ENERGY THRESHOLDS AND TEMPORAL CHARACTERISTICS OF EXPLOSIVE BOILING UP AND VAPORIZATION OF AEROSOL PARTICLES IN A CO_2–LASER RADIATION FIELD

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Results of analysis of experimental data on explosive boiling up and vaporization of liquid aerosol particles in a CO_2*–laser radiation field are presented in the paper. The energy threshold of explosive vaporization is shown to depend on the rate of the particle heating. The vaporization time increases with the particle size growth, and the explosion time changes the dependence on the particle radius in going from the regime of volume explosion to the regime of surface explosion.*

Interaction of high–power laser radiation with aerosol is accompanied by nonlinear effects (evaporation, explosion, and breakdown) being threshold by nature for energy parameters of acting light field. The values of thresholds essentially depend on microphysical characteristics of aerosol particles and radiation parameters.

The present paper analyzes thresholds of explosive boiling up and vaporization of aerosol particles depending on their heating rate.

Energy thresholds of explosive boiling up, i.e., the minimum laser radiation energy density E_{tb}, at which explosion occurs, was studied adequately both for the case of small homogeneously absorbing particles[4,8] $\alpha_a r_0 < 1$, where α_a is the coefficient of volume absorption of the material of particles (for $\lambda = 10.6$ μm and water, $\alpha_a = 800$ cm^{-1}, see Ref. 1), r_0 is the initial radius of a particle, and for large particles $\alpha_a r_0 > 1$, characterized by nonuniform distribution of heat release fields in the particle volume.[5,12] It has been found experimentally and theoretically that the explosion threshold depends slightly on the particle size and the laser pulse duration.

Figure 1 shows (by filled symbols) the data on the explosion thresholds obtained by various authors. It is clear that in wide ranges of particle size $2.7 < r_0 < 400$ μm and pulse duration $4\cdot10^{-7} < t_p < 10^{-5}$ s the threshold values are within $E_{tb} = 1 - 3$ J/cm^2. A theoretical criterion of explosive boiling up is the attainment of the temperature $T_b = 578 - 593$ K sufficient for spontaneous formation of vapor nuclei within the particle.[5] In this case, only the number of bubbles depends on the rate of energy injection in a particle, which is determined by the laser pulse duration at a given energy density, i.e., not the occurence of explosion by itself but the character of its evolution. In experiments, a methodical criterion of explosion is the emission of vapor condensate from the particle surface observed in direct (photographic) studies[12,13,16,17] or a qualitative change of characteristics of the objects under consideration connected directly with this emission (transmission of aerosol volume, scattering by particles, acoustic response) in indirect methods of investigation.[2,9,11,14]

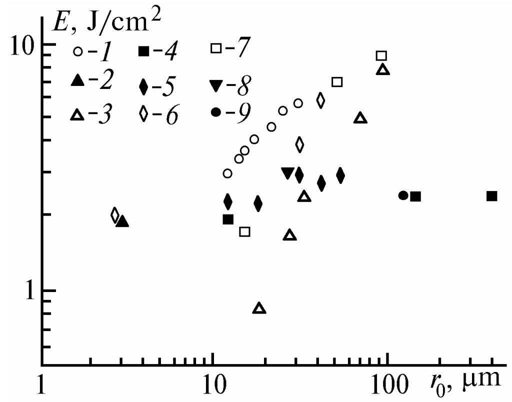

FIG. 1. Dependence of the explosive threshold of boiling up E_{tb} *(filled symbols) and the vaporization threshold* E_{vt} *(empty symbols) on the initial radius of particles* r_0*: 1) Ref. 7, 2) Ref. 8, 3) Ref. 14, 4) Ref. 13, 5) Ref. 12, 6) Ref. 11, 7) Ref. 9, 8) Ref. 17, and 9) Ref. 16.*

When determining the explosion threshold both experimentally and theoretically, neither symmetrical (volume) threshold nor emission of vapor condensate from local sources of heat release within the particle volume was considered. Since the small and large particles differ only in the distribution of a light field of acting radiation inside particles, it does not influence the criterion of explosion threshold as the particle radius changes.

