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VACUUM HEATING OF SPHERICAL ALUMINA PARTICLES

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Heating of spherical alumina particles by high-intensity laser radiation under vacuum conditions to the melting temperature is investigated with account for the nonuniform distribution of energy sources with respect to the particle volume.

The problems associated with propagation of laser radiation stimulate interest in the influence of the latter on solid disperse particles. Vacuum heating of microparticles with high absorption is investigated in [1–3]. However, in the stratosphere along with strongly absorbing particles weakly absorbing particles may exist, including those of anthropological origin.

The present work is devoted to investigation of vacuum heating of spherical alumina particles exposed to laser radiation up to the melting point with account for the nonuniform distribution of energy sources with respect to the particle volume and the temperature dependences of thermophysical properties of the substance.

The melting temperature of alumina is 2327 K. The initial heating temperature is taken equal to 293 K. According to [4, 5], the complex refractive index $m = 1.79 - i \cdot 10^{-7}$ changes weakly with temperature at the wavelengths 0.69 and 1.06 μm. For the temperature-dependent specific heat and thermal conductivity the following approximate relations are obtained based on the numerical data reported in [6, 7]:

$$c(T) = 0.098 \ln T - 0.37 \quad (293 \le T \le 800 \text{ K}),$$

$$c(T) = 3.85 \cdot 10^{-5} T + 0.25 \quad (800 < T \le 2327 \text{ K}),$$

$$\lambda_1(T) = \exp[-2.78 \cdot 10^{-3}(T - 273) - 2.35] \quad (293 < T \le 400 \text{ K}),$$

$$\lambda_1(T) = 2.19 \cdot 10^{-8}(T - 273)^2 - 5.69 \cdot 10^{-5}(T - 273) + 0.05$$

$$(400 < T \le 2327 \text{ K}).$$

In heating the substance the density is assumed to depend weakly on temperature and to equal $\rho = 3.72$ g/cm^3.

A distinctive property of weakly absorbing particles is the focusing of radiation inside them until the effects of superfine optical resonances develop; here the radiation density in the particles increases by several orders of magnitude (see, e.g., [8]).

The change of the temperature with time inside a spherical particle of radius r_0 exposed to radiation at the wavelength λ is described by the heat conduction equation in a spherical coordinate system:

$$c(T)\rho \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r}\left[\lambda_1(T) r^2 \frac{\partial T}{\partial r}\right] + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta}\left[\lambda_1(T) \sin\theta \frac{\partial T}{\partial \theta}\right] + Q(r, \theta). \quad (1)$$

Assuming that in vacuum heating of a solid particle, heat is transferred only by radiation in accordance with the Stefan-Boltzmann law, we may write the following boundary and initial conditions:

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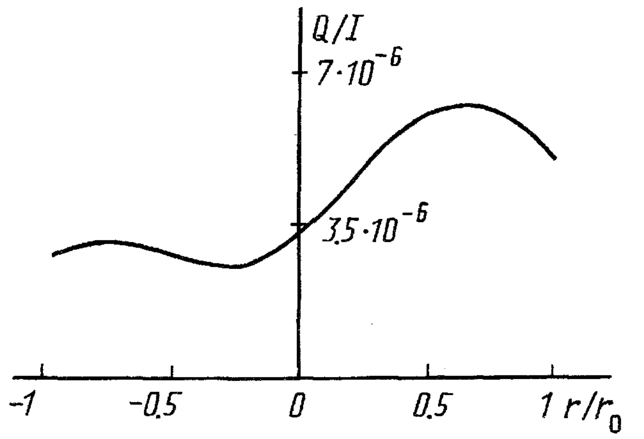

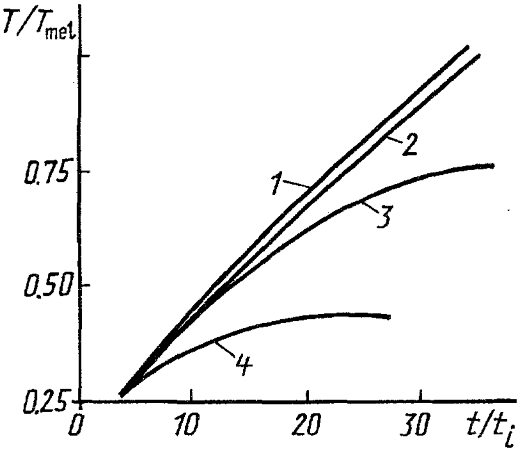

Fig. 1. Distribution of the heat release Q/I (μm^{-1}) along the principal axis of an alumina particle with the radius $r_0 = 0.15\ \mu m$ at $\lambda = 0.69\ \mu m$, $m = 1.79 - i\cdot 10^{-7}$.

