FORMAÇÃO DE FLUXOS HETEROGÊNEOS SUPERSÔNICOS EM ACELERADORES DINÂMICOS A GÁS COM GRANDE ALONGAMENTO

FORMATION OF THE SUPERSONIC HETEROGENEOUS STREAMS IN THE GAS-DYNAMIC ACCELERATORS WITH GREAT ELONGATION

ФОРМИРОВАНИЕ СВЕРХЗВУКОВЫХ ГЕТЕРОГЕННЫХ ПОТОКОВ В ГАЗОДИНАМИЧЕСКИХ УСКОРИТЕЛЯХ С БОЛЬШИМ УДЛИНЕНИЕМ

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RESUMO

O presente artigo descreve os resultados da investigação experimental e teórica da dinâmica dos gases e da troca de calor no decurso de um fluxo supersônico da mistura gás-pó dentro dos aceleradores gasodinâmicos axialmente simétricos, que possuem pequenas seções críticas ($d_{\text{crítico}} = 1...3 \text{ mm}$) e alongamento substancial ($L/d_{\text{crítico}}$ de 70 a 200). A necessidade de realização de tais investigações foi determinada por dois aspectos. O primeiro é o desenvolvimento de tecnologias de inovação com o objetivo de formar revestimentos resistentes ao calor e outros revestimentos com várias funções e propriedades necessárias (formação desses revestimentos com a ajuda de correntes heterogêneas supersônicas). A segunda é a criação de fluxos heterogêneos supersônicos, necessários para o desenvolvimento de investigações experimentais de processos de desgaste erosivo e corrosivo de componentes estruturais de aeronaves de alta velocidade que voam em anomalias atmosféricas (nuvens de chuva e poeira). Para criar um modelo matemático mais confiável da corrente de fluxos heterogêneos não isentrópicos em aceleradores dinâmicos a gás com grande alongamento, uma série de estudos experimentais foi realizada. Os parâmetros de fluxo de gás viscoso foram calculados usando o modelo clássico da camada limite plana. A significância das características do fluxo de gás portador, a dispersão de partículas e seu material para acelerar partículas no fluxo heterogêneo foram esclarecidas. O estudo mostrou que o projeto de microaceleradores dinâmicos a gás deve ser realizado levando em consideração o aumento da espessura da camada limite ao longo das paredes do acelerador de partículas. Também foi esclarecido o entendimento da dinâmica dos gases do fluxo e da transferência de calor de misturas heterogêneas em aceleradores supersônicos dinâmicos a gás com uma concentração de massa de partículas de pó ("fase K") na corrente de até 15%.

Palavras-chave: gás portador, "fase K", revestimentos multifuncionais, anomalias atmosféricas, transferência de calor entre fases.

ABSTRACT

The present article describes results of the experimental and theoretical investigation of gas dynamics and heat exchange in the course of a supersonic flow of the gas-powder mixture within the axially symmetric gas-dynamic accelerators, which have small critical cross-sections (d_{critical} from 1 to 3 mm) and substantial elongation (L/d_{critical} from 70 to 200). The necessity of performance of such investigations was determined by two aspects. The first is the development of the innovative technologies with the purpose of formation of the heat-resistant coatings and other coatings with various functions and necessary properties (formation of such coatings with the help of supersonic heterogeneous streams). The second is the creation of the supersonic

heterogeneous streams, which are required for the development of experimental investigations of processes of the erosive and corrosive wear of structural components of the high-speed air vehicles, which conduct flights in atmospheric anomalies (rain clouded sky and dust-in-air conditions). This study describes the entire cycle of the experimental investigations, which were performed with the purpose of construction of the more reliable mathematical model of flow of the nonisentropic heterogeneous streams in the gas-dynamic accelerators with great elongation. The viscous gas flow parameters were calculated using the classical model of a flat boundary layer. The value of the characteristics of the carrier gas flow, the dispersion of particles and their material for accelerating particles in a heterogeneous flow were found out. The study showed that the design of gas-dynamic micro accelerators must be carried out taking into account the increase in the thickness of the boundary layer along the walls of the particle accelerator. In addition, this article presents a more detailed description of gas dynamics of flow and heat exchange of the heterogeneous mixtures within supersonic gas-dynamic accelerators with mass concentration of the powder particles ("K-phase") in the stream up to 15%.

