ENGINEERING TECHNOLOGICAL SYSTEMS

The object of this study is the screen-exhaust device in the TV3-117 engine of the Mi-8MSB-B helicopter.

To reduce visibility in the thermal range, a system of mixing hot engine exhaust gases with ambient air is used; this technique makes it possible to reduce the infrared radiation of engines. For this purpose, a new sample of screen-exhaust device was designed for testing.

A thermal imaging survey of the helicopter was conducted. Three variants of thermal images were acquired: a helicopter without installation of a thermal visibility reduction system, a helicopter with standard exhaust shields installed, and a helicopter with newly developed shield exhaust devices installed. Based on the obtained experimental results, the characteristics of the intensity of infrared radiation were determined for three variants of research in the range of thermal waves of $3–5\ \mu m$. The study uses a comprehensive approach to solving the tasks, which includes a statistical analysis of known and promising ways to protect a helicopter from guided missiles with infrared homing heads based on reduced radiation forces and a theoretical method for calculating flow and temperature fields. The advantages of placing the section of the exhaust channel of the designed screen-exhaust device in the horizontal plane for complete shielding of infrared radiation in the lower hemisphere have been experimentally proven. The benefits of directing the flow of exhaust gases from the screen-exhaust device into the space above the helicopter propeller and dividing this flow into four separate flows were shown. The results of experimental research could be used to design new or improve existing screen-exhaust devices by the developers of military aviation

Keywords: gas turbine engine, screen-exhaust device, thermal visibility, intensity of infrared radiation

DETERMINING INFRARED RADIATION INTENSITY CHARACTERISTICS FOR THE EXHAUST MANIFOLD OF GAS TURBINE ENGINE TB3-117 IN MI-8MSB-B HELICOPTER

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1. Introduction

The development of aviation science and technology, the construction of complex multi-mode aerial vehicles (AV) requires intensive scientific research into the development and construction of both gas turbine engines (GTE) and their individual elements. Increasing requirements for the efficiency of power plants and ensuring a small external resistance during their integration with the airframe led to the need for detailed studies of the output device as one of the most important elements of GTE.

The characteristics of output devices significantly affect GTE operation, the level of thrust, predetermine the thermal visibility and dependence of an aerial vehicle on a possibility being hit by missiles with infrared homing heads. Output devices, as one of the main elements of GTE, perform the following functions:

– provision of noise absorption;

– removal of exhaust gases under the mode of maximum efficiency of their energy use;

– lowering the temperature of exhaust gases;

– discharge of outgoing gases in the desired direction with minimal losses;

– reducing the concentration of harmful emissions into the atmosphere.

Military helicopters perform many different tasks, and the scope of their use is constantly expanding. The history of the development of military equipment shows that any means of armed struggle (including a helicopter) is characterized by three generalized properties: combat power, mobility, and survivability.

The survivability of a helicopter is defined as the ability to perform the assigned task after a single exposure to the means of destruction. The work of specialists is often related to the improvement of the following four elements of the system [1, 2], which affect survivability:

1. Conspicuity – inability to prevent visual, acoustic, or radar detection.

2. Perception – inability to prevent or evade means of damage.

3. Vulnerability – inability to withstand damage.

4. Recoverability – associated with taking into account the long-term impact of various factors after exposure, damage control, fire safety, restoration of functional properties, or in extreme cases, emergency abandonment of the aircraft.

Accordingly, a high level of survivability is ensured by the use of any tactical techniques, procedures, and methods, as well as specialized equipment or its possible combination, which makes it possible to increase the probability of aerial vehicle survival when operating under conditions of enemy resistance.

Portable anti-aerial vehicle missile systems (MANPADs) have become one of the most effective and widespread means of combating aircraft, helicopters, and other aerial objects during hostilities. However, their widespread use for terrorist purposes has greatly aggravated the problem of the safety of civil aircraft and helicopter flights, making it one of the most acute and relevant under current conditions. Therefore, a new and promising area of ensuring the safety of air transport is the design of aerial vehicle protection systems against possible damage by missiles with infrared homing heads.

Scientific research into this area is important. Conducting theoretical and experimental studies of subsonic gas ejectors of various schemes and with various active gas flow parameters is an urgent scientific task. Solving this problem will make it possible to increase the effectiveness of the use of existing and promising aviation equipment when performing combat tasks.

