

# DEVELOPMENT OF BREAKTHROUGH TECHNOLOGIES FOR CREATING NODES AND DETAILS FROM CERAMIC AND POLYMER COMPOSITE MATERIALS FOR SMALL-SIZED AIRCRAFT ENGINES

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## ABSTRACT

Within the framework of the approaches described in Central Institute of Aviation Motors by P.I. Baranov (CIAM), work has been carried out on the development of design and technological solutions to ensure the creation of parts of engine from composite materials with their design and experimental studies that allow the development of up to technological readiness level 6 (TRL). Such details are:

- impeller of high-pressure turbine made of ceramic matrix composite (CMC);
- nozzle apparatus made of dispersed-hardened ceramic materials [1] and a flame tube made of ceramic matrix composites [2];
- impeller of centrifugal compressor from high-temperature polymer composites [4];
- impeller of lower pressure made of carbon fiber reinforced plastic and dispersed hardened Al-SiC;
- ceramic and hybrid bearings with rolling elements of dispersed hardened ceramic materials.

Research shows:

- The technological possibility of creating composite structures from super hard, dispersed-simplified diamond powder of silicon carbide, ensuring its compatibility with the reciprocal metal components of the turbine;
- Test results and technological solutions of flame tube made of CMC reinforced carbon fiber.

## 1 INTRODUCTION

Mastering in the engine building of new composite materials is economically expedient way in which at first they are introduced into small-sized and short-resource engines. As experience accumulates, basic data on composite materials properties, understanding of their behavior in different operating conditions, the scope of application of composite or ceramic materials expands into auxiliary and power-driven power plants, transport and, finally, civil aviation.

The increase working and economic characteristics of small-sized gas turbine aircraft engines (SSGT) for engines in the near future largely depends on the fact:

- polymer composite materials,
- composite materials on a metal matrix or intermetallic matrix,
- ceramic matrix composite,
- carbon-carbon composite materials with coatings;

The objectives of the work were:

- Development of constructive and breakthrough technologies for the creation of SSGT with detailed and components from domestic composite materials (polymer composite materials, composites on metal and / or intermetallic matrix, ceramic composite materials, carbon-carbon composite materials).

- Decrease in weight and content of elements by 40% or more, raising the gas temperature in front of the turbine by 20-25%, improving environmental performance and other technical and economic indicators;

- Tests and demonstration of the performance of engine components from ceramic and composite materials by means of details development and experimental studies of parts in the operating mode of the engine;

- Creation of prototypes of rotor and stator engine elements from ceramic and polymer composite materials;
- Creation of a scientific and technical background on the use of composite and / or ceramic materials in engine designs for various purposes.

New design solutions and breakthrough technologies for the use of ceramic and composite materials with the realization of their characteristics in engine designs have been developed. Experimental studies of both samples and experimental details and assemblies from new ceramic and composite materials have been carried out. Information has been obtained on the physicomechanical properties of new ceramic and composite materials at normal and high temperatures associated with the use of these materials in promising SSGT. The models of stator and rotor (Fig. 1) units of SSGT with ceramic and polymer composite materials are manufactured and assembled.



Fig. 1 - Stator unit with a flame tube and nozzle apparatus made of ceramic material and rotary assembly with low-pressure, high-pressure impellers and composite turbines.

In particular, the manufacturing technology has been worked out, the elements of SSGT have been manufactured and tested:

- Nozzle apparatus made from a dispersed-hardened ceramic material with diamond particles [1];
- A flame tube made of ceramic composite material  $C_f/SiC$  [2].

## 2 DESIGN AND TECHNOLOGICAL SOLUTIONS

### 2.1 Development of design and technological solutions of nozzle apparatus from ceramic material

Silicon carbide ceramics, both sintered (SiC) and reaction-bonded (Si / SiC), have low density, good mechanical properties, high hardness and wear resistance, low thermal coefficient of linear expansion, and air-resistance at high temperatures. This combination of the properties of silicon carbide ceramics also provides them with significant advantages in terms of specific mechanical characteristics and determines their prospects for use in gas turbine engines.

