The Influence of Laminarizers on the Turbulent Boundary Layer and Prediction of Effective Flow Conditions around Surfaces

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Abstract. The development of effective methods for boundary layer laminarization is a fundamental task for the efficient and reliable operation of power equipment. The main objective of the work is to study the effect of a damping surface on flows in the boundary layer occurring in complex gas-dynamic conditions and to implement a method for predicting effective conditions for flow past damping surfaces. The implementation of the mathematical model allows performing calculations and creating a database for analyzing and selecting the most effective conditions for using a damping surface. To achieve the set goal, the following tasks were solved: development of a damping surface, complex experimental studies of wall flows on models with a damping surface, systematization of experimental data results, development of an original semi-empirical model of turbulent transfer in the boundary layer on a damping surface with its subsequent implementation in a software package for studying the boundary layer in a wide range of gas-dynamic conditions with external intense effects. The most important result of the work is the development of a method for laminarization of the boundary layer by means of a damping surface, the operating principle of which is to suppress turbulent pulsations of velocity and pressure near the streamlined surface. The significance of the obtained results lies in the proposal of a method for laminarization of the turbulent boundary layer and a technique for predicting effective conditions of flow past surfaces, to reduce turbulent friction and increase the efficiency of surface cooling.
***Keywords*:** boundary layer, turbulence, laminarization, modeling, heat and mass transfer, gas dynamics.

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Influența laminarizatoarelor asupra stratului limită turbulent și predicția condițiilor efective de curgere în jurul suprafețelor

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Rezumat. Dezvoltarea unor metode eficiente de laminarizare a stratului limită este o sarcină fundamentală pentru funcționarea eficientă și fiabilă a echipamentelor de putere. Obiectivul principal al lucrării este de a studia efectul unei suprafețe de amortizare asupra debitelor din stratul limită care apar în condiții gazodinamice complexe și de a implementa o metodă de predicție a condițiilor efective pentru curgerea peste suprafețele de amortizare. Implementarea modelului matematic permite efectuarea de calcule și crearea unei baze de date pentru analizarea și selectarea celor mai eficiente condiții de utilizare a unei suprafețe de amortizare. Pentru atingerea scopului stabilit, au fost rezolvate următoarele sarcini: dezvoltarea unei suprafețe de amortizare, studii experimentale complexe ale fluxurilor de pereți pe modele cu suprafață de amortizare, sistematizarea rezultatelor datelor experimentale, dezvoltarea unui model semiempiric original de transfer turbulent în stratul limită pe o suprafață de amortizare cu implementarea sa ulterioară într-un pachet software pentru studiul unui interval larg de efecte dinamice ale stratului limită de gaze intense. Cel mai important rezultat al lucrării este dezvoltarea unei metode de laminarizare a stratului limită prin intermediul unei suprafețe de amortizare, al cărei principiu de funcționare este acela de a suprima pulsațiile turbulente de viteză și presiune în apropierea suprafeței raționalizate. Semnificația rezultatelor obținute constă în propunerea unei metode de laminarizare a stratului limită turbulent și a unei tehnici de predicție a condițiilor efective de curgere pe lângă suprafețe.
***Cuvinte-cheie*:** strat limită, turbulență, laminarizare, modelare, transfer de căldură și masă, dinamica gazelor.

Влияние ламинаризаторов на турбулентный пограничный слой и прогнозирование эффективных условий обтекания поверхностей

