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INVESTIGATION OF THE PROCESSES OF ACCELERATION, HEATING, AND MELTING OF THE PARTICLES OF REFRACTORY MATERIALS IN GASDYNAMIC CIRCUITS OF TORCHES FOR FLAME SPRAYING

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The problems of heating and acceleration of the particles of refractory materials to provide the process of high-velocity flame spraying are considered. Based on numerical investigations, recommendations on selection of fuel components are given. Estimates of the flow rates of fuel components and the geometric parameters of a gasdynamic circuit, which provide the acceleration and melting of the particles in accordance with their size and mass fraction, are presented.

A peculiarity of the process of melting of the particles of refractory materials in a gasdynamic circuit is the comparability of their melting temperature and the equilibrium temperature of stagnation of the combustion products of a fuel. Because of this, melting of such particles in a gas flow is possible only on condition that the effective energy exchange between the combustion products and the particles is provided. The main problem is that the conditions of increasing the velocity and temperature of the particles are mutually exclusive: the increase in the temperature of the particles is favored by an increase in the time of their stay in the flow, whereas the increase in the velocity leads to a decrease in this time. To solve this problem, it is necessary to make a functional subdivision of the processes occurring in a gasdynamic circuit. According to the gasdynamic scheme proposed in [1, 2], the gasdynamic circuit is subdivided into the portions of heating and acceleration. The particles in a flow of combustion products having a high temperature and a low velocity are heated on the initial portion of the system and accelerated on the second portion. This scheme of control of a two-phase flow is realized by the consumption method, i.e., by feeding fuel components or combustion products, in units, which are positioned along the gasdynamic circuit.

In the present work, we discuss problems of providing rational conditions for the transfer of the energy of the combustion products of hydrocarbon fuels to the particles of refractory materials for their heating and acceleration in gasdynamic circuits of torches.

Selection of the Fuel Pair. In the gasdynamic circuits of torches designed for heating, melting, and acceleration of particles, hydrogen, methane, and acetylene are usually used as the fuel while air or oxygen is used as the oxidizer. Let us evaluate the energy potential of these fuel pairs with allowance for their application to heating and acceleration of the particles of refractory materials.

When the above-mentioned fuels are burned in air, the temperature required for the melting of refractory materials is not attained. For example, the equilibrium temperature of the combustion products of hydrogen does not exceed 2500 K in a wide range of pressures (0.1–10 MPa), which is lower than the melting temperature of many refractory materials. Because of this, in what follows we will consider the burning of hydrocarbon fuels in oxygen. In the case of the equilibrium composition of a gas mixture, the maximum possible temperature of combustion products increases with increase in the pressure. In particular, for the fuel pair hydrogen–oxygen T_e = 3400 K at P = 1 MPa, T_e = 3600 K at P = 5 MPa, and T_e = 3700 K at P = 10 MPa.

The specific heat of combustion of hydrogen ($1.196 \cdot 10^5$ kJ/kg) is more than twofold higher than the heat of combustion of methane ($0.4995 \cdot 10^5$ kJ/kg) and acetylene ($0.4865 \cdot 10^5$ kJ/kg) [3]. To obtain 1 kg of combustion prod-

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TABLE 1. Parameters of the Products of Combustion of Hydrocarbon Fuels in Oxygen

Fuel	T_e, K	C_{pe}, kJ/(kg·K)	ΔQ, kJ/kg
Hydrogen	3362	14.788	$0.133 \cdot 10^5$
Methane	3325	10.151	$0.100 \cdot 10^5$
Acetylene	3696	10.119	$0.123 \cdot 10^5$

TABLE 2. Thermophysical Properties of Materials

Material	Thermophysical Properties				
	ρ^*, kg/m^3	T_m, K	C_a, kJ/(kg·K)	Q_m, kJ/kg	Q_Σ, kJ/kg
Cr	7.16	2180	0.729	409.7	1780.8
Al_2O_3	3.96	2327	1.244	1092.6	3617.3
ZrO_2	5.73	2983	0.683	730.4	2565.0
WC	15.63	3050	0.277	331.9	1095.3
Al	2.70	933	1.054	398.9	1068.0

