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INVESTIGATION OF THE PROCESSES IN TORCHES FOR HIGH-SPEED GAS-PLASMA SPRAYING OF POWDER MATERIALS WITH THE USE OF THE FLOW-RATE METHOD OF ACTION ON THE FLOW

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The comparative characteristic of torches with geometric and flow-rate methods of control of the characteristics of a two-phase flow are given. Based on the mathematical model proposed, the advantage of the flow-rate method is shown by calculation. By using particular examples, the estimates of the optimum values are given for the relation of the flow rates in feeding units and for the length of the heating portion for torches with a flow-rate method of control of the two-phase flow.

High-speed gas-plasma spraying is one promising trend in the deposition of coatings. The technology of high-speed gas-plasma spraying makes it possible to produce thermal coatings of high quality virtually from any metallic materials and many powder cermets. The energy potentialities of the method allow the particles of the majority of materials to attain the temperatures and velocities required for the production of high-grade functional coatings from new progressive composite materials based on high-melting alloys and ceramics.

The existing systems of high-speed gas-plasma spraying (Jet Kote-23, Top-Gun, Met-Jet, and JP-5000) employ the traditional method of control of the flow; this method is based on geometric action. The particles are simultaneously heated and accelerated as they move in a high-temperature flow of combustion products in the gasdynamic circuit of a torch. The traditional gasdynamic schemes make it impossible to realize in full measure the energy potential of this method of deposition of coatings. The possibilities of increasing the particle energy with the use of a traditional scheme of control of flow parameters are practically exhausted. The conditions for increasing the velocity and temperature of particles are mutually exclusive: to increase their temperature one must increase the time of stay of the particles in the flow, while the increase in the velocity of particles reduces the time of their stay in the gasdynamic circuit. The traditional method makes it impossible to accelerate the particles of high-melting materials to the velocities required for the production of a high-quality coating, simultaneously melting them. Furthermore, for the traditional scheme with a prescribed geometry of the gasdynamic circuit the possibilities of controlling the characteristics of a two-phase flow are limited and imply that one can change only the parameters in the combustion chamber. An unusual feature of designing the gasdynamic circuits of a torch is that the incorporation of contraction portions (which are most prone to the erosional destruction by solid particles and the adhesion of molten particles to the channel walls) into these circuits is undesirable.

The drawbacks inherent in the traditional method can be minimized by the employment of the flow-rate method of control of the flow [1]. A distinctive feature of this method is a functional subdivision of the

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gasdynamic circuit into a portion of heating of particles in the flux of combustion products of high temperature and low velocity and a portion of acceleration of a two-phase flow to supersonic velocities. The flow-rate method of control of a two-phase gas flow is realized owing to the supply of the components of the fuel or the combustion products in feeding units which are located along the gasdynamic circuit of the torch on the subsonic portion. The advantages of the method are as follows. It enables one to create a heating portion in the gasdynamic circuit on which the gas velocity is low, which leads to an increase in the time of stay of a particle in the high-temperature flow. The particles on the heating portion of the gasdynamic circuit are heated in a reducing or oxidizing medium which is optimum to them. The acceleration of the flow to the velocity of sound is carried out by the flow-rate method in a cylindrical channel. This enables one to eliminate both the contraction portion and the portions of sharp changes in the flow area, which prevents the erosional damage by solid particles and the adhesion of molten particles to the walls of the gasdynamic circuit of the torch. The flow-rate method provides the possibility of controlling with greater flexibility the characteristics of the two-phase flow owing to the increase in the parameters of action, i.e., the lengths of the heating and acceleration channels and the relation of the flow rates of the components of the fuel or combustion products of different types of fuel that are additionally supplied in feeding units. Since the processes occurring in the gasdynamic circuit of a torch with a flow-rate action on the flow are multiparametric, the values of the diagnostic variables and the optimum operating regimes of the torch must be selected using mathematical modeling. The existing mathematical models [2, 3] describe the gasdynamic flows in torches with a geometric method of action on the flow. As a rule, these models disregard the interference of the phases, a change in the composition of the gas phase along the circuit, and the dependences of the thermophysical characteristics of a two-phase flow on the temperature.

