COMBUSTION OF SHOOT PARTICLES DURING PROPAGATION OF LASER BEAMS THROUGH A TURBID ATMOSPHERE

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Received September 5, 1989

We study the combustion of soot particles under conditions where the thermal fields overlap. We also derive the equations for the time variation in the particle radius, particle temperature, and average air temperature in the vicinity of the beam. We find that complete combustion of the carbon particles can occur in a dense aerosol.

Gordin, et al.[1] have shown that the large energy losses to the environment due to heat conduction mean that combustion of isolated submicron-size soot particles upon exposure to a laser beam virtually ceases once the particles reach a certain critical radius which depends on the light Intensity. However, in situations where the aerosol density is high ($N \geq 10^5$ cm^{-3}), the temperature fields of the individual particles may overlap, leading to a reduction in the outflow of heat from the particles and allowing the particles to heat up more thoroughly. This change in heat outflow may be taken into account by introducing the mean aerosol temperature T, which may be determined using the adiabatic heating equation for air:

$$c_p \rho \frac{\partial T}{\partial t} = \alpha \omega, \tag{1}$$

where c_p, ρ, and $\alpha$are the heat capacity, density and absorption coefficient of aerosol, and ω is the intensity of the radiation. Equation (1) is valid under conditions where the time scale for heat loss from the region occupied by the beam $t = c_p \rho a^2 / 4\lambda_{air}$ (where a is the radius of the laser beam and λ_{air} is thermal conductivity of air) is much greater than the duration of the pulse. The parameters using in the present paper for the aerosol and laser beam correspond to the conditions used in the experiments involving the exposure of a sooty aerosol to a pulse of duration $t_p \approx 10^{-3}$ s at $\lambda = 1.06$ μm. Since Eq. (1) is therefore valid for $a \geq 0.1$ cm, as observed in the experiments. Since the mass ratio of soot particles in air did not exceed 0.001, the aerosol density ρ may be assumed equal to the air density. In this case, the absorption coefficient of the aerosol, α is the connected to ρ and the function g (which takes the combustion of the particles into account) via the following relation:

$$\alpha = \frac{\alpha_0}{\rho_0} \rho g \tag{2}$$

(ρ_Q and α_Q are the initial density and absorption coefficient of the aerosol). The quantity ρ takes into account the variation in a due to expansion of the aerosol, and g takes into account the variation in a due to combustion of the particles:

$$g = \int_0^\infty \pi R^2(t) K_a(R(t)) n(R) \, dR / \alpha_0, \tag{3}$$

where R is the particle radius, K_{abs} is a factor which describes the efficiency of absorption, n is the particle size distribution function, and $g(t = 0) = 1$. Substituting Eqs. (2) and (3) into Eq. (1) and integrating, we obtain the expression for T

$$T = T_0 + \frac{\alpha_0}{c_p \rho_0} \int_0^t \omega g \, dt. \tag{4}$$

Substituting the temperature given by Eq. (4) rather than the constant T_Q into Eqs. (3) –(4) of Gordin, et al.,[1] we obtain the following system of equations describing the variation in the radius R and temperature T_{abs} of the burning soot particle (taking the heating of the medium in the vicinity of the beam into account):

$$R' = -31.6 \frac{M_C}{M_{CO}} \frac{1}{\rho_C} \exp\left[\frac{W}{R_r}\left(\frac{1}{1240} - \frac{1}{T_v}\right)\right] \frac{C(T_v)P}{R_a T_v}, \tag{5}$$

$$\frac{4}{3}\pi R^3 c_C \rho_C T'_v = -4\pi R^2 Q \rho_C R' - 4\pi R^2 \frac{T_v - T}{R} \lambda_m \times \times \left(\frac{T_v + T}{2}\right) + \pi R^2 K_a(R) \omega(t), \tag{6}$$

where ρ_c and c_c are, respectively, the density and heat capacity of carbon; Q is the heat of combustion; W is

