Features of commissioning a gas turbine unit with a low-emission combustion chamber

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Abstract. Environmental safety issues are a priority in the modernization development of aviation or ground-based combustion chambers of gas turbine engines. In order to reduce the emission of harmful substances from combustion products, a low-emission combustion system, which is based on the concept of LPP (Lean-premixed and prevaporised), is being used today. This concept implements the principle of burning “ultra-poor” premixed air-fuel mixtures. The operational experience of combustion chambers developed in accordance with the indicated concept shows that one of the implementation problems is the difficulty in ensuring a good start. This paper presents the results of adjusting the operating process of a modern combustion chamber, launching a gas turbine unit, including drawing up a fuel supply control algorithm, experiments with igniting ignition devices and setting the gas turbine on idle mode. A feature of the commissioning work is the debugging of the operating process of the combustion chamber directly as part of the gas turbine unit, bypassing the traditional pilot-testing on the rig.

1. Introduction

Developers of aircraft and ground gas turbine engines (GTE) are faced with the task of radically improving environmental performance, increasing reliability, economic efficiency and operational efficiency. This requires the implementation of rigorous research into the regularities of the formation of harmful substances’ emissions in combustion products and their connection to the design of not only combustion chambers, but also the engine as a whole. As a new breakthrough technology, today we are considering the concept of creating a low-emission fuel combustion system, which is based on the concept of LPP (Lean-premixed and prevaporised) “poor, mixed, vaporized mixture”. For several decades, this new approach has been developed in the form of developing a low-emission combustion system and a new type of combustion chamber that implements the principle of burning “ultra-poor” premixed air-fuel mixtures. Currently accumulated positive experience in creating combustion chambers and burner devices made it possible to develop this combustion system for a gas turbine unit (GTU) [1]. Low-emission combustion systems include:
- the development of a multi-circuit low-emission combustion chamber;
- the development of a program of automated, strictly dosed fuel supply to the burners with a three-stage system for connecting the burners depending on the engine operating conditions and atmospheric conditions, i.e. automatic combustion chamber control system.

The practice of operating a low-emission combustion chamber has shown that when it comes to achieving high operational reliability, the main problem is starting the engine. Below are commissioning features of a gas turbine unit with a low-emission combustion chamber. The peculiarity of the study is that the development of the operating process, including start-up, is carried out directly as part of the gas turbine, excluding the traditional design development on an autonomous rig alone.

2. Designing a low-emission combustion chamber

A new low-emission combustion chamber was designed at the JSC “Metallist-Samara”, and a low-emission fuel combustion system was developed based on a synthesis of not imported experience in ensuring environmental safety by ground and aviation gas turbine engines.

The base material for the design was the standard version of the gas turbine engine GT-009M developed by the Energomash group of companies. The modernized unit with a low-emission combustion chamber was called LGT-010. The GTU LGT-010 is a single-shaft unit with an axial gas output after the turbine and a counter-flow combustion chamber, consisting of eight external flame tubes placed on the turbine casing. LGT-010 operates in
two main operational modes: cogeneration (without a regenerative air heater) and regenerative (with a regenerative air heater). The modernized low-emission combustion chamber and its placement on the turbine housing are shown in Fig. 1.

The main design changes made in the modernized low-emission combustion chamber are the replacement of 7 standard fuel burners in the burner device with 6 universal dual-circuit burners that provide good mixing of the air-fuel mixture, multi-circuit fuel supply to the combustion chamber, and the use of three manifolds for fuel supply with an automated system of fuel management according to the tested program. The design of the flame tube remains standard with a reasonable reduction in air flow for cooling the front wall and secondary air for mixing. The reduced airflow for cooling the walls of the flame tube is used to deplete the composition of the fuel assemblies in the burners in order to reduce emissions. The modernized burner device of the GTU LGT-010 low-emission combustion chamber is shown in Figure 2.
3. The adopted methodology for low-emission fuel combustion

To ensure environmental safety at GTU LGT-010, the following methodology for low-emission fuel combustion was adopted:
- homogenization and highly efficient mixing of the previously prepared “poor” mixture;
- development of the combustion process of the “poor” mixture at a flame temperature of not higher than 1800 K in all operating modes;
- a multi-stage combustion scheme with a short residence time of combustion products in the high temperature zone.