The aim of the present work is to investigate the characteristic features of heating and acceleration of particles in the gasdynamic circuit of a torch with a flow-rate method of action on the flow based on the mathematical model formulated.

Mathematical Model of Flow. In formulation of a mathematical model of a two-phase flow in the gasdynamic circuit of a torch with a flow-rate method of action on the flow, we introduce the following assumptions. The gas phase is an equilibrium mixture of chemically reacting perfect gases. The dispersed phase represents spherically shaped solid or liquid particles of prescribed material; they have the same diameter and do not interact. The exchange of mass between the phases is absent. The mixing of the components of the fuel with each other and with the carrier gas in the feeding units and the reaction between the components of the fuel in the high-temperature zone of the feeding units occur instantaneously. In the feeding units, the parameters of the particles are assumed to be frozen and equal to their values before the unit [1]. The temperature of the hot walls of the gasdynamic circuit of the torch is constant; it can be prescribed depending on the materials used. The walls of the gasdynamic circuit of the torch are technically smooth.

The two-phase flow in the gasdynamic circuit of a torch is described using a simplified model [1, 4, 5] which is based on the quasi-one-dimensional gas-dynamic equations in which account is taken of the friction and heat exchange of the two-phase flow with channel walls and the friction and heat exchange between the phases. The system of equations has the form

$$\frac{d\mathbf{A}}{dx} + \mathbf{G}_0 + \mathbf{G}_1 = 0 \,, \tag{1}$$

where

$$\mathbf{A} = (\rho u,\ \rho u^2 + P,\ \rho u H,\ \rho_{\rm p} u_{\rm p},\ \rho_{\rm p} u_{\rm p}^2,\ \rho_{\rm p} u_{\rm p} H_{\rm p})^{\grave{o}} \,;$$

$$\mathbf{G}_0 = \left(\frac{\rho u}{F}\frac{dF}{dx} \,,\ \frac{\rho u^2}{F}\frac{dF}{dx} + F_\tau \,,\ \frac{\rho u H}{F}\frac{dF}{dx} - Q_{\rm w} \,,\ \frac{\rho_{\rm p} u_{\rm p}}{F}\frac{dF}{dx} \,,\ \frac{\rho_{\rm p} u_{\rm p}^2}{F}\frac{dF}{dx} \,,\ \frac{\rho_{\rm p} u_{\rm p} H_{\rm p}}{F}\frac{dF}{dx} \right)^{\grave{o}} \,;$$

$$\mathbf{G}_1 = (0, F_d, Q_v + F_d u_p, 0, -F_d, -Q_v - F_d u_p)^{\grave{o}} ;$$

$$F_d = \omega (u - u_p) ; \quad Q_v = \vartheta [h (T) - h (T_p)] ; \quad \omega = \frac{3}{4} C_d \frac{q\rho_p\rho}{d_s\rho_s^*} ; \quad \vartheta = 6 \frac{\mathrm{Nu}}{\mathrm{Pr\,Re}} \frac{q\rho_p\rho}{d_s\rho_s^*} ; \quad q = |u - u_p| ;$$

$$\mathrm{Re} = \frac{d_s \rho q}{\mu} ; \quad \mathrm{Pr} = \frac{\mu C (T_p)}{\lambda (T_p)} ; \quad F_\tau = \frac{4}{d_h} \tau_w ; \quad \tau_w = \frac{\xi}{4} \left(\frac{1}{2} \rho u^2\right); \quad d_h = \frac{4F}{\chi} ;$$

ξ is the coefficient of resistance determined from the empirical relations [6] that take into account the influence of the dispersed phase,

$$Q_w = \frac{4}{d_h} q_w ; \quad q_w = \frac{\alpha_w}{C_p (T_w)} [h (T_w) - h (T)] ; \quad \alpha_w = \frac{\lambda (T_w)\,\mathrm{Nu}_w}{d_h} ; \quad \mathrm{Pr}_w = \frac{\mu C_p (T_w)}{\lambda (T_w)} ;$$

$$\mathrm{Nu}_w = 0.022 \mathrm{Re}_w^{0.8} \mathrm{Pr}_w^{0.43} ; \; H = \frac{u^2}{2} + h ; \quad H_p = \frac{u_p^2}{2} + h_p ; \quad E = \rho H - P ; \quad E_p = \rho_p H_p .$$