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Abstract. Турбулентный пограничный слой обусловлен нестационарными течениями, протекающими в сложных газодинамических условиях. Разработка эффективных способов ламинаризации пограничного слоя является фундаментальной задачей для эффективной и надежной эксплуатации энергетического оборудования. Реализация методов и инструментов для исследования и прогнозирования течений в пограничном слое позволяет разрабатывать эффективные научно-технические решения. Перспективной технологией для ламинаризации пограничного слоя является демпфирующая поверхность. Основная цель работы заключается в исследовании влияния демпфирующей поверхности на течения в пограничном слое, протекающие в сложных газодинамических условиях и реализации метода для прогнозирования эффективных условий обтекания демпфирующих поверхностей. Важную роль в реализации предлагаемого подхода занимает математическое моделирование течений в пограничном слое при сложных газодинамических и тепловых условиях. Реализация математической модели позволяет проводить вычисления и создать базу данных для анализа и выбора наиболее эффективных условий применения демпфирующей поверхности. Для достижения поставленной цели были решены следующие задачи: разработка демпфирующей поверхности, проведение комплексных экспериментальных исследований пристенных течений на моделях с демпфирующей поверхностью, систематизация результатов экспериментальных данных, выявление закономерностей ламинаризации пограничного слоя, разработка оригинальной полуэмпирической модели турбулентного переноса в пограничном слое на демпфирующей поверхности с последующей её реализацией в программном комплексе для исследования пограничного слоя в широком спектре газодинамических условий с внешними интенсивными воздействиями. Наиболее важным результатом работы является разработка способа ламинаризации пограничного слоя посредством демпфирующей поверхности, принцип работы которого заключается в подавлении турбулентных пульсаций скорости и давления вблизи обтекаемой поверхности. Значимость полученных результатов заключается в предложении способа ламинаризации турбулентного пограничного слоя и методики прогнозирования эффективных условий обтекания поверхностей, для снижения турбулентного трения и увеличения эффективности охлаждения поверхностей.

***Ключевые слова*:** пограничный слой, турбулентность, ламинаризация, моделирование, тепломассообмен, газодинамика.

INTRODUCTION

Today, there are many active and passive methods of flow control, many of which have found practical application; however, the development of technical devices, requirements for fuel and environmental efficiency, as well as the development of technological sovereignty, create a need to develop new or optimize existing methods of flow control. Active development of flow control systems began in the mid-1970s, and a large amount of experience has been accumulated in studying the possibilities of reducing turbulent friction using passive and active methods of controlling turbulent shear flows [1].

Boundary layer flow control allows weakening or preventing flow separation on a streamlined surface, maintaining a laminar flow regime in the boundary layer, which leads to a decrease in friction resistance and heat transfer, and the opposite effect is also possible due to flow turbulization, which is used to increase heat transfer and control separated flows. The advantage of passive methods is the impact on the boundary layer without spending various types of energy on control; however, a significant disadvantage is the inability to change the level of impacts during operation, which leads to a limitation of the range of effective operation. The main ideas and mechanisms of impact on the structure of the boundary layer are based on reducing the longitudinal momentum near the wall, changing the boundary conditions on the streamlined surface, changing the boundary conditions inside the boundary layer, suppressing turbulent pulsations of velocity and pressure, reducing turbulent pulsations by ionizing the boundary layer. The results of scientific research and practical methods of BCS mainly in gaseous media are presented in the works [2-5].

Based on the variety of methods for influencing wall flows, researchers have developed individual approaches to solving gas dynamics problems that take into account physical factors. Differential systems of equations used to describe gas flows cannot be solved analytically. This is due to the complexity of the equations, the high dimensionality of the problems, the lack of systematic rules of inference and the impossibility of describing complex processes [6]. This is precisely why there is a need to develop modeling methods that allow us to close the system of equations and perform calculations with a known accuracy.

For most practical problems of gas dynamics, the Navier-Stokes equations are used [7], during the existence of which many modifications have been carried out and turbulence models have been implemented, including hybrid ones [8, 9]. Today, there is a tendency to couple the solution of gas dynamics problems with machine learning. This allows for calibration and optimization of model parameters, for example, by calculating empirical coefficients [10]. In addition, machine learning methods are used in calculating supersonic flows [11]. Also, approaches to implementing inverse problems are implemented using machine learning [12]. In addition, the use of machine learning together with the PIV system allows for a more accurate study and modeling of turbulent flow characteristics [13]. Despite the achievements in the field of flow modeling and the availability of some Ansys, Star-CCM+, Autodesk software packages for CFD modeling [14], the calculation of new technical ideas is performed using semi-empirical turbulence models. Their demand is due to their practicality, availability and computational efficiency, which allows them to work out and obtain fundamental results [15, 16]. The paper proposes a method for laminarizing the boundary layer using damping surfaces (Patent RF, no. 225978, 2024). Laminarization is the process of maintaining an ordered, layered flow in the boundary layer of streamlined bodies, which allows for reducing friction resistance and increasing aerodynamic efficiency. The damping surface is shown in Fig. 1.

