Improving the cooling air supply system for the HPT blades of high-temperature GTE

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Abstract

This paper describes the results of studies of the system for supplying cooling air to the HPT of high-temperature aviation bypass GTE. In the cooling cavity of the blade, a dividing partition is installed, which allows cold air to be supplied to the front cooling cavity of the blade, taken out of the high-pressure compressor, and to the rear cavity - air with lower pressure and temperature, taken from the intermediate stage of the compressor. Air cooled by the working blades of a GTE is fed into the tubes of a U-shaped air-to-air heat exchanger blown with air from the outer contour of this GTE. The results of the studies showed that the temperature of the air taken from the compressor in the AtA HE can be reduced by 110 ... 240 °, depending on the geometric dimensions of the tubes and the configuration of the AtA HE. Problems to be solved: minimization of pressure losses in the external circuit of a gas turbine engine, development of methods for constructively increasing the intensity of air temperature reduction in tubular AtA HE and schemes for the optimal supply of this air to the inlet of cooled propeller blades. A tubular row-type AtA HE was designed, with micro heat transfer intensifiers installed on the inner surface of small-sized thin-walled tubes, cylindrical or oval, into which cooled air drawn after the compressor or another, colder, but with lower pressure from its intermediate stage, is supplied. The system of cooling air cut-off, in the channels for supplying the rear cavity of the working blade of the turboprop engine on the cruising mode of GTE operation, implemented in the blades of the turbine rotor with a vortex matrix, is considered. In conclusion, the work presents recommendations on the design methodology of these units in modern and future aviation gas turbine engines.

Keywords: gas turbine engine, high pressure turbine, heat exchanger;

Abbreviations

GTE – gas turbine engine; LPT, HPT – high/low pressure turbine; LPC, HPC – high/low pressure compressor; ND – nozzle diaphragm; RB – rotor blade; AtA HE – Air-to-Air heat exchanger; ALV – auto-lock valve of cooling air; BP/BPR – bypass/bypass ratio; A/B – afterburner;

Introduction

The development trends of modern civil and military aircraft engines are directed along the path of forcing the main operating parameters of the thermodynamic cycle: the degree of increase in air pressure in the compressor π^*_c, air temperature behind the compressor T^*_c and the temperature of the gas in front of the turbine T^*_{gas}. When creating gas turbines for promising gas-turbine engines, one of the main problems is to ensure high efficiency and operational reliability of their thermally loaded parts and assemblies with increased parameters of the operating cycle. Existing practice has shown that the growth rate of the strength characteristics of materials used to manufacture parts of modern turbines does not keep pace with the rate of forcing the parameters of the thermodynamic cycle of a gas turbine engine. Table 1 shows the main parameters of current and future jet engines. From the data of Table 1 it can be seen that the increase in T^*_{gas} in front of the turbine is accompanied by the simultaneous requirement to increase its resource, which is proof of the task relevance of improving its cooling system.

Table 1. Key parameters of modern and perspective jet engines

Generation	III (1965…1975 y.)	IV (1985…1995 y.)	V (2000…2015 y.)	VI (2025…2030 y.)
Construction type	Turbojet engine (A/B)	BP turbofan engine, Turbojet engine A/B	BP turbofan engine, Turbojet engine A/B	BP turbofan engine (A/B)
T^*_{gas}, K	1450	1650	1850…1950	2100…2300
m/ $\pi_{к\Sigma}$	0…2/15…20	2…6/25…35	8…12/35…45	≥ 12≥ /50…60
C_R, (kg/kg*h)	0,70…0,80	0,63…0,65	0,53…0,54	0,44…0,47
Resource (cold/hot part; thousand cycles)	5/…	25/17	40/20	50/25

The main share - up to 70% of the cost of air for cooling the turbine is associated with satisfaction the requirements for reliability and ensuring the required service life of the blades and HPT disk, as the most loaded parts for which the reduction of long-term strength is crucial. Numerical studies of the thermodynamic model of a cooled gas turbine and experimental data from real aviation GTE have shown that at present, every 100 K increases in the value of T^*_{gas} force an additional 2.0…3.3% of the air to be drawn from the compressor for cooling the turbine, which leads to reduced engine performance in general. Consequently, an extremely important and urgent task is to reduce the airflow for cooling the turbine, without which a further increase in the cycle parameters does not significantly improve the efficiency and thrust of the GTE. The creation of efficient cooling and thermal protection systems for components and parts of modern, high-temperature gas turbines are relevant and is one of the most important tasks, which ensures further improvement of modern and future aircraft engines.