The system of equations (1) is supplemented with the equation of state for the gas phase written in quasiperfect form:

$$P/\rho = R_0 T/\overline{m} = h'/\overline{Z}\,\overline{Z} , \tag{2}$$

where $\overline{Z}\,\overline{Z} = \overline{m} h'/(R_0 t)$ and $h' = h + C_p(T^*, P^*)T^* - h(T^*, P^*)$, and T^* and P^* are the characteristic values of the temperature and the pressure.

Closing of the mathematical formulation of the problem is carried out by prescribing the dependences for determination of:

(a) the coefficients of force (C_d) and thermal (Nu) interphase interaction;

(b) the thermophysical coefficients of the materials of particles $C = C(T)$ and others;

(c) the coefficients of transfer of the combustion products $\mu(T)$ and $\lambda(T)$;

(d) the coefficient of resistance of the channel ξ;

(e) the Nusselt number on channel walls Nu_w.

In this analysis, the coefficient of resistance of spherically shaped particles $C_d = f(\mathrm{M}, \mathrm{Re})$ was calculated from approximation relations [7, 8]. The Nusselt number was calculated from the formula of R. M. Drake with L. L. Kavanau's correction [9] for compressibility. For the specific heat of the particle material we used the polynomial dependence [10]. The coefficient of dynamic viscosity of the gas mixture μ was calculated from the formula of C. R. Wilke, while the coefficient of thermal conductivity of the mixture λ was calculated from the formula of E. A. Mason and S. C. Saxena with a correction for the case of multiatomic gases [11].

For the particles we formulate the Cauchy problem, i.e., the problem with initial data. The velocity, the temperature, and the coefficient of the two-phase nature of the flow (the ratio of the mass flow rate of the particles to the flow rate of the gas) are considered to be prescribed at the inlet to the channel. For the gas phase we take as being prescribed the static pressure, the total enthalpy, and the elemental composition in the inlet cross section of the gasdynamic circuit and the pressure at the outlet from the gasdynamic circuit. The problem is boundary-value.

The solution of the boundary-value problem formulated is reduced to solution of a set of Cauchy problems. The initial conditions are set in the inlet cross section of the channel. The boundary condition at the outlet from the channel is satisfied by selection of the lacking parameter (the gas velocity u) in the initial cross section. The iterative algorithm of determination of this parameter depends on the regime of flow in the channel. When the regime of flow is subsonic the condition of equality of the static gas pressure to the counterpressure is set at the outlet from the channel. When the regime of outflow from the channel is supersonic the condition $u = a$ must be fulfilled in the critical cross section.

For a numerical solution of the system of equations (1) we employed the two-step Euler scheme with implicit approximation of the components of the vector of free terms G_1 [12], which enabled us to overcome the difficulties associated with the rigidity of the system of equations with decrease in the degree of dispersion of the solid phase. As a result of the numerical integration of Eqs. (1) we determined the vector of generalized gasdynamic complexes $\mathbf{A}_m^* = \mathbf{A} + \theta\Delta x\mathbf{G}_1$ at each calculational step for the value $\theta = 1$ at the first step and $\theta = 0.5$ at the second step. To recalculate the parameters of the two-phase flow by the generalized gasdynamic complexes we solved the system of six algebraic equations according to the following algorithm:

(a) the initial approximation for the gas velocity in the initial cross section of the channel $u_1^{(k)}$ is prescribed;

(b) the gasdynamic parameters of the gas mixture and the "gas" of the particles at the inlet cross section of the channel are determined for $u_1^{(k)}$;

(c) marching calculation of the two-phase flow in the channel described by the system of equations (1) is performed. At each marching step, we determined the vector $\mathbf{A}_m^*$ by which the parameters are recalculated. The gas velocity u is found from solution of the quadratic equation. The sign in front of the square root of the discriminant Δ of this equation is selected depending on the type of flow realized: "+" corresponds to subsonic flow and "–" corresponds to supersonic flow. The critical cross section corresponds to $\Delta = 0$. The value of the discriminant Δ is analyzed at each integration step. If $\Delta > 0$ in any cross section, the flow in the channel is subsonic everywhere. If $\Delta < 0$ in a certain cross section of the channel, the chocking of the flow has occurred in it. The cross section of the channel is critical if $\Delta = 0$ in it and the flow behind this cross section becomes supersonic;

