Development and prospects for the introduction of a low-emission combustion system for ground-based gas turbine engines and gas turbine units

V V Biryuk, I E Vorotyntsev, D D Tyulkin and Yu I Tsybizov
Samara National Research University, 443086, 34, Moskovskoye shosse, Samara, Russia
E-mail: tyulkin.dmitriy@gmail.com

Abstract. Today, more and more “stringent” requirements are established in the world for the emission of harmful substances in the combustion products of gas turbines operated and newly developed, which is why the issue of ensuring environmental safety is relevant. The article presents the basic principles of organizing low-emission fuel combustion based on a generalization of experience in the successful operation of gas turbines of the NK family, which ensured that modern requirements for reliability and environmental safety are met. An example is given of the modernization of the gas turbine combustion chamber in order to reduce the levels of emissions of harmful substances. The experience of introducing into serial production of additive technology for the manufacture of basic elements of low-emission combustion chamber using selective laser melting technology is described.

1. Introduction
Currently, the main direction of improving the combustion chambers of aircraft gas turbine engines (GTE) and ground-based gas turbine units (GTU) is associated with a decrease in the concentration of harmful substances (emission of NOx and CO) in the exhaust gases while ensuring efficiency, reliability and operational efficiency. To meet the needs of gas transportation and energy, aviation derivatives (convertible) gas turbine engines, which have spent their flying resources on the “wing”, but retaining 70 ... 75% of the assemblies and components of the basic gas turbine engine, are widely used [1]. The main trends in the development of convertible gas turbine engines are revealed. This is a reduction in design development and an increase in the creation of various modifications that have proven themselves in the operation of gas turbines. Due to the fact that the main goal of enterprises today is to maximize profits, this approach greatly complicates the task of implementing new developments and introducing high technology. An analysis of the environmental characteristics of operating not imported ground-based gas turbines shows that the overall level of environmental performance does not meet international standards. The main reason for the failure to comply with these standards is due to:
- the absence of complete combustion theory and calculation of the combustion chamber, similar to the method of calculation of impeller machines, resulting in most of the leading design engineering bureau forced to develop its own methodology and experimental base mining combustion;
- the absence of scientific and technical advance on the organization of the workflow of low emission combustion;
the absence of at most enterprises of the full volume of chamber test rigs equipped with the necessary measuring and information-computer complex;

– the absence of centralized cooperation on mining the low emission combustor of GTE and GTU and the desired financing.

As a new breakthrough technology, the concept of creating a low-emission fuel combustion system [2–4], based on the concept of LPP (Lean-premixed and prevaporized) “poor, pre-mixed and vaporized mixture”, is considered. The difficulty of using this concept lies in the fact that a decrease in NOx emission leads to an increase in CO emission and increased pressure pulsations, as well as to difficulties in starting and ensuring stable combustion. In matters of achieving environmental safety and reliability, the most acceptable experience is the development of low-emission combustion based on the results of operation of the NK-38ST, NK-37, NK-36ST engines [4]. At the same time leader working hours low-emission combustion chamber GTU NK-37 (Lida CHP station Republic of Belarus) for 2019 totaled about 32,000 hours.

Key results achieved:

1. The possibility of reducing the emission of NOx <15 ppm and CO <75 ppm in the converted gas turbines unit with high thermodynamic cycle parameters (compression ratio $\pi_k =25$) in the combustion chamber conventional scheme with use and standardized dual-circuit burners.

2. Reducing the emission of NOx to 10-15 ppm was achieved due to design measures that ensured high efficiency of mixing the “lean” mixture with optimal interaction of the standby and main combustion zones, the introduction of cascade connection of burners, automated fuel supply along the circuits using 3 proportioning unit control stationary and the use of a "thick" heat-shielding coating up to 600 microns.

3. Steady burning preformed "poor" well stirred mixture, conditioning:

– high uniformity of the temperature and velocity field at the exit;

– increase in effective efficiency due to the uniformity of the flow at the entrance to the turbine.

