In conclusion we note that the value of the precise form of Eq. (3) for the spectral components of the radiation flux in principle permits finding the total flux by simple numerical integration. However performing such detailed calculations requires a high speed wide bus computer.

NOTATION

ω, frequency; λ, wavelength; c, speed of light; k_B, Boltzmann's constant; T, temperature; $\hbar$, Planck's constant; r, radius; ε, dielectric permittivity; μ, magnetic permeability; κ, conductivity; P_ω, spectral thermal flux; e_ω, spectral radiation coefficient of sphere into cavity; x, diffraction parameter; γ, ratio of cavity radius to particle radius; i, imaginary unit; j, n, $h = h^{(2)}$, spherical Bessel functions of the first, second, and third sorts.

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BEHAVIOR OF MONODISPERSED METAL PARTICLES IN VARIOUS MEDIA

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UDC 621.762

Processes determining the final properties of monodispersed metallic microgranules are considered.

At present the problem of producing monodispersed metallic systems with special properties is of great practical importance. One of the methods used to produce such systems is high speed cooling of dispersed materials in order to amorphize them, thus producing special properties. Amorphous metal structures are widely used to produce dispersed systems with a characteristic dimension of $\sim 10^{-5}$ m, and are created at cooling rates of 10^4-10^6 K/sec, which can be achieved by interaction of the objects to be cooled with gaseous or solid media.

In analyzing factors which lead to high cooling rates, we must note the following major ones: contact area, temperature difference between cooling surface and surface being cooled, and thermal conductivity of the material. For a moving metallic microparticle its velocity and temperature are important characteristics controlling the cooling rate (since they influence the contact area), so that it is important to provide a correct mathematical description of processes in order to model the behavior of high temperature dispersed metal systems upon their interaction with various media.

The present study will attempt to consider the possibiity of amorphization of metallic dispersed systems with characteristic dimensions of 10^{-4} m. To solve this problem we will analyze the motion of high temperature ($T \geqslant 1000$—$2000\,°C$) metal (Cu, Mo) microparticles in air and their cooling rate on a copper substrate. The high temperature metal particles were generated by the pulsed arc method [1]. The coefficient of microgranule variation over size did not exceed 5%. Figure 1 shows copper microgranules 140 μm in radius, obtained by this method.

The change in temperature (brightness method) and velocity of the newly formed microgranules was determined as they moved along the vertical axis. The microparticle velocity $v = h/t_r$ was determined by photographic recording of particle motion through a chopper with

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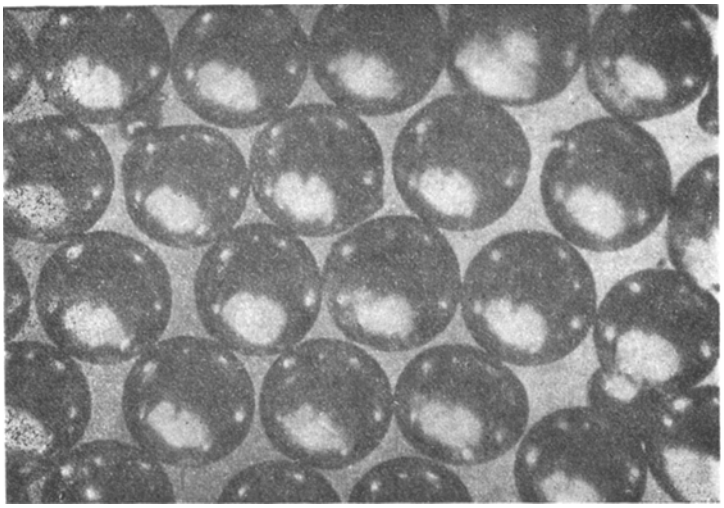

Fig. 1. Microphotograph of 140-μm radius copper particles.

rotation period t_r = 7.6 msec. The motion of copper and molybdenum particles was studied. Results for motion velocity for the metal microparticles in air are shown in Fig. 2.

