SOLID–PHASE AEROSOL PARTICLE IN THE INTENSE LIGHT FIELD. UNDER–BREAKDOWN REGIME OF INTERACTION

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Results of physical experiment on the interaction of intense laser radiation with individual particles of solid–phase aerosol (NaCl, SiO_2, and clay) are presented. It is shown that the radiation–induced centers of the gaseous phase in the particle volume affect the dynamics of the particle size.

Recently evaporative interaction of intense light field with individual particles of water–droplet aerosol has been studied in detail.[1,2] A semi–empirical model of explosive fragmentation of water–droplet aerosol particles irradiated by pulses of laser radiation was developed.[3] Results of investigations of optical breakdown of air initiated by solid–phase aerosol upon exposure to the laser radiation with the intensity $I \geq 10^7$ W/cm^2 and of combustion of carbonaceous aerosol particles for $I < 10^5$ W/cm^2 were summarized in Ref. 4. Much less attention was paid to the investigation of individual particles of the incombustible solid–phase aerosol of various chemical composition when they were exposed to the intense laser radiation (ILR) in the under–breakdown regime. The available experimental papers[5–7] pointed out the possibility of fragmentation of aerosol particles irradiated by the continuous and pulsed ILR. The fragmentation occurred due to the formation and evolution of the gaseous phase in the particle volume in the form of individual bubbles.[5] The distribution of heat sources inside the quartz particles placed in the field of the CO_2 laser radiation was calculated in Ref. 7. It was shown that similarly to the liquid particles[8,9] the maximum of heat release coincided with the so–called hot points caused by the nonuniform distribution of the optical field in the particle volume, in which the phase of substance was changed and gaseous phase was formed.

The evaporation of incombustible solid–phase aerosol and fragmentation conditions were not studied experimentally. First of all it was connected with the methodical difficulties, which made it impossible to determine the size of the high–temperature particle at each moment of time. The authors of Refs. 10–14 treated theoretically the evaporation of solid high–melting incombustible particles. These results were systematized in Ref. 1.

This paper presents the results of experimental study of the ILR ($I \leq 10^6$ W/cm^2) interaction with the individual particles of the solid–phase aerosol (NaCl, SiO_2, and clay). The continuous and pulsed regimes of irradiation were used. The particle radius a_0 varied in the range $10\ \mu m \leq a_0 < 100\ \mu m$ in different experimental series.

The method of high–speed cinemicrography was used for experimental study of the dynamics of the ILR interaction with the aerosol particles. The method provided the most complete picture of the processes occurring on the surface of the particle and inside its volume (for transparent particles). The particles of a nearly spherical shape obtained by preliminary melting of particles upon exposure to the radiation with $I \leq 200$ W/cm^2 were used. Then the particles were spatially fixed either by putting them on the nonabsorptive substrates for the case of continuous radiation or on adhesive fibers with diameter less than 3 μm for the case of a pulsed regime of lasing of a CO_2 laser. The size a_0 of the particle before exposure was filmed, then the particle was irradiated during the time t^*. After the time t^*, the irradiation by the ILR ceased, the particle cooled down, and its final size a_f undistorted by its self–radiation was filmed again. The process of irradiation was also filmed. The experiments accompanying by fragmentation of the particle substance, were excluded from the analysis of evaporation of the solid particles.

Tables I–IV present the measurements of the ratio $\frac{a_f}{a_0}$. The absence of the values of $\frac{a_f}{a_0}$ in the corresponding columns is due to the removal of the particles from the field of view of the optical system caused by the light reactive forces which arise as a result of decrease of mass accompanying the local explosion similar to the case of water–droplet aerosol particles.[15]

TABLE I. The dependence of the ratio $\frac{a_f}{a_0}$ on the ILR energetics at $t^* = 0.5$ s for the particle of NaCl.

