EXPERIMENTAL STUDY OF THE ACOUSTIC SIGNAL FROM ISOLATED AEROSOL PARTICLES IN AN INTENSE LIGHT FIELD

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In this paper we present the experimental investigation into the opto–acoustic effect induced in isolated aerosol particles of different size by a pulsed laser radiation. Influence of the particle size on the amplitude of acoustic signal at particle's vaporization and explosion has been revealed in the experiment.

Recently, optophone method has been showed to be a useful technique for measurement of gas medium absorbing ability.[1] This method is based on optoacoustic effect, i.e., on formation of acoustic waves in investigated sample which is placed in an isolated volume and illuminated by a light flux. The absorbed radiation energy transforms to the thermal energy of the medium, and acoustic signal appears. Closed cell is used mainly for isolation from external noise and therefore for increase in sensitivity of the method.

Optophone method was used also in absorption measurements of aerosol media.[2] However, some specific features of this technique result in certain difficulties when studying aerosol media. High sensitivity of the method to external noise, when the cell is open, does not permit the measurements to be carried out at aerosol recirculation through the gas volume. When dropping–liquid aerosol is studied, sticking of microphone diaphragm occurs thus decreasing sensitivity of the method in uncontrollable way. Deposition of aerosol particles on the output windows makes difficult the optical control of aerosol concentration. Scattering of the incident beam by aerosol particles results in occurrence of additional noise signal from the walls of optophone. In the closed volume of the cell a gas fraction containing vapors of dropping–liquid aerosol forms. Being uncontrollable, it affects the amplitude of optical acoustic signal.

When using high power lasers, it is possible to enhance the capabilities of optoacoustic method due to higher amplitudes of signals. In this case, acoustic signals with amplitudes being at the noise level can be confidently separated out by standard microphones without isolation of the medium in the closed cell. Different effects occurring owing interaction of high–power laser radiation with aerosol medium including nonlinear phenomena (vaporization, explosion, and breakdown) enable one to study different parameters of the medium (concentration of aerosol particles, their size, water content, and chemical composition) among with its absorptivity.

Results of study of optoacoustic effect in water aerosol in an open volume are reported in Refs. 3 and 4. Peak pressure in the acoustic pulse was studied as a function of concentration of water aerosol and CO_2–laser pulse radiant density.[3] In particular, it was shown that, when threshold of explosion of aerosol particles ($E \approx 2$ J/cm^2) was reached, the factor of transformation of laser energy into acoustic wave energy changed. It was found[5] that, when water content of aerosols with different microstructure was the same, the finely dispersed aerosol produced an acoustic signal of highest amplitude at particles explosion. Polydisperse aerosol produced average acoustic signal from the particles of different sizes. Therefore, it was impossible to obtain the quantitative dependence of amplitude of acoustic wave on size of aerosol particles.

In this paper we describe experimental investigation into optoacoustic effect for isolated particles of different size. This investigation is of interest not only as experiment in an open volume but also as experiment on regular and explosive vaporization of liquid particles at high rates of heating.

A CO_2 laser providing 1 J in $3.5 \cdot 10^{-7}$ s output pulse was used. Laser beam fell on the particle after passing a $3 \cdot 10^{-2}$ m lens. Laser radiant density in the region of interaction reached $1.4 \cdot 10^3$ J/cm^2. Energy of incident beam was varied by means of saran and teflon attenuators with transmittance of $T_1 = 0.85456$ and $T_2 = 0.6418$, respectively. Location of the particle with respect to the focal plane was controlled by observation with microscope of the optical breakdown of aerosol particle. A system of synchronization enabled us to adjust laser, aerosol generator, and plasma light source in such a way that steady picture of the interaction between laser beam and aerosol particle at a given moment of time can be observed in the ocular of the microscope.

Aerosol particles were produced by a generator whose piezocrystal under the action of the voltage pulses broke a stream of liquid into separate drops at a certain repetition rate. Stream diameter was determined by changeable piezoceramic plates with hole diameter from $1.2 \cdot 10^{-5}$ to 10^{-4} m. The size of the particles was calculated by the equation

$$r = [3M/4\pi\rho t f]^{1/3},$$

where f is piezocrystal vibration frequency, M is liquid consumption, t is time period of measurements, and ρ is density of the liquid under study.