(d) the membership of the integral curve in the first or second family of solutions depending on the type of flow is determined. For the integral curve corresponding to a totally subsonic flow we considered the difference $\Omega = P_2^{(k)}/P_\mathrm{e} - 1$, where $P_2^{(k)}$ is the static pressure at the outlet from the channel which corresponds to the gas velocity at the inlet $u_1^{(k)}$. The integral curve belongs to the first family when $\Omega < 0$ and to the second family when $\Omega > 0$. In the case of mixed flow in the channel with a supersonic portion of flow, the first family includes the integral curves in which $\Delta > 0$ in each cross section, while the second family includes the curves in which $\Delta < 0$ in a certain cross section;

(e) the fulfillment of the condition of convergence of the iterative process in selection of the value of $u_1^{(k)}$ is checked (for the subsonic flow in the channel $|\Omega| < \varepsilon$, while for the mixed flow $|\Delta| < \varepsilon$). In the case where the condition of convergence of the iterative process is not fulfilled, we prescribe a new approximation for the gas velocity $u_1^{(k)}$ and repeat the calculation beginning with item (b).

Results of Numerical Investigations and Their Analysis. To elucidate the regularities of the influence of different factors on the characteristics of the two-phase flow in the gasdynamic circuit of a torch with a flow-rate method of action on the flow we performed parametric investigations for the layout selected. A scheme of the gasdynamic circuit with two feeding units is shown in Fig. 1. We selected the following values of the geometric parameters: L_1 = 6 mm, L_2 = 6 mm, $D_\mathrm{h.ch}$ = 8 mm, $L_\mathrm{h.ch}$ = 120 mm, $D_\mathrm{sub.ch}$ = 8 mm, $L_\mathrm{sub.ch}$ = 15 mm, $\beta = 6^\mathrm{o}$, D_out = 12 mm, and $L_\mathrm{sup.ch}$ = 120 mm.

In addition to the geometric parameters of the gasdynamic circuit, the parameters of the gas phase (the fuel couple, the temperatures of the supplied fuel T_f^* and oxidizer T_0^*, the static pressure in the combustion chamber P_1, the excess-oxidizer coefficients in the feeding units α_1 and α_2, the coefficients of flow rate of the gas phase in the first k_G1 and second k_G2 feeding units) and the dispersed phase (the particle material, the particle diameter d_s, the coefficient of the two-phase nature of the flow k_p, the initial velocity U_p0 and temperature T_p0 of the particles) constitute the diagnostic variables of the problem. All the calculations have

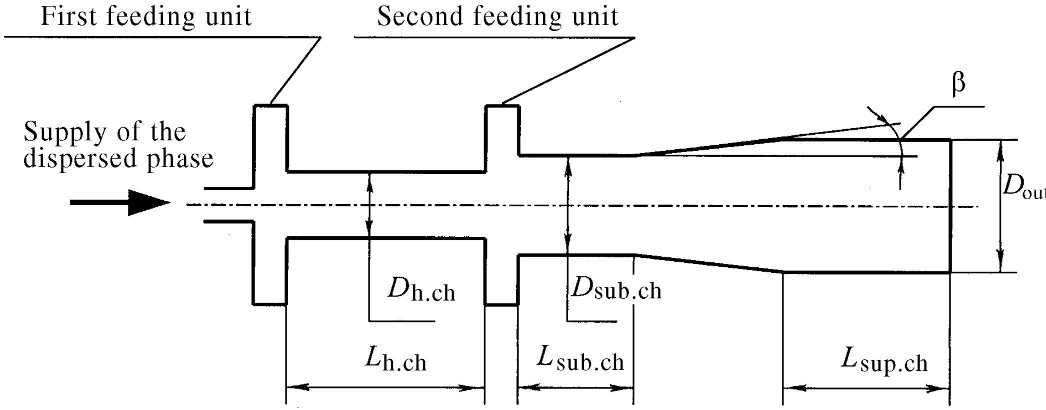

Fig. 1. Scheme of the gasdynamic circuit of a torch with two feeding units.