Fig. 2. Heating temperature T/T_{mel} of an alumina particle vs time t/t_i ($i = 1, 2, 3, 4$) for $r_0 = 0.15\ \mu m$; $\lambda = 0.69\ \mu m$, $m = 1.79 - i\cdot 10^{-7}$; 1) $I = 10^{10}$ W/cm^2, $t_1 = 10^{-7}$ sec; 2) $I = 10^8$ W/cm^2, $t^2 = 10^{-5}$ sec; 3) $I = 10^7$ W/cm^2, $t_3 = 10^{-4}$ sec; 4) $I = 10^6$ W/cm^2, $t_4 = 10^{-3}$ sec.

$$- \lambda_1 (T) \frac{\partial T}{\partial r}\Big|_{r=r_0} = \sigma\varepsilon T^4 , \tag{2}$$

$$\frac{\partial T}{\partial \theta}\Big|_{\theta=0} = \frac{\partial T}{\partial \theta}\Big|_{\theta=\pi} = 0 , \tag{3}$$

$$|T(0, t)| < \infty , \quad T(r, \theta, 0) = T_0 . \tag{4}$$

Here

$$Q(r, \theta, \varphi) = \frac{4\pi n\kappa}{\lambda} IB , \quad B = (E_r E_r^* + E_\theta E_\theta^* + E_\varphi E_\varphi^*)/|E_0|^2 .$$

By analogy with [9], in order to solve approximately the above system of equations we construct, on a computer, an absolutely stable local one-dimensional iteration scheme on a space-time grid, put the initial problem into correspondence with the difference one, and then solve the obtained system of equations by the factorization method [10–12]. The boundary-value problem has a solution and it is unique.

A spherical particle is illuminated by a parallel beam of unpolarized light, and therefore, the temperature distribution inside the particle is symmetric relative to the diameter that coincides with the direction of beam propagation (the major axis). Therefore the temperature distribution is considered in the plane of the cross section of a great circle of the particle. To investigate the distribution dynamics of the temperature field, we calculate temperatures in the plane of the cross section of a great circle of the particle upon attaining the temperatures $T_{mel}/4$, $T_{mel}/2$, $3T_{mel}/4$, and T_{mel} inside the particle.

At first we shall consider heating of a small alumina particle exposed to laser radiation at $\lambda = 0.69\ \mu m$. Despite a small absorption coefficient the nonuniformity in heat release distribution is insignificant, i.e., the focusing of radiation inside small particles is insignificant, which is illustrated by the heat release distribution shown in Fig. 1 for particles of radius $0.15\ \mu m$. In this case the relative degree of nonuniformity of heat release, which is determined, according to [9], by the expression $\delta Q = (Q_{max} - Q_{min})/Q_m$ ($Q_m = 3Ik_a/4r_0$ is the density of the absorbed energy averaged over the particle volume), is $\delta Q \approx 1.5$. The region of highest values of Q/I is located in the shadow hemisphere. Figure 2 shows the time dependences of the heating temperature in the region

TABLE 1. Time $t \cdot 10^2$ (μsec) Required for an Alumina Particle Exposed to Radiation with $I = 10^9$ W/cm^2 and $\lambda = 1.06$ μm to Attain the Temperatures $T_{mel}/4$, $T_{mel}/2$, $3T_{mel}/4$, and T_{mel}

r, μm	$T_{mel}/4$	$T_{mel}/2$	$3T_{mel}/4$	T_{mel}
5	7.57	45	108	201
7	2.67	11	22	37
9	1.77	6.68	13	20
12	1.05	3.93	7.3	11
15	1.09	3.7	6.8	10.3
17	0.8	2.7	4.9	6.9