The main components of the developed combustion system are:
- multi-circuit low-emission combustion chamber based on a unified dual-circuit burner;
- the program of automated, strictly dosed fuel supply to the burners with a three-circuit system for connecting the burners depending on the operating modes of the engine, that is, an automatic combustion chamber control system [2].

The main element ensuring the operability of the low-emission combustion chamber is the universal dual-circuit burner [3]. Figure 3 shows the model of this burner, which determines the presence of two separate combustion zones of the standby (pilot) and main fuel, having an air annular channel with an axial swirler (1), in the blades of which holes are made on both sides to supply the main fuel gas (2). At the inlet of the swirl, a turbulence stimulator (3) is located to reduce the influence of unevenness of the input velocity field. The main fuel is fed into the mixing chamber (4), where a homogeneous fuel assembly is prepared in a turbulent swirling flow.

![Figure 3. Unified double-circuit low-emission burner](image)

4. Algorithm for fuel operating of the modernized low-emission combustion chamber of the GTU LGT-010

During the development of the fuel consumption control algorithm in the modernized low-emission combustion chamber, the authors used the experience of developing an automatic combustion chamber control system for aircraft and converted engines of the NK family as well as the data of testing the fuel supply system of the GTU LGT-010. The control program used in the GTU LGT-010 provides for the supply of fuel to the standby (pilot) and main combustion zones using a three-circuit fuel supply. Figure 4 shows the dependence of the maximum allowed fuel consumption (Gt) on power, taken as a first approximation as the basis of the fuel dosage algorithm along the contours. Control of the gas turbine operation is carried out by limiting the turbine entry temperature (TET) according to the correlation dependence on the temperature of the gases in front of the free power turbine.
Figure 4. The dependence of the maximum fuel consumption on power in the regenerative mode GTU LGT-010

Figure 5 shows the dependence of the maximum total fuel consumption (standby and main zone) on the time of rotor spin up when entering idle mode. An algorithm for controlling the supply of fuel to the gas turbine combustion chamber is developed in accordance with this data.

Figure 5. The dependence of the maximum total fuel consumption on the time of the rotor spin when entering idle GTU LGT-010

The automatic combustion chamber control system of the modernized low-emission combustion chamber uses one proportioning unit control stationary (PUCS) with three control valves and one throttle washer that control fuel supply to three circuits: standby (pilot) circuit, main circuit 2a and main circuit 2b. The fuel supply circuit
along the contours is shown in Figure 6. The gas temperature behind the turbine is controlled by thermocouples installed on the turbine housing (behind the last stage of the turbine in the exhaust diffuser).

Figure 6. Fuel circuit diagram:

PUCS1 - proportioning unit control stationary; OG1 - orifice gage collector pilot zone; V1 - control valve collector pilot zone; V2 - control valve collector 2a zone; V3 - control valve collector 2b zone.

To start the gas turbine, a previously tested program with the following fuel supply algorithm was used:

1. During rotor spinning, fuel is supplied to the standby circuit of all burners of each section of the combustion chamber.
2. The low-emission combustion chamber ignition control and gas turbine start-up is controlled by flame control sensors.
3. Upon completion of the start, at the stage of acceleration of the rotor at a rotational speed of about 2350 rpm, the PUCS is turned on. The distribution of fuel along the circuits is carried out by valves.
4. Idle mode operation is performed at the required fuel consumption rate. The fuel is supplied to the main circuit 2b (the main circuit of three burners of each section of the combustion chamber) and the standby (pilot) circuit of all six burners of each section.
5. Furthermore, with a load of about 0.4 from the nominal mode, the circuit 2a is switched on, i.e. the main circuit of all six burners of each section is operating.
6. Operation in the nominal mode is carried out at a maximum fuel consumption rate through the main circuits 2a and 2b and with minimum fuel consumption through the standby (pilot) circuit of the burners of each section.