Further improvement in the properties of SiC ceramics proceeds along the path of their reinforcement, for example, filamentary crystals and continuous fibers [4], but an analysis of the aggregate of SiC ceramics and other materials shows that the SiC ceramic is diamond in the form of a finely dispersed powder. The latter has excellent mechanical and thermal properties, markedly superior to silicon carbide.

The diamond / SiC material developed by JSC "CNIM" has high thermal conductivity, low specific gravity, high elastic modulus at normal temperature [1], [2], [4]. Despite the fact that the diamond raw material is not susceptible to chemical attack, the diamond / SiC material is stable at high temperatures. In Fig. 2 is a graph of the strength changes in the evaluation of diamond / SiC materials on a three-point bend.

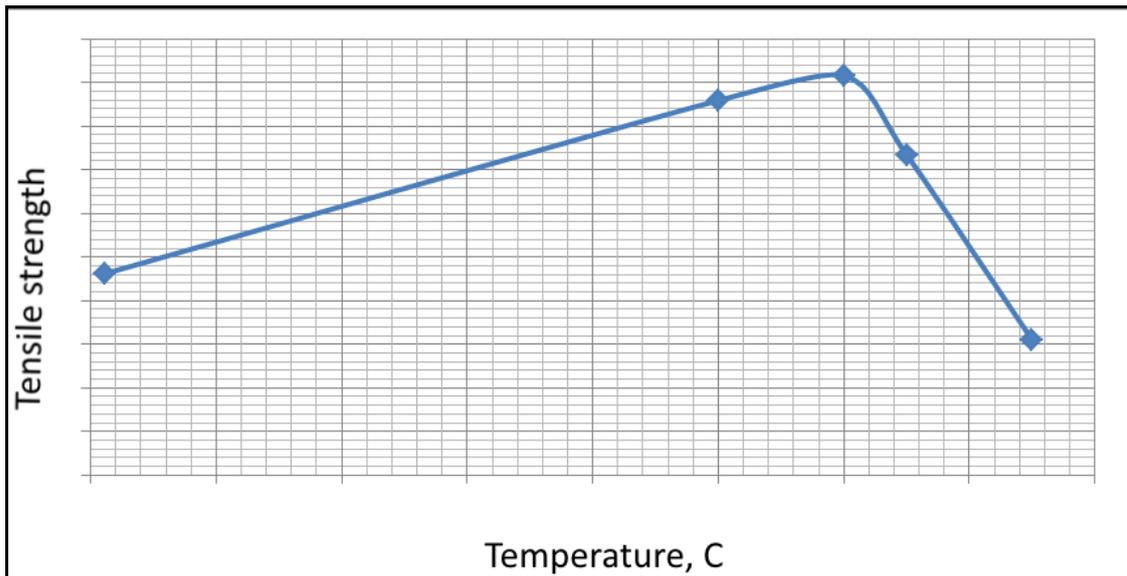


Figure 2: Graph of change in strength of diamond / SiC material as a function of temperature.

When developing a nozzle device from a ceramic composite material, diamond / SiC, it is necessary to take into account the brittleness and high modulus of elasticity of the material, these data primarily affect the dimension of the elements of the nozzle, which must be produced taking into account the scale factor. In general, manufacturers carry out a composite, rather than a monolithic nozzle design, taking into account technological, constructive factors and, above all, the stress-strain state of the structure.

To create a composite nozzle design from the CMC, a high precision of manufacturing elements and careful assembly are necessary.

In CIAM, with respect to a small-sized gas turbine engine (SSGT), a non-metallic SA design was developed, consisting of 19 segments of a diamond / SiC material (Fig. 3). Each segment is made from the bottom and top shelf, as well as blades of sintered ceramic material [1].