of maximum heat release of the alumina particle for different intensities of incident radiation. As is seen, for incident radiation intensities up to $I = 10^7$ W/cm^2 the temperature in the alumina particle increases nonlinearly with time, unlike the linear increase in the case of a strongly absorbing soot particle of the same size [2]. For the incident radiation intensity $I = 10^6$ W/cm^2 heating of an alumina particle of radius $r_0 = 0.15$ μm (curve 4) is hardly probable, unlike a strongly absorbing soot particle, with only $t \approx 1.3 \cdot 10^{-8}$ sec required to heat it to T_{mel}. This dependence becomes linear for an alumina particle only for an intensity of incident radiation $I \geq 10^8$ W/cm^2. Already for the intensity $I = 10^8$ W/cm^2 of incident radiation the melting temperature T_{mel} is attained in the particle in the time $\approx 3.6 \cdot 10^{-4}$ sec. However, this time exceeds substantially the times of temperature relaxation $t^0 = r_0^2 c(T)\rho/\lambda(T)$. Actually, the temperature relaxation times are equal for the initial temperature, $t_1^0 = 1.7 \cdot 10^{-9}$ sec, and at the melting temperature, $t_2^0 = 0.3 \cdot 10^{-10}$ sec. Consequently, in the case under consideration the temperature field distribution is practically uniform [9].

With a tenfold increase in the particle radius, the absolute value of maximum heat release increases by approximately two orders of magnitude, and the distribution nonuniformity of heat sources increases as well. To calculate the time required to attain T_{mel} in the case under consideration, the following approximate formula is obtained:

$$t = 2.01 \cdot 10^4 \, I^{-1.04} . \tag{5}$$

The calculation error does not exceed 13%. According to (5), for $I = 10^8$ W/cm^2 the time for attaining T_{mel} for a particle of radius 1.5 μm is $t = 9.3 \cdot 10^{-5}$ sec, which is approximately one-fourth of the time required for a particle with $r_0 = 0.15$ μm and is larger than the temperature relaxation time. A comparison reveals that $9.5 \cdot 10^{-4}$ sec is required to heat an alumina particle of the considered radius by radiation with the intensity $I = 10^7$ W/cm^2, which is longer by approximately a factor of 10^6 than for a soot particle. It is noteworthy that the absorption index of alumina is almost seven orders of magnitude lower than for soot. The discussed heating conditions for a spherical alumina particle pertain to the situation where the heating time is also longer than the time of temperature relaxation. In such heating, the nonuniformity of the temperature field distribution in a particle does not exceed, as calculations show, 10% for intensities up to $I = 10^8$ W/cm^2.

With a further size increase for the alumina particle, the focusing of radiation in the shadow hemisphere becomes even more pronounced. The density of the electric intensity increases by several orders of magnitude (see, e.g., [13]). As a consequence, heat release in the particle increases, which creates favorable conditions for rapidly attaining the melting temperature. Table 1 presents calculation results for the heating of melted alumina particles of different radii by irradiating them with the intensity $I = 10^9$ W/cm^2 at the wavelength $\lambda = 1.06$ μm. In almost the all cases of heating (with the exception of particles with $r_0 = 5$ μm) given in the table, the time for attaining T_{mel} is less than that of temperature relaxation. It is seen that with an increase of the radius of the alumina particle the time for attaining the melting temperature decreases, unlike the highly absorbing soot particles, where the analogous dependence $t_{mel}(r)$ is of opposite nature [2]. The temperature field distribution in such particles is rather nonuniform and is largely characterized by the distribution of the heat sources. For instance, in heating a particle