The joint operation of the valves regulating the dosage of fuel along circuits 2a and 2b is set up according to a special tested program that provides an acceptable level of distribution of combustion temperatures and the minimum possible emissions of NOx and CO during such work.
5. Commissioning tests of the combustion chamber LGT-010 when entering idle mode

The firing up of ignition devices of the GTU LGT-010 was carried out before the start-up and adjustment work (Figure 7). Ignition devices are designed for the initial ignition of fuel-air mixture entering the combustion chamber. According to the principle of their work, the ignition devices of the LGT-010 combustion chamber belong to flare igniters. The ignition device works according to the spark-gas scheme, initially a voltage is applied to the plug, where a powerful spark is formed in the form of an electric arc, after which a fuel-air mixture is supplied to form the ignition process. In front of the ignition device there is a mixer in which fuel formations are formed through fuel gas and air mixing together. For a stable ignition of the ignition device, the necessary air ration \( \alpha \) should be in the range of 0.9 ... 1.2 at the outlet of the ignition device, and the flow rate should provide ignition without extinction at the outlet of the ignition device.

![Figure 7. Ignition device of the combustion chamber of the GTU LGT-010](image)

The fuel-air mixture is supplied to all eight ignition devices through the air-fuel manifold; a fire-retardant device is installed at the entrance to this manifold, which eliminates the possibility of the reverse flame propagating through the manifold to the fuel injection equipment. The fuel injection equipment start line has three fuel supply lines: the first line is used to supply fuel gas to the mixer, the second line is used to supply air to the mixer, on the third line, the finished air-fuel mixture is transferred from the mixer to the distribution collector on the ignition device. In front of the pressure reducing valve on gas line 1, there is a starting shut-off valve designed for pulsed supply of fuel gas to the mixer.

The air-fuel mixture supply to the ignition device was adjusted by installing two throttle washers TW1, TW2 on the first line and one throttle washer TW3 on the second line. During the tests for ignition of the ignition device, the main variable parameters were the following values: diameters of the flow area of the throttles TW1, TW2, TW3, as well as excessive fuel gas pressures and the starting shut-off valve cycle.

In the process of testing ignition of the ignition device, 35 starts were made, as a result of which it was possible to achieve stable ignition of the ignition device with the following parameters: the diameter of the throttle washer TW1 - 2.2 mm, the diameter of the throttle washer TW2 - 3.5 mm, the diameter of the throttle washer TW3 - 12 mm, cycle of the starting shut-off valve \( S = 2 \), i.e. gas supply time -1s and pause time - 1s.

The low-emission combustion chamber ignition and gas turbine engine idling were carried out on the basis of the positive stage of the ignition device ignition. Tests of the combustion chamber of the GTU LGT-010 were carried out under the following atmospheric conditions: ambient temperature \( T_H = 17 \ldots 25 ^\circ C \), ambient pressure \( P_H = 100658 \ldots 101992 \) Pa, humidity \( \varphi = 70 \ldots 85% \). A schematic diagram of the supply of fuel gas to the standby, main 2a and 2b circuits is shown in Figure 8. Ignition was performed at reduced compressor speeds of 2350 rpm. 76-80 kg/h were received on the bypass line of the standby circuit through the throttle washer TW4 with a diameter of 3.6 mm. The fuel gas supply line to the burners of the main circuit 2a was plugged, because of the fact that when entering idle mode, only the standby and the main 2b circuits are used. The valve, mounted on a standby controlled circuit, was fully open. The main 2b circuit opened by 6% at speeds of more than 5100 rpm, and at speeds of about 6100 rpm it opened by no more than 11%.
Figure 8. Schematic diagram of fuel gas supply to the standby and main 2a and 2b circuits:
1 - mass flowmeter; 2 - GS16 fuel gas dispenser; 3 - throttle washer TW4 bypass line standby circuit;
4 – flow control valve in the standby circuit; 5 - plug in the main 2A circuit; 6 – flow control valve in the main
2b circuit; 7 - shut-off valve on the supply line to the dispenser (2 pcs.)

During the testing the start is carried out in automatic mode. The rotation of the rotor to a frequency of 2350
rpm in the "Ignition" mode is carried out from a thyristor frequency converter (TFC). The “Dry motoring” mode
is used to ventilate the engine’s gas-air duct. After ventilation, the engine is ignited at a speed of 2300-2350 rpm
for 100 seconds, after which a command to turn on the ignition system is issued, valves are opened, fuel gas begins
to flow into the mixer, and, after the formation of air-fuel mixture, it flows into the fuel supply manifold and
ignition devices of each section.