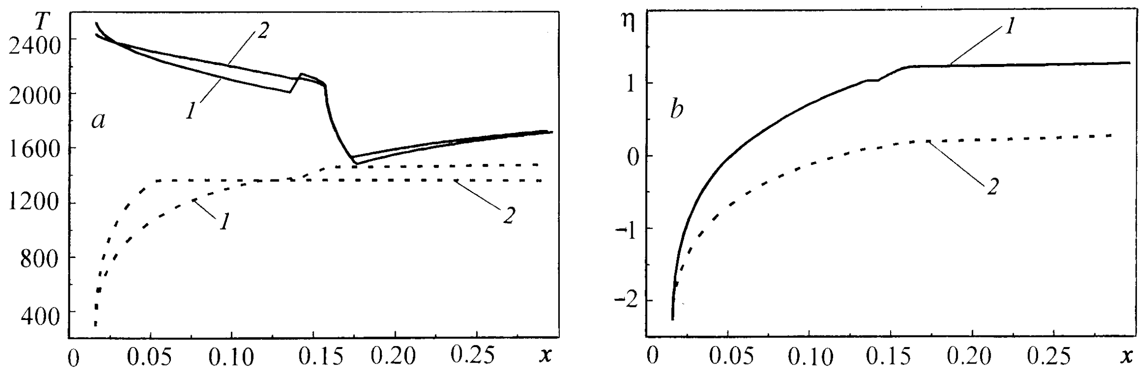

Fig. 2. Distribution of the temperature and of the degree of melting along the gasdynamic circuit in the flow-rate (1) and traditional (2) methods of action. *T*, K; *x*, m.

been performed for the following reference values of the diagnostic variables: the fuel couple was hydrogen + air, $T_f^* = 290$ K, $T_0^* = 700$ K, $P_1 = 0.8$ MPa, $\alpha_1 = \alpha_2 = 1$, $k_{G1} = 0.5$, and $k_{G2} = 0.5$; the particle material was copper, $d_s = 50$ μm, $k_p = 0.5$, $U_{p0} = 5$ m/sec, and $T_{p0} = 290$ K.

The temperature of the inner wall of the channel of the gasdynamic circuit was taken to be equal to $T_w = 1000$ K, while the coefficient of flow rate of the fuel in the initial feeding unit (the ratio of the flow rate of the fuel to the total flow rate of the gas phase) was taken to be $k_{G0}^* = 0.05$.

To compare the flow-rate and geometric (traditional) methods of control of the flow we calculated the parameters of the two-phase flow in the gasdynamic circuit for different values of the flow-rate coefficient k_{G1}. For the flow-rate method $k_{G1} = 0.5$ and for the traditional method $k_{G1} = 1.0$. In order to ensure the same flow rate in both cases, for the traditional method of control of the flow the diameter of the heating channel $D_{h.ch}$ and of the subsonic part of the acceleration channel $D_{sub.ch}$ were selected to be equal to 8.7 mm. The calculations were performed for the reference values of the diagnostic variables. Comparison of the temperature distributions of the gas and the particles along the gasdynamic circuit and the change in the degree of melting of the particles are given in Fig. 2. The solid curves show the gas phase and the dashed curves show the dispersed phase. The degree of melting of the particles is calculated from the formula [12]

$$\eta = \frac{1}{Q_m} \int_{T_m}^{T} C(T)\, dT . \tag{3}$$

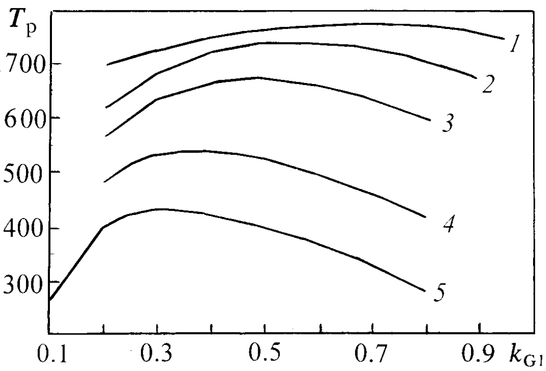

Fig. 3. Temperature of the particles at the outlet from the gasdynamic circuit of a torch with flow-rate action on the flow vs. coefficient of flow rate in the first feeding unit: 1) d_s = 10, 2) 20, 3) 30, 4) 50, and 5) 70 μm. T_p, K.