2. Literature review and problem statement

In modern warfare, air superiority is required to dominate air combat. Portable shoulder-based air defense systems, other surface-to-air missiles with infrared (IR) guidance, and air-to-air missiles pose a deadly threat to helicopter survivability [3]. Heat-seeking missiles with infrared detection systems use techniques to acquire and intercept airborne targets by passively detecting the target's IR radiation. The growing importance of infrared signatures and the constant increase in sensitivity of missile detectors in the form of multispectral and multicolor thermal imaging systems have increased the ability to detect infrared guided missiles. These factors indicate the need for detailed research into characteristics of infrared radiation in order to prevent the destruction of modernized and new types of missile weapons with infrared target detection systems.

Summarizing the experience of armed conflicts that have occurred in the world in recent years convincingly shows that the greatest losses of the fleet of aerial vehicle and helicopters were caused by the use of guided missiles. These missiles belong to the «air-to-air» and «ground-to-air» classes, equipped with homing heads [4]. In this regard, the task of protecting aerial vehicle from damage by guided missiles is one of the most important for aviation. The theoretical aspects of detecting (selecting) an object from the surrounding background in the IR range are sufficiently studied. But there is a need for further studies of IR radiation covering the ranges of 1–3 μm, 3–5 μm, and 8–14 μm.

Paper [5] presents a model of the screen-exhaust device (SED), which is integrated into the tail part of the helicopter; mathematical modeling of the thermal radiation of the helicopter using SED was performed. It is shown how the exhaust gases heat the tail part of the helicopter and how this process increases the thermal visibility of the helicopter. However, such a solution cannot be implemented for helicopters of the Mi-8 family due to the design features of this aerial vehicle. Such a feature for Mi-8 and Mi-24 helicopters requires further research.

Thus, IR-guided missiles have become one of the most powerful threats to the survivability of combat helicopters. In paper [6], only a numerical study and analysis of the thermal radiation of the helicopter were carried out. The 1.9–2.9 μm and 3–5 μm ranges are shown to be mainly used to detect hot engine parts, while the rear fuselage emits more heat in the 8–12 μm range. The analysis of the radiation ranges of 2.7 μm, 4.3 μm, 5.5 μm, 6.5 and 15 μm due to the emission of CO_2, CO, and H_2O present in exhaust gases is performed in more detail in [7]. Numerical studies carried out by the authors have scientific value but do not provide an opportunity to obtain reference data that could be used for design calculations of SED for a specific type of helicopter.

With an increase in the speed of direct flight, the ejection coefficient increases and the average temperature of the initial mixed flow decreases, which leads to a decrease in the intensity of infrared radiation. exhaust flow in the range of 3–5 μm [8]. However, the effect of the forward flight speed on the total radiation intensity of the helicopter from SED is not monotonic due to the complex interaction between the forward flow and the washover flow. It is necessary to carry out numerical studies with verification of experimental studies to determine the functional dependence.

Taking into account the effect of solar radiation on the total thermal radiation of the helicopter is reported in [9]. This aspect is very important because the side of the helicopter, the elements of which are heated by solar radiation, has a greater thermal visibility. The study proved that the time of year has an effect on the thermal visibility of the helicopter, on the days of the autumn and spring equinoxes and the summer solstice, the thermal radiation of the helicopter increases by about 7 %, 11 %, and 21 %, respectively. The results of the research were determined by numerical modeling and require experimental confirmation.

Screen-exhaust devices are used to minimize the level of IR radiation of the helicopter engine, thereby increasing its thermal invisibility. The results of numerical modeling are given in [10]. It is shown that masking the hot parts of the engine and reducing the temperature of the visible part of the exhaust pipe by cooling it with air is effective in reducing the thermal visibility of the helicopter. The reduction of the peak temperature of exhaust gases occurs by increasing the mixing of exhaust gases with ambient air. A comparative analysis of the results obtained by the authors with the characteristics of screen-exhaust devices existing in operation was not carried out.

Sources of the infrared signature of a helicopter in flight are given in work [11]; schematic structural solutions of SED used by leading manufacturers of combat helicopters are described. The effectiveness of the use of SED for shielding the heated surfaces of the output devices of the gas turbine has been proven. The results of numerical modeling of gas-dynamic flow and thermal radiation when using SED are represented in a generalized form, which makes it impossible to compare them with known SED designs.

The temperature distribution on the fuselage is regulated by heat transfer between the skin and internal hot elements and between the skin and the external environment. The temperature distribution is affected by many factors, namely: disturbances caused by the rotation of the helicopter blades, radiation from the internal elements of the engines, convection heat exchange between the fuselage and the atmosphere,

solar irradiation of the fuselage. Of particular value are the results of work [12], in which simulations of the zones of impact of aerial vehicle by thermal missiles are given.