Table 1 shows the parameters of the GTU LGT-010 in idle mode. During the first operation of the gas turbine
in idle mode standby valve is open 100%, the main 2a circuit is closed. At a rotor speed of 2350 rpm, fuel is
supplied to all burners in the standby circuit. Up to a rotation speed of 5045 rpm, the burners work in diffusion
mode, the air ratio of the burners is in the 1.1-2.78 range. Starting from revolutions of 5045 rpm, the 2b circuit
is connected, half of the burners begin to work in homogeneous and diffusion modes, the air ratio of diffusion burners
is in the range of 4-4.5, and burners operating in homogeneous and diffusion modes are in the range of 2.2- 2.5.

Table 1. The parameters of the GTU LGT-010 at idle mode

| Rotational rate, rpm | Total fuel consumption GtΣ, kg/h | Bypass of standby circuit, kg/h | Dispenser G0Σ, kg/h | Valve of standby circuit, kg/h | Valve of 2b, kg/h | Airflow rate, kg/s | % opening of the PUСS | % opening of the valve of 2b |
|---------------------|-------------------------------|-------------------------------|-------------------|-------------------|-----------------|-----------------|------------------|--------------------------|
| 2350,00             | 586,00                        | 76                            | 510,00            | 510,00            | 0,00            | 8,12            | 30,00            | -                        |
| 2780,00             | 629,00                        | 76                            | 553,00            | 572,00            | 0,00            | 10,83           | 30,00            | -                        |
| 3037,00             | 663,00                        | 76                            | 587,00            | 587,00            | 0,00            | 12,55           | 30,00            | -                        |
| 3700,00             | 563,00                        | 76                            | 487,00            | 487,00            | 0,00            | 17,74           | 27,00            | -                        |
| 4400,00             | 830,00                        | 76                            | 754,00            | 754,00            | 0,00            | 24,65           | 34,00            | -                        |
| 5045,00             | 955,00                        | 76                            | 879,00            | 879,00            | 0,00            | 32,63           | 38,00            | -                        |
| 5585,00             | 1046,00                       | 76                            | 970,00            | 698,57            | 271,43          | 39,34           | 40,50            | 6,90                     |
| 6000,00             | 1196,00                       | 76                            | 1120,00           | 724,24            | 395,76          | 43,75           | 44,00            | 10,10                    |
The analysis of the first GTU LGT-010 operation in idle mode showed that the ignition of the low-emission combustion chamber sections occurs in a predetermined time range, time corresponds to the required values, the idle mode operating temperature does not exceed 250 °C, when it comes to the temperature unevenness the average value at the outlet of the turbine does not exceed 14 °C. These facts indicate the high quality of the burners and burner devices.

During the commissioning, it was found that due to the gas turbine heating during operation, total fuel consumption is significantly reduced. Figure 9 shows the dependence of the change in fuel consumption on the operating time of the gas turbine, which made it possible to determine the required warm-up time for reaching the stationary mode of the modernized gas turbine, which is 30 minutes.

![Figure 9. The dependence of the change in fuel consumption on the time of operation of the gas turbine at idle mode](image)

### 6. Conclusion

The modernized low-emission combustion chamber, designed by the specialists of JSC “Metallist-Samara” and installed on the GTU LGT-010, showed high-quality operating parameters during commissioning. A feature of the commissioning work is the debugging of the operating process of the combustion chamber directly as part of the gas turbine unit, bypassing the traditional pilot-testing on the rig.

In view of the successful operating of the GTU LGT-010 in idle mode, it can be concluded that the debugging of the workflow as part of the GTU was successful, and that this approach to completing the debugging of the combustion chamber can significantly reduce financial and time costs.

The low-emission combustion chamber development work is continued. The following steps entail testing the output of gas turbine engines in nominal mode with and without regenerative air heater, as well as taking environmental characteristics off of the low-emission combustion chamber fuel supply scheme to ensure the required standards for the emission of harmful substances.
References

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