MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

NATIONAL AVIATION UNIVERSITY

AEROSPACE FACULTY

DEPARTMENT OF AIRCRAFT ENGINES

ADMIT TO PROTECTION
Head of the department
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"_" 2022 p.

QUALIFICATION WORK (EXPLANATORY NOTE)

APPLICANT FOR THE EDUCATIONAL DEGREE "MASTER"

ACCORDING TO THE EDUCATIONAL AND PROFESSIONAL PROGRAM
"MAINTENANCE AND REPAIR OF AIRCRAFT AND AIRCRAFT ENGINES"

Topic: "Improvement of high-pressure turbine blade cooling of a double-circuit turbojet engine for medium-haul aircraft".

He did it: VASHCHENKO YAROSLAV

Head: Doctor of Technical Sciences, prof. __________ Y.M. Tereshchenko

Consultants on individual sections of the explanatory note:

labor protection: __________

environmental protection: __________

Regulator __________

Kyiv 2022

NATIONAL AVIATION UNIVERSITY
Faculty of Aerospace
Department of aircraft engines
Educational degree "Master"
Specialty 272 "Air transport"
Educational and professional program "Maintenance and repair of aircraft and aircraft engines"

APPROVE
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TASKS

to perform a diploma work

VASHCHENKO YAROSLAV

1. Theme of the work: **"Improving the cooling of high-pressure turbine blades of a double-circuit turbojet engine for medium-range aircraft" was** approved by the order of the rector
of November 0, 2022 No. / art.

2. Term of work: from October 2022 to February 2022.

3. Initial data for work: statistical data on gas turbine cooling systems of turbojet double-circuit engines.

4. Content of the explanatory note: analysis and optimization of the parameters of cooling systems for diagnostics of gas turbines of the flow part of the engine by the parameters of the work process.

5. List of mandatory graphic (illustrative) material: research scheme, research results and their analysis.

Graphic (illustrative) material is made using Microsoft Office Excel, Power Point and presented in the form of presentations.

6. Calendar plan-schedule.

Objectives.	Term execution	Note on execution
Analysis of the state of the problem. Setting the purpose and objectives of the study.	16.10.22 - 28.10.22	
Cooling of gas turbine blades.	29.10.22 - 19.10.22	
Optimization of film cooling holes.	20.10.22 - 28.10.22	
Implementation of individual sections of the work: labor protection, environmental protection	29.10.22 - 5.11.22	
Preparation of explanatory note and illustrative material	6.11.22 - 8.11.22	
Preliminary defense of the thesis	2.11.22 - 10.11.22	

7. Consultants from individual sections.

Section.	Consultant	Date, signature	
		Objectives. published	The task was accepted by
Labour protection			
Environmental protection			

8. Date of issue of the task: "___"____________ 2022.

Thesis supervisor _________________ ________________

The task was accepted for execution _________________ ________________

SUMMARY

Explanatory note to the diploma work: **"Improvement of high-pressure turbine blade cooling of a double-circuit turbojet engine for a medium-haul aircraft".**
00000 p., 00000 figures, 000 tables, 000 sources.

The object of research is a high-temperature turbine of double-circuit engines for medium-haul aircraft.

The subject of research is the processes of cooling blades of high-temperature turbojet double-circuit engines for medium-haul aircraft.

The purpose of the thesis is to improve the cooling of gas turbine blades of turbojet double-circuit engines.

The main objectives of the study: analysis of existing methods of cooling gas turbine blades of turbojet double-circuit engines. development of a numerical model of the film cooling hole and its verification, structural and parametric optimization of film cooling holes.

Research methods.

To solve the tasks, the method of structural-parametric optimization was used.

The practical significance of the work lies in the fact that the developed method of structural and parametric optimization of elements of cooled turbines based on the results of numerical modeling allows to reduce the time spent on optimization of elements of the flow part and the cooling system of the turbine by 5-6 times, to increase the efficiency of technical operation of aircraft.

BLADE COOLING, EFFICIENCY IMPROVEMENT, OPTIMIZATION, GAS TURBINE ENGINE.

CONTENTS

LIST OF ABBREVIATIONS, SYMBOLS AND INDICES

GTD - gas turbine engine;
EEC - European Economic Community;
ZPS - runway;
KW - high pressure compressor;
CST - low pressure compressor;
EFFICIENCY - coefficient of efficiency;
COP - combustion chamber;
RK - impeller;
RL - working blade;
SA - nozzle apparatus;
SBAR - Structural Multiparameter Analysis and Renovation of Turbines;
TVT - high pressure turbine;
TNT - low pressure turbine;
CYANIDE - Central Institute of Aviation Engine Building;
AFRA - Association for the utilization of the aircraft fleet;
ANSYS CFX - a tool for computational fluid dynamics;
CAN - Aviation Noise Committee;
CAEP - Committee on Environmental Protection;
CAN - Aviation Noise Committee;
CFD -.Numerical gas dynamics;
IAA - International aviation partners;
ICAO - International civil aviation organization;
ISO - International Organization for Standardization;
IEC - International Electrotechnical Commission.

Symbols and notation

D - Hole diameter;

F - area of the flow part at the outlet of the impeller;

M - air parameter;

N – capacity:

T - Temperature, K;

Tg - gas temperature;

Shh - wall temperature;

.

TV - cooler temperature;

S - is the axial clearance between the SA and the RC;

V – is the kinematic viscosity of the flow;

Uc – is the rate of jet emission;

b - CA scapular chord;

Θ - cooling efficiency;

$\Delta\bar{Y}^*$ - A dimensionless criterion for evaluating the accuracy of optimization results;

Δy^* - is the height of the first cell of the calculation grid;

$\boldsymbol{u}^+$ - shear flow velocity near the wall;

πt * - the degree of reduction of the total pressure in the turbines;

γ - adiabatic index;

y+ - Dimensionless height of the first cell of the calculation grid;

δ - relative deviation;

Δ - absolute deviation;

* - parameters of the stalled flow.

INTRODUCTION

One of the most dynamically developing varieties of aviation GTE in recent years are twin-circuit turbojet engines (turbojet engines) with take-off thrust less than 10 tc, designed for regional aircraft. Aircraft of this class, which occupy an intermediate position between the aircraft of local lines and near main lines, are equipped mainly with double-circuit engines.

Relevance of the topic

Creation of advanced gas turbine engines, both for aviation technology and for industrial applications in the production and generation of electricity, in gas pumping units and other areas is impossible without a comprehensive increase in the parameters of the operating cycle (the degree of pressure increase in the compressor, gas temperature at the inlet to the turbine). At present, the role and influence of research works in the creation of new GTD has significantly increased.

The world aircraft engine industry is one of the most dynamically developing industries. The financial capacity of the world market of gas turbine equipment is very large. The market of production and maintenance of aircraft engines is attractive, many countries of Europe, America and Asia are trying to enter it

Three companies are developers of regional aircraft (with TRDD): Embraer (Brazil) - ERJ type; Bombardier (Canada) - CRJ type; BAe Systems Regional Aircraft (UK) - Avro RJ type.

Regional aircraft of the considered class are designed to carry 35-110 passengers and have a maximum take-off weight of 15500 ... 50000 kg. The maximum flight range for standard modifications is 1650 ... 3100 km and 2850 ... 4300 km with an increased range.

The power plant of most regional aircraft includes two main engines. As a result of the implementation of technical solutions in modern turbofan engines for regional aircraft, the indicators have been achieved:

- specific fuel consumption 0.63 ... 0.68 kg / kgs - h; specific weight 0.19 ... 0.22

kg / kgs;

- operation according to technical condition since commissioning, operating time on the "wing" - not less than 10000 ... 12000 hours;
- reduction of service cost by 20 ... 30%;
- the level of emission of harmful substances is 40 ... 50% lower than the existing requirements;
- noise level - 15 ... 20 dB below the existing requirements.

An important feature of the considered power plants is the way of placing the engines: on the fuselage or under the wing. For regional aircraft with a large take-off weight, the option of installing engines on pylons under the wing is preferable.

The way the engine is placed on the aircraft affects the choice of its scheme.

The main developers and manufacturers of turbofan engines for regional aircraft abroad are four companies: General Electric (USA) - CF34 engines; Honeywell (USA) - LF507-1F, AS900 engines; Rolls - Royce (UK) - AE3007A, AE3007A1 engines; Pratt & Whitney (Canada) - PW306B, PW800 engines.

There are a number of aviation framework programs of the European Union, aimed at a comprehensive solution to the problem of creating new, competitive and cost-effective gas turbine engines. Since the 2000s, during the framework programs, a significant number of research projects have been implemented in the European Union, which affect the full range of issues of creating gas turbine engines: from the development and improvement of gas turbine engine design methodologies to the creation of new promising materials and environmental issues. At the moment, research projects under the seventh framework program of the European Union are underway, and the preparation of projects that will be included in the program "HORIZON 2020" (2014 - 2020) has begun. The main objectives of the research programs of the European Union are: increasing the economic efficiency of aircraft engines, reducing the harmful impact on the environment. The achievement of these goals is carried out through comprehensive research of various aspects of the aviation industry. A large number of research projects are devoted to the development of existing and creation of new design methods and techniques.

Significant efforts to improve the samples of gas turbine engines are made by manufacturers of gas turbine equipment. All leading manufacturers have their own research programs on creation of scientific and technical achievements in the field of development and production of new designs for GTE parts and components, and development of new design methods: General Electric, Rolls - Royce, Pratt - Whitney and others.

Further development and improvement of GTE characteristics is the reason for the increasing growth of time and financial costs required to achieve the set goals. Due to the high level of sophistication of modern GTE, the main reserves for improving the characteristics and creating advanced engines are to improve the aerodynamic and thermal efficiency of GTE elements by optimizing their shape and geometric parameters.

Such elements include a cooling gas turbine. Its efficiency level largely determines the characteristics and competitiveness of the engine as a whole. Today, the general directions of development of cooled turbines are to increase the gas temperature before the turbine to increase the effective efficiency of the engine and improve the specific parameters of the turbine, for example, by reducing weight or increasing aerodynamic efficiency.

Increasing the cooling efficiency of the hot elements of the turbine by 0.5% allows raising the gas temperature by 50 degrees, which leads to a significant increase in effective efficiency, and is estimated to give a 5% increase in engine thrust. The current level of gas temperature in the turbine (in civilian engines of the fifth generation at the inlet to the high-pressure turbine it can exceed 2000K) requires the use of a very complex, integrated cooling system in combination with the use of the most effective heat-resistant materials. Even at the inlet of the inter-turbine transition duct and in the low-pressure turbine, the gas temperature can reach 1300 - 1400K, which leads to the need for cooling of the low-pressure turbine parts. To improve the cooling efficiency, it is necessary to improve the convective and film components by optimizing their elements. The film component has a significant impact on the overall cooling efficiency, which is also influenced by various factors. For example, optimizing the shape of the outlet cross-section of the perforation hole can increase the film cooling efficiency by more than 30%.

In cooled turbines, there are practically no possibilities to reduce the mass of rotor parts and blade rings. However, for turbines with a large degree of double-circuit there is a certain reserve. It consists in reducing the length of the transition channel between the turbines, which leads to a reduction in weight and dimensions (the use of an "aggressive" transition channel). In this case, the task of optimizing the gas-dynamic efficiency of the channel comes to the fore. Reduction of full pressure losses in the transition channel by 1% allows to reduce specific fuel consumption by 1.5 - 2%.

The development of a universal method for solving the problems of increasing the efficiency of the elements of the flow part and cooling system makes it possible to comprehensively increase the efficiency of cooled turbines.

The way out of this situation can be the use of structural-parametric optimization. This approach is based on a combination of methods of compression and transformation of geometric information (principal component method) with methods of random search with adaptation and regression analysis. Structural-parametric optimization allows to find hidden relationships between geometric parameters of turbomachinery elements and its characteristics and to improve them. Elements of this approach are described in the works of V. V. Nalimov, A. G. Ivakhnenko, A. A. Rastrygin, E. M. Braverman. This method was widely applied to the problems of improving and proving the GTD in the works of V.F. Bezyazykovyi, V.N. Shishkin and others.

Structural-parametric optimization allows to find a solution to the problem on the basis of only 5 - 10 initial options, but its application has always been based on the results of experiments and existing designs of GTE elements. The time and financial costs of the experiment offset its advantages at the design stage, where such information is usually absent. Here, the combination of structural-parametric optimization with numerical modeling methods becomes relevant, which will lead to a significant reduction in the time and computational resources required to solve the problems of improving the efficiency of elements of cooled turbines.

The relevance and necessity of improving the aerodynamic and thermal efficiency of the elements of cooled turbines by developing new ways to reduce the time and computational costs of solving optimization problems at the design stage determine the **following research objective**: to improve the efficiency of a gas turbine by structural and parametric optimization of the elements of the flow part and cooling system.

To achieve this goal it is necessary to solve the following **tasks:**

- to analyze the existing ways to improve the efficiency of gas turbines, identify shortcomings and possible ways of improvement;
- development of a numerical model of the film cooling hole and its verification.
- Structural and parametric optimization of film cooling holes.

They are put on defense:

1) Results of the analysis of the problem of cooling of gas turbine blades.
2) Results of calculations of the optimal shape of the holes using numerical simulation.
3) Results of structural and parametric optimization of film cooling.

SECTION 1

ANALYSIS OF THE PROBLEM. SETTING GOALS AND OBJECTIVES RESEARCH

The creation of modern GTE and their further improvement is impossible without a comprehensive increase in the operating cycle parameters (the degree of pressure increase in the compressor, gas temperature at the turbine inlet). A fundamental role in this is played by the development of new design and technological solutions aimed at reducing specific fuel consumption, increasing traction performance, as well as reducing engine weight. Such solutions include the use of new, more advanced designs, new materials with lower weight, improved heat resistance, cyclic durability, etc. The main reserve for improvement lies in the most structurally complex and loaded elements of the engine.

One of such elements of a modern engine is a gas turbine. The main trends in the development of modern gas turbines can be considered an increase in the aerodynamic load on the stage and an increase in the gas temperature at the turbine inlet. Both these trends reflect the general directions of development of gas turbine engines: increasing the effective efficiency by increasing the gas temperature and the degree of pressure increase and increasing the specific parameters by reducing the size, weight, reducing the number of stages and blades [1].

Figure 1.1 shows ways to improve the efficiency of gas turbines and the challenges that arise in their implementation.

Let us consider the above directions of development of cooled gas turbines, as well as possible ways to improve the efficiency of the GTD turbine in more detail.

Figure 1.1 - Ways to improve the efficiency of gas turbines

1.1 Thermal condition of turbine elements

On modern civilian high thrust turbofan engines, the gas temperature in front of the turbine is almost equal to the temperature in front of the turbine of military turbofan engines. The maximum gas temperature in front of the rotor of a high-pressure turbine reaches
1700 .. .1850К.

Engines for short- and medium-haul aircraft (SBM56, U2500) have a significantly lower temperature level.

The working and nozzle blades of the turbine work in direct contact with high-temperature gas, while the permissible temperature of the blade alloys is 200 ... 500 ° C lower than the operating temperature of the gas before each crown.

The greatest difficulty is to ensure the reliability of the blades, especially in a high-pressure turbine. They, along with the nozzle blades, are subject to thermal fatigue, vibration, gas corrosion and erosion, and gas loads. In addition, the working blades are subject to centrifugal forces. In view of all this, for reliable operation, the average temperature of the blade metal should not exceed 900. 1000 ° C, and the maximum level - 1100 ° C. The level of permissible operating temperatures directly depends on the characteristics of the blade material used.

Some rotor and stator parts of the turbine are also directly affected by gas: casings, rim of disks, labyrinths and other less loaded parts. To ensure their reliable operation during the specified service life, they are used:

- special heat-resistant, heat-resistant and corrosion-resistant alloys capable of resisting sulfide-oxide corrosion;
- manufacturing of blades by directional crystallization or from single crystal;
- coating to increase the heat resistance of the material (for example, aluminum oxide);
- metal multicomponent coatings to increase the corrosion heat resistance of the material - for example, a coating of four components (nickel - chromium - aluminum - yttrium);
- heat protective coating made of ceramic materials with low thermal conductivity - to reduce the heat flow into the blade metal;
- various schemes of air (for industrial turbines sometimes even steam) cooling.

The optimal turbine design from the point of view of the engine life cycle cost implies the optimal combination of all the above mentioned main ways of ensuring operability. The use of expensive heat-resistant alloys increases the cost of the material, but reduces the need for cooling. The use of a more complex and efficient cooling system for the turbine blade increases its cost, but allows the use of less expensive materials.

Designing an optimal cooling system involves consistently finding a reasonable compromise at all stages of the project.

1.2 Improvement of gas turbine by increasing gas temperature

The simplest and most logical way to achieve high effective efficiency of the engine is to increase the gas temperature before the turbine. The obvious solution to the problem of ensuring the required turbine life at higher operating temperatures is the use of new heat-resistant materials for the most loaded and critical parts. These materials are able to withstand high temperatures and high mechanical loads during the specified service life. The most widely used in turbines are heat-resistant and heat-resistant alloys based on nickel, alloyed with various rare earth elements, such as Rhenium, Ruthenium, Tantalum. The mechanical properties of heat-resistant materials are constantly improving, but the rate of increase in the maximum operating temperature, due to the improvement of metallic materials, has lagged behind, and will continue to lag behind the rate of increase in gas temperature required to create competitive modern GTEs.

There is an obvious need to cool all the main elements of the turbine flow part in order to ensure the required thermal condition of the parts. The surface temperature must be reduced to a level at which reliable operation of parts and assemblies is ensured throughout the entire specified service life.

Professor V. L. Ivanov notes that "since the 1960s, the growth rate of the gas temperature in front of the turbine significantly exceeds the growth rate of heat-resistant materials, which is explained, first of all, by achievements in the creation of effective cooling systems" [2].

Such tendencies are most typical for aircraft engines (both military turbofan engines and civilian turbofan engines), but also for transport and stationary GTUs at a lower gas temperature. At the moment, these trends continue.

Gas turbine cooling systems are usually classified according to two principal features: by the nature of the refrigerant used - air, liquid and air-liquid (dual-circuit); by the method of using the cooler - open, closed and semi-closed.

The results of a large number of experimental and numerical studies of the elements of modern high-temperature turbines are presented in the works of the staff of the Baranov CAAD [3]. Basically, the convective-film method is used for blade cooling in these works: an internal convective system of loop or coplanar channels with heat exchange intensifiers in combination with a developed system of film cooling holes.

Obviously, to solve the problem of increasing the efficiency of the cooling system, it is necessary to improve and optimize both convective and film components.

1.3 Principles of cooling of gas turbine blades of gas turbines

The most popular cooling system of modern turbines is the scheme of open (with the coolant discharge into the flowing part of the turbine) air cooling. To cool the turbine, air can be used, which is taken through the high-pressure channel or through one of its stages. For external cooling of the turbine casings (and radial clearance control) air is used through the low pressure channel or through a fan. From the point of view of the overall efficiency of the turbine in the engine, it is usually necessary to design the cooling system firstly with a minimum flow of cooling air, and secondly with the use of air extraction through the intermediate stages of the compressor as far as possible.

Reduction of air consumption for turbine cooling can be achieved:

- formation of the optimal radial epure of the gas temperature at the short circuit;
- reduction of the district temperature irregularity in the short circuit;
- the use of a swirling apparatus to swirl the air in the direction of rotation of the disk at the inlet to the rotor of the fuel element (this reduces the temperature of the cooling air);
- pre-cooling of the air in the air-heat exchanger installed in the external circuit of the turbocharger (such a scheme is implemented on engines D - 30F6 and AL - 31F) or (in the case of an industrial engine) taken out of the engine and blown by an electric fan;
- reduction of cooling air leakage into the flowing part of the turbine;
- increasing the efficiency of the blade cooling system;
- reduction of cooling air pressure losses when supplying to the blades (this allows to save and effectively use the potential of cooling air pressure directly in the blades).

There are three ways of air cooling of turbine nozzles and blades:

1) by internal convective heat exchange;

2) by film - barrier cooling;

3) by penetrating (porous) cooling

It is also possible to combine several cooling methods.

In convective cooling, cooling air is supplied through the root part of the blade, passes through specially made channels inside the blade and then is released into the flowing part of the turbine. The air can flow in different directions through the internal channels.

Convective cooling of turbine parts is realized by removing heat by air flow from the internal surfaces of cooling channels in blades and other parts with subsequent release of air into the flow section. The air is usually released into the flowing part in areas with relatively low gas pressure (in the area of the outlet edge or in the area of the upper end of the blade behind the sealing combs). Therefore, the convective scheme allows for a fairly intensive use of the pressure margin in the internal channels of the parts and the use of quite significant hydraulic resistances to intensify heat transfer on the internal surfaces of the parts.

Depending on the nature of the cooling air movement, the blades are made with longitudinal, transverse and mixed cooling channels. Typical designs of blades with longitudinal cooling channels are first stage impellers**.** Cooling air enters from the locking part of the blade into all channels, flows through the longitudinal channels and is ejected into the radial gap. The blades of this scheme ensure the operation of the turbine at gas temperatures before the turbine up to 1400 K and 1360 K, respectively, at a cooling air flow rate of about 2% of the gas flow rate through the turbine, reducing the temperature of the blade in its middle part by 220 ... 260 K.

The main advantage of the longitudinal cooling scheme of blades is a simpler technology of their manufacture. The cooling efficiency of such blades is quite high, but there is a significant unevenness of the temperature field both in height and in the blade profile, which reaches 150 ... 200 K and more. In this case, the most heated are the input and output edges.

There is a generally accepted characteristic of the cooling system efficiency - relative cooling efficiency, which evaluates the efficiency of the system and allows to determine the blade temperature at a known air flow rate. The relative cooling efficiency is the ratio of the real reduction of the blade metal temperature (Tl) relative to the gas Tg to the maximum possible reduction to the cooling air temperature (Tp). Accordingly, the relative cooling efficiency is determined by the formula:

$$\boldsymbol{c} = (T_{\text{г}} - \mathrm{Tl}) / (T_{\text{г}} - \mathrm{Tp}). \tag{1.1}$$

Fig. 1.2 presents the progress in the field of cooling efficiency (due to the design improvement of cooling schemes) and its decisive contribution to the increase of gas temperature in front of the fuel assembly rotor in modern designs.

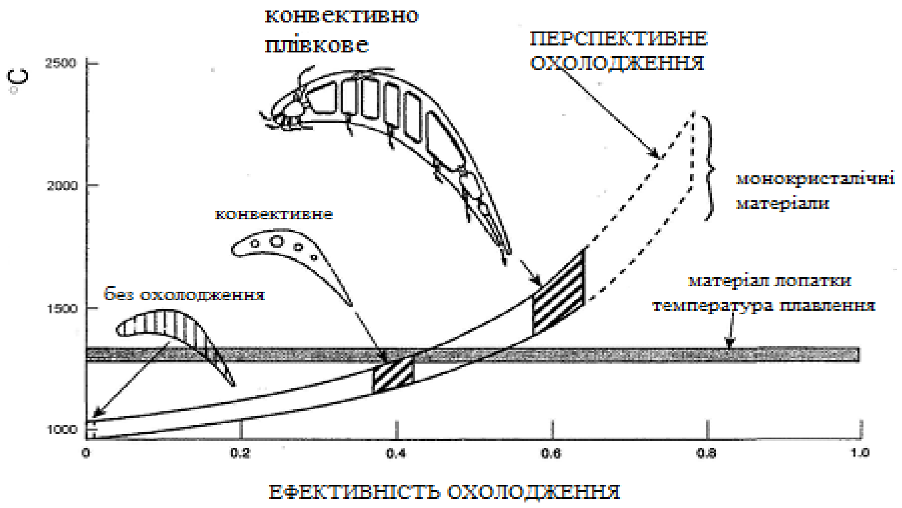

Figure 1.2 - Increase of gas temperature in front of the turbine rotor.

Figure 1.3 shows approximate dependences of the average (by blade cross-section) relative cooling efficiency for convective and convective-film cooling. For large air flow rates, the convective scheme is difficult to implement (due to limitations on the blade capacity). At low air flow rates it is difficult to implement film cooling (due to lack of air on the film).

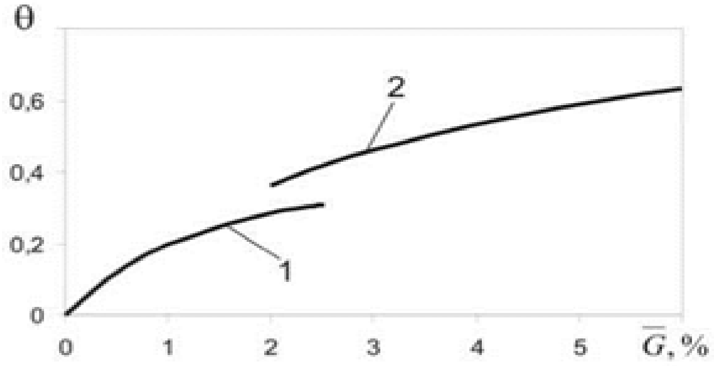

Figure 1.3 - Relative cooling efficiency for the average cross-section of the blade:

1 - convective cooling;

2 - convective-film cooling.

Convective heat exchange makes a significant contribution to the efficiency of the cooling system of any blade with intensive use of the film on the outer surface (see Figure 1.4, 1.5.).

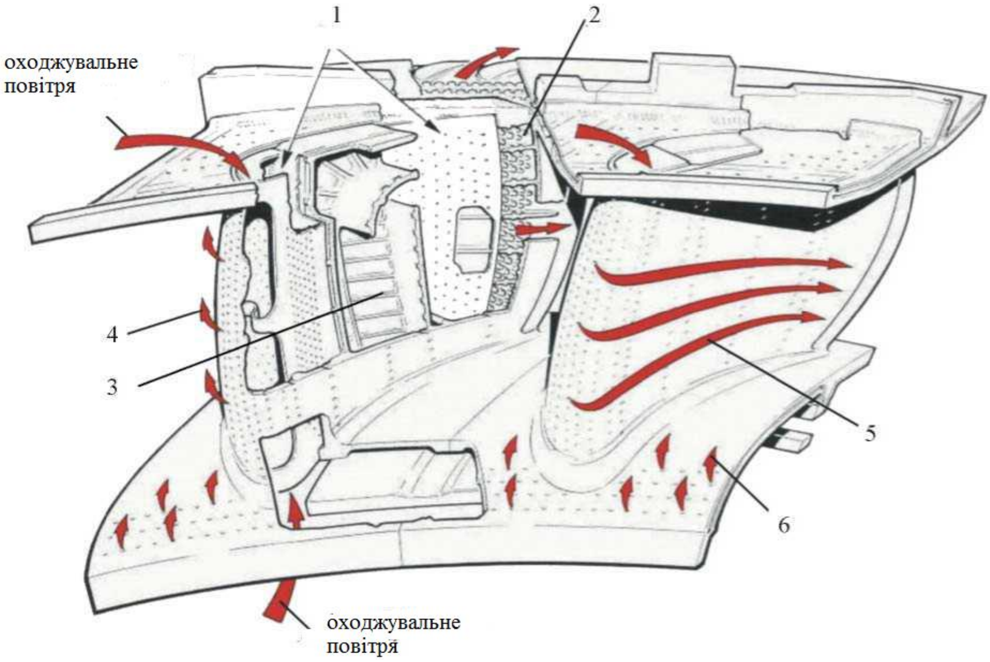

Figure 1.4 - Scheme of convective-film cooling of the nozzle blade of the 1st stage RB211-535E4 Rolls-Royce .