The interaction of the turbulent boundary layer and its laminarization occurs due to the suppression of turbulent energy in the damping cavities. The turbulent boundary layer has a high three-dimensional distribution of pressure and velocity pulsations, due to which some mass of gas from the boundary layer flows into the cavities and back to the surface through perforations with a diameter of no more than 0.8 mm. As a result of the gas flow, turbulent pulsations are damped and turbulent energy is aligned along the surface, the flow in the boundary layer acquires a more co-directional movement.

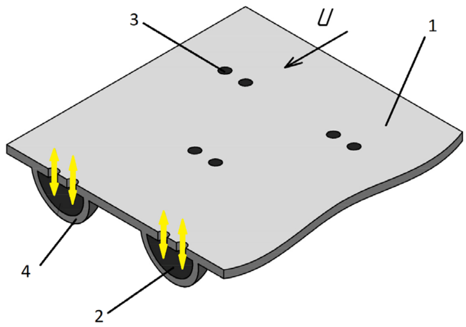

Fig. 1. The damping surface. 1 – streamlined surface, 2 – damping cavity, 3 – perforation hole, 4 – hemispherical protrusion.

The damping surface is an innovative technology, the application of which can be implemented with other control methods, for example, blowing into the boundary layer. The proposed method of boundary laminarization can be used in thermal protection systems for heat-loaded surfaces in conjunction with active methods of boundary layer control, allowing to increase the efficiency of the thermal curtain due to the suppression of turbulence and intensify surface cooling.

During the experimental studies using the PIV method [17], the results were obtained on the velocity distribution in the boundary layer under the action of damping surfaces with different characteristics. The obtained results were systematized to optimize the control of the boundary layer by the damping surface. These results formed the basis of a semi-empirical model of turbulence. The developed method made it possible to develop approaches to modeling turbulent transfer on surfaces using boundary layer laminarization methods. A description of the mathematical model and the numerical method for solving the system of differential equations is presented in [18].

This work is devoted to the study of the influence of a damping surface on boundary layer flows occurring under complex gas-dynamic conditions and the implementation of a method for predicting effective flow conditions around damping surfaces. The most important result of the work is a method for laminarizing the boundary layer using a damping surface, the operating principle of which is to suppress turbulent velocity and pressure pulsations near the streamlined surface. The significance of the obtained results lies in the development of technical solutions using damping surfaces and the possibility of predicting the gas-dynamic conditions of the boundary layer. This approach will allow determining the parameters of damping surfaces and predicting the conditions of their flow for the development of effective scientific and technical solutions.

METHODS, RESULTS AND DISCUSSION

The implemented mathematical model is based on the system of differential equations proposed by L. Prandtl. The system of equations describes the boundary layer of gas flows in a two-dimensional formulation. The system of equations, the numerical method and approaches to modeling are implemented in the original software package, the development and improvement of which has been carried out at Ulyanovsk State Technical University since 2001. The system of differential equations, methods for solving them and approaches to modeling intensive impacts are described in [18]. The program code is written in the C++ programming language [19].

The impact of the damping surface is described in the system of equations indirectly through the coefficients of turbulent heat transfer λ_T and momentum μ_T.

The coefficient of turbulent heat transfer λ_T is defined as:

$$\lambda_T = \frac{\mu_T C_P}{\mathrm{Pr}_T}; \qquad (1)$$

where Pr_T is the turbulent Prandtl number.

Momentum is defined as:

$$\mu_T = \frac{\rho l^2 \partial u}{\partial y}; \qquad (2)$$

where l is the length of the mixing path,

$$l = æ\left\{1 - \exp\left[\frac{-\rho v_* y}{26\mu}\right]\right\}; \qquad (3)$$

where $æ$ is the coefficient reflecting the intensity of turbulent transfer of momentum; $v_* = \sqrt{\frac{\tau_w}{\rho_\infty}}$ is the dynamic velocity; τ_w is the tangential friction stress on the wall surface; μ is the dynamic viscosity coefficient.

