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MATHEMATICAL MODELING AND THE STUDY OF EXCHANGE PROCESSES IN DISPERSE BOUNDARY LAYER CONTROL ACTIONS

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A significant interest of researchers is attracted to the effective management and forecasting of exchange processes in the boundary layer, which are key for the implementation of effective and reliable equipment. Modeling of exchange processes occurring in a high-speed dispersed boundary layer with external influences is a very difficult task. Mathematical modeling allows us to develop reliable devices and engines for the fields of aircraft, energy, shipbuilding with minimal costs for its creation. Despite the interest of numerous groups of researchers around the scientific projects and a large number of works, the current theory of the boundary layer is imperfect. This may be due to several circumstances: firstly, the theory of single-phase turbulent flows of continuous media is far from being completed, secondly, turbulent flows with dispersed impurities in the form of particles greatly complicate the already intricate flow pattern. Interest in dispersed flows is particularly relevant due to the fact that almost all gas-dynamic flows contain a certain concentration of particles, and their impact can provoke significant changes in the structure of the boundary layer and affect the intensity of exchange processes. The article proposes a two-fluid mathematical model describing the motion of a high-speed dispersed boundary layer on a surface with hemispherical damping cavities. The use of hemispherical damping cavities allows to reduce turbulent exchange in the boundary layer, which makes it possible to control the intensity of metabolic processes. The possibility of a significant reduction of turbulent heat transfer and friction in the dispersed boundary layer is established. The proposed method of impact on the turbulent transport in the boundary layer will improve the equipment and installations, including GTU and GTE used in various industries of our country, such as energy, aircraft, shipbuilding.

Key words: turbulent transport, hemispherical damping cavities, mathematical modeling, boundary layer, heat transfer.

INTRODUCTION

The technical progress is based on the constant equipment efficiency and performance upgrade. The actual trend in efficiency raise is the management of exchange processes in the boundary layer. The management method uses the decrease in intensity of highly turbulent pulses in the boundary layer achieved due to turbulence energy damping in hemispheric damping cavities. The implementation of the method may also result in the boundary layer lamination, the reduction in heat-exchange, the decrease of vibration processes generation, and aerodynamic noise pollution decrease. The theoretical grounds being developed will allow to show the gas-dynamic conditions within dynamically unsteady boundary layer and to optimize the processes for particular technical devices and systems.

THE THEORETICAL GROUNDS AND RESEARCH METODS OF DISPERSED FLOWS

The research of dispersed flows with phase transitions is carried out at the research centers of the USA, the UK, Germany, Denmark, China, Japan, Israel and Russia. The theoretical development is intense for the aspects of heat and mass exchange and fluid and gas mechanics connected with the dispersed two-phase flows.

The developer of mathematical models and methods faces certain challenges. Firstly, numerous physical processes taking place in the dispersed flows have to be taken into consideration. Secondly, physical processes in conditions of high temperatures are not always indisputable, so the modelling methods developed may insufficiently adequate results. Thirdly, the model cannot be comprehensive, it has to have certain application boundaries and limits. Thus, the research supposes thorough analyses and accentuation on the most critical physical aspects for the problem solution.

At present, the active research on the dispersed flows has led to a significant knowledgebase. The paper [2] provides a review of both theoretic and experimental research on the turbulent dispersed flows around bodies of different shapes: sphere, cylinder, plates and cascaded airfoils. It has been proved that the presence of particles in the flow may cause significant erosive wear, gas dynamic spatter, icing, light emission increased heat exchange and overheating. Such phenomena, for instance, appear when aircraft are travelling through dust-filled atmosphere, also in case of powerplants in operation [5, 6, 7]. The basic phenomena in the context of dispersed flows are spotted in the boundary layer. They lead to the increased intensity of metabolic processes, vortex shedding and turbulent wake formation [8] In order to correctly assess the physical processes in the dispersed boundary layer it is necessary to consider the velocity distribution, the temperatures (non-isothermal condition), and the particle concentration depending on the flow field around the surface and the surface type. The papers [2, 9] classify the possible disperse flow field regimes using the Stokes number StK_f for the mean motion, which characterizes the velocity relaxation for gasses and particles in the vicinity of the boundary/wall [2]. The papers [10, 11] observe the influence of the particles on the boundary-layer drag and heat-exchange noticing the quality changes in metabolic processes depending on the particle concentration, size and flow angles.