The mixing of the exhaust gases reduces the velocity of the flow to the extent that the velocity of the gases becomes too low to escape far from the fuselage of the helicopter. This leads to the formation of hot zones on the rear part of the fuselage [13], and accordingly to an increase in thermal visibility. Research points to the obviousness of the problem but does not provide recommendations for its solution. The solution to the above problem should also be taken into account when designing new structures of SED.

In order to ensure complete thermal invisibility of the infrared system of the release of helicopter exhaust gases, in [14], a project of a model for reducing thermal visibility, a model of protection against infrared radiation based on a secondary ejector is given. But the structure of the above design will not be able to protect the helicopter from being hit by air-to-air missiles when attacking the helicopter from higher altitudes than the helicopter's flight.

Taking into account the experience of previous studies and the current state of thermal visibility of helicopters, there is a task of further improvement of the thermal visibility reduction system. Weapons of defeat by missiles with infrared homing heads are constantly being modernized and improved. As before, the main technique for protecting helicopters from such weapons is the development of means of reducing the level of infrared radiation and reducing the temperature of the outgoing gases. It is necessary to study the mechanisms of the IR signature emitted by a helicopter under different flight modes. This should be taken into account for different types of helicopter designs, and should also take into account their modernization, which may make certain changes to improve the means of protection against thermal visibility.

3. The aim and objectives of the study

The purpose of our work is to experimentally determine the characteristics of the IR radiation of the exhaust manifold of the TV3-117 gas turbine engine in the Mi-8 helicopter using various SED sets. This will make it possible to investigate the thermal visibility of the helicopter in the specified ranges using the developed system of mixing hot engine exhaust gases with ambient air with the newly designed SED.

To achieve the goal, the following tasks must be solved:

– to design a new full-scale sample of SED;

– to investigate the theoretical method of calculating the flow fields and temperature of subsonic gas ejectors of screen-exhaust devices in GTE, to analyze the geometric and gas-dynamic parameters of the ejector mixing chambers;

– to conduct full-scale experimental studies of the designed screen-exhaust device.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the screen-exhaust device in the TV3-117 engine of the Mi-8MSB-B helicopter.

The subject of research is the internal aerodynamics of screen-exhaust devices of gas turbine engines, which determines their efficiency and cooling efficiency of the exhaust jet and hood housing.

The hypothesis of this study was to prove that the SED, fabricated according to the new technology, could lead to a decrease in the thermal visibility of the helicopter. The new structural solutions used in the newly designed screen-exhaust device would outperform standard old SED samples in terms of their parameters.

Assumptions were adopted that additional shielding of SED with ejection-cooled blades could reduce the thermal radiation of the emission zone of the helicopter's exhaust gases mixed with air.

The use of spot welding of metal structural elements without riveting and the use of cheaper heat-resistant structural elements can be considered a simplification of SED design.

4. 2. Experimental model

The exhaust manifold is used on helicopter GTEs to divert exhaust gases in the desired direction, as well as to increase the efficiency of the engine, which is achieved by a certain diffusivity of the exhaust channel. Such a structural solution allows part of the kinetic energy of the exhaust gases to be converted into compression work and increase the pressure drop on the free turbine, and accordingly, the power of the gas turbine.

Under a number of engine operating modes, the gas flow at the entrance to the exhaust channel may have a significant twist. Therefore, the quality of the exhaust manifold, its characteristics, affect the characteristics of the entire engine.

The above-mentioned features of the exhaust manifold were taken into account when designing a new screen-exhaust device.

Fig. 1 shows a new screen-exhaust device for left and right TV3-117 engines of all types installed on Mi-8MSB-B, Mi-8MT, Mi-14, Mi-24 helicopters. The designs of SED for the left and right engines are completely identical, differing only in mirror images of each other.

The principle of operation of this screen-exhaust device is described in [15]. For conducting experimental studies, the SED set was installed on the Mi-8MSB-B helicopter, Fig. 2.
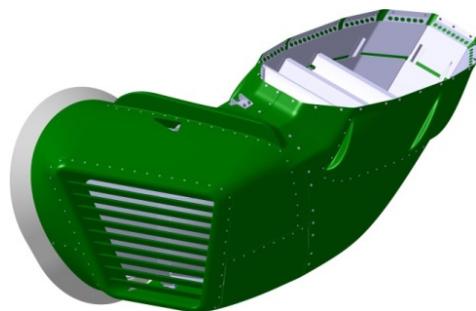

Fig. 1. Screen-exhaust device of a helicopter

Fig. 2. Screen-exhaust device installed on the Mi-8 helicopter for experimental tests

At the stage of flight tests, we experimentally determined the characteristics of IR radiation of the helicopter with a SED kit to assess the degree of reduction in the strength of IR radiation of the engine output devices. The methodology for conducting these studies is given in [16].