TABLE 3. Stored Heat of the Combustion Products of Hydrocarbon Fuels and the Relative Stored Heat

Material	Stored heat Q_*, kJ/kg			Relative stored heat m_*		
	H_2	CH_4	C_2H_2	H_2	CH_4	C_2H_2
Cr	8724	6551	9006	4.90	3.68	5.06
Al_2O_3	8179	6120	8644	2.26	1.69	2.39
ZrO_2	4349	2923	5869	1.70	1.14	2.29
WC	3741	2432	5445	3.42	2.22	4.97

ucts for the stoichiometric ratio between the oxidizer and the fuel, it is necessary to burn 0.11 kg of hydrogen, 0.2 kg of methane, or 0.252 kg of acetylene. Because of this, the heat actually released in this case per kg of combustion products is $0.133 \cdot 10^5$ kJ for hydrogen, $0.1 \cdot 10^5$ kJ for methane, and $0.123 \cdot 10^5$ kJ for acetylene. The parameters of the combustion products at the pressure $P = 0.8$ MPa, obtained according to the program of [4], are presented in Table 1. It is seen that the equilibrium temperatures of the combustion products of hydrogen and methane are close, and the equilibrium temperature of combustion products of acetylene is much higher, but the specific equilibrium heat capacity of the combustion products of hydrogen is higher than that of the combustion products of methane and acetylene by a factor of almost one and a half. Because of this, the amount of heat released as a result of cooling of the combustion products of hydrogen is larger than that for methane and acetylene at the same temperature difference.

For high-velocity flame spraying, of interest are the following refractory materials: chromium (Cr), alumina (Al_2O_3), zirconium dioxide (ZrO_2), and tungsten carbide (WC). The thermophysical properties of these materials, determined according to the program of [4], are presented in Table 2. The refractory properties of the materials are characterized by the heat Q_Σ and the temperature T_m. The thermophysical parameters of aluminum, which has a low melting temperature at a specific melting heat comparable to that of the refractory materials Cr and WC, are also given in this table for comparison.

The equilibrium temperatures of the combustion products exceed the melting temperatures of any of the particle materials considered (see Tables 1 and 2). Because of this, any of the above-mentioned hydrocarbon fuels can be used for melting of particles.

For further comparative evaluations of fuel pairs, it is convenient to introduce the notion of the stored heat of combustion products and of the relative stored heat of combustion products. By the stored heat of combustion products Q_* is meant the heat that can be transferred from 1 kg of combustion products to the particles when the temperature of the gas mixture decreases from the equilibrium temperature T_e to the melting temperature of the particle material T_m. The quantity Q_* is calculated as the difference between the specific enthalpies of the gaseous combustion products at T_e and T_m. The larger this quantity, the larger the amount of heat stored by the combustion

TABLE 4. Relative Stored Heats m_* at Different Pressures

Fuel pair	Particle material	P, MPa			
		0.4	0.6	0.8	1.0
H_2+O_2	Al_2O_3	2.24	2.25	2.26	2.26
	Cr	4.86	4.87	4.88	4.89
	ZrO_2	1.44	1.59	1.68	1.75
	WC	2.70	3.13	3.39	3.58
CH_4+O_2	Al_2O_3	1.66	1.67	1.68	1.69
	Cr	3.64	3.65	3.66	3.66
	ZrO_2	0.93	1.05	1.13	1.19
	WC	1.65	1.99	2.20	2.36

products. By definition, the heat stored depends on the type of hydrocarbon fuel and the material of the particles and can provide, for the corresponding mass fraction of particles, their heating and complete melting without superheating. The relative stored heat m_* is determined as the ratio of the stored heat to the heat that must be supplied to 1 kg of particles to heat them and melt them completely, $m_* = Q_*/Q_\Sigma$. The parameter m_* characterizes the energy potential of the fuel in relation to the particle material considered. The physical meaning of this parameter is the ratio of the maximum possible mass of melted particles to the mass of the combustion products of the fuel.