The damping surface has a direct effect on the coefficient $æ$ characterizing the intensity of turbulent transfer. The effect occurs due to the interaction of the damping cavities with the flow through perforations, which leads to a decrease in the transverse flow velocity and, as a consequence, turbulence. This effect is observed on the inner side of the surface. The outer side of the damping surface has hemispherical protrusions formed by the outer wall of the damping cavities. The protrusions allow the flow to turbulize and increase the intensity of turbulent transfer, which contributes to an increase in heat exchange in the boundary layer. To take into account the influence of processes occurring in the boundary layer on the damping surface, expressions are proposed for determining the coefficient $æ$ on the outer and inner sides of the damping surface. The coefficient characterizing the turbulent transfer of momentum on the inner wall is calculated using the following expression:

$$\frac{æ}{æ_0} = \frac{\sqrt{1 - 8.4 * 10^5 A_v^* \overline{f^2} \exp(1-n)}}{1 + 21.4 \dfrac{u_\infty du_\infty / dx}{u_0 (du/dy)_{y=0}}}; \qquad (4)$$

where A_v^* is the coefficient characterizing the operation of hemispherical damping cavities, the index v characterizes the volume of the damping cavity; $\overline{f}$ is the relative perforation area; n is the number of perforation holes per each damping cavity; u_∞ is the flow velocity outside the boundary layer (in the flow core), m/s; x is the longitudinal coordinate, m; u is the velocity at a given point, m/s.

To determine the intensity of turbulent transfer on the outer wall of the damping surface, taking into account the quantitative and qualitative characteristics of the protrusions, the following expression is proposed:

$$\frac{æ}{æ_0} = \frac{0.54\sqrt{(h/d)^{0.12} \exp(-f \tau_w)}}{1 + 21.4 \dfrac{u_\infty du_\infty / dx}{u_0 (du/dy)_{y=0}}}; \qquad (5)$$

where h is the height of the hemispherical protrusion; d is the diameter of the hemispherical protrusion; f is the relative density of the protrusions on the channel wall (the ratio of the total surface area under the protrusions to the area of the original smooth surface without protrusions) taken in the range from 0.056 to 0.485.

Gas flows at speeds below the speed of sound are considered incompressible. When implementing the mathematical apparatus, the conditions of incompressibility of the medium were observed.

To expand the calculation functionality, the software package has a knowledge base with parameters of gaseous media, namely hydrogen, air, carbon dioxide, carbon monoxide, nitrogen. The numerical solution method is implemented using an implicit six-point difference scheme of the second order of approximation by spatial variables. The choice of the difference scheme is justified by low machine time costs combining high accuracy of the results obtained.

All calculations are saved in the database for subsequent research and search for the best conditions for boundary layer control depending on external conditions. Having an accumulated database, machine learning methods are used for a dynamic search for effective technical solutions for boundary layer control depending on external conditions, which allow analyzing a large amount of data, identifying patterns and providing results in a short period of time, in comparison with traditional modeling. In complex problems consisting of many parameters that have a nonlinear dependence, a deep learning approach is used to determine the hidden function, in which the main element is an artificial neural network (ANN), which acts as a universal approximator [20].

ANN is a smooth, continuous "black box" model, unlike common boosting models built on the basis of decision trees that implement piecewise constant (discrete) functions. This feature allows ANN to more accurately predict output parameters, as well as to assess the sensitivity and significance of each input parameter to identify key points of influence on the system under study.

In this work, for the problem of multiple regression, a deep fully connected neural network was developed, which is called a multilayer perceptron (MLP), it has the following structure:

- Number of input layer neurons - 8;
- Number of hidden layers - 4;
- Number of neurons in hidden layers - 112;
- Number of output layer neurons - 8;
- Activation function - Swish.
- Optimizer - Adam;
- Loss function - MSE.