1 - deflectors; 2 - pin matrix; 3 - wall ribs; 4 - inlet edge; 5 - trough; 6 - bottom shelf.

Nozzle blades of the 1st stage of TVT have the most developed convective film cooling system. All types of convective cooling are used in the design of the nozzle blade (Figure 1.4):

- jet cooling of the walls through the deflectors 1 in the front and rear cavities;
- pin matrix 2 in the area of the outlet edge;
- transverse wall ribs 3 in the central channel, as well as film cooling of the inlet edge 4, trough 5 and lower shelves 6.

The most efficient method of convective cooling is jet cooling - when jets from holes in the intermediate wall or deflectors are impinging on the surface and provide very high heat transfer in the contact spot. Although heat transfer drops rapidly with distance from the centre of the jet, in general jet cooling is considered the most efficient compared to other convective cooling methods. Figure 1.5 shows a typical nozzle blade cooling system in which all the major cooling methods are used.

The air passing through the holes 1 into the deflectors 2 provides jet cooling of the inner surface of the blade wall 3. The remaining air pressure potential is used to organize film cooling of the wall through the holes 4. The protrusions 5 on the deflectors keep it at the required distance from the blade walls and at the same time create a pin matrix for turbulence of the flow and increase convective heat removal from the wall in the cavity between the deflector and the wall.

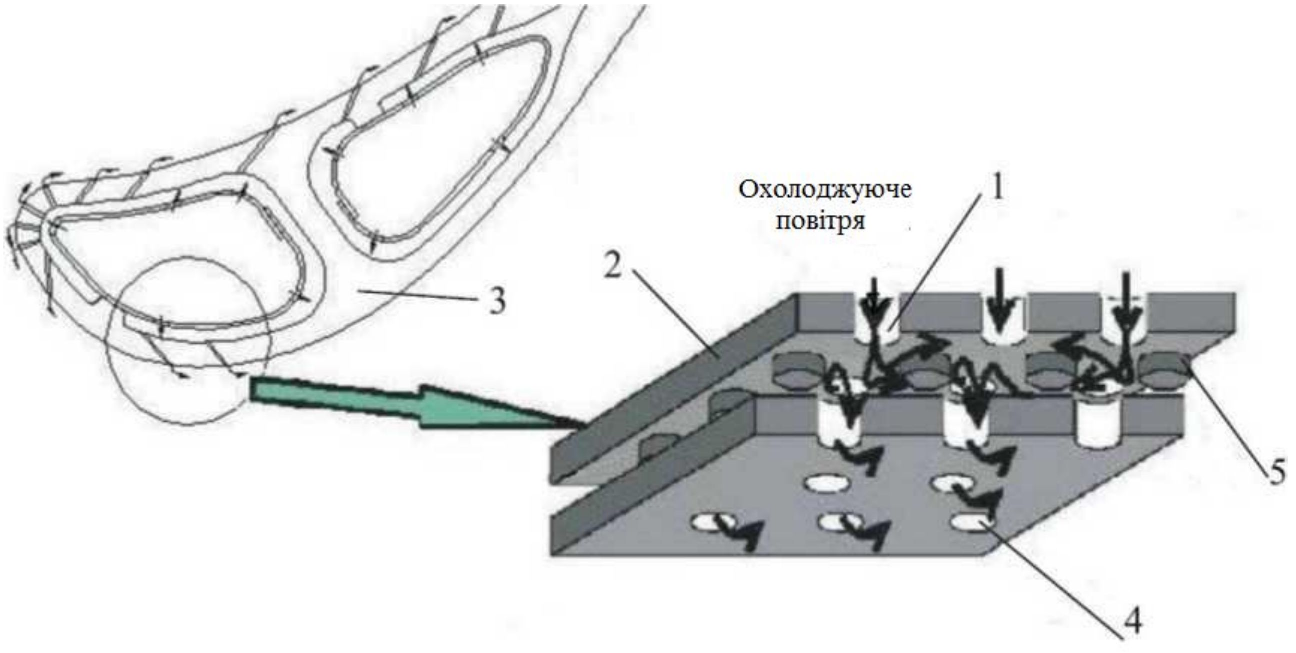

Figure 1.5 - Scheme of convective-film cooling of the nozzle blade wall

1 - holes in the deflector; 2 - deflector; 3 - blade wall; 4 - holes in the blade wall; 5 - pins

Increasing the heat transfer intensity by turbulizing the flow in the channel with the help of an array of pins (see Figures 1.4, 1.5) is used both in the nozzle and in the impeller blades. The disadvantage of the pin matrix is the relatively high hydraulic resistance, as it provides high heat transfer by creating hydraulic resistance for the entire flow in the cooling channel.

However, the greatest resistance to the heat exchange of air with the blade wall is provided by the boundary layer, which has the lowest velocity due to the braking at the wall and, accordingly, the greatest thermal resistance. Therefore, such a method of increasing the intensity of convective heat transfer as the destruction of the boundary layer with the help of wall transverse ribs is so widespread in blades (see Figure 1.6).

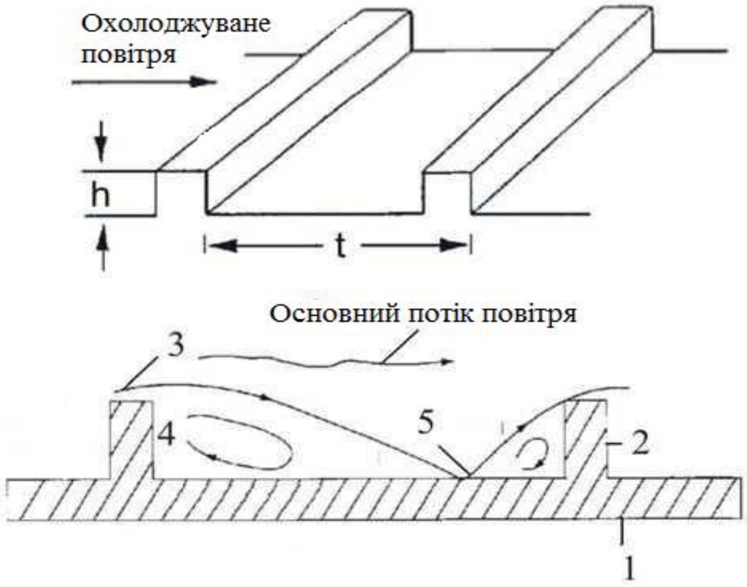

Figure 1.6 - Intensification of heat transfer by means of turbulizing fins 1 - wall; 2 - fin; 3 - separation point; 4 - zone of turning flow; 5 - connection point.

The air flow along the wall 1 of the cooling channel flows to the fins 2 with the flow separation at the point 3 and the formation of the turning flow zone 4. The flow rejoins the wall at the point 5 and repeats the cycle of separation at the next fin. The optimal ratios of fin height to fin pitch for different channel heights and flow parameters (Reynolds number) were experimentally determined.

The main flow is not affected and the increase in hydraulic resistance for the entire flow is quite acceptable. Maximum (judging by experiments on round pipes) heat transfer coefficient can increase by 3 times due to wall intensification. It should be borne in mind that in all cases the coefficient of hydraulic resistance for the flow in the channel will increase to a greater extent than the heat transfer coefficient.

The fins are usually made at an angle of 30 ... 45 degrees to the direction of flow to reduce the coefficient of hydraulic resistance (the most favorable ratio between the increase in heat transfer and the increase in hydraulic resistance is realized). There are optimal values of fin height and pitch for different channel heights and different Reynolds numbers**.**

In the main cooling scheme for blades - loop cooling scheme with numerous "passes" of cooling air (discussed in detail in the next section) both main methods of convective cooling are used. These are jet cooling of the inner surface of the inlet edge through cast holes in the inner wall and flow in long (with numerous 180 degree turns) internal channels (see Figure 1.7) with transverse wall fins.

Figure 1.7 shows the development of the cooling system of the Rolls-Royce blades from single pass convective scheme 1 to single pass convective-film 2 (with film on the inlet edge and on the trough of the outlet edge) and then to multi-pass convective with intensive film cooling.

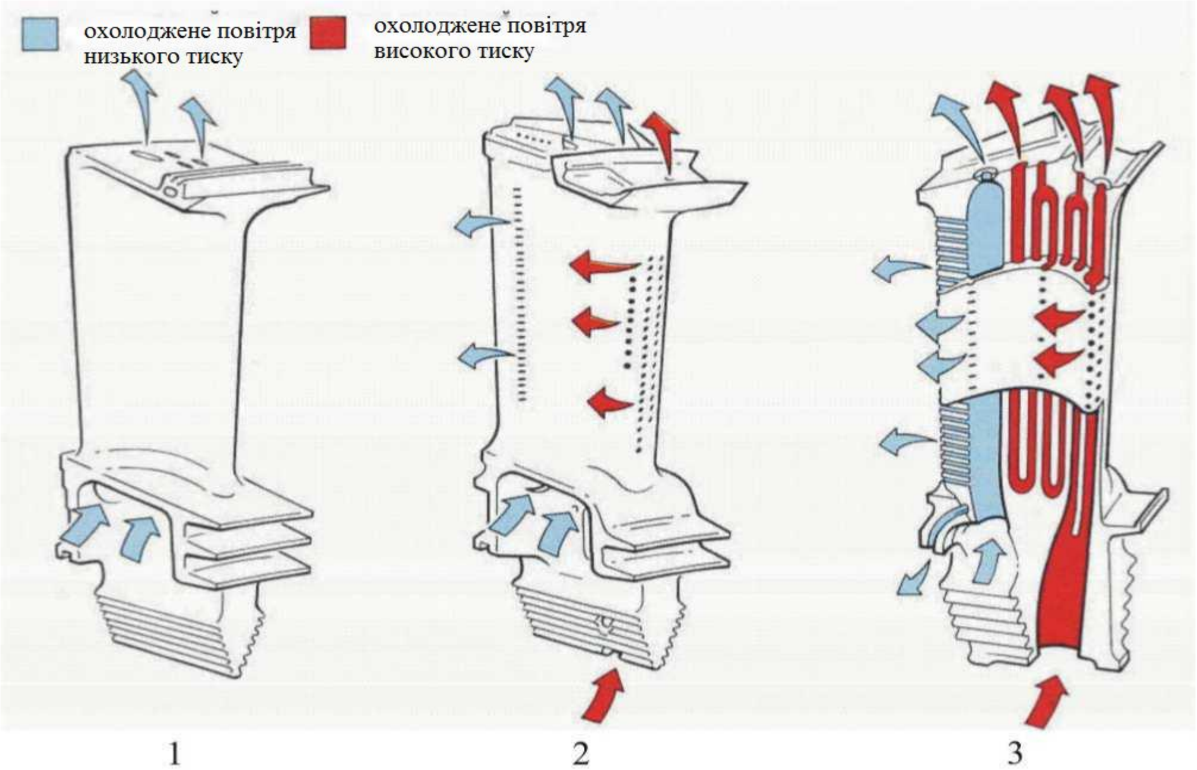

Figure 1.7 - Development of cooling schemes of TVT blades of Rolls-Royce company.

Film cooling additionally intensifies heat removal from the metal due to the creation of additional cooling surfaces in the holes for air release to the blade surface. Almost continuous film cooling is used in the nozzle blades of the first stages of high-temperature turbines. At the same time, the additional effect of increasing the heat transfer surface due to the film cooling holes can be very significant (the temperature drop due to this factor reaches 100 ° C and more).

The greatest effect of increasing the heat transfer surface can theoretically be achieved with porous cooling blades. The porous wall implies a large internal cooling surface and the creation of a uniform film on the outer surface. The implementation of such a scheme in its classical sense is hardly possible due to the difficulties of manufacturing and more than likely clogging of the working channels in the walls of the blade.

The cooling air flow rate to the blade (as well as to other turbine parts) is usually measured in relative terms - as a percentage of the air flow rate at the inlet to the turbine. Comparison of different blade designs is most informative for relative cooling efficiency at the same relative cooling air flow rate.

However, always higher intensity of internal heat transfer (which provides higher cooling efficiency) is achieved at the expense of higher full pressure losses in the blade itself. And the increase in pressure at the blade inlet is always associated with an increase in parasitic leakage of cooling air in the supply system.

The desire to increase the cooling efficiency and reduce the unevenness of the blade temperature field led to the appearance of loop circuits (Figure 1.8, a), deflector blades with transverse cooler flow and developed internal heat transfer surface, the introduction of fins on the inner surface of the inlet and outlet edges and blades with combined (convective-film) cooling. An example of a blade design with a deflector and a cross-flow cooler is a working blade proposed by S. K. Tumansky (Figure 1.8, *b).*

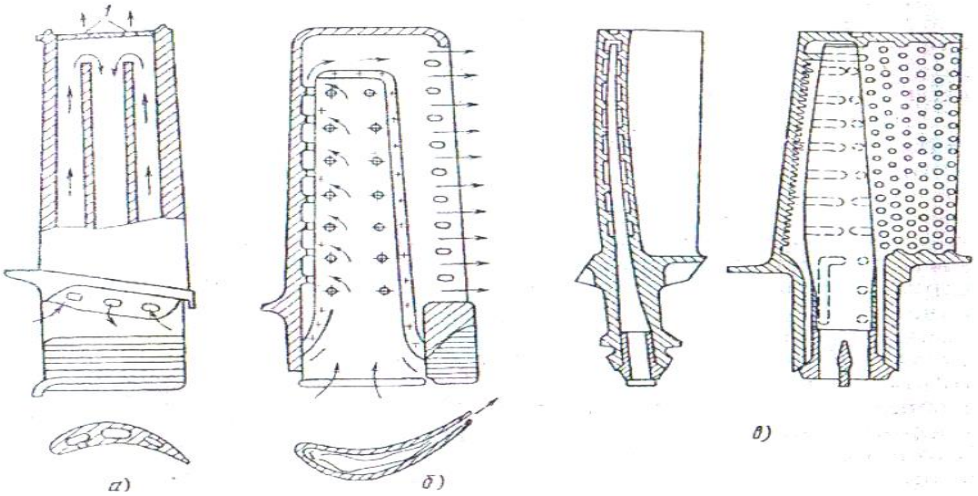

Figure 1.8 - Blade cooling schemes:

a - loop diagram; b - blade with internal deflector and transverse ribs on the inner surface; c - diagram of the turbine blade of the turbine turbine;

1 - holes for dust removal.

Figure 1.9 shows some of the design schemes of blades with longitudinal and mixed flow of cooling air, with cylindrical rods (bridges) connecting the back and concave surface of the profile part of the blade, with baffles of various shapes that deflect the flow of cold air in a given direction.

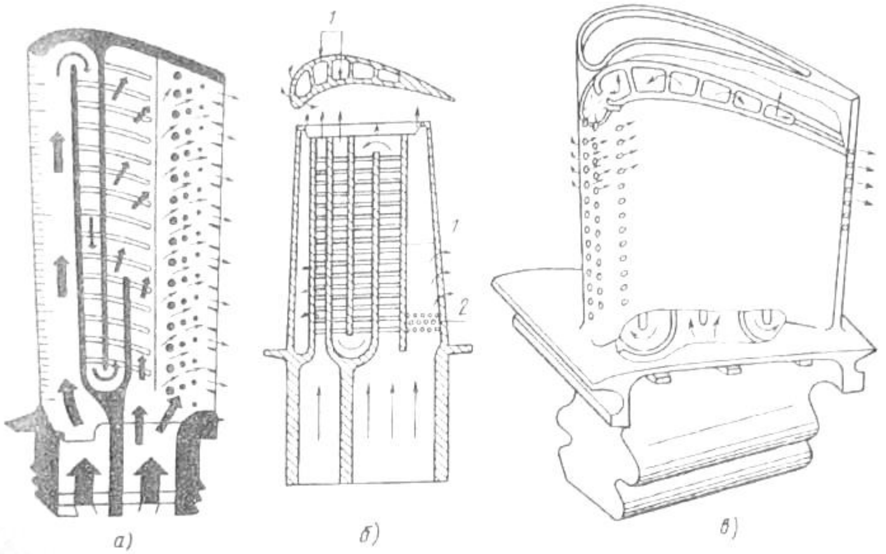

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Figure 1.9 Blades with longitudinal and mixed cooling air flow:

A - without perforation; b and c - with perforation; 1 - protrusions in the form of ribs;

2 - pins

Blades with a deflector and fins in the area of the inlet and outlet edges have a high cooling efficiency and provide greater uniformity of the temperature field of the blade, but they also have disadvantages: great design and technological difficulties associated with the placement of the deflector and ensuring the strength of such blades.

A significant increase in the efficiency of internal convective cooling of the blades can be achieved due to various intensifiers: wavy channels, through turbulators contacts, etc.

The considered schemes of internal convective cooling can provide long-term operation of blades at gas temperatures not exceeding 1450 ... 1500 K. At higher gas temperatures, it is necessary to apply more complex combined cooling schemes, where along with internal cooling, external, so-called film (barrier) cooling is also used (Figure 1.10).

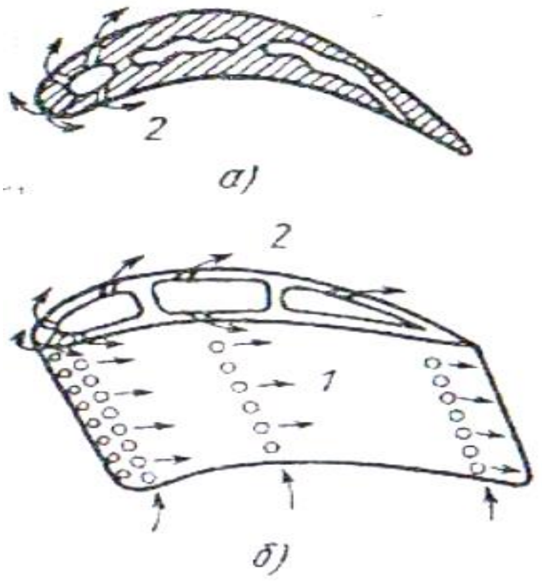


Figure 1.10 - Schemes of blades with convective-film (a) and film (b) cooling: 1 - hot gas; 2 - cooling air.

Film cooling of parts implies the reuse of air after convective cooling - its release on the gas-washed surface of the blade to create a film between the gas and metal. Film cooling is most effective when the air is released on the most heated surfaces of the blade - the inlet edge, the concave surface of the working blade and so on. Air discharge to these areas requires maintaining a sufficiently high pressure potential, i.e. moderate use of its convective cooling pressure reserve.

It should be borne in mind that film cooling is accompanied by convective heat exchange.

Thus, for example, blades with combined convective-film cooling of turbine TF-39, according to "General Electric", provide a resource of 15000 hours at gas temperature = 1580 K and cooling air flow rate on this grille is about 3%. Cast cobalt alloy turbine blades of the JT9D turbine with longitudinal channels of wave-like shape and sinuous inner surface of heat exchange are designed for operation at = 1620 ... 1640 K.

The most effective is **porous cooling**. The blade with such cooling (Figure 1.11) consists of an internal bearing rod 1 with profiled ribs and a porous shell 2, which forms the profile part.

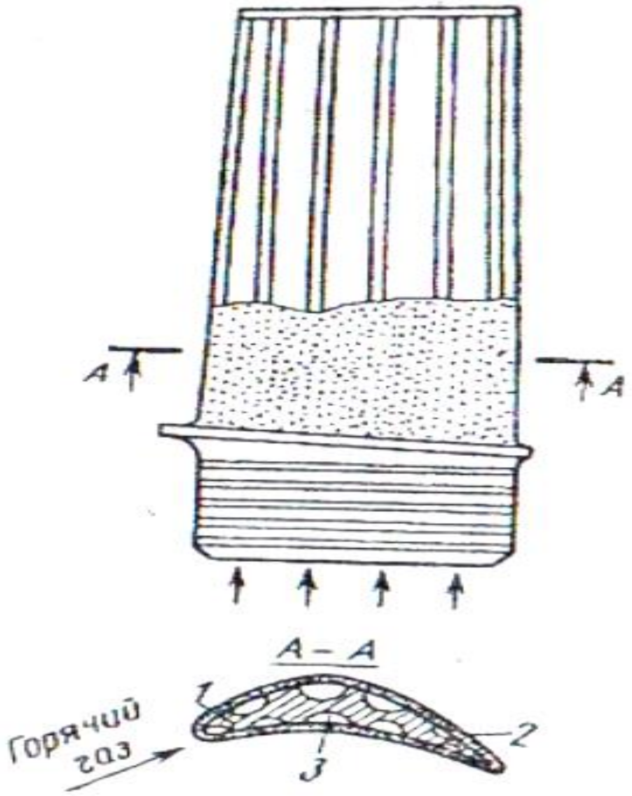


Figure 1.11 - Diagram of the blade with porous cooling:
1 - bearing rod; 2 - porous shell; 3 - cooling air;
A - A is the cross-section of the scapula.

The blade shell is made of permeable materials (porous, multilayer perforated, mesh). Ribs on the core serve to reinforce the shell and form longitudinal channels through which the cooling air passes.

Therefore, at present, simpler variants of porous cooling are being implemented - the so-called "Lamilloy" (Rolls - Royce-Allison) and the so-called scheme of penetrating cooling or "blade with cooled walls" (schemes of such blades are published, for example, by Rolls - Royce - Figure 1.12).

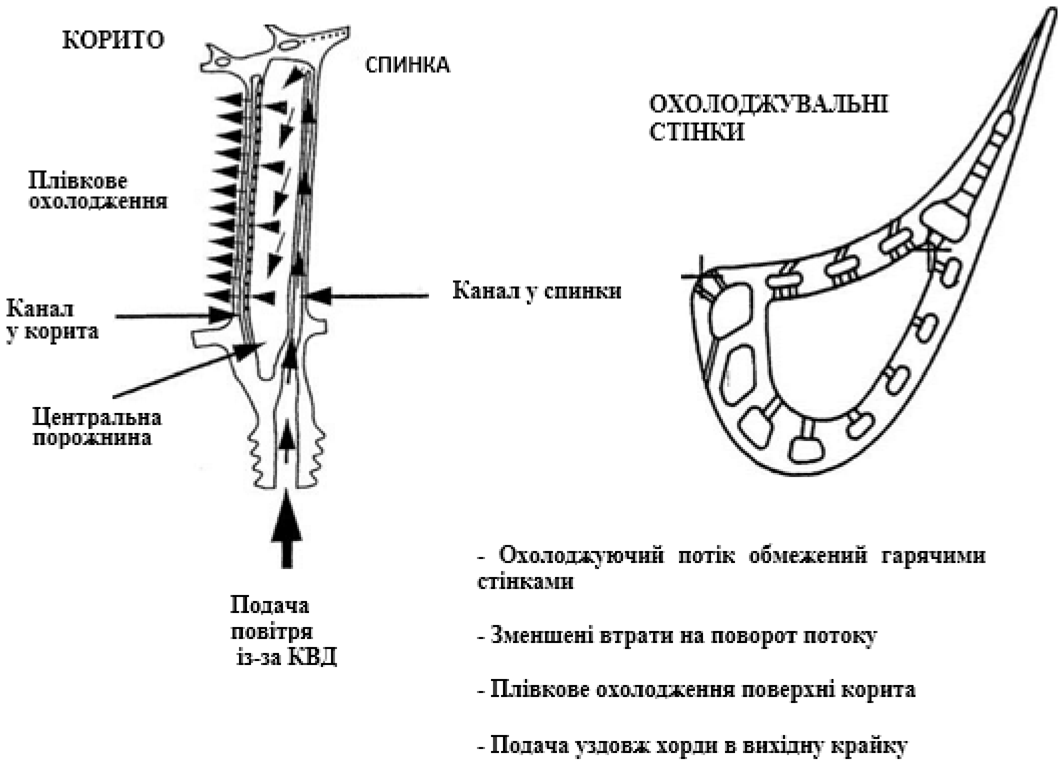


Figure 1.12 - Perspective cooling scheme "blade with cooled walls" of Rolls-Royce company

Porous cooling differs from film cooling by smaller size of holes (pores) and less orderly arrangement of them. The essence of porous cooling is that the air, passing through small holes (pores or perforations) in the blade wall, takes away heat from it and forms a continuous heat-protective layer on its outer surface.

The best result of the porous cooling scheme is given by the shell made of multilayer perforated material (Figure 1.13).

Studies of such blades show that with the rational arrangement of holes in the layers of the material, it is possible to increase the cooling efficiency by 1.5 ... 1.6 times compared to the blades of the channel design; practically maintain the aerodynamic perfection of the profiles at the level of modern cooled turbines and eliminate the disadvantage of porous shells is the rapid contamination of pores with dust and scale. This is achieved by making holes in the sheet material with a diameter of 100 ... 200 microns, while the maximum size of dust particles in the purified air is 15 ... 30 microns.

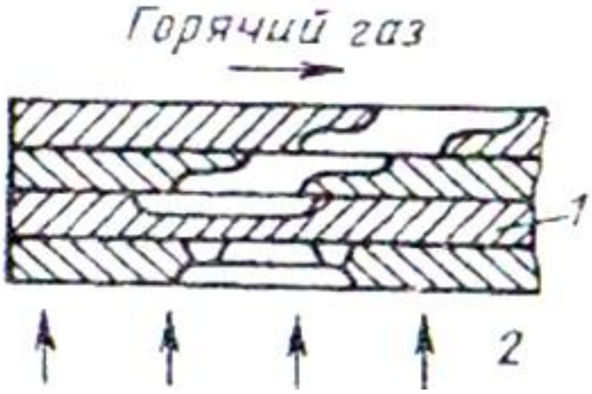


Figure 1.13 - Scheme of multilayer perforated material:
1 - multilayer material; 2 - cooling air

In conclusion, it can be noted that insufficient heat resistance of the material of porous shells does not allow to fully realize the effect of temperature increase. During long-term operation of the engine, the pores of the shell are clogged with solid particles of dust and combustion products, which also impairs the reliability of the cooling system.

SECTION 2

COOLING OF GAS TURBINE BLADES

2.1 The task of increasing the efficiency of convective cooling

Intensification of convective heat exchange can significantly increase the cooling efficiency of the CA or RC blade. There are a large number of works in the literature devoted to possible ways to intensify convective heat transfer. For example, physical processes in cooled blades with deflectors are considered by E. N. Bogomolov [4] and S. Z. Kopelev [5].

Of great interest as a means of intensifying convective heat transfer is the "vortex" method of intensifying heat transfer through the use of matrices of coplanar channels. Nagoga G. P. notes that "the use of more effective methods of heat transfer intensification is constrained by strict requirements and limitations, namely: technological and design availability for their industrial implementation in cast blades; operational stability of the properties of FTA; lack of influence of heat transfer intensifiers on the static and dynamic strength of thin-walled blade shells" [6]. The physical laws of heat transfer when using this method of intensification, its practical application are highlighted in the works of G. P. Nagog [6].

