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NUMERICAL RESEARCH OF FLAME PROPAGATION CONDITIONS IN NARROW CHANNELS USING THE TECHNOLOGY OF THERMAL IMPULSE TREATMENT OF TURBINE BLADES

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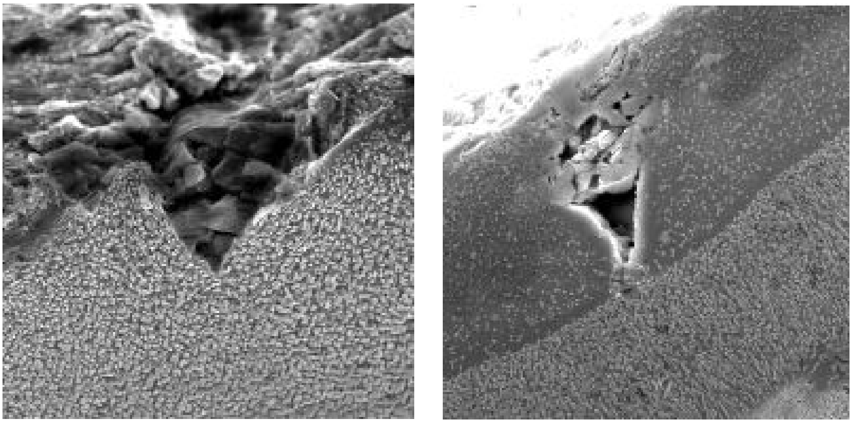
Abstract. The analysis of the main modern trends in the development of views on the issue of cleaning of the cooling channels of turbine blades in gas turbine engines in the process of manufacture and repair at military repair enterprises has been carried out; the usage of the method of thermo impulse treatment with detonating gas mixtures for cleaning of the cooling channels of turbine blades in gas turbine engines is proposed.

Cleaning the cooling channels of turbine blades of modern gas turbine engines is one of the most complex processes in their manufacture and repair. At the manufacturing stage, the cleaning process is necessary to remove microparticles of ceramics and cutting chip that are produced during the formation of the output edges of the cooling.

Key words: weapons and military equipment, aircraft engine, aircraft turbine cooling system.

1. Introduction. In modern conditions of armaments and military equipment development to maintain high combat readiness of aviation units, to ensure constant readiness of military aircraft to perform their tasks on time, timely and high-quality repair of aircraft engines RD-33 and AL-31F MiG-29 and SU-27 aircraft accordingly, it is important. In modern conditions, repair of aircraft gas turbine engines in technical condition is difficult due to the lack of reliable information characterizing the real state of the surface of parts and units in the stages of demolition. This causes the sudden failures associated with the destruction of hot gas turbine engine parts leading to flight events and accounting for approximately 70% of their total.

Cleaning the cooling channels of turbine blades of modern gas turbine engines is one of the most complex processes in their manufacture and repair. At the manufacturing stage, the cleaning process is necessary to remove microparticles of ceramics and cutting chip that are produced during the formation of the output edges of the cooling holes and channels. And at the repair stage – to remove products of high-temperature oxidation and sulfide corrosion Abrasive cleaning of cooling channels in the manufacturing process leads to impregnation of abrasive particles into the surface, which dramatically reduces the quality of protective coatings that are applied (Fig. 1) [1]. The resistance of oxidation products to the effect of acidic and alkaline electrolytes and their high firmness also makes it impossible to use traditional chemical or abrasive methods for their removal [2].



