EFFECT OF NONLINEAR SCATTERING ON THE TRANSPARENCY DYNAMICS OF BURNING AEROSOL IN A LASER FIELD

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The attenuation of laser rdiation by burning particles and by induced thermal and gas aureoles is investigated theoretically.

In the optical probing of aerosols of carbon origin, such as smoke, soot, etc., by means of strong laser sources, the problem arises of determining the radiation energy loss with an allowance for the particle combustion processes and nonlinear (aureole) scattering. The aureole scattering angles in a carbon aerosol were calculated in [1]. The thermal aureole contribution to the laser radiation attenuation by burning carbon particles was considered in [2] under the assumption of a linear temperature dependence of the thermal conductivity of air. However, the temperature dependence of the thermal conductivity at T = 1000-4000°K is essentially nonlinear. If the actual temperature dependence is taken into account, the results of our calculations differ from the data given in [2] by a factor of more than 1.5-2.

Using the actual temperature dependence of the thermal conductivity of air, we have investigated numerically the attentuation of laser radiation by burning particles and induced aureoles. In the quasistationary approximation, which is realized for the optical action duration $t_u \gg a^2/\varkappa$, $a^2/\varkappa_a$, the temperature field and the field of reagent concentrations in the medium are given by [3]:

$$\operatorname{div}(\mu(T)\,dT/dr)=0,$$
$$\operatorname{div}\left(\frac{D(T)}{k_B T(r)}\frac{dP_i}{dr}\right)=\gamma_i\alpha_4(T)\,f(P_1,\ P_2)/2,\ i=\overline{1,3}, \tag{1}$$
$$\sum_{i=1}^{4}P_i=1,\ \gamma_1=1,\ \gamma_2=1,\ \gamma_3=-2,$$
$$f(P_1,\ P_2)=\begin{cases}P_1/k_B T & \text{for } P_1<P_2,\\ P_2/k_B T & \text{for } P_2<P_1.\end{cases}$$

The boundary conditions for system (1) are

$$T\big|_{r=a}=T_s,\ T\big|_{r=\infty}=T_0,$$
$$D\left.\frac{dP_i}{dr}\right|_{r=a}=\begin{cases}(\alpha_1+\alpha_2)P_s & \text{for } i=1,\ r=a,\\ -\alpha_1P_s-\alpha_3P_3 & \text{for } i=2,\ r=a,\\ \alpha_3P_3-\alpha_2P_s & \text{for } i=3,\ r=a.\end{cases} \tag{2}$$

The surface temperature of a particle T_S is found from the thermal balance equation and is considered to be known in subsequent calculations [3]. The nonlinear equation for the refraction index n(r) is obtained from the Lorenz–Lorentz relationship:

$$n(r)=1+4\pi\sum_{i=1}^{4}P_i\beta_i/k_B T(r). \tag{3}$$

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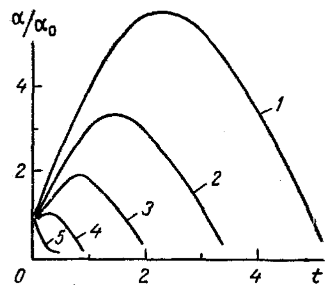

Fig. 1. Relative volumetric attenuation factor α/α_0 as a function of the time t (sec) for $I_0 = 2.4 \cdot 10^8$ W/m² and different values of the initial radius of monodisperse aerosol particles. 1-5) a_0 = 10, 8, 6, 4, and 2 μm, respectively.

In the "soft" particle approximation $|n^2 - 1| \ll 1$, and a small lead of the wave phase, $\int_a^\infty (n^2 - n_\infty^2)\, kdr \ll 1$, the efficiency factor of light scattering on optical nonhomogeneities is given by [4]

$$k_{os} = \frac{k^2a^2}{4} \int_0^\pi \left(1 + \cos^2\Theta d\cos\Theta \left[\int_1^{R(t)/a_0} (n^2(z) - n_\infty^2)\, z \times \right.\right. \tag{4}$$
$$\left. \times \sin(2ka_0 z \sin(\Theta/2))/\sin(\Theta/2)\, dz \right]^2 .$$

Here, $z = r/a_0$, and R(t) is the aureole radius which satisfies the differential equation [2]

$$\frac{dR^3(t)}{dt} = 3\frac{d}{dt}\left(\int_0^t a^2(t)(k_n I + 4K_s(a,\ T_s)Q dt)\right) \Big/ 4\rho c_p (T - T_0) \tag{5}$$

for the initial condition $R(t = 0) = a_0$. Here, Q is the total thermal effect of the complex of chemical reactions $2C + O_2 \rightarrow 2CO + q_1$, $C + O_2 \rightarrow CO_2 + q_2$, $CO_2 + C \rightarrow 2CO + q_3$, and $2CO + O_2 \rightarrow 2CO_2 + q_4$.