The SED kit is designed to reduce the infrared visibility of helicopters equipped with TV3-117 type turboshaft engines of all modifications for Mi-8MSB-V, Mi-8MT, Mi-14, and Mi-24. The designs of the screen-exhaust devices for the right and left engines of the helicopter are completely identical, in a mirror image, they are performed by measuring and constructing a circular indicator of the power of IR radiation. In order to exclude the influence of reflected solar radiation and infrared radiation of the helicopter, the work was performed in cloudy weather in the absence of rain, snow, and fog. There should be no natural or artificial sources of IR radiation (the Sun, powerful electric lamps, heating appliances, etc.) in the direction of the ground-based equipment for measuring the magnitude of the IR radiation within an angle of ±20° vertically and horizontally.

Ground equipment for measuring the magnitude of IR radiation was located at a distance of 300 m from the helicopter.

The indicator of the strength of IR radiation was taken in five positions of the ground equipment for measurement relative to the helicopter:

– at angles of orientation of the helicopter to the ground equipment for acquiring the magnitude of IR radiation force of 30°, 45°, 90°, 135°, 180°;

– in each position, the engine was brought to modes: cruising, maximum duration, take-off.

During the tests, synchronization (time binding) of the data received from the measuring equipment was ensured.

Determining the compliance of the tactical and technical characteristics of the SED set during testing is carried out under the specified conditions of influence of external factors of a natural nature, as well as under the specified modes of operation of the test object.

When conducting tests, the following methods are used to assess the compliance of the SED set with the requirements of TT:

1. At the stage of ground tests:

– calculations – when evaluating changes in the characteristics of the range and flight duration of the helicopter, which are associated with the installation of the SED kit;

– engineering analysis – when assessing the sufficiency of the provided materials, which confirm the strength of the design of the SED experimental set (calculations, references, conclusions);

– evaluation of the technical level of the SED set.

2. At the stage of flight tests:

– experimental determination of traction characteristics of a helicopter with an SED kit to estimate engine power losses;

– experimental determination of the characteristics of the IR radiation of a helicopter with an SED kit to assess the degree of reduction in the power of the IR radiation of the output devices of the engines.

4. 3. Theoretical method for calculating the current and temperature fields

The equations for the flow fields and the temperature of the helicopter are very complex. The external flow around the attack helicopter body resulting from propeller rotation and the internal flow inside the exhaust nozzles from the petal nozzles are computed under a coupled mode to deter-mine the temperature distribution on the helicopter skin and in the exhaust plume. The governing equations include the conservation equations of mass, momentum, and energy, as well as the mass transport and radiation transport equations. These equations will take the following form:

$$\nabla \cdot (\rho v) = 0, \tag{1}$$

$$\rho (v \cdot \nabla) v = -\nabla p + \nabla \cdot \tau, \tag{2}$$

$$\nabla \cdot \left[v(\rho E + p) \right] = \nabla \cdot \left[\lambda_{eff} \nabla T - \sum_j h_j J_j \right], \tag{3}$$

$$\nabla \cdot (\rho v Y_j) = -\nabla \cdot J_j, \tag{4}$$

$$\nabla \cdot \left[L(r,s)s \right] + \alpha L(r,s) = \alpha \frac{\sigma T^4}{\pi}, \tag{5}$$

where ρ is gas density; v is the velocity vector; p – static pressure; τ is the tension tensor; E – total energy; λ_{eff} – effective conductivity ($\lambda_{eff} = \lambda + \lambda_t$); λ is thermal conductivity, λ_t is turbulent thermal conductivity); T – temperature; h_j and Jj represent the enthalpy and diffusion flux for species J, respectively; Yj is the local mass fraction of species j and L; (r, s) – radiation; s is the direction vector; α – absorption coefficient; σ_p is the Stefan-Boltzmann constant.

A significant number of factors affect the maximum flight range of an anti-aircraft missile guided by IR. This maximum range is determined by the formula:

$$D_{THD} = \sqrt{\frac{I_\alpha S_0 \tau_0 \eta_a \tau_a (D)}{m F_n}}, \tag{6}$$

where I_α is the radiation power of the target in the spectral sensitivity range $\lambda_1 - \lambda_2$ of the IR GOS radiation receiver in the direction of the guided missile attacking the target, which is specified by the sighting angle α; S_0 is the working area of the IR GOS lens; τ_0 is the transmission coefficient of the IR optical system of the target radiation in the range of wavelengths $\lambda_1 - \lambda_2$; η_a is the efficiency factor of the image analyzer used in the IR GOS; $\tau_\alpha(D)$ is the transmission coefficient of atmospheric radiation of the target in the range $\lambda_1 - \lambda_2$, which is a function of the distance D between the missile and the target; m is the signal/noise ratio, which is necessary for reliable target detection; F_n is the sensitivity threshold of the IR GOS radiation receiver.