Generalization of experience of successful working off effective system of low-emission combustion gas turbine family NK is the foundation of modernization low-emission combustion chamber designs developed, in including, according to the program of import substitution and import independence enterprise's Samara region.

2. Low-Emission Fuel Combustion System

A new approach to the design of the low-emission combustion chamber is the implementation of sustainable “ultra-lean” combustion, which has concentration limits beyond which the existence of a stable process is impossible due to the action of hydrodynamic, acoustic, thermoacoustic, diffusion-thermal and other influences and disturbances. The basis of the low-emission fuel combustion system is the low-emission combustion chamber with a universal dual-circuit burner [5].

The formation of the image of the low-emission combustion chamber under development is subordinated to ensuring the required final results: environmental compatibility; profitability; operational efficiency. For the prototype, a combustion chamber with known characteristics is selected that most closely meets the requirements. The following factors influence the choice of the design of the low-emission combustion chamber:

– the purpose of the gas turbine, the dimension and parameters of the thermodynamic cycle (compression ratio $\pi_k$, combustion chamber inlet temperature $T_i^*$, turbine entry temperature $T_{g^*}$ effective efficiency $\eta_{eff}$);

– type, structural scheme of gas turbines (stationary, as a rule, single-shaft and aircraft derivative – two and three-shaft);

– organization of the air-fuel mixture preparation, burner device, type of fuel, organization of fuel supply and low – emission combustion process control, cooling system;

– acquired experience in the creation and operation (research and technological groundwork), production and experimental base, qualifications of design and technological staffing;

– the required funding and qualified guidance in the design and development of the workflow.
A typical (accepted as the basis) design of the low-emission combustion chamber GTU of the NK family is presented in figure 1. The double-circuit burner (figure 2) forms two separate combustion zones of the standby (pilot) and main fuel and has an air annular channel with an axial swirler, in the blades of which holes are made on both sides to supply the main fuel gas [3,4]. A turbulence stimulator is located at the entrance to the swirl to reduce the influence of nonuniformity of the input velocity field. The main fuel is fed into the mixing chamber, where a homogeneous air-fuel mixture is prepared in a swirling turbulent flow.

Figure 1. Low-emission combustion chamber GTU family NK.

Figure 2. Double-circuit burner of the low-emission combustion chamber: 1 – swirl case; 2 – hollow swirl blades; 3 – central body; 4, 5 – hole fuel supply to the standby zone and the main zone; 6 – holes air supply to the standby zone; 7 – rod; 8 – channel fuel supply of the main zone; 9 – channel fuel supply standby zone; 10 – turbulence stimulator.
2.1. General requirements for the low-emission combustion chamber and the basic principles of low emission combustion

The low-emission combustion chamber should first of all ensure compliance with the target (expected) local and international requirements for the emission of harmful substances from combustion products. A detailed analysis of current general requirements for the low-emission combustion chamber shows that it is mainly necessary to ensure an increase in gas temperature by 200 ... 300 K and an increase in the durability of the flame tube by 3 ... 4 times with a multiple decrease in the proportion of air for wall cooling. Creating a workable low-emission combustion chamber is associated with the successful solution of the following problematic issues:

1. Homogenization and highly efficient mixing of the previously prepared “ultra-poor” mixture with minimal hydraulic resistance – determination of the optimal distribution of fuel in the standby and main combustion zones.
2. Testing the combustion process of the “ultra-poor” mixture at a flame temperature of no higher than 1800K in all possible operating modes.
3. A multi-stage combustion scheme with a short residence time of combustion products in the high temperature zone, including:
   – implementation of measures for the fine fuel management system,
   – variable guide vane regulation and air bypass from the combustion chamber,
   – cascade connection of burners.
4. Ensuring the absence of flame penetration and pressure pulsations, ensuring the stability of combustion in all operating conditions.
5. Development of an effective cooling system for structural elements using heat-protective coatings and new materials.
6. Ensuring reliable start and stable operation.