To prevent gradient decay, the Swish function was used as the activation function, which is calculated as follows:

$$\text{swish}_{\beta}(\hat{z}) = \hat{z}\,\text{sigmoid}(\beta\hat{z}) = \frac{\hat{z}}{1+e^{-\beta\hat{z}}} \qquad (6)$$

where β is the interpolation coefficient, which in this work is equal to 1.

This ANN was developed in the Python programming language using the Pytorch deep learning library [21].

To improve the quality of training, preliminary scaling of the data was used to bring them to a single scale. The StandardScaler module, which is part of the open-source library scikit-learn [22], was used to implement the scaling procedure. In addition, to avoid the so-called overfitting of the model, which could lead to irrelevant forecasts, a batch normalization layer from the Pytorch library was used.

To optimize the hyperparameters, the Optuna library [23] was used, with which the following values were obtained:

- Learning rate - 0.001;
- Number of epochs - 1850.

The following characteristics of the operating conditions in which the use of a damping surface is assumed act as input data: flow rate, temperature, pressure, pressure gradient, cooling type, gas type, Reynolds number at the inlet to the section, surface length. At the output of the ANN, we obtain the characteristics of the damping surface that meet the specified conditions: the number of perforations, the volume of the cavity, the height of the hemispherical protrusion, the distance between the cavities, the adiabatic wall temperature, the Nusselt number, the Prandtl number, and the surface cooling efficiency. To train the ANN, a database was formed based on the results of experimental studies of the boundary layer in a wide range of gas-dynamic conditions using the software package described above. More than 12,000 data values were obtained for training. The data set was randomly divided into training and test samples in a ratio of 80/20. In total, the training sample consisted of 9.600 examples, and the test sample consisted of 2.400.

The trained neural network showed an average value of the determination coefficient R^2 at the level of 0.886, which indicates that the proposed approach has good accuracy results and can be used to search for and predict effective flow conditions around surfaces with a damping surface. Using the developed computational solutions and their software implementation, a study of the turbulent boundary layer and prediction of the characteristics of the damping surface for effective laminarization of the boundary layer on streamlined models were performed.

Input data u = 110 m/s, T = 500 K, p_0 = 0.5 MPa, grad p = - 0.15, lg(Re) = 5.72, l = 0.17 m, cooling type - none, gas type - air. Fig. 2 shows the results of the velocity distribution in the boundary layer at two points along the length of the model under consideration.

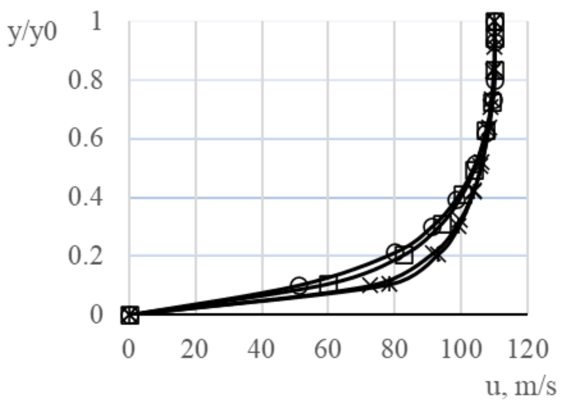

Fig. 2. Velocity distribution by the boundary layer height: × – at point lg(Re) = 5.75, ∗ – at point lg(Re) = 5.88, ○ – at point lg(Re) = 5.75 on the damping surface, □ – at point lg(Re) = 5.88 on the damping surface.

The results of the distribution of the friction drag coefficient are also presented in Fig. 3.

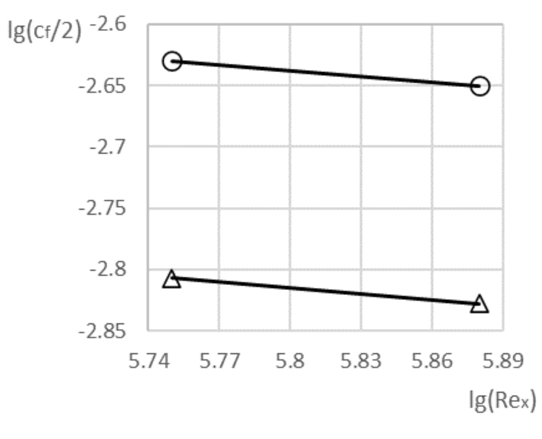

Fig. 3. Coefficient of frictional resistance along the length of a streamlined body: ○ – on a smooth surface, △ – on a damping surface.