Analysis of the curves obtained was performed by comparing experimental data with results of solving the equation of motion of the hot particles in the gas with consideration of convective and radiant heat exchange with the surrounding medium [2], while the resistance force produced by the gaseous medium was described by Klyachko's expression with $T_{ef} = (T_m + T_p)/2$. The equation of motion along the vertical x-axis has the following form:

$$m\frac{d^2x}{dt^2} = mg - F_r, \tag{1}$$

where

$$F_r = 6\pi\eta r\frac{dx}{dt}\left[1 + 0{,}265\left(\frac{r\frac{dx}{dt}}{\nu}\right)^{2/3}\right], \tag{2}$$

and the heat exchange is described by

$$mc\frac{dT_p}{dt} = -2\pi r\lambda\left[2 + 0{,}6\left(\frac{2r\frac{dx}{dt}}{\nu}\right)^{1/2}\mathrm{Pr}^{1/3}\right](T_p - T_m) - 4\pi r^2\sigma\varepsilon(T_p^4 - T_m^4). \tag{3}$$

Two reasons are possible for the poor agreement between the theoretical and experimental data: unsatisfactory description of the process of particle heat exchange with the surrounding medium, the result of which is incorrect determination of t_p, or unsatisfactory description of the aerodynamic resistance of the surrounding medium to motion of the hot particle by Klyachko's expression.

To eliminate the first factor the experimentally determined microparticle temperature was substituted in the equation of motion [3]. As is evident from Fig. 2, the calculated curve obtained in this case produces better agreement with the experimental data, although still not satisfactory. The equation of motion of the copper and molybdenum particles was also integrated using the resistance force defined by the expression of [4]:

$$F_r = 13\pi r\gamma\nu v. \tag{4}$$

The gas density was determined from the medium temperature, and the kinematic viscosity, from the particle temperature. Calculation results with Eq. (4) substituted in Eq. (1) are shown in Fig. 2. This calculation is characterized by significant elevation of the calculated resistance force above the experimental value, due to the fact that Eq. (4) was proposed for coals with characteristic combustion temperature of ~1100°C and therefore yields an elevated resistance force for objects with higher temperatures.

Thus, our study has shown that Klyachko's expression describes hot particle motion in a gaseous medium unsatisfactorily, since it was intended for determining the aerodynamic re-

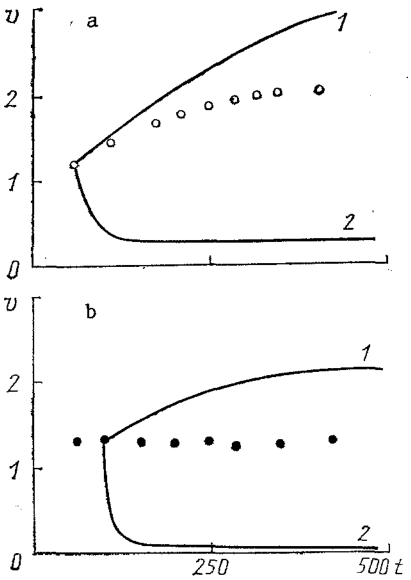

Fig. 2. Velocity of copper (a) and molybdenum (b) particles vs time: 1) aerodynamic resistance considered by Klyachko's method; 2) aerodynamic resistance force calculated after [4]. v, m/sec; t, msec.

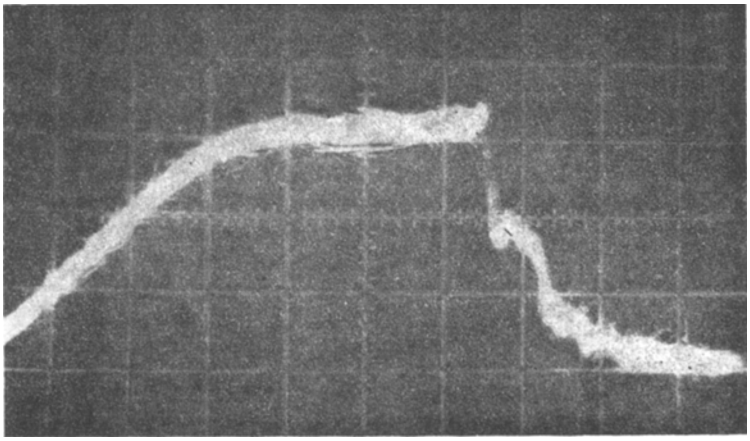

Fig. 3. Oscillogram of brightness of particle cooling on plate.

sistance to motion of particles in a homogeneous temperature field, and must thus be refined by an additional resistance mechanism.