In the short term, it is planned to use additives of a methane-hydrogen mixture (synthesis gas) to expand the range of stable operation of the low-emission combustion chamber on an “ultra-poor” mixture.

The problem of determining an acceptable geometry, including the number of burner devices or nozzles and the row arrangement of them on the front plate, is being solved. An acceptable distribution of air flow into the combustion zones is determined, for cooling and mixing, with an optimal distribution of fuel in the burner devices with a short residence time in the high temperature zone, with high combustion, low hydraulic losses and the required temperature and velocity field at the combustion chamber exit. Low-emission combustion chamber is required to be fully compatible with a compressor, turbine, and other systems. (The wave principles of the organization of combustion are not considered in the form of a pulsating working process, the basis of which is unsteady thermoacoustic effects of a wave nature, significantly reducing the combustion reaction).

2.2. Solving the problem of "flashback" of the flame, reducing the level of pulsation and mixing quality

According to the available local and international experience [6], one of the most difficult problems in creating low-emission combustion chamber operating on premixed homogeneous mixtures is the “flashback” of the flame into the mixing zone. This problem is the key to creating the low-emission combustion chamber. The “flashback” of the flame can occur in various forms:

– in the form when the flame propagates against the main stream in the boundary layer, where the normal speed of propagation of the flame exceeds the speed of the main stream;
– in the form of flame propagation with a reverse gas flow due to unstable turbulent flow.

It should be noted that a large flame propagation velocity and a short self-ignition delay time can aggravate the solution to the problem of flashback of the flame, especially for gas turbine engines with pressure increase degrees of $\pi_K \geq 30$. According company Pratt and Whitney "flashback" of the flame in any form and auto ignition fuel are excluded in the combustion chamber with propulsive front device by using the air supply in the circulation zone and stabilizers for supplying fuel through a large
number of nozzles or gas turbine burners. Activities has determined to eliminate "flashback" of the flame:
  – maintaining a speed level of at least 100 m/s at the outlet of the mixing volume of the burner;
  – elimination of shear and high currents in the wall region of the flame tube with software in the wall temperature is not above 800 °C.

Measures were also worked out against an increased level of pressure pulsations: stabilization of the recirculation zone closure behind the stabilizer and setting the optimal ratio of gas flow to the standby (pilot) and main combustion zones.

To effective preparation activity fuel ratio and a high quality of mixing include:
  – the fuel supply through the hollow vane swirler burner of normal to the incoming air flow;
  – increased pressure drop on the walls of the flame tube (up to 4 ... 4.5%).

2.3. Testing activities to eliminate conflicting communication emission NOx and CO

Research that made in Russia and in the world, allowed to some extent overcome marked inconsistencies in the formation of CO and NOx, due to considerable complication of construction: air bypass of the combustion chamber, using automated fuel delivery systems, the use of new thermal barrier coatings, providing a constituent hot near-wall region of the flame tube. In this case, 2 tasks should be solved:

1. Working out the required level of emission and at nominal mode.
2. The implementation of the control program, ensuring for low-emission combustion chamber preservation of the optimal air ratio \( \alpha = \alpha_{\text{nom}} = \text{const} \) in transient conditions from 0.5 to the nominal mode.

The specified program is achieved through the introduction and testing of compressor mechanization (bypass valves, variable guide vane); air bypass systems in the combustion chamber; cascade switching on the burners according to the operating modes and the “thin” system of automated fuel supply along the circuits using the proportioning unit control stationary. However, in accordance with the well-known laws of the chemical kinetics of combustion of the air-fuel mixture in the gas phase, in some cases it is not possible to achieve “target” norms, since the possibilities of homogeneous combustion in achieving a sharp decrease in the emission of gas turbine engines and gas turbines are practically exhausted. In the future, the possibility of switching to catalytic combustion and the use of hydrogen additives is considered.