The optimization of the convective cooling system of the cooling blade as a whole is a complex problem due to the multi-criteria and multi-parameter nature due to the need for a trade-off between thermal, hydraulic and strength. The literature is dominated by attempts to optimize individual elements of the convective cooling system. Thus, the authors of [7] investigate the physical laws of flow in the element of the convective cooling system and optimize the shape of the guide element in the C-shaped channel of the loop cooling system. Figure 2.1 shows the design options considered by the authors.

In [7], a simple search of options was used based on their own experience and general physical laws without the use of optimization methods or the theory of experiment planning [8].

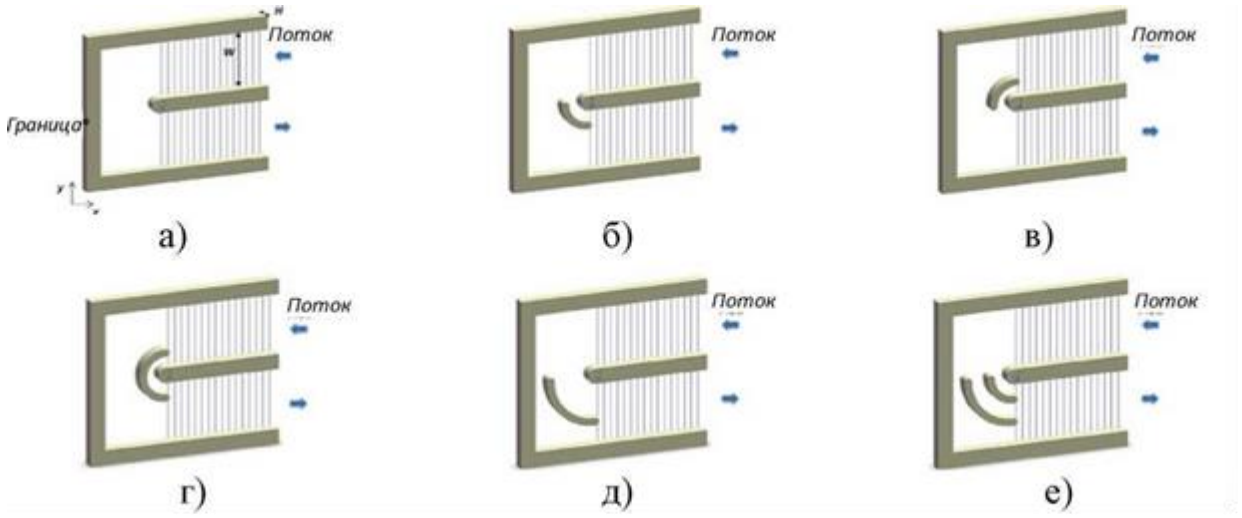


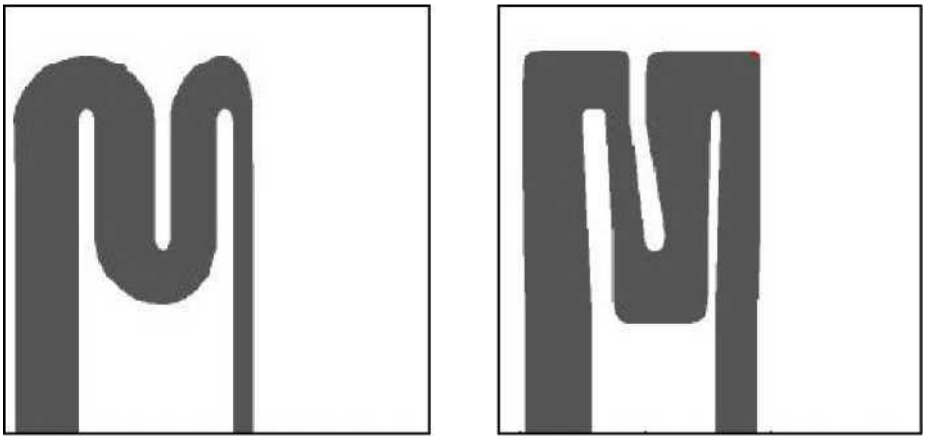
Figure 2.1 - Variants of the element of the loop cooling circuit.

The authors obtained ambiguous results: for the non-rotating cooling system of the SA, the best results were shown by options b) and c), for the rotating cooling system of the RL, options d) and e).

Thus, the search for ways to improve convective cooling efficiency even for its elements is difficult without the use of highly effective optimization methods. Thus, the use of genetic algorithms for optimization of the internal cooling system is the subject of work [9].

In [10], the optimization of thermal and strength of a model turbine blade with a loop cooling system was performed using indirect optimization algorithms based on self-organization. To determine the response of the system (thermal and stress state) to changes in variable parameters, finite element analysis was used without modeling the characteristics of the coolant and hot gas flow. Their contribution to the thermal state was taken into account by setting boundary conditions on heat transfer coefficients.

Figure 2.2 shows the initial and optimized versions of the geometry of the loop cooling system of the model turbine blade [10].



а) **б)**

Figure 2.2 - Initial (a) and optimized (b) geometry variants loop cooling system.

In the process of performing the task, the authors faced a serious problem of parameterization of the cooling system geometry and a large number of calculations required to solve the problem (more than 2000).

2.2 The task of increasing the efficiency of film cooling.

Further increase of gas temperature before the turbine leads to the fact that internal air convective cooling does not provide the required level of cooling efficiency and uniformity of its distribution. It is especially difficult to provide the required level of efficiency at the most heat-stressed areas (inlet and outlet blade edges, end surfaces between the blade channel). In these cases, it is necessary to use a barrier convective-film cooling of the blade for the entire blade or its sections. Air is blown onto the blade blade profile through perforation holes (holes of small diameter usually from 0.3 to 0.5 mm), the axes of which make an angle with the tangent to the surface. The angle of inclination of the hole to the blowing surface should be such that the negative gas-dynamic effect of the blowing jets on the gas flow is minimized. A significant number of domestic and foreign studies [4, 11] show that the optimal angles, in most cases, are close to 30 °.

Perforation holes that provide cooling air blowing on the blade surface are usually arranged in rows; hole sizes, pitches and angles of inclination are determined by the results of calculation and optimization works, both for individual elements and for the entire system as a whole. The number of factors affecting the characteristics of the film cooling system is significant. These include the features of the air flow in the internal channels of the blade, the gas-dynamic characteristics of the external flow, the position of the perforation row and the shape of the film cooling hole. The latter factor has the most significant impact on the characteristics of film cooling, so the study of the physics of processes during the operation of the film cooling hole, as well as the assessment of the impact of its parameters on the characteristics is widely covered in the scientific literature.

The work on the study of the characteristics of jets injected into the transverse flow has been carried out for a long time, but a detailed study of the physical laws of such processes in relation to the problem of film cooling began in the 80s of the XX century. One of the most complete and detailed works on this topic are [12] and [13]. They describe in detail the processes occurring in the film cooling hole during its operation in different modes. Figure 2.3 [13] shows the flow structure when blowing an air jet into a transverse flow at different velocity ratios.

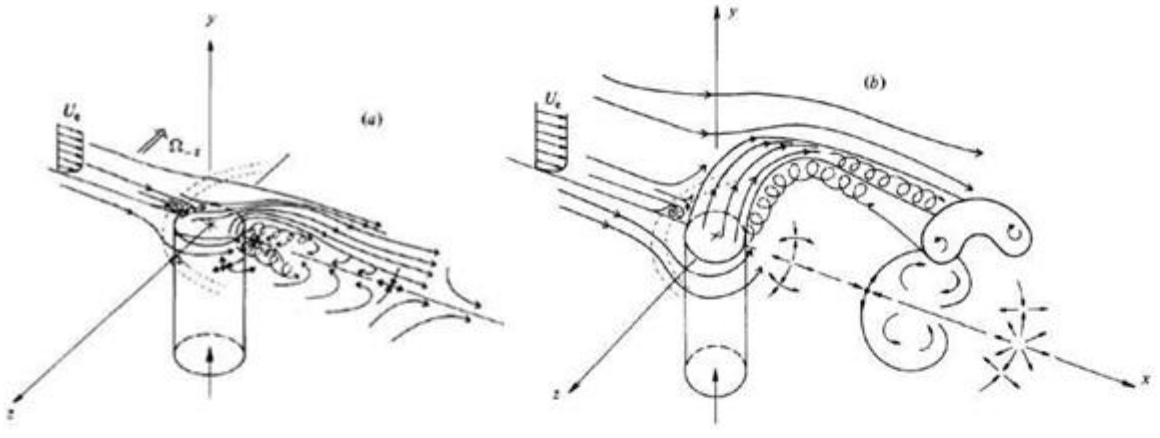


Figure 2.3 - Structure of the flow when blowing the air jet into the transverse flow at different velocity ratios: 0.5 (a); 2 (b)

The flow structure in the mixing region of intersecting jets is complex. It is important to note that the change in the jet blowing mode (the secondary flow momentum is less or much greater than the main flow momentum) significantly changes the flow pattern.

The common feature here is the mutual deflection of the jet and the cross flow. Their interaction changes with the distance from the blowout region: at the initial section, the jet is captured by the transverse flow, later the interpenetration and suction of the main flow under the jet begins due to the pair vortex that forms the jet in the transverse direction. At the blowing parameter $M > 1.5$, the jet penetrates much further into the transverse flow and retains its structure. This is decisive in the process of organizing film cooling, etc. To create a barrier veil, it is necessary to spread the coolant along the wall. In the eighties of the XX century, a large number of works were published on the experimental study of film cooling processes and determination of its characteristics [14].

The development of computing technology and methods of numerical gas dynamics in the nineties of the XX century made it possible to model some processes occurring during the blowing of secondary air jets into the crossflow, as well as to quantify the efficiency of film cooling organization by calculation. A significant number of articles devoted to numerical studies of film cooling processes and the influence of various factors on its characteristics have been published. The most interesting works include a series of four articles by D. K. Walters, J. H. Leylek [15]. The authors describe a systematic methodology that combines numerical simulation, experimental studies and theoretical explanation of the processes occurring during the organization of the film cooling process. The first paper [15] is devoted to the processes occurring during film cooling by means of cylindrical holes. A detailed verification of the applied numerical methods is carried out, and areas where CFD shows incorrect results are identified. The second article is devoted to the study of the influence of the angle of inclination of the cylindrical hole on the cooling characteristics. The third paper, following a similar structure to the first one, investigates the effect of different perforation hole shapes on the performance, and the fourth paper analyzes the effect of inclination angle for the two most promising hole shapes. Thus, the series of papers is a summary of the accumulated information on the processes occurring in film cooling and the influence of various parameters such as shape, inclination, operating mode on the cooling efficiency.

Figure 2.4 shows the two most common shapes of film cooling holes: cylindrical (a) and fan (b).

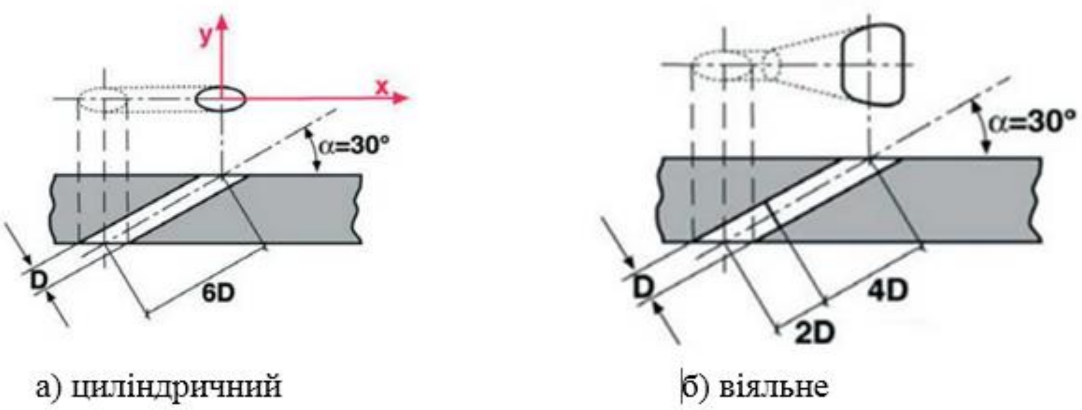


Figure 2.4 - The most common shapes of film cooling holes.

It should be noted that the methods of computational gas dynamics used by the authors [15] were far from perfect due to the poor development of computing resources and computational methods. The rapid growth and widespread use of CFD methods has led to the fact that in the first decade of the XXI century, a large number of works devoted to numerical studies of various aerodynamic processes, and in particular, film cooling processes, appeared in the scientific literature [16, 17, 18, 19].

The size of the computational grids, the amount of computational resources spent, as well as the accuracy of the results have increased significantly. Most of the authors used a model statement of the problem, using a flat plate with a hole with a diameter i = 3...5 mm to ensure the gas-dynamic similarity in terms of Reynolds number with the possibility of qualitative measurements. A little later, attempts were made to model film cooling on the blade surface, taking into account the rotor rotation and features of the gas-dynamic flow of the blade profile [20].

With the development of process modeling tools, the task of improving the performance of the cooling system by optimizing its elements became more and more urgent.

As noted above, the film cooling system is a multi-row system of perforation holes, depending on the gas temperature level, covering either the most important and heat-stressed areas of the profile (inlet edge of the blade) or the entire surface of the profile. The obvious way of optimization is the rational distribution of rows of film cooling holes along the profile. However, the multi-parametric nature of the interaction of gas-dynamic and thermal efficiency, the peculiarities of the cooling blade profile flow, the complex nature of the pressure distribution along the profile leads to the fact that the solution of such a problem is very difficult.

In this formulation of the optimization problem, it is necessary to take into account the parameters of the external hot gas and internal cooling air. Changing the position of the perforation rows has serious limitations due to the influence of the cooling air parameters in the internal cavity on the flow regime from the holes. This is due to the change in the characteristics of the cooler during the flow inside the blade, as well as the design features of the internal cooling system.

In this case, the total number of variables to be varied for a modern cooling blade exceeds 100. When using the most common optimization methods, such as response surface methods, genetic algorithms, several thousand calls to the computational model are required for optimization. The optimization process can take several years, which eliminates the feasibility of such studies. Therefore, the tasks of optimization of film cooling in most cases are set for its individual elements (position of perforation holes on the surface of the profile, changing the shape of the holes, changing the parameters of the cooling air), and their mutual influence is taken into account either in boundary conditions or by conducting additional calculation studies.

In general, the optimization of the cooling system is usually understood as the search for such a blowing scheme at which the required level of wall temperature would be achieved at the lowest total coolant consumption [4].

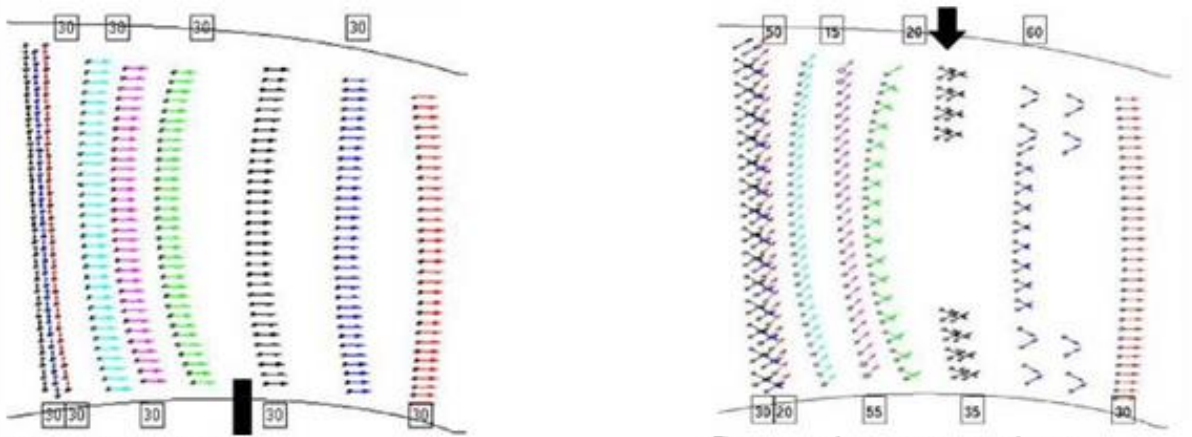
The literature presents various attempts to optimize the film cooling system based on computational models of different levels. For example, Bogomolov O. M. considers an algorithm for finding the optimal position of the perforation rows on the inlet edge and the surface of the cooling blade profile. As a calculation model, the algorithm for calculating the wall temperature and cooling efficiency, based on the numerical solution of the equation of heat conduction and balance of heat fluxes by the Monte Carlo method in a flat formulation, is used. The results of calculations by an approximate method show the practical applicability of this approach in the design of a film cooling system [4].

When using such an approximate approach, the gas-dynamic features of the profile flow, the features of the cooling air parameters in front of the perforation rows, for example, the change of the blowing parameter along the height of the internal cooling channels, etc. are ignored.

These factors can be partially taken into account in numerical calculations of viscous three-dimensional flow of a compressible heat-conducting gas. The authors of [21] performed the process of optimizing the position of the perforation rows on the cooling blade of the nozzle apparatus using this approach to numerical calculations. In the article, the position of the perforation holes on the blade surface was optimized, while the internal heat transfer and hydraulics were not modeled, but taken into account using boundary conditions. The perforation holes were set by discrete sources of cooling air blowing, which leads to a significant error in determining the blowing parameter and flow regime in the hole.

For optimization, the authors used genetic algorithms [22]. In general, these are search algorithms that solve optimization problems by random selection, creating combinations and varying parameters using mechanisms close to natural selection in nature. The authors used a significant number of variables to be varied, which required 600 design points just to create the initial population. During optimization, 13 generations of additional populations of 100 design points were performed. The total number of design points was almost 2000. At the same time, the authors managed to achieve a significant reduction in the blade surface temperature while optimizing the amount of air flow used (Figure 2.5).

Thus, the technology used by the authors allowed to provide a significant increase in cooling efficiency, but required a huge amount of time and computing resources. Such shortcomings will lead to serious difficulties in the application of such optimization methods in the real design process.



а) вихідний варіант

б) оптимізований варіант

Figure 2.5 - Comparison of the initial (a) and optimized (b) variants of the perforation holes position on the CA blade

The second, most significant aspect of improving the film cooling system is the optimization of the shape of the film cooling holes. This area of research has been actively developing since the late eighties of the XX century.

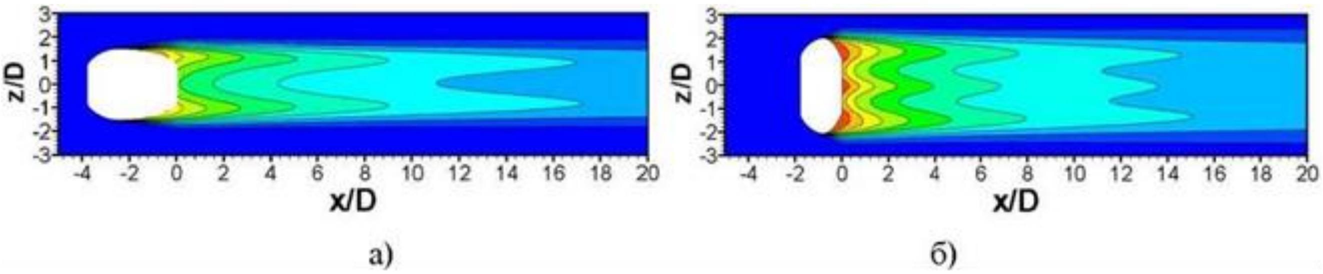
The general principle of operation of perforation holes of complex shape, for example, fan-shaped (Figure 2.4 (b)) is to inhibit the flow before blowing onto the washed surface. In this case, there is a decrease in the local blowing parameter simultaneously with an increase in the area washed by the cooler. Accordingly, it is advisable to optimize the optimization process by changing the shape of the outlet section and the internal structure of the orifice in the area of flow inhibition. Then the problem is reduced to optimizing the shape of the diffuser channel.

A small number of works on optimization of the shape of the film cooling hole have been published in foreign scientific literature. Most of the works were carried out in 2008 - 2012, which is associated with the further growth of available computing resources and the gradual improvement of optimization methods. The main differences between the works will be the current optimization methods and the formulation of the optimization problem in the field of determining the variables.

The most successful works on optimization of the shape of film cooling holes include the articles by Ki - Don Lee, Kwang - Yong Kim [23, 24]. In [23], the authors optimized the fan hole to improve the efficiency of film cooling. To carry out the optimization, the authors used methods for building substitute models, such as the response surface method, radial basis functions, etc.

To obtain the characteristics of the considered hole designs, the authors used numerical simulation. Four variables were used as variables: the angle of inclination of the hole, the angle of transverse opening, the angle of trimming the edge of the hole and the ratio of length to diameter. The film cooling performance was evaluated by the cooling efficiency averaged over the area behind the hole. Due to the large number of design points required to build a replacement model, the authors had to perform 35 calculations using experimental design methods. The number of calculations required to build a replacement model for all the optimization methods considered by the authors [23] exceeds the degree dependence N = 2, where N is the number of design points required to build a replacement model; to is the number of variables varied. It should be noted that in [23], after building a substitute model and optimization, a significant increase in optimization criteria was obtained.

The cooling efficiency for the original and optimized holes is shown in Figure 2.6 [23]. The increase in cooling efficiency was 34% compared to the original shape of the outlet cross-section of the perforation hole.



a) б)

Figure 2.6 - Cooling efficiency for fan undercut (a) and optimized (b) film cooling holes

Thus, it is possible to significantly increase the efficiency of film cooling by optimizing the shape of the outlet cross-section of the perforation hole. Such an increase in efficiency makes it possible to significantly increase the gas temperature before the turbine without reducing the resource.

Film cooling with the help of a large number of perforation holes is mainly used in the TWT, which is due to the general level of gas temperature at the inlet. However, when organizing the cooling of some elements of the TNT, namely the first nozzle of the low-pressure turbine, it is necessary to solve the problem of eliminating local overheating associated with the inhomogeneity of the hot gas flow after the interturbine transition channel, such as the influence of the geometry of the racks, flow breaks in the case of the use of an "aggressive" channel. In this case, the use of perforation holes with a complex, profiled shape of the outlet section allows to organize effective cooling by using a minimum number of holes and, accordingly, with minimal coolant consumption.

And all this makes the task of optimizing the outlet cross-section of the perforation hole relevant. Widespread optimization methods on substitutive models make it possible to provide a significant increase in the efficiency of film cooling. However, such methods require a large number of numerical calculations to solve the optimization problem.

2.3 Improvement of gas turbine design parameters.

Improvement of the cooling gas turbine involves ensuring the maximum possible characteristics of the turbine (specific power, efficiency) while reducing the size, number of blades, weight of the main parts and increasing aerodynamic efficiency.

A large number of articles are devoted to the optimization of the aerodynamic characteristics of the turbine by re-profiling the blade rims or meridional contours, for example, the work of CIAD [3], in which the re-profiling of the blade rims of the TNT was performed.

The possibilities of reducing the weight of the most loaded parts of the GTE turbine, especially blades and disks, are seriously limited due to the severe working conditions of the parts and the limitations imposed by the material properties.

The rotor is the most critical element of the turbine, as it, unlike the stator parts, is subjected not only to mechanical and thermal loads, but also to centrifugal and dynamic loads associated with its rotation. Rotor parts are critical for the cyclic life of the turbine. When a turbine rotor fails, it is almost impossible to localize the damage inside the casing. Thus, achieving a significant reduction in rotor weight compared to existing designs is an extremely difficult and expensive task.

Reducing the weight of stator parts by reducing the amount of material (part thickness) also faces significant limitations. Since turbine casings are included in the power scheme of GTE and are essentially shells with different types of profiles (cylindrical, stepped, conical, etc.), a significant number of different requirements are also imposed on these parts.

Turbine casings must provide the necessary strength characteristics, shape stability, ensuring the tightness of flange joints, impermeability - localization of damage inside the casing in the event of destruction of rotor parts, for example, blade breakage or disc destruction.

The need to meet all the above requirements, severe working conditions in terms of temperature and stress-strain state also impose significant restrictions on the possibility of reducing the weight of stator parts of the cooling turbine.

In this regard, the most promising way to reduce weight is to reduce the longitudinal dimension of the turbine. Such a design change allows to provide a significant weight reduction. The maximum result can be obtained by reducing the number of stages, but there are also serious limitations associated with the peculiarities of aerodynamic design and the principle of operation of the axial gas turbine.

Professor A. A. Inozemtsev notes that "insufficient value of the circumferential speed for the required specific work leads to an increase in aerodynamic load" [1].

In HST, the maximum possible peripheral velocity is limited by the strength and mass of the disc, and in HST - by the maximum permissible rotation frequency of the low-pressure stage due to the restrictions on the peripheral velocity at the ends of the fan blades due to the significant noise level, as well as the weight and dimensions of the HST itself. These restrictions on the value of the distributed peripheral speed in the TNT lead to a significant reduction in the maximum possible degree of expansion in one stage. As a result, the number of stages in the TNT in civil turbofan engines with a significant degree of dual-circuit is much higher than in the TVT. In a modern PDE, a high-pressure turbine can have one or two stages, while a low-pressure turbine in most cases has five or six stages, but their number can be up to eight. These factors seriously limit the possible reduction of the longitudinal dimension of the turbine, and, accordingly, its weight by reducing the number of stages.

However, for civil turbines there is another reserve to reduce the length and weight of the turbine. It consists in reducing the length of the transition channel between high and low pressure turbines. The need to use a transition channel between the turbine cascades is due to the desire to raise the level of peripheral speed in the HPT to obtain the required level of efficiency. Limitations on the level of rotor speed of the HPT due to the requirements for fan noise in the PDE leads to the need for a serious (two or more times) increase in the average diameter in the HPT compared to the PDE. A transition channel is used for gas-dynamic matching of flowing parts and ensuring the flow transition from the fuel element to the TNT with a minimum level of losses.

CONCLUSIONS TO SECTION 2

1) Due to the high level of perfection of modern GTE, the main reserves for improving the characteristics and creation of advanced engines are to increase the aerodynamic and thermal efficiency of GTE elements and components by optimizing their shape and geometric parameters.

2) The main directions in the development of modern gas turbines are to increase the gas temperature in front of the turbine to increase the effective efficiency of the engine and improve specific parameters by reducing weight and increasing aerodynamic efficiency.

3) Development of a way to increase the efficiency of the elements of the flow part of the turbine and the cooling system makes it possible to comprehensively improve the cooled turbines.

4) Optimization of the shape of the outlet section of the film cooling hole allows to significantly increase the cooling efficiency at high blowing parameters.

SECTION 3. OPTIMIZATION OF FILM HOLES COOLING

The results of optimization of the meridional contour of the "aggressive" interturbine transition channel are based on the analysis and justification of the studies presented in [25 - 40].

3.1 Summary of information about film cooling holes

With a constant increase in the temperature level in the turbine, one of the most difficult and urgent problems is the development of effective cooling systems. To cool the most heat-stressed parts of the turbine, such as nozzle and blades, the convective-film cooling method is widely used, in which a significant role is played by the formation of a curtain of cooling air on the surface of the object, which protects it from the effects of hot gas.