According to the latest tendencies, the two-phase flow calculation contains the modeling of impulse, the mass and heat transfer for each of the phases, and also the modeling of phase interaction within the flow. The current two-phase flow mathematic models are divided into two classes: Euler (two-fluid) and Euler-Lagrange.

The theory and application of two-fluid model calculation is shown in research papers [1, 2, 12].

Two-fluid models have the advantage of using similar equations to describe the homogeneous and non-homogeneous flows thus enabling to solve the system of equations using one numerical approach and, as follows, to increase the timing efficiency of the modelling adequacy processing and check. The criticisms of such models are: the solution error resultant from the disperse phase approximation: the missing data of the motion of separate particles in the non-homogeneous flow; the cumbersome boundary conditions for non-homogeneous flows on the surfaces causing the flow restrictions. The advantage of Euler-Lagrange model is the detailed approach. The model takes into consideration the complete information about the environment, including the particle motion and their interaction in the vector flow with the known temperature field. The principal difficulties are connected with the specific turbulent nature of the motion: the interaction of the dispersed cluster particles with the external phase turbulent vortices and with one another as a result of the particle contact with the boundary/wall and setting on the wall; the influence of turbulent fluctuations on the phase transition speed; the back reaction of the particles on the turbulence [1]. Having analyzed both approaches, we should acknowledge that the criticisms of the first class of models are the advantages of the second class of models, and vice versa.

The paper by L.I. Zaichik and V.M. Alipchenko studies the statistic theory and continual method of the modelling of hydrodynamics and heat-exchange in two-phase flows. The research thoroughly investigates the basic theoretical problems caused by the particle motion in the turbulent flows, the phenomenon of particle accumulation in the near-wall layer. The authors claim that statistic models can be used for effective accounting of the particle interaction with the small-scale vortices to determine the sub-grid turbulence within the large-scale vortex method.

Considering the challenges mentioned above, it is impossible to come to direct numerical method of solution for the system of differential equations. Making equations for the instant parameters is problematic for modeling of the dispersed flow turbulence. At the same time it is known that outer effects on the dispersed flow typical of gas turbine engines lead to a number of specific features of turbulent transfer, which as a matter of principle cannot be considered neither using a classical model of Prandtl "mixing length" model, nor the widely differential two-parameter *"k-e"* used turbulence model. To cope with the difficulties mentioned above it is necessary to develop the model which will adequately describe the motion and the heat-exchange of the dispersed flow in the boundary layer considering the outer effects.

To implement the model, it is essential to develop as an analytical kernel the two-fluid model of the boundary layer. The original mathematical model takes into consideration the inner sources of the heat and the amount of motion, and also the turbulent transfer in the boundary layer and the outer factors in action. Moreover, the immediate effect of the particles on the carrying medium will be considered by the boundary conditions and corresponding members, which are conditional to the particle impact.

The intermediate impact will be considered using the eddy diffusivities of momentum and heat.

The two-fluid model [4, 13], describing the high-speed boundary layer with outer impact, will be shown as differential equations:

The differential equation of motion:

$$\rho\left(\frac{\partial T}{\partial \tau}u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\frac{\partial}{\partial y}\left[(\mu+\mu_T)\frac{\partial u}{\partial y}\right]-\frac{\partial p}{\partial x}; \quad (1)$$

The differential equation of energy:

$$\rho c_p\left(\frac{\partial u}{\partial \tau}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial y}\left[(\lambda+\lambda_T)\frac{\partial T}{\partial y}\right]+(\mu+\mu_T)\left(\frac{\partial u}{\partial y}\right)^2+u\frac{dp}{dx}+\frac{\partial p}{\partial \tau}; \quad (2)$$

The differential equation of continuity:

$$\frac{\partial \rho}{\partial \tau}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0; \quad (3)$$

Pressure-volume relation

$$\rho=\frac{p}{RT}, \quad (4)$$

where T – temperature; τ – time; $u,\ v$ – longitudinal velocity component, cross-stream velocity component; $x,\ y$ –longitudinal and transverse coordinate; ρ – density; c_p – specific heat capacity at constant pressure; λ – code of heat conductivity; λ_T – eddy diffusivity of heat; μ – coefficient of dynamic viscosity ; μ_T – eddy diffusivity of momentum; q_v – internal heat source intensity value; s_v – eddy momentum flux intensity value; p – flow pressure; R – individual gas constant.