3. Development of a low emission combustion chamber

As a typical example of the environmental safety confronting developers GTU combustion chambers, the joint stock company "Metallist-Samara" implemented modernization of combustion chambers GT-009M engines operated in gas turbine CHP station. The emission level in operation is: NOx more than 42 ppm and the CO over 85 ppm. In this regard, to ensure environmentally perspective 2020 characteristics (emission of NOx to 10 ppm and CO to 75 ppm) for the gas turbine GT-009M developed low-emission combustion systems. Modernized engine was called LGT-010.

The starting material for the modernization is the standard version of the eight sectional combustion chamber of the GT-009M gas turbine unit developed by the Energomash Group of Companies (figure 3).

Gas turbine combustion chamber of the engine GT-009M – sectional, comprises 8 sections, enclosed in a housing (turbine casing). The sections are located at an angle of 18° to the axis of the turbine rotor. The schematic layout of the standard combustion chamber is shown in figure 4.

Each of the eight sections consists of the following basic elements:
  – burner device;
  – combustion liner (flame tube);
  – transition liner (from the combustion liner to the guide vane of the turbine);
  – cross-fire tubes system;
  – casing;
– auxiliary ignition device;
– flame control sensor.

![Figure 3. GTU GT-009M assembly.](image)

![Figure 4. Schematic layout of the combustion chamber GTU GT-009M (One section):](image)

1 – burner device; 2 – combustion liner; 3 – a casing; 4 – transition liner;
5 – flame control sensor; 6 – igniter.

Burner device is seven-burner (figure 5), located on a flange on the outside of the turbine housing. Fuel to the compressor enters through the gas nozzles of the burners 1. Burner device connects to the head part of the flame tube through a piston ring 2, is located in a groove on the outer cylindrical surface of the burner device bottom 3. The ignition of the combustion chamber is carried out by the ignition system through auxiliary ignition device 4 in each section. The control over the operation of the compressor is carried out using sensors for controlling the extinction of the flame SL-90 5 and the temperature of the gases behind the turbine. A separate burner is shown in figure 6.

During the operation of a gas turbine unit under the standard measurement scheme, the following parameters of the compressor are controlled:
– fuel gas consumption;
– air pressure behind the reheater;
– pressure drop gas fuel burner;
– air temperature at the inlet to the combustion chamber;
– gas temperature behind the turbine;
– control of the presence of the flame in the flame tube.

Figure 5. Burner device GTU GT-009M:
1 – Gas nozzles of the burners, 2 – Piston ring, 3 – Burner device bottom, 4 – Auxiliary ignition device, 5 – Sensor for controlling the extinction of the flame.

Figure 6. Separate burner.

The development of a low-emission combustion chamber is carried out using the following proven solutions on engines of the NK family of ground-based applications:
1. The introduction of a unified dual-circuit burner.
2. Implementation of multi-circuit fuel supply and 3-collector supply with an automated fuel supply control system according to a special program.
3. The introduction of a "thick" (up to 600 micrometer) heat-protective coating of the walls of the combustion liner (planned to be introduced when the combustion chamber is refined).

During the modernization of the gas turbine engine GT-009M, the parameters of the low-emission combustion chamber were determined; mathematical model of the combustion chamber is developed. The design calculation of the modernized low-emission combustion chamber is performed. The base of the design calculation is the well-known generalization of the research results of individual phenomena of the combustion process and statistical data of the existing experience in developing such a design [5–6].

