A PARTICLE OF A COARSE DISPERSE AEROSOL IN HIGH–POWER LIGHT FIELD: INFLUENCE OF THE INITIAL CHARACTERISTICS OF A PARTICLE ON THE DEVELOPMENT OF A LOCAL PERTURBATION OF AMBIENT AIR

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This paper presents some results of a physical experiment on interaction between a high power laser radiation and an isolated particle of solid aerosol (soot, coal, and SiO_2). It is shown that an irradiated volume filled with burning fragments is an optically active core in the region of a local perturbation of a medium.

The propagation of powerful laser radiation (PLR) in dusty atmosphere must occur with a number of nonlinear optical effects, which develop owing to absorption of the radiation energy by aerosol particles. The burning carbon particles causing the thermodynamic local perturbation of a medium during their interaction with powerful laser radiation is one of the most low–threshold nonlinear effects. Around the particle interacting with PLR the thermodynamic and optical parameters of ambient medium change. Appearing gradients of refractive index are determined by a number of factors, namely, processes of heat and mass transfer,[1,2] particle fragmentation,[1,3–5] homogeneous combustion reaction of the carbon monoxide and hydrogen,[6,7] and appearance of convective flows.[8] A rich variety of works is devoted to the influence of halo diffusion on extinction coefficient of aerosol medium. These results are accumulated in Ref. 2. However, experimental study of such aspects as energy thresholds, mechanisms of formation, size and shape of the optical perturbation region around aerosol particles, and dynamics of the process had received little attention.[9–12] The reason is in the serious methodological difficulties; it is impossible to illustrate directly process of the optical perturbation development around aerosol particles which dominate the real atmosphere ($a_0 \le 10$ μm).

Present paper is devoted to experimental study of influence of the initial microphysical characteristics of the coarse–dispersed aerosol particle on appearance of the optical perturbation region in the vicinity of a particle iniciated by PLR.

We used the method of high–speed microfilming as the process recorder for long–duration interaction between PLR and a particle and the method of photographing for the interaction time of no more than 2 ms.

We studied the PLR action on aerosol either by the continuous CO_2 laser radiation, or the pulsed laser radiation with wavelength $\lambda = 1.06$ μm (radiation pulse duration of 10^{-3}s).

The investigation was concerned with two types of aerosol particles, namely, the particles inflaming in high power light field (coal, soot) and noninflaming, refractory ones (SiO_2).

Profiles of the luminance distribution for particles with different composition in horizontal cross–section plane are presented in Fig. 1. The profiles are obtained by photometric scanning of the high–speed microfilming sequences over a particle diameter ($2a_0$). A value of r determines the boundary of the luminance zone near the aerosol particle interacting with PLR. We selected sequences of maximum luminance, which correspond to the quasi–steady temperature conditions of the particle surface (~30 ms from the start of acting). The arrow shows the PLR acting direction. The profiles are sufficiently asymmetric. The maximum of the profiles' symmetry was observed for refractory particles after their surface fusing. The coal particles profile modulation was caused by presence of homogeneous reactions of CO_2 and H_2 combustion around the burning particle.[6,7] During the process of the carbon–bearing particles burnup the ratio r/a_0 increases in shady hemisphere, however, the symmetry remains unattainable. The coal particles' profiles become comparable with those of the refractory particles after coal complete burning out and a slag residium formation. As coal particles burn out the halo luminance dims and the slag residium luminance becomes comparable with the SiO_2 one.

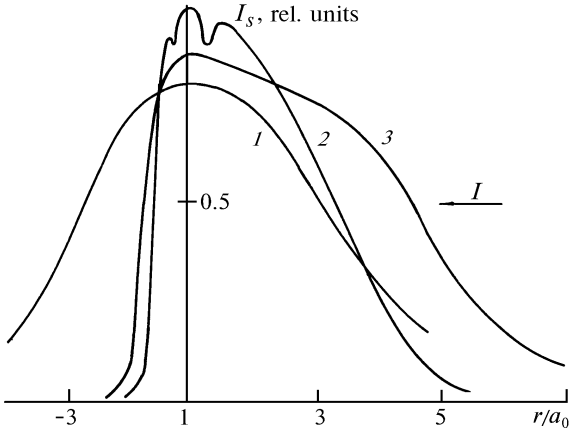

FIG. 1. Distribution of boundaries of luminous region around aerosol particles interacting with PLR, $I = 2.5 \cdot 10^2$ W/cm^2; $a_0 = 50$ μm. SiO_2 particle (1), coal particle (2), and soot particle (3).