In the single scattering approximation, the change in the transparency of the gas-dispersion medium satisfies the following system of equations:

$$\frac{dI}{dz} + \alpha I = 0,$$

$$\alpha(a,\ z,\ t) = \pi a^2(t)(k_{att} + k_{os}) N,$$

$$\frac{da}{dt} = -K_s(T_s,\ a)/\rho c$$

for the boundary conditions $a(t = 0) = a_0$ and $I(z = 0) = I_0$. Numerical calculations were performed for carbon particles with radii of 1-10 μm, using intensities from $I_0 = 2.4 \cdot 10^8$ W/m² to $I_0 = 10^9$ W/m², $\lambda = 10.6$ μm, and $N = 10^8$ m⁻³.

Calculations indicate that aureoles are formed primarily at the expense of the energy absorbed by particles from the external laser field. The maximum contribution to thermal aureole formation by the combustion reaction does not exceed 7%; it is greatest near the ignition point. Figure 1 shows the calculation results pertaining to the dynamics of the relative volumetric factor of radiation attenuation by particles with radii of 2-10 μm. Calculations show that the action of radiation on particles with a radius $a_0 \geq 4$ μm causes the aerosol to become turbid (its transparency is reduced) over a fairly long period of time, which is due to the rapid aureole growth and the predominant influence of aureole scattering on the total attenuation. After a certain time, as a result of a reduction in the geometric cross section of a burning particle, the total attentuation factor diminsihes, which, in the final analysis, leads to a clearing of the gas-dispersion medium. For particles with a radius $a_0 \leq 2$ μm, the thermal self-stress does not cause the turbidity in the medium (Fig. 1, curve 1). Calculations also show that variation in the radiation intensity alters the

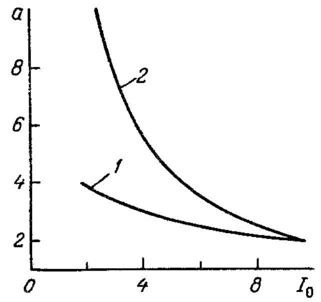

Fig. 2. Upper limit of the combustion region where evaporation is not accounted for (2) and dependence of the threshold particle radius a_0 (μm) on the intnesity I_0 (W/m²) (1).

threshold radius of particles beyond which turbidity of the medium does not set in with laser action, so that clearing occurs immediately (Fig. 2, curve 2). Curve 1 in Fig. 2 bounds the region of combustion conditions where evaporation is neglected.

NOTATION

x and x_a, thermal diffusivity of air and of the particle material, respectively; a and a_0, present and initial particle radius, respectively; μ(T), thermal conductivity of air; D(T), diffusion coefficient; k_B, Boltzmann constant; T, temperature of the medium; r, present coordinate; $\alpha_j(T_s)$, chemical reaction rates; P_s, partial pressure of oxygen at the particle surface; P_i, partial pressure of the reagents; β_i, polarizability coefficients; k, wave number; θ, scattering angle; n_∞, reflection index of the unperturbed medium; c_p and ρ, isobaric specific heat and density of air, respectively; I, radiation intensity; k_n, efficiency factor of light absorption by particles; $K_s(a, t_s)$, rate of particle combustion; q_j, thermal effect of the chemical reaction; k_{att}, efficiency factor of radiation attenuation by particles; α, volumetric factor of radiation attenuation by particles and by the aureole; α_0, volumetric attenuation factor of unperturbed aerosol; ρ_c, carbon density; λ, wavelength. Subscripts: i = 1, oxygen; i = 2, carbon monoxide (CO); i = 3, carbon dioxide; i = 4, nitrogen; j = 1, 2, 3, 4.

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