SELF-ACTION OF A HOLLOW BEAM OF OPTICAL RADIATION PROPAGATING IN A SOLID-PARTICLE AEROSOL

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The self-action of a hollow beam of optical radiation propagating in a solid-particle (metal) aerosol was studied by solving the system of equations numerically on a computer. It is shown that self-focusing of the beam is possible, and the calculations are compared with experimental data.

Nonlinear propagation of high-power optical radiation in a atmospheric solid-particle aerosol was investigated experimentally and theoretically in Refs. 1 and 2 (see also the references). It is of special interest to study the thermal self-focusing of a beam of radiation in a solid-particle aerosol. In Ref. 3 it was demonstrated experimentally that self-focusing of a hollow beam of radiation with wavelength $\lambda = 10.6$ μm is possible in an aerosol medium consisting of aluminum particles. In this paper we present the results of numerical modeling of the propagation of a hollow beam of radiation in a metal aerosol under conditions close to those of the experiment of Ref. 3.

We shall study the propagation of a hollow parallel beam of radiation with $\lambda = 10.6$ μm and intensity distribution

$$I = I_0 \exp\left[-(R - R_m)^2/R_b^2\right] \quad (1)$$

where $I_0 \approx 10^5$ W/cm^2 is the constant maximum intensity of the radiation at the radius $R_m = 0.5$ cm and $R_b = 0.25$ cm is the characteristic radius along the X axis of a cylindrical coordinate system X, R in a layer of aerosol consisting of monodispersed ~ 6 μm aluminum particles with a mass concentration $W \sim 1$ g/m^3. The thickness of the layer $\Delta X = X_2 - X_1 \approx 1$ m, where X_1 and X_2 are the coordinates of the front and back boundaries of the aerosol layer. These parameters correspond to the average parameters of the aerosol and the focused beam of radiation near the focal plane in the experiment of Ref. 3, since it is precisely in this region with maximum radiation intensity that the processes which determine the appearance of self-defocusing of the beam develop. The thermal self-action of the beam of radiation was studied based on the numerical solution of the system of equations formulated in Ref. 4 and including the parabolic equation of quasioptics taking into account the real mechanisms of formation of the field and the index of refraction n_λ of the gaseous medium (air). The numerical values of the parameters of the problem and the temperature dependences of the thermophysical quantities, the transport coefficients, and the index of refraction of the gas medium for $\lambda = 10.6$ μm were taken from Refs. 5–7.

The numerical results show that in this case the temperature of the particles heated by the radiation does not exceed $1.7 \cdot 10^3 \ldots 1.8 \cdot 10^3$ K, and there is virtually no vaporization of the particles.[8] Therefore the vaporization of the particle material does not contribute to the heating of the gas and the change in the index of refraction of the medium. Energy is released in the gas owing to removal of heat from the particles by means of heat conduction and molecular absorption of the radiation energy. The energy release is proportional to the local value of the radiation intensity and the profile of the gas temperature formed will be qualitatively the same as the profile of the radiation intensity in this section of the beam. Since the index of refraction n_λ depends on the temperature of the gas T_c (Ref. 5) this leads to formation of a nonstationary two-dimensional field of the index of refraction of the aerodispersed medium, which, in its turn, determines the propagation of the beam of radiation.

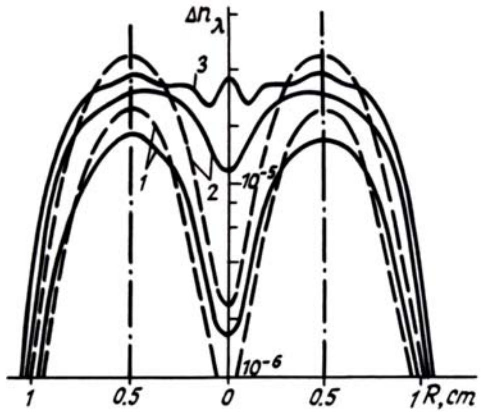

FIG. 1. The distribution of the change Δn_λ in the index of refraction of the gas medium as a function of R for $X = X_1$(– – –) 1 and $X = X_2$(——), $t = 3 \cdot 10^{-9}$ (1), $1.2 \cdot 10^{-2}$ (2), $1.8 \cdot 10^{-2}$s (3).