The solution to this complex task can be achieved in the following ways:

- lowering the temperature of the cooling air taken from the compressor;
- the use of low-pressure air with less energy for its compression, which contributes to reducing the cost of cooling;
- effective distribution of cooling air through the cooling channels from its place of extraction to the entrance into the cavity of the turbine rotor blade;
- intensification of heat transfer in the cooling system channels;
- reduction of air leakage from the cooling system;
- regulation of air flow for cooling elements of a gas turbine;

1. HPT and its cooling system

The modern airborne system of the aviation jet engines solves a large number of very different tasks. In addition to ensuring the required level of turbine components cooling, it is necessary to ensure the optimum value of the axial force acting on the thrust bearing of the rotor, cooling the main rotor bearings, supercharging the rotor support labyrinth system, in order to prevent oil from being released into the flow part of the jet engine, etc. Therefore, the design of the air system of an aircraft engine should be carried out taking into account the whole complex of factors affecting the efficiency of the engine as a whole [1].

In fig. 1 shows a structural diagram of a modern turbine, in the bypass of which AtA HE is installed with a section of three tubes, in cross section having an in-line configuration.

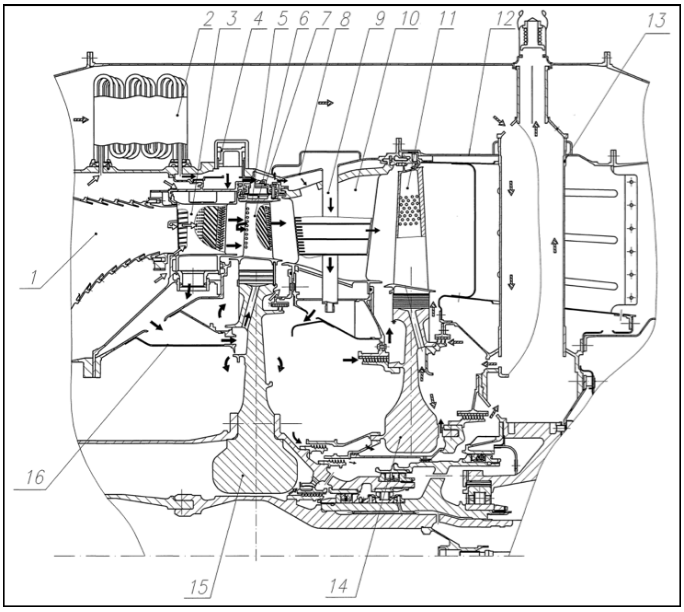


Fig. 1. The composition of the nodes and the scheme of the turbine cooling system of a two-shaft turbofan engine with a small degree of BPR: 1 - a combustion chamber; 2 - cross-current AtA HE with U-shaped tubes; 3 - cooled ND of the HPT; 4 – ALV ; 5 - RB of HPT; 6 - outer ring; 7 - cellular inserts; 8 - rim of the ND; 9 - bypass cooling air into the wheel space cavity; 10 - ND blade of the LPT; 11 – RB of LPT; 12 - the case of a back support of the turbine; 13 - LPT power rack; 14 — LPT disk; 15 – HPT disk; 16 – swirling device.

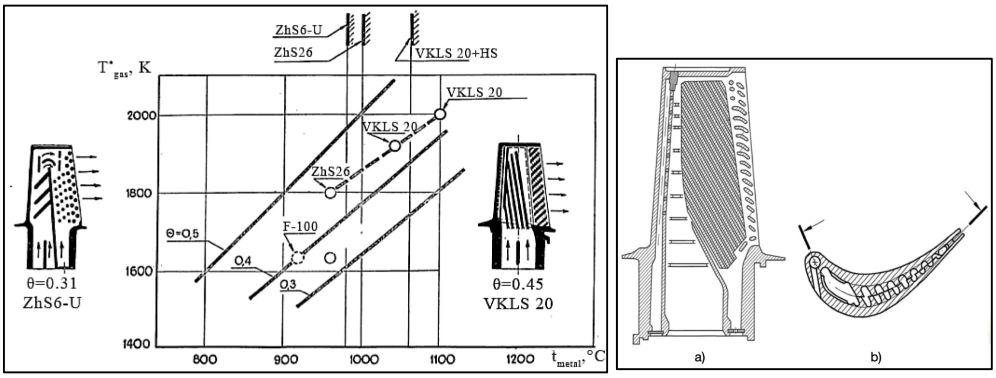
In Fig. 2 a) shows the complex dependence of the change [3] of the cooling intensity of the RB of the HPT on the magnitude of the gas temperature in front of the turbine T^*_{gas} and the magnitude of its cooling intensity:

