Investigations of thermal barrier coatings of turbine parts using gas flame heating

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Abstract. The development of methods for the calculated and experimental investigations thermal barrier coatings and thermal state of gas-turbine engine parts with a thermal barrier coatings is actual work. The gas flame heating was demonstrated to be effectively used during investigations of a thermal ceramic barrier coatings and thermal state of such gas-turbine engine parts with a TBC as the cooled turbine blades and vanes and combustion liner components. The gas-flame heating is considered to be preferable when investigating the gas-turbine engine parts with a TBC in the special cases when both the convective and radiant components of thermal flow are of great importance. The small-size rig with gas-flame flow made it possible to conduct the comparison investigations with the purpose of evaluating the efficiency of thermal protection of the ceramic deposited thermal barrier coatings on APS and EB techniques. The developed design-experiment method was introduced in bench tests of turbine blades and combustion liner components of gas turbine engines.

1. Introduction
Progress in gas-turbine engine (GTE) manufacturing is continuously linked with a rise of operating temperature of engine gas path elements, especially the turbine parts. More advanced cooling systems, structural materials and thermal barrier coatings (TBC) and other coatings provide the required life and strength reliability of these components. While engines are in use, the necessity arises to repair turbine blades and vanes with a TBC and combustion liners. At the same time, it is difficult to estimate the durability of the turbine blades and combustor components with a TBC and vanes because of the complexity of simulation of the damaging factors acting under service conditions and also because of problems in obtaining the input data required for making such estimations. Therefore, the development of methods for the calculated and experimental investigations thermal barrier coatings, thermophysical properties of TBC and thermal state engine parts with a TBC is of great importance. While conducting these investigations, the main tasks are the comparative estimation of the design and production (or repair) process solutions and verification of the methods of thermal calculation of the durability of engine parts with a TBC. To provide simulation of loading conditions for the hot engine parts with a TBC under service conditions, the test procedure shall ensure the possibility of cyclic surface heating of the object under testing (simulating its heating in hot gas flow) up to temperatures of 1150 °C and more at heating rates of 150-200 °C/s and subsequent cooling.
2. Ceramic thermal barrier coatings
For the purpose of providing the serviceability of high efficiency aircraft gas turbine engines and gas turbine plants of new generations, it is necessary to improve existing cooling systems, to design new refractory and ceramic high-temperature materials, and to enhance the protection of parts of the high-temperature section of gas turbine engines with the use of heat-resistant and refractory coatings [1-12]. Improvement of the internal heat removal system leads to the transformation of parts into heat exchangers, which is accompanied by an increase in the thermal stress and a decrease in the thermal cycle life. Currently widely used refractory materials based on nickel usually operate in gas turbine engines at maximum allowable temperatures. The gas temperature can be allowed to increase only in the case where care is taken to restrict the passage of heat flow through the wall of the part. The heat flow from the gas to the wall of the base material of the part can be considerably reduced by means of either using a well-organized protective cooling without ejection or depositing thermal barrier coatings on the surface of the most strongly heated regions of the part.

In recent years, works on introduction and practical use of thermal barrier ceramic coatings on parts of a high-temperature system of gas turbine engines have been carried out especially actively. The protection of the material of the part against the heat flux with heat-barrier coatings is most effective when the ceramic coatings used are based on ZrO$_2$ [4-6, 10]. The heat-protective effect of the thermal barrier ceramic coating reaches 100-120 °C under operating conditions. The heat-protective effect – decrease of metal temperature is function of thickness and heat conductivity of a thermal barrier ceramic coatings and thermal flows in a wall of a protected detail. The values of thermal flows on workers turbine GTE blades are in a range from 1.0 up to (2÷2.5)×10$^6$ W/(m·K) in works [3-5]. In some cases the thermal flow makes 3×10$^6$ W/(m·K) and more [6]. In the given work with the use of system ANSYS the calculated investigations of influence of the specified factors on decrease of metal temperature of cooled blades were carried out and the estimations of the heat-protective effect of a thermal barrier ceramic coatings for cooled details have been obtained by Lepeshkin A.R. The results of calculated investigations are presented in figure 1 and figure 2.