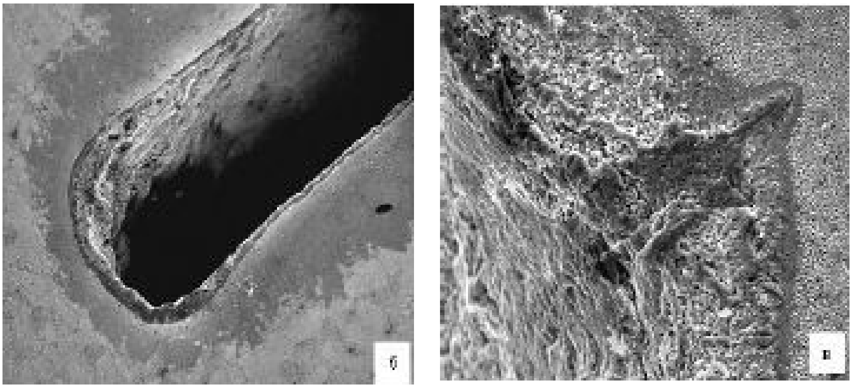
(a) (b)

Fig. 1. Impregnation of the abrasive particles of corundum into the flow channel of single crystal turbine airfoil of GTE with alloy ZhS26-VI and the formation of defects in the protective coating: (a) surface after preventative treatment; (b) surface after applying ion-plasma coatings [1]

Cracks, which arise as a result of thermal fatigue is yet another difficulty during repairment (Fig. (2)). Their characteristic feature is a high density (crack width can be up to 1 μm). Such cracks can hardly be found by means of non-destructive testing, which are used during production. Removal of high-temperature oxidation products from the surfaces of such cracks is rather difficult.

At the present stage, a limited number of methods are used to clean the surface of the cooling channels of turbine blades. These include: fluorocarbon purification method at temperatures from 815°C to 1000°C [3]; reducing heat treatment in hydrogen at temperatures from 1000°C to 1200°C [1]; hydrothermal treatment in concentrated alkaline solutions and thermochemical treatment in the melt of alkali metal fluorides [5].

It is important to note that the common disadvantage of these methods is the processing time and the need for high-tech equipment. It is possible to carry out such repair works with the specified technologies only at the specialized enterprises. In our opinion, one of the possible solutions to this problem of cleaning the cooling channels is the use of thermal impulse treatment with detonating gas mixtures [6].



(a) (b)

Fig. 2. Damage to the surfaces of the single crystal turbine airfoil of GTE with alloy ZhS26-VI during operation: a) oxidation of the inner surface of the cooling channel; b) formation of thermal fatigue cracks in the cooled channel [2]

However, the use of this method is complicated by the fact that the diameter of the cooling channels of the blades, as a rule, is less than the critical value that allows flame propagation [7]. This makes it impossible to use thermal impulse treatment of cooling channels in its traditional version. Therefore, the purpose of this work is to find technological solutions to enhance the capabilities of the thermal impulse cleaning method for its use in military repair facilities. In order to achieve this, during the first stage, we used multiple modeling of the flame propagation process in the channel, taking into account the heat exchange of combustion products with the walls.

2. Problem Formulation. We have considered the results of experimental studies [8, 9] that examined the characteristics of combustion gas in the small tube and used them during our task. Experiments were carried out during work [9] with a U-shaped quartz tube at a wall temperature of about 1000ºC, they have shown the possibility of stable flame propagation in a methane mixture in the channels with a critical diameter.

Therefore, the simulation was tasked to evaluate the possibility of using preheated parts to ensure the spread of flame in the channels with a critical diameter of the mixture pressure, which is typical for thermal impulse treatment. In numerical studies, the diameter of the channel and the temperature of its walls varied.

The model of single-phase multicomponent flow of reacting gases was used for the calculations [10]. The model uses the laws of conservation of mass, momentum and thermal energy, and in order to determine the component composition of the gas – the concentration equation. Neglecting mass forces and considering the inflow of energy only through thermal conductivity, these equations were written in the following form:

$$\frac{\partial \rho}{\partial t} + div(\rho\vec{u}) = 0, \tag{1}$$

$$\rho\frac{d\vec{u}}{dt} = divP, \tag{2}$$

$$\rho\frac{de}{dt} = div(\lambda gradT) + \sum_{i=1}^{N} Q_i - Q_{em} + P\cdot grad\vec{u}, \tag{3}$$

$$\rho\frac{\partial c^i}{\partial t} = -div\vec{I}^i + \dot{S}^i\ , i=1,\ldots,N\text{-}1, \tag{4}$$

where $\rho(\rho^i)$, $p(p^i)$ – stands for the density and pressure of the mixture and its i^{th} component; P– the stress tensor; Q_i– emission (absorption) of heat for all reactions with the formation of the i^{th} component; Q_{em} – volume gas emission; $\vec{I}^i = \rho^i\vec{w}^i$ – the flux vector diffusion; S^i – mass velocity of the formation of the i^{th} component of the mixture; e– is the internal energy of the gas.