To solve the system of equations it is necessary to find the values of λ_T, μ_T, q_v, s_v.

The parameters which characterize the presence of the disperse phase in the boundary layer are considered through the thermal and aerodynamic particle influence [4]:

$$q_v = a\left(T_{sm} - T\right); s_v = b\left(u_{sm} - u\right), \tag{5}$$

where a and b are the complexes characterizing the particle parameters; T_{sm} – normal temperature distribution; u_{sm} – normal velocity distribution

$$a = \frac{6\alpha_s \rho_s}{\rho_в d_s} \tag{6}$$

$$b = \frac{0{,}75 \rho_s \rho c_{fs} \left|u_s - u\right|}{\rho_в d_s} \tag{7}$$

where α_s,c_{fs} – unit surface conductance and dispersed medium condensed particle resistance coefficient; ρ_s – condensate phase density (the mass of condensed particles per the unit of the medium volume); $\rho_в$ – density of particle matter; u_s, T_s – particle velocity and temperature; d_s – particle diameter.

The complexes a and b are averaged within the boundary layer, as they encounter insignificant changes (at different iterations at the moment of clarification of the medium flow field), relative to q_v and s_v.

The profiles of temperature T_{sm} and velocity u_{sm} and the particles of the representative fraction in the sections of the boundary layer are determined using the equations [4]

$$u_{sm} = u_{sm\infty}\left[\varphi_u + \left(1 - \varphi_u\right)\frac{u}{u_\infty}\right]; T_{sm} = T_{sm\infty}\left[\varphi_T + \left(1 - \varphi_T\right)\frac{T}{T_\infty}\right] \tag{9}$$

where φ_u, φ_T – coefficients varied from 0 to1 and characterizing the particle diameter and cross travel speed. The more is the cross travel speed and its diameter, and the less is the boundary layer gauge, the bigger is the coefficient, and, accordingly, vice versa. The research conditions were $\varphi_u = \varphi_T = \varphi_S = 1$.

To find the value of the coefficients a, b, φ_u, φ_T the particle trajectory and parameters are calculated using the methods listed in [4].The methods suggested allow to estimate and calculate the boundary layer for the case of the high-speed dispersed flow around the surface. The most common disperse phase flows are the CO_2 (exhaust gas) flows. The sizes of small solid particles in the fluidized state, formed by the fuel combustion range from 10^{-8} to 10^{-6} depending on the fuel type, grade and the combustion process. The exhaust gases are seldom emitted into the atmosphere, as they contain an enormous amount of heat energy. For different types of engines the exhaust gases are used for heating and inner and outer joints ice accretion prevention (compressor guide vanes, casing), in energy efficient gas turbine engines the exhaust gases are used for heat energy recuperation by passing the exhaust gas heat to the air which is later used for fuel combustion. Papers [15, 16] introduce the ways of heat regeneration and recuperation, and also the schemes of heat regeneration in aviation gas turbine engines. The analyses show that a significant part of the exhaust gas energy (kinetic and heat) is wasted before it reaches the areas of potential use. Thus, there is a task of methods development and research for maintaining the exhaust gases energy so that to increase the efficiency of their use.

For the conditions in question, the methods stated in [17] determine the thermophysical properties of CO_2

$$\frac{\mu}{\mu_0} = (T/T_0)^{0.717}; \ \ \frac{c_p}{c_{p0}} = (T/T_0)^{0.939}; \ \ \frac{\lambda}{\lambda_0} = (T/T_0)^{0.236} \tag{10}$$

One of the effective and perspective ways of the boundary layer influence is the use of semispherical damping cavities. (figure 1) The presence of damping cavities on the surface allows to reduce the turbulent-flow resistance and the heat-exchange of the solid body in flow. The outer impacts on the boundary layer, including the semispherical damping cavities impact may be expressed in terms of eddy diffusivity of momentum and eddy diffusivity of heat determined by means of the modified Prandtl “mixing length” model:

$$\lambda_T = \mu_T c_p/Pr; \ \ \mu_T = pl^2\, \partial u/\partial y. \tag{11}$$

where Pr – Prantdl number; l – the mixing length, calculated as:

$$l = æy[1 - \exp(-\rho v_* y/26\mu]. \tag{12}$$

where æ – coefficient showing the intensity of the turbulent transfer in the boundary layer; v_* – dynamic speed.