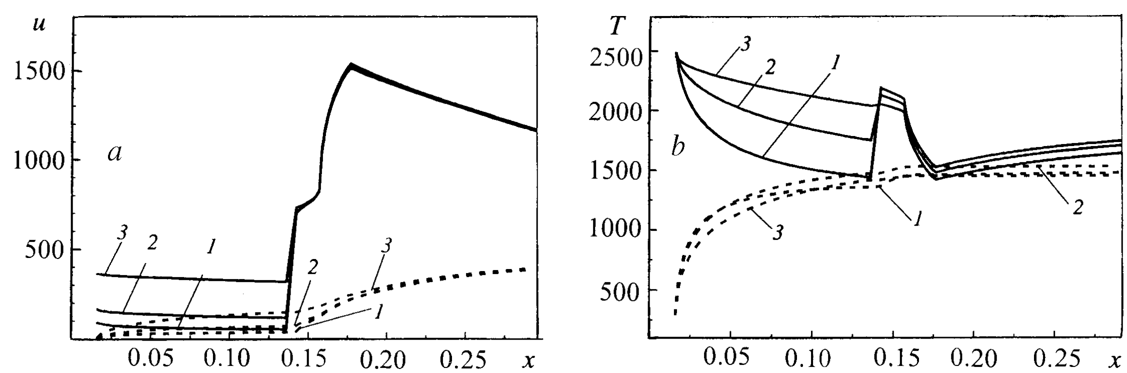

Fig. 4. Distribution of the velocity (a) and temperature (b) of the two-phase flow along the axis of the gasdynamic channel of a torch with flow-rate action: 1) k_{G1} = 0.2, 2) 0.35, and 3) 0.70; the solid curves show the gas phase and the dashed curves show the dispersed phase. u, m/sec.

The calculation results show that with the flow-rate method of action the temperature of the particles and the degree of their melting is higher. The reason is that in this case the particles stay on the heating portion for a longer time interval than in the traditional method. In the case of the traditional action on the flow the entire mass of the gas supplied passes through the initial cross section of the gas dynamic circuit, which leads to an increase in the initial gas velocity and a decrease in the heating time of the particles. Consequently, the flow-rate method makes it possible to more efficiently utilize the chemical energy of the fuel.

We modeled the influence of the flow-rate coefficient in the first feeding unit k_{G1} on the characteristics of the two-phase flow in the gasdynamic circuit and at the outlet from it. The range of the parameter varied was k_{G1} = 0.1–1.0, the fuel couple was hydrogen + air, T_0^* = 900 K, and the particle material was chromium. The remaining diagnostic variables took on the reference values. The calculated dependences of the particle temperature at the outlet from the gasdynamic circuit are presented in Fig. 3 for different degrees of dispersion of the particles. The dependence of the particle temperature on the parameter k_{G1} is nonmonotonic in character with an extremum lying, as a rule, in the range k_{G1} = 0.3–0.7. The position of the temperature maximum depends on the degree of dispersion of the particles. As it increases this maximum shifts toward lower values of the flow-rate coefficient k_{G1}. The presence of the extremum is caused by the interference of two factors. The absolute velocity and the slip velocity of the particles in the heating channel increase