Keywords: *gas-carrier, "K-phase", coatings with various functions, atmospheric anomalies, interphase heat exchange.*

АННОТАЦИЯ

В данной статье изложены результаты экспериментального и теоретического исследования газодинамики и теплообмена при сверхзвуковом течении газопорошковой смеси в осесимметричных газодинамических ускорителях с малыми критическими сечениями ($d_{кр} = 1...3$ мм) и значительным удлинением ($L/d_{кр} = 70...200$). Необходимость в постановке таких исследований обусловлена двумя аспектами. Первый – это разработка инновационных технологий формирования термостойких и других разнофункциональных покрытий с необходимыми свойствами с использованием сверхзвуковых гетерогенных потоков. Второй – создание сверхзвуковых гетерогенных потоков для постановки экспериментальных исследований процессов эрозионно-коррозионного износа элементов конструкции высокоскоростных ЛА, совершающих полёт в атмосферных аномалиях (дождевая и пылевая облачность). В работе с целью создания более достоверной математической модели течения неизоэнтропических гетерогенных потоков в газодинамических ускорителях с большим удлинением проведен цикл экспериментальных исследований. Были проведены расчёты параметров потока вязкого газа на базе использования классической модели плоского пограничного слоя. Было выяснено значение характеристик потока газа-носителя, дисперсности частиц и их материала для ускорения частиц в гетерогенном потоке. Исследование показало, что проектирование газодинамических микроускорителей необходимо осуществлять с учетом нарастания толщины пограничного слоя вдоль стенок ускорителя частиц. Также было уточнено понимание газодинамики течения и теплообмена гетерогенных смесей в сверхзвуковых газодинамических ускорителях с массовой концентрацией частиц порошка («К-фаза») в потоке до 15%.

Ключевые слова: *газ-носитель, «К-фаза», разнофункциональные покрытия, атмосферные аномалии, межфазный теплообмен.*

1. INTRODUCTION

Gasdynamics studies the motion of compressible continuous media and their interaction with solids. Shock application of a load causes the formation of shock waves in the solid, their interference and other processes that form the task, the solution of which will create a technology for the formation of high-quality coatings. The process of formation of a boundary layer increasing in thickness with a viscous gas flow deforms the velocity field across and along the length of the channel, which has a noticeable effect on the kinematics of particles in the case of a heterogeneous mixture flowing in it. Therefore, the development of a design technique for accelerating channels is relevant (Fang *et al.*, 2016; Chernov and Dudin, 2019).

Specific features of flow of the heterogeneous mixture in the gas-dynamic accelerators with great elongation are as follows: 1. formation of process of the adiabatic flow of the heterogeneous mixture within the gas-dynamic duct of accelerators (in this context "adiabatic flow" means the flow without any heat exchange between a stream and the accelerator wall); 2. implementation of process of the interphase heat exchange within the volume of a stream between the nonisothermal high-speed "K-phase" and the nonisothermal gas-carrier. At the present time, these specific features are considered as challenging problems in the sphere of scientific investigations (Suciu *et al.*, 2018).

The first problem of the above-mentioned problems is connected, first of all, with dynamic characteristics of acceleration of the solid phase

(of particles) within the high-speed gas-carrier. This solid phase (particles) forms the resulting coating. This process is implemented in the stream of the viscous gas that flows with acceleration in the special channels (gas-dynamic accelerators), which have profiles in accordance with the gas dynamics laws. This problem is increasingly complex owing to the fact that such accelerators must have not only a design-basis profile but relevant elongated shape as well (in order to ensure achievement of the required velocity of particles at the output from the gas-dynamic accelerator).