A number of well-known and promising ways of protecting a helicopter from guided missiles with IR GOS are based on reduced radiation force I_α. The power of radiation is proportional to the product:

$$I_\alpha = \varepsilon_i \eta_i k_i S_i T_i^4, \tag{7}$$

where ε_i is the radiation coefficient; η_i is a coefficient that indicates how much of the radiation of the target helicopter belongs to the range of wavelengths $\lambda_1 - \lambda_2$, in which the radiation receiver of the thermal head of the homing missile works; k_i is a coefficient that indicates how much of the radiation of the target helicopter, which is in the range of wavelengths $\lambda_1 - \lambda_2$, is used by the radiation receiver of the thermal homing head of the missile; S_i is the area of the sensitive emitter head; T_i is the temperature of the emitter.

5. Results of the thermal imaging examination of the helicopter

5. 1. Structural construction of the newly designed gas-dynamic circuit of the screen-exhaust device

A new full-scale SED sample was designed (Fig. 3). The rotary gas-dynamic circuit of the SED, through which the exhaust gases of the engine are diverted, structurally consists of the main nodes: receiver (1); the front part of the contour (2); power belts (3, 4); the rear part of the contour (5); seal (6).

All the above nodes are made of sheet heat-resistant stainless steel with a thickness of 0.6...1 mm and are connected to each other by spot welding.
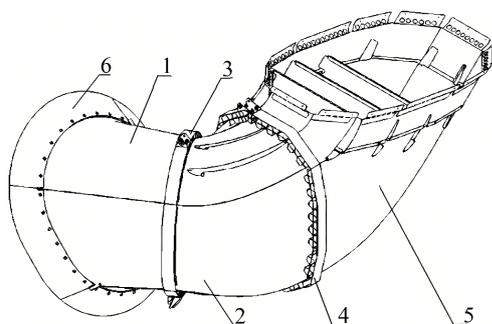
Fig. 3. Rotating gas-dynamic circuit of the screen-exhaust device

A seal made of heat-resistant rubber (6) is bolted to the front edge of the receiver (1). On the power belts (3, 4), brackets for SED suspension are fixed with bolts on the fastening nodes. In the flow part of the gas-dynamic circuit, straightening blades are fixed by welding. The blades are made of sheet heat-resistant stainless steel with a thickness of 0.6...0.8 mm, they have slots for the organization of ejection processes when the engine exhaust gases flow along the circuit.

5. 2. Results of a numerical study of the organization of the gas-dynamic flow in the screen-exhaust device

The theoretical method of calculating the flow fields and temperature of subsonic gas ejectors of screen-exhaust devices in GTE was studied, and the geometric and gas-dynamic parameters of the ejector mixing chambers were analyzed.

The quality of the flow, the absence of secondary flows, the inspection of injection phenomena along the path in the structure of the SED and the nozzles of the engine under the same boundary conditions using the exhaust nozzle were determined.

Fig. 4 shows the current lines in the regular nozzle with the SED attached. The nature of the flow has a complex spatial structure with a small number of vortex zones, which are concentrated in the zone of attachment of SED to the side of the helicopter around the exhaust nozzle [15].

The shortcomings revealed in the process of numerical studies regarding the organization of the gas dynamic flow in SED were taken into account during the further structural optimization of the SED. The results of our study could be used in the verification of the results of the numerical study by comparison with the results of further experimental studies and field tests under the conditions of a helicopter flight.
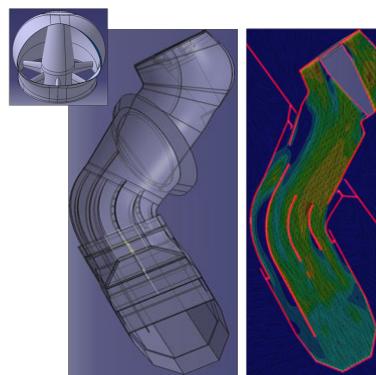

Fig. 4. Flow lines in a standard nozzle with an attached screen-exhaust device

5. 3. Experimental studies of the designed screen-exhaust device

We have conducted research during the thermal imaging examination of the Mi-8 helicopter. The indicatrix of the magnitude of the IR radiation force was taken in five positions of the ground equipment for measurement relative to the helicopter at the orientation angles of the helicopter to the ground equipment for the measurement of the IR radiation force of 180°, 190°, 200°, 210°, 220°, 230°, 240°, 270°, 300°, 330°, 0°.