In Refs. 3 and 6, in addition to the explosive threshold of boiling up E_{tb}, the explosive vaporization threshold E_{vt} was determined, that is, the energy density of laser radiation necessary for the explosion of aerosol particles resulting in their vaporization as a whole. In Ref. 3, it was shown that the vaporization threshold exceeds the explosive threshold of boiling up by a factor of 3.8, and in Ref. 7 the dependence of vaporization threshold on the particle radius was measured within the limits $r_0 \sim 10 - 30$ μm for continuous radiation. In Fig. 1, this dependence is indicated by number *1*. In Ref. 3, the dependence of $E_{vt}(r_0)$ was not measured. Based on the data available, it was assumed that $E_{vt} \sim r_0$

and was independent of the other parameters of the particle and radiation.

In recent years, a literature has evolve that enables one to supplement the existing concepts of the vaporization threshold. In Ref. 9 the explosion of single particles of different radii was investigated by the acoustic method based on the optoacoustic effect of transformation of absorbed radiation energy to thermal energy of a medium resulting in generation of an acoustic signal.

The obtained dependence of peak pressure of acoustic signal on the acting energy density has the typical saturation thresholds due to the change of the regime of acoustic wave generation. Since the single particles were used in experiment, the approximation of a so–called N–wave,[18] whose pressure is inversely proportional to the volume in which acoustic signal is formed, was used for interpreting the results. Thus, the change of the character of the pressure increase P in a received signal, depending on the acting energy density, can be connected with the change of the explosive volume, that is, the transition from surface vaporization in the regime of explosion to complete vaporization of a particle. Inflection points of the dependence $P(E)$ corresponding to the vaporization threshold of particles E_{vt}, obtained for different r_0, are denoted in Fig. 1 by number *7*.

It is evident that the dependence $E_{vt}(r_0)$ has the same tendency to increase as the particle size grows, as in Ref. 7, but the values of the threshold energy density are much lower. The conditions of experiments performed in Refs. 7 and 9 differ in that the continuous radiation was used for particle heating in Ref. 7, whereas in Ref. 9 the pulsed radiation was used, with the pulse duration $t_p = 4\cdot10^{-7}$ s. Thus, the factor affecting the threshold of explosive vaporization is the rate of particle heating J, which in Ref. 7 was $J = 3\cdot10^6 - 6\cdot10^6$ K/s and in Ref. 9, $J = 10^9 - 5\cdot10^9$ K/s. The calculation was carried out using the formula from Ref. 5. A supplementary analysis of the results given in Ref. 11, where the explosive vaporization of aerosol in the field of laser pulse with duration $t_p = 3\cdot10^{-6}$ s was investigated based on a backscatter signal (Fig. 1, *6*), and in Ref. 14, where the transmission change was studied in the regime of explosion of aerosol irradiated by a pulse of duration $t_p = 8\cdot10^{-8}$ s (Fig. 1, *3*), demonstrates that the increase of heating rate results in the decrease of the explosive vaporization threshold E_{vt}. The dependence of the explosive vaporization threshold on the heating rate is shown in Fig. 2 for three particle radii.

One of the main parameters, in addition to the thresholds of explosive boiling up and vaporization, is the time of explosion t_{ex}, defined for theoretical model of Ref. 5 as the time from the beginning of laser irradiation of a particle to its heating to the temperature of explosive boiling up and formation of vapor–phase nuclei, and in experiments – to the start of emission of vapor condensate. For small particles ($\alpha_a r_0 < 1$), in Ref. 8 it was shown experimentally that t_{ex} depends on the energy density of the acting radiation. In Ref .15, the $t_{ex}(E)$ dependence was obtained for particles with $r_0 = 35$ μm.