I, W/cm^2	a_0, μm					
	25	40	55	65	80	100
250	1.0	1.0	1.0	1.0	~0.99	~0.99
300	~0.99	~0.99	1.0	~0.99	~0.99	0.97
350	~0.99	~0.98	0.97	0.97	0.98	0.97
400	~0.98	~0.98	0.98	0.97	0.97	0.97
500	~0.98	–	0.97	0.95	0.96	–

TABLE II. The dependence of the ratio $\frac{a_f}{a_0}$ on the time of exposure for $I = 400$ W/cm^2 for the particle of NaCl.

t^*, s	a_0, μm					
	25	40	55	65	80	100
0.3	~0.99	~0.99	~0.99	~0.99	0.98	0.98
0.5	~0.98	~0.98	0.98	0.97	0.97	0.97
1.0	0.96	0.97	0.96	0.96	0.96	0.96
1.5	0.96	0.96	0.94	0.94	0.95	0.94
2.0	0.95	0.95	0.94	–	0.93	0.93

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TABLE III. The dependence of the ratio $\frac{a_f}{a_0}$ *on the time of exposure and the ILR energetics for the particles of* SiO_2

I,W/cm^2	t^*,s	a_0, μm			
		20	30	75	90
200	0.05	0.97	0.95	0.95	0.95
	0.1	0.95	–	0.9	0.93
250	0.05	0.97	–	0.93	0.94
	0.1	0.95	0.93	–	–
280	0.05	0.97	0.94	0.93	–
	0.1	0.93	0.93	0.89	–

TABLE IV. The dependence of the ratio $\frac{a_f}{a_0}$ *on the time of exposure and the ILR energetics for the particles of clay (*a_0 = 0.94 μm *and* I = 210 W/cm^2*).*

t^*, s	0.3	0.5	0.7	1.0	2.0	3.0	6.0	9.0	12.0
$\frac{a_f}{a_0}$	0.98	0.97	0.97	0.96	0.94	0.83	0.69	0.55	0.55

When the particles of SiO_2 were exposed to pulsed radiation of a CO_2 laser the fiber burned out and the particle fell free on the trapping substrate. The obtained values of $\frac{a_f}{a_0}$ are presented in Table V. The absence of the value of $\frac{a_f}{a_0}$ for $I = 10^6$ W/cm^2 when a_0 = 10 and 30 μm is caused by the fragmentation of the initial particles.

TABLE V. The dependence of the ratio $\frac{a_f}{a_0}$ *on the radiation energetics for the particle of* SiO_2.

I,W/cm^2	a_0, μm				
	10	30	50	80	100
10^5	0.95	0.98	0.99	1.0	1.0
$5\cdot10^5$	0.9	0.96	0.98	1.0	1.0
10^6	–	–	0.96	0.98	0.98

The sign "~" in Tables I and II indicates the presence of the values of a_f in the data array which differ from the average value given in the tables by 10%. An averaging was performed over 20–30 values of a_f.

A special series of measurements on determination of the location, size, and number of the gaseous phase centers in the volume of the SiO_2 particle was performed to select the mechanisms of decreasing the size of the incombustible particles. The main products of its dissociation in the pyroliz zone are SiO, O_2, and O dissolved in melted silica.[16] Because of the radial temperature gradient, the gradients of concentration of these products were formed in the vicinity of the hot point. The gaseous bubbles indicated the location of absorbing micro–impurities or hot points in the particle volume.

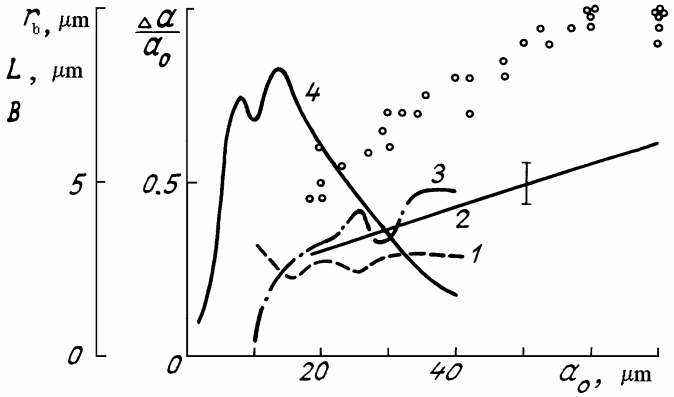

FIG. 1.

Figure 1 illustrates the results of determining the location of the hot points and size of the bubbles forming in the particle volume.