This problem is connected (in the first instance) with the fact that the length of the channel determines the velocity of particles. Therefore, the channel length determines the most important parameters of the entire technological process, which is implemented in order to ensure application of coatings, such as quality of coating, productivity, coefficient of the powder utilisation, and so on (Nikitin and Stepanenko, 2006; Nikitin, 2010; Mikhatulin *et al.*, 2011).

As it is well known from the gas dynamics, the viscous flow of gases in the channels is accompanied by the formation of the boundary layer, the thickness of which increases. This process deforms the field of velocities both across the channel and along the length of the channel. In the case of the flow of the heterogeneous mixture in the channel, the process of increase of the boundary layer exerts significant influence upon the kinematics of particles, as well as upon distribution of various particles within the stream. Therefore, there is the topical problem of developing relevant methodology, which will ensure designing of the accelerating channels with the purpose of formation of such two-phase streams, which would have optimal parameters (Golosnoy *et al.*, 2009; Hu *et al.*, 2015; Zhang *et al.*, 2016; Gusev *et al.*, 2018; Chugunkov *et al.*, 2018; Cui *et al.*, 2019).

The second problem of the above-mentioned problems is connected with the interaction of the high-speed particles (which have various degrees of dispersion) with the solid surface. It is known from the mechanics of rigid bodies that impulsive application of a load to the surface of a body causes the formation of shock waves within the body, interference of these waves, as well as other processes. In this situation, the following processes are implemented within the zones of concentration of waves: processes of elastic and plastic

deformation, adiabatic transformation of mechanical power into thermal energy, dissipation of energy, dynamic diffusion, possible structural, and phase changes, as well as erosion and corrosion processes (Fedyaev *et al.*, 2015; Yin *et al.*, 2016).

As the final result, the entire set of these processes forms the multiparameter problem. Development of the mathematical model of this problem, as well as solving and verification of this problem will make it possible to create both innovation technology of formation of the high-quality coatings, which have various goal-seeking functional properties, and the problem of erosive and corrosive wear of structural components of the high-speed air vehicles in the course of flying through the cumulonimbus and dusty clouds (Toma *et al.*, 2013; Yin *et al.*, 2014; Kornienko *et al.*, 2016; Liu *et al.*, 2018).

As it was already noted above, the shaped channel, within which acceleration of the heterogeneous stream is ensured, is the most important component of the test (experimental) stands, which create the supersonic heterogeneous streams with possibilities of parameters changing in a wide range. As concerns actual installations, which are used in the real world, they are based on utilization of the elongated accelerating channels (such as convergent-divergent nozzles; de Laval nozzles), which have a conical shape or a flat (rectangular) shape.

At the same time, these elongated accelerating channels are characterized by small angles of expansion of the supersonic section. Due to the fact that critical cross-sections have small areas (d_{critical} is changed from 1 mm to 5 mm), relative elongation of such channels can be changed over the wide range (L/d_{critical} is equal to from 50 to 200). The last fact determines the velocity of the "K-phase" at the perpendicular cut of the channel (Cui *et al.*, 2019; Bogdan *et al.*, 2019; Flamant and Clarke, 2019).

As it is known, the key feature of flows of viscous gases within the channels, which are characterised by the elongated shapes, is connected with the fact that the boundary layer, which was created on the surface of walls of these channels, ensures an essential decrease of the actual flow cross-section of the channel as compared with the design/calculated cross-section. This fact decreases both the mass flow rate per second of the stream and the velocity of this stream. If this effect will not be taken into consideration in the process of designing of such

channels, then the boundary layer will be closed up inside the nozzle. Therefore, the established turbulent flow occurs within the following sections of such channels (in the downward flow direction). Such flow is similar to the flow, which occurs and then is implemented within the main section of the smooth of the cylindrical tube. As it is known, such flow is accompanied by the intensive dissipation of the stream energy.