$$\theta = \frac{T_{gas} - T_{blade}}{T_{gas} - T_{cooling\ air}} \qquad (1)$$

$$\theta = \frac{1700-1165}{1700-710} = 0{,}54 \qquad (2)$$

$$\theta = \frac{1700-1120}{1700-626} = 0{,}54 \qquad (3)$$

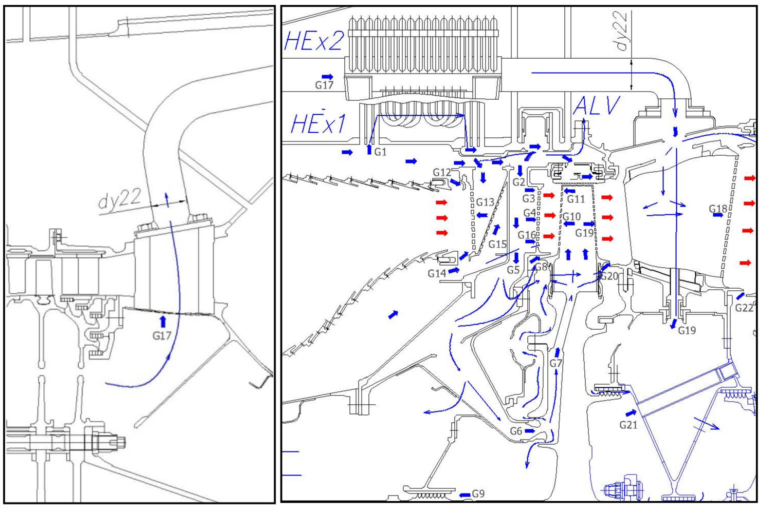
Below, on dependences (2) and (3), for example, the results of two calculations are shown, showing the magnitude of the decrease in temperature of the turbine blade depending on the change in temperature of the cooling air. When the intensity of its cooling is θ = 0.54, a decrease in the cooling air temperature by 84° leads to a decrease in the temperature of the blade wall by 45°, their ratio to:



a) b)

Fig. 2. a) The effect of T^*_{gas} before the HPT, the magnitude of the intensity of cooling and the characteristics of the metal on the temperature of the HPT blade. b) Show a screw-channel RB of a HPT, with cooling intensity is θ = 0.54.

Unlike Fig. 1, in Fig. 3 shows the cooling system of the HPT with AtA HE. In HE1, the cooling air is supplied due to the HPC, then this air G_6 enters through the twisting grate under the covering disk, cools its upper part and, with a temperature increased by 60°, is directed into the internal cavity of the RB.



a) b)

Fig. 3. a) The scheme of selection of cooling air supplied to the disk wheel space of HPT; b) Scheme of the cooling system of the turbofan engine with a RB having a one-sided supply of cooling air. In the blade, under the cover plate, cooling air is supplied due to the pressure build-up. This system includes two AtA HE, where the cooled air taken out from the HPT is supplied to HE1, and the air from the compression cavity is recycled to HE2.

Air G_{17} from the unloading cavity for the HPC is fed to the entrance to the HE2 and then sent to the wheel space cavity.

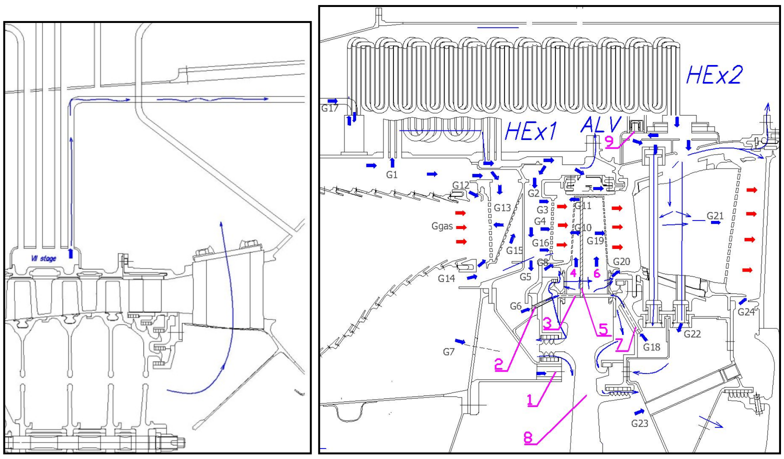
Table 2 shows the results of calculating the values of the flow rates of cooling air, its pressures and temperatures, which characterize the features and efficiency of the consider cooling system. The disadvantage of the studied cooling system is an increase in the temperature of the cooling air due to its low peripheral speed, compared with the diametric size corresponding to the base of the turbine blade, as well as due to its heating from the disk. The level of this increase in temperature corresponds to about half the magnitude of the decrease in its temperature in AtA HE.