When implementing the convective-film method of cooling to ensure the required level of efficiency of the air curtain, a large number of small diameter perforations are used, which leads to problems with ensuring the strength and deterioration of the manufacturability of the cooled turbine elements. Therefore, when designing a system of film cooling of turbine elements, it is necessary to perform multi-parametric optimization of the following criteria: increasing the efficiency of the curtain, increasing the surface area cooled by one hole, minimizing the required number of perforation holes, hydraulic resistance of the film component of the cooling system, which leads to minimization of the required coolant flow rate.

Modern manufacturing technologies allow to produce complex shapes of miniature elements of cooling systems. It is known that the introduction of preliminary twisting of the cooler flow [25] or vortex energy separators can increase the efficiency of film cooling. However, such methods of intensification of the film component have certain difficulties when implemented in engine conditions.

In the current conditions, the task of optimizing the shape of the film cooling holes comes to the fore. It is the shape of the holes that has recently become the most significant factor considered by researchers to improve the cooling system. A significant number of both domestic and foreign scientific works [26 - 28] are devoted to the study of the processes occurring in the film cooling hole during the organization of the air curtain. The authors consider the peculiarities of the cooling air flow from the holes, at different operating modes of the cooling system, different speeds of the main flow and blowing parameters *M*. The blowing parameter is the ratio of the pulses of the secondary and main flow, which is calculated as:

$$M = \frac{\rho_{\text{г}} \cdot c_{\text{г}}}{\rho_{\text{в}} \cdot c_{\text{в}}}, \qquad (3.1)$$

where ρ is the density and flow rate;

index "c" - refers to the cooler flow;

index "g" - to the main hot gas flow.

In [29,30], a strong influence of the vortex structure of the main flow and twisting of the cooler jets on the parameters of the resulting curtain was established. As an example, Figure 3.1 shows the idealized shape of the cooler jet and the structure of its paired vortices [29].

Figure 3.1 shows that the flow pattern in the area of the optimal curtain has a complex complex character. A significant number of geometric and physical parameters affect the cooling characteristics provided by the use of perforation holes of complex shape. Therefore, to solve the optimization problem based on the results of numerical simulation by constructing a full factorial experiment, a significant number of numerical calculations are required.

The regime parameters that have the greatest impact on the efficiency of film cooling include the blowing parameter, the ratio of the cooler density to the main flow, the intensity of the cooler turbulence and the main flow, as well as the pressure gradient and the parameters of the boundary layer on the cooled surface.

Figure 3.1 - Scheme of the idealized vortex structure of the cooler jet at the flow from the hole of complex shape

The geometric parameters of the film cooling orifice have a great influence. Regardless of the type and shape of the hole used, they include: the angle of inclination of the cross-section of the hole, the distance between adjacent holes, the angle of installation in the hole of the main flow, the length of the hole, as well as the shape of the outlet cross-section of the hole [31]. For some parameters, based on the results of a large number of experimental studies, a recommended range of values was obtained that ensures maximum cooling efficiency. For example, for the angle of inclination of the orifice, the recommended values are between 25° and 45°, which is a compromise between cooling efficiency and manufacturability of the orifice.

The main opportunities to increase the efficiency of film cooling are to change the shape of the outlet section of the hole, etc. In the use of perforation holes of complex shape. It is in this direction of optimization that the greatest increase in the efficiency of film cooling was achieved. Comparison of holes with a complex shape of the outlet section with classical cylindrical holes is given in [26, 27, 29].

To date, there is no known successful attempt to solve the complex problem of film cooling optimization, which is explained by the large number of optimization parameters and the complex nature of their mutual influence, despite the fact that a significant number of works devoted to the study of these processes are known. The complexity of the physical process that occurs when the coolant jet is blown into the main flow is proved by the number of vortex structures formed during this process.

Figure 3.2 shows the main vortex structures that are formed when the coolant jet is blown into the transverse gas flow. They include: a horseshoe vortex in the area of the jet blowing out, transverse shear vortices in the contact between the coolant jet and the main flow, paired vortices that carry the coolant bulk and cause its mixing with the main gas flow, as well as associated vortices that arise between the coolant bulk and the stagnant zone between it and the wall.

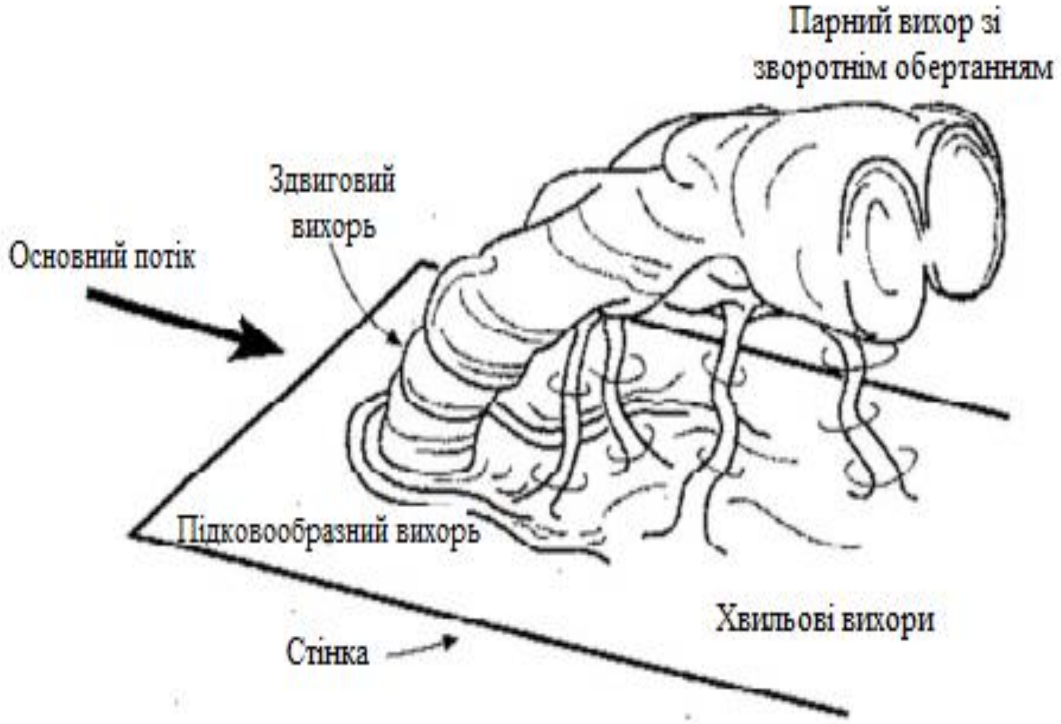


Figure 3.2 - Basic vortex structures of the cooler jet at the flow from the orifice.

The complexity of the interaction of these vortices with each other and the dependence of the flow on the geometric parameters of the holes makes the process of modeling and improving the shape of the holes difficult. The problem is complicated by the fact that in most works the research is carried out on model problems (isolated film cooling hole on a flat plate). However, even solving the optimization problem for an isolated film cooling hole in model conditions allows us to hope for a significant increase in cooling efficiency, as shown in [26, 28] and confirmed by the results of experimental studies.

Classical cylindrical film cooling holes have a number of significant drawbacks. These include a strong dependence of the cooling efficiency on the hole blowing parameter. Schematically, the structure of the cooler flow from a cylindrical hole at different blowing parameters is shown in Figure 3.3. The cylindrical perforation hole is effective only at low blowing parameters M = 0.5 ... 0.8 (Figure 3.3 a), b). When the blowing parameter is increased to M = 1 (Figure 3.3 c) and higher, the coolant jet penetrates deeply into the hot gas flow, and their intensive mixing without forming a cooling air veil on the surface.

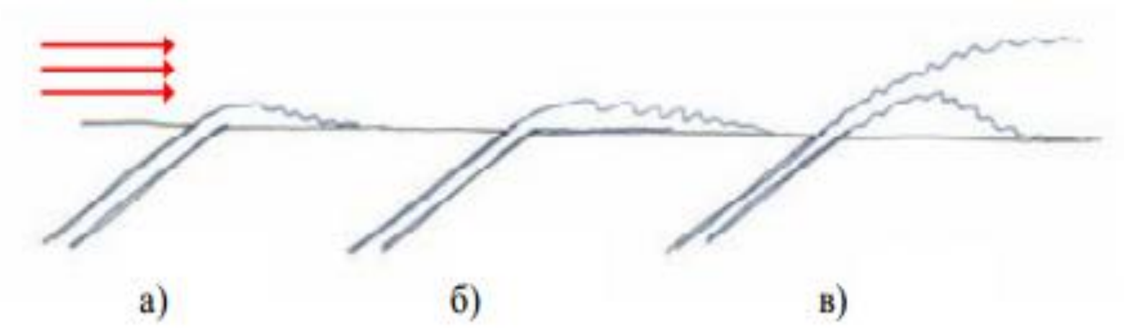


Fig. 3.3 - Structure of the cooler flow from the cylindrical hole at different blowing parameters.

In a modern high differential flow cooling turbine, the greatest problems with the organization of film cooling arise in areas with high main flow velocities. These include the areas on the blade back (area 2 in Figure 3.4) and on the end surfaces for the SA or the trajectory shelf of the blade also on the back side (area 1 in Figure 3.4). The position of these regions on the CA is shown in Figure 3.4.

It should be noted a significant level of cooling air pressure in the internal cavities of the blades. This is due to the need to overcome the high hydraulic resistance of the convective cooling system due to the presence of heat exchange intensifiers and to ensure high intensity of convective cooling due to the maximum heat transfer coefficient on the inner walls of the blade.

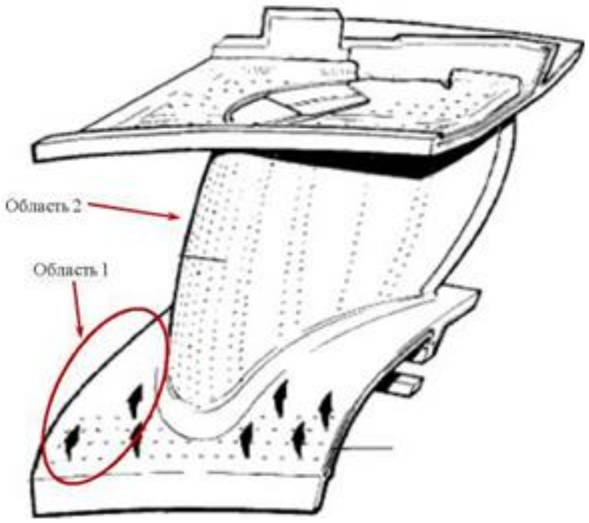


Figure 3.4 - Areas of difficult organization of film cooling on the turbine nozzle.

All this together leads to the fact that in the above areas there are large blowing parameters $M > 1$. At such conditions standard cylindrical holes will be ineffective. To ensure high-quality film cooling, it is necessary to slow down the flow of cooling air before the formation of the cooler curtain on the wall and to ensure the distribution of the cooling air curtain on it.

This task is effectively solved by using perforation holes of complex shape. There are a large number of different shapes of film cooling holes. A common feature of most of them is the presence of a diffuser area before the exit from the hole, where it becomes possible to inhibit the flow and thus ensure high cooling efficiency at high blowing parameters.

The most common film cooling holes are fan-shaped holes. In this hole design, the diffuser area is formed by expanding the hole in the transverse direction. This type of film cooling hole gives greater efficiency than a cylindrical hole and at the same time has acceptable manufacturability. The combination of these factors led to the widespread use of holes of this shape in real turbine designs of modern turbofan engines, as shown in Figure 3.5.

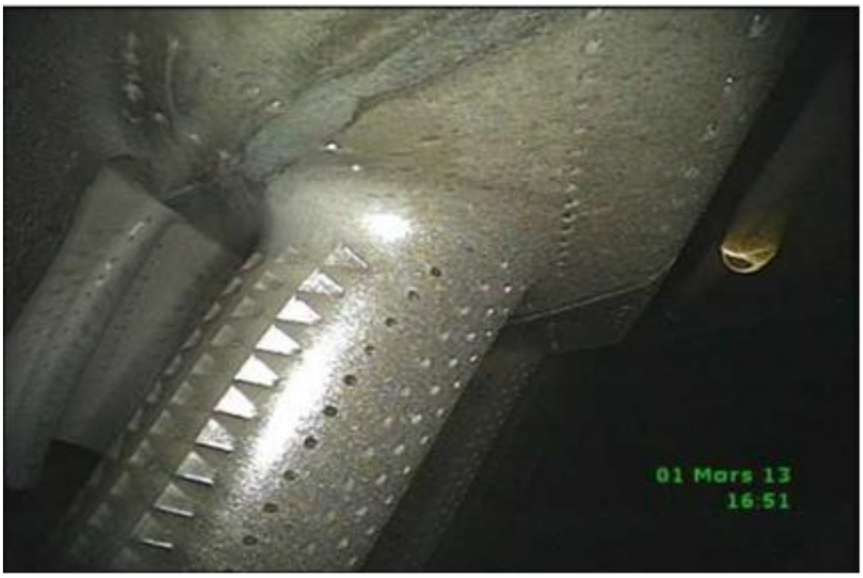


Figure 3.5 - Fan-shaped perforation holes on the nozzle apparatus of the TVT.

In addition to the fan, there are a large number of other designs and shapes of film cooling holes.

One of the most complete and detailed reviews of various shapes of film cooling holes is [32]. In it, Saumweber describes the six most common and typical shapes of film cooling holes, named according to the shape of the projection of the outlet cross-section: cylindrical hole, oval, fan, oval fan, conical and slotted (CONSOLE). Figure 3.6 shows sketches of the shapes of the holes under consideration.

The minimum number of initial options for the shapes of holes for structural and parametric optimization is five. The holes considered in [32] can serve as initial variants for structural-parametric optimization, as they have different shapes and cooling efficiency, which will ensure the completeness of the information space of the principal components for building a structural replacement model.

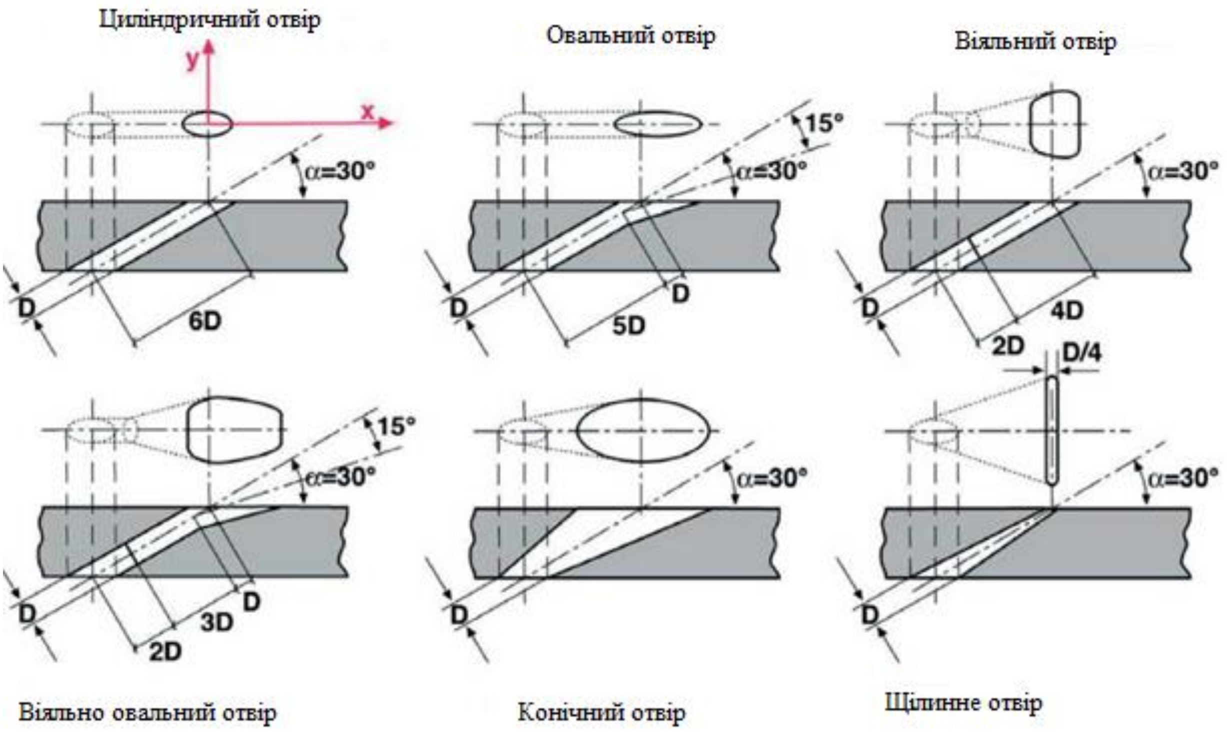


Figure 3.6 - Main types of film cooling holes**.**

All the considered holes are described in the open scientific literature. A large number of articles are devoted to the study of the characteristics of cylindrical and fan-shaped holes, including oval holes [24, 26, 27]. Conical holes and their application for the organization of film cooling were considered and described by A. Yosif in [33] and H. Zuniga in [34]. Slotted holes of CONSOLE type were described by J. Sargison in [35]. This type of holes differs from others in that its cross-section changes from almost circular at the inlet to slotted at the outlet. Figure 3.6 shows that in the frontal view the cross-section of the hole narrows, and in the top view it widens. However, the narrowing in the frontal view is more significant, which leads to a decrease in the cross-sectional area at the outlet of the orifice, and, accordingly, to the acceleration of the flow from the inlet to the outlet. Thus, the maximum flow velocity is achieved at the outlet of the orifice. However, the small thickness of the cooler jet and its large width in the transverse direction provide good film cooling efficiency according to the experimental study in [35].

The solution of the optimization problem for a film cooling hole using the radial basis function neural network method in [23] required 35 CFD calculations using only four variables: the angle of inclination of the hole, the angle of transverse opening, the angle of trimming the edge of the hole and the ratio of length to diameter. By applying the developed optimization method, this number should be reduced several times.

To perform the structural-parametric optimization, the cooling efficiency characteristics for all the holes considered are required. The characteristics can be obtained by calculations on a verified three-dimensional numerical model.

3.2 Development of a numerical model of the film cooling hole and its verification.

To obtain the cooling efficiency of all the considered types of holes, numerical simulation was performed. The computational domain for 3D calculations in the ANSYS CFX 14.5 software package is shown in Figure 3.7. In accordance with the Saumweber experiment, large diameter holes were used (for a cylindrical section D = 5 mm).

The adiabatic efficiency of film cooling was used as the orifice characteristics, which is formulated as:

$$\Theta = \frac{T_{\text{Г}} - T_{\text{ст}}}{T_{\text{Г}} - T_{\text{в}}} \qquad (3.2)$$

where Tg is the gas temperature;

Tst - wall temperature;

Tc - cooler temperature.

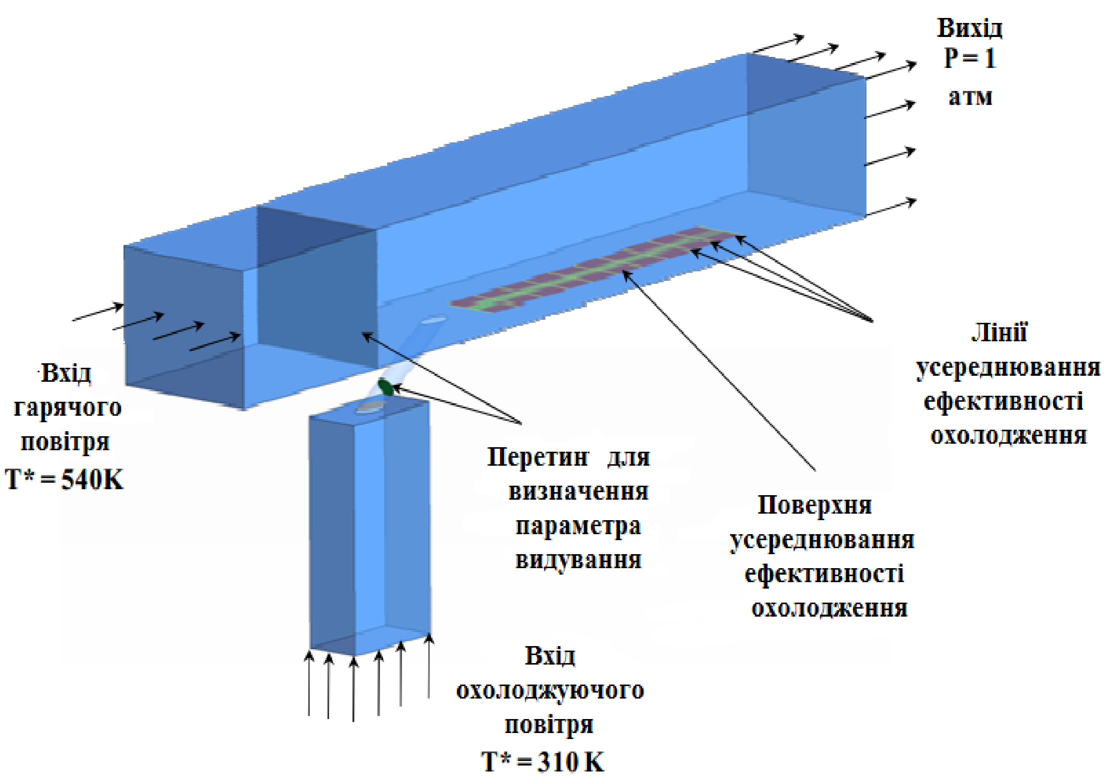


Figure 3.7 - Computational domain for numerical simulation.

For calculations, the Navier-Stokes equations averaged over Reynolds (RANS approach) were used with the closure of the system of equations using the SST turbulence model [36]. In a large number of works devoted to modeling and analysis of film cooling processes, the SST model is used [23, 24, 38]. Bardina in [37] showed that the SST turbulence model better predicts the flow separation than other turbulent viscosity models, which allows more accurate modeling of heat transfer in the boundary layer.

The computational domain consists of a main channel with hot gas, a cavity with a cooler and a film cooling orifice (Figure 3.7). The main channel has a length of 35 orifice diameters, which ensures equalization of flow parameters upstream and downstream of the orifice. All boundary conditions were chosen according to the experimental studies of Saumweber [32] and are given in Table 3.1.

Table 3.1 - Boundary conditions of calculations

Boundary conditions	The value of the value
Full pressure of hot gas at the inlet, *Pg**	100400 Pa
Static pressure of hot gas at the outlet, P_{ou} t	93500 Pa
Hot gas temperature, Tg	540 К
Cooling air temperature, Tc	310 К
Blowing parameter, *M*	0,5; 1; 1,5; 2,5
Intensity of hot gas turbulence, Tu	5 %

The computational mesh for the calculations was built in the software package ANSYS ICEM CFD 14.5. Unstructured tetrahedral mesh with prismatic layers on the walls was used for correct modeling of the boundary layer. The mesh in the boundary layer was constructed in such a way as to achieve the dimensionless height of the first cell $\boldsymbol{y}^+ = 1$. This value is defined as:

$$y^+ = \frac{\Delta y^* \cdot u^+}{u}, \qquad (4.3)$$

where Δy^* is the height of the first cell of the calculation grid;

and$^+$ - shear flow velocity near the wall;

V is the kinematic viscosity of the flow.

At $\boldsymbol{y}^+ = 1$, direct modeling of the viscous sublayer in the boundary layer is performed, without the use of functions, which increases the accuracy of modeling. The height of the first cell of the computational grid in the studied areas was 1e-6 m.

To check the influence of the design mesh on the obtained cooling efficiency values and also to determine the optimal number of nodes of the design mesh, a preliminary lattice convergence study was performed. Figure 3.8 shows the distribution of cooling efficiency averaged across the plate obtained on grids with different number of nodes: from 600 thousand to 5 million nodes.

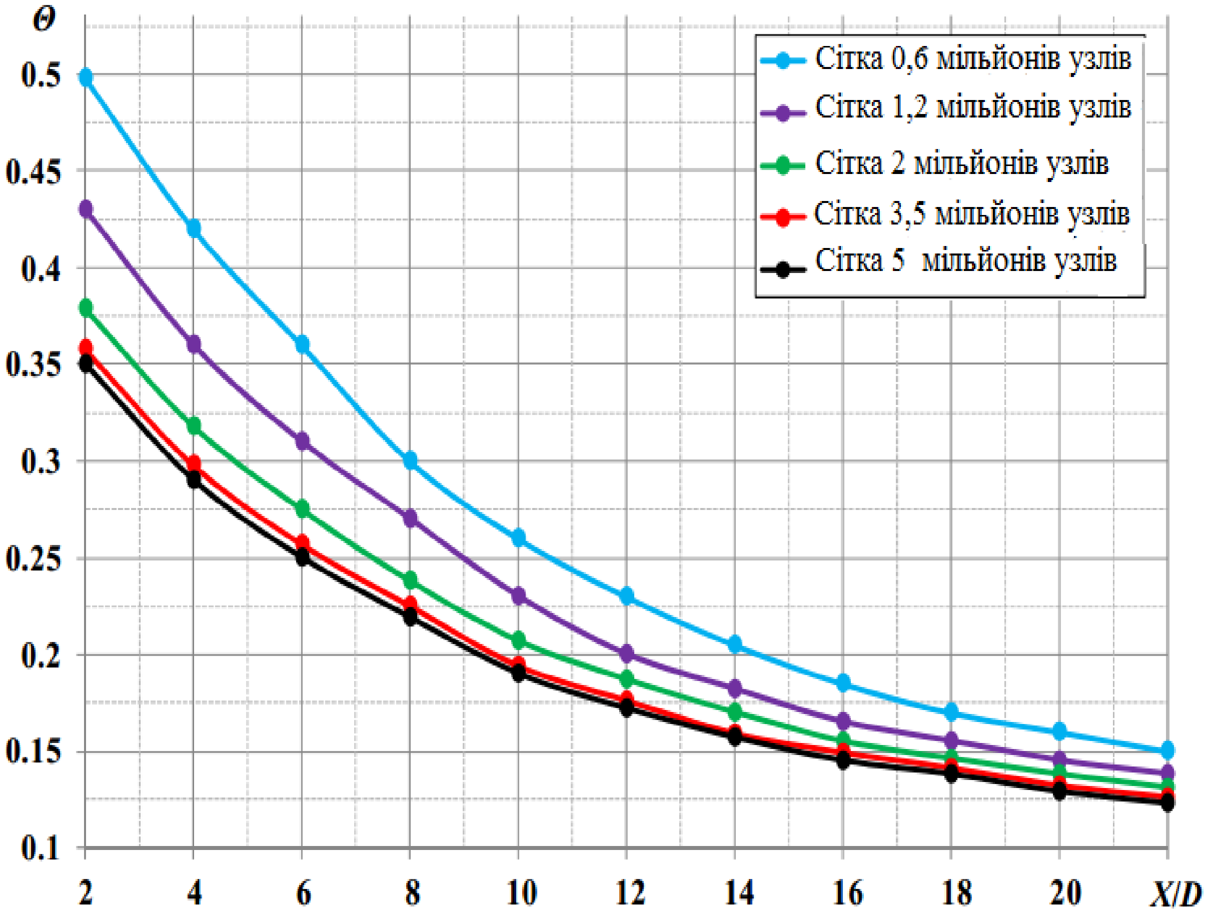
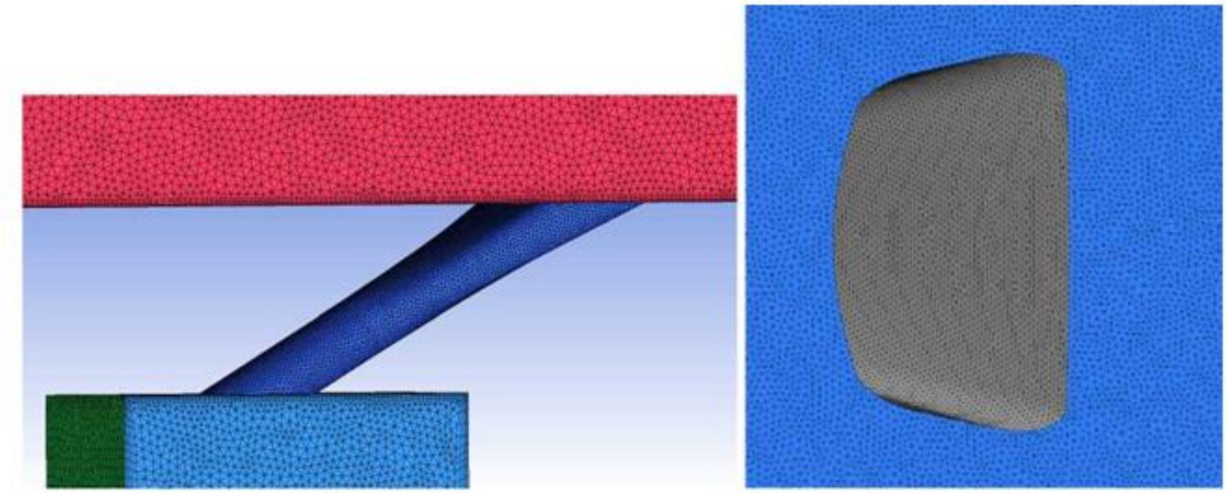


Figure 3.8 - Results of mesh convergence studies

Calculations were performed for fan holes of film cooling. Increasing the number of calculated nodes in the grid to a certain limit reduces the predicted value of cooling efficiency on the plate closer to the hole and brings the predicted values closer to the experimental data. The results for the meshes of 3.5 million nodes and 5 million nodes are practically the same. Accordingly, the optimal number of nodes of the computational grid is 3.5 million. This grid dimension was chosen for further calculations. The general view of the selected computational grid is shown in Figure 3.9.