The metal particles moving at the indicated velocities (Fig. 2) and temperatures [3] fell onto a copper substrate in the form of a cylinder with dimensions much greater than the particle dimensions ($R \gg r$, $H \gg r$). Upon particle contact with the substrate the change in temperature was recorded by the brightness method.

In measuring the metal microparticle cooling rates the radiation detector was installed in the plane of the substrate upon which the particles landed. An S8-13 oscilloscope operating in triggered mode recorded the signal which allowed simultaneous determination of the flight speed, original temperature, and cooling rate of the microparticle. A characteristic oscillogram of the process is shown in Fig. 3. Preliminary calibration of the system determined the distance from the substrate at which signal recording from the hot microparticle commenced. By determining the time from the moment of appearance of the particle in the field of view to contact with the substrate, the rate of particle descent was determined. This quantity was found to lie in the range $v \sim 1\text{-}2$ m/sec. The signal amplitude was used to determine the initial particle temperature: $T_{Cu} \approx 1500°C$, $T_{Mo} \approx 2500°C$. The oscillogram allows determination of the time required for cooling of the droplet from its original temperature to $T \sim 900°C$, as determined by the brightness sensitivity of the radiation detector. The oscillograms showed that the characteristic cooling rate for a particle with $r = 140$ μm was of the order of $\sim 10^6$ K/sec for a radius of the contact spot with the substrate equal to 75 μm.

Mathematical modeling of the heat exchanges of the microparticle with the massive substrate was also carried out. For this purpose the thermal conductivity equation $\partial T/\partial t = \chi \Delta T$

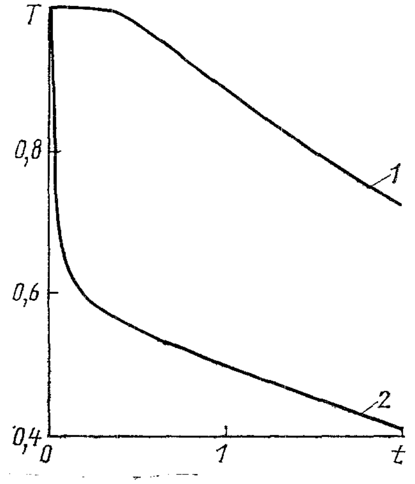

Fig. 4. Dimensionless temperature vs dimensionless time for two points within droplet cooling on substrate: 1) point furthest removed from substrate; 2) point on droplet-substrate boundary.

was integrated over a range modeling the geometry of the experimental situation. It was assumed that upon contact with the substrate the droplet was deformed such that its shape could be modeled by a sphere with segment removed. With consideration of axial symmetry of the model the thermal conductivity equation was written in two-dimensional form

$$\frac{\partial T}{\partial t} = \chi\left(\frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\rho\frac{\partial T}{\partial \rho}\right) + \frac{\partial^2 T}{\partial z^2}\right).$$

The integration region was specified in the following manner

$$0 \leqslant \rho \leqslant 5r \text{ for } -3r \leqslant z \leqslant 0,$$

$$0 \leqslant \rho \leqslant \sqrt{r^2 - (\sqrt{r^2 - r_p^2} - z)^2} \text{ for } 0 < z \leqslant \sqrt{r^2 - r_p^2} + r.$$

After dedimensionalizing all equations we take boundary

$$\mathbf{n}\nabla T = 0 \text{ for } z \geqslant 0,\ T = 0 \text{ for } z < 0$$

and initial conditions

$$T = 1 \text{ for } z \geqslant 0,\ T = 0 \text{ for } z < 0.$$

The result of the calculation is a series of curves of dimensionless temperature vs dimensionless time within the cooling droplet. Figure 4 shows curves for the most "rapid" point, on the boundary between the droplet and substrate, and the "slowest" point at the very top of the droplet, i.e., furthest removed from the substrate. The calculations show that after the time of 0.5 dimensionless units a field with a smoothly changing temperature gradient is established within the droplet. This leads to differences in the cooling rate at various points of no more than 50%.