Our analysis of the results published in Refs. 8, 10, 11, 13, and 15 has made it possible to construct the experimental dependence of $t_{ex}(r_0)$ shown in Fig. 3 by filled symbols. The values of t_{ex} in the plot are for the range of variation of the energy densities $E = 2 - 3$ J/cm^2. It is evident that the explosion time increases when the particle radius increases in the range characterized by volume absorption ($r_0 < 10 - 15$ μm). For $r_0 > 15$ μm, the explosion time decreases with the r_0 increase. According to the theoretical model of Refs. 4 and 5, the explosion time depends on the heating rate and is practically independent of r_0.

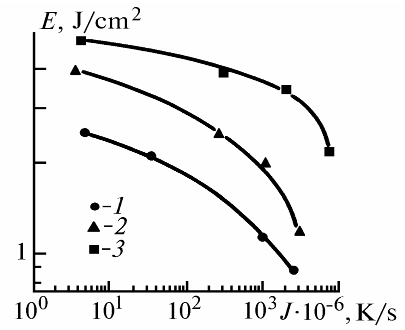

FIG. 2. Dependence of the explosive vaporization threshold E_{vt} on the heating rate J: r_0 = 15 (1), 20 (2), and 30 μm (3).

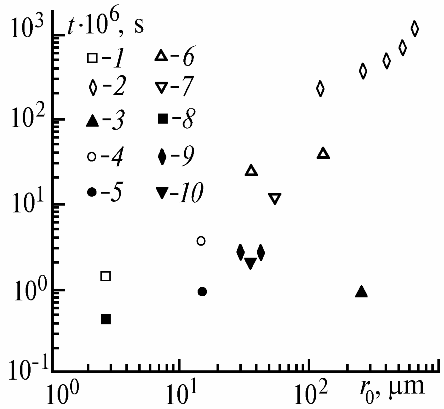

FIG. 3. Dependence of the explosion time t_{ex} (filled symbols) and the vaporization time (empty symbols) on the initial radius of particles r_0: 1 and 9) Ref. 11, 2) Ref. 14, 3 and 6) Ref. 13, 4 and 5) Ref. 10, 7) Ref. 12, 8) Ref. 8, and 10) Ref. 15.

It should be noted that with the increase of acting energy, the explosion time t_{ex} decreases and the amount of decrease is the greater, the shorter is the laser radiation pulse, i.e., the higher is the heating rate. This is in good agreement with theoretical conclusions of Ref. 5. Figure 4 shows the dependence of t_{ex} on the heating rate J for three particle radii.

The total explosion time t_{ex} defined as the time from the onset of explosion to the completion of vaporization process can be taken as one more temporal characteristic of explosion. Figure 3 shows (by empty symbols) the dependence of t_{ex} on the initial radius r_0 of particles. It is clear that $t_{ex} \sim r_0$.

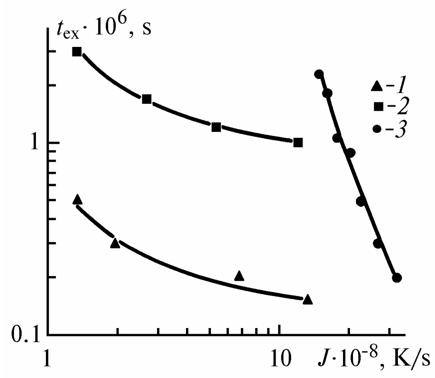

FIG. 4. Dependence of the explosion time t_{ex} on the heating rate J. 1) 2.7 μm, *Ref. 8, 2)* 30 μm, *Ref. 11, and 3)* 35 μm, *Ref. 15.*

The dependence of the explosive vaporization energy threshold on the particle size and the particle heating rate has been obtained from an analysis of experimental data on explosion of aerosol particle irradiated by a high–power CO_2 laser. It is evident that the threshold energy density, at which the complete vaporization of particles occurs, decreases with the heating rate increase. We have found that the explosive vaporization time becomes longer with particle size increase. As the initial radius increases, the time of explosion increases in the regime of volume particle explosion and decreases in going to the regime of surface explosion.

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