а) б)

Figure 3.9 - General view of the design mesh (a) and the original cross-section of the hole (b)

To verify the computational model, the cooling efficiency of fan holes was calculated. The fan hole was chosen because there is a large amount of experimental data for this type of hole, and the flow in it is characterized by the complexity of the nature and the presence of a gap in the central region of the hole, since there is a flow inhibition due to the diffuser nature of this area of the hole.

When setting the task of structural-parametric optimization, it was decided to use the surface-averaged cooling efficiency as an optimization criterion, so much attention was paid to this characteristic during verification.

Figure 3.10 shows the calculated and experimental values of cooling efficiency averaged over the surface, depending on the blowing parameter. Area averaging was carried out over a rectangle with the main axis coinciding with the projection of the hole axis, the length of this region was 22D width ± 2D.

The results of calculations for fan holes are in good agreement with the experimental data, both for low and high blowing parameters, the deviation does not exceed $\Delta\Theta = 0.02$. For the cylindrical hole, the maximum deviation from the experiment was obtained for the blowing parameter $M = 0.5$ and was $\Delta\Theta = 0.04$.

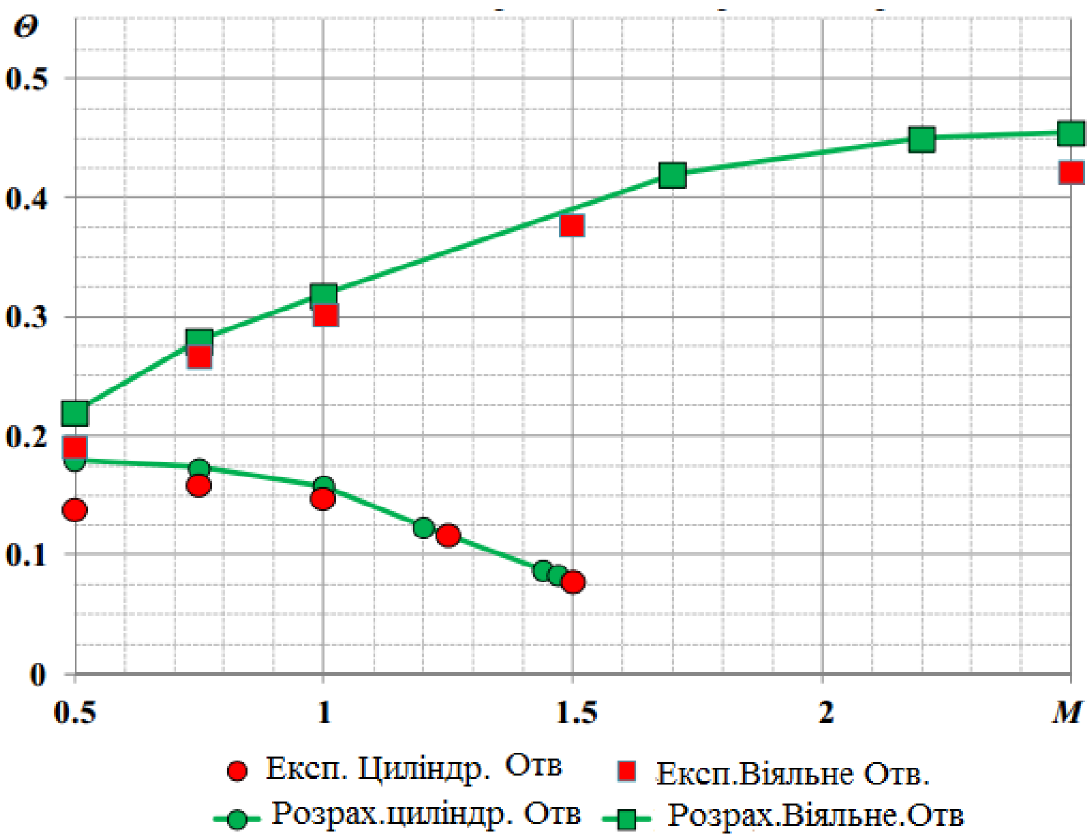


Figure 3.10 - Calculated and experimental values of cooling efficiency, averaged over the surface, depending on the blowing parameter for cylindrical and fan holes

At a low blowing parameter M = 0.5, a good agreement with the experimental data was obtained along the entire length of the plate, the average deviation from the experiment for this mode does not exceed $\Delta\Theta = 0.02$. At a high blowing parameter, the calculation overestimated the level of cooling efficiency relative to the experiment in the first half of the plate length ($2 < X/D < 6$), while in the middle part of the plate ($10 < X/D < 16$) the calculation results are in good agreement with the experimental data. On the far from the hole part of the plate the calculated values of cooling efficiency are slightly lower than the experimental data.

Figure 3.11 shows the distribution of cooling efficiency averaged across the plate for fan holes for two operating modes M = 0.5 and M = 2.5.

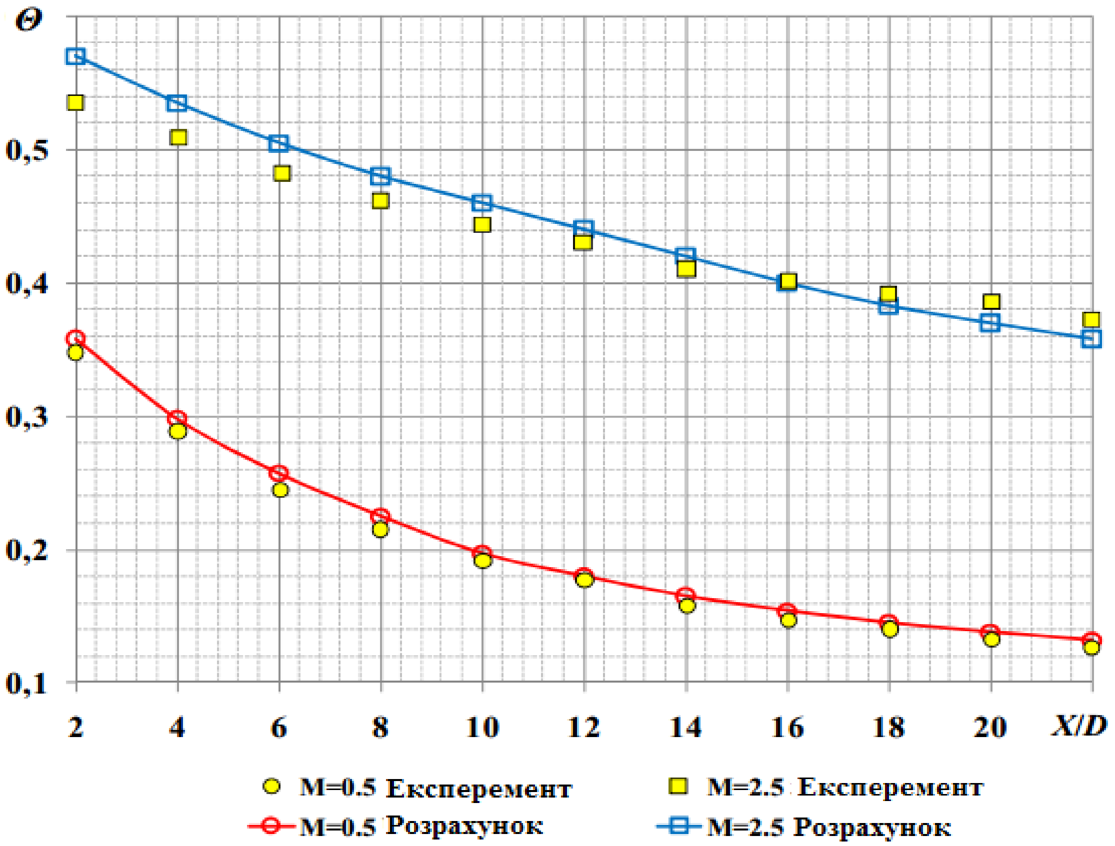
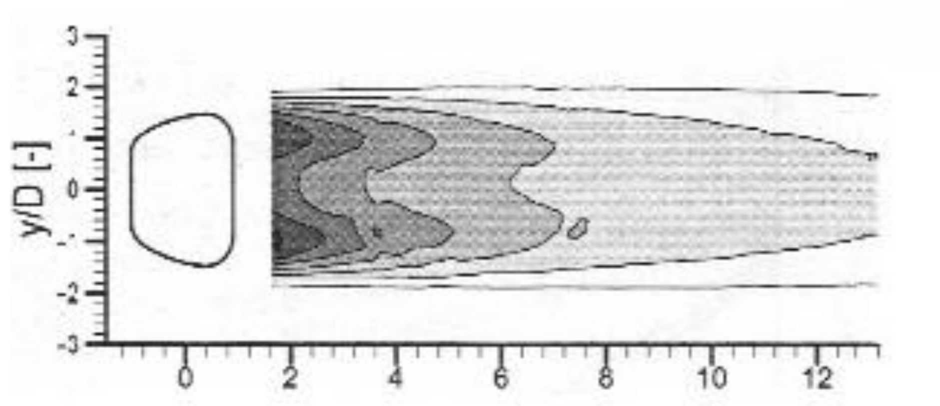


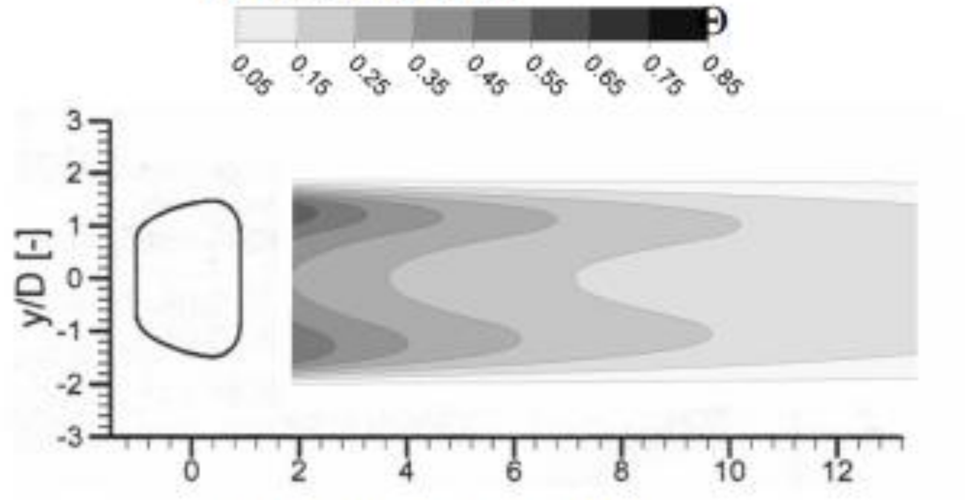
Figure 3.11 - Distribution of cooling efficiency averaged across the plate for the fan hole at two operating modes M = 0.5 and M = 2.5

Thus, the results of numerical simulation predict with sufficient accuracy the change in cooling efficiency at different blowing parameters.

Figure 3.12 shows the local distribution of the cooling efficiency obtained from the calculation, as well as the results of the experimental study by Saumweber [32], which shows that the calculation models the flow structure with sufficient accuracy.



а) Експеремент



б) Результати розрахунку

Figure 3.12 - Comparison of the calculated local distribution of cooling efficiency on the plate with experimental data.

This leads to the fact that the calculated and experimental pictures of the cooling efficiency distribution are in good agreement with each other

Thus, the developed numerical model allows simulating the processes of film cooling in an isolated hole with sufficient accuracy and can be used as a source of data on the cooling efficiency of holes of different types and for further structural and parametric optimization based on these initial options.

3.3 Structural and parametric optimization of film cooling holes.

To perform structural-parametric optimization, it is necessary to collect geometric information about the shapes of the holes. The geometric parameters were obtained from the sketches of the initial cross-sections of the holes.

To reduce the number of variables considered, a special approach to transform the hole geometry was developed. The geometry was represented in polar coordinates through radius vectors with fixed angles: j = - 180°, - 160°, -140°, - 120°, - 100°, - 80°, - 60°, - 40°, - 20°, 0° (Figure 3.13).

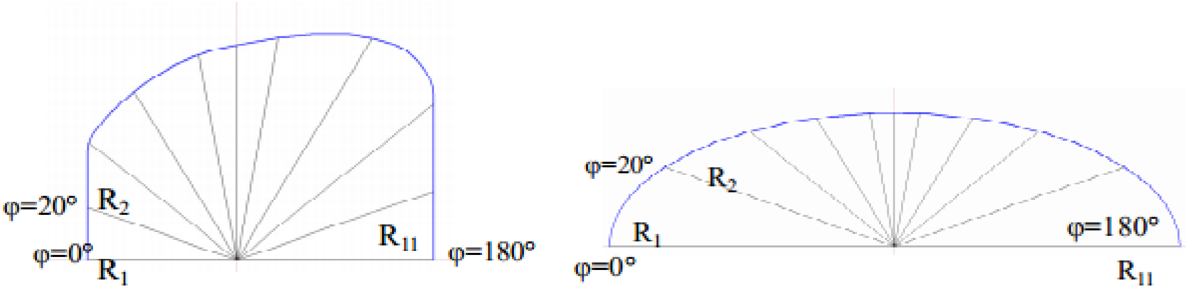


Figure 4.13 - Description of the hole geometry in polar coordinates.

The developed approach made it possible to describe the geometry of the hole not by points with two coordinates X and Y, but only by a radius vector of one length. Due to the symmetrical shape of the holes, only half of the hole relative to its axis was taken into consideration. The applied approach allowed to describe the geometry of the film cooling hole with high accuracy by 11 parameters.

The lengths of radius vectors for all six holes considered are given in Table 3.2.

Table 3.2 - Radius of the vector for the initial variants of holes

Radius vectors	1	2	3	4	5	6
	Cylindrical	Oval	Fan	Oval vector	Conical	Slit
R1	20,00	20,00	20,00	20,00	60,00	5,20
R2	17,13	15,52	21,28	21,29	51,36	5,53
R3	13,24	11,29	25,9	25,69	39,66	6,79
R4	10,97	9,36	27,64	27,76	32,83	10,4
R5	10,00	8,75	29,44	29,6	29,90	29,93
R6	9,88	8,82	30,38	30,5	29,56	51,06
R7	10,00	9,14	31,88	31,35	29,90	29,15
R8	10,97	10,78	36,23	35,51	32,83	10,12
R9	13,24	14,92	34,45	44,76	39,66	6,61
R10	17,13	26,35	28,08	63,05	51,6	5,39
R11	20,00	46,62	26,39	69,57	60,00	5,06

The initial information on the hole geometry (Table 3.2) was transformed into a principal component matrix (Table 3.3) using the SBART software package. Table 3.3 also includes eigenvalues of all obtained principal components.

Table 4.3 - Main components of cooling hole geometry.

№	*U1*	*U2*	*U3*	*U4*	*U5*
1	-0,41512	-1,33198	-0,16536	-2,38739	0,30491
2	0,29366	-1,81695	0,15682	-2,11872	-0,39680
3	-1,02421	1,06868	0,10231	1,08522	-0,08643
4	0,31438	0,26035	-0,07706	2,29803	-1,54257
5	0,34020	-0,72243	-0,00704	3,57273	1,28173
6	0,49109	2,54233	-0,00966	-2,44988	0,43916
X	0,353	2,654	0,014	7,083	0,895

Figure 3.14 shows the columns of the matrix of Table 3.2, the coordinates of which correspond to the two principal components of Table 3.3 selected by the maximum eigenvalues of X.

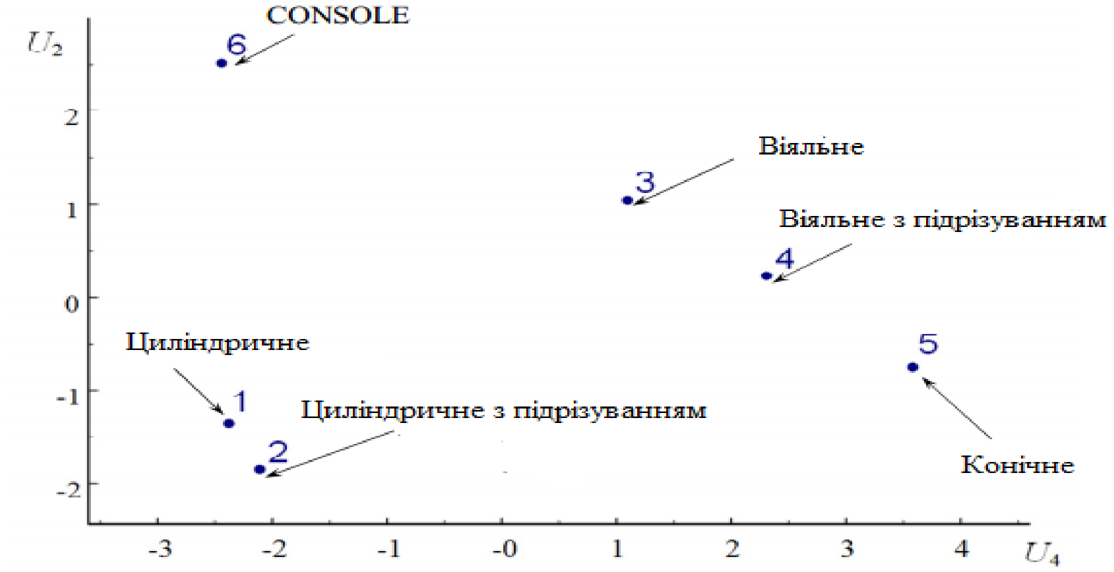


Figure 3.14 - Relative position of the considered geometry options in the space of two principal components *U2* and *U4*

As a characteristic describing the efficiency of the holes, the area-averaged cooling efficiency Θ was used. For all the initial shapes of the holes, numerical simulations were performed in accordance with the developed computational model. The results of calculations for the considered types of holes (dependence of the surface-averaged cooling efficiency on the blowing parameter) are shown in Figure 3.15.

As can be seen from Figure 3.15, the cylindrical and oval holes rapidly lose their efficiency as the blowing parameter increases. At low blowing parameters all the considered hole shapes show similar values of cooling efficiency.

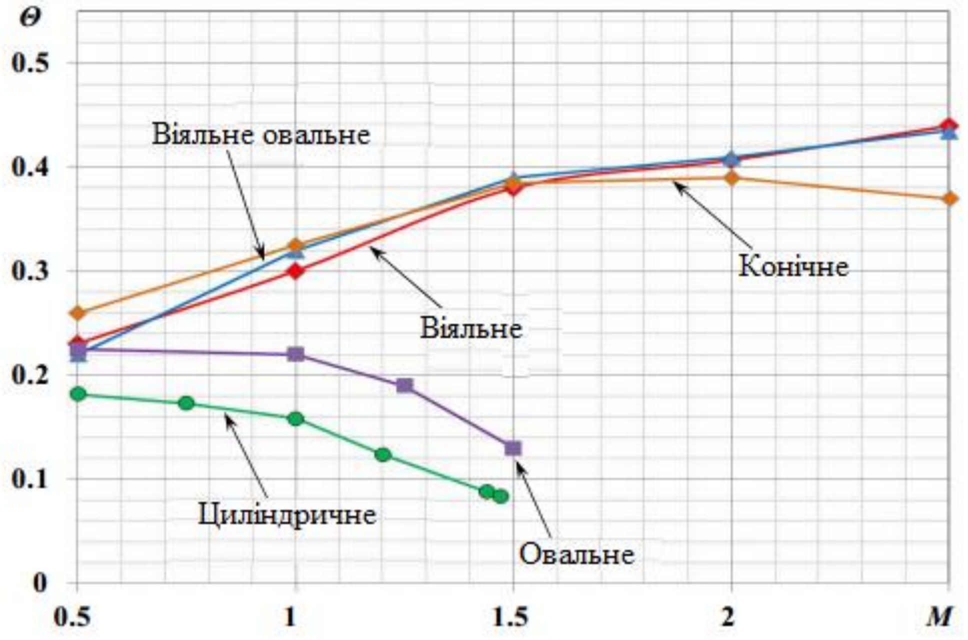


Figure 3.15 - Dependence of the calculated surface average cooling efficiency on the blowing parameter for the considered holes.

Efficient operation of the orifice at high blowing parameters is necessary to ensure film cooling of the rarefaction surfaces on the SA and RL of the turbine. Therefore, it was decided to carry out optimization at the blowing parameter M = 2.5. Calculated average values of cooling efficiency at M = 2.5 are given in Table 3.4.

Table 4.4 - Area-averaged cooling efficiency for M = 2.5.

№	1	2	3	4	5	6
Title	Cylindrical	Cylindrical with undercutting	Fan	Fan with trimming	Conical	Slit
Average efficiency	0,03	0,08	0,44	0,43	0,38	0,37

Prior to the structural-parametric optimization, the geometric characteristics of hole No. 4 (oval fan-shaped hole) were reversed to check the quality of the constructed structural replacement model. The results are shown in Table 3.5.

Table 3.5 - Initial and restored values of radius vectors of hole No. 4

Hole number 4 (oval fan)		
Source.	Restored	Δ,%
20	20,02	-0,10%
21,28	21,3	-0,09%
25,9	25,88	0,08%
27,64	27,65	-0,04%
29,44	29,45	-0,03%
30,38	30,44	-0,20%
31,88	31,86	0,06%
36,23	36,25	-0,06%
34,45	34,51	-0,17%
28,08	28,04	0,14%
26,39	26,4	-0,04%

The reverse restoration of the geometric characteristics of hole No. 4 has a high accuracy of coordinate restoration. The error of geometric characteristics restoration does not exceed 0.2%.

Further, in accordance with the developed method in the SBART software package, the form of the coupling equation was searched and the structural substitution model was built.

The structural equation of the relationship is as follows:

$$\overset{?}{Y}= 0.293334 + 0.08034 -U2 + 0?04903645 - U4. \tag{4.4}$$

For the obtained structural substitution model, the multiple correlation coefficient is equal to R = 0.991, which confirmed the close connection of the cooling efficiency of the hole with the geometry of its outlet section.

The desired level of the objective function was set to the average cooling efficiency equal to $\Theta = 0.53$. This level of cooling efficiency was chosen after the analysis of works [21, 29], where such a level of efficiency is indicated as promising.

In the principal component space, the points of variants No. 3, No. 4 and No. 6 with almost identical values of the optimization criterion were obtained (Figure 3.16).

Obviously, the maximum cooling efficiency should be in the vicinity of these points, which have the maximum characteristics among all the considered holes.

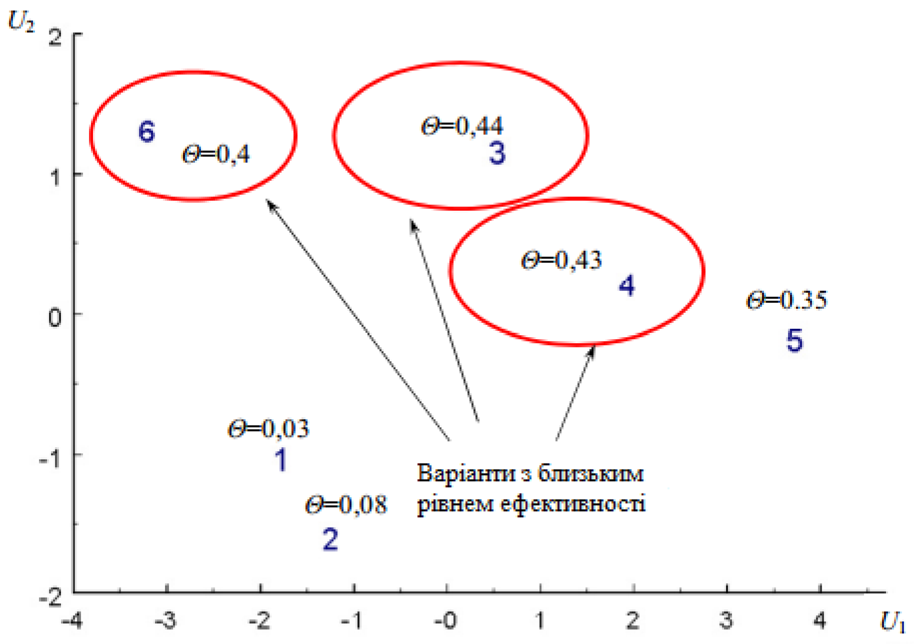


Figure 3.16 - Main components of the 6 output hole options

To effectively search for the optimal geometry, a random multiplicative search method with a cone guide was used. The error of the numerical simulation was set equal to ΔCFD = 0.04, which was the maximum error obtained for the fan hole at the blowing parameter M = 2.5. According to the results of the search from three points, the values of the accuracy criterion $\Delta\bar{Y}^*$ were obtained, shown in Table 3.6.

Table 3.6 - Values of the criterion for assessing the accuracy of search results for three points.