Acoustic signal was detected by capacitive microphone produced by Brul and Kjer company 1/4 inch in diameter, having sensitivity of 1.6 mV/Pa and detection frequency region from 4 Hz to 100 kHz. This signal was recorded by Tetronix 2464 oscilloscope with pass band up to 400 MHz and sensitivity of input channels up to 2 mV/division.

In the case of $\lambda = 10.6$ μm radiation, distiled water having absorption factor $\kappa = 8.5 \cdot 10^{-2}$ was used. Nd–YAG laser at $\lambda = 0.53$ μm irradiated water solution of nigrosine. Its absorption factor at nigrosine concentration of $7.71 \cdot 10^{-3}$ g/l was $\kappa = 10^{-3}$. Two factors prevented from experiments with higher absorption and variation of size of aerosol particles when Nd–YAG laser was used. First, high viscosity of the solution makes difficult its recirculation in the generator. Second, increase in concentration of the solution results in the worse stability of the particle beam and separate particles, that makes

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difficult to obtain spherical particles and synchronize the "laser–generator" system.

Figure 1 presents peak pressure of acoustic signal as a function of laser pulse radiant density ($\lambda = 10.6$ μm). Reliable reception of the acoustic signal from the irradiated particle was provided at a level of radiant density of 0.4 J/cm^2. Lower radiant density led to the acoustic signal coincident in order of magnitude with the level of laboratory noise $P = 10^{-1}$ Pa. The upper limit of the measurements $E = 2 \cdot 10^2$ J/cm^2 corresponds to the optical breakdown on the surface of the particle. These results are in agreement with micrograph data.[6] Occurrence of the optical breakdown was detected by sharp increase in amplitude of the acoustic signal as well as by visual observation through the microscope. Results obtained for three different sizes of aerosol particles $r = 15$ (*1*), $r = 49$ (*2*), and $r = 92$ μm (*3*) are presented in Fig. 1. The case of interaction between laser beam and water surface is shown as extreme one (*4*).

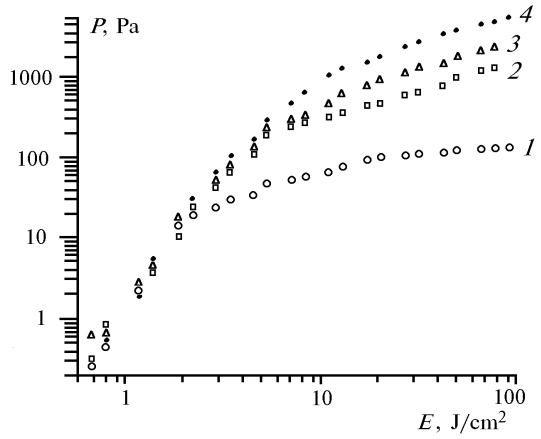

FIG. 1.

Figure 2 presents $P(E)$ function for the case of Nd–YAG laser ($\lambda = 0.53$ μm and $t_p = 5 \cdot 10^{-8}$ s) irradiating a particle of nigrosine solution of $r = 50$ μm. Since absorption factor of the particle is rather low ($\kappa = 10^{-3}$) the explosion is observed in the narrow range of radiant density (5–13 J/cm^2). Threshold values for explosion and optical breakdown are in good agreement with data obtained by other method[6] regardless of our experiments.

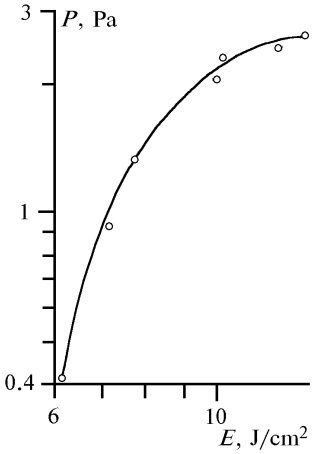

FIG. 2.