The main parameters of the gas turbine unit LGT-010 in nominal mode are presented in table 1.
Table 1. The main parameters of the gas turbine unit LGT-010 in nominal mode

| Name of indicator                                           | Value          |
|-------------------------------------------------------------|----------------|
| Rated power, MWatt                                          | 10.0           |
| Air consumption at the inlet to the combustion chamber, kg/s: |                |
| nominal at \( t_0 = +15 \, ^\circ \mathrm{C} \)             | 44.9           |
| Fuel gas consumption, kg/h, (nm\(^3\)/h)                   | 3049.7 (4564.1) |
| Gas temperature before combustion chamber, \( ^\circ \mathrm{C} \) | 268            |
| Gas pressure before combustion chamber, MPa (kgf/cm\(^2\))  | 0.67 (6.83)    |
| Exhaust gas temperature, \( ^\circ \mathrm{C} \)             | 1039           |
| Air ratio                                                   | 3.1            |
| Combustion efficiency factor                                | 0.995          |
| Losses in the combustion chamber, %                         | 5.8            |

Figures 7–10 summarizes statistics main parameters determining the appearance of constructive GTE combustion chambers. An analysis of the parameters of the designed low-emission combustion chamber in comparison with the indicated generalization results shows that they are in fairly good agreement with the statistics. (The calculated points of the designed combustion chamber in figure 7–10 are indicated by a red rhomb).
The basic constructively features of the modernized combustion chamber – introduction of a front device 6 double-circuit burners 7 instead of regular fuel burners, multi-circuit fuel supply and 3-collector supplying fuel from the automated fuel supply control system for piloted program. When this flame tube structure is in the normal version with reasonable reduced flow and air cooling in the wall of the front portion and the secondary air for mixing. The reduced airflow for cooling the walls of the combustion liner is used to deplete the composition of the fuel assemblies in the burners in order to reduce emissions. The fuel supply scheme in one section is shown in figure 11.

![Fuel circuit diagram: PUCS1 – proportioning unit control stationary; OG1 – orifice gage collector pilot zone; CV1 – control valve collector pilot zone; CV2 – control valve collector 2a zone; CV3 – control valve collector 2b zone.](image)

**Figure 11.** Fuel circuit diagram: PUCS1 – proportioning unit control stationary; OG1 – orifice gage collector pilot zone; CV1 – control valve collector pilot zone; CV2 – control valve collector 2a zone; CV3 – control valve collector 2b zone.

Configured span hydraulic calculation and the calculation process of the combustion liner in combustion chamber LGT-010 at the nominal mode in the software package ANSYS Fluent. Physical flow pattern in the combustion liner, represented in figure 12, shows, in section and on an exit from the burner flow rate values reach 151 m/s, which allows to solve the problem of "flashback" of the flame in the zones combustion. Based on the results of the calculation of the combustion process (figure 13), we can conclude that the temperature level in the wall layer inside the combustion liner, which determines the thermal state of the walls of the combustion liner, does not exceed 1100 K, i.e. below the permissible working wall temperature equal to 850°C, and the radial temperature plot at the exit of the combustion liner is shifted to the center, which favorably affects the temperature state of the guide vane of the turbine.
Figure 12. Speed fields of the section of the combustion liner GTU LGT-010.

Figure 13. Temperature fields of the section of the combustion liner GTU LGT-010.

A general view of the low-emission burner device of a separate section of the modernization low-emission combustion chamber and mounted sections on the turbine housing is shown in figure 14 and 15. In figure 16 shows low-emission burner devices of the GTU LGT-010 manufactured at Joint Stock Company «Metallist-Samara».

Along with low-emission combustion system has been developed and a new efficient technology manufacturing element to design low-emission combustion chamber. Using the experience Samara University and data fabrication turbine blades working SGT-400 and repair burners low-emission combustion chamber GTU SGT-700 and SGT-800 [7,8], developed a new design of double-circuit burner, particularly adapted for fabrication by selective laser melting (SLM) metal powders according to mathematical CAD-models [9].
Figure 14. low emission burner device LGT-010:
1 – Double-circuit gas burner, 2 – Burner device bottom, 3 – Wye connector, 4 – Collector of the standby zone, 5, 6 – Collectors of the main zone 7 – Sensor for controlling the extinction of the flame, 5 – Auxiliary ignition device

Figure 15. Placement of sections of low-emission combustion chamber of GTU LGT-010 on the turbine housing:
1 – Turbine housing, 2 – Burner device.
Figure 16. Manufactured burner devices of the GTU LGT-010.