Three variants of thermal images were obtained: a helicopter without installing a thermal visibility reduction system (Fig. 5), a helicopter with installed standard screen-exhaust devices (Fig. 6), a helicopter with installed screen-exhaust devices of a new development (Fig. 7). These figures show the results of measuring the magnitude of the IR radiation force at an angle of 180°.

According to the results of our research, diagrams of temperature distribution in percentage value were constructed. Fig. 8 shows a diagram of temperature distribution in percentages with the installed old system of reducing thermal visibility. Fig. 9 shows a diagram of temperature distribution in percentage values without installing a system for reducing thermal visibility. Fig. 10 shows a diagram of the temperature distribution in percentages with the installed new system for reducing thermal visibility.
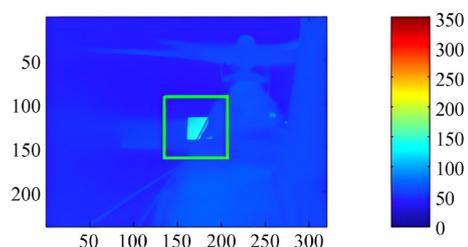

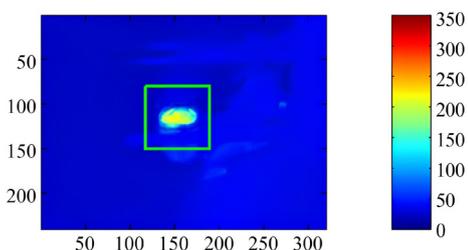Fig. 5. Thermal images of a helicopter without a thermal visibility reduction system installed

Fig. 6. Thermal images of a helicopter with an old thermal visibility reduction system installed
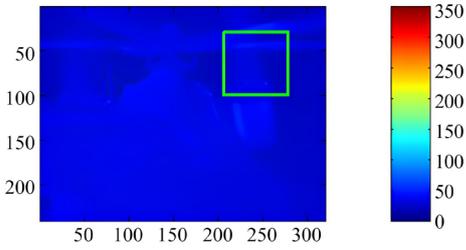
Fig. 7. Thermal images of the helicopter with the new thermal visibility reduction system installed

Based on the results of thermal imaging surveys, the characteristics of the infrared radiation intensity of the helicopter body were constructed. Fig. 11, 12 show a comparison of the intensity of thermal radiation of standard and new screen-exhaust devices.

As can be seen from Fig. 11, 12, the radiation power I_α during the study of the newly designed screen-exhaust devices is lower at angles of 180–270 °C than the radiation power of regular SEDs.

Fig. 11. Characteristics of the intensity of infrared radiation of the helicopter body: — helicopter without installation of a thermal visibility reduction system; — helicopter with installed standard screen-exhaust devices; — helicopter with installed newly developed screen-exhaust devices
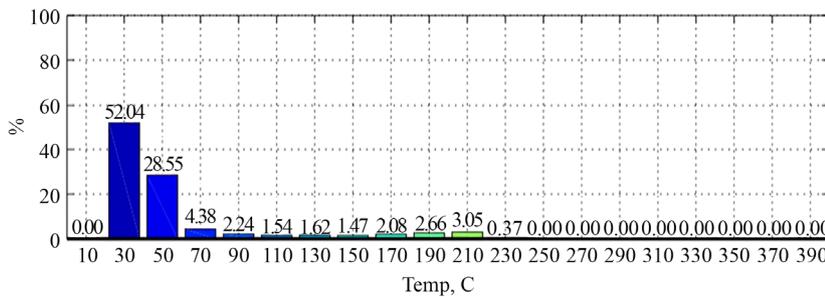

Fig. 8. Temperature distribution diagram in percentage with the old thermal reduction system installed
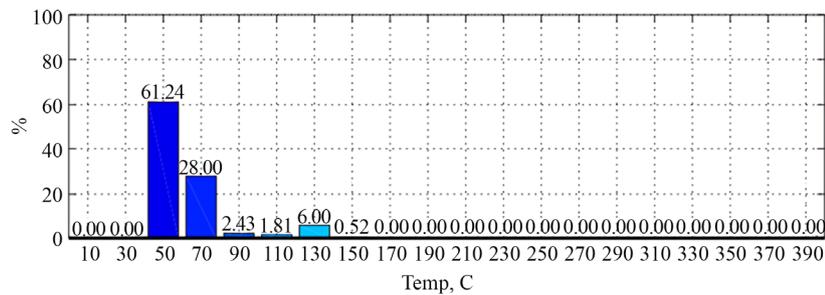