The parameters Q_* and m_* at the pressure $P = 0.8$ MPa for different fuels and particle materials are presented in Table 3. The largest relative stored heat (mass of melted particles) is obtained in the case of burning of acetylene. This is explained by the fact that the equilibrium temperature of the combustion products of acetylene is more than 300 K higher than the equilibrium temperature of the combustion products of hydrogen and methane. The combustion products of acetylene have the highest level of stored heat at a melting temperature of ~3000 K, but at lower melting temperatures (~2200 K) the stored heats of the combustion products of acetylene and hydrogen are comparable. The combustion products of acetylene can most efficiently be used to heat the particles of tungsten carbide, which has the highest temperature and the smallest heat of melting as compared to the materials considered.

The relative stored heats m_* at different pressures are presented in Table 4. For ZrO_2 and WC, whose melting temperature is ~3000 K, the quantity m_* depends on the pressure, while for Al_2O_3 and Cr, which have a lower melting temperature, this quantity is practically independent of the pressure. This effect is explained by the fact that the equilibrium-dissociating composition of combustion products depends on the pressure at fairly high temperatures (~3000 K), whereas at lower temperatures (~2200 K) the dissociation effects practically cease and pressure changes have a smaller influence on the composition of the combustion products. These results correspond to the condition of a complete maximum possible melting of particles.

The evaluations made allow one to select the fuel pairs and determine the stored heats for the selected materials and the maximum possible mass fractions of particles that can be completely melted. The main problem is to provide the conditions for the transfer of the thermal energy of the combustion products to particles in the form of thermal and kinetic energy. To determine the rational method of transfer of the energy of the combustion products to the particles, it is necessary to investigate flows in gasdynamic circuits.

Results of Numerical Investigations in Gasdynamic Circuits. Conditions for transfer of the energy of the combustion products of hydrocarbon fuels to solid particles of refractory materials for their heating, melting, and acceleration in a gasdynamic circuit are realized in a torch with the consumption method of action on the flow. The use of a gasdynamic circuit with two units for feeding combustion products positioned at the beginning and at the end of the heating portion is considered. The length of the heating portion and the relations between the flow rates of the combustion products in the feed units are the parameters of the problem and can be selected from the condition of the maximum total energy of particles in the outlet cross section of the gasdynamic circuit or from the condition of fulfillment of another criterion.

It is assumed that the flow rate of the combustion products in the first feed unit should provide a gas-phase flow with a small subsonic velocity along the heating portion, but sticking of the particles to the walls of the channel should be precluded. On the heating portion, the combustion products heat and melt the particles and give up a portion

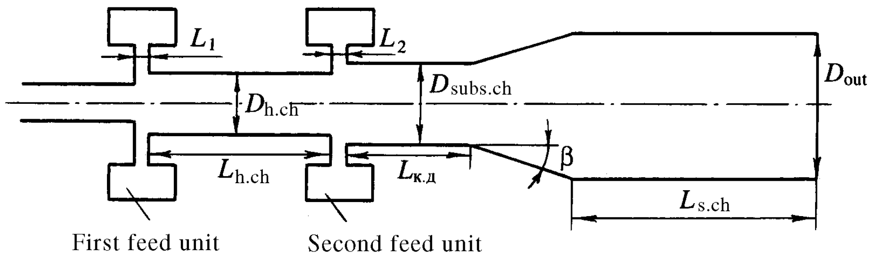

Fig. 1. Diagram of the gasdynamic circuit of a torch with two feed units.

of heat, through the wall, to the side surface of the channel. The length of the heating portion should be selected from the condition that the heat transfer from the gas phase to the particles is maximum. The maximum heating of the particles is not attained when the heating portion is short, and in the case of a very long heating portion, the heat removal through the wall of the channel is predominant. The two-phase flow is accelerated behind the second feed unit. The calculations made have shown that if the temperature relaxation occurs practically always on the heating portion, the velocity relaxation for particles with a dispersivity $D_p > 20\ \mu m$ is not realized in the gasdynamic circuit, and at the outlet from it we have the velocity retardation of particles. When the length of the supersonic acceleration portion is significant, it is possible to increase the velocity of the particles at the outlet from the gasdynamic circuit, but their energy characteristics are adversely affected by the decrease in the static temperature of the flow.