![Figure 1](image1.png)

**Figure 1.** Values of decrease of metal temperature $\Delta t$ on a surface of cooled GTE blades depending on thermal flows $q$ at thickness $h = 0.14$ mm of ceramic coatings ZrO$_2$ and different heat conductivity: 1 – 1.5 W/(m·K); 2 – 0.8 W/(m·K)

The values of decrease of metal temperature on a surface of cooled GTE blades depending on The values of decrease of metal temperature on a surface of cooled GTE blades depending on thermal flows at thickness $h = 0.14$ mm of ceramic coatings and different heat conductivity coatings are shown in figure 1. The values of decrease of metal temperature on a surface of cooled GTE blades depending on thickness of ceramic coatings at gas thermal flow $q = 1.8$·10$^6$ W/m$^2$ and different heat conductivity of coatings in figure 2. However, the questions regarding the thermal cyclic fatigue life are very problematic because the fracture strength of these coatings under tension is very low and thermal cycling usually leads to the appearance of alternating thermal stresses. Moreover, during operation of turbine blades, oxygen from an oxidizing medium (air, fuel combustion products) penetrates into the "ceramics-metal" interface.
The penetration of oxygen through the ceramic layer results in the oxidation of the sublayer. The formation of oxides gives rise to additional stresses and decreases the adhesion of the ceramic layer. Therefore, the above factors must be taken into account in the design of coatings. The efficiency of thermal protection of coatings depend not only on the thermophysical properties (figure 1 and figure 2) but also on the technique used for depositing of the coating. Among numerous techniques currently employed for depositing of the coatings, the electron-beam technique provides the best thermal protection.

Development of thermal barrier coatings applied to cooled blades is one of the trends for improving gas turbines. Unlike aluminide protective coatings, the ceramic coatings not only protect blade surfaces from high-temperature oxidation and corrosion but also prevent base material softening at high temperatures. Thermal barrier coating application allows the reduction of the blade temperature and the significant increase in its service life. Under both steady-state and transient conditions, the application of ceramic TBC can diminish temperature gradients over the blade surfaces as well as reduce thermal stresses in them. A typical design of a TBC is presented in figure 3. The ceramic coating deposited directly on the superalloy surface does not show the required service life. Penetration of oxygen through the ceramic layer to the superalloy surface results in its quick oxidation and in spallation of the ceramic layer. That is why, as a rule, a TBC consists of at least two layers.

The outer zirconium oxide/yttrium oxide (ZrO2-Y2O3) system base ceramic layer can be applied by two techniques (figure 4): air plasma spraying of powders (APS-technique) or vapor condensation at electron beam evaporation of ceramic pellets (EB-technique). For this system, ceramic coating service
life depends on Y$_2$O$_3$ content. The ZrO$_2$-(6 to 9%) Y$_2$O$_3$ compositions are usually applied, because they have demonstrated maximum service lives in the tests carried out [7, 9].

For providing the above-indicated heating conditions, there are various ways of heating such as gasdynamic heating and radiant heating, for example, in a reflective furnace electrical current (AC or DC) or induction heating with the use of high-frequency currents. The gasdynamic (flowing hot gas) heating has been used for more than 50 years. When using this method, a more accurate simulation of the heat exchange conditions from gas flow to the part is realized relevant to the gas-turbine engine. The rigs with gasdynamic heating enable a high heating rate to be provided to the part, to investigate the influence of oxidation in gas flow.

![Figure 4. Thermal barrier ceramic coating ZrO$_2$-Y$_2$O$_3$: a - APS-technique, b - EB-technique](image)

3 **Investigations of thermal barrier properties of ceramic coatings using gas-flame heating**