Table 2

Local cooling air flow rates (Fig. 4)		G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}	G_{11}
Parameters	G (kg/s)	5,982	5,982	0,67	1,882	2,882	1,976	0,726	1,321	0,132	1,367	0,11
	P (Pa)	39,32	32,05	29,78	30,07	30,95	30,95	29,58	17,68	17,58	21,21	21,21
	T (K)	610	505	505	505	515	515	515	540	455	635	659

Parameters		G_{12}	G_{13}	G_{14}	G_{15}	G_{16}	G_{17}	G_{18}	G_{19}	G_{20}	G_{21}	G_{22}	G_{23}	G_{24}
Parameters	G (kg/s)	1,982	1,53	3,616	2,592	0,652	5,141	3,241	2,59	0,778	1,009	0,353	0,415	0,565
	P (Pa)	39,28	39,12	39,75	34,73	37,93	26,53	20,71	19,28	10,67	9,054	11,36	6,2	5,994
	T (K)	610	615	610	631	617	574	496	568	586	543	511	518	552

In Fig. 4 presents a new cooling scheme for a modernized HPT, also with AtA HE and ALV, which can be used in the designs shown in Fig. 1 and Fig. 3.



a) *b)*

Fig. 4. a) The scheme of selection of the cooling air supplied to the rear cavity of the RB of the HPT; b) Scheme of the cooling system of a HPT with a RB having a radial partition 5, ALV and two AtA HE, where HE1 supplies air drawn from the ALV, and HE2 supplies air with a lower temperature taking of the seventh step of the HPC.

As can be seen from Fig. 4, in this HPT there are two supply of cooling air entering the internal cavity of the working blade: air G_6 is fed into the front cavity 4 of the RB HPT, which enters through the twisting lattice 2, which is located as high as possible; G_{18} air enters the rear cavity 6 through another twisting lattice 7 and this air is cut off at cruising mode of engine operation by means of a ALV installed in the manifold under HE2, in order to save fuel consumption due to a decrease in air supply to cool the turbofan.

For the jet engines with a low BPR, the level of the outer contour of the outer loop with the AtA HE units is of great importance. One of the requirements for AtA HE of promising GTE is the minimum hydraulic resistance $\Delta\sigma_{AtA} = k\cdot\sigma_{II}$, where: $\sigma_{II} = 4 \ldots 6\%$; $\Delta\sigma_{AtA} \leq 2.5\%$. The presence of two AtA HE does not allow to satisfy the requirements. To solve this problem in Fig. 5 shows a cooling scheme for a HPT with one AtA HE in a row configuration, in the U-shaped tubes of which air is cooled, taken out of the seventh stage of the HPC and at the exit from it.

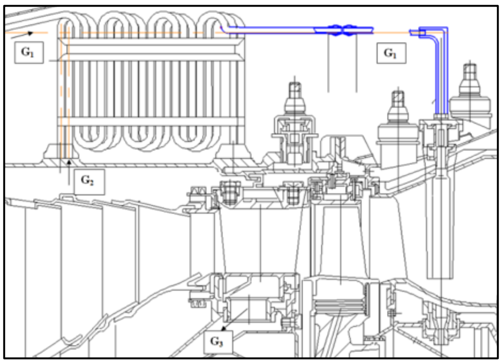


Fig. 5. Constructive scheme with one AtA HE, in which the air is cooled G_1 taken from the intermediate stage and G_2, taken behind the last stage of the HPC.