It is assumed that the gaseous bubble is formed in the center of maximum heat release coinciding with the maximum in the optical field distribution over the particle volume. The experimental data (curve *2*) for I = 300 W/cm^2 well agree with the results of calculations (curve *1*) of the location of the maximum heat release $\frac{\Delta a}{a_0}$ (see Ref. 7). The dependence shown by curve *2* was obtained by the least–squares method. The vertical bar indicates the spread of the experimental data points, and Δa is the distance from the center of the maximum to the surface of the shadowed hemisphere of the particle (in the experiment Δa was counted off from the center of the bubble). Curve *3* shows the extension L of the main maximum of heat release in the direction of the diameter of particles of various size at a level of e^{-1} (see Ref. 7). The experimentally measured radii of the gaseous bubbles r_b (dots) for I = 300 W/cm^2 correspond to a level of $e^{-0.5}$. Behavior of $\frac{\Delta a}{a_0}$ with a_0 is similar to the case of water droplets.[17] The magnitude of the maximum of heat release increases with increase of the particle size and the maximum shifts towards the center of the particle. According to Ref. 7 for the CO_2 laser radiation the magnitude of the maximum heat release decreases for $a_0 \geq 14$ μm because of attenuation of radiation by the particle substance. The dependence of B on a_0 illustrates this phenomenon (curve *4*), where B is the dimensionless parameter, which takes into account the interaction between the field of the incident wave and substance in the particle volume,[9,18] and quantitatively determines the excess of the internal electric

field above the external one. The dependence of r_b on a_0 obtained in the experiment saturates only at $a_0 \sim 60$ μm which may be explained by the significant variation in the optical properties of the aerosol substance as a function of temperature.

In this way, for the particles with $a_0 \sim 5$–25 μm the heat release in the region of the main maximum significantly exceeds the heat release in the other regions of the particle volume and is the main reason of formation of gaseous phase. For the pulsed CO_2 lasers with moderate energetics the depth of temperature homogenization in the volume of the SiO_2 particle irradiated by a single pulse is not greater than 10 μm owing to the small time of the interaction between the radiation and substance. Hence, it follows that particle with $a_0 > 20$ μm cannot be melted completely[7] and the egress of gaseous phase can be considered as the partial decrease of the mass of the particle substance. We did not observe the complete fragmentation of the particle with $a_0 > 30$ μm in our experiments (Table V).

The heat release from the SiO_2 particle upon exposure to the cw CO_2–laser radiation substantially differs from the case of the pulsed irradiation. The gaseous phase is formed in the particle volume only after its melting. The heat–conducting mechanism of the temperature homogenization within the particle is completed by the convective mechanism. For $I \sim 10^3$ W/cm^2 the velocity of convective motion reaches 0.15 cm/s.

In addition to steady formation of a bubble in the region of the main maximum in the intensity distribution the gaseous bubbles with the radii (0.2–0.5) r_b were formed in the particle volume, while their location was random. It seems that the centers of their formation are strongly absorbing microimpurities in the particle substance. Their number reached 15–20 in experiments. Being entrained by the convective motion, the bubbles can form conglomerates and reach interface between the substance and air. Dispersion of the fractionation products directly depends on the number of bubbles in the particle volume and on the intensity of heating radiation. Figure 2 shows the effect of the intensity of the cw CO_2–laser radiation on the size of the bubble located in the region of the main maximum of heat release $r_b(I)$ and on the total number $n(I)$ of bubbles with constant radius in the particle volume.

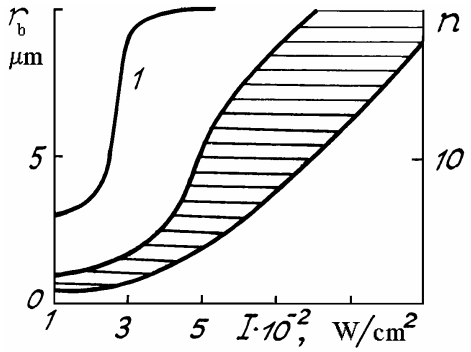

FIG. 2. The effect of the energy contribution of the ILR on the radius of the bubble (curve 1) located in the region of the main maximum of heat release and on the total number of bubbles in the volume of the quartz particle with radius a_0 = 70 μm (hatched area).

The egress of the gaseous bubbles formed around the microimpurities did not produce the noticeable recoil momentum of the particle and could not always be distinguished on the motion picture film from the background of glow of the main particle. Nevertheless, this process makes a significant contribution to the value $\frac{a_f}{a_0}$. Sharp acceleration of the process at $t^* > 2$ s (Table IV) is caused by the egress of the bubbles from the particle volume. The theory of evaporation of solid particles disregards this process.

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