As concerns the experimental supersonic gas-dynamic stand, it is understood that this process is the harmful one, because of availability of this process will not make it possible to ensure a rigorous calculation of the stream parameters at the perpendicular cut of the channel (Ovsyannik and Makeeva, 2018; Avezova *et al.*, 2019; Babak *et al.*, 2019). In the course of flow of the heterogeneous mixtures within the accelerators, which are characterized by such shapes due to the small dimensions of particles (within the submicron range), it is possible to consider that motion of the particles along these channels is the motion in the straight line.

2. MATERIALS AND METHODS

Turbulisation of the stream within the channel (due to the fact of the above-mentioned reasons), which occurs, ensures changes both in the nature of motion of particles and in the law of distribution of velocities of particles over the transversal cross-section of the relevant stream. In addition, the relevant energy dissipation effect ensures significant decrease velocity of particles as compared with the design/calculated velocity. For example, many experiments proved that velocities of the particles within the two-phase streams (provided these velocities were measured with the help of the laser Doppler velocimeter system) can be essentially different (up to 50%) as compared with the of the values, which were calculated in accordance with the theory of the adiabatic flows. This is the reason why it is necessary to estimate the influence of the boundary layer upon the dynamics of the flow of the heterogeneous mixture within the channels, which have various elongated shapes.

In the course of performance of this analysis, a certain number of assumptions were accepted. For example, due to the small dimensions of particles, no drops in the temperatures of particles within the volume of these particles were taken into consideration. The last fact is similar to the actual conditions because in accordance with the existing

estimates value of the Biot number is changed within the following limits: Bi is equal to from 10^{-3} to 10^{-4} . In addition, it was previously understood that the viscous effects, which (for all intents and purposes) do not depend upon temperature of the surface, due to the fact low levels of the particle temperatures do not exert any essential influence upon the aerodynamic resistance of a particle.

Therefore, in the course of analysis within the framework of the approximated model of the interphase interaction between a particle and the gaseous stream, this fact has made make it possible to analyze the dynamic and thermal problems as two independent problems. In these circumstances, the algorithm of calculation of all other parameters of stream of the viscous gas must be developed in accordance with the classic model of the flat boundary layer (Nikitin *et al.*, 1982).

In this case, the dynamic problem was presented as the system of the integrodifferential equations in Equation 1 where x is the coordinate position along the generatrix of the relevant accelerator, δ^* is the thickness of the momentum loss within the boundary layer, while τ_w denotes the shearing surface stresses. The rest parameters are the parameters, which are universally accepted parameters in the mechanics of fluids and gases.

As it is well known, the Mach criterion of the approaching stream M_∞ , the temperature factor T_w/T_{gas} , as well as the Reynolds criterion Re_w have no essential influence upon the shape of the velocities profile (distribution) in respect of thickness of the boundary layer. Therefore, Equation 2 has been assumed, where y is the coordinate position along the normal to the accelerator surface, while δ denotes the thickness of the boundary layer in the design/calculated cross-section. In the situation, interconnection between various integral characteristics of the boundary layer was determined in accordance with the following form (Equations 3-5) where δ^* denotes thickness of displacement within the boundary layer. The above-presented system of equations in respect of the boundary layer had made it possible to calculate the supersonic flows, which were registered in the actual supersonic accelerators. in order to perform further calculations The following stagnation parameters of stream were assumed as the initial data: pressure P_0 , temperature T_0 , and geometrical dimensions of actual supersonic accelerators.

Table 1 presents certain results of the calculations, which were performed in respect of the axially symmetric gas-dynamic accelerator. It follows from the data, which are presented in the above Table, that values of actual diameters of the output cross-section of accelerator $d_{aver. phase}$ and calculated values of this accelerator $d_{aver. calculated}$ are different. In addition, actual values of the Mach criterion ($M_{aver. phase}$) and values of the Mach criterion, which were calculated in accordance with the adiabatic theory of the ideal flow $M_{aver.p.}$ and the Mach criterion $M_{aver.}$, which was determined in the course of experiments with the same accelerator, do not correspond with each other. By comparison, the above Table presents the data of the article (Alkhimov *et al.*, 2000) in the last two lines of this Table. These results are in satisfactory correlation with each other. It is obvious that there exists a significant influence of the increase of the boundary layer thickness upon the nature of flow of the viscous gas in the elongated gas-dynamic accelerators.