Fig. 9. Diagram of temperature distribution in percentage values without installation of the thermal visibility reduction system
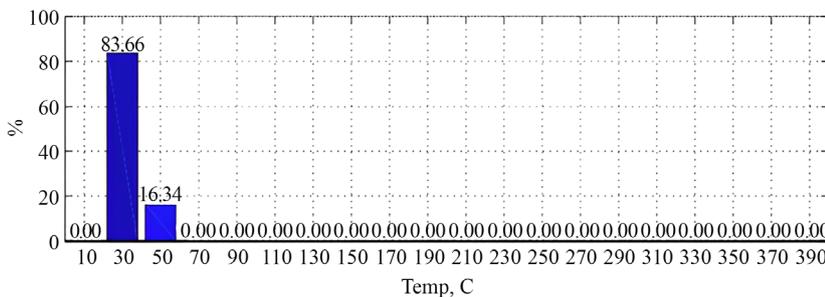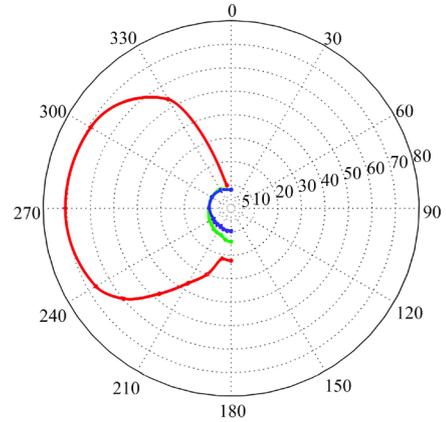

Fig. 10. Temperature distribution diagram as a percentage with the new thermal visibility reduction system installed
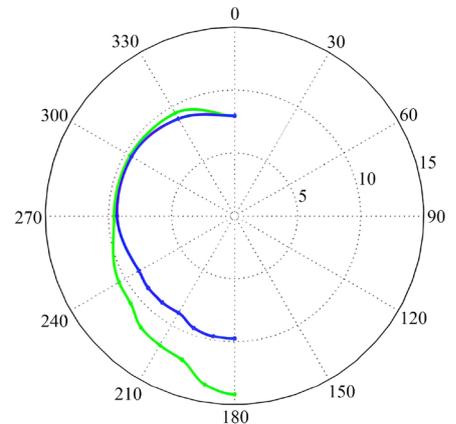

Fig. 12. Characteristics of the infrared radiation intensity of the helicopter body: — helicopter with installed standard screen-exhaust devices; — helicopter with installed newly developed screen-exhaust devices

6. Discussion of results of investigating the characteristics of infrared radiation intensity of the helicopter exhaust manifold

A new full-scale sample of SED has been designed. Additional shielding of the SED with blades with ejection cooling is proposed, which can reduce the thermal radiation of the emission zone of the helicopter's exhaust gases mixed with air (Fig. 3). The metal body and elements made of sheet heat-resistant stainless steel with a thickness of 0.6...0.8 mm have slots for the organization of ejection processes when the exhaust gases of the engine flow through the circuit. Previous resource tests of SED on the bench showed the effectiveness of structural and technological solutions adopted in terms

of strength. We proposed vertical separation of the high-temperature core of helicopter exhaust gases into three streams.

Based on the results of numerical modeling of the flow and temperature fields of the newly designed screen-exhaust device of the gas turbine engine based on real structural dimensions (Fig. 4), the gas-dynamic parameters of the ejector mixing chambers were obtained. Verification of injection phenomena along the tract in the design of the SED is defined. The results are given in more detail in [15]. In further experimental studies, these results will be compared with the aim of introducing correction factors and adopted models during further numerical modeling and improving the method for calculating the zazodynamic flow in SED.

Three variants of thermal imaging studies were obtained: a helicopter without installation of a thermal visibility reduction system, with installed standard screen-exhaust devices, and a helicopter with installed screen-exhaust devices of a new development.

As can be seen from the diagram shown in Fig. 11, the helicopter will remain vulnerable in the absence of shielding of heated surfaces. Because the radiation from a small visible part of the metal surface of the exhaust manifold, on the contrary, is more noticeable than the radiation from the entire uncooled exhaust gas. Fig. 8 shows the temperature distribution in percent, the maximum visible temperature at a measurement angle of 180° was more than 210 °C, while the radiation power I_α was 27.25 W/sr. During the thermal imaging examination of a regular SED, Fig. 9, the temperature range was 50–130 °C. When examining the temperature as a percentage with the new system installed, the percentage value of the reduction in thermal visibility was 30–50 °C.