For these conditions, the ANN predicted the damping surface parameters: number of perforations - 2, cavity volume - 0.62 mm^3, distance between cavities 17.45 mm. The shape of the damping cavities under these conditions does not matter, since the surface is not thermally loaded. Using the obtained data, a technical solution (Patent RF, no. 232188, 2025) is proposed for the guide vane of the axial compressor of a gas turbine, shown in Fig. 4.

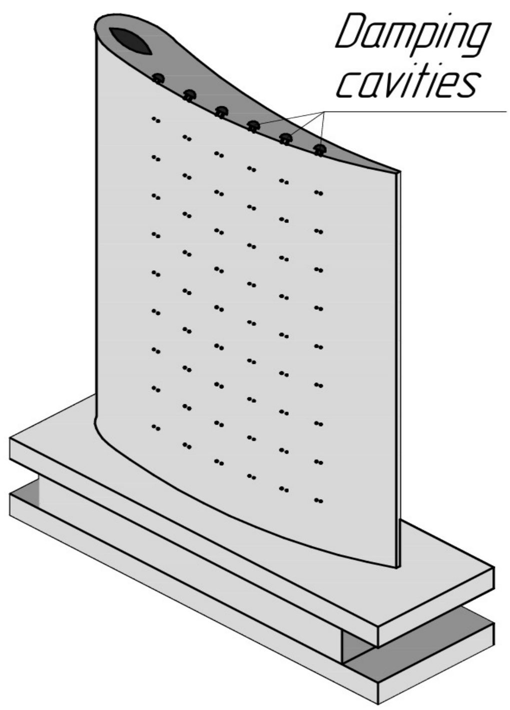

Fig. 4. Axial compressor guide vane of a gas turbine with a damping surface on the back.

The use of a damping surface allows increasing the efficiency of the axial compressor guide vane of a gas turbine by reducing turbulent friction by 6.5% in the area of the blade feather back (for the conditions under consideration). In addition, when the gas flow passes around the guide vanes with an unsteady flow due to a violation of the operating modes, for example, surge, strong flow pulsations may occur. Pulsations will lead to a shift in the separation zone of the boundary layer, the appearance of vibration and a decrease in the productivity of the axial compressor. The damping surface will allow dissipating part of the energy, which will increase the reliability of the unit in unsteady operating modes.

Calculation for the thermal boundary layer has been performed. Input data: u = 110 m/s, T = 1500 K, p_0 = 0.8 MPa, grad p = - 0.15, lg(Re) = 5.68, l = 0.17 m, cooling type - injection, gas type - CO_2. Based on the operating conditions, the ANN filtered the data and predicted the damping surface parameters. Fig. 5 shows the results of the velocity distribution in the boundary layer at two points along the length of the model under consideration.

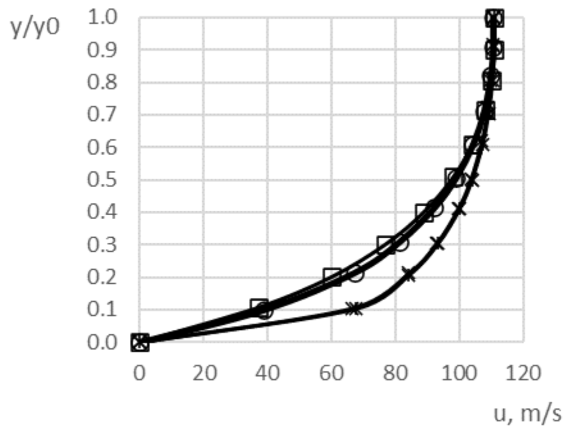

Fig. 5. Velocity distribution over the boundary layer height in the presence of injection Tw = 1050 K: ○ - at point lg(Re) = 5.72, □ - at point lg(Re) = 5.81, ✕ – at point lg(Re) = 5.72 with a damping surface, ✱ - at point lg(Re) = 5.81 with a damping surface.

