NONSTATIONARY HEATING OF PARTICLES BY A PLASMA WITH AN EXPONENTIALLY CHANGING TEMPERATURE

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Using a computational method, we investigate the change in the temperature of alumina particles in the process of heating by a hydrogen, steam, air or argon plasma whose temperature decreases exponentially. It is found that on changing from argon to hydrogen the duration of heating to the melting temperature decreases by two orders of magnitude, whereas the difference between the temperatures of the surface and center of a particle increases from 17 to 1700 K.

Introduction. The rate and the law of change in the temperature of particles heated in a plasma jet greatly determine the kinetics of subsequent physical and chemical conversions of the particle material. When the Biot number exceeds unity, a temperature gradient appears over the particle radius.

The problem of particle heating in plasma jets with allowance for the nonuniformity of the temperature distribution over the radius of the particles was considered, for example, in [1, 2]. However, these works ignored the change in the plasma temperature in the process of particle heating, which was unavoidable because of the sink of heat into the particles, transporting gas, and the surrounding medium.

Below, we present a solution of the problem of nonstationary heating of particles by a plasma whose temperature changes exponentially.

Mathematical Model. To calculate the heating of particles in a plasma jet, we assume that a single spherical particle interacts with the plasma, the flow around the particle is continuous, and that the mechanism operative in heat transfer from the plasma to the particle is convection. The latter two assumptions were substantiated in [3, 4]. So, according to the estimates given in [3], when particles are heated by a plasma of monatomic gases ($P \sim 1$ atm, $T \sim 10^4$ K), the continuum condition is valid for particles whose diameter exceeds 50 μm. When $T \sim 10^4$ K for argon or $T \sim 8000$ K for biatomic gases, one can neglect their radiation and absorption [4].

Suppose that the initial temperature of a particle of radius r_0 is equal to $T(t = 0) = T_0 = \text{const}$ and that from the time $t = 0$ there is convective heat exchange between the particle surface and plasma, whose temperature is equal to $T_{\text{pl}} = \varphi(t) = (T_1 - T_2) \exp(-bt) + T_2$. The coefficient b is determined from the heat balance or experimentally; it is adopted in calculations that $b = 100$.

In spherical coordinates for a symmetrical problem the heat conduction equation of a particle has the form

$$\frac{\partial T}{\partial t} = a^2 \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right).$$

The boundary condition on the surface of the sphere $r = r_0$ is

$$\left. \frac{\partial T}{\partial r} \right|_{r=r_0} = h \left[\varphi(t) - T \right] \Big|_{r=r_0}.$$

The initial condition is

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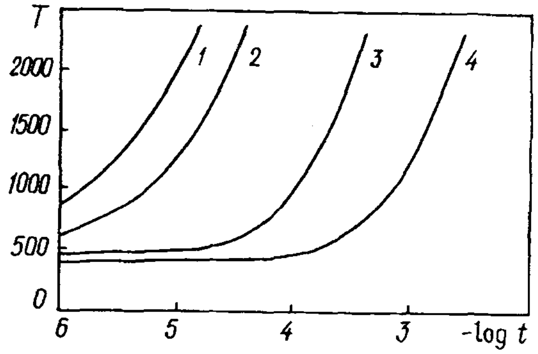

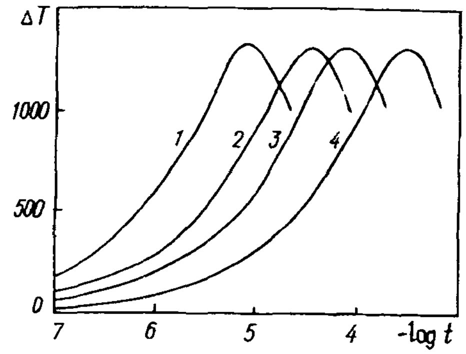

Fig. 1. Change with time of particle temperature (K) ($-\log t$, sec) depending on the type of plasma-forming gas: 1) hydrogen, 2) steam, 3) air, 4) argon.