The semispherical damping cavities will have the immediate influence on the coefficient æ, as they affect the intensity of the boundary layer transfer. The decreased intensity of the turbulent transfer occurs due to the turbulent vortices suppression in the semispherical damping cavities (figure 1).

To model the impact of semispherical damping cavities on the boundary layer in a broad band of gas-dynamic conditions, it is suggested that the coefficient expressed the intensity of the turbulent transfer momentum.

$$\frac{æ}{æ_0} = \frac{\sqrt{1 - 8.4 \cdot 10^5 A_{\text{v}}^* \overline{f^2} \exp(1-n)}}{1 + 21{,}4 \dfrac{u_\infty\, du_\infty/dx}{u_0 (du/dy)_{y=0}}} \tag{13}$$

where A_{v}^* – empirical coefficient, which characterizes the impact of semispherical damping cavities depending on the cavity volume; $\bar{f}$ – perforation relative area; n – the number of perforation holes; u_0 – velocity scanning value; u_∞ – velocity at the boundary layer ceiling.

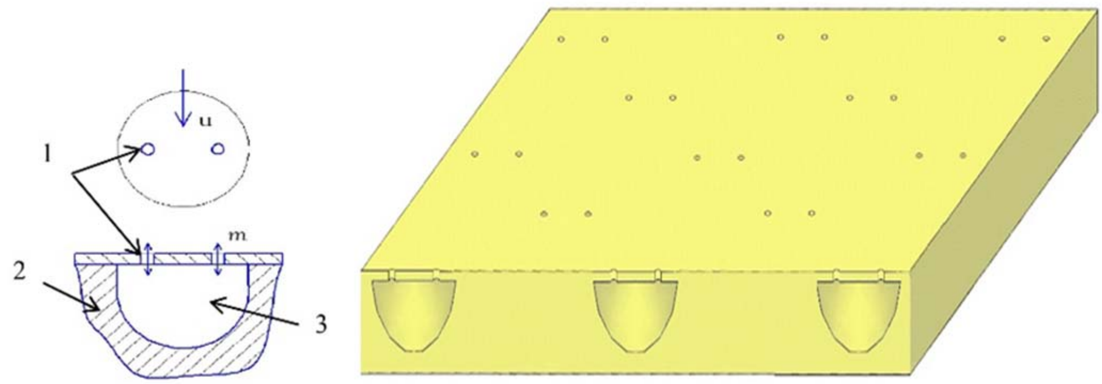


Fig. 1. Diagram of the damping cavity (a) and the damping surface (b) with two perforations, hemispherical form: 1 – perforations; 2 – wall; 3 – hemispherical damping cavity

The coefficient was determined using the approximation of the experiment data. The method of cubic/isometric approximation was used to get the coefficient with minimum error [18]. The empiric data on the reduced turbulent friction on the surface under the impact of semispherical damping cavities were used as approximating values [19].

THE RESULTS OF THE RESEARCH OF DISPERSED BOUNDARY LAYER ON THE SURFACE WITH SEMISPHERICAL DAMPING CAVITIES

To study the exchange processes and conditions of semispherical damping cavities impact the modelling has been carried out using the two-fluid modified mathematical model of high-speed dispersed boundary layer.

The experiment conditions: the flat surface in the dispersed flow without the inertial particle fallout $\varphi_u = 1$; $\varphi T = 1$; $\varphi s = 0$. The surface length given was 0.6 m. The semispherical damping cavities with the volume of 0.575 cm^3 , their contact with the flow was via two perforated holes Ø=0.8 mm, the relative perforation area on the surface $\bar{f} = 0.0012$; $u = 40$ m/s; $T = 640$ K; $R = 189$ J/º kg·K; the coefficient of particle aerodynamic impact G = $0.5 \cdot 10^{-6}$; G = $0.5 \cdot 10^{-8}$ (figure 2).