In Eq. (3), the last term is a component of two second-rank tensors with two indicestensor [10: $P\cdot grad\vec{u} = -p\cdot div\vec{u} + T\cdot grad\vec{u}$, where T –is the viscous stress

The mass rate of formation of the i^{th} component was determined by summation over all K reactions in which it participated:

$$\dot{S}^i = \sum_{m=1}^{K} m^i(v''_{im} - v'_{im})\omega_m, \tag{5}$$

where ω_m– is the speed of the m^{th} chemical reaction; v''_{im}, v'_{im} - stoichiometric coefficients of the i^{th} component before and after the m^{th} reaction.

In the study of combustion model the finite speed of chemical reactions was used. Arrhenius factors were used to determine the constants of forward and reverse reactions [11]:

$$F_m = A_{m1}T^{\beta_{m1}}\exp\left(-\frac{E_m}{RT}\right), \tag{6}$$

$$B_m = A_{m2}T^{\beta_{m2}}\exp\left(-\frac{E_m}{RT}\right), \tag{7}$$

where A_m, β_m – stands for empirical coefficients; E_m– activation energy.

The value of heat Q_i release/absorption for the i^{th} component is calculated as the sum of reproduction for all elementary reactions with its participation:

$$Q_i = W^i\sum_{m=1}^{K}(v''_{im} - v'_{im})\omega_m. \tag{8}$$

According to the recommendations contained in [12] the mechanism of combustion of methane was used during the simulation, which consists of 52 elementary reactions, which include 19 of the reactants.

Standard mixing rules are used to calculate the density, pressure, enthalpy, and gas constant of a mixture with N^{th} components. The model was closed by the SST equations of the turbulence model [13].

A scalable method of wall functions based on Kader's analytical solution was used to determine the temperature profile in the wall layer [14]:

$$T^+ = \mathrm{Pr}\cdot \tilde{y}^+ \exp(-\Gamma) + \left[2.12\ln(1+\tilde{y}^+) + \beta\right]\exp(-1/\Gamma), \tag{9}$$

where $\beta = \left(3.85\,\mathrm{Pr}^{1/3} - 1.3\right)^2 + 2.12\ln(\mathrm{Pr})$; $\Gamma = \dfrac{0.01(\mathrm{Pr}\cdot\tilde{y}^+)^4}{1+5\,\mathrm{Pr}\cdot\tilde{y}^+}$.

In Eq. (9) the dimensionless temperature calculated as:

$$T^+ = \frac{\rho c_p \tilde{u}_\tau (T_w - T_f)}{q_w}, \tag{10}$$

where T_w– stands for the wall temperature; T_f– temperature of combustion products in the core of the flow; q_w – convective heat flow into the wall; $\tilde{u}_\tau$ – velocity profile in the layer at the wall.

From Eq. (10) the dependence for calculation of convective heat flux is obtained:

$$q_w = \frac{\rho c_p \tilde{u}_\tau}{T^+}(T_w - T_f). \tag{11}$$

In the simulation, taking into account the short duration of the thermo impulse treatment process, the wall temperature was considered as constant. Its value, as already noted, was one of the variable parameters in the problem.

3. Simulation results and discussion. To reduce the computation time, the problem was considered in a symmetric formulation. The propagation of the flame in the chamber of the thermo impulse machine with its subsequent inflow into the channel was simulated. The tetrahedral grid of finite elements was condensed at the place of ignition of the methane-air mixture and in the area of the studied channel (Fig. 3).