As is known, the twisting lattice allows to reduce the temperature of the cooling air entering the cavity of the working blades of the HPT. In order to reduce the temperature of the cooling air and create, at the maximum radius of the disk, a shock-free entrance of the root parts of the RB to the interscapulum cavities, cooling air should be supplied to the turbine rotor with a preliminary twist equal to the peripheral rotor speed at this diameter, that is, when $C_{1u} = U$. As a result, an axial inlet $W = C_a$. The decrease in temperature of the cooling air is determined by the formula (4):

$$\Delta T^* = T_c^* - T_{c_a}^* = T + \frac{c^2}{2\frac{k}{k-1}R} - \left(T + \frac{c_a^2}{2\frac{k}{k-1}R}\right) = \frac{u^2}{2\frac{k}{k-1}R} = \frac{u^2}{2010} \qquad (4)$$

where: ΔT^* - a decrease in the temperature of the cooling air; T_c^* - temperature of the cooling air without twisting; $T_{c_a}^*$ - cooling air temperature with a twist; T - static temperature; C - swirling flow rate; k - adiabatic index; R - universal gas constant; C_a - axial speed of the cooling air; u - circumferential speed of the rotor in the place of installation of the twisting lattice;

2. Constructive ways to improve the efficiency of HPT tubular AtA HE.

Consider the features of the choice of design and parameters of AtA HE HPT with different diameter of thin-walled tubes. A known structural scheme and parameters of a tubular AtA HE cross current installed on the body of the combustion chamber in the internal circuit of the jet engines (Fig. 1). In these schemes, there is a cooling air cut-off system on the cruise mode of the engine in order to increase its efficiency. The initial outer diameter of the tubes of the studied AtA HE is 5.0 mm, the wall thickness is 0.3 mm, the number of tubular modules is $N_m = 64$. The number of tubes in one module is six. The total number of tubes is 384, the length of one tube in the sweep is L = 679 mm. All tubular modules are evenly spaced around the circumference on the annular body of the jet engine bypass. Let's present the operational parameters of the AtA HE: for cooled air, inside the tubes - flow rate $G_1 = 6.45$ kg/s, gas inlet pressure $P_{11} = 23 \cdot 10^5$ Pa, gas inlet temperature $T_{11} = 774$ K; in the heated air of the external circuit, the flow rate is $G_2 = 40$ kg/s, the gas pressure at the inlet is $P_{21} = 3.66 \cdot 10^5$ Pa, the gas temperature at the inlet is $T_{21} = 438$ K. In an experimental study of AtA HE in the engine, it was found that the loss of the total pressure of the cooled air, in general, amounted to 8.5%. In the bypass - the total pressure loss from the AtA HE installation was 1.6%. The change in the efficiency of heat exchange of this AtA HE, estimated by the parameter ε, is determined by the initial value of the cooled air temperature decrease $\Delta T_{AtA} = 120°$ and its estimated maximum value, $\Delta T_{maxAtA} = 180°$. Then we get the value of ε equal to:

$$\varepsilon = \frac{\Delta T_{AtA}}{\Delta T_{maxAtA}} = 0{,}67 \qquad (5)$$

To achieve such heat transfer efficiency, we consider the effect of changing two design parameters of this AtA HE, diametric size of the tubes 4.0 ... 6.0 mm and their length - from 0.1 m to 1.2 m, on the reduction level ΔT_{AtA} [4]. Fig. 6 shows the graphs of the dependence ΔT = f (L; d) for cross-flow AtA HE tubes obtained by calculation in the ANSYS CFX system.

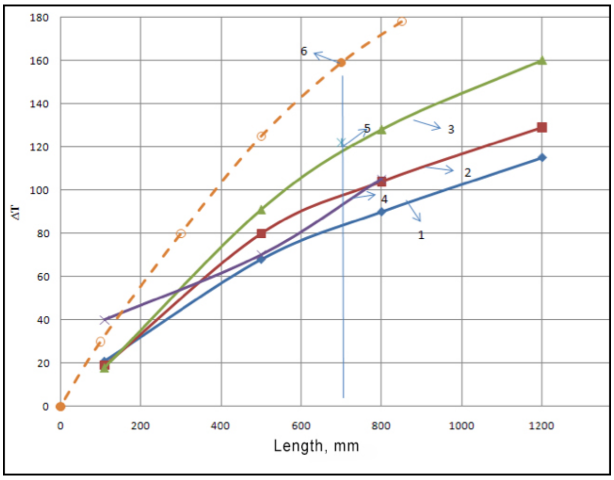


Fig. 6. Calculated graphs of the dependence ΔT = f (L; d) for cross-flow inertial current tubes, calculated in the ANSYS CFX.