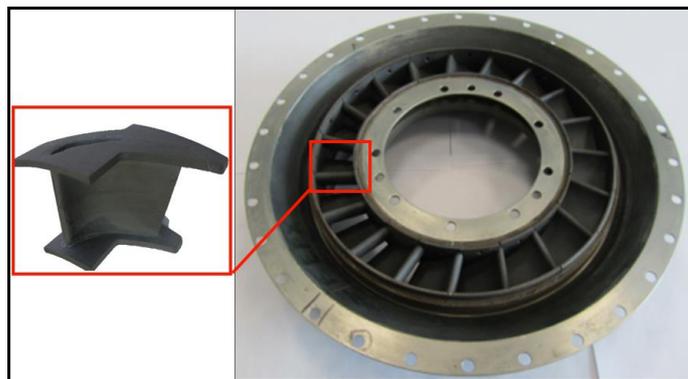


Figure 3: The developed and manufactured segment of the modified structure nozzle.

The key technology of the completed nozzle design of the modified design was the diffusion welding (sintering) of the shelves and blades, which makes it possible to manufacture the segment nozzle. Shelves are made with allowance, in which a special solder paste is pressed into the special segment for the manufacture of the nozzle segment. After high-temperature processing, the shelves with the blade form an inseparable connection with the strength properties of the seam, comparable to the strength of the base material (Fig. 4).

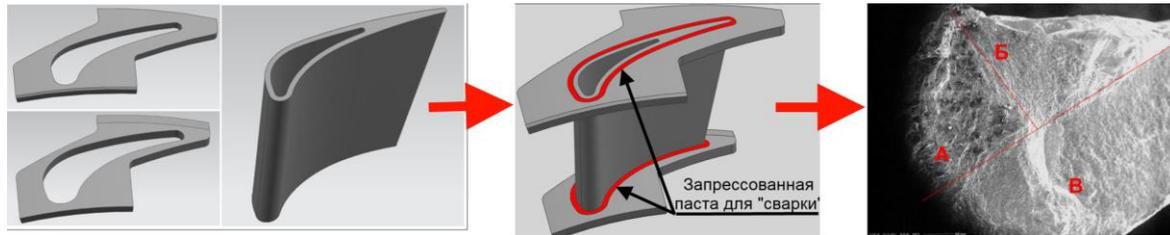


Figure 4: Sintering of finished elements for the manufacture of segment nozzle.

Application of this technology allows the development of nozzle segments with 2 and a large number of blades in one segment. In Fig. 5 shows the advanced nozzle for engine of three blades. Experienced nozzle of CMC is made in the dimensions of the engine and is prepared for preliminary tests on the propulsion stand.

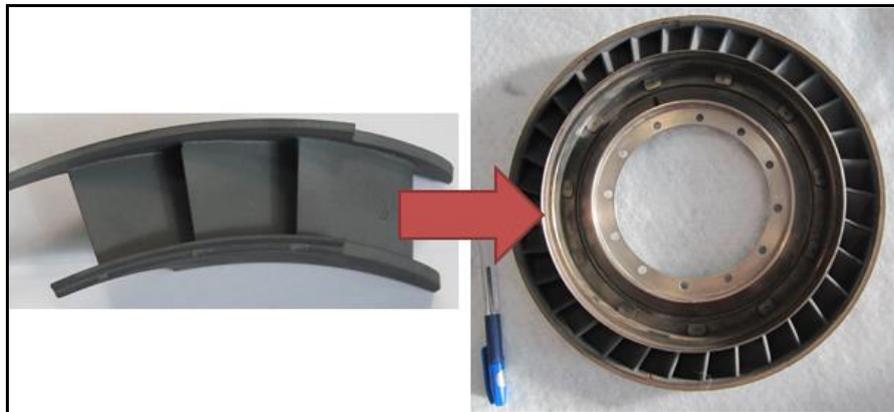


Figure 5: Experienced nozzle from CMC with segments of three blades.

One of the key problems is the problem of connecting nozzle segments from CMC with low thermal coefficient of linear expansion and retarded metal parts with high thermal coefficient of linear expansion

The joining of segments is mainly carried out through elastic elements in the form of elastic rings, springs, staples, special conical surfaces, using a dovetail attachment type, etc. The CIAM has developed and implemented a scheme for securing nozzle segments through a damping layer of high-temperature compliant material between ceramics and metal, which makes it possible to compensate for the thermal expansion of the metal [1].

High characteristics of thermal conductivity allow us to ensure in the elements of the designed nozzle a low level of temperature stresses, which is necessary to ensure its durability. Compared with the metal analog, the mass is reduced by 35% and there is no need to cool the nozzle.