The rate of the optical perturbation region expansion around burning particles essentially depends on the radiant exitance I (example of such a dependence is in Fig. 2). The time of particle inflammation in PLR beam is taken as the origin. Points on the graph correspond to values averaged over 5 to 10 realizations. Spread in the obtained values of V is marked by the vertical segments. Final size of luminous halo depends on the radiant exitance, size of particle and PLR beam.

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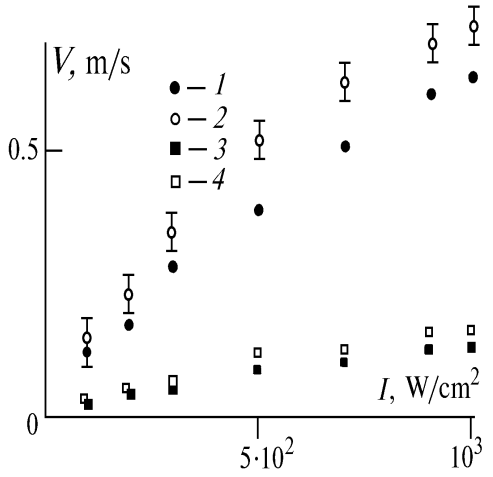

FIG. 2. Rate of boundary expansion of luminous region near burning soot particle for $t = 5 \cdot 10^{-4}$ s (1) and (3), and for $t = 10^{-3}$ s (2) and (4); (1) and (2) correspond to expansion rate from illuminated surface while (3) and (4) correspond to expansion rate from shady one.

The main products of carbon particle combustion, namely, CO and CO_2 have an index of refraction different from that of air. A significant part of a particle volume (particularly, of soot particles) transforms into fragments ($a_f \ll a_0$). An estimation of the possible mechanisms of the optical perturbation origin near burning particle shows that the change of air value $(n - 1)$, owing to increase of partial pressures of combustion gases, at distance $r \sim 3a_0$ ($a_0 \simeq 100$ μm) is no more than 5% (see Ref. 6). Owing to heating of ambient air, $(n - 1)$ changes approximately to 80%. It may be inferred that the optical perturbation near a solid aerosol particle is determined mainly by conductive heating of medium and fragmentation. In accordance with Ref. 11, the shift of boundaries of temperature front from the particle owing to conductive heating and free convection is proportional to $\sqrt{t}$ and t^2. At $t > 10^{-2}$ s the medium perturbations owing to free convection prevail. Under pulsed PLR acting free convection can be neglected.

Stretching of the carbon particles profiles towards the PLR (see Fig. 1) testifies that the theoretical model of spherical symmetric burnup of particles[13] does not hold and this stretching is caused by fragmentation. If to judge perturbation region shape round the soot particle by the fragments velocities, then something like spherical symmetry was observed for large particles ($a_0 \sim 100$ μm) only after the time required to heat the particles up to maximum temperature $t_h \sim \rho^s C_p^s a_0^2 / \mu(T)$ had been passed. Here C_p^s and ρ^s are the heat capacity and the density of particle substance; $\mu(T)$ is heat conductivity of air. According to the experimental data, a particle has essentially burned out by the time t_h ($a \sim 0.2a_0$). For particles with $a_0 \sim 10 \ldots 20$ μm, t_h practically coincides with the inflammation moment, i.e. arising of spherical symmetric burnup must be determined by t_i. Nevertheless, in the experiments we observed one–sided separation of particle substance into fragments and only after $t \sim (2 \ldots 3)\, t_i$ had passed the fragmentation process reached the shady surface of the particle. In these cases the rate of the substance fragmentation is always higher for illuminated surface.

Thus, the optical activity of the perturbation region essentially depends on the presence of burning fragments of initial particle in it. Let us consider the conditions of combustion sustaining for these particles. It is known that the secondary particles ($a_f \sim 1 \ldots 2$ μm) can burn for a some time being unexposed to radiation.[1] Nevertheless, the combustion rate of the unirradiated soot fragments is at least halved (from 0.02 m/s to ≤ 0.01 m/s at $I \sim 2 \cdot 10^2$ W/cm^2). We estimated the combustion rate for small particles by photometric scanning of their traces on a film before and after exposure them to radiation. The irradiation was stopped when a fragment left PLR beam in a time $t \sim 2 \cdot 10^{-4}$ s. In the process the radius of the secondary particle ($a_f \sim 2$ μm) can decrease to 30% (at $I \sim 10^5$ W/cm^2, Ref. 14). At values of PLR radiant exitance less than or equal to 10^3 W/cm^2 one can expect small change of a_f. Consequently, the decrease of combustion rate was caused by disturbance of the particle thermal balance (i.e. external de–energizing). We had revealed the dependence of the secondary particles combustion time on a_0 and I. The estimations of temperature field around the initial particle ($a_0 \sim 100$ μm, $I \sim 2 \cdot 10^2$ W/cm^2) show the ambient air temperature to become comparable with carbon inflammation temperature at distance of radius from the surface. The radiant exitance increase up to $(6 \ldots 7) \cdot 10^2$ W/cm^2 extends the heated zone to $r \sim 3a_0$. Combustion rate of the scattering secondary particles did not change after termination of irradiation until the particles had passed the heated zone.