In Fig. 6, curves 1, 2, and 3 are smooth straight tubes, distinguished by their outer diameter - 4.0 mm, 5.0 mm, and 6.0 mm, respectively; curve 4 is made with six bends of the tube, a U-shaped tube with a diameter of 6.0 mm, with heat transfer intensifiers installed on the inner smooth surface of these tubes, with projections 0.3 mm high, arranged with a step of 5.0 mm; curves 5 and 6 are U-shaped tubes with six turns, diameter 5.0 mm, smooth and with similar intensifiers of heat exchange on their inner surface. Analysis of the dependences shows that tubes of small diameter heat up faster. However, to reduce the temperature of the same amount of cooled air, the number of tubes of small diameter should be increased, which affects the increase in their mass, slightly increasing, by about 10%.

Fig. 7 a) and b) show the streamlines and the structure of the flow of cooled air in different parts of the U-shaped tubes, when the flow is turned and in straight sections. The protrusions localize the spread of the thickened boundary layer; [4] therefore, the flow velocity adjacent to the cooled tube walls increases, which proportionally affects the increase in the heat exchange rate of this AtA HE.

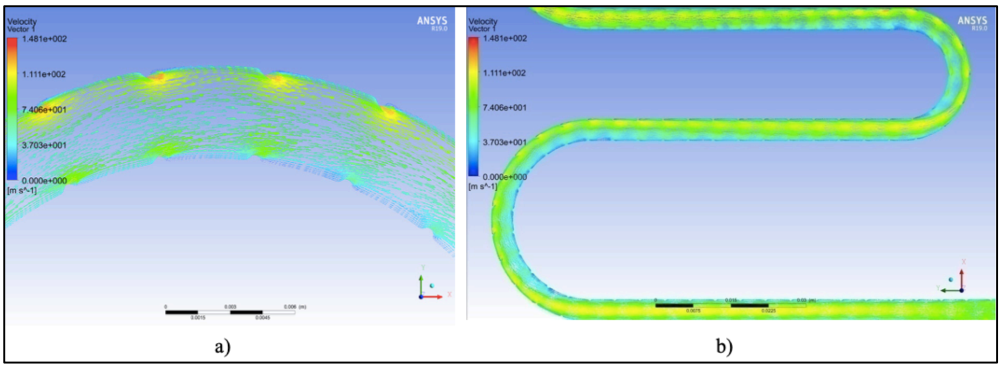


Fig. 7. The structure of the flow of cooled air: a) In the radius of the channel of AtA HE; b) In its two U - shaped cylindrical channels.

3. Conclusion

1. In a bypass jet engine, a tubular inline AtA HE installed in its outer contour must have rows of tubes oriented along the axis of the engine. These tubes can be supplied with cooled air taken from different stages of high-pressure boiler with different temperatures, as well as cooling other elements of the construction of the HPT.
2. The use of heat exchange intensifiers in the form of annular or screw protrusions with a height of not more than 0.3 mm, installed in straight or U-shaped cylindrical tubes with diametric dimensions of 4.0 ... 6.0 mm, allows increasing the cooling rate of hot air flowing through these tubes, about 50 - 60%, and for the investigated lengths of tubes increases $\Delta T_{cooling}$ up to values of 160 - 180°.
3. The loss of pressure of the cooled air in the AtA HE tubes, when using annular heat transfer intensifiers with a height of not more than 0.3 mm, should be no more than 15–20%.

References

1. Nesterenko V.G., Nesterenko V.V., Asadollahi Gokhiekh A. and others. Research and analysis of the efficiency of air cooling systems for blades of high-pressure turbines of gas turbine engines // Aerospace Engineering and Technology. 2014. No. 7. P. 83–93.
2. Design and design of aircraft gas turbine engines: Textbook / Edited by D.V. Hronin.- M .: Mashinostroenie, 1989. - 368 p.
3. Revant Reddy A., Nesterenko V.G. Constructive methods for improving the critical nodes of the cooling system of modern high-temperature theaters of aviation gas turbine engines // Scientific – Technical Bulletin of the Volga region, - 2018 - № 5. - P. 73–77.
4. Kalinin EK. Effective heat exchange surfaces. - M .: Energoatomizdat, 1998. - 408 C.
5. Cengel.Y.A., Ghajar A.J., Heat and Mass Transfer, 5-th edition. Tata McGraw Hill Education Private Limited, 2013.- 902 P.
6. Incropera F. P.,Lavine A.S. and De Witt D. P., Fundamentals of Heat and Mass Transfer, 6-th edition. John Wiley & Sons, 2007.- 997 P.