	Search from point #3	**Search from point #4**	Search from point #6
Θ	0,53	**0,53**	0,53
ΔCFD	0,04	**0,04**	0,04
d	0,2	**0,18**	1,581
$\Delta\bar{Y}^*$	66,25	**73,25**	8,38

For the variant from point number 3: $\Delta\bar{Y}^* = 66.25$; for the variant from point number 4: $\Delta\bar{Y}^* = 73.25$; for the search from point number 6: $\Delta\bar{Y}^* = 8.28$. The small value of the accuracy criterion for the search variant from point number 6 is due to the high value of the normalized variance, due to the search results going beyond the available statistics. The results of the reverse recovery from this point with a high probability will not have physical meaning, so this point was excluded from consideration.

The results of the optimization search from the other two points gave almost the same result. According to the maximum value of the accuracy criterion, the search result from point number 4 was selected. The resulting point in the principal component space is located as shown in Figure 3.17.

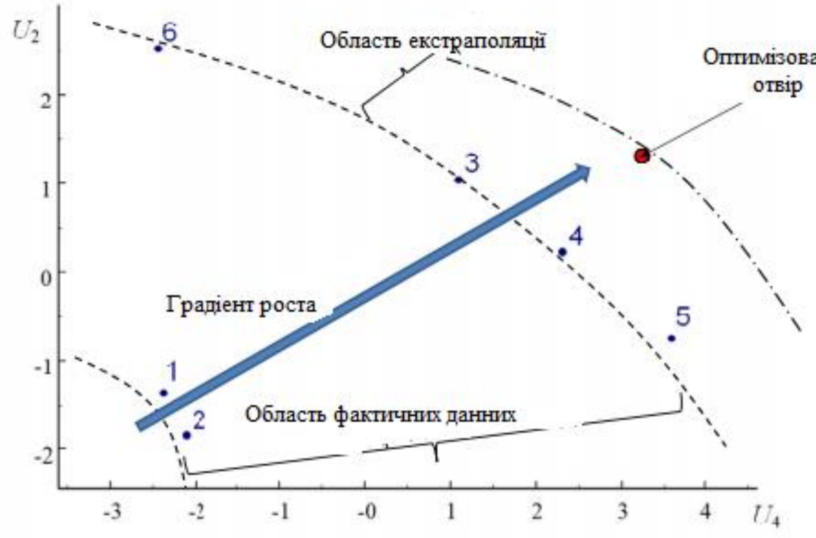


Figure 3.17 - Finding the optimal shape of the hole in the principal component space.

The reverse restoration of the geometric characteristics of the hole corresponding to the specified cooling efficiency from the structural replacement model allowed to obtain the shape of the hole with the predicted cooling efficiency, which is equal to $\Theta = 0.53$. The initial cross-section of the synthesized shape of the film cooling hole is shown in Figure 3.18. The resulting shape of the hole combines the narrowing of the original cross-section when approaching the axis of symmetry with its expansion when moving away from it. In general, the obtained shape of the hole has common features with the hole of the "dumbbell" type, which are considered in [21].

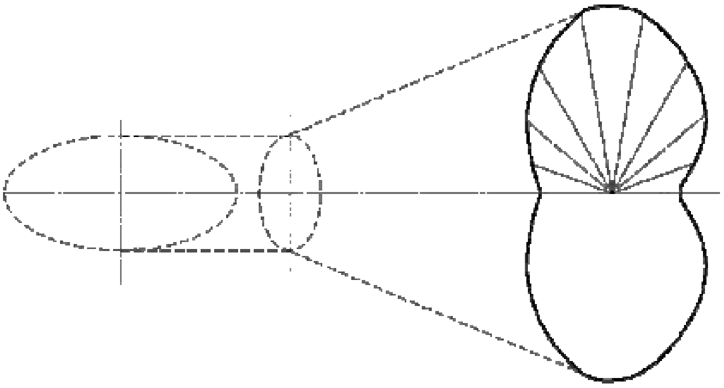


Figure 3.18 - Synthesized shape of the outlet section of the hole

To evaluate and verify the accuracy of the predicted level of cooling efficiency, numerical simulation of the obtained variant of the hole geometry was performed.

The computational model and mesh, as well as the solver settings were chosen similarly to the previous calculations of the initial geometry variants. Due to the peculiarities of the problem statement (analysis of only symmetrical half of the hole), the shape of the hole has sharp corners at the junction of the halves. Therefore, for the numerical calculation, rounding of sharp corners near the axis was added. The results of calculating the cooling efficiency for the resulting shape of the hole in comparison with the fan-shaped hole as the best of the initial options are shown in Figure 3.19.

The comparison was performed for the cooling efficiency averaged over the length of the plate, which is one of the most important indicators of the hole efficiency.

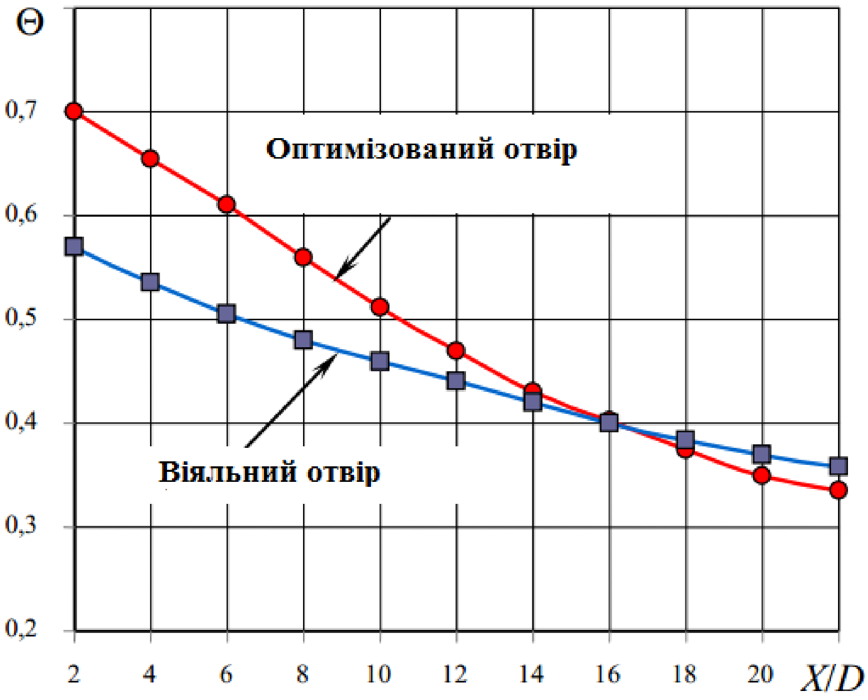


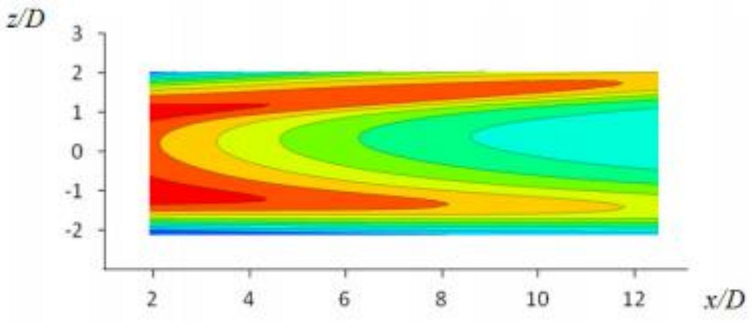
Figure 3.19 - Distribution of cooling efficiency along the length of the plate for fan hole and optimized hole.

The hole synthesized as a result of optimization has a higher cooling efficiency than the fan hole. The maximum increase in efficiency (ΔΘ = 0.12) was obtained in the area near the outlet of the hole (X/D = 2). When moving away from the exit of the hole, the difference between the characteristics decreases and on the last part of the plate the optimization result shows the lowest efficiency than the fan hole.

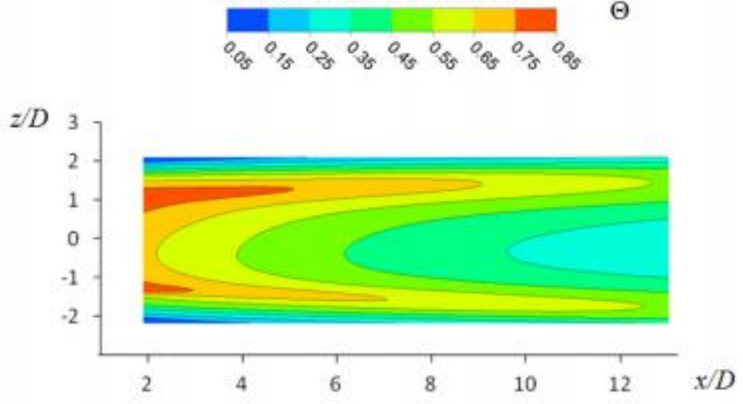
Increasing the cooling efficiency in the vicinity of the hole gives a serious advantage in terms of the operation of the perforation hole in real conditions on the blade or end face, since the effective length of the film cooling in a real turbine does not exceed 4 - 10 X/D. This is followed by either erosion of the cooler shroud or its re-establishment with the next row of perforations.

According to the calculation results, the average area cooling efficiency for the obtained variant was ΘOPT = 0.52, while the value predicted by the structural substitution model was Θ = 0.53. Thus, the error of the structural replacement model in relation to the CFD calculation was only 2%. For the fan cooling hole, the average efficiency is equal to ΘBO = 0.44. Accordingly, the difference between the efficiency of the holes is ΔΘ = 0.08, which is 18% of this value.

Figure 3.20 shows a comparison of the local circuits in terms of cooling efficiency for the optimization result and the fan perforation.



а) Результат оптимізації



б) Віяльний отвір

Figure 3.20 - Distribution of local cooling efficiency for optimized and fan aperture.

Figure 3.20 shows that the new optimized orifice geometry has much higher cooling efficiency at the edges of this region (the area of paired vortices), and in the region close to the outlet of the orifice (2 < X/D < 4). The lowest cooling efficiency, as in the case of the fan hole, is observed in the midline region, which is associated with the physical features of the coolant jet flow from the perforation hole of complex shape at high blowing parameters. Figure 3.21 shows the general view of the current lines when the coolant flows from the optimized hole.

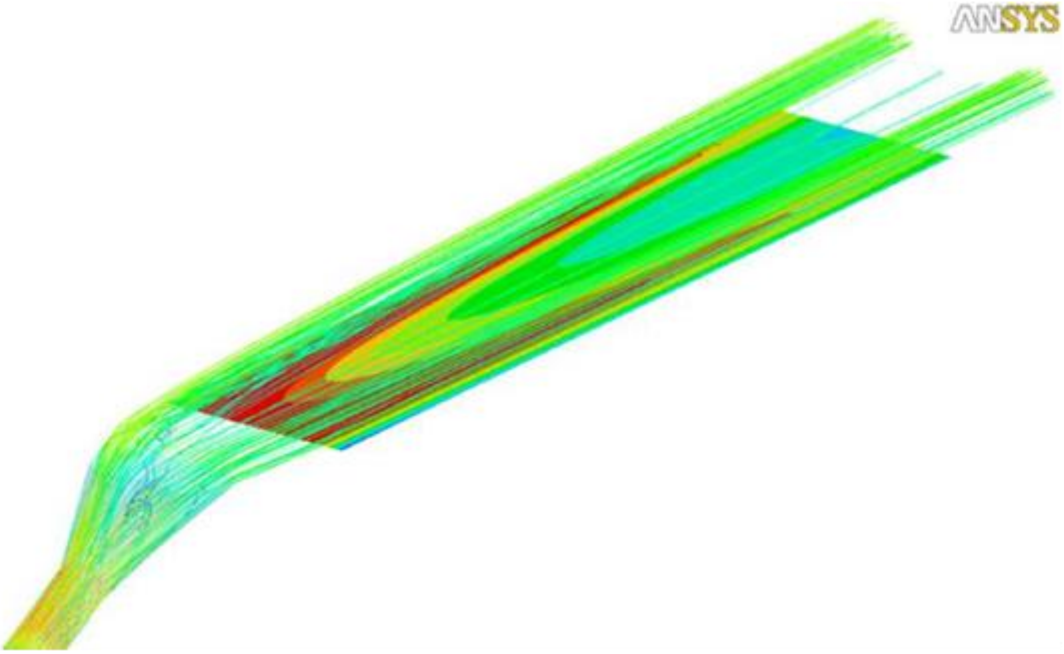
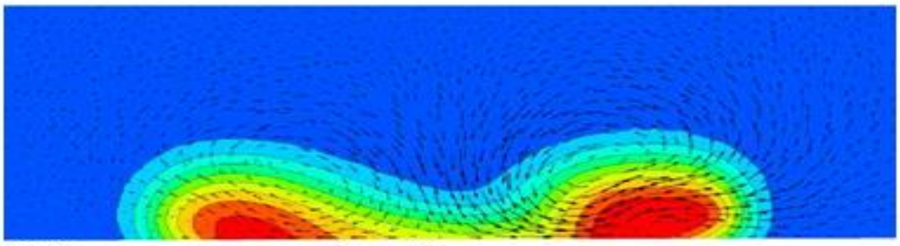


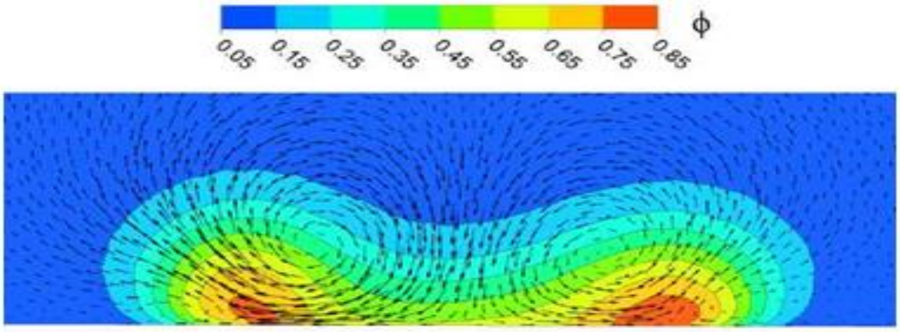
Figure 3.21 - Current lines when the cooler flows from the optimized orifice.

It is of interest to compare the flow structure of the fan hole and the optimization result. Figure 3.22 shows the cross section of the cooler jets for these holes at a distance X/D = 4 from the outlet of the hole.

Figure 3.22 shows the contours for the dimensionless temperature f. The dimensionless temperature is calculated similarly to the cooling efficiency, but the local flow temperature at a point is used instead of the wall temperature. The rotational component of the flow velocity is shown by vectors. The figure shows that the flow structure for both orifices is characterized by the presence of paired reverse vortices. In this case, the optimized orifice provides better pressing of the coolant flow to the wall due to a more compact vortex structure, in contrast to the fan orifice.



а) Результат оптнізації



б) Віяльний отвір

Figure 3.22 - Flow structure in the cross section of the cooler jet at x/D = 4

The results obtained by numerical simulation confirm the effectiveness of the developed optimization method. On the basis of six initial variants of holes and seven numerical calculations, structural and parametric optimization was performed, which provided an increase in cooling efficiency by 18%. The solution of this optimization problem by the method of building a neural network required 35 calculations.

Thus, the computational costs were reduced by almost 5 times, provided that the required accuracy of the structural substitution model was ensured.

The following should be noted as recommendations for the use of the SBART software package to optimize the shape of the film cooling holes:

- the number of points describing the cross section of the hole should be 11 - 13;
- optimally use six initial variants of the hole geometry;
- the compression accuracy parameters of geometric information should be set to $\rho = 0.01$ and $\Delta = 0.001$;
- the correlation coefficient of the structural substitution model equation must be greater than I = 0.98.

CONCLUSIONS ON SECTION 3

1) The developed optimization method is applied to solve the problem of increasing the efficiency of film cooling by optimizing the shape of the outlet cross-section of the perforation hole. The optimized film cooling hole provides an increase in cooling efficiency by 18% relative to one of the best initial options (fan hole).

2) A method of converting the geometric information about the initial cross-section of the film cooling hole by translating the geometry of the cross-section into the polar coordinate system has been developed.

3) Compared to the method of building a neural network of radial basis functions, the number of numerical calculations required for optimization was reduced from 35 to 7. Thus, a 5-fold reduction in computational costs was achieved, provided that the required accuracy of the structural substitution model is ensured.

4) The reliability of the obtained calculation results is ensured by the correct use of methods and means of numerical modeling, the compliance of the calculation results with reliable experimental data, as well as the absence of contradictions to basic physical laws, facts and laws.

CHAPTER 4

OCCUPATIONAL HEALTH AND SAFETY

4.1 Influence of harmful factors when working with the stand

The test station includes: boxes in which the test objects and equipment necessary for the tests are installed; adjacent to the boxes auxiliary technological premises, where part of the measuring equipment, control cabins, fuel, oil, compressed air, electricity supply systems and some others are located (for example: water supply and drainage system during hydraulic brake tests of the TVT, the system of absorption of electricity produced by generators, hydraulic loading system of aircraft units, etc.

The test station is located on the leeward side of the plant to reduce the ingress of exhaust gases and reduce the effect of noise.

Aviation GTE test bench means a single complex of facilities and test equipment designed for testing of aviation GTE in ground or simulated operating conditions.

Test benches of aircraft serial GTE are designed to check the quality, determine the parameters and output characteristics of GTE by testing in ground or partially simulated operating conditions and should provide all types and categories of control and resource tests provided by the general technical conditions for serial production, as well as after their repair.

Test benches, their systems and assemblies (as part of the GTD) are designed for testing, research should ensure the conduct of experimental, proving, determining, preliminary, interdepartmental, state, resource, special, final, and appropriate types and categories of control tests.

When testing the traction properties of the engine at the workplace, the following dangerous and harmful production factors may occur:

- failure to provide light comfort parameters;
- increased or decreased air humidity in the working area;
- increased noise level in the workplace;
- increased vibration level;
- electric shock;

- increased concentration of harmful substances;
- a list of hazardous areas from moving elements of the stand;
- elevated surface temperatures of heated parts and equipment;
- explosion and fire hazard factors;
- excessive pressure in the hydraulic system.

Requirements for the stand

The main method of determining the acoustic characteristics of engines is the method of measurements in the far sound field on open engine stands.

The measuring site of an open bench with a radius of at least 300 m (for small engines at least 60 m) should be flat and free from buildings and various obstacles that are directly connected with the bench and can introduce noticeable distortions in the sound field at the places of engine noise measurement. The engine is installed in the middle of the measuring site.

Placement of service buildings is allowed no closer than 25 m from the engine and only on the side opposite to the semicircle of the measuring belt. The height of the service buildings shall not exceed the height of the engine axis above the bench surface.

It is allowed not to expose the outer surfaces of the walls of service buildings with sound-absorbing material if the total height of the walls is less than the height of the engine axis by the value of two engine diameters.

The suitability of the stands for determining the acoustic characteristics is determined by the results of departmental tests (certification) or state tests (certification) with the issuance of a certificate.

The height of the engine axis above the surface of the stand should be at least 1.5 engine diameters. The microphones shall be installed at two heights: at the level of the engine axis and at a distance of (0.5 ± 0.1) m from the surface of the test bench. When testing small-sized engines, the microphone shall be installed at a distance of 1.6 m from the surface of the test bench.

The bench shall be equipped with means to measure engine thrust, fuel consumption, turbocharger cascade speed, as well as temperature, pressure, humidity, wind speed and direction.

4.2 Recommendations and methods to reduce harmful factors when working with the stand

The typical scheme of the test bench, the main equipment and measuring systems, the aerodynamic scheme of the conducting air and gas exhaust devices are selected based on the purpose of the bench, the design features, layout and characteristics of the GTE, the type and purpose of the tests.

To conduct bench tests of modern vehicles, test benches can be created where the tested vehicle is placed in a test box or on a specially equipped open area.

The design and operational properties of the test bench, the layout and placement of the main equipment should ensure:

- free air supply to the inlet of the GTE and to the ejector-exhaust
bench design and minimal impact of the bench aerodynamics on the main parameters of the tested vehicle;

- reliable operation and functioning of all systems and equipment of the test bench in accordance with their purpose;

- free access to the test vehicle and test bench equipment for the necessary technological operations, maintenance and replacement of units;

- the possibility of heating the air at the inlet to the GTD in accordance with the test program;

- the possibility of heating fuel and oil at the entrance to the GTD in accordance with the test program;

Test benches made according to the scheme with an open area for the installation of the tested vehicle must meet the following requirements due to the specifics of their layout:

- the test bench shall be equipped with a gas exhaust device that ensures safe removal of the gas jet from the GTE operating at the site to exclude direct impact on the surrounding structures, vegetation and soil cover, as well as the ingress of gases to the inlet of the operating GTE;

- shielding of the GTE operating on the site should be provided to prevent the flying of structural fragments in case of its destruction during testing;
- the location of the test site on the territory of the test station should ensure the noise level from the operating GTE does not exceed the permissible values;
- the test site with the installed vehicle shall be equipped with a canopy and easily removable devices to protect the personnel from wind and precipitation during maintenance of the vehicle under test;
- the test site must have a circular fence to prevent accidental entry of people, animals, vehicles, etc. into the area of the working GTE.

Insufficient lighting affects the functioning of the visual apparatus, that is, determines the visual performance, the human psyche, his emotional state, causes fatigue of the central nervous system, which occurs as a result of efforts to recognize clear or dubious signals.

Optimal and permissible norms of temperature, relative humidity in the working area of production facilities are given in Table 4.1 [41].

Table 4.1 - Optimal and permissible norms of temperature, relative humidity in the working area of production facilities

Period year	Category of work	Temperature, °C					Relative humidity	
		optimal	permissible				optimal	acceptable in the workplace
			upper		lower			
			in the workplace					
			permanent	Fickle	permanent	Fickle		
Cold	Lung - I a	22-24	25	26	21	18	40-60	75

	Light - I b	21-23	24	25	20	17	40-60	75
	Medium severity - II a	18-20	23	24	17	15	40-60	75
	Medium severity - Pb	17-19	21	23	15	13	40-60	75
	Severe - III	16-18	19	20	13	12	40-60	75
Warm	Lung - I a	23-25	28	30	22	20	40-60	55 (at 28 °C)
	Light - I b	22-24	28	30	21	19	40-60	60 (at 27°C)
	Medium severity - II a	21-23	27	29	18	17	40-60	65 (at 26 °C)
	Medium severity - Pb	20-22	27	29	16	15	40-60	70 (at 25 °C)
	Severe - III	18-20	26	28	15	13	40-60	75 (at 24 °C and below)

Noise can cause:

- causes instant deafness and hearing damage at very high noise intensities;

- prolonged exposure to high intensity noise causes irreversible hearing loss, the so-called hearing loss;

- short-term exposure to high-intensity noise leads to temporary hearing loss, which then recovers.

Normative values of noise levels at workplaces are given in Table 4.2 [42].

Table 4.2 - Normative values of noise levels at workplaces

Workplace.	Sound pressure level in dB in octave bands with geometric mean frequencies, Hz								Sound level, dBA
	63	125	250	500	1000	2000	4000	8000	

Work requiring concentration; work with increased requirements for monitoring and remote control of production cycles. Workplaces at the consoles in monitoring and remote control booths without speech communication by phone, in laboratories with noisy equipment, in rooms for noisy computer units	91	83	77	73	70	68	66	64	75

The main causes of vibration that occur when working on the stand:

- unbalanced parts of the equipment;
- uneven wear of machine components;
- use of oils that do not meet the operating conditions of the equipment;

Maximum permissible values of normalized parameters of vibration of workplaces at the duration of vibration exposure of 480 min (8 h) are given in Table 4.3 [43].

Table 4.3 - Maximum permissible vibration values

Geometric mean band frequencies, Hz	Limit values along the axes Ho, Y							
	Vibration acceleration				Vibration speed			
	m/s^2		dB		m/s ^{2}		dB	
	1/3	1/1	1/3	1/1	1/3	1/1	1/3	1/1
1,6	0,089		99		0,89		105	
2,0	0,079	0,14	98	103	0,63	1,30	102	108
2,5	0,070		97		0,45		99	
3,15	0,063		96		0,32		96	
4,0	0,056	0,10	95	100	0,22	0,45	93	99
5,0	0,056		95		0,18		91	
6,3	0,056		95		0,14		89	
8,0	0,056	0,10	95	100	0,11	0,22	87	93
10,0	0,070		97		0,11		87	
12,5	0,089		99		0,11		87	
16,0	0,110	0,20	101	106	0,11	0,20	87	92
20,0	0,140		103		0,11		87	
25,0	0,180		105		0,11		87	
31,5	0,220	0,40	107	112	0,11	0,20	87	92
40,0	0,280		109		0,11		87	
50,0	0,350		111		0,11		87	
63,0	0,450	0,79	113	118	0,11	0,20	87	92
80,0	0,560		115		0,11		87	
Adjusted and equivalent adjusted and their levels		0,10		100		0,20		92

4.3 Problems and regulation of aviation noise on the ground

Reducing environmental noise is a worldwide problem. However, approaches to its solution vary from country to country and are highly dependent on the culture, economy and politics of each country. Currently, there is no unified global system for assessing the impact of environmental noise on the population and the cost of the damage caused.

However, in the countries of the European Union since 1996, such a system has been in place and it
is set out in the so-called EU Green Paper. According to the Green Paper, it is estimated that currently more than 20% of the world's population is constantly exposed to noise, i.e. about 80 million people suffer from unacceptable levels of noise, which manifests itself in sleep disturbances, increased irritability and ultimately in adverse health effects. Another 170 million. European citizens live in areas where the population is exposed to noise during the daytime.

In financial terms, the costs to society of dealing with environmental noise range from 0.2% to 2% of gross domestic product, even the smallest of these figures is significant.

Civil aviation, as one of the most modern vehicles on a global scale, is a high-tech industry of the world economy. Therefore, the whole history of civil aviation development is accompanied by the interaction of interests of states, airlines, airports, companies - manufacturers of aviation equipment.

The close attention of society to environmental problems and fierce competition in the air carrier market led in the late 20th century to a new scale of priorities in the creation of aircraft, in which the second place after flight safety was firmly occupied by the problem of noise in the area.

For many decades, the International Civil Aviation Organization (ICAO) has been directly influencing the problem of environmental protection from the impact of aviation. B

The Chicago Convention on International Civil Aviation, signed by the states in 1944, did not devote any article to this issue. But 20 years later, due to the rapid development of civil aviation, ICAO came to the need to regulate and limit aircraft noise on the ground.

In the late 60s, the ICAO established the Committee on Aviation Noise (CAN), which in 1983 was transformed into the Committee on Aviation Environmental Protection (CAEP) in order to address aircraft noise and aircraft engine emissions in parallel. In 1971, Annex 16 to the Chicago Convention appeared, the first volume of which regulates the certification of aircraft and helicopters for noise in the field, and the second volume regulates aircraft engine emissions.

ICAO policy on environmental protection has a great impact on all aspects of civil aviation activities in almost all countries of the world. At the same time, in its decisions ICAO implements a balanced approach, taking into account the uneven economic development of different countries, peculiarities of their geographical and regional location, historical aspects, scientific and technical potential.

Despite the obvious achievements of the world community in regulating the problem of aircraft and helicopter noise on the ground, there are objective reasons for the aggravation of this problem. And this is primarily the high rate of development of the world civil aviation.