## 2.2 Development of design and technological solutions of flame tube from CMC

To develop a nonmetallic flame tube in the CIAM, it is made:

- designing of details from ceramic composite materials (CMC);
- development of an experimental technology for manufacturing the preform of a flame tube before high-temperature heat treatment;
- high-temperature tests of the construction of a flame tube from the CMC.

The developed ceramic composite materials of ceramic-forming polymers and carbon fibers combines: low density with high mechanical strength, heat resistance, the possibility of obtaining large-sized products of complex shape and can work in a fuel combustion environment [2].

The accumulated joint experience in Russian research institutes allows the production of laboratory and experimental samples of experimental products from the CMC and the results obtained allow us to develop and produce a flame tube.

In the design of the flame tube from the CMC, all the openings on the inner and outer shells available on the metal prototype for storing air into the combustion zone and the aerodynamic profile are retained. The material of the flame tube does not require cooling, therefore, the belt does not have cooling air inlet belts. Thus, with the absence of holes and elements, the design of the flame tube from the CMC is much simpler and the number of technological operations is reduced, but the thickness of the wall of flame tube is increased from 1 mm to 3 mm for technological and strength parameters.

The design of the flame tube consists of separate elements (Figure 6):

- the front part, Fig. 6 A;
- outer shell, Fig. 6 B;
- the inner shell, Fig. 6 C

Each element was manufactured on a separate technological tool by the method of laying impregnated fabric and a bundle of carbon fibers. After assembly, the preform of the flame tube was subjected to high-temperature processing, after which the preparation of a flame tube made was formed into material, after which a protective coating was applied to the surface (Figure 6 D).

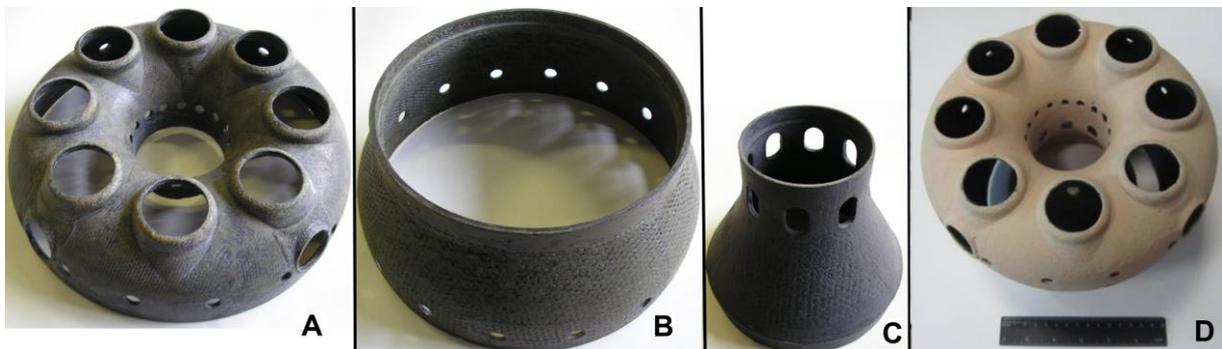


Figure 6: Elements of the flame tube construction from CMC.

### 3 EXPERIMENTAL

#### 3.1 Experimental of the ceramic nozzle

CIAM conducted experimental studies of the segment of the nozzle apparatus with diffusion welding of three blades and shelves for non-uniform local high-temperature heating by gas to a temperature of 1250 °C (Fig. 7). The purpose of the test is to confirm the high heat resistance of the diamond/SiC material, and also to test the strength of the connection of the shelves and blades in the "welding" locations under high-temperature influences.

To control the temperature, a thermocouple was attached to the leading edge of the central vane, which measured the temperature of the gas. In tests to establish the temperature distribution over the surface of the segment of the nozzle apparatus, a multi-transitional thermo-paint was used. Thermo color changes its color when exposed to temperature and allows you to evaluate the temperature levels due to the gradient of colors. This paint has 17 color transitions in the temperature range from 146 °C to 1277 °C.