Figure 1 demonstrates different behavior of P vs E for different sizes of the particles. In the case of small drops ($2\alpha_a r < 1$, α_a is volume absorption factor), when radiant density slightly exceeds the explosion threshold value, the degree of vaporization (quantity of liquid transformed into the vapor) becomes close to its maximum value since the entire volume of the particle is heated up to the temperature of explosive boiling. Therefore, the increase in medium density, related to the quantity of liquid transformed into the vapor during the explosion, insignificantly depends on the further increase of absorbed energy. The larger is the size of the particle, the more substantial is increase in the amplitude of acoustic signal when laser radiant density increases over the explosion threshold value (curves *2* and *3*). For density slightly exceeding the threshold conditions, the explosion of large ($2\alpha_a r \gg 1$) particles occurs in the narrow surface layer. The thickness of this layer is approximately equal to the absorption depth of the laser beam. Further increase in laser radiant density leads to the heating of deeper–laying layers of the liquid to the temperature of explosion.[7] Hence, degree of vaporization as well as amplitude of acoustic signal increases due to heating of "cool" part of the drop. The same behavior of P vs E is observed for a layer of liquid (curve *4*). Simple estimations of the thickness of the layer, where the threshold energy density is reached, can be made using Bouguer law. For $\alpha_a = 800$ cm^{-1} at $\lambda = 10.6$ μm, they give that thickness of the layer approaches 49 μm for $E = 100$ J/cm^2 (curve *4*). This corresponds to the entirely superheated volume of the particle of $r = 95$ μm.

When comparing data represented in Fig. 1 (laser beam at $\lambda = 10.6$ μm irradiates water) to those represented in Fig. 2 (laser beam at $\lambda = 0.53$ μm irradiates coloured particles) it is evident that decrease in absorption factor from $\kappa = 8.5 \cdot 10^{-2}$ to $\kappa = 10^{-3}$ results not only in the displacement of heat–release zone from irradiated hemisphere to the shadow hemisphere[7] but also in decrease in superheated part of the particle. The latter conclusion can be made basing on large difference in amplitudes of acoustic signals in these two cases. Assuming that increase in the pressure in the acoustic signal is determined mainly by increase in the mass of superheated liquid we estimated the linear dimension of the heat–release zone in 50–μm particles with $\kappa = 10^{-3}$ (Fig. 2) to be approximately 20 times smaller than that in the same water particles (curve *2*, Fig. 1) with $\kappa = 8.5 \cdot 10^{-2}$.

Therefore, it is shown, that under explosive vaporization of isolated aerosol particles an increase in its size leads to increase in the amplitude of acoustic signal due to augmented mass of the liquid vaporized. The higher is the incident laser radiant density the larger is difference between acoustic signals from large and small particles.

REFERENCES

1. V.P. Zharov and V.S. Letokhov, *Laser Optoacoustic Spectroscopy* (Nauka, Moscow, 1984), 319 pp.
2. B.G. Ageev, A.A. Zemlyanov, A.M. Kabanov, and Yu.N. Ponomarev, Atmos. Oceanic Opt. **5**, No. 2, 88–90 (1992).
3. N.N. Bochkarev, A.A. Zemlyanov, N.P. Krasnenko, et al., Pis'ma Zh. Tekh. Fiz. **14**, No. 1, 25–29 (1988).
4. V.P. Zharov, A.E. Negin, and Ya.O. Simanovskii, Kvant. Elektron. **16**, No. 1, 98–99 (1989).

5. N.N. Bochkarev, Yu.E. Geints, A.A. Zemlyanov, and A.M. Kabanov, Atm. Opt. **1**, No. 10, 111–112 (1988).
6. R.G. Pinnick, A. Biswas, and R.L. Armstrong, Appl. Opt. **29**, No. 7, 918–925 (1990).
7. A.P. Prishivalko, *Optical and Thermal Fields in the Light Scattering Particles* (Nauka i Tekhnika, Minsk, 1983), 189 pp.