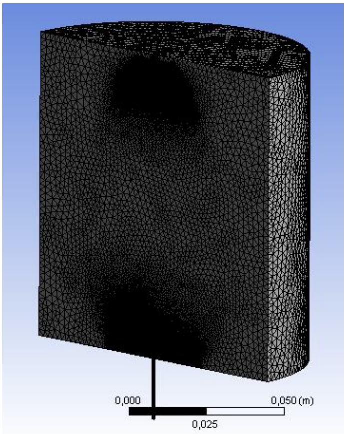


Fig. 3. Finite element model of the camera with the channel of critical diameter

During the simulation, a significant influence of the diameter of the channel and the temperature of its walls on the possibility of flame propagation was determined.

Using Ansys CFX software, the combustion of the stoichiometric methane-air mixture was simulated with an initial pressure of 0.5 MPa at a chamber and channel surface temperature of 300 K, which corresponds to the usual conditions of detonation cleaning during production operations.

The simulation results for this case,

namely the value of the end time of combustion for different values of the diameter of the dead channel, as well as the distribution of the variable progress of the reaction (for channels with a diameter of 3.0; 2.6; 2.2 mm) and temperature (for channels with a diameter of 1.8, 1.4, 1.0 mm) are shown in the Fig. 4.

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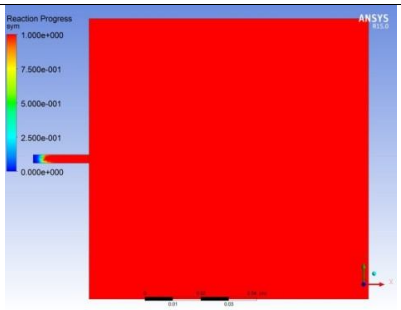
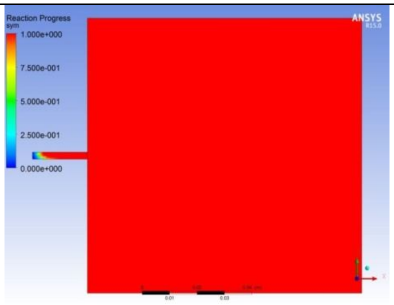
<tr><td colspan="2">
</td><td colspan="2">
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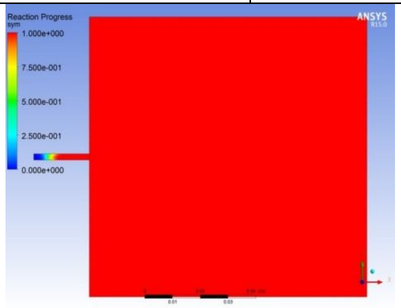
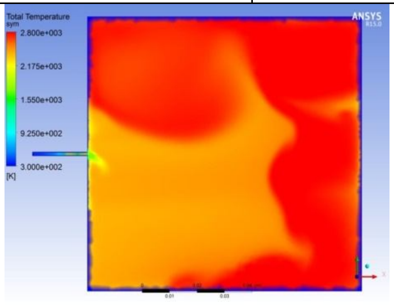
<tr><td>∅ 3 mm, T=300 K</td><td>t = 0,0300275 s</td><td>∅ 2,6 mm, T=335.7 K</td><td>t = 0,035s</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
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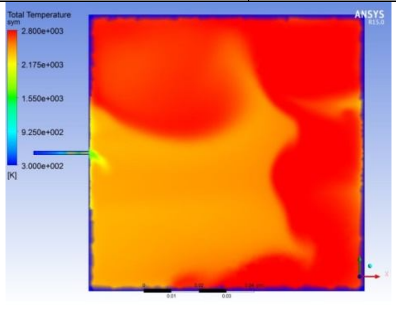
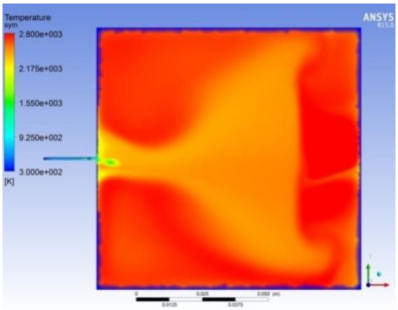
<tr><td>∅ 2,2 mm, T=383.47 K</td><td>t = 0,0300178 s</td><td>∅ 1,8 mm, T=463.85 K</td><td>t = 0,0300461s</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
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<tr><td>∅ 1,4 mm, T=567.6K</td><td>t = 0,0300175 s</td><td>∅ 1,0 mm, T=700 K</td><td>t = 0,0300853 s</td></tr>
</table>