Nowadays, the noise levels of aircraft on the ground during take-off and landing are the main criterion that determines the possibility of operating an aircraft on international and domestic airlines. In all countries over the past decades, the problem of combating acoustic pollution of the environment from air transport, especially near airports, is relevant. More research has been devoted to aircraft noise than to any other environmental noise problem. Therefore, the design of new aircraft, the choice of take-off and landing modes, as well as the construction of new and reconstruction of old airports, take into account the noise problems that may arise.

Air traffic generates significant noise near both civilian airports and military airfields. Aircraft take-offs are known to generate intense noise, including rumble and vibration. Landing of aircraft generates significant noise along the corridors within which flights usually take place at low altitudes. Noise is generated not only by the engines, but also by the landing gear and wing mechanics, as well as when reverse thrust (engine reversal mode) is applied during the run of the aircraft on the runway. In general, a larger and therefore heavier aircraft generates more noise than a lighter aircraft.

There are two types of noise regulation in general and aviation noise in particular: sanitary and technical.

Sanitary regulation is designed to protect people from the harmful effects of noise. It regulates the intensity and other characteristics that determine the degree of damage caused to the human body. Sanitary standards establish maximum permissible noise levels in places of human presence - in residential areas, near sanatoriums and medical institutions, in public places, at workplaces, etc.

Technical standardization establishes noise limits for different types of transport, machinery and equipment. If sanitary standards establish the required degree of noise attenuation, technical standards determine the technical possibilities of noise attenuation.

Restriction of aircraft noise on the ground is carried out in the field of both sanitary and technical standards. At the same time, sanitary norms of aviation noise have the character of national norms and are not the same in different countries in terms of assessment units and maximum permissible values of noise level.

Technical standards for aircraft noise have both international and national status. International standards are developed within the framework of ICAO - the International Civil Aviation Organization - using various technical requirements defined by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC).

Airworthiness standards for aircraft (Aviation Rules).

The chronology of strengthening of international requirements for noise levels of mainline aircraft on the ground has its own history. In 1971, Annex 16 to the Convention on International Civil Aviation appeared, where in Chapter 2 the first norms on aircraft noise levels were formulated. Noise levels are regulated at three control points on the ground, located, respectively, on the side of the runway and under the take-off and landing trajectories.

In the 70s, in connection with the introduction of turbojet engines with a high degree of dual-circuit in civil aviation, there was a decrease in aircraft noise. In response to this, in 1978, new, more stringent requirements for noise levels appeared, formulated in Chapter 3 of Volume 1 of Annex 16. These norms are still in force today, but they have already been replaced by new norms already adopted by ICAO in 2001, known as the norms of Chapter 4 of the ICAO standard.

These standards are stricter than the "Chapter 3" standards by 10 EPN dB in total at three control points on the ground.

Technical noise standardization provides the maximum permissible noise reduction of equipment, devices, vehicles in terms of the introduction of existing scientific achievements, the latest technologies, the use of new materials, improvement of production processes. Therefore, technical norms are periodically reviewed in order to tighten regulatory restrictions on noise. Sanitary and hygienic norms determine the necessary degree of noise attenuation, and technical norms indicate the achievable in practice values of noise levels of technical sources.

According to the IKAO international standards, aircraft noise is normalized depending on the maximum take-off weight for three control points. Figure 4.1 shows the location of the noise measurement points.

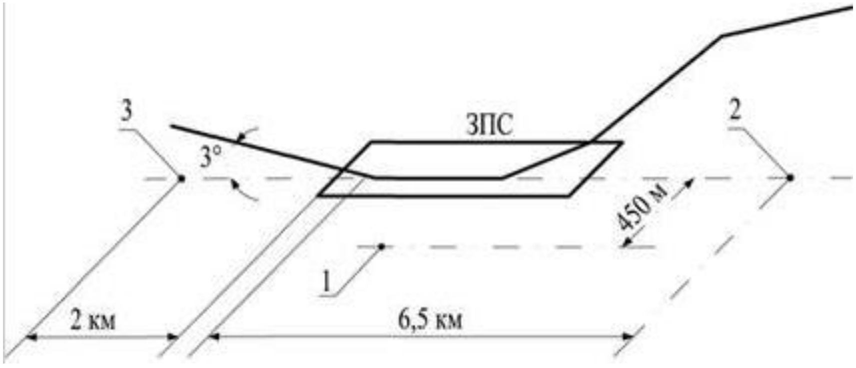


Figure 4.1 - Control points for aircraft noise measurement

Microphones are installed at the following points: 1 - at take-off, at a distance of 450 m from the runway axis for new types of aircraft; 2 - when the aircraft is gaining altitude, at a distance of 6500 m from the start of the run-up; 3 - when landing on a standard glide path, at a distance of 2000 m to the runway threshold.

The extent of noise impacts from transport facilities depends significantly on the structure of the vehicle fleet, the intensity of their operation and the development in the vicinity of transport routes. For example, with regard to civil aviation, during the 1980s the world fleet of transport category aircraft increased by about 30%, reaching approximately 12 thousand aircraft by 1990. Today the structure of this fleet is such that the noisiest jet aircraft make up 75%, the rest are propeller aircraft. At the same time, 20% of the fleet consists of aircraft with turboprop engines, 5% - with screw piston engines. The result of these efforts is that modern aircraft equipped with engines with a high degree of dual-circuit and significant acoustic treatment of flow channels are 15...25 dB "quieter" than the first turbojets.

Table 4.4 Regulatory noise requirements for aircraft with jet engines according to Chapter 3 of Annex 16 to the IKAO Convention

Maximum take-off weight M, ton	20.2	28.6	35	48.1	280	385	400
Noise levels for side point, EPN dB	94		80.87 + 8.51 lgM				103
Noise levels during landing approach, EPN dB	98		86.03 +7.75 lgM				105
Noise levels at takeoff, 2 motors, EPN dB	89		66.65 + 13.29 lg M				101

An illustration of the results in the form of 65 dBA noise contours before and after decommissioning of aircraft whose noise levels do not meet the requirements of Section 3 of Annex 16 to the ICAO Convention is shown in Figure 4.2.

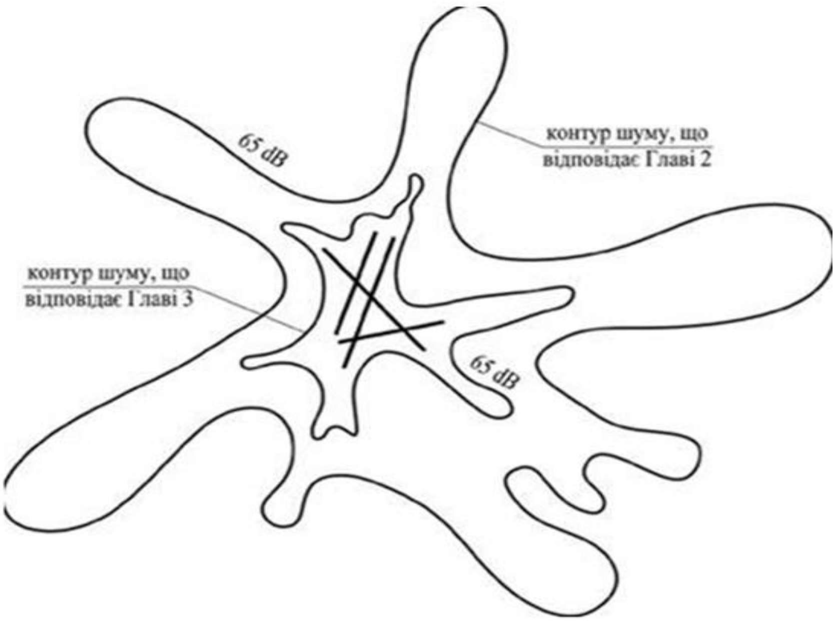


Figure 4.2. Comparison of noise contours for aircraft fleets

Noise generated by different types of aircraft differs significantly in its characteristics. This is primarily due to the different noise sources in these aircraft.

In aircraft with jet engines, noise is caused by the following reasons:

- with a jet stream;
- turbine;
- with a compressor;
- with a fan.

The main parameters on which the sound wave emission of compressors and fans depends are the rotor blade speed, the number of rotor and stator blades, the distance between the stator and rotor, the diameter of the compressor or fan. As the distance between the input blades and the rotor increases, the noise level first decreases and then becomes constant.

If the speed of the blades exceeds the speed of sound, shock waves are formed that differ from each other due to the non-identity of the blades.

Physically, a sonic boom is formed by a shock sound wave in the air generated by an aircraft when it is flying at a speed (even slightly) greater than the local speed of sound. The shock sound wave propagates from the aircraft in a cone shape. At the point in question, the passage of the shock sound wave causes an initial sudden increase in atmospheric pressure, which is then followed by a gradual drop to a lower than normal pressure value, after which it suddenly rises to normal. These pressure fluctuations are called N-waves or shock waves. When they occur with a time interval longer than 100 μs, a sonic boom manifests itself as a characteristic double sound. High intensity sound shocks can damage buildings. Low intensity sound shocks can cause a startle response in both humans and animals. The startle response is a secondary effect due to the sudden and unforeseen exposure.

The sonic boom can be heard as a very loud and percussive sound. It can be heard at a distance of more than 50 km. It depends on the altitude and size of the aircraft. The area of the ground surface where this impact is felt is called the sonic boom zone.

The directional characteristics of the acoustic radiation of modern TRDDs have a number of characteristic maxima in the front and rear hemispheres, corresponding to the radiation of different sources.

In the PDE with a high degree of double-circuit maximum directivity characteristics in the front hemisphere of the engine is formed by radiation propagating mainly through the air intake channel (Figure 4.3), and in

rear hemisphere - radiation propagating through the exhaust tract of the engine and radiation from the jet.

Figure 4.3 - Characteristics of acoustic radiation directionality of modern RTDs.

The maximum noise directivity characteristics of a single-stage fan in the front hemisphere corresponds to the direction of radiation propagation φ = 500-700, considering the angle from the axis of the air intake duct. In the rear hemisphere, the maximum radiation intensity of the fan corresponds to the direction of propagation φ = 1100 - 1200. The turbine emits noise of the highest intensity in the directions φ = 1200 - 1300, and the jet - in the directions φ = 1350 1450.

In the TRD and TRDD with a low degree of dual-circuit maximum directional characteristics of the total acoustic radiation is determined by the radiation of the jet and takes place in the rear hemisphere of the engine in the directions φ = 1350 - 1450.

4.3.1 Turbine noise of the turbine

When the aircraft is flying in approach mode, with the engines operating at reduced throttle, the acoustic radiation from the turbofan turbine can have an impact on the overall noise level of the aircraft at a reference point on the ground. this is particularly noticeable in aircraft with turbofan engines with a high degree of dual-circuit, which do not have sound-absorbing materials in the exhaust path of the gas generator. [44]

In this regard, the study of the regularities and mechanisms of noise generation by the turbine is of some practical interest. Turbine noise is usually studied in experiments of two types: when the turbine is operating in the engine system or when the isolated stage is operating.

In the first case, it is possible to take into account the influence of numerous parameters on the total acoustic field of the turbine, but it is difficult to independently change these parameters. In the second case, we have the opposite picture. In this regard, the experimental data, as a rule, do not have the necessary degree of commonality for the construction of reliable analytical or empirical methods for calculating the far acoustic field of turbines operating in the turbofan system.

A number of works devoted to turbine noise radiation are known. As a result of the research it was found that in the far acoustic field of a turbofan engine the radiation from the last stage of the turbine, which serves to drive the engine fan, is usually noticeable.

The spectrum of acoustic radiation of the turbine, as well as other turbofan blade machines, includes discrete and broadband components. The mechanisms of noise generation in the turbine and fan stages are generally similar.

However, in the turbine stage, noise generation is complicated by the presence of a field of flow temperature fluctuations. In this case, the most important source of noise is the pressure fluctuations on the surface of the blades of the impeller (RK) and nozzle (guide) apparatus (SA) when they interact with turbulent wakes behind the blades located upstream. The conditions of turbine and fan noise propagation are significantly different.

Propagation of turbine noise upstream is complicated due to cluttering of the channel cross-section by the combustion chamber and compressor stages and convection of sound by the flow.

The sound propagation down the flow is significantly influenced by the impedance of the nozzle cut in the axial direction, velocity and temperature fluctuations in the flow, velocity and temperature gradients in the mixing zones of the gas and air jet of the turbofan exchanger with each other and with the ambient air environment.

Due to refraction of sound waves and dispersion of sound velocity in the zones turbulent mixing of flows, which lead to unregulated changes in the amplitude and phase of oscillations along the front, there is a dissipation of energy of harmonic oscillations in the frequency region adjacent to the frequency of passage of the blades of the RC turbine.

As a result of these phenomena, the turbine radiation at the frequency of passage of the blades of the RC is manifested in the far acoustic field in the vicinity of the "blurred" spectral maximum in frequency. Measurements carried out at Rolls-Royce showed that directly behind the turbine in the pressure pulsation spectrum there is a discrete component at the frequency of passage of the RC blades, but after the sound passes through the exhaust jet in the far acoustic field only a "blurred" frequency maximum pressure was recorded.

It has been experimentally established that the intensities of individual components in the spectrum of acoustic radiation of the turbine depend on the relative position of the nozzles of the inner and outer circuits of the turbofan, on the ratio of the numbers of nozzle and impeller blades, on the twist of the SA blades, on the degree of uniformity of the distribution of the RC blades by pitch, on the value of the axial gap on the stage and the number of rotor revolutions, etc.

Experimental study of the acoustic field of the turbine operating in the engine system for domestic dual-circuit turbofan engines with a high degree of dual-circuit, which have a separate exhaust of the flows of the inner and outer circuits and a shortened channel of the outer circuit (type D.36, D.18T), allowed to clarify some of the known results.

There is a scattering of the acoustic energy of the turbine radiation at the frequency of blade passage into the adjacent frequency region, but the degree of this scattering depends on the type of engine, its operating mode and the direction of sound propagation relative to the axis of symmetry of the turbofan engine. For example, in the D.18T turbofan engine, the transfer of acoustic energy is especially noticeable at maximum operation, when the velocity and temperature gradients in the mixing zones of the jet jets also reach maximum values.

4.3.2 Calculation of turbine noise of the turbine

The turbine noise can be calculated by the following formulas. [44] The total sound pressure level in the direction of maximum radiation (θ = 120°) is equal to:

$$L_{\Sigma} = 8.751\lg\left(\frac{\Delta T}{T}\right) + 201lg\bar{M} + 10lgF - 5\lg\left(\frac{2S}{b}\right) - 20lgR + 150. \qquad (4.1)$$

The level of the discrete component of the turbine radiation at the frequency of passage of the blades of the last stage in the direction of maximum radiation intensity is defined as:

$$L_{Д} = 21\lg\left(\frac{\Delta T}{T}\right) - 20lgU_{T} + 10lgF - 10\lg\left(\frac{2S}{b}\right) - 20lgR + 200. \qquad (4.2)$$

The following notations are used in the above formulas:

M is the final number M in relative motion at the inlet to the turbine impeller;

F - area of the flow part at the outlet of the impeller;

S is the axial clearance between CA and RC;

b - chord of scapula CA;

R - distance from the nozzle center to the noise measurement point;

$\frac{\Delta T}{T} = 1 - \left(\frac{1}{\pi_T^*}\right)^{\frac{\gamma-1}{\gamma}}$ – is the relative temperature drop in the turbine;

πt * - the degree of reduction of the total pressure in the turbine;

γ is the adiabatic index.

The scattering of sound energy emitted by the turbine in the mixing layer of the jet stream with the environment causes a decrease in the level of the discrete component of the turbine noise in the far acoustic field by a value that for a turbofan engine with separate exhaust of flows from the inner and outer circuits can be approximately estimated by
correlation:

$$\Delta L = 40lgU_c + 20\lg\left(1 + \frac{l}{D}\right) - 85, \qquad (4.3)$$

where Uc is the jet jet emission velocity,

D - diameter of the nozzle of the outer circuit of the engine,

l - distance between the nozzle sections of the channels of the internal and external circuits of the TRDD.

To reduce the noise of internal sources, it is necessary to improve the aerodynamics of the internal channels of the engine, to reduce the unsteadiness of the flows. A very effective means of reducing this noise is the placement of sound-absorbing structures in the exhaust tracts of the engine. In addition, a significant reduction

"Internal" noise can be achieved by shielding it with the wing, plumage and fuselage of the aircraft.

4.3.3 Main directions of aircraft power plant noise reduction

When analyzing the main methods of aircraft propulsion noise reduction, the following two main areas are considered:

- noise control at the source, that is, the impact on the generation of noise by engine elements - blades, machines, combustion chamber, and on the generation of noise by the jet;
- reduction of radiation intensity in the process of its propagation through the engine channels and through the air intake channel.

Both passive and active noise control methods can be applied in each of these areas. Fan noise control

- optimization of the fan stage design, including the optimal shape of the RC and CA blades, the distance between the RC and CA wheels, the ratio between the number of RC and CA blades;
- control of the shape of the air intake channel - selection of the shape of the channel and the outlet section of the air intake, which provides shielding of supersonic radiation;
- cladding of the walls of the mixing chamber of the flows of the channels of the internal and external circuits of the PDE (for engines with a common mixing chamber);

- ure lining of the walls of the outer contour channel with concrete ashlar - placement of concrete ashlar both on the "cold" outer surface of the outer contour channel and on the "hot" inner surface of the BHA;
- Combustion chamber noise control - optimization of geometric and thermo-gas-dynamic characteristics of the combustion chamber according to the criterion of minimum intensity of acoustic radiation of the combustion chamber.

Jet jet noise control - optimization of the parameters of the mixer of flows of internal and external circuits, placement of devices on the nozzle cut that affect the structure and gas-dynamic characteristics of the jet.

4.4 Fire safety.

- application of automatic fire alarm system;
- impregnation of objects with flame retardant and application of fire retardant paints (compounds) on their surfaces.

Limiting the spread of fire outside the fire is achieved by using an emergency shutdown device [45].

Extinguishing the fire is achieved by portable fire extinguishers used to extinguish fires of the following classes:

- A - combustion of solids;
- B - combustion of liquid substances;
- E - fires of electrical equipment under voltage.

For extinguishing the above classes of fire, the most suitable are carbon dioxide fire extinguishers.

Periodic inspection of fuel system equipment is mandatory. Wiping and combustible material should be stored in closed containers. All necessary means for fire extinguishing must be in good working order.

4.5 Safety instructions for working with the engine

To work as engine testers (hereinafter - the tester) are allowed men and women not younger than 18, trained and certified in the specialty, as well as passed the knowledge test.

Upon entry to work, the test worker undergoes a medical examination, an introductory briefing on occupational safety and an initial briefing at the workplace, which must be confirmed by his signature in the checklist of occupational safety briefing and in the registers of registration of introductory briefing and briefing at the workplace.

4.5.1 Safety requirements before starting work

Before starting work, the tester is obliged:

a) check the serviceability by external inspection, put on overalls and other personal protective equipment established for this type of work;

b) obtain a work assignment from the foreman and, when performing new types of work or changing working conditions, obtain a description of the technological process and occupational safety instructions from the foreman (before performing work with increased danger, undergo a targeted briefing with a receipt in the work permit);

c) inspect the workplace, remove foreign objects, clear passages, check for safety signs;

d) if there is water, oil products and other technical liquids on the floor, decking, etc., clean, remove, wipe dry and, if necessary, sprinkle with sand (sawdust);

e) check the serviceability of equipment, protective covers, tools, lifting equipment and mechanisms;

f) inspect the reliability of fastening of the braking device, the fence of the coupling and the engine under test to the base plate (frame), as well as the reliability of connection of the piping system, electrical harnesses to the engine;

g) make sure that there are no foreign objects and tools on the engine, in the braking device, as well as in the absence of leaks in the connectors and connections of the fuel, oil and water systems, tightness of air and gas pipelines;

h) when testing gas turbine engines, check the serviceability of the bench fuel installation, open the damper on the exhaust gas pipe, inspect the bench, the inlet and outlet tracts of the engine, make sure that there are no foreign objects;

i) transport the engine on a trolley at a speed not exceeding
5 km / h and a team of at least two people;

k) when performing slinger's work and work with increased danger, have a permit and the corresponding certificate for the right to perform these works.

4.5.2 Safety requirements during operation

The tester is obliged:

a) comply with all safety measures, monitor the serviceability and safe condition of equipment and tools used in the work, special clothing and footwear, as well as hands must be dry;

b) maintain order at the workplace, prevent cluttering with materials, equipment and production waste, prevent the spillage of fuel and lubricants and water (in case of spillage of oil products and other liquids, immediately clean up and wipe the spill site dry);

c) during work to be attentive, not to be distracted and not to distract other workers from work, to monitor the serviceable condition and safety of protective equipment, cleanliness of overalls;

d) carry the tool only in bags, boxes, cases specially equipped for this purpose;

e) with the engine running, monitor the normal operation of ventilation and all systems that serve the stand;

f) during short-term stay in the premises of the test bench (with the engine running), use personal noise protection equipment;

g) all operations on adjustment of the gas turbine engine shall be performed only after the engine is stopped (entering the box with the engine running is allowed in exceptional cases to determine the defect, while the engine must be running at low throttle, and the master must be at the control panel);

h) stop the engine if leaks are detected in the fuel and oil systems, a sharp increase in the temperature of the coolant or oil, as well as exhaust gases at the engine outlet;

i) use portable lamps with a voltage not exceeding 12 V to inspect the engine.

The tester is not allowed:

a) violate the requirements of explosion and fire safety (work shall be performed in strict accordance with the technological documentation and in compliance with the established safety measures);

b) work in defective personal protective equipment established for this type of work;

c) to perform installation and dismantling works on the suspended engine;

d) work on faulty equipment and with faulty tools;

e) work under faulty or insufficient lighting;

f) pass and stay under the lifted load;

g) be near the engine during its initial start-up;

h) to start the engine by means not provided for in the technological documents (instructions);

i) start the engine with the intake manifolds of the exhaust system folded back, as well as with the ventilation not working;

j) turn the engine crankshaft manually when the fuel supply is on;

k) leave the control panel and the observation window of the test cabin while the engine is running;

l) to carry out troubleshooting, grinding and tightening of connections (fasteners) on the running engine;

m) when testing a gas turbine engine, enter the box with the engine running.

4.5.3 Safety requirements in emergency situations

In case of accident or violation of the test station (stand) operation mode, the tester is obliged:

a) stop work and warn workers about the danger;

b) take measures to stop the engine, shut down the equipment by switching off the test bench and disconnecting the fuel supply;

c) take measures to eliminate the emergency situation in compliance with safety requirements and immediately inform the master about what happened;

d) in case of an accident with another employee or a sharp deterioration of his/her health, he/she shall be immediately provided with first aid.

4.5.4 Safety requirements after the end of work

The tester is obliged:

a) stop the engine, shut off the taps on the fuel and oil systems, turn off the power supply to the stand equipment, dismantle the engine and pipelines (if necessary) with the subsequent installation of standard plugs (avoiding the flow of combustible materials);

b) to check the technical condition of the equipment and systems of the test station and prepare it for further operation;

c) put the workplace and equipment in order, clear the aisles, put the tools in the tool box (cabinet), electric lamps in the tool room, garbage and dirty rags in the designated place;

d) close the equipment and mechanisms, install fences and safety signs in the necessary places and make sure that no one who worked together remained at the station, turn off the lighting;

e) inform the master of all detected faults during the test of the engine and systems.

CONCLUSIONS ON SECTION 4

Civil aviation is an integral part of the unified transport system of Ukraine. The role of civil aviation in the overall transport complex is determined by its ability to provide a much higher speed of transportation of passengers, cargo and mail compared to other modes of transport, which is especially evident during long-distance transportation.

Safety measures during the maintenance and repair of aircraft are regulated by: state and industry standards of the System of Occupational Safety Standards; guidelines for flights, technical operation and repair of aircraft; maintenance regulations; repair technology; manuals and instructions on occupational safety, etc.

Protection of human life and health is a priority direction of the state social policy. The general laws of Ukraine defining the basic provisions on labour protection are the Constitution of Ukraine, the Law of Ukraine "On Labour Protection.

Occupational safety is a state of organization of labor activity of employees of enterprises, institutions and organizations, which allows to achieve the maximum level of their protection from the negative impact of various hazards and threats to their health and life at the optimal cost of corporate resources, which in turn allows the enterprise to achieve a high level of economic security by saving costs for compensation and social benefits. Thus, to gain competitive advantages, to ensure an adequate level of financial stability and profitability of the business entity, to preserve the reputation in the business world, domestic enterprises will be helped by a qualitatively and efficiently organized labor safety system, formed in close connection and functional subordination to the economic security system of the organization, in the form of its mandatory element in view of the intensification of risks of all types of economic activity in Ukraine without exception.

SECTION 5 . ENVIRONMENTAL PROTECTION

5.1 Legislative framework for environmental protection in aviation

Environmental safety and protection involves reducing the negative impact of aviation activities on the environment, determining the environmental capacity of airports, strengthening the role of environmental management, improving and developing the national regulatory framework and adapting it to international requirements.

In order to regulate activities on environmental protection, the State Aviation Service develops and implements a regulatory framework that will allow the implementation of ICAO practices and recommendations in the policy of environmental protection in the field of aviation.

Ukraine fully supports ICAO's environmental policy and practices as defined by ICAO Assembly Resolution A39 - 2 and is committed to achieving the global desired goal of maintaining carbon neutrality from international aviation starting in 2020, as well as the introduction in 2020 of a global market mechanism designed to reduce emissions from civil aviation.

Among the main problems of environmental protection from the impact of aviation are defined:

- pollution of air, soil, water bodies due to emissions of harmful substances from aircraft engines and stationary sources;
- noise pollution;
- irrational planning and organization of land use;
- negative impact on the environment during the transportation of hazardous and radioactive substances, including accidental pollution due to the use of low-quality, outdated equipment.

The relevance of the topic is due to the fact that in the conditions of the global world the role of civil aviation in the economy of modern countries is steadily growing, but with the increase in air traffic, the area of agricultural land cultivated from aircraft, the intensity of the operation of aviation equipment, it was realized that such equipment significantly affects the growth of environmental pollution.

In this regard, it should be emphasized that the right to a safe and healthy environment occupies a prominent place among the constitutionally enshrined human rights in Ukraine. It is assumed that it should be properly implemented [46]. It is quite clear that objectively there is a need for additional legislative guarantees.

It should be noted that in Ukraine, environmental safety as one of the most important priorities of our country was declared in the "Declaration of State Sovereignty"[47] Independent Ukraine, along with other countries of the world, has also assumed international legal obligations to create a national effective legal mechanism that would reliably guarantee the priority of environmental safety; an environmentally safe environment for human life and health; implementation of preventive measures to protect the environment; safety of wide implementation of the

Thus, among the important international achievements of Ukraine are signing of the UN Framework Convention on Climate Change and ratification of the Kyoto Protocol. Thus, Ukraine has undertaken certain obligations to implement a policy of reducing greenhouse gas emissions. Ukraine is among the twenty largest polluters of the planet and bears its share of responsibility for the negative consequences of economic activity.