Fig. 2. Change with time of difference between temperatures of surface and center of particles heated by air depending on their diameter: 1) $d = 50\ \mu$m, 2) 100, 3) 150, 4) 300.

$$T(r, 0) = T_0 .$$

We present the total solution of the problem as

$$T(r, t) = \frac{hr_0^2 (T_1 - T_2)}{p \cos p - (1 - hr_0) \sin p} \exp(-bt) \frac{\sin p \frac{r}{r_0}}{r} +$$

$$+ T_2 + 2hr_0^2 \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\sqrt{\mu_n^2 + (1 - hr_0)^2}}{\mu_n (\mu_n^2 + h^2 r_0^2 - hr_0)} \times$$

$$\times \left[(T_0 - T_2) - \frac{\mu_n^2}{\mu_n^2 - p^2} (T_1 - T_2) \right] \times \exp\left(- \frac{a^2 \mu_n^2 t}{r_0^2} \right) \frac{\sin \mu_n \frac{r}{r_0}}{r} .$$

The properties of the particle material, namely, λ, c_p, and ρ are functions of temperature; for calculations they are determined from interpolation formulas. The heat transfer coefficient α is determined in terms of the Nusselt number [5]:

$$\mathrm{Nu} = 2 \frac{\lambda_w}{\lambda_g} + 0.6\, \mathrm{Re}^{1/2}\, \mathrm{Pr}^{1/3} \left(\frac{\rho_g \eta_g}{\rho_w \eta_w} \right)^{0.2} .$$

Results of Calculations and Their Discussion. The change in time of the temperature of an α-Al_2O_3 particle of diameter 50 μm is presented in Fig. 1 as a function of the plasma-forming gas. The temperature of the latter changes exponentially from 4000 to 3500 K, since it is in this range that the heat conduction coefficient of the gases considered (except for argon) takes the maximum value [6]. As is seen from the figure, on changing from argon to hydrogen the time required for heating is reduced by two orders of magnitude. Calculations show that by changing the type of plasma-forming gas and its initial and final temperatures, one can change the rate of particle heating within several orders of magnitude.

Increasing the particle diameter from 50 to 300 μm leads to an increase in the time required for their heating to the melting temperature (2319 K [7]) from $0.17 \cdot 10^{-4}$ to $0.5 \cdot 10^{-3}$ sec (Table 1).

Calculations showed that inside particles heated by plasma a temperature difference ΔT appears, whose dependence on the of heating time has an extremal character (Fig. 2). During the first time interval, ΔT increases to the maximum value and then, when the process of temperature relaxation by the mechanism of molecular heat conduction becomes prevailing, the difference between the temperatures of the surface and center of the particle

TABLE 1. Change with Time of Temperature (K) of Particles of Different Diameters

d, μm	Heating time −log t, sec					
	6.0	5.5	5.0	4.5	4.0	3.5
50	875	1325	2000	–	–	–
100	575	825	1200	1875	–	–
150	500	650	900	1350	2125	–
300	250	475	600	850	1250	1900

decreases gradually. When particles are heated by a hydrogen plasma, ΔT attains 1700 K. As the thermal conductivity of the gas decreases, ΔT also decreases. So, in the case of an argon plasma, ΔT does not exceed 15 K. When the diameter of the heated particle increases, the interval of time needed to attain the maximum value of ΔT also increases.

CONCLUSIONS

1. We suggest a mathematical model of the process of heating of microparticles by a plasma whose temperature changes exponentially. The model makes it possible to find the distribution of temperature inside the particles.

2. We show that the difference between the temperatures of the surface and center of an α-Al_2O_3 particle can reach 1700 K, depending on the conditions of heating (diameter of the particle and type of plasma-forming gas). This fact should be taken into account when developing plasma-technological processes such as sputtering of powders, their spheroidization, and synthesis of multicomponent compounds.

NOTATION

r_0, r, initial and current radius of particle, respectively; d, diameter of particle; T_1, T_2, T_{pl}, initial, final and current temperature of plasma, respectively; t, time; b, coefficient; a, λ, c_p, ρ, thermal diffusivity, thermal conductivity, isobaric heat capacity, and density of particle, respectively; $h = \alpha/\lambda$; α, coefficient of heat transfer from plasma to particle; $p = (r_0/a)\sqrt{b/6}$; μ_n, positive roots of transcendental equation; $\tan\mu = \mu/(1 - hr_0)$, $n = 1, 2, 3, \ldots$. Subscripts: g, gas; w, particle; pl, plasma.

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