Fig. 4. Influence of the diameter of the dead channel on the completeness of methane mixture combustion

At such wall temperature, thermal impulse treatment of channels with a diameter less than 3 mm is impossible.

The characteristic diameter of the channel of the cooling channels of turbine blades of GTE is 0.5-1 mm, so the influence of the wall temperature on the possibility of flame penetration into the channel was further investigated.

The simulation results showed that for a diameter of 3.0 mm the combustion of the fuel mixture in the channel with a relative length *l* /□= 6 was incomplete. With decreasing diameter, the part of the channel with the unburned mixture increased, and with a diameter of less than 1.5 mm, the combustion of the mixture in the channel almost stopped.

Further modeling was performed with increasing channel surface temperature in the range from 300 to 900 K. This choice of the range of variation of the temperature of the walls of the channel is due to the properties of some materials used for the manufacture of parts of the gas turbine engine.

For example, the temperature of phase transitions in titanium alloys widely used for the manufacture of gas turbine parts is: for alloy VT6 – 950…1000°C; VT3-1 – 920…960°C; VT9 – 910…940°C, and for modern heat-resistant nickel-based alloys used for the manufacture of parts of aviation gas turbine engines exceeds 1200°C (Table 1).

Table 1

Temperatures of phase transformations in foundry heat-resistant nickel alloys, °C

Alloy	$T_{п.р}$ the temp of complete dissolution of the dispersed γ-phase in the matrix γ-solid solution	$T_{эвт}$ melting point of nonequilibrium phases of eutectic origin	$T_с$ solidus temp	$T_л$ liquidus temp	T_{MeC} the temp of the carbides release beginning
ZhS3DK	1186	-	1262	1366	1300
ZhS6K	1230	-	1257	1346	1322
ZhS6U	1234	1249	1276	1360	1324
VZhL12U	1229	1256	1273	1333	1320
VZhL12E	1250	1275	1282	1353	1300
VZhL20	1244	1265	1265	1348	1308
ZhS26	1275	1280	1294	1382	1350
ZhS30	1245	1272	1295	1404	1318
ZhS32	1276	1310	1310	1408	1350

The results of numerical simulations showed that increasing the temperature of the wall of the cylindrical channel to 900 K provides the penetration of flame into the channel with a diameter of less than 0.5 mm.

In Fig. 5 there is a graph of the obtained dependence of the minimum diameter of the channel at which the flame propagation is possible on the temperature of the channel wall. The pressure of the fuel mixture is the same in all cases. The simulation results showed that for the diameters typical for the cooling channels of turbine blades, their temperature should be from 700 K to 900 K. This temperature range is significantly lower than the operating temperatures of fluorocarbon purification processes of the reducing heat treatment in hydrogen and thermochemical treatment in the melt of alkali metal fluorides.

Thus, the results of numerical simulation show that the preheating of the turbine blades of GTE with cooling channels can provide conditions for their thermal pulse cleaning. Further studies of this process should be carried out experimentally, according to the methodology that is determined in the studies [15, 16].