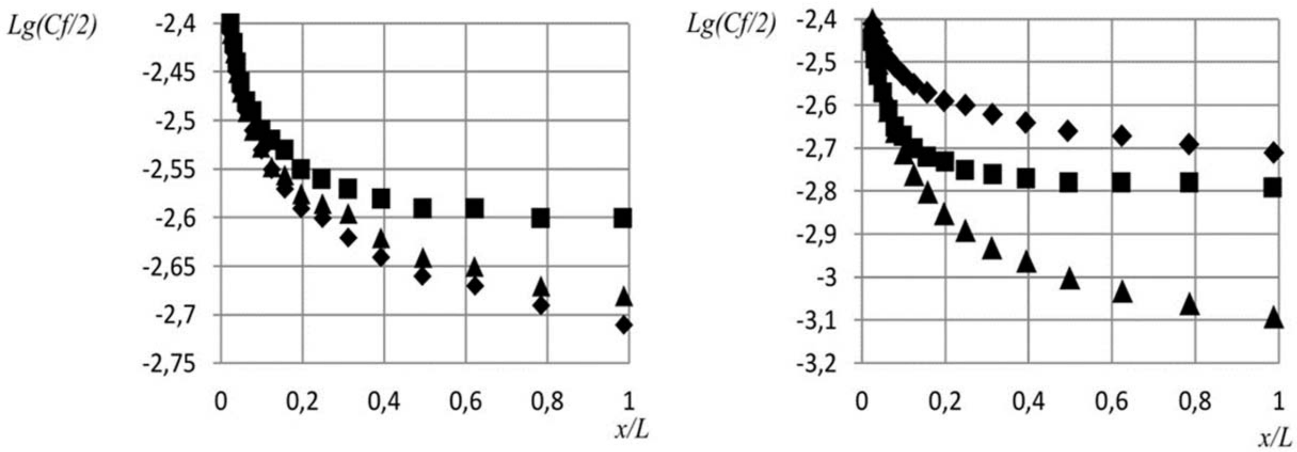
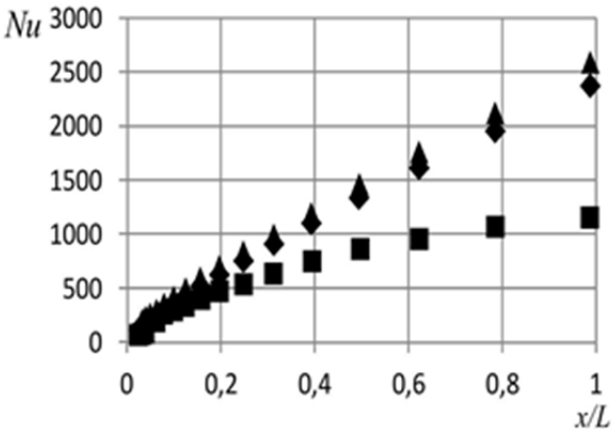


Fig. 2. Study of the coefficient of friction resistance in the boundary layer of the dispersed flow in the flow of smooth (a) and damping surface (b): ■ – aerodynamic coefficient of action of particles G = $0.5 \cdot 10^{-6}$; ▲ – aerodynamic coefficient of action of particles G = $0.5 \cdot 10^{-8}$; ♦ – pure gas flowing smooth surface

The presence of dispersed phase in the flow significantly increases its resistance, for the conditions in question, the resistance turbulent friction coefficient has increased by 2.7% at $G = 0.5 \cdot 10^{-8}$, and at particle impact $G = 0.5 \cdot 10^{-6}$ it increased by 9.8%. The impact of semispherical damping cavities on the boundary layer allows to reduce the turbulent friction significantly. With the impact of cavities the turbulent friction resistance coefficient is decreased by 3.1% at $G = 0.5 \cdot 10^{-6}$, and in case of the particle impact $G = 0.5 \cdot 10^{-8}$ the decrease reaches 17%.

Also, the research on heat loss of the turbulent dispersed flow for the smooth and damping surfaces has been carried out (figure 3).



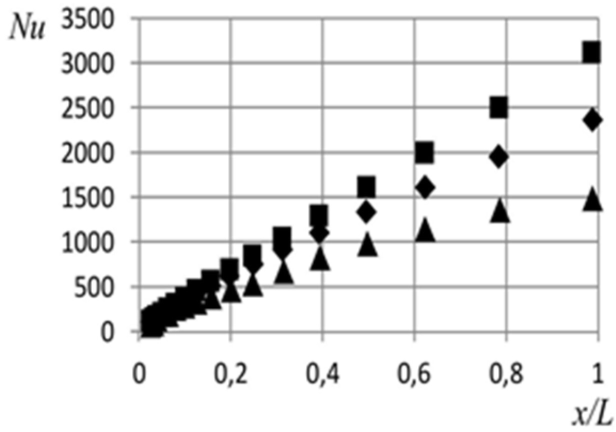


Fig. 3. The study of heat transfer in the boundary layer of a dispersed flow on a smooth (a) and damping (b) surface: ■ – aerodynamic coefficient of the impact of particles $G = 0.5 \cdot 10^{-8}$, with a flow around the damping surface; ▲ – aerodynamic coefficient of the impact of particles $G = 0.5 \cdot 10^{-8}$, when flowing around a smooth surface; ♦ – clean gas, when flowing smooth surface