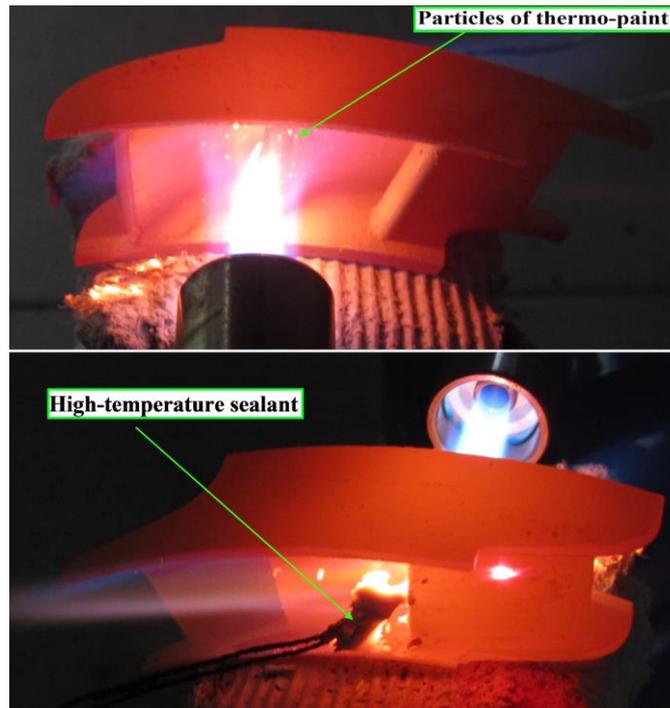


Figure7: High temperature heating of a segment of the nozzle with three blades of diamond/SiC.

### 3.2 Experimental of the flame tube construction from CMC

Experimental studies were carried out on the basis of CIAM on a high-temperature bench. In Fig. 8 shows the design of a test of a flame tube in the open air during the combustion of oxygen and methane.

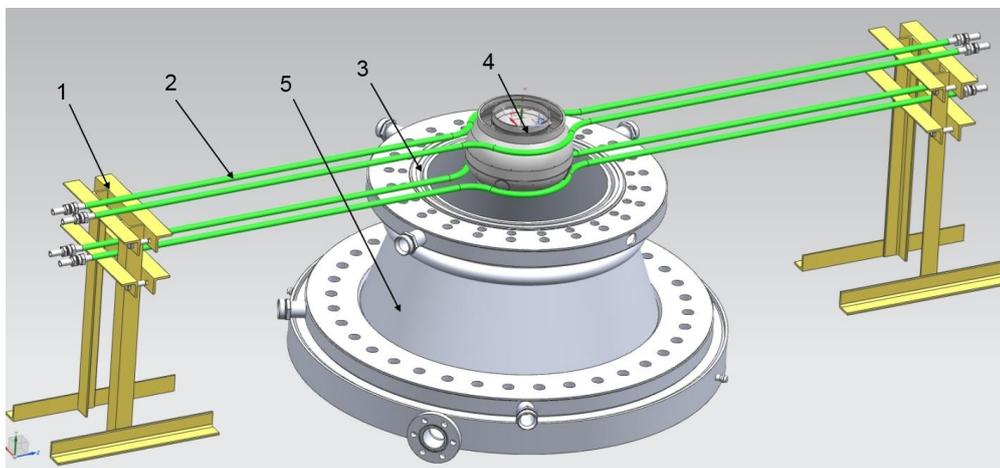


Figure 8: Tests of the flame tube from the CMC

1 - racks, 2 - cooling tubes for fixing the flame tube, 3 - burner nozzle, 4 - experimental object, 5 – burner.

During the tests, the working temperature of the material was 1350 ° C. Temperature control was carried out using a thermocouple No. 2, which was located outside the front of the flame tube. In Fig. 9 shows the flame turbine during (A) and after the tests (B).

The tests were carried out on cyclic regimes. The test time is 60 minutes with the process of start-up, warm-up, operation, purging and primary cooling. The graph of the temperature change with respect to the thermocouples is shown in Fig. 10 that was outside, for ~ 250 seconds of testing failed, it is also possible to see a difference of ~ 180 °C in the temperature outside and inside the wafer pipe

by analyzing the thermocouple No. 4 that was inside the flame tube. After the first stage of the tests, a visual inspection of the flame tube was made, where it was ascertained that there were no visible damages and strong detachments of the coatings.