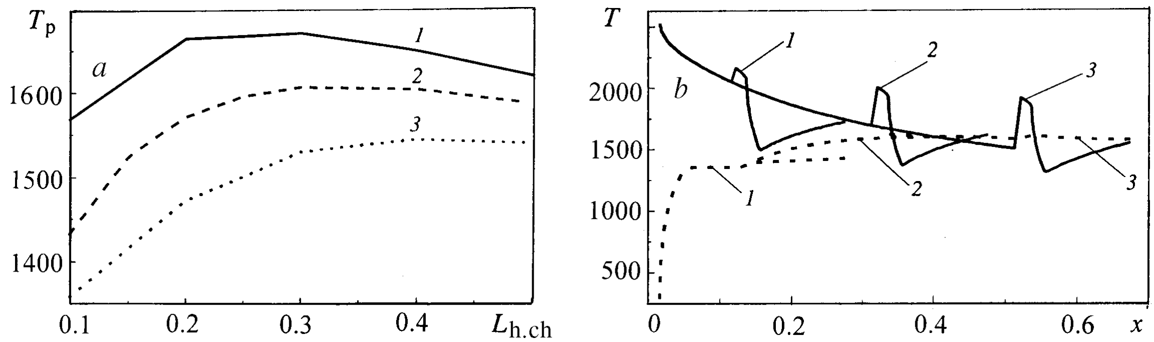

Fig. 5. Temperature of the particles at the outlet from the gasdynamic circuit vs. length of the heating portion (a) and the temperature distribution of the two-phase flow along the axis of the gasdynamic circuit (b) for a torch with flow-rate action: (a) 1) d_s = 40, 2) 50, and 3) 60 μm; (b) 1) $L_{h.ch}$ = 100, 2) 300, and 3) 60 mm; (b) 1) $L_{h.ch}$ = 100, 2) 300, and 3) 50 mm; the solid curves show the gas phase and the dashed curves show the dispersed phase. *L*, m.

with k_{G1}, which leads to a decrease in the time of stay of the particles on the heating portion. On the other hand, the gas-flow energy that causes an increase in the temperature slip of the particles increases and consequently the thermal interphase interaction is intensified. These conclusions are confirmed by the dependences (Fig. 4) of the velocity and temperature of the two-phase flow along the gasdynamic circuit.

We investigated the influence of the length of the heating portion $L_{h.ch}$ on the characteristics of the two-phase flow in the gasdynamic circuit. The calculations were performed for copper particles with the degree of fractionation d_s = 40, 50, and 60 μm for the values of the varied parameter $L_{h.ch}$ = 100, 120, 150, 200, 250, 300, 400, and 500 mm. The nonmonotonic dependence of the temperature and of the degree of melting of the particles at the outlet from the gasdynamic circuit on $L_{h.ch}$ was established by calculation (Fig. 5a). The value of the parameter $L_{h.ch}$ for which the maximum is attained depends on the material of the particles and their degree of dispersion. As the latter increases, the position of the maximum shifts toward larger values of the parameter $L_{h.ch}$. The maximum value of the temperature and of the degree of melting of the particles at the outlet from the gasdynamic circuit is attained for the value of the parameter $L_{h.ch}$ which is determined from the condition of equality of the temperatures of the gas and dispersed phases at the end of the heating portion (Figs. 5b). The optimum length of the heating portion depends on the prescribed temperature of the gasdynamic circuit, since the removal of heat through the wall of the heating channel leads to a decrease in the gas temperature and consequently decreases the capacity of the gas to heat the particles. The influence of the parameter $L_{h.ch}$ on the velocity of the particles at the outlet from the gasdynamic circuit is insignificant. As the value of $L_{h.ch}$ increases the particle velocity decreases.

Conclusions. 1. We have developed a mathematical model of the two-phase flow in the gasdynamic circuit of a torch for high-speed gas-plasma spraying with a flow-rate method of action on the flow; the model is based on quasi-one-dimensional gas-dynamic equations in which the friction and heat exchange of the two-phase flow with channel walls is taken into account as is the friction and heat exchange between the phases.

2. We have performed a calculational comparison of the flow-rate and geometric (traditional) methods of control of the flow in the gasdynamic circuit of the torch. It has been shown that when the velocities of the particles in the outlet cross section of the nozzle channel of the torch are equal, in practice, the flow-rate method of action ensures a higher level of values of the enthalpy of the particles; the temperature of the particles and the degree of their melting are also higher. Therefore, the flow-rate method makes it possible to more efficiently utilize the chemical energy of the fuel.