Considering the results, it is worth mentioning that the use of cavities allows to reduce the heat loss on the surface, thus reducing the heat impact on the surface and the flow heat loss. The decrease of heat exchange in the dispersed boundary layer with the aerodynamic particle impact coefficient $G = 0.5 \cdot 10^{-8}$ reaches 24,3%, but in case of the particle impact coefficient increase to $G = 0.5 \cdot 10^{-6}$ the efficiency of the impact is significantly reduced and reaches 13.6%. Such decrease results from the increase in the boundary layer turbulence due to the aerodynamic impact of the particles.

The damping cavities allow to significantly reduce the resistance and the heat exchange on the surface, which makes their use appropriate in order to increase the device efficiency.

THE RESULTS ANALYSES AND CONCLUSION

The use of semispherical damping cavities leads to significant decrease in the turbulent transfer in the boundary layer, which allows to reduce the energy of turbulent vortices and to reduce the coefficient of turbulent friction Cf/Cf_0 by 17%. The decrease of heat exchange using cavities for loosely dusted flows reached Nu/Nu_0 24.3%, and for dusty flows the given value reached Nu/Nu_0 13.6%. The example of the effective application of semispherical damping cavities is the Patent of the Russian Federation №170277 "the combustion chamber of the gas turbine engine with laminaring panels" developed to enhance the aviation gas turbine engine efficiency. The outer case of the combustion chamber implies the laminaring panels with semispherical damping cavities which facilitate the turbulent transfer in the boundary layer. The mathematical model suggested allows to forecast the effectiveness of semispherical damping cavities application on the surfaces subjected to high-speed dispersed flows.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ И ИССЛЕДОВАНИЕ ОБМЕННЫХ ПРОЦЕССОВ В ДИСПЕРСНОМ ПОГРАНИЧНОМ СЛОЕ С УПРАВЛЯЮЩИМИ ВОЗДЕЙСТВИЯМИ

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К эффективному управлению и прогнозированию обменных процессов в пограничном слое, являющихся ключевыми для реализации эффективного и надежного оборудования, привлечен значительный интерес исследователей. Моделирование обменных процессов, протекающих в высокоскоростном дисперсном пограничном слое с внешними воздействиями, является весьма сложной задачей. Математическое моделирование позволяет разрабатывать надежные устройства и двигатели для областей авиастроения, энергетики, судостроения с минимальными издержками на их создание. Несмотря на интерес многочисленных групп исследователей по всему миру и множество работ, существующая теория пограничного слоя несовершенна. Это может быть связано с несколькими обстоятельствами: во-первых, разработанная теория однофазных турбулентных течений несовершенна и на сегодняшний день содержит множество эмпирических зависимостей; во-вторых, турбулентные потоки с дисперсными примесями в виде частиц сильно осложняют и без того замысловатую картину течения. Интерес к дисперсным потокам особенно актуален вследствие того, что практически все газодинамические течения содержат некоторую концентрацию частиц, а их воздействие может спровоцировать значительные изменения структуры пограничного слоя и повлиять на интенсивность обменных процессов. В статье предложена двухжидкостная математическая модель, описывающая движение высокоскоростного дисперсного пограничного слоя на поверхности с полусферическими демпфирующими полостями. Применение полусферических демпфирующих полостей позволяет снижать турбулентный обмен в пограничном слое, что дает возможность управления интенсивностью обменных процессов. Установлена возможность существенного снижения турбулентного теплообмена и трения в дисперсном пограничном слое. Предложенный способ воздействия на турбулентный перенос в пограничном слое позволит усовершенствовать оборудование и установки, в том числе газотурбинных установок и газотурбинных двигателей, применяемые в разных областях промышленности нашей страны, таких как авиастроение, энергетика, судостроение.

Ключевые слова: турбулентный перенос, полусферические демпфирующие полости, математическое моделирование, пограничный слой, теплообмен.

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