For maintenance of competitiveness of aircraft engines it is necessary to raise a gas temperature over 1700 K in front of the turbine. Thus serviceability of details of a high-temperature gas can keep only at perfection of their heat-protection. Thus the serviceability of details of a high-temperature gas probably keep only at perfection of their heat-protection. It is known, that in world practice the ceramic heat-protective coatings on basis ZrO$_2$ are widely used. At the same time the data on heat conductivity and thermal conductivity and efficiency of a heat-protection of details with help thermal barrier ceramic coatings at their heating in a gas flow are rather limited. The characteristics of heat conductivity thermal barrier ceramic coatings have received at use of various known laboratory methods are inconsistent. Basically the preference is given the thermal barrier ceramic coatings have deposited on a plasma technology. At use of laser pulse heating it has been received that heat conductivity of plasma coatings approximately in 3 times is lower than at the coatings have deposited on the electron beam technology. The laser pulse method is inexpedient to use for determination of the temperature in part transparent ceramic coatings as the part of a beam flow warms up directly a metal on which it is deposited coating. The protective thin metal screen with thickness 10-15 μm deposited by researchers on surface of coating on the side of the laser at heating, itself starts to let out a beam flow. In real conditions the turbine blades and walls of combustion chambers are heated up by a gas flow. In the given work the developed technique by an objective estimation of efficiency of a heat-protective of metal with the help of coatings of plasma and electron beam technology is resulted at gas-flame heating of object on the developed rig. The essence of the given original technique protected by the patent RU will be that through the demountable specimen (collected from two halves) the high-temperature gas flow (figure 5) is passed.
The investigations for evaluating the efficiency of thermal protection of materials of the turbine blades and parts with use TBC (received on electron beam technology and plasma technology) against the convective and radiant components of the high-temperature gas flow were conducted. In this case, it is recommended to conduct the tests at the small-size rig and use the small-size specimens whose surfaces during tests are accessible for inspecting the thermal state both by the contact and contactless methods. This rig in particular is usable effectively for conducting the comparison thermal barrier properties and thermocycles tests of various coatings. The rate of change of the temperature in a thermocycle reaches 100 °C/s. For performing these investigations, a test rig has been developed with gas-flame heating of model specimens. The gas generator is a water electrolysis device equipped with a control system; it provides the variable flammable gas flow. Hydrogen has a high combustion temperature and this fact ensures high-speed heating of the specimens. This test rig has a system for providing enrichment of the flammable gas with different fuels. This makes it possible to attain the required gas composition. While testing, the burner is installed fixed, however the attachment allows its position to be adjusted. The hollow specimen is of an axisymmetrical form. Before the test, the burner is installed in a way ensuring coincidence of the specimen axis with the flame torch axis in the process of heating. While investigating the efficiency of influence of ceramic coating on specimen temperature state, the unit with specimens was fixed. A special specimen construction was developed for these tests. The hollow specimen was cut longitudinally in two equal portions. The ceramic coating under investigation was applied on one half of the specimen, the other half remained uncoated. The thermocouples ∏ by diameter of 0.2 mm weld on an external surface of halfs of a compound specimen (figure 5) and are connected to recording computer system. The half of a specimen is protected from products of combustion by a coating it is warmed up less, than unprotected half. The difference of temperatures Δt of protected wall with coating and unprotected wall characterizes the efficiency and thermal conducting of the thermal barrier coatings. Heat insulating material was placed between them to exclude the influence of heat transfer through the contacting edges of the specimen halves. While heating, temperature was measured on the outer (opposite to flame torch) specimen side. Conditions for heating the inner surfaces of both specimen halves by flame were the same, but with a difference in heat protection efficiency the outer surface of the specimen with a TBC had a lower temperature than the surface without a TBC. The after of lighting of a combustible gas the heating of an internal walls of both halfs of model begins. The difference of temperatures on lateral side grows until the heat transfer from a hot surface of a wall to cold surface is less, than a heat-conducting from an external surface in an environment. At absence of the organized cooling lateral side of a wall the maximal difference of temperatures Δtmax outside of both of halfs corresponds to a gradient of temperatures on TBC under these conditions. In experiment Δtmax it is reached at temperature of a cold wall 600 °C. The results of investigations are presented on figure 6 and figure 7.
The models with ceramic TBC ZrO$_2$ + 8%Y$_2$O$_3$ deposited on plasma technology were made of Ni-alloy. Other models with TBC of columnar structure deposited on electron beam technology were made of other Ni-alloy. Unprotected halves of each model were made of the same material as halves with TBC.

The tests on each model were repeated some times for maintenance of reliability of determination of heat-protective efficiency. At retesting the model was unwrapped about the axis on 180°. The difference of temperatures at repeated measurements did not exceed 10 °C. The maximal temperature on the "cold" side of a wall made 900 °C. The temperature of a gas flow made 1773 K. The experimental investigations have shown that the efficiency of decrease of metal temperature at gas-flame heating after deposited TBC by thickness $\delta = 120 \mu$m on plasma and electron beam technologies make correspondingly $\Delta t_{\text{max}} = 60$-70 °C and $\Delta t_{\text{max}} = 100$-110 °C. By he received results it is possible to estimate the thermal conductivity EB ceramic coatings which on the average in 1.6 times is lower than at APS coatings. Thus the received results of experimental estimation of the thermal conductivity and decrease of wall temperature of heat-resistant materials after deposited TBC of ZrO$_2$ + 8%Y$_2$O$_3$ by thickness about 120 μm show that at gas-flame heating of models the investigated EB coating of columnar structure protects metal is better than the tested APS coating. The developed original method of the experimental determination of thermal conductivity and estimation of efficiency of the thermal protection of details with thermal barrier ceramic coatings at gas flame heating provides the reception of more exact data about thermophysic properties of ceramics under operating conditions of turbine details of aviation engines.
4. Conclusion
The gas flame heating was demonstrated to be effectively used during investigations of a thermal ceramic barrier coatings and thermal state of such gas-turbine engine parts with a TBC as the cooled turbine blades and vanes and combustion liner components. Gas-flame heating is considered to be preferable when investigating the gas-turbine engine parts with a TBC in the special cases when both the convective and radiant components of thermal flow are of great importance. The small-size rig with gas-flame flow made it possible to conduct the comparison investigations with the purpose of evaluating the efficiency of thermal protection of the ceramic deposited thermal barrier coatings on APS and EB techniques. The developed design-experiment method was introduced in bench tests of turbine blades and combustion liner components of gas turbine engines.

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