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INFLUENCE OF WEAKLY ABSORBING SOLID AEROSOL PARTICLES IN LOWERING THE OPTICAL BREAKDOWN THRESHOLD OF AIR

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The influence of a subtance in the disperse state on the optical breakdown conditions of air is investigated.

The propagation of high-intensity laser radiation in the atmosphere is known to be accompanied by various kinds of nonlinear effects [1, 2], in particular, the optical breakdown of air. The presence of aerosol particles in the air usually lowers the threshold radiation intensity required for the initiation of optical breakdown by roughly two orders of magnitude. According to Zuev et al. [2, 3], the reduction of the optical breakdown threshold of air in the presence of absorbing disperse particles is caused by volatilization of the material of these particles when they are heated by laser radiation.

The present article is a theoretical investigation of the action of high-intensity laser radiation on weakly absorbing solid aerosol particles, whose presence can create conditions for lowering the optical breakdown threshold of air. The calculations are carried out for spherical particles of fused aluminum oxide with optical constants $m = 1.75 - i \cdot 10^{-7}$ and particle radii $R = 7$-17 μm. The wavelength of the incident radiation is $\lambda = 1.06$ μm. The energy density of the electric field both inside and outside the particle is characterized by the quantity B, which is expressed in terms of the electric field components

$$B = (\mathbf{E} \cdot \mathbf{E}^*)/|\mathbf{E}_0|^2. \tag{1}$$

Expressions for the components of the electric field in the interior of a spherical particle are given in [4, 5]. The components of the electric field for the diffracted near field can

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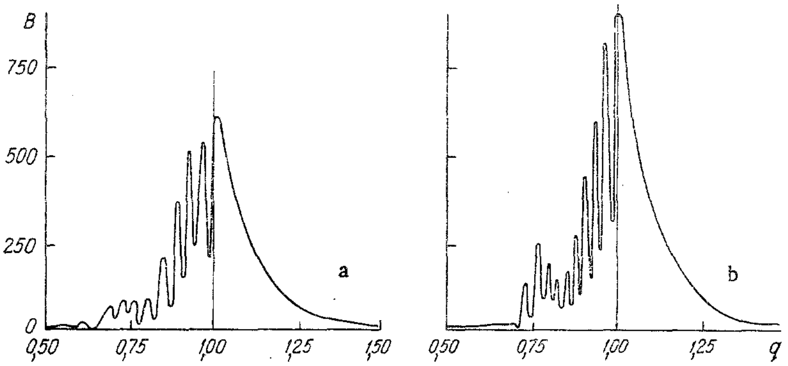

Fig. 1. Distribution of the energy density B of the internal and diffracted fields along the principal diameter of a spherical Al_2O_3 particle for $m = 1.75 - i \cdot 10^{-7}$; the vertical line indicates the boundary of the particle. a) R = 9 μm; b) R = 12 μm.

be written in the form

$$E_r = \frac{E_0 \cos\varphi}{k_a^2 r^2} \sum_{l=1}^{\infty} l(l+1) \left\{ i^{l-1} \frac{2l+1}{l(l+1)} \psi_l(k_a r) + C_l \xi_l(k_a r) \right\} Q_l(\theta) \sin\theta,$$

$$E_\theta = \frac{E_0 \cos\varphi}{k_a r} \sum_{l=1}^{\infty} \left\{ \left[C_l \xi_l'(k_a r) + i^{l-1} \frac{2l+1}{l(l+1)} \psi_l'(k_a r) \right] S_l(\theta) + \left[B_l \xi_l(k_a r) + i^{l-1} \frac{2l+1}{l(l+1)} \psi_l(k_a r) \right] Q_l(\theta) \right\},$$

$$E_\varphi = -\frac{E_0 \sin\varphi}{k_a r} \sum_{l=1}^{\infty} \left\{ \left[C_l \xi_l'(k_a r) + i^{l-1} \frac{2l+1}{l(l+1)} \psi_l'(k_a r) \right] Q_l(\theta) + i \left[B_l \xi_l(k_a r) + i^{l-1} \frac{2l+1}{l(l+1)} \psi_l(k_a r) \right] S_l(\theta) \right\}. \quad (2)$$