A traditionally unified double-circuit burner is made using casting and consists of six separate parts, namely: swirler 1, burner body 2, central body 3, washer 4, plug 5 and rod 6 (figure 17). Cast burners are expensive and have a high reject rate due to the complicated design of the swirlers and the system of channels for supplying fuel. Moreover, two welded and six soldered joints are present in the burner design, which complicates the production process and increases the cost of a double-circuit burner. To eliminate these shortcomings, a fundamentally new double-circuit burner design has been developed, adapted for additive production by the method of selective laser melting of metal powders. The burner adapted for the SLS method, in comparison with the traditional design, has the following advantages: reduced nomenclature of parts (burner consists of 3 parts (figure 18): burner body 1, cylinder 2, rod 3), shortened production time, wide range of possibilities for finalizing the burners, which allowed to minimize the number of defective products. The design of the original and modernized burners in comparison are presented in figure 17 and 18.

Figure 17. The initial low - emission dual-circuit burner design:
1 – Swirler, 2 – Burner body, 3 – Central body, 4 – Washer, 5 – Plug, 6 – Rod.
Figure 18. Modernized under the SLM method low – emission dual-circuit burner design:
1 – Burner body, 2 – Cylinder, 3 – Rod.

4. Conclusion
In order to meet modern environmental safety requirements, the possibility of implementing the concept of low-emission combustion during the modernization or manufacture of combustion chambers of ground-based gas turbines by introducing fundamentally new structural elements, an automatic control system and new effective technology for manufacturing structural elements of a low-emission combustion chamber is shown. The introduction of additive manufacturing technologies for the main elements of the combustion chamber can significantly reduce costs, improve quality and reduce production time.

References
[1] Gritsenko E A, Danilechenko V P, Lukachev S V, Reznik V E and Tsybizov Yu I 2004 Conversion of aircraft GTE to ground-based GTU (Samara: Samara Science Center Russian Academy of Sciences)
[2] Gritsenko E A and Tsybizov Yu I 1999 Methodology for creating low-emission combustion chambers of aircraft and convertible engines of the NK family Actual problems of aviation and aerospace systems 2 (8) 16–29
[3] Lavrov V N, Postnikov A M, Tsybizov Yu I, Malchikov G D, Grebnev V V and Morozov A V 2007 Developing of low emission fuel burning system in gas turbine engines Samara: Vestnik of SSAU 2 118–27
[4] Bantikov Yu D, Eliseev Yu S, Lavrov V N, Pchelyakov A A, Fedorchenko D G and Tsybizov Yu I 2013 Results of primary operation of NK-37 engine low emission combustion system Samara: Vestnik of SSAU 3(41) part 2 9–14
[5] Bantikov D.Yu., Vasil’ev V.I., Lavrov V.N., Tsibisov Yu.I., Kustov D.I. and Sharikov B.Yu.
Maloemissionnaya gorelka [Low emission burner]. Patent RF, no. 2442932, 2012. (Publ. 20.02.2012, bull. no. 5)

[6] Postnikov A M 2002 Reduction of nitrogen oxides in the exhaust gases of gas turbines (Samara: Samara Science Center Russian Academy of Sciences) p 287

[7] Andresson O, Brodin H, Graychen A and Navrotskiy V 2017 Developing additive manufacturing technology for burner repair Turbines and Diesels 3 4–11

[8] April 2017 The tests of a Siemens turbine with blades manufactured using additive technologies have been completed Turbines and Diesels turbine-diesel.com/rus/node/4479.

[9] Fedorchenko D G, Tsybizov Yu I, Tyulkin D D, Vorotyntsev I E, Zherelov D A, Dulov A S, Smelov V G, Sotov A V and Agapovichev A V 2020 New manufacturing techniques for a low-emission combustion chamber of a gas turbine plant Samara: Vestnik of Samara University. Aerospace engineering, technology and engineering 19 118–26