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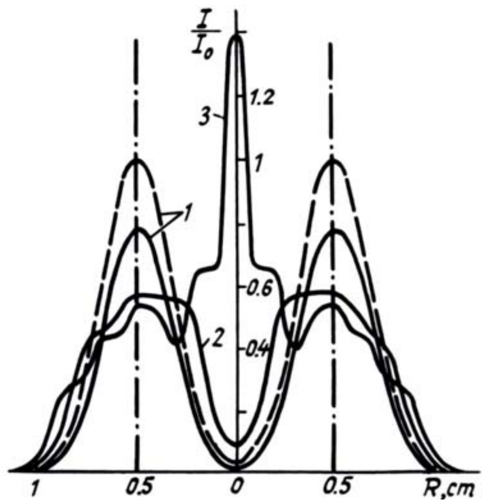

FIG. 2. The distribution of the normalized radiation intensity I/I_0 as a function of R for $X = X_1$(– – –), $t \geq 0$ (1), $X = X_2$(——), $t = 0$ (1), $6 \cdot 10^{-3}$ (2), $1.2 \cdot 10^{-2}$ s (3).

Figure 1 shows distributions of the change in the index of refraction of the medium $\Delta n_\lambda = n_{\lambda 0}$, where n_λ and $n_{\lambda 0}$ are, respectively, the instantaneous and initial value of the index of refraction of the gaseous medium, as a function of R for two cross sections of the beam at $X = X_1$ and $X = X_2$ and at several times. Because of the value of the mass concentration of particles W used the contribution of the heat owing to heat conduction from the heated particles to heating of the gas reaches on the average ~ 96–98% of the molecular absorption. Therefore the aerosol particles have a determining effect on the formation of the temperature and index of refraction fields of the gas. A focusing lens forms in the region of the beam near the axis with $R < R_m$ at the instant the radiation starts to act. With time (by the time $t \sim 1.2 \cdot 10^{-2}$ s) this leads to distribution of the intensity in the cross section of the beam, self-focusing, and formation of a peak of intensity on the axis of the beam at $X = X_2$ (Fig. 2). The time during which self-focusing develops, determined experimentally in Ref. 3, is less than 0.1 s. In the process a defocusing lens, which somewhat expands the beam of radiation, forms at the periphery of the beam for $R > R_m + R_b$. The formation of maximum of intensity on the axis of the beam of radiation with time (by the time $t = 1.8 \cdot 10^{-2}$ s) gives rise to the formation of a maximum of the temperature on the axis and a defocusing lens next to the axis of the beam for $X \leq X_2$ (Fig. 1). This results in a decrease of the intensity on the axis of the beam. In addition, temporal oscillations can arise in the distribution of the radiation intensity over the cross section and along the axis of the beam. These oscillations are caused by the self-action of the beam on the time-dependent two-dimensional profile of the index of refraction of the medium. We note the gas temperature (T_c) in separate spatial regions of the beam reaches approximately 350 ... 400 K. As a result, with time heat conduction affects the formation of the profile of Δn_λ, and the local changes in the index of refraction reach $\Delta n_\lambda \sim -4 \cdot 10^{-5}$.

Thus we have confirmed by numerical modeling the possibility, established experimentally in Ref. 3, of redistribution of intensity in a hollow beam of radiation propagating in a metal aerosol. In Ref. 3 the self-focusing is attributed to the breakup of the particles under the action of the radiation. The results of our calculations shows that self-focusing is caused primarily by the formation of the corresponding field of the index of refraction. Particles can break up in the regions of the beam where as a result of self-focusing the intensity of the radiation is appreciably higher than I_0. The numerical results show that the temperature of the particles can rapidly reach $T_0 \sim (3 \ldots 5) \cdot 10^3$ K, and thereby lead to breakup of the particles.

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