The processes in the gasdynamic circuit are modeled on the basis of the mathematical model [2] realized in the TwoPhase software system [5]. Using this methodological software, one can select the geometric parameters of a gasdynamic circuit and the regime parameters of a torch to provide optimum conditions for the transfer of the energy of the carrying phase to the particles. The regime and geometric parameters of the gasdynamic circuit are optimized by the criterion of the maximum total energy of particles at the outlet from the gasdynamic circuit, and their complete melting is allowed in this case.

The degree of melting of the particles is evaluated using the parameter η determined by the formula [6]

$$\eta = \frac{1}{Q_{\text{m}}} \int_{T_{\text{m}}}^{T} C(T)\, dT\,. \tag{1}$$

The values of the parameter $\eta \le 0$ correspond to the solid aggregative state of the particles, the values $0 < \eta < 1$ correspond to the transient state (incomplete melting of the particles), $\eta = 1$ corresponds to the complete melting at $T = T_{\text{m}}$, and the values of $\eta > 1$ correspond to the melting with superheating. Direct use of formula (1) on the melting portion is difficult because of the singularity in the integrand function ($C(T) \to \infty$ at $T = T_{\text{m}}$). Because of this, the parameter η is conveniently determined as the ratio of the difference between the running specific enthalpy of the particles and the specific enthalpy of unmelted particles at their melting temperature to the specific heat of melting.

As the energy characteristic of the particles, we used the parameter η_{k} characterizing the complete melting of a particle with allowance for the conversion of a portion of its kinetic energy to thermal energy. On condition that in the case of collision of a particle with an obstacle, 70% of its kinetic energy is converted to thermal energy [7, 8], the parameter η_{k} is calculated from the formula

$$\eta_{\text{k}} = \frac{1}{Q_{\text{m}}} \left(I_{\text{p}}(T_{\text{p}}) - I_{\text{p}}(T_{\text{m}}) + A_{\text{k}} \frac{U_{\text{p}}^2}{2} \right).$$

For the gasdynamic circuit with two feed units, shown diagrammatically in Fig. 1, the investigations were carried out for different values of the initial data. The physical initial data of the problem are as follows: the fuel pair, P_1, T_{ox0}, T_{f0}, α_1, α_2, k_{g1}, and k_{g2}; the particle material, D_{p}, k_{p}, U_{p0}, and T_{p0}. The geometric parameters of the problem are $L_{\text{h.ch}}$, $D_{\text{h.ch}}$, $L_{\text{subs.ch}}$, $D_{\text{subs.ch}}$, L_1, L_2, β, $L_{\text{supers.ch}}$, and D_{out}.

For the oxygen-fuel gasdynamic circuit used for acceleration, heating, and melting of particles of refractory materials, the following values of the geometric parameters were prescribed: $L_1 = 4$ mm, $L_2 = 4$ mm, $D_{\text{h.ch}} = 8$ mm,