After the control, the tests were continued with increased oxygen and methane flow rates, at which the maximum possible gas temperature was reached. With a secondary visual inspection, the construction of the flame tube made of CMC was not damaged, except for the partial entrainment of the applied thermal paint.



Figure 9: The flame tube from the CMC during the tests (A) and after (B).

## 4 RESULTS AND DISCUSSION

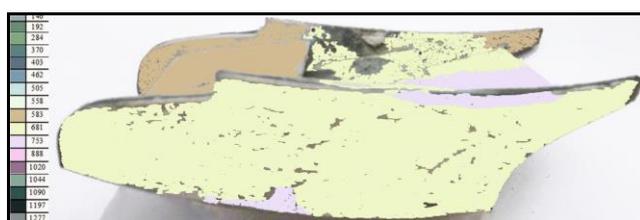
### 4.1 Results and discussion experimental of the ceramic nozzle

At the first stage, the maximum gas temperature was 1140 °C, the average temperature was about 1110 °C. Test time ~ 900 sec. The maximum temperature at the back of the blade was determined from the readings of the pyrometer. It is at a level of 600 °C. The glow of the segment of the scapula is weak. The material of the structure has a high thermal conductivity and heat output to the atmosphere, as a result, at the first stage the material has warmed up to 600 °C.

At the second stage, the maximum gas temperature was 1250 °C, the average temperature was 1200 °. Test time ~ 900 sec. The maximum temperature of the back of the blade, where the main gas flow was directed, is 739 °C according to the pyrometer. Glow of the segment of the scapula is average. The gas consumption in the second stage is maximal. In Fig. 7 shows how the tongues of the flame are clearly rotated by the angle of twist of the blade of the nozzle apparatus.

When testing the segment of the nozzle apparatus at the 2nd stage, one can see a gradual decrease in temperature, which was the result of an increased gas flow and a drop in pressure in the cylinder. It must be said that the tests were conducted in an outdoors room, the ambient temperature was ~ 12 °C.

As a result of the interpretation of the thermo-color readings (Figure 10), it can be seen that the leading edge of the blade, where the gas flow was directed, warmed to a maximum temperature of 754 °C, but the lower shelf of the segment of the nozzle apparatus has a maximum temperature value of 888 °C. This is due to the fact that the segment was installed on a metal pedestal, coated with asbestos cloth and mat, where there was minimal heat exchange of the test material with the atmosphere. As is known, the thermal conductivity of the asbestos material is 0.05-0.07 W / mK. Low heat transfer in this area led to the fact that the lower shelf warmed up to the maximum possible temperature under these conditions.



Top shelf Maximum T = 681 °C



Outlet edges of blades Maximum T = 753 °C

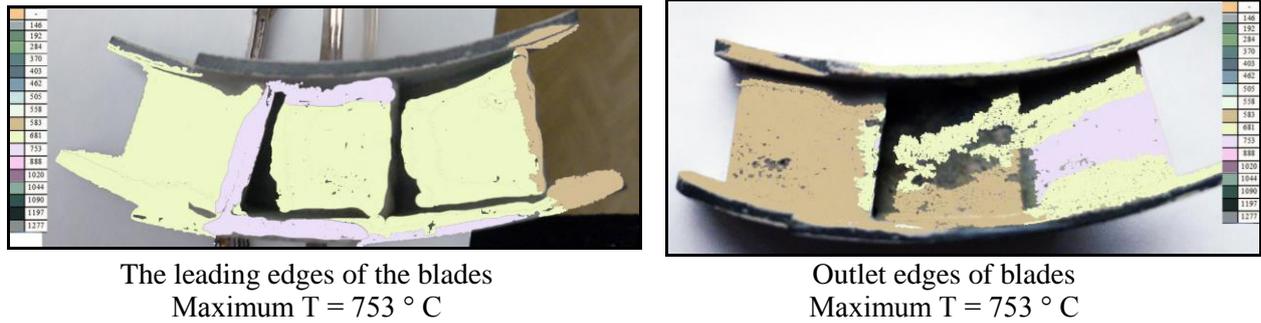


Figure 10: Decoding of the thermo-color after heating the segment of the nozzle.