3. For a torch with a flow-rate action on the flow we have investigated the influence of the coefficient of flow rate in the first feeding unit k_{G1} and of the length of the heating portion $L_{h.ch}$ on the characteristics of the two-phase flow in the gasdynamic circuit. It has been established that the dependence of the particle temperature at the outlet from it on the parameter k_{G1} is nonmonotonic in character with an extremum lying in the range k_{G1} = 0.3–0.7; as the degree of dispersion of the particles increases the temperature maximum shifts toward lower values of the flow-rate coefficient k_{G1}. The dependence of the temperature and degree of melting of the particles on $L_{h.ch}$ is also nonmonotonic in character with a value of the maximum dependent on the material of the particles and their degree of dispersion.

NOTATION

A, vector of complexes; $\mathbf{G}_0$ and $\mathbf{G}_1$, vectors of free terms; ρ, density of the gas phase; u, velocity of the gas phase; P, static pressure of the gas phase; H, total enthalpy of the gas phase; E, total enthalpy of the gas phase in unit volume; h, specific static enthalpy of the gas phase; a, local velocity of sound of the gas phase; T, static temperature of the gas phase; ρ_p, density of the dispersed phase; u_p, velocity of the dispersed phase; H_p, total enthalpy of the dispersed phase; E_p, total energy of the dispersed phase in unit volume; h_p, specific static enthalpy of the dispersed phase; T_p, static temperature of the dispersed phase; F, cross-sectional area of the channel; F_d, volume-mean force of aerodynamic resistance to the motion of particles; F_τ, force of friction of the two-phase flow against the channel wall; Q_v, volume-mean energy release as a result of the convective heat exchange between the phases; Q_w, heat flux between the channel wall and the gas; τ_w, friction stress on the channel wall; q_w, specific heat flux from the unit area of the channel surface; ω, coefficient of proportionality of force interaction of the phases; ϑ, coefficient of proportionality of thermal interaction of the phases; ξ, coefficient of resistance of the force of friction against the channel walls; C_d, coefficient of resistance of a single spherical particle; Re, Reynolds number; Pr, Prandtl number; Nu, Nusselt number; M, Mach number; q, slip-velocity modulus; ρ_s^*, density of the particle material; $C(T)$, specific heat of the particle material at prescribed temperature; $C_p(T)$, specific heat of the gas at constant pressure and at prescribed temperature; $\lambda(T)$, coefficient of thermal conductivity of the gas phase at prescribed temperature; μ, coefficient of viscosity of the gas phase; α_w, coefficient of heat transfer between the gas and the channel wall; d_s, diameter of a single particle; d_h, hydraulic diameter of the channel in the running cross section; χ, wetted perimeter of the channel in the running cross section; R_0, universal gas constant; $\overline{m}$, molecular mass of the gas mixture; $\overline{Z}\,\overline{Z}$, coefficient that takes into account the deviation of the properties of the gas mixture from the properties of the perfect gas; h', generalized specific static enthalpy of the gas mixture; x, longitudinal corodinate reckoned from the initial cross section of the channel along its rectilinear axis; Δx, running step of integration of the system of equations (1); θ, coefficient of proportionality at the first and the second step of integration of the system of equations (1); Δ, discriminant of the quadratic equation for the velocity of the gas phase; P_e, pressure in the environment (counterpressure); ε, calculational error; T_m, melting temperature of the particles; Q_m, melting heat of the particles; η, degree of melting of the particles. Geometric characteristics of the gasdynamic circuit: L_1 and L_2, lengths of the portions of the first and second units of feeding of the gas; $D_{h.ch}$, diameter of the portion of the heating channel; $L_{h.ch}$, length of the portion of the heating channel; $D_{sub.ch}$, diameter of the subsonic part of the acceleration portion; β, angle of half-opening of the conical acceleration portion; $L_{sup.ch}$, length of the supersonic cylindrical part of the acceleration portion; D_{out}, diameter of the outlet cross section of the channel. Subscripts: w, wall; p, dispersed phase; 0, zero, initial values of the parameters; *, characteristics values of the parameters; t, transposed; h.ch, heating channel; sub.ch, channel of the subsonic acceleration portion; sup.ch, supersonic channel of the acceleration portion; m, characteristics of the particles in melting; s, solid.

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