TRANSMISSION OF A LASER PULSE THROUGH A SOOT AEROSOL

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The transmission of a laser pulse through a soot aerosol consisting of submicron particles was investigated. It was found that the aerosol is significantly cleared as a result of collective combustion of the particles and removal of the particles from the region of the beam by the expanding heated air. An equation for the energy density is derived for arbitrary parameters of the beam and aerosol. The results of the solution of the equation are in good agreement with the experimental data.

In Refs. 1–5, which are devoted to the study of the transmission of laser beams through a soot aerosol, it was found that the clearing and turbidity of the aerosol depend on both the intensity of the radiation and the sizes of the carbon particles. The clearing of the aerosol, which was accompanied by intense glowing of the particles, was of an inertial character.[3]

In this paper the clearing of a soot aerosol by a laser pulse with width $\tau_p \sim 10$ s and energy 30–120 J at the wavelength $\lambda = 1.06$ μm is studied. The aerosol was produces by burning machine oil in a chamber with length $L = 20$ cm and it consisted of submicron-size particles.[6] The radiation source was a GOS-301 laser and the radiation detectors were IMO-2 and IKT-1M energy meters. The laser beam was formed with the help of lenses with different focal lengths and it was cut off along the edges at the inlet into the chamber with a diaphragm 1.3 cm in diameter. The energy distribution in the transverse cross section of such a beam was close to rectangular. The temporal shape of the envelope of the pulse was recorded with an F-23 photoelectric cell, onto whose glass plate part of the energy of the laser beam was diverted at the chamber outlet and was recorded on the screen of a storage oscillograph.

Significant clearing (up to ~ 70% of the total optical thickness) was observed in the experiments. The clearing depth was determined from the formula

$$\Delta\tau = \tau - \ln E_0/E, \tag{1}$$

where τ is the initial optical thickness of the aerosol, E_0 is the energy of the laser beam at the outlet of a clean chamber, and E is the energy at the outlet from the aerosol layer. In Fig. 1 the measured values of $\Delta\tau$ measured for parallel and focused beams are plotted as dots. The measurement error, owing primarily to the instability of the optical line, was equal to ~ 30% of the absolute value of the measured quantity. The dynamics of the development of the clearing process, which is illustrated by Fig. 2 where curve 1 is the envelope of the initial pulse and curve 2 is the envelope of the pulse transmitted through an aerosol layer with $\tau = 4.6$.

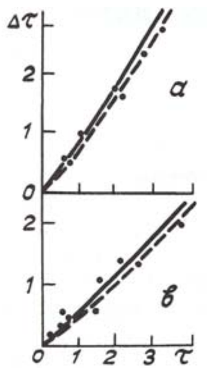

FIG. 1. The clearing depth of a soot aerosol versus the optical thickness of the aerosol (the experimental data are plotted as dots; the solid curves were computed taking into account the combustion of the particles; the dashed curves were computed neglecting the combustion of the particles; a) parallel beam, $\Phi = 120$ J/cm², b) focused beam, $\Phi = 33$ J/cm², $F = 4$ cm).

FIG. 2. The temporal shapes of the laser pulse envelope with $\Phi = 40$ J/cm² at the outlet of a clean chamber (1) and for a laser pulse transmitted through an aerosol with $\tau = 4.6$ (2, 3). The solid curves are the experimental dependences and the dashed curve is the computed dependence.

The radiation absorbed by the particles heats up the surrounding medium. Particles can be removed from the beam owing to expansion of the heated air. To calculate the clearing of the aerosol by the removal and burning of the particles[7] we shall study the following equations. In Ref. 7 it is shown that the equations of adiabatic heating of the air

$$c_p \, \rho \, \frac{\partial T}{\partial t} = \alpha\omega \tag{2}$$

applies and the aerosol absorption coefficient a is related with the aerosol density ρ and the function g

$$\alpha = \frac{\alpha_0}{\rho_0} \rho g \tag{3}$$

(c_p and T are the heat capacity and temperature of the air and ρ_0 and α_0 are the initial density and absorption coefficient of the aerosol). The function g accounts for the fact that a varies as the particles burn, initially it is equal to unity, and it has form

$$g = \int_0^\infty \frac{\pi}{\alpha_0} R^2 K_a(R) \, n(R) \, dR, \tag{4}$$

where K_a is the absorption efficiency factor and n is the particle size distribution function. Since the pressure equalization time

$$t_s = a/\upsilon_s \approx 2\cdot10^{-5} \text{ s} \ll t_p = 10^{-3} \text{ s} \tag{5}$$