Adopted in 2003, the Law of Ukraine "On the Fundamentals of National Security of Ukraine" took into account the established international legal requirements, explicitly stating the importance of ensuring environmentally and technogenically favourable conditions for the life of citizens and society, preservation of the environment [49].

Thus, based on these legislative provisions, it can be stated that the purpose of ensuring the environmental safety of civil aviation is essentially to minimize the harmful effects of its activities by maintaining a balance between the damage caused to the environment as a result of aviation activities and the ability of the environment to regenerate itself.

It should be noted that civil aviation can adversely affect both the environment as a whole and its individual systems. It is no coincidence that Part 1 of Article 16 of the

Law of Ukraine "On Transport" clearly states that transport enterprises are obliged to ensure environmentalprotection [50]. This fully applies to air transport enterprises. But given that civil aviation aircraft are the main users of airspace, the legal protection of atmospheric air from the negative impact of civil aviation has become a priority. It should be borne in mind that the atmospheric air as an object of legal protection and use by its physical characteristics differs significantly from other natural resources. The state of atmospheric air is affected by: emissions of pollutants into the atmosphere and harmful physical impact. The latter includes radiation, sound vibrations, noise, etc. In this regard, it should be emphasized that during the years of state independence, an inter-sectoral legal mechanism aimed at the legal protection of atmospheric air in Ukraine in the context of the aviation industry was created. It includes the norms of constitutional, administrative, civil, economic and criminal law, as well as transport, environmental, environmental and air law of Ukraine. Thus, the intersectoral mechanism of legal protection of atmospheric air has recently expanded significantly. The leading place (if we take quantitative characteristics) in this mechanism is occupied by the norms of environmental, administrative and air law of Ukraine.

It is worth noting that the new Air Code of Ukraine for the first time provides a legislative definition of aircraft engine emissions as the emission of harmful gaseous substances such as smoke, unburned hydrocarbons, carbon oxides and nitrogen oxides by an aircraft engine [51]. The new Air Code of Ukraine has also taken into account Ukraine's obligations under the Kyoto Protocol to regulate emissions into the atmosphere, explicitly stipulating that market-based measures to limit or reduce emissions that affect global climate change are introduced taking into account the recommendations of the International Civil Aviation Organization and in accordance with the legislation of Ukraine [51].

Thus, there is a certain positive dynamics in the development of air legislation of Ukraine. It concerns not only the number of norms contained. By the way, if the Air Code of 1993 had only two articles aimed at protecting the atmospheric air from the negative impact of civil aviation [52], the new Air Code already contains a special section X "Environmental Protection"[53]. Taking into account the scope of regulation of such norms, it applies not only to the direct protection of the environment from the harmful effects of civil aircraft, protection of the population from the harmful effects of pollutant emissions, noise, electromagnetic radiation, the risk of aviation accidents during the operation of aircraft, but also to the registration of civil aircraft, airworthiness of a civil aircraft, etc. In total - about 20 items.

For example, with regard to aircraft certification, the new Air Code already clearly states that the authorized civil aviation authority may refuse to register a civil aircraft if the aircraft does not meet the requirements for airworthiness, environmental protection or other restrictions established by the authorized civil aviation authority [54]; while the previous Air Code did not provide for such a condition at all.

Analyzing the state of legal protection of atmospheric air from the negative impact of civil aviation, it should also be taken into account that one of the main factors of the negative impact of civil aviation on the environment is aviation noise. In this regard, it should be noted that the regulation of harmful physical impact on the atmosphere, in particular noise reduction, is one of the areas of legal measures for the protection of atmospheric air Air transport occupies a significant place in the noise regime of settlements. The sources of noise on the territory of the aviation enterprise and adjacent areas are aircraft power plants with gas turbine and piston engines; auxiliary power plants of aircraft and launch units; special airfield maintenance machines for various purposes, including thermal and wind machines created on the basis of aircraft engines that have exhausted their flight life.

The acoustic situation in the airport area is determined by the mode of operation of the airline company; types of aircraft operated at the airport; existing routes of arrival and departure of aircraft; location of residential buildings relative to the runway, as well as measures taken by the airport to reduce the adverse impact of aviation noise on the environment. Thus, the object of negative impact of civil aviation is not only the environment, but also the population.

It is worth noting the increased attention to this important issue in the air law of Ukraine.

Thus, the new Air Code of Ukraine clearly states that the maximum permissible noise level during aircraft operation, aircraft engine emissions and electromagnetic radiation from aviation facilities shall not exceed the maximum permissible level established by the aviation rules of Ukraine; and if the noise level during civil aircraft operation exceeds the established maximum permissible noise level, the authorized civil aviation authority has the right to restrict or prohibit the flight of civil aircraft. Measures aimed at reducing noise levels at and near the airport based on a balanced approach to aviation noise regulation may include spatial zoning of the territory around the airport, taking into account the conditions of aviation noise and other adverse environmental factors; introduction of operational measures during take-off and landing of aircraft; appropriate organization of air traffic to reduce the impact of aviation noise, etc.

The legislation of Ukraine imposes obligations in the context of solving this problem not only on aviation enterprises and aviation authorities, but also on executive authorities, local self-government bodies, enterprises, institutions, organizations and citizens, who, in accordance with Article 24 of the Law of Ukraine "On Ensuring Sanitary and Epidemic Welfare of the Population", are obliged to Noise at protected facilities during any type of activity should not exceed the levels established by sanitary standards for the relevant time of day [56].

As for the owners of aerodromes, operators, commanders and crews of aircraft, they are obliged to prevent or minimize noise during the operation of aircraft on the ground and in the air.

The current noise standards clearly regulate not only the permissible noise levels, but also the methods of its measurement, flight modes during certification tests, as well as the processing of the results and their reduction to baseline conditions in order to protect the environmental rights of citizens and prevent violations in the use of airspace by air transport. It is worth paying attention to the role and place of the institute of legal responsibility in the intersectoral mechanism of legal regulation of environmental problems of civil aviation safety. In this regard, it should be noted that on these issues, mainly such types of legal liability are established as administrative and disciplinary liability, to a much lesser extent civil - legal liability, in special cases - criminal liability.

At the same time, the norms of legislation aimed at the protection of atmospheric air, in terms of liability, as a rule, have a referential character. Therefore, in each specific case, differentiated application of special legislation is required to establish specific legal liability.

Thus, for example, administrative liability is implied in Article 11 of the Law of Ukraine "On Atmospheric Air Protection", which establishes a permit system for regulating emissions into the atmosphere, the violation of which gives rise to appropriate legal consequences [57]. The Law of Ukraine "On Protection of Atmospheric Air" also establishes a direct prohibition on intentional emission of fuel into the atmosphere in case of unsuccessful engine start or after its shutdown. For violation of this norm comes administrative responsibility. Article 3 of the Law of Ukraine "On Environmental Protection" provides for the collection of fees for environmental pollution and deterioration of the quality of natural resources [58].

It should be noted that the new Air Code of Ukraine also pays attention to this issue. Thus, the Code provides that aviation entities are obliged to comply with the established standards for the content of pollutants in exhaust gases and the impact of physical factors during the operation of aircraft on the ground and in the air and to take measures to reduce the volume of emissions of pollutants and reduce noise, electromagnetic and radiation radiation, as well as prohibit the discharge of substances, wastes and matting from aircraft harmful to human health and the environment. Persons guilty of such actions are liable according to the law [59].

The legal measures of air protection also include the establishment of penalties for emissions into the atmosphere by stationary sources, including civil aviation enterprises. Thus, according to Article 11 of the Law

According to the Law of Ukraine "On the Protection of Atmospheric Air", emissions of pollutants into the atmosphere by stationary sources may be carried out after obtaining a permit issued by the territorial body of the specially authorized central executive body on ecology and natural resources in coordination with the territorial body of the specially authorized central executive body on healthcare [60]. As for the nature of the established liability, the law states that persons guilty of emissions of pollutants into the atmosphere without the permission of specially authorized executive authorities shall be liable in accordance with the law.

As for liability, it is implied, for example, in Article 34 of the Law of Ukraine "On Atmospheric Air Protection", which provides for compensation for damage caused by violations of the legislation on atmospheric air protection [61].

5.2.1 Air pollution during aircraft operation

Aircraft pollute the atmosphere due to the emission of harmful substances with exhaust gases from aircraft engines.

During the flight, aircrafts move from one airport to another, and the atmosphere is polluted on a global scale, i.e. significant pollution occurs both in the areas of airports and on flight routes. Moreover, if on the flight routes (at an altitude of 8 - 12 km) the danger from this pollution is small (flights of aircraft at high altitude and high speed cause the dispersion of combustion products in the upper atmosphere and over large areas, which reduces the degree of their impact on living organisms), then in the airport area it is impossible to ignore such pollution.

Gases are emitted into the atmosphere by engine nozzles and exhaust pipes. This process is called aircraft engine emissions.

Gases generated by aircraft engines account for 87% of all civil aviation emissions, which also include emissions from special vehicles and stationary sources.

The most unfavorable operating modes *are* low speeds and engine idling, when pollutants are emitted into the atmosphere in quantities significantly exceeding the emissions under load conditions.

The chemical composition of emissions from fuel combustion depends mainly on the type and quality of fuel, production technology, combustion method in the engine and the technical condition of the engine.

The main components of exhaust gases of modern aircraft engines that pollute the atmosphere:

- sulfur oxides ;

- nitrogen oxides ;
- carbon monoxide;
- hydrocarbons that are not completely burned;
- aldehydes;
- soot (finely dispersed particles of pure carbon) - is released in the form of a plume behind the engine nozzles during takeoff (soot is generally not much).

During take-off, approximately 50% of emissions in the form of microparticles, including many heavy metals, are immediately dispersed in the areas adjacent to the airport. The other part remains in the air for several hours in the form of aerosols and then also settles on the ground.

Each developed engine (for aircraft) before launching into mass production undergoes a series of tests (certification), including environmental safety studies, so the International Civil Aviation Organization (ICAO) has developed strict standards for aircraft engine emissions.

5.3 Disposal of aviation waste

The results of the analysis of aircraft utilization are based on the analysis and substantiation of the work of S.V. Boychenko, O.V. Ivanchenko, A.V. Yakovlev.

The rapid processes of European integration and the adopted international environmental standards force all aviation industry enterprises to intensify their activities to reduce the negative impact on the environment. The aggravation of the global ecological and economic situation associated with environmental degradation, depletion of natural resources and climate change on Earth has shown that all countries, including including Ukraine, need fundamentally new approaches to the implementation of domestic and foreign economic policy, with the help of which it is possible to form an improved strategy of relations between society and nature in a market economy and, thus, to implement the universally recognized principles of sustainable development declared at the UN Conference on Environment and Development (Rio - 92) and the Paris Agreement (entered into force on November 4, 2016).

In accordance with these principles, recently there has been a steady global trend towards the introduction of environmentally friendly and energy efficient technologies.

Today, the problem of disposal of aircraft components that have expired their service life is one of the main problems for the entire aerospace industry. Every year an increasing amount of aerospace equipment (AE) accumulates at various sites, occupying and polluting large areas ofland.

5.3.1 Analysis of recent research and publications

In recent years, a number of scientific papers have been published that study the effectiveness of recycling programs, as well as the environmental, ethical, economic, technical and technological aspects of this issue.

J. Winston Porter was engaged in the development of national recycling programs planning. German chemist M. Braungardt studied production from the standpoint of reverse logistics and life cycle management (LC) of products [62,63].

Since the 80s of the twentieth century, the problem of handling aircraft has become increasingly important due to the accumulation of a large number of decommissioned aircraft, the storage of which is associated with additional costs for conservation and rental space.

As the shelf life of potentially hazardous aircraft expires, the risk of emergencies increases dramatically, which complicates the process of their further proper handling [64 - 66]. In the world market, according to Airbus forecasts, up to 8453 aircraft units will be sent for write-off for the period from 2009 to 2028.

Based on the Boeing report, the potential market for aircraft disposal will be about 6 thousand units. From 1990 to 1999, an average of 170 commercial airliners were written off per year, according to an average of 750 aircraft will be written off annually, in the future - up to 1000 [67].

In the United States, the Mojave Airport, located in the desert eastern part of the U.S. state of California, is the last refuge for civilian aircraft that have reached the end of their service life. For several decades, airliners have been brought here and kept in the hot desert until further separation and recycling.

5.3.2 Summary of the main material

Aircraft construction as a type of economic activity is innovation-oriented.

However, since the activities of aircraft manufacturing enterprises are associated with environmental pollution, aviation and aircraft repair production is considered to be environmentally hazardous.

The modern development of ecological and economic activity should cover not only the production of environmentally friendly products, but also the introduction of new technologies for resource conservation, rational use of existing resources, the use of solid waste in the production process, the replacement of materials with new environmentally friendly ones [68,69].

These areas of ecological and economic activity are related to the implementation of innovative developments, their experimental implementation and further use in production.

In turn, this requires significant funding and the development of an appropriate strategy. Like any product, aircraft depreciate over time. The decline in value arises from a number of factors, including the increasing cost of maintenance, repairs and upgrades in accordance with legislation. At some point, maintenance, repairs and upgrades become unprofitable, at which point the owner will consider decommissioning the aircraft.

In many cases, decommissioned aircraft will contain valuable components and parts that can be returned for maintenance through the secondary market of spare parts or by implementing the processes of aircraft recycling and integrated recycling of aircraft [70,71]. In mid-December 2014, the first International Symposium on Aircraft Recycling was held in Stuttgart (Germany). According to the data presented at the event, more than 25% of the civil aircraft fleet will be decommissioned in the next 15 years. Hence, the issue of proper handling of decommissioned aircraft is acute.

Aeroturbine's experience has shown that the recycling of Boeing 747 can bring significant revenues. On board the aircraft there are more than 6 million different parts, 66 tons of high-quality aluminum, 30% of parts, components and structures will continue to work on other aircraft.

Aeroturbine estimates that the disposal of such large aircraft takes almost two weeks. In total, the company's income can be up to 6.8 million dollars. US DOLLARS [72].

In Ukraine, the practice of recycling shows that only 10-15% of the value of recycled equipment is rehabilitated, compared to 60-70% in the world [73,74].

Thus, the recycling of a medium-class aircraft yields 60-70% of aluminum and its alloys, 10-15% of steel, 10% of composite materials and precious metals, including titanium, relative to its total weight. The cost of recycling is much lower than the cost of new metals and materials.

The Aircraft Fleet Recycling Association (AFRA), founded in 2006, is the world leader in the proper management of decommissioned aircraft, including Boeing, Bombardier, Embraer, Rolls-Royce and others. Located in Châteauroux, France, the AFRA center works to increase the productivity of the aviation industry and make aircraft dismantling environmentally safe and cost-effective. AFRA has developed a special dismantling procedure that allows to quickly isolate valuable alloys and metals. Leading experts of the Association are working on a detailed study of the aircraft life support system and are thinking about how to provide it in the future exclusively from materials that can be reused.

According to them, the aircraft disassembly procedure takes place in three stages, first, liquids and gaseous substances, many of which are very toxic, are removed from various tanks. Then the equipment is dismantled in order to isolate all parts that can be reused. Finally, the aircraft is completely dismembered, but before that, the parts containing valuable alloys and metals are removed. The main task of AFRA is to take away all the most valuable parts, namely: landing gear, engine, auxiliary power plant, then everything related to avionics, air conditioning system and so on, in order to offer all this on the used parts market.

The problem of proper management of aircraft out of service has arisen relatively recently, and all developed countries have faced it.

Decisions on aircraft decommissioning in many countries are not unambiguous. Thus, in the United States, most aircraft produced after World War II are kept in a mothballed state, many of them are ready for operation. European governmental bodies are trying to develop a system of relations with companies engaged in disposal and recycling that would make these processes economically profitable for all participants.

Today, China, anticipating the rapid change of the current aircraft fleet, is investing 2 billion US dollars. USA in the construction of a plant capable of processing 50 units of equipment per year. Domestic experts and industry leaders differ in choosing the only way to use aircraft that have exhausted their resources. Hundreds of aircraft are still in operation, despite the extreme degree of wear. Some of the aircraft have been modernized over the past years: power units have been replaced, electronic and software have been updated. The re-equipment mainly affected military aircraft. The passenger fleet that does not meet the EEC (European Economic Community) standards has been subject to complete disposal since 2002 [69].

An aircraft consists of millions of components (parts), which, after the machine is written off, must be subject to further processing. In other words, an aircraft is

a huge number of metal and composite parts that have to fly synchronously at a speed of 900 km/h (0.85 of the speed of sound, this is a typical speed of Boeing-787 Dreamliner) at an altitude of 10 km. That is, a couple of three million parts are manufactured and assembled into one product - and the plane flies, providing comfort to passengers and profit to owners. But at the end of the life of the aircraft, the aircraft itself and its parts become waste. Some of them are disposed of using automated systems, some require a lot of manual labor. Part of aviation waste is sent to landfills forever. Some part of the waste is temporarily stored in anticipation of the emergence of appropriate technologies.

And such technologies are aircraft recycling and utilization. Description of the recycling technology begins at the airport parking or at the aircraft storage base. Here the aircraft is a part (component, element) of a complex transport aviation system in the aviation - technical complex.

First of all, it is removed from the aircraft systems:

- fuel residues that could not be completely drained from the car;
- technical fluids used in various systems of the units;
- catapult explosive devices;
- technological electronic devices;
- passenger equipment;
- plastic linings, overlays, etc;
- auxiliary technological equipment - wires, power and transmission devices of landing gear drives, ailerons, flaps, control rudder - hundreds of units (Fig. 5.1).

In France, for example, most of such units are sold for reuse.

Further processing is individual for each group of materials. Aircraft bodies are delivered to workshops where ferrous (25%) and non-ferrous metals (more than 70%) are melted down. Devices, boards, radio elements are sent for processing to other enterprises.

The purpose of recycling is to obtain copper, tin, silver, gold and platinum from the parts of decommissioned computers, navigation equipment, and communication equipment. The remains of the equipment are first disassembled and sorted manually. At the second stage, chemical processing of materials is carried out in technological lines.

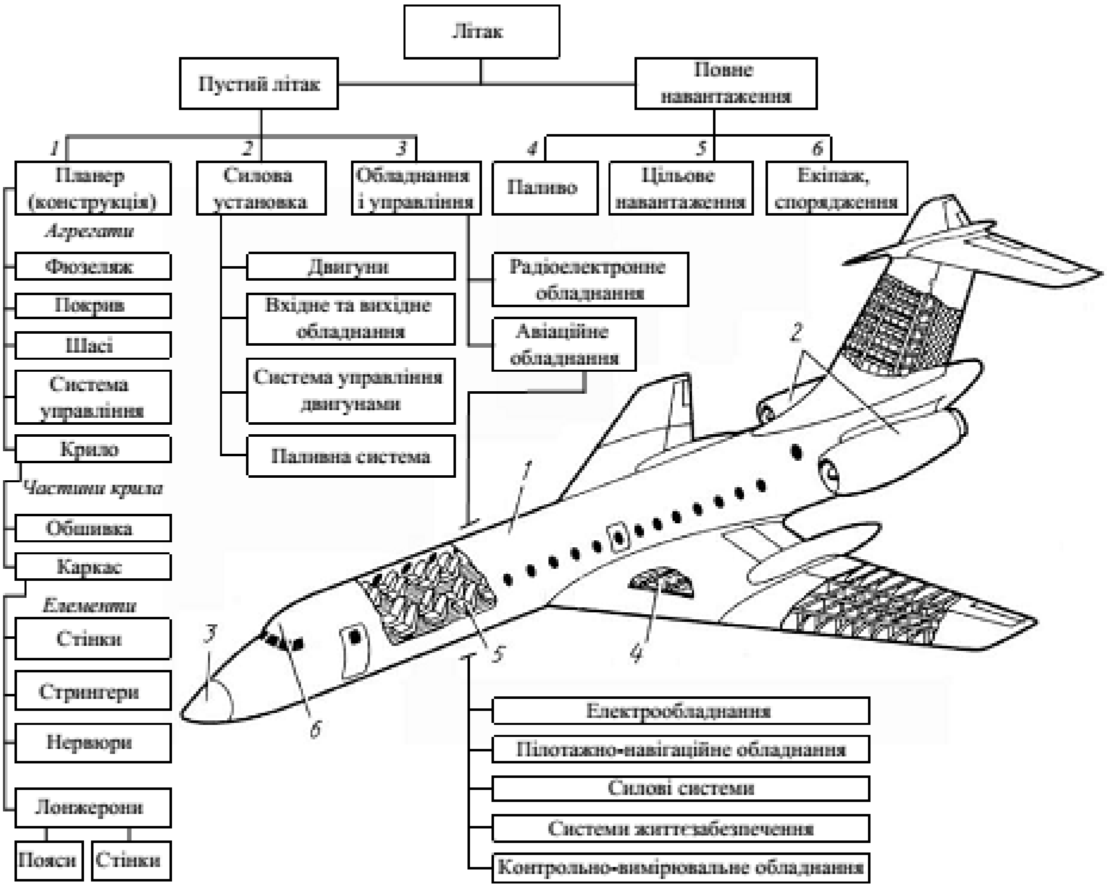


Fig. 5.1. Morphological composition of aircraft waste

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However, despite a certain technological level of aviation waste utilization that exists in the world today, in the near future, other technologies are needed for its implementation: instead of metal, the proportion of composite materials increases, and precious metals are not used in such quantities in the devices.

Composite materials consisting of reinforcing carbon mesh and polyamide (polystyrene) fillers are subject to dissolution during disposal.

According to waste recyclers, the disposal of aircraft in isolation from the process of their creation is economically unreasonable. The cost of materials extracted from the aircraft is comparable to the costs required to disassemble it: a team of specialists and equipment must be delivered to the aircraft abandoned at a distant airfield; dismantling of the liner's equipment is not only time-consuming, but also associated with compliance with increased sanitary safety standards for the work, collection, storage and removal of many (often toxic) materials; further sorting, logistics and processing are quite costly activities. However, this is only the tip of the iceberg. According to estimates of the world's leading airline corporations, about 35 thousand airliners will need to be updated by 2030. The manufacture of each machine requires from 50 tons of metal, hundreds of kilograms of polymers. At the same time, more than 500 aircraft are written off annually in the industry - the same thousands of tons of aluminum, nickel, steel and polymers. The task before aircraft manufacturers is to optimize the material cycle, turning the sphere of production and use of the aircraft fleet into a closed cycle.

An important player in the aftermarket is International Aircraft Associates (IAA) - one of the largest distributors of components for aircraft engines. If necessary, carriers and repair companies are increasingly turning to the secondary market in search of spare parts for power plants such as CFM56 - 7B, as they do not want to maintain their own pool of such components. Airlines either put their own stocks of parts for sale or try to use them to the maximum: it becomes unprofitable to simply keep spare parts in stock.

Over the last 5 - 7 years, the desire of air carriers to stock spare parts has waned as it has become apparent that outsourcing is an efficient and more cost-effective solution.

Boeing Aircraft Company and Alcoa Corporation (American metallurgical company) have formed a closed program to expand the aircraft recycling of aluminum alloy scrap used in the production of aircraft. The Boeing and Alcoa program provides for the recycling of alloys used in the manufacture of wing and fuselage components of Boeing aircraft.

This program maximizes the value of the entire supply chain while reducing waste. Also, Alcoa Fastening Systems (a division of Alcoa, the largest US manufacturer of fasteners for the aerospace and automotive industries) signed an agreement with a Chinese commercial aircraft manufacturer in early 2013.

Also, Alcoa Fastening Systems (AFS) announced a new strategic technology and commercial cooperation agreement with Chinese commercial aircraft manufacturer COMAC. COMAC is a manufacturer of large passenger aircraft in China and has ambitions to compete with Boeing and Airbus

The deal will help Alcoa to gain a foothold in the Chinese aerospace market, which is one of the fastest growing markets in the world [69].

European scientists have also achieved significant achievements in the implementation of recycling processes in the aviation industry.

They are developing methods of aircraft recycling of structural parts made of composite material containing carbon fiber. The research is part of the Inasmet - Tecnalia project, which aims to obtain carbon fiber from this type of waste.

The research team also plans to evaluate the possibility of using the fiber obtained in this way in other industries.

Currently, three methods of obtaining carbon fiber from composite aircraft wings are being considered. The most effective method is pyrolysis, a thermal process in an argon environment that removes resins without affecting the carbon fiber. The resulting fiber is mixed with polypropylene and poly amide in proportions of 15 and 30%, which gives the material optimal mechanical properties. Such materials can be used in industries that require the use of high quality composites with good technical characteristics, but at a lower price [71].

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CONCLUSIONS ON SECTION 5

Environmental safety and protection involves reducing the negative impact of aviation activities on the environment, determining the environmental capacity of airports, strengthening the role of environmental management, improving and developing the national regulatory framework and adapting it to international requirements.

It is necessary to state that at the present stage in Ukraine a certain inter-sectoral regulatory mechanism regulating environmental aspects of civil aviation safety has been created. But, as it seems, it needs further improvement for practical application; in particular, through the development of precautionary measures in this area in the light of international requirements and standards, it is worth noting the increase of environmental norms in the air legislation of Ukraine.

Aircraft manufacturers are faced with the task of optimizing the material cycle, turning the sphere of production and use of the aircraft fleet into a closed cycle [67].

The modern development of ecological and economic activity should cover not only the production of environmentally friendly products, but also the introduction of new technologies for resource conservation, rational use of existing resources, the use of solid waste in the production process, the replacement of materials with new - environmentally friendly [68,69]. faces the problems of increased competition and increased fuel costs.

The obvious solution to these problems is to reduce the weight of the structure through the use of alternative composite materials. Currently, the percentage of composites in the structures of modern aircraft is about 15%, but in the new generation of aircraft this percentage will increase significantly. The most striking example at the moment is the Boeing-787 DREAMLINER. More than half of the parts of this aircraft are made of composite materials, it has a higher efficiency compared to the previous analogue and lower fuel consumption [75].

GENERAL CONCLUSIONS

The main result of the work is the development of a method of structural and parametric optimization of elements of cooled turbines.

Optimization of the shape of the outlet cross-section of the film cooling hole allows to significantly increase the cooling efficiency at high blowing parameters.

1) The developed optimization method is applied to solve the problem of increasing the efficiency of film cooling by optimizing the shape of the outlet cross-section of the perforation hole. The optimized film cooling hole provides an increase in cooling efficiency by 18% relative to one of the best initial options (fan hole).

2) A method of converting the geometric information about the initial cross-section of the film cooling hole by translating the geometry of the cross-section into the polar coordinate system has been developed.

3) Compared to the method of building a neural network of radial basis functions, the number of numerical calculations required for optimization was reduced from 35 to 7. Thus, a 5-fold reduction in computational costs was achieved, provided that the required accuracy of the structural substitution model is ensured.

4) Also, within the framework of the diploma work, the instructions on labor protection when working with the test bench were worked out, as well as environmental protection measures during the operation of aviation equipment.

The scientific novelty is as follows:

A method of structural and parametric optimization of elements of cooled turbines based on the results of numerical simulation, which allows to perform structural and parametric optimization of elements of cooled turbines at the design stage with minimal time costs.

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