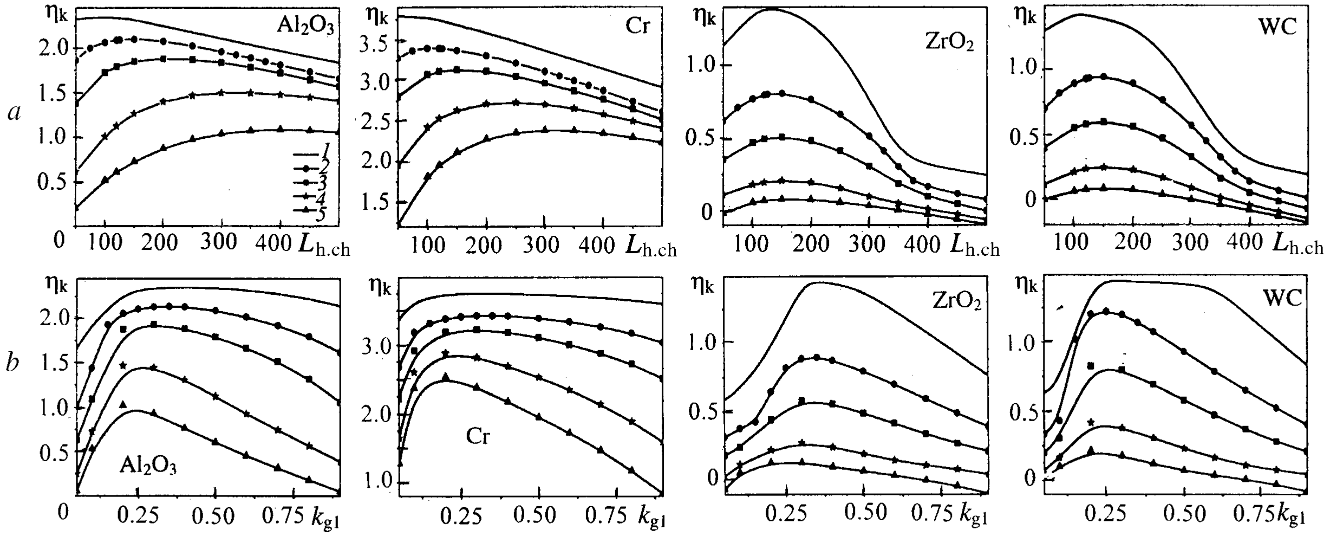

Fig. 2. Change in the degree of complete melting of the particles at the outlet from the gasdymanic circuit as a function of the length of the heating channel $L_{h.ch}$ (a) and the flow-rate coefficient in the first feed unit k_{g1} (b) for Al_2O_3, Cr, ZrO_2, and WC: 1) D_p = 10, 2) 15, 3) 20, 4) 30, and 5) 40 μm. $L_{h.ch}$, mm.

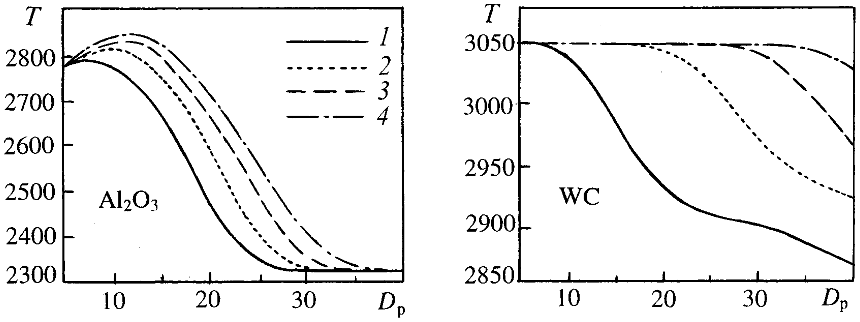

Fig. 3. Change in the temperature T_p of the particles at the outlet from the gasdynamic circit as a function of their dispersivity D_p for Al_2O_3 and WC: 1) P_1 = 0.4, 2) 0.6, 3) 0.8, and 4) 1.0 MPa. T_p, K; D_p, μm.

$L_{h.ch}$ = 120 mm, $D_{subs.ch}$ = 8 mm, $L_{subs.ch}$ = 50 mm, $\beta = 6.83^o$, D_{out} = 14 mm, and $L_{supers.ch}$ = 120 mm. The parametric calculations were carried out with the use of the following reference values of the physical parameters: T_{f0} = 290 K, T_{ox0} = 290 K, P_1 = 0.8 MPa, $\alpha_1 = \alpha_2 = 1$, k_{g1} = 0.5, k_{g2} = 0.5, D_p = 50 μm, k_p = 0.3, 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 = 500 K.

The influence of the length of the heating channel $L_{h.ch}$, the coefficient of flow rate of the fuel in the first feed unit k_{g1}, the particle size D_p, and the static pressure in the combustion chamber P_1 on the degree of complete melting and the velocity U_p and temperature T_p of the particles at the outlet from the gasdynamic circuit was investigated. The calculations were carried out for the reference values of the parameters for the fuel pair H_2+O_2 and four types of particle material: Al_2O_3, Cr, ZrO_2, and WC. The results obtained are presented in Figs. 2 and 3.