The highest radiation power was recorded at angles of 240–300° – 75 W/sr, which is shown in Fig. 11.

A shortcoming of this study worth noting is that the effect of solar radiation on the overall thermal radiation of the helicopter was not taken into account. This aspect is very important because the side of the helicopter whose elements are heated by solar radiation has greater thermal visibility.

Modern missile guidance heads operating in the spectral range with wavelengths of 3–5 μm can receive weaker signals from less heated radiating surfaces. The use of a new screen-exhaust device reduces thermal visibility by almost 9 times. The value of the radiation power I_α is in the range of 13 W/sr. When using a standard SED, the maximum radiation power was 17.3 W/sr. Smaller indicators of the radiation power I_α in the newly designed screen-exhaust device are achieved by placing the section of the exhaust channel in a horizontal plane and dividing the flow of exhaust gases in the section of the exit from the SED into four separate streams. The use of ejector systems in the new screen-exhaust device contributed to the effective mixing of cold ambient air with the exhaust stream, which reduces the CO_2 concentration and temperature and reduces the visibility of the helicopter.

The works of our colleagues [6, 10] make it possible to resolve the issue of numerical modeling of SED, calculation of their design parameters. Methods of calculation of output devices of the ejector type for various applications have been developed, as well as highly effective experimental samples of output devices of the ejector type. And there are no methods for solving the task of determining the parameters and tactical-technical characteristics in the study of full-scale SED samples as part of a helicopter with working engines in the literature available to the author, which predetermines the prospects of our research.

The results of our research make it possible to partially compare the simulation results of the simulation of the zones of impact of aerial vehicle by thermal missiles, modeled in paper [12] with the real indicators of the radiation power I_α.

Determining the conformity of the tactical and technical characteristics of the SED set during the tests should be carried out under the given conditions of the influence of external factors of a natural nature, as well as under the given modes of operation of the test object. However, it was not possible to fully conduct such experimental studies. Only the stage of ground tests was used to the fullest and possible extent.

But the limitations inherent in this study did not affect the results obtained. Experimental studies gave an opportunity to practically check the application of the proposed solutions regarding the new structure of SED and to compare with standard SEDs.

The ranges of input data within which the results are obtained are adequate and can be reproduced, leading to the claimed effects and characteristics of SED. Experimental studies were carried out according to the methodology given in [16]. The tests were carried out in accordance with the tactical and technical characteristics of the SED set under the given conditions of influence of external factors of a natural nature, as well as under the given modes of operation of the test object. Work [16] reports available and standard means of on-board measurement of information and their characteristics used in research.

It is advisable to carry out further experimental studies in order to verify the results of numerical studies by comparing them with the results of further experimental studies and field tests under the conditions of a helicopter flight.

7. Conclusions

1. We have designed a new full-scale SED sample, the structural scheme of which is more effective in terms of hydraulic losses and more technological in production compared to regular screen-exhaust devices. Compared to standard SEDs, the newly designed structure of a screen-exhaust device has a more perfect aerodynamic shape, which led to a decrease in total pressure losses. The application of the connection of metal parts and structural elements using spot welding instead of riveting can lead to the possibility of cheaper production and the manufacture of more aerodynamically perfect parts of SED.

2. The applied theoretical method for calculating the flow fields and temperature of subsonic gas ejectors of screen-exhaust devices of gas turbines and the gas-dynamic parameters of the ejector mixing chambers obtained by the method of numerical modeling based on the geometric dimensions of the newly designed SED was analyzed. This was necessary for comparison with the results of field tests. In further experimental studies, these results are compared with the purpose of introducing correction coefficients of the models during further numerical modeling and improving the method for calculating the gas-dynamic flow in the SED of other designs and schemes.

3. Experimental studies of the designed screen-exhaust device were carried out. It was found that placing the section of the exhaust channel of the designed SED in the horizontal plane compared to the standard SED ensures a reduction of IR radiation in the lower hemisphere. Directing the flow of exhaust gases from the SED into the space above the helicopter

propeller, the desired effect of mixing them with the surrounding air is achieved. As a result, the temperature of the exhaust gases and the total infrared radiation of the helicopter itself decrease sharply. The distribution of the flow of exhaust gases at the SED section into four separate streams allows for their rapid mixing with air in the surrounding atmosphere.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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