The presence of a damping surface under the conditions under consideration allows the boundary layer to be laminarized. Fig. 6 shows the distribution of the friction drag coefficient along the length of the surface in the presence of blowing.

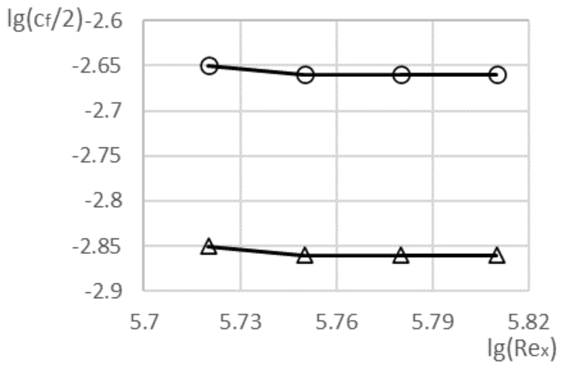

Fig. 6. The coefficient of frictional resistance along the length of a streamlined body in the presence of injection Tw = 1050 K: △ – on a smooth surface, ○ – on a damping surface.

Due to the decrease in the intensity of turbulent pulsations, the turbulent exchange in the boundary layer is reduced and a more stable layered flow is formed, increasing the cooling efficiency. In addition, as a result of air entering the damping cavities and exiting back onto the blade back, the surface of the heat shield in the "cooling air - blade" system increases, which also leads to additional cooling. The temperature distribution by the height of the boundary layer is shown in Fig. 7.

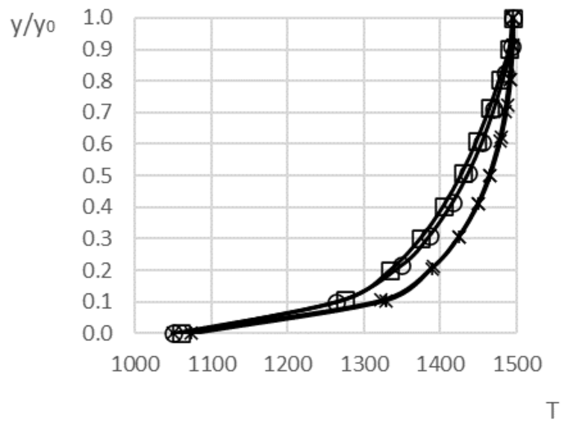

Fig. 7. Temperature distribution over the boundary layer height in the presence of injection Tw = 1050 K: ✕ - at point lg(Re) = 4.506, ✱ - at point lg(Re) = 4.7, ○ – at point lg(Re) = 4.506 with a damping surface, □ - at point lg(Re) = 4.7 with a damping surface.

Figure 8 shows the distribution of the Nusselt coefficient values along the surface length, illustrating the distribution of the heat exchange intensity between the flow and the wall.

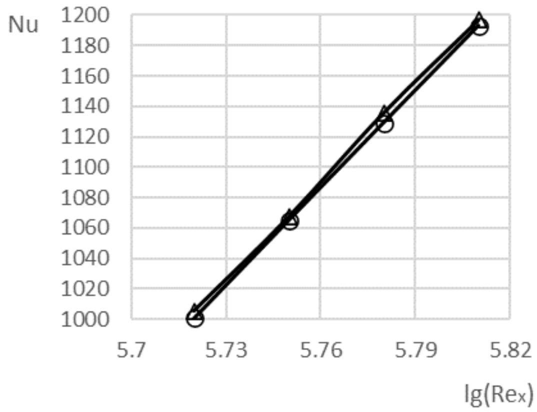

Fig. 8. The value of the Nu number along the length of the streamlined body K: △ – on a smooth surface and coolant injection Tw = 1050, ○ – on a damping surface and coolant injection Tw = 1050.