For a copper droplet with radius 140 μm on a copper substrate (contact spot radius 75 μm) characteristic cooling rates of the order of 10^6 K/sec were found. This rate is realized in the first 0.2 msec after cooling begins. The cooling rate then falls, but during that time the droplet cools by 20% of its initial dimensionless temperature, which is completely sufficient for amorphization of the majority of alloys. The agreement between the experimental and calculated cooling rates shows the applicability of the proposed calculation model for determining cooling rates on the substrate.

As a result of the study performed it was established that use of Klyachko's expression for mathematical modeling of moving monodispersed systems of hot metal particles leads to falsely lowered values of the resistance to particle motion. Consequently, it is necessary to consider additional resistance forces related to burning of the metal particles. The calculations performed, confirmed experimentally, show the possibility of reaching cooling rates of 10^6 K/sec for dispersed objects with characteristic dimensions of 10^{-4} m upon contact with metal substrates. Such cooling rates are sufficient for amorphization of the majority of alloys.

NOTATION

T_m, T_p, temperature of medium and metallic particle; v, velocity; h, distance between initial points of microparticle track; t_r, chopper rotation period; x, vertical coordinate;

t, temperature; m, particle mass; g, acceleration of gravity; F_r, aerodynamic resistance force; η, ν, dynamic and kinematic viscosities of gaseous medium; r, particle radius; Pr, Prandtl number; c, specific heat; σ, Stefan–Bolzmann constant; ε, emissivity of particle surface; λ, gas thermal conductivity; γ, gas density; R, radius of substrate cylinder; H, height of substrate cylinder; T_{eff}, effective temperature; χ, thermal diffusivity; T, temperature; ρ, z, cylindrical coordinates; r_s, radius of contact spot between droplet and substrate; n, normal vector; T_{Cu}, T_{Mo}, temperatures of copper and molybdenum particles.

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LIMITING PARTICLE CHARGE FOR ELECTRIFICATION IN A CORONA DISCHARGE FIELD

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An experimental study is performed of electrification of objects from a dielectric fluid within a corona discharge field. Use of jet monodispersion permits comparison of data on charging of a cylindrical surface and spherical particles, elimination of the effect of dynamic factors, refinement of the electrification mechanism and limiting charge value. It is shown that aside from other factors, the limiting charge is defined by the cross sectional area of the electrified object, and is approximately 30% less than previously accepted values.

A most important factor in electron–ion and droplet jet technology is the study of conditions for electrification of material and the physical processes which accompany this phenomenon. One of the most studied and widely used methods is charging of material in the field of a corona discharge [1]. This method is universal in the sense that it can be applied to both conductive and dielectric materials.

Depending on the dimensions of the particles being charged, the physical kinetics of charging under corona conditions can be described by two different methods: for particles with diameter $\leqslant 1$ μm the major role is played by diffusion charging, while for particles with diameter $\geqslant 10$ μm shock ionization dominates, in accordance with which the particle charging dynamics are described by the equation

$$q(t) = q^* \frac{en_0kt}{4\varepsilon_0 + en_0kt}.$$

In this expression the value of the limiting particle charge q* plays a most important role, since it in fact determines the efficiency of device operation. The widely accepted method of determining q* is based on the condition of equality to zero of the field intensity on the surface of the particle turned toward the corona electrode:

$$\mathbf{E}_c + \mathbf{E}_p + \mathbf{E}_q = 0,$$

where $\mathbf{E}_c$ is the field intensity of the corona discharge; $\mathbf{E}_p$ is the polarization component of the field; $\mathbf{E}_q$ is the field of the charges deposited on the surface.

To determine $\mathbf{E}_p$ it was assumed that particle electrification occurs with a uniform distribution of the accumulating charge over the surface and the value of the charge is such that the field created by this charge at all points of the surface corrsponds to the highest intensity. Based on this, the maximum charge of a conductive spherical particle, for example,

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