These calculations, which were have been performed with utilization of the above-presented system of Equations 1-5 demonstrate that (for example) the boundary within the conical gas-dynamic accelerator (diameter of critical cross-section $d_{critical}$ of which is equal to 1 mm) layer will be closed up at the distance of L , which is equal to from 10 to 12 mm from the critical cross-section. In the case of a further increase of the critical cross-section diameter of the nozzle up to $d_{critical}$ up to 2 mm, the boundary layer will be already closed up at the distance of L , which is equal to from 100 mm up to 120 mm. In accordance with further processes, the turbulent flow will be established in both downward flow directions.

This fact creates essential complications for the application of the gas-dynamic micro accelerators within various experimental stands. It is necessary to perform the designing of such micro accelerators taking into consideration the increase of the boundary layer thickness along the walls of the relevant accelerator of particles. Similar problems have been analyzed in articles (Rabinskiy and Tushavina, 2019a; Rabinskiy and Tushavina, 2019b; Rabinskiy *et al.*, 2019).

3. RESULTS AND DISCUSSION:

As it is well known, acceleration of particles within the heterogeneous stream is determined by characteristics of stream of the gas-carrier (velocity of the gas-carrier u_{gas} , density of the same gas-carrier ρ_{gas} and so on),

as well as by the degree of dispersion of particles and kind of material of these particles. In addition, the nature of the flow of the gas-carrier within the channel of accelerator plays an important role in this process.

Figure 1 presents the dimensionless set of parameters (Equation 6), where $L_{accelerator}$ denotes length of the relevant accelerator, d_{yac} ($d_{particle}$) denotes diameter of a particle, P_i denotes pressure within the design/calculated i -th cross-section of this accelerator, $V_{particle,i}$ denotes velocity of a particles within the design/calculated cross-section, $u_{gas,i}$ denotes gas velocity within the design/calculated cross-section (in accordance with the calculations, which were carried out in the article (Alkhimov *et al.*, 2000)), Δ denotes relevant experiment (Alkhimov *et al.*, 2000), O denotes results of this article, C_f is equal to 0.5, while $\bullet$ denotes results of this article C_f is equal to 1.0.

Figure 1 presents the results of calculations and measurements of the relative velocity of the aluminum and copper particles as compared with results, which were obtained in (Alkhimov *et al.*, 2000). These experiments were performed with the help of the industrial powders, degree of dispersion of which d_{yac} is equal to from 2.5 to 25·10⁻⁶ meter. Velocity of the gas-carrier within the heterogeneous stream was changed within the limits of V_{gas} , which is equal to from 200 to 1200 m/second. Figure 1 presents the results of the computational experiment, which was performed in the Moscow Aviation Institute in accordance with the above-described methodology. Conditions of this experiment are similar to the conditions of the experiment, which was performed in (Alkhimov *et al.*, 2000). The single exception is as follows: in this case, calculations were performed for the conical nozzle (Lomakin *et al.*, 2017; Formalev *et al.*, 2018; Formalev and Kolesnik, 2019).

From this point of view, the main complexity of application of this methodology is connected with the fact that shape of particles of the industrial powders, which are utilized in the experimental and technological practice, has essential differences in respect of the spherical shape, for which dependency of the aerodynamic drag coefficient C_f is equal to $f(Re_w)$ and which is already well-known. Therefore, it is possible to explain the fact of difference of results of calculation of the relative velocity for the spherical particles, the value of C_f of which is equal to 0.5, while the value of C_f is equal to 1.0. Figure 1 presents the results of calculations for the particles, which have a nonspherical shape at the

value of C_f , which is equal to 1.0. As is evident from this Figure, there exists a proper correlation of results of both articles (Figure 2), if C_f is equal to 1.0.