#### 4.2 Results and discussion experimental of the flame tube construction from CMC

Computer interpretation of the thermo-color readings after the tests is shown in Fig. 11. At the inlet and outlet, the flame tube warmed up according to the indications of the thermal paint from 780 ° C to 1150 ° C, this is due to the uneven fitting of the flame tube to the cooled tubes, so the heating is not uniform. In the center, the flame tube made of ceramic KM warmed up also unevenly. This is due to the fact that the tests were carried out not in the purge channel, but on the flare of an open flame, which did not allow to ensure the uniformity of the temperature field around the flame tube.

As a result of testing the C / SiC flame tube and high-temperature coating, the following conclusions can be drawn:

- 1) The temperature gradients along the thickness of the wall of the flame tube in the tests reached ~ 180 ° C;
- 2) At the first stage of cyclic tests with a maximum gas temperature - no damage, chips and visible cracks;
- 3) During cyclic tests in the second stage at the maximum temperature of the gas, the material warmed based on the thermo-color decoding, as a result of the damage studies there are no except chaotic coating exfoliations, which indicates the expediency of continuing the studies.

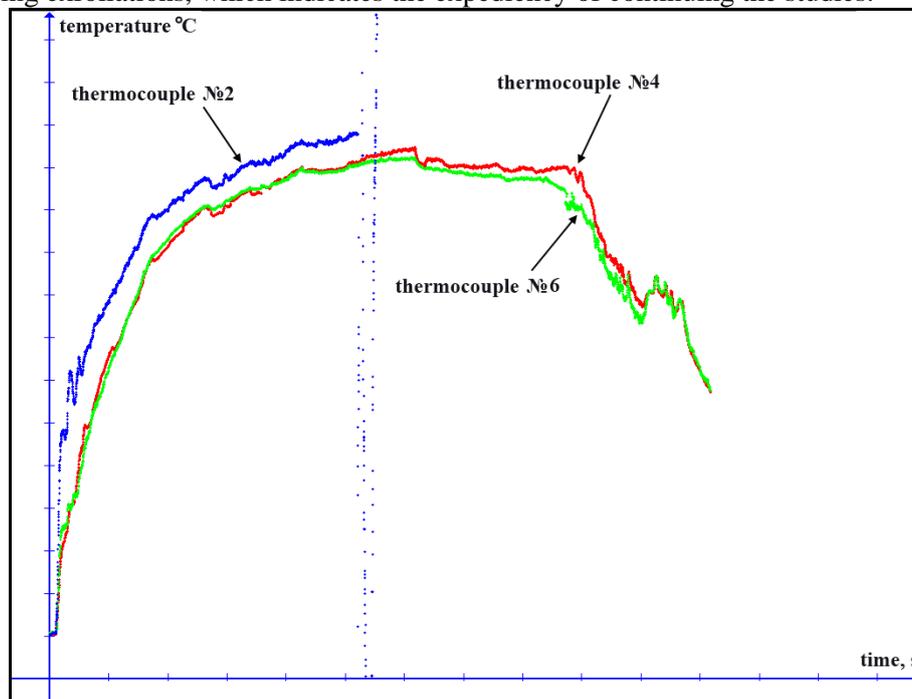


Figure 11: Graph of temperature distribution by two thermocouples during the 1st stage of the test. Y - temperature, x - time sec.