0235-6880/90/02 187–03 $02.00

the activation energy; R_g is the universal gas constant; R_{air} is the specific gas constant of air; P is the atmospheric pressure; M_C and M_{CO} are the molecular weights of carbon and carbon monoxide, respectively; K_{abs} is the absorption efficiency factor, $C(T)$ is the relative oxygen content; λ_{mix} is the thermal conductivity of the gaseous mixture surrounding the particle, which is described by the following formula as a function of temperature:

$$\lambda_m(T) = \lambda_m(T_0) \cdot [1 + b \cdot (T - T_0)] \quad (7)$$

($b = 2.7 \cdot 10^{-3}\ K^{-1}$). In Eq. (6), vie have dropped the terms describing the losses due to the radiation emitted by the particles themselves in addition to terms describing the losses due to particle evaporation. The contribution of thermal emission from the particles to the overall heat balance was at most 0.2%, and the losses due to particle evaporation only become noticeable at temperatures greater than ~ 4000 K. An estimate of the time required for the energy absorbed by a particle with $R = 0.1$ μm to be lost to the surrounding medium, $t_s = R^2\rho_c c_c/3\lambda_{air} \approx 0.6 \times 10^{-6}$ s, indicates that this time is much smaller than either the duration of the pulse ~ 10^{-3} s or the time for the radiation Intensity to reach its peak value ~ $2 \cdot 10^{-4}$ s.

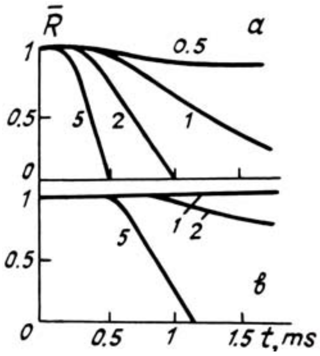

FIG. 1. Relative radius $\bar{R} = R/R_0$ as a function of time for a soot particle with initial radius $R_0 = 0.15$ μт [a) $\Phi = 100$ J/cm^2; (b) $\Phi = 30$ J/cm^2; the numbers adjacent to each curve indicate the initial aerosol optical depth τ].

The fact that $g(t)$ depends on the radius of each aerosol particle means that we must solve a large number of simultaneous equations. The resulting complexity may be lifted by introducing a mean radius R_{av} satisfying the equation

$$\pi R_m^2 K_v(R_m) N = \int_0^\infty \pi R^2 K_v(R) n(R)\, dR = \alpha_0. \quad (8)$$

An exact calculation indicates that the error in g(t) due to this approximation is no greater than ~ 7%. When the function $g = g(t)$ is known, the process of determining the parameters for particles of any size reduces to solving Eqs. (4)–(7).

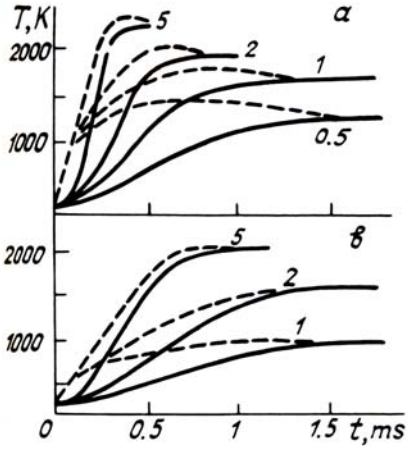

FIG. 2. Particle temperature (dashed lines) and mean aerosol temperature (solid lines) as a function of time. The parameters of the particle, the aerosol, and the laser pulse are as per Fig. 1.

Figures 1 and 2 show the particle radius, particle temperature, and mean aerosol temperature T as a function of time for a particle of initial radius $R_0 = R_{av} = 0.15$ μm. For energy density $\Phi = \int_0^t \omega(t)dt = 100$ J/cm^2 and optical depth $\tau < 2$, we have complete combustion of the particles within the time over which the pulse acts, in contrast to the case where the heat from the particle flows off into the surrounding medium, with the initial temperature T_Q unchanged. The particle temperature does not decrease to its initial value, but increases to the same level as the mean aerosol temperature.

This theoretical representation of the particle combustion mechanism in principle explains the large brightening of sooty aerosol when it is exposed to pulses of laser light.[2]

REFERENCES

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2. Yu.N. Grachev and G.M. Strelkov, in*: Abstract of Papers at the 3rd All-Union Conference on the Propagation of Laser Light in Dispersed Media,* Part 4, Obninsk (1985), pp. 157–160.