For the given conditions, the ANN filtered the optimal technical parameters of the damping surface: number of perforations - 2, cavity volume - 0.43 mm^3, hemispherical protrusion height - 7 mm, distance between cavities 15.1

mm. For these conditions, it is recommended to use spherical cavitiesю The spherical shape of the protrusions allows to significantly reduce the thermal stress of the metal. Using the obtained data, a technical solution (Patent RF, no. 232165, 2025) for combined cooling of a gas turbine engine working blade is proposed shown in Fig. 9.

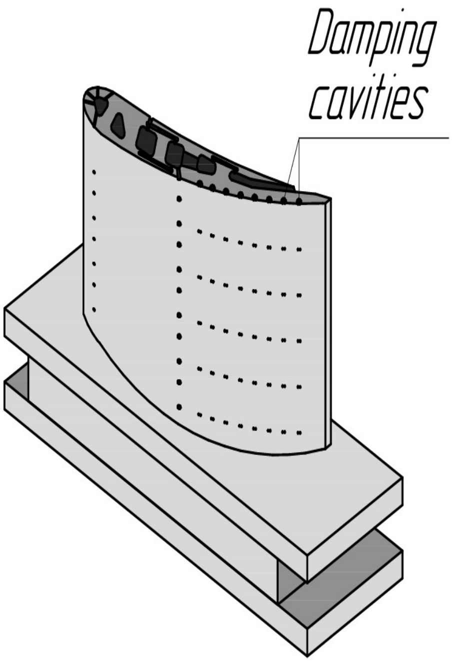

Fig. 9. Working blade of a gas turbine engine with a combined cooling system.

On the back of the blade feather there are damping cavities with perforation holes. The damping surface will increase the reduction of turbulent friction by 7.51% in the area of the blade feather back (for the conditions under consideration) and increase the efficiency of surface cooling by about 3%. The cooling efficiency is increased by two key factors. Firstly, due to the laminarization of the flow, the intensity of heat exchange between the blade back and the environment is reduced, which allows for a reduction in the thermal load. Secondly, due to the laminarization of the boundary layer, the air curtain of thermal protection is drawn in along the streamlined surface.

The approach described in the work is distinguished by its universality. It allows taking into account a wide range of conditions and selecting optimal technical parameters of the damping surface for them. Thanks to the use of ANN, it is possible to significantly reduce computing power, as well as minimize the time spent on calculations and selection of optimal technical solutions.

DISCUSSION AND CONCLUSIONS

The development of new and effective methods of boundary layer laminarization is a fundamental task for increasing the efficiency of power equipment. A promising method of boundary layer laminarization by means of a damping surface is proposed, the operating principle of which consists in suppressing turbulent pulsations of velocity and pressure near the streamlined surface due to the flow of a certain mass of gas from the boundary layer into the cavities and back to the surface through perforation holes. The method of boundary layer laminarization is implemented in the form of utility model (Patent RF, no. 225978, 2024). The paper describes an approach to modeling a boundary layer with a damping surface, and also proposes a technique for searching and predicting the most effective conditions for flowing around surfaces. A deep fully connected neural network has been developed to predict the conditions for flowing around damping surfaces and to search for optimal parameters of cavities. The neural network works with a database that contains modeling results for a wide range of gas-dynamic conditions. The trained neural network showed an average value of the determination coefficient R^2 at the level of 0.886, which indicates good accuracy results. Using the above approaches, a technical solution for the guide vane of the axial compressor of a gas turbine (Patent RF, no. 232188. 2025) and a technical solution for cooling the blade of a gas turbine engine (Patent RF, no. 232165, 2025) were implemented. The use of a damping surface allows to reduce turbulent friction by 6.5% in the area of the back of the blade feather of the guide vane of the axial compressor, which will increase the compressor performance. In addition, the damping surface will allow some of the energy to be dissipated, which will increase the reliability of the unit under non-stationary operating conditions, for example, during surge. The use of a damping surface in the area of the back of the blade feather of a gas turbine engine will reduce turbulent friction by 7.51% and increase the efficiency of surface cooling by 3% due to a decrease in the intensity of heat exchange between the back of the blade and the surrounding environment, as well as the tightening of the air curtain of thermal protection along the streamlined surface.

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