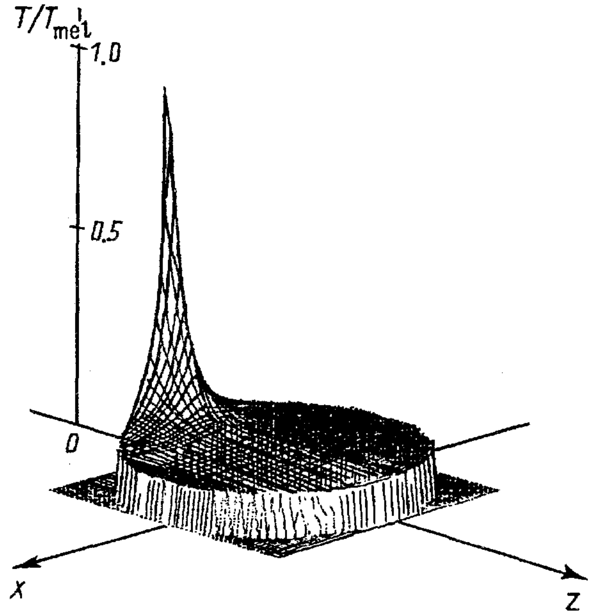

Fig. 3. Topographical projection of the temperature distribution in the main cross section of a spherical alumina particle with $r_0 = 15\ \mu_0$, $I = 10^9$ W/cm^2, $\lambda = 1.06\ \mu$m, $m = 1.79-i\cdot 10^{-7}$ at the moment $t = 1.03\cdot 10^{-7}$ sec.

of radius $r_0 = 15\ \mu$m to the melting temperature the degree of heat release nonuniformity is close to 90%; i.e., upon attaining T_{mel} in the shadow hemisphere, the particle remains almost "cold" in the illuminated hemisphere. This is illustrated in Fig. 3 by the topographical projection of the temperature distribution in the plane of the cross section of a great circle of an alumina particle. The center of the sphere coincides with the center of the coordinate plane xz, and the incident light propagates in the negative direction of the z axis. The value of T/T_{mel} is counted off perpendicularly to the xz plane. As is seen the region, where the melting temperature is attained is small and amounts to 4% of the total area of the circle, which coincides with the zone of maximum heat release. In the cases under consideration, for evaluation of the heating time of a particle we may neglect the first two terms on the right-hand side of Eq. (1). Then the formula for the time for attaining the melting temperature acquires the form

$$t_{\text{mel}} = \bar{c}\rho\ (T_{\text{mel}} - T_0)\ \lambda/4\pi n\kappa IB\ , \tag{6}$$

where for simplicity $c(T)$ is replaced by its mean value $\bar{c}$. Calculations show that in this case the time for attaining the melting temperature is determined with an error of no more than 50%. Using this expression for t_{mel} and the formula for the temperature relaxation time, we may write a criterion that must be satisfied by the optical and thermophysical characteristics of a particle and the intensity of incident radiation in order to attain the melting temperature rapidly:

$$\frac{4\pi n\kappa r_0^2 IB}{\lambda\ (T_{\text{mel}} - T_0)\ \lambda_1} >> 1\ . \tag{7}$$

It is worth noting that these expressions may also be used for calculation of the heating time of particles when superfine optical resonances are realized in the latter. The heating time of such particles to T_{mel} may decrease by two-three orders of magnitude compared to the heating of a nonresonant particle for a given intensity of the incident radiation as a consequence of an increas3 in the maximum heat release in resonant particles by the same value.

To sum up, we have revealed that with an increase in the size of alumina particles the time for attaining the melting temperature decreases, unlike soot particles. A relationship is found between the particle parameters and the intensity of incident radiation that allows determination of the nature of the heating regime of a weakly absorbing alumina particle to the melting temperature under vacuum conditions. In the case of rapid attainment of the melting temperature an expression is given for evaluation of the time for it.

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NOTATION

T, temperature, K; t, time, sec; T_0, initial heating temperature; T_{mel}, melting temperature of alumina; t^0, time of temperature relaxation; t_{mel}, time for attaining the melting temperature; r, θ, φ, coordinates of a point inside a particle; r_0, particle radius; $c(T)$ and $\lambda_1(T)$, temperature-dependent specific heat and thermal conductivity of alumina; $\bar{c}$, mean specific heat; ρ, substance density; E_0, electric intensity in an incident wave; λ, wavelength of incident radiation; I, intensity of incident radiation; E_r, E_θ, E_φ, components of the electric intensity inside a particle; $m = n - ik$, complex refractive index of the particle substance: σ, Stefan–Boltzmann constant; ε, emissivity factor; δQ, relative degree of heat release nonuniformity; Q_{m}, particle volume-averaged density of the absorbed energy; k_{a}, absorption coefficient of a particle.

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