Figure 2a shows the dependences of the degree of complete melting η_k on the length of the heating channel $L_{h.ch}$ for different diameters of the particles D_p. The calculations were carried out for $L_{h.ch}$ = 50–500 mm at D_p = 10, 15, 20, 30, and 40 μm. With increase in $L_{h.ch}$, the degree of complete melting behaves nonmonotonically, reaching the maximum $\eta_{k.m}$ at a certain value of $L_{h.ch.opt}$ dependent on the particle material. The length of the heating channel $L_{h.ch} = L_{h.ch.opt}$ is optimum from the viewpoint of the maximum utilization of the chemical energy of the fuel. For Al_2O_3 and Cr, the value of the parameter $L_{h.ch.opt}$ depends on the particle size and increases with increase in D_p. For ZrO_2 and WC particles, the optimum length of the heating channel is practically independent of their size and takes the value $L_{h.ch.opt}$ = 150 mm. With increase in the size of Al_2O_3 and Cr particles, the extremum of the dependence $\eta_k(L_{h.ch})$ becomes more pronounced, while for ZrO_2 and WC particles conversely. Chromium particles of different size and Al_2O_3 particles with a diameter of up to 20 μm are melted completely. The particles of ZrO_2 and WC with a diameter D_p = 10 μm are melted completely only when the value of $L_{h.ch}$ is close to the optimum $L_{h.ch.opt}$ = 150 mm.

Figure 2b shows the dependences of the degree of complete melting η_k on the coefficient of flow rate of the fuel in the first feed unit k_{g1} for different diameters of the particles D_p. The calculations were carried out for k_{g1} = 0.05–0.9 at D_p = 10, 15, 20, 30, and 40 μm. The dependences of η_k on k_{g1} have the same characteristic features as the dependences of η_k on $L_{h.ch}$. The value of k_{g1}, at which η_k reaches the maximum $\eta_{k.m}$ is determined by the particle material and depends only weakly on the particle size. In the case of the optimum selection of k_{g1}, Al_2O_3 particles with a diameter $D_p \le 30$ μm, WC particles with $D_p \le 15$ μm, and ZrO_2 particles with D_p = 10 μm are melted completely. Chromium particles are melted completely independently of the value of the parameters k_{g1} and D_p.

Figure 3 shows the dependences of T_p on D_p for Al_2O_3 and WC particles at different static pressures in the combustion chamber (P_1 = 0.4, 0.6, 0.8, and 1 MPa). The character of the dependences $T_p(D_p)$ is determined by the material of the particles and the difference between their aggregative states. The calculated dependences $T_p(D_p)$ for Al_2O_3 particles have an extremum in the vicinity of D_p = 10 μm at all the pressures P_1 considered, and the temperature of the particles with a small diameter exceeds the melting temperature. Particles with a diameter $D_p > 25$ μm are melted incompletely, which is evidenced by the portion of the curve where their temperature equal to the melting temperature T_m = 2327 K is constant. Tungsten-carbide particles with a small diameter are also melted incompletely, and their temperature coincides with the melting temperature T_m = 3050 K. Larger particles are in the crystalline state, which is evidenced by the descending portions of the curves on which the temperature is lower than the melting temperature. The diameter of the particles for which their crystallization begins increases with increase in the pressure P_1. As for the dependences of the degree of complete melting and velocity of the particles on the pressure in the combustion chamber, it has been revealed that the values of both parameters increase with increase in P_1 and decrease with increase in the particle diameter. For example, for Al_2O_3 particles of diameter D_p = 20 μm we have U_p = 800 m/sec at P_1 = 0.4 MPa, U_p = 900 m/sec at P_1 = 0.6 MPa, U_p = 1050 m/sec at P_1 = 0.8 MPa, and U_p = 1100 m/sec at P_1 = 1 MPa. For the same particles, at a pressure of P_1 = 1 MPa we have U_p = 1500 m/sec for D_p = 10 μm, U_p = 1100 m/sec for D_p = 20 μm, U_p = 900 m/sec for D_p = 30 μm, and U_p = 800 m/sec for D_p = 40 μm. The qualitative character of the obtained dependences of η_k and U_p on D_p is the same for all the materials considered.

Selecting the length of the heating channel $L_{h.ch}$ and the flow rate of the coefficient of fuel in the first feed unit k_{g1}, one can attain the maximum degree of complete melting of particles $\eta_{k.m}$ at the outlet from the gasdynamic circuit. Selection of the parameters $L_{h.ch}$ and k_{g1} gives the maximum effect when the particle size increases.

