DIAGNOSTICS OF THE THERMAL HALOS SURROUNDING PARTICLES BURNING AT REDUCED ATMOSPHERIC PRESSURE

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The optical disturbance of a medium in the vicinity of an isolated aerosol particle of soot, burning in the field of powerful CO_2 laser radiation at reduced atmospheric pressure, was studied experimentally with the help of a shearing interferometer. It is shown that the conductive heating of the medium makes the main contribution to the optical disturbance. The rate of growth of the thermal halo increases as the air pressure decreases. A formula is proposed for describing the appearance and development of thermal halos in a limited time interval prior to the appearance of convection.

The interaction of a powerful laser beam with a solid burning aerosol particle is accompanied by the formation of heat and mass halos around the particles.[1] These halos significantly affect the character of the propagation of the radiation. To model the propagation of powerful laser radiation in aerosols at reduced pressure of the surrounding medium, for example, in the upper layers of the atmosphere, it is necessary to have information about the heat and mass halo of separate particles under such conditions. The purpose of this work is to study experimentally the optical characteristics of heat and mass halos arising around carbon aerosol particles, burning in the intense optical field of a CO_2 laser under conditions of a low vacuum, i.e., at pressures P ranging from normal atmospheric pressure up to $P \sim 1.3 \cdot 10^2$ Pa, (Ref. 2).

The dynamics of the index of refraction of the heat and mass halos were studied with the help of a shearing interferometer[3] in which the interference pattern was filmed. A diagram of the experimental arrangement is shown in Fig. 1. A spherical soot particle 7 (containing ~ 99% carbon) was placed on the upper top end face of a quartz filament, positioned vertically in the vacuum chamber 22. Glass plates 16 and 17 were used as windows for the probing helium-neon laser 1 radiation with wavelength $\lambda = 0.63$ μm. The input window 6 for the high-power heating radiation was made of cesium iodide for maximum transmission of a beam from a CO_2 laser 2 of the LG-25B type with 2 nominal power $N = 25$ W and wavelength $\lambda = 10.6$ μm. All experiments were performed with the maximum possible intensity I of the heating radiation for the given type of laser when halo effects were clearly pronounced. In the region of particle the value of I was equal to $2 \cdot 10^7$ W/m^2. The vacuum in the chamber was created with a vacuum pump 8 and monitored with a manometric vacuummeter 9 with an error of not more than 15%. The probe radiation, directed with the help of the mirrors 12 and 13, the microobjective lens 14, objective lenses 15, 18, and 19, with long focal lengths, and a wedge-shaped glass plate 20 on the object under study, entered the objective lens 21 of a SKS-1M high-speed motion picture camera. The CO_2 laser radiation was focused with an NaCl lens 5 with a focal length $f = 10$ cm. The diameter of the focusing spot was equal to 0.8 mm. It was determined by recording on the motion picture film the burning of the asbestos plate placed at the location of a particle followed by photometric measurements on the negative. To mark the start of the location of the high-power radiation on the particle part of the beam from the helium-neon laser directed with the help of a beam-splitting plate 10 and a mirror 11 into the motion picture camera. When the shutter 3 is actuated (it moves from the position a to the position a' in Fig. 1) the CO_2 laser beam is uncovered and at the same time the radiation from the helium-neon laser, reflected from the plate 10, is covered. This moment is recorded on the motion picture film. The speed of the electromagnetic shutter was equal to 0.6 msec.

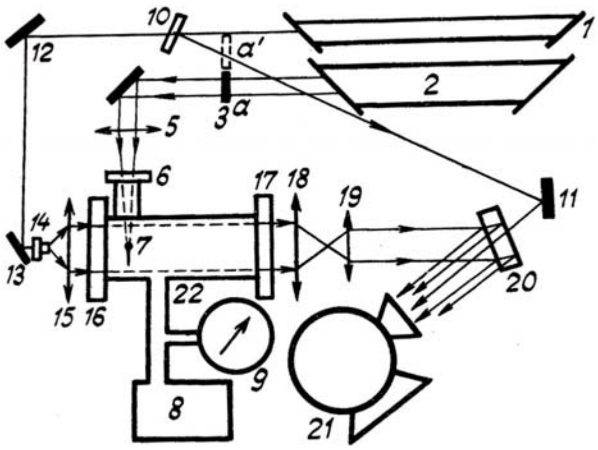

FIG. 1. Block diagram of the experimental arrangement.