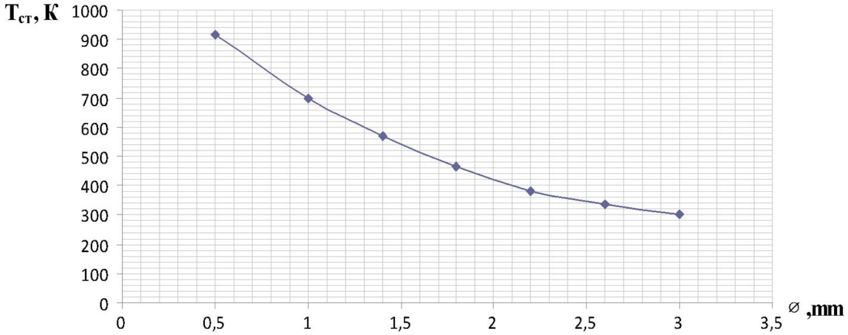

Fig. 5. Dependence of the minimum diameter of the channel to the temperature of the wall for the thermal impulse cleaning

Conclusions. It is shown that the diameter and temperature of the channel wall significantly affect the possibility of flame propagation in it, which is the main condition for the possibility of carrying out the thermo impulse cleaning process.

Based on the numerical study of combustion process with heat exchange with the walls of the channel, it has been shown that for the dimensions of the channel characteristic of the cooling channels of turbine blades of GTE, thermo impulse cleaning is possible when the temperature of parts is from 500°C to 700°C, which is significantly below the operating temperature of the methods used at the present stage for this purpose.

Using the advanced capabilities of thermal pulse cleaning method of the gas turbine engines blades RD-33 and AL-31F of the MiG-29 and Su-27 aircraft during their repair at military repair enterprises will reduce the risk of flight accidents due to the destruction of the components of gas turbine engines.

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ЧИСЕЛЬНЕ ДОСЛІДЖЕННЯ УМОВ ПОШИРЕННЯ ПОЛУМ’Я У ВУЗЬКИХ КАНАЛАХ З ВИКОРИСТАННЯМ ТЕХНОЛОГІЇ ТЕРМІЧНОЇ ІМПУЛЬСНОЇ ОБРОБКИ ЛОПАТОК ТУРБІНИ

Проведено аналіз основних сучасних тенденцій розвитку поглядів на питання очищення каналів охолодження лопаток турбін у газотурбінних двигунах у процесі виготовлення та ремонту на військово-ремонтних підприємствах; запропоновано використання методу термоімпульсної обробки детонуючими газовими сумішами для очищення каналів охолодження лопаток турбін у газотурбінних двигунах.

Очищення каналів охолодження лопаток турбін сучасних газотурбінних двигунів є одним із найскладніших процесів при їх виготовленні та ремонті. На етапі виготовлення необхідний процес очищення для видалення мікрочастинок кераміки та ріжучої стружки, що утворюються при формуванні вихідних кромок охолодження.

Ключові слова: озброєння та військова техніка, авіаційний двигун, система охолодження турбіни літака.

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NUMERICAL RESEARCH OF FLAME PROPAGATION CONDITIONS IN NARROW CHANNELS USING THE TECHNOLOGY OF THERMAL IMPULSE TREATMENT OF TURBINE BLADES

The analysis of the main modern trends in the development of views on the issue of cleaning of the cooling channels of turbine blades in gas turbine engines in the process of manufacture and repair at military repair enterprises has been carried out; the usage of the method of thermo impulse treatment with detonating gas mixtures for cleaning of the cooling channels of turbine blades in gas turbine engines is proposed.

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Проведено аналіз основних сучасних тенденцій розвитку поглядів на проблему очищення каналів охолодження лопаток турбін у газотурбінних двигунах у процесі виготовлення та ремонту на військово-ремонтних підприємствах; запропоновано використання методу термоімпульсної обробки детонуючими газовими сумішами для очищення каналів охолодження лопаток турбін у газотурбінних двигунах.

Рис. 5. Бібліог. 16 назв.

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The analysis of the main modern trends in the development of views on the issue of cleaning of the cooling channels of turbine blades in gas turbine engines in the process of manufacture and repair at military repair enterprises has been carried out; the usage of the method of thermo impulse treatment with detonating gas mixtures for cleaning of the cooling channels of turbine blades in gas turbine engines is proposed.

Fig. 5. Ref. 16

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