Figure 1 shows the energy density B of the internal and diffracted fields as a function of the relative coordinate q = r/R along the diameter of a spherical particle in the direction of propagation of the incident radiation (we shall refer to this diameter as the principal diameter for brevity). Since the greatest nonuniformity of the energy distribution inside and outside the spherical particle occurs along its principal diameter, the results of the calculations are given only for this direction. We assume that the radiation propagates from left to right, and the origin is located at the center of the particle. It is evident from the figure that the distribution of the energy density B of the internal electric field near the particle surface in the shadow hemisphere exhibits a strongly oscillating behavior. The oscillations are smoothed in the illuminated hemisphere and in the central zone of the particle, and the energy distribution there is nearly uniform. Consequently, only the zone of maximum oscillations is shown in the figure. The maximum value of the energy density is located on the surface of the particle in the shadow hemisphere. It is almost 20 times the maximum value of B in the illuminated zone and is 600-900 times the energy density of the incident radiation. The energy density of the field immediately outside the sphere in the forward direction also increases by two or three orders of magnitude simultaneously with the electric field inside the particle, i.e., the spherical particle manifests focusing properties (see also [6]). The radial half-width of this zone extends approximately 1 μm beyond the boundary of the particle. The quantity B increases by 1/7 to 1/8 relative to the maximum energy density on the particle surface at a distance 0.2R from that surface, and it decreases by 1/60 at a distance 0.5R from the surface. The occurrence of a maximum of the electrical energy near the shadow surface of the particle is of practical significance from the point of view of a possible reduction in the threshold of nonlinear optical phenomena. For example, if the energy density of the incident radiation on the given particle is equal to 10^{13} W/m², the energy density is approximately 10^{15} to 10^{16} W/m² near the surface of the particle in the shadow region, i.e., according to [7, 8], the threshold intensity for the optical breakdown of pure air is attained. If the heating time of weakly absorbing Al_2O_3 particles to the melting point is much greater than the characteristic time (usually 20-40 nsec [8]) for the onset of breakdown of pure air, the mechanism for the inception of breakdown can differ from the breakdown mechanism in the presence of absorbing solid aerosol particles.

To estimate the heating time of the investigated weakly absorbing particles to the melting point, we solve a model boundary-value problem describing the heating of a solid spherical particle irradiated by pulsed radiation with allowance for the nonuniform distribution of internal energy sources in the volume of the particle and the temperature dependence of the thermophysical properties of Al_2O_3. We assume here that the initial temperature of the particles corresponds to 293 K. The calculations show that the heating time of spherical particles to the melting point decreases as the particle size is increased. For example, the heating time t = 0.6 μsec for particles of radius R = 7 μm, t = 0.22 μsec for R = 9 μm, and t = 0.12 μsec for R = 17 μm. It is evident from these results that the heating time from the start of irradiation until melting takes place for aluminum oxide particles with radii from 7 to 17 μm is 5-10 times the characteristic time of optical breakdown in pure air. Consequently, when radiation with λ = 1.06 μm acts on aluminum oxide particles of such radii, the increase of the energy density of the diffracted field by two or three orders of magnitude near a particle can cause optical breakdown of the air to set in before the particle itself is heated to the melting point and begins to vaporize.

We can conclude from the foregoing discussion that the presence of weakly absorbing particles in air can create conditions for a reduction of the threshold radiation intensity required for the initiation of optical breakdown in air. However, the nature of the process clearly differs from the case of optical breakdown of air in the presence of absorbing particles. This problem deserves special consideration.

NOTATION

C_ℓ, B_ℓ, amplitude coefficients of electric and magnetic partial waves in well-known equations of Mie theory for radiation scattering and absorption factors; ψ_ℓ, ξ_ℓ, Riccati–Bessel functions; $Q_\ell(\theta)$, $S_\ell(\theta)$, angular functions expressed in terms of Legendre polynomials; $k_a = 2\pi m_a/\lambda$, wave number in medium surrounding particle; m_a, refractive index of medium; r, θ, φ, coordinates of point inside and outside particle; the prime everywhere denotes derivatives with respect to argument of a function; m, refractive index of particle material; R, particle radius; λ, wavelength of incident radiation; t, heating time of particle to melting point.

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