The heat and mass halos were studied for particle with an initial radius $r_0 \sim (100–300)$ μm. The radiation was directed onto the particle from above along the axis of the quartz filament. This made it possible to create an axisymmetric phase object.

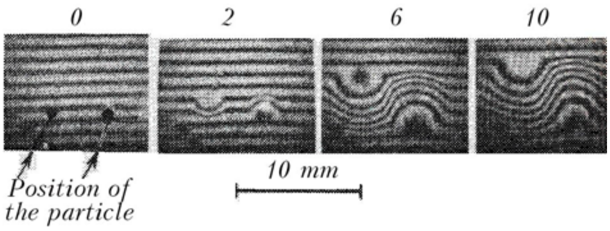

FIG. 2. The dynamics of the heat and mass halos of a particle with a radius of 150 μm *at a pressure $P = 1.014 \cdot 10^{-5}$ Pa. The numbers indicate the time in milliseconds from the start of the laser action. The radiation is incident on the particle from above. The position of the particle is marked in the first frame.*

Interference motion pictures, characterizing the dynamics of the heat and mass halos, are presented in Fig. 2. The double image of the object is caused by the constructional features of the shearing interferometer[3] which creates two mirror-symmetric patterns. In the experiments it was found that the rate of growth of the heat and mass halos increases as the pressure decreases. The results of these measurements for different pressures are presented in Fig. 3.

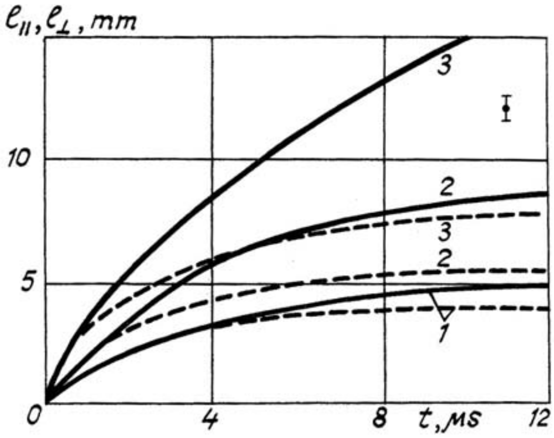

FIG. 3. The time dependence of the vertical $l_\parallel$ (solid line) and horizontal $l_\perp$ (broken curve) dimensions of the thermal halo of burning particles *at different pressures $P = 1.011 \cdot 10^5$ Pa (1), $P = 6.946 \cdot 10^4$ Pa (2), and $P = 4.053 \cdot 10^4$ Pa (3). $R = 180$* μm.

In Fig. 3 the dependence $l_\parallel(t)$ corresponds to the growth of a halo owing to convection and heat conduction, while $l_\perp(t)$ is determined solely by heat conduction. It is also observed that the form of the heat and mass halos is nearly spherical at the start of the laser action, and in addition as the pressure decreases the asphericity of the process is manifested more quickly (see Fig. 3). An explanation of the spherical symmetry of heat and mass halos at the start of the process is given in Ref. 4. It consists of the fact that when the particle starts to burn heat conduction plays a larger role than convection, after which convection predominates.

Figure 4 shows the time dependence of the index of refraction n of the surrounding medium at a point located at a distance $r = 10\ r_0$ from the center of the particle in the horizontal plane. The values of n were calculated from interferograms using Abel's equation.[5]

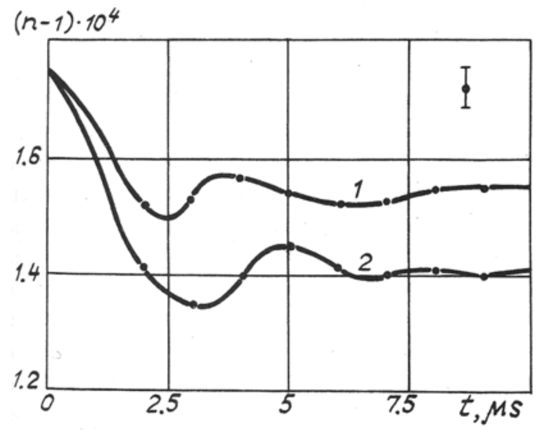

FIG. 4. Experimental dependence of the index of refraction n of the medium on the time t with pressure $P = 6.946 \cdot 10$ Pa. Curve 1 corresponds to a particle with radius $r_0 = 100$ μm *and curve 2 corresponds to $r_n = 250$* μm.