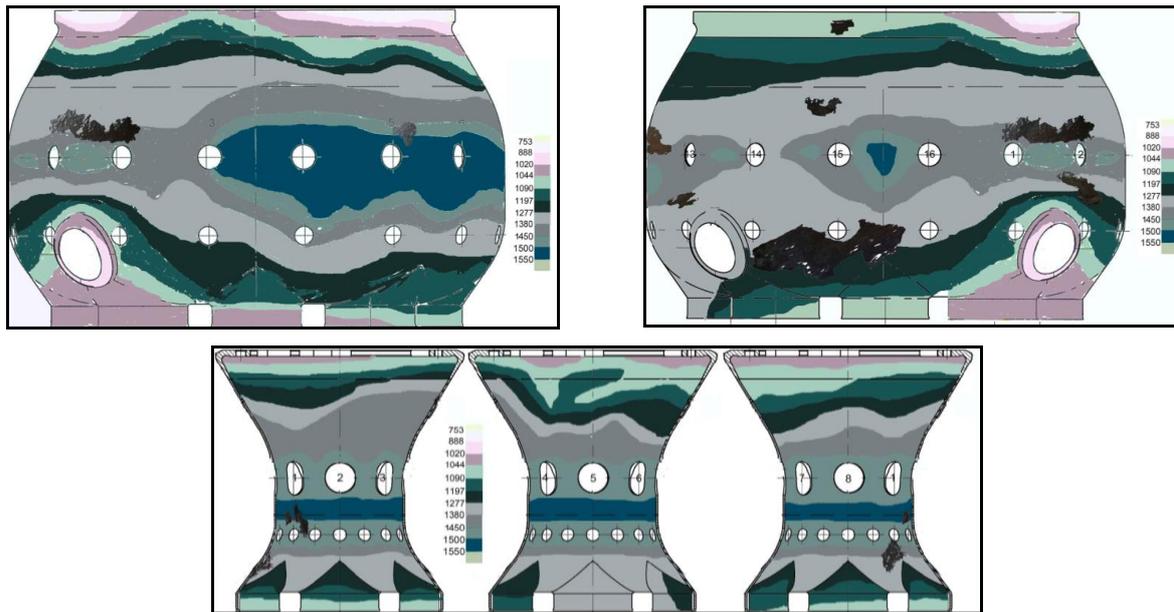


Figure 12: Explanation of the thermal-paint.

## 5 CONCLUSIONS AND OUTLOOK

The weight reduction of the nodes was ~ 49.5% compared to the metal prototypes. The flame tube, nozzle apparatus and turbine, made of ceramic composite materials, can increase the efficiency of the engine by 1.5-2% by cooling and raising the temperature of the gas in front of the turbine. Developed and manufactured assemblies of ceramic and composite materials correspond to world achievements in the field of promising SSGT, and some details do not have foreign analogues.

Developments allow improving the tactical and technical characteristics of SSGT and can be used in various engines.

The results of the work will be used when finalizing the details and assemblies of SSGT from ceramic and composite materials to the VI technological readiness level (TRL), as well as for the development of perspective engines for various applications with wide application of parts and assemblies of ceramic and composite materials [5].

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### REFERENCES

- [1] T.D. Karimbayev, MA Mezentsev - "Ceramic flame tube and nozzle apparatus integrated into the one design of the SSGT", XXXII All-Russian Conference on Science and Technology, 12-14 June 2012 in Miass, Chelyabinsk Region;
- [2] T.D. Karimbaev, S.S. Solntsev et al. – "Quasiplastic high-temperature carbon-ceramic nanocomposites for "hot" parts of aircraft engines", Materials of the III International scientific and technical conference "Avia-engines of the XXI century", 30.11.10-03.12.10, CIAM, Moscow.
- [3] T.D. Karimbayev, M.A. Mezentsev, A.Y. Yezhov - "Technological appearance and experimental studies of the impeller of a centrifugal compressor made of high-temperature polymer composite material", Aviadvigateli XXI century, Moscow, November 24-27, 2015. Collection of abstracts. - m.: CIAM 2015, p. 715;

- [4] T.D. Karimbayev, M.A. Mezentsev, A.Y. Ezhov, S.K. Gordeev, S.B. Korchagina - "Disperse-hardened compositions of diamond-silicon carbide - new materials for mechanical engineering", *Journal of Composites and Nanostructures*, Vol. 7, No. 2, pp. 61-71, 2015.
- [5] M.A. Mezentsev, T.D. Karimbaev - "Constructive and technological appearance of elements of small-size gas turbine engine from composite and ceramic materials", X International Scientific Conference on hydroaviation "Gelendzhik 2014", Gelendzhik, September 5 - 6, 2014;