(υ_s is the velocity of sound), in the equation of state of the gas

$$p = \rho R_a T \tag{6}$$

the pressure p is a constant (R_a is the specific gas constant of air). In this case Eq. (6) determines a single-valued relation between the air density ρ and the air temperature T.

We shall derive the radiation transfer equation for a focused beam, making the assumption that the focal length of the lens F is much greater than the radius of the beam at the chamber inlet a_0 ($z = 0$). The power P of a beam whose transverse cross-sectional area is S and which is Bouguer-attenuated over the distance $z + dz$, can be written as

$$P(z + dz) = \omega(z + dz)\, S(z + dz) = \omega(z) S(z)\, e^{-\gamma(z)dz}, \tag{7}$$

where γ is the aerosol extinction coefficient, which is related with α by the dependence

$$\alpha = u\,\gamma \left(u = \int_0^\infty \pi R^2 K_a(R) n \, dR \Big/ \int_0^\infty \pi R^2 K_{ex}(R) n \, dR,\right.$$

K_{ex} is the extinction efficiency factor). Taking into account the diffraction divergence of the beam the area of the transverse cross section of the beam satisfies the relation

$$\frac{S(z + dz)}{S(z)} = \frac{[1 - (z + dz)/F]^2 + D^2(z + dz)}{[1 - z/F]^2 + D^2(z)}, \tag{8}$$

where $D(z) = 2z / ka_0^2$ is the dimensionless diffraction length (k is the wave number).[8] Substituting Eq. (8) into Eq. (7) and expanding the expression obtained up to first order infinitesimals we arrive at the equation

$$\frac{\partial\omega}{\partial z} + \left[\gamma(z,t) - 2\,\frac{F - z - 4F^2 z/(ka_0^2)^2}{(F - z)^2 + 4F^2 z^2/(ka_0^2)^2}\right]\omega(z,t) = 0 \tag{9}$$

The system of equations (2), (3), (6), and (9) describe the passage of a laser pulse through the aerosol. By means of a series of substitutions and transformations this system can be reduced to an equation for the energy density

$$\Phi(z,t) = \int \omega(z,t)\,dt : \frac{\partial\Phi}{\partial z} + \frac{pc_p}{uR_a} \ln\left[1 + \frac{\alpha_0 R_a}{pc_p}\int_0^t \omega g \, dt\right] -$$

$$- 2\,\frac{F - z - 4F^2 z/(ka_0^2)^2}{(F - z)^2 + 4F^2 z^2/(ka_0^2)^2}\Phi = 0, \tag{10}$$

which is valid for a focused beam with a transverse intensity distribution $\omega = \omega(r, z)$ (z is the distance from the axis of the beam). The function ω is self-similar as a function of the distance. This condition was satisfied in the experiments performed, in which the intensity distribution in the beam remained rectangular over the length of the chamber $L = 20$ cm.

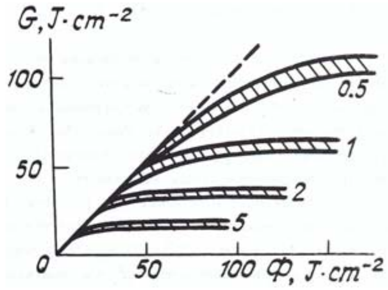

FIG. 3. G versus the energy density Φ (the numbers on the curves are the optical thickness of the aerosol τ and the broken line corresponds to G = Φ).