The temperature at which the carbon starts to evaporate from the surface of the particle under conditions of a low vacuum is $T \sim 3400$ K.[6] In our experiments the intensity of the acting radiation was too low to achieve such high temperatures, so that the particle burned. In this case the gradient of the index of refraction around the particle appears as result of conductive heating of the medium as well as the appearance of products of combustion. The main products of combustion of the carbon particle are CO and CO_2, whose refractive indices are different from that of air. We shall estimate the contribution of CO and CO_2 to the index of refraction n with the help of the data from Ref. 7 on the values of the partial pressures of CO, CO_2, and O_2 around a burning particle with radius $r_0 = 100$ μm. The calculations show that at a distance $r \sim 2.8\ r_0$ in the region of maximum CO_2 concentration the change in the value of $(n \sim 1)$ of air does not exceed 5%, while heating changes $(n\sim 1)$ by approximately 70%. This shows that heat and mass halos are caused primarily by conductive heating of the medium. For this reason, in what follows we shall employ the term "thermal halo". The relation between the index of refraction field $n(r, t)$ and the temperature field $T(r, t)$ under conditions of spherical symmetry can be written in the form[8]

$$n(r,\ t) = T_0(n_0-1)/T(r,\ t), \tag{1}$$

where r is the distance from the center of the particle; t is the time; and, T_0 and n_0 are, respectively, the temperature and index of refraction of cold air.

To determine the field $T(r, t)$ we shall write the nonstationary heat-conduction equation in the spherically symmetric case[9]

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \lambda_c \frac{\partial T}{\partial r}\right], \tag{2}$$

where ρ, C_p, and λ_c are, respectively, the density, the heat capacity, and the thermal conductivity of air. It is shown in Ref. 10 that if the boundary conditions $T(r, 0) = T_0$ and $T(r_0, t) = T_0 + kt$, where k is the rate of growth of the temperature of the surface of the particle before a quasistationary state is established, are used, then Eq. (2) can be solved analytically. The solution is valid for the initial period of burning, when the thermal halo is spherical and has the form

$$T(r,\ t) = T_0 + r_0 kt F(z)/r, \tag{3}$$

where

$$F(z) = 2\cdot\left\{[1-\Phi(z)]\cdot(1+z^2) - z\frac{\exp(-z^2/2)}{\sqrt{2\pi}}\right\},$$

$$z = \sqrt{(r-r_0)^2 C_p \rho/(2\lambda_c t)}\ ;$$

$\Phi(z)$ is the normal distribution function. According to the data of Ref. 11 the quantity k is virtually independent of the pressure of the medium under the conditions of a low vacuum and for our case $k \simeq 1.7 \cdot 10^5$ K/s.[4]

In order to give a physical explanation for the more rapid growth of the thermal halo as the pressure decreases we shall determine the position of its boundary with cold air l_b from the where condition $F(z)$ 0. The function $F(z)$ decreases rapidly as r increases; for example, already at $z = 5$ $F(z) \sim 10^{-7}$. Let l_b □ $r_0 + z'\sqrt{2\lambda_c t/(C_p\rho)} = r_0 A\sqrt{t/\rho}$, where z' and A are constants (since $\lambda_c \neq \Lambda(P)$ and $C_p \neq C_p(P)$ under the conditions of a low vacuum[12]). From the last estimate it is evident that l_b □ $1/\sqrt{\rho}$, i.e., as the pressure of the medium decreases the size of the thermal halo increases. Comparing the experimental data with the calculations, performed by the method proposed in Ref. 10, showed that the formulas (1) and (3) describe satisfactorily the appearance and development of thermal halos in a limited time interval before the start of convection.

We were not able to record thermal halos experimentally at pressures $P < 10^4$ Pa. This indicates that the halos rapidly vanish and the interferometer is not sensitive enough to record the object under study.

Therefore for laser radiation power densities $I \leq 10^7$ W/m^2 the effect of the scattering by the halo on thecharacter of the propagation of a high-power optical beam decreases as the pressure decreases.

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