different methods of calculating the Combustion Chamber were used (Mingazov et al., 2015). Based on the 1D calculations, a tubular reverse-flow combustor is designed Fig. 3, operating on gas fuels.

It consists of pilot 1 and main 2 zones for burning combustible mixtures. Each of the combustion zones in the front area has its own fuel manifold 4, 8 and swirlers with tangentially located vanes 6, 10. For better mixing of the air-fuel mixture, gas fuel is supplied through holes located between the vanes of the swirlers 5, 9. Air is supplied into the combustor through two swirlers and two liner holes 7, 11. The combustion process in the pilot zone starts immediately after the swirler 6, which is a flame stabilizer.

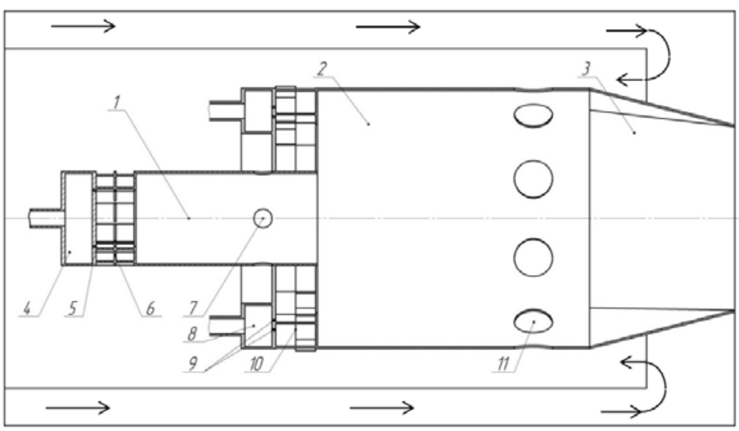

Fig. 3. Schematic of low emission gas turbine combustor

The liner holes 7 air jets penetrate and mix with hot combustion products in the pilot zone for achieving $\alpha_{pz} \approx 1.6 \ldots 1.8$. Further, the combustion products ignite the main fuel mixed with air entering through a double tangential swirlers with counter-rotation, at $\alpha_{mz} \approx$ 1,1…2,0. Thereafter, intense combustion of the air-fuel mixture occurs to the liner holes in the main zone 11.

4. Results and discussions

In the course of experimental studies, we obtained results showing changes in the concentration of CO and NOx in ppm depending on the equivalence ratio α_{Σ} in the combustor as in Fig. 4. The figures show the results of the combustor operation:

- with fuel supply only in the pilot zone;
- with fuel supply only in the main zone;
- with fuel supply simultaneously in the pilot and main zones.

From these graphs it can be seen that the minimum emission values CO = 70 ... 80 ppm is achieved at α_{Σ} = 3,5...4 when the pilot and main zones work at the same time. Wherein the values of NO_x=10…12 ppm. These values should be considered optimal for a combustor with a two-zone combustion formation with low values of T_{comp} = 450 K and T_c=1000 K.

The outlet temperature fields of the combustor were investigated at Fig. 5 in operating regimes G_a=220 g/s, T_{comp} = 430 K, α_{Σ} = 3.5, and the mean and maximum temperature field non-uniformities θ_{av} and θ_{max} were obtained in Fig. 6, which do not exceed 15%.