CONCLUSIONS

1. With respect to the particle material considered, the energy potential of a fuel is characterized by the stored heat and the relative stored heat of the products of its combustion. These parameters allow one to make a comparative analysis of the energy potential of different fuels and select the fuel pairs for concrete materials of particles and the maximum possible mass fractions of particles which can be completely melted. For refractory materials, the largest relative stored heat (the mass of particles melted without superheating) is obtained in burning of acetylene in oxygen.

2. The optimum use of the energy potential of combustion products is determined by the flow in gasdynamic circuits. For heating, melting, and acceleration of the particles of refractory materials, it is appropriate to use gasdynamic circuits with the consumption method of control of the flow.

3. The dependences of the parameters of a two-phase flow at the outlet from a gasdynamic circuit with the consumption method of control of the flow on the length of the heating portion and the relations between the coefficients of flow rate of the fuel in the units for feeding combustible components have been calculated. It is shown that the degree of complete melting of the particles has an extremum for certain lengths of the heating portion and relations between the flow-rate coefficients in the feed units.

4. By selecting the optimum values of the length of the heating portion and of the coefficient of flow rate of the fuel in the first feed unit, one can extend the dispersivity range of the particles, in which the condition of complete melting of the particles is fulfilled. With increase in the dispersivity of the particles, the efficiency of optimization of the selection of these parameters increases.

NOTATION

A_k = 0.7, coefficient accounting for the conversion of the kinetic energy of particles to thermal energy; C, specific heat capacity of the particle material; C_a, average value of the specific heat capacity when the particle material is heated from the initial temperature T_0 = 298 K to the melting temperature T_m; C_{pe}, equilibrium specific heat capacity of the combustion products at constant pressure; D_{out}, diameter of the outlet cross section of the channel; D_p, diameter of the particles; $I_p(T)$, enthalpy of the particles at the temperature T; k_{g1} and k_{g2}, relative fractions of flow rate of the gas phase in the first and second feed units (flow-rate coefficients); k_p, coefficient of the two-phase flow, determined as the ratio of the flow rate of the particles to the total flow rate of the gas phase; $L_{h.ch}$ and $D_{h.ch}$, length and diameter of the heating channel; $L_{h.ch.opt}$, optimum length of the heating channel; $L_{subs.ch}$ and $D_{subs.ch}$, length and diameter of the subsonic acceleration channel; $L_{super.ch}$, length of the supersonic cylindrical portion of the channel; L_1 and L_2, lengths of the mixing portions in the first and second feed units; m_*, relative stored heat; P, pressure; P_1, static pressure in the combustion chamber; Q_m, specific heat of melting of the particle material; Q_Σ, heat that must be supplied to 1 kg of the particle material with an initial temperature of 298 K for heating and complete melting; Q_*, stored heat of the combustion products; T_m, melting temperature of the particle material; T_{f0}, temperature of the fed fuel; T_{ox0}, temperature of the fed oxidizer; T_p, temperature of the particles; T_{p0}, initial temperature of the particles; T_e, equilibrium temperature of the gas mixture; T_w, temperature of the inner wall of the channel of the gasdynamic circuit; U_p, velocity of the particles; U_{p0}, initial velocity of the particles; α_1 and α_2, coefficients of excess oxidizer in the first and second feed units; β, angle of half-opening of the conic portion of the channel; ρ^*, density of the particle material; η, degree of melting of the particles; η_k, degree of complete melting of the particles; $\eta_{k.m}$, maximum degree of complete melting of the particles; ΔQ, combustion heat of the fuel per kg of a mixture for the stoichiometric ratio of the components. Subscripts: p, particle; h.ch, heating channel; subs.ch, subsonic channel; supers.ch, supersonic channel; opt, optimum; a, average; m, melting; k, kinetic; k.m. kinetic maximum; e, equilibrium; ox, oxidizer; f, fuel; g, gas; out, outlet; 0, initial value; 1, first unit for feeding the combustion products of the fuel; 2, second unit for feeding the combustion products of the fuel.

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