The equation (10) can be solved exactly only if the time dependences of the particle radii at each point along the beam are calculated simultaneously, since the function g enters into the equation. Figure 3 shows the results of the calculation of the integral $G = \int^t \omega g dt = G(\Phi)$, which is proportional to the radiation energy absorbed by the aerosol, for the dependences $\omega = \omega(t)$ corresponding to the temporal envelopes of the laser pulse shown by the curves 1 and 2 in Fig. 2 as well as a rectangular pulse. The hatched regions in the graph show the spread in the computed values of G. With an error of not less than 4% different temporal forms of the pulse give practically the same dependence $G = G(\Phi)$. This makes it possible to solve Eq. (10) independently of the equations for particle radii. The dashed line corresponds to the case of nonburning particles ($g = 1$, and $G = \int^{t} \omega dt = \Phi$. The function G reaches its asymptotic value when the particles are completely burned up. For a parallel beam the last term in Eq. (10) vanishes and the equation reduces to the quadrature

$$\int_{\Phi(z,t)}^{\Phi(0,t)} \frac{h d\Phi}{\ln\left[1 + hG(\Phi)\right]} = \gamma_0 z, \qquad (11)$$

where $h = \alpha_0 R_a/(\rho c_p)$.

Since in the experiments the energy density in the transverse cross section of the beam was constant the computed value of the clearing depth was found in the form

$$\Delta\tau = \tau - \ln \bar{\Phi}(L,\ t_p) \,/\, \Phi(L,\ t_p), \qquad (12)$$

where $\bar{\Phi}(L,\ t_p)$ is the energy density at the outlet of the chamber with no aerosol and $\Phi(L,\ t_p)$ is the energy density at the outlet from the aerosol layer. The results of the calculations of Лτ are shown in Fig. 3 (solid curves). The good agreement between the experimental and theoretical results proves the validity of the proposed model in which the aerosol is cleared as a result of the collective burning of particles and their removal from the beam by the expanding air.

To evaluate the effect of the burning on the clearing depth we calculated $\Delta\tau$ for a nonburning aerosol (Fig. 3, broken curve). The small discrepancy between the theoretical dependences $\Delta\tau = \Delta\tau(\tau)$ for the burning and nonburning aerosols is not an indication that burning plays an insignificant role in the clearing process. Burning of the particles diminishes the absorption of radiation by the aerosol, which, in its turn, diminishes the heating of the air and its expansion.

We also studied clearing mechanisms such as removal of particles owing to light pressure, coagulation of particles, photophoresis, and vaporization of particles. We found that these effects cannot make an appreciable contribution to the clearing observed in the experiments.

The equation (10) makes it possible to calculate any temporal and spatial characteristics of the beam and aerosol. Curve 3 in Fig. 2 shows the computed time dependence of the radiation intensity at the outlet from the aerosol layer.

Particle removal can be significant in a quite dense aerosol. Assuming that clearing occurs when $\Delta\tau/\tau > 0.1$, we calculated the threshold of the clearing regime (shown in Fig. 4). The obtained threshold is approximately described by the relation $\Phi\alpha \approx 0.1$ with the units shown in the figure. As found in the calculations, the collective burning of the particles is significant for higher values of Φ, when the temperature of the particles reaches ~ 1000 K. For $\Phi \lesssim 3$ J/cm^2 there is virtually no clearing of the aerosol. The energy density $\Phi \approx 1000$ J/cm^2 with pulse width $t_p \approx 10^{-3}$ s corresponds to radiation intensity $\omega \approx 10^7$ W/cm^2, at which breakdown can develop in air containing aerosol particles. It should be noted that the results presented in Fig. 4 are valid when the inequality (5) is satisfied; this inequality gives a maximum beam diameter of ~ 15 cm.

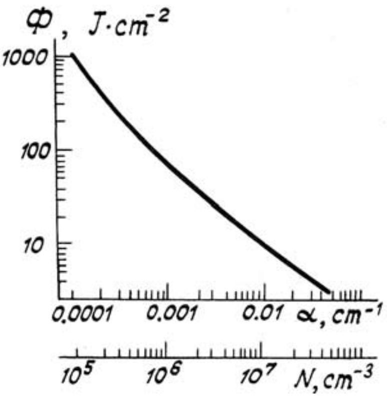

FIG. 4. The threshold of particle removal from the laser beam.

All the results obtained here for a soot aerosol are applicable for any other combustible and noncombustible absorbing aerosol.

In summary, we can conclude that a soot aerosol irradiated with a laser pulse is cleared by means of removal of particles from the beam expanding heated air and collective burning of the particles.

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