The conditions of sustaining the secondary coal particles combustion are analogous to those for soot, mentioned above.

The initial stage of development of the optical perturbation region for coal particles is determined by their mineral composition. The coal particle heating causes breaking the bonds between macromolecules of organic part of coal substance. It results in formation of gaseous volatile substances which inflame and burn away at certain temperature ($T \geq 380$ K) in the particle neighborhood. Owing to egress of volatile substances and their rapid oxidation during coal particles combustion, the high–temperature halos are generated. These halos affect the combustion behavior and optical characteristics of the region of local perturbation of a medium. Time of volatile substances combustion $t_v((2 \ldots 80) \cdot 10^{-3}$ s) determines the first maximum in temporal dependence of coal particle surface temperature T_a (Ref. 15), and in its turn depends mostly on a_0. An increase of I does not change the behavior of $t_v(a_0)$, only slightly decreasing its absolute magnitude. The form of $T_a(t)$ changes, i.e., a dip between the first and the main maximums lessens. $T_a(t)$ similarly behaves at constant intensity and increase of a_0. Observed dispersion of t_v values is determined by ash content in coal particles, formed during mechanical processes of the aerosol particle formation. Under equal conditions, rate of the volatile substances egress increases at heating with decrease of particles' size. Determination of ash content, combustion heat, and content of volatile substances for particles with $a_0 \sim 25$ and $a_0 \sim 50$ μm (Ref. 16) had shown that for particles of greater size ash content is 10% less, combustion heat is 2% above, and content of volatile substances is 7% above these characteristics for small particles. We had milled a piece of Ekibastuz coal and had taken three specimens of

particles of fixed size. Ash content in a particle determines size of slag residium a_{sr}. Radiant exitance remained constant ($I = 2 \cdot 10^2$ W/cm^2). Table I gives the averaged values of ratio a_{sr}/a_0.

TABLE I.

a_0, μm	100	50	25
a_{sr}/a_0	0.72	0.75	0.82

One can see from Table I that ash content in particles of $a_0 = 25$ μm increases by 9 ... 13% in comparison with those of $a_0 = 50$ μm.

It is necessary to note the influence of surface relief of particles on time of volatile substances egress. Inflammation starts on microprotuberances on particles surface exposed to PLR. This causes rapid burnup of them and melting of their base. The motion pictures of the process show decay of gaseous torch in these local surface points.

The process of developing of the optical perturbation region essentially accelerates if aerosol exposed to pulsed PLR. Life time t_l of particles in PLR beam decreases as the radiant energy increases (see Table II). As in the case of continuous radiation, the fragmentation begins under the combustion temperature. The optical perturbation region has a form of ellipsoid of revolution with principal axis directed along the PLR propagation. Size of the region of local perturbation for particles of atmospheric aerosol ($a_0 \le 5$ μm) can be estimated in accordance with obtained empiric relations; semiaxis a is approximately equal to $20a_0$, b is approximately equal to $50a_0$. Rate of the optical perturbation region expansion is equal to several meters per second and depends on I.

TABLE II. The destruction time of soot particles interacting with PLR.

I, W/cm^2	$0.7 \cdot 10^5$	$1.1 \cdot 10^5$	$1.3 \cdot 10^5$
t_l, s	$1.2 \cdot 10^{-3}$	10^{-3}	$0.6 \cdot 10^{-3}$

In case of noninflammable aerosol particles the form of the optical perturbation region is cylinder with generatrix oriented along PLR beam axis. The cylinder radius approximately equals 2 to $3a_0$.

It should be noted that if particle moves along PLR beam axis, then nonlinear scattering on the optical perturbation region is less that in case of motionless particle.[17] Experiments showed the majority of particles inside the PLR beam volume to move along the beam axis.

Hence, the study of dynamics of development of the optical perturbation region near aerosol particle in optical field of moderate radiant exitance ($I \le 10^3$ W/cm^2) and in pulsed optical field ($I \sim 10^5$ W/cm^2) (see Ref. 18) allows us to conclude that the region exposed to radiation and filled with burning particles' fragments is an optically active core in the region of a local perturbation of a medium.

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