4. CONCLUSIONS:

The article presents results of the algorithm of the calculations (in accordance with section 1), which were performed in order to determine the dynamics of the flow of particles as well as dynamics of the interphase heat exchange within the high-speed heterogeneous stream. Kind of the gaseous phase is air; "K-phase" denotes copper particles (Cu) with diameter at the level of 40 micrometers. The shape of the supersonic gas-dynamic accelerator is a conical one.

Figure 2 presents the results of these calculations. It follows from this Figure that the maximum speed of heating of a particle is implemented within the precritical area of the nozzle, that is, in the area of maximum temperature and maximum density of the gas-carrier.

There exists strong influence upon the intensity of heating of a particle within the precritical area of the nozzle, and this influence is connected with the fact that relevant particles stay within this section of the nozzle during relatively prolonged time due to the fact that velocities of the gas-carrier (U_{gas}) and velocities of particles (V_{particle}) are small.

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$$\frac{d\delta^{**}}{dx} = \frac{\tau_w}{\rho_{\infty} \cdot u_{\infty,203}^2} \quad (\text{Eq. 1})$$

$$\frac{u(y)}{u_{\infty}} = \left(\frac{y}{\delta} \right)^{1/7} \quad (\text{Eq. 2})$$

$$\frac{\delta^{**}}{\delta} = 1 - \frac{\delta^*}{\delta} - n \int_0^1 \frac{z^{n+1} dz}{\left(1 + \frac{k-1}{2} M_{\infty}^2 \right) \left[(1 - \bar{T}_w) z + \bar{T}_w \right] - \frac{k-1}{2} M_{\infty}^2 z^2} \quad (\text{Eq. 3})$$

$$\frac{\delta^*}{\delta} = 1 - n \int_0^1 \frac{z^n dz}{\left(1 + \frac{k-1}{2} M_{\infty}^2 \right) \left[(1 - \bar{T}_w) z + \bar{T}_w \right] - \frac{k-1}{2} M_{\infty}^2 \cdot z^2} \quad (\text{Eq. 4})$$

$$\frac{\delta}{x} = \frac{0,0575}{\text{Re}_x^{0,2}} \left(\frac{\delta^{**}}{\delta} \right)^{-0,8} \frac{\left(1 + \frac{(k-1)}{2} M_{\infty}^2 \right)^{0,6}}{\left(1 + 0,75 \frac{(k-1)}{2} M_{\infty}^2 \right)^{1,05}} \bar{T}_w^{0,6} \left(\frac{2}{1 + \bar{T}_w} \right)^{1,05} \quad (\text{Eq. 5})$$

$$A = \left(\frac{d_{vac}}{L_{yck}} \right)^{0,5} \left(\frac{\rho_{vac} \cdot u_{203}^2}{P_i} \right)^{0,5} \quad (\text{Eq. 6})$$

Figure 1. Change of the relative velocity of a particle depending on the dimensionless set of parameters A

Figure 2. Distribution of velocities and temperatures of the gas and solid phases along the length of the supersonic of accelerator: 1 is the velocity of the gas phase, 2 is the temperature of the gas phase, 3 is velocity of the cuprum particle, 4 is the temperature of the cuprum particle

Table 1. Design/calculated parameters for the axially symmetric gasdynamic accelerator

$d_{crit.}$	$d_{aver.}$	$M_{aver. phase}$	Re_x	$M_{aver..p}$	$d_{aver. phase}/d_{aver..p}$	$M_{aver..ak}$
mm	mm	-	-	-	-	-
3.5	12.2	3.45	6.3×10^5	4.14	0.71	-
4.5	9.5	2.55	4.36×10^5	3.05	0.84	2.48
4.5	9.5	2.67	5.19×10^5	3.05	0.845	2.6
2.72	12.65	3.87	1.2×10^5	4.8	0.67	-
4.72	12.65	2.84	0.27×10^5	3.58	0.71	-