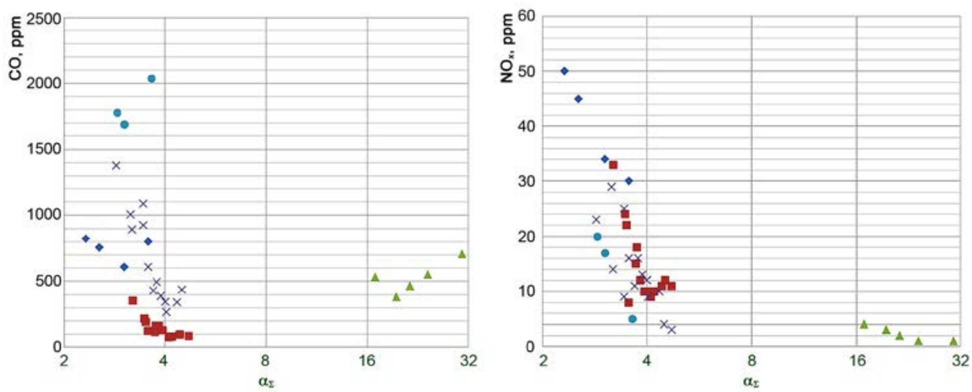

Fig.4. Emissions of CO (left) and NOx (right) for different equivalence ratio in the combustor (×–P_{comp}=105325 Pa, G_a=0.25 kg/s, T_{comp}=277 K, g_{pz}=0 kg/s; g_{mz}=0.0045…0.006 kg/s; ●–P_{comp}=105325 Pa, G_a=0.25 kg/s, T_{comp}=277 K, g_{pz}=0.0007…0.001 кг/с; g_{mz}=0.003…0.005 kg/s ♦–P_{comp}=105325 Pa, G_a=0.22 kg/s, T_{comp}=423 K, g_{pz}=0 kg/s; g_{mz}=0.0038…0.006 kg/s ■–P_{comp}=105325 Pa, G_a=0.22 kg/s, T_{comp}=423 K, g_{pz}=0.0005…0.0007 kg/s; g_{mz}=0.0023…0.0035 kg/s ▲–P_{comp}=105325 Pa, G_a=0.22 kg/s, T_{comp}=423 K, g_{pz}=0.0005…0.001 kg/s; g_{mz}=0 kg/s)

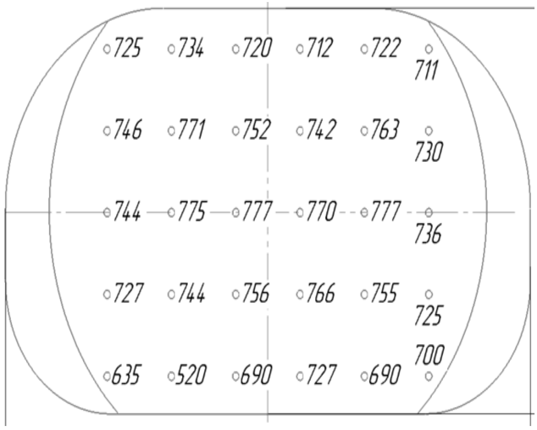

Fig. 5. Outlet temperature distribution in °C, G_a=220 g/s, T_{comp}=423 K, α_Σ = 3.5.

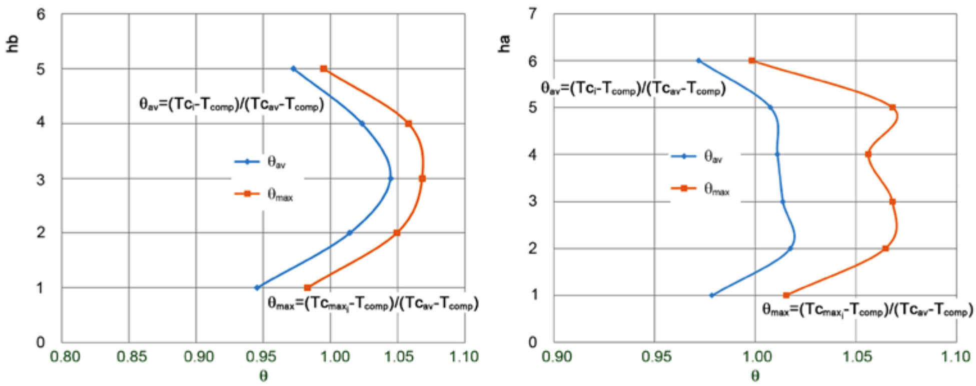

Fig. 6. The unevenness of the temperature field at the cut: left – along the height and right – around the circumference

5. Conclusions

The major conclusions from the study include the following:

Experimental studies of a tube countercurrent combustion chamber in atmospheric conditions P = 105325 Pa, flow rate G_a = 0.22 kg/s and air temperature T_{comp} = 430 K, showed:

- low emission values (CO = 70 ... 80 ppm, NO_x = 10 ... 12 ppm) at the design operating regimes α_Σ = 4.0, T_c = 1000 K;
- acceptable values of the non-uniformity of the outlet temperature field in the modes with a temperature T_c = 1000 K in the design operating regimes corresponding in height θ = 0.95-1.05 and in circumference θ = 0.97-1.07;
- the scheme of the combustor with a pilot zone by which stable operation is ensured in modes with α_Σ = 2 ... 3.2.
- The selected turbulence model gives good agreement with experimental data and can be used to calculate processes in a combustion chamber with swirling flows.
- The supply of fuel between the vanes of the double tangential swirler gives an efficient mixture of fuel with air.

- To reduce emissions and improve the performance of the combustor, the combustion process must:
  - organize the combustion in two stages: the pilot zone and the main combustion zone;
  - increase the efficiency of mixing fuel and air by supplying fuel between the vanes of the double tangential swirler;
  - increase the flow turbulence intensity through the use of a double tangential swirler with counter-rotation.

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