SOUND GENERATION BY A LASER BEAM IN A LIQUID WITH ABSORBING PARTICLES

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Sound generation by a laser beam within a liquid, related to liquid boiling at absorption centers, has been studied relatively little. Acoustic effects upon liquid boiling in a laser beam were first reported in [1]. A change in the index of refraction of a liquid has been observed under the action of acoustical radiation of microbubbles formed on absorbing particles in the zone irradiated by a laser beam [2-4]. However direct measurements of acoustical radiation from a set of microbubbles uniformly distributed over the volume of laser beam-liquid interaction has yet to be performed, to the authors' knowledge. The present study is a preliminary report of results of an experimental study of this class of optico-acoustical phenomena.

The acoustical radiation was produced by a laser beam (λ = 1.06 μm) operating in the Q-modulation mode (τ_i = 10 nsec). The beam passed through an input window into a chamber filled with liquid containing particles of soot. The chamber was 1.7 cm long in the direction of beam propagation. The acoustical signal at right angles to the beam was recorded by a wide-band hydrophone. Beam diameter was equal to 3 mm, and the beam-hydrophone distance R = 1.5 cm.

The soot particle distribution over size, as measured by a Coulter TA2 counter, was close to uniform for particles with radii $a \leqslant 7$ μm with a smooth falloff thereafter. The total number of particles per unit volume $N \sim 10^5$ cm^{-3}.

We will consider what form of laser energy dependence on laser beam energy density E/S we may expect. It is known that for nonstable bubbles in a liquid with lifetime τ the Fourier component of the acoustical signal

$$dp_\omega \sim (\rho_l/r)\omega^2\tau\Delta v \quad \text{at} \quad \omega\tau \leqslant 1, \tag{1}$$

where ρ_l is the liquid density; r is the distance to the recording point; Δv is the maximum bubble volume [5]. Upon fulfillment of the coherence condition

$$\omega/2\pi = f \leqslant f_{\text{coh}} \simeq c/(L_{\max} - L_{\min}) \tag{2}$$

the Fourier components of the signals from the various bubbles combine, and the amplitude of the total signal will be

$$p \simeq \omega|p_\omega| \sim \frac{\rho_l}{R}\omega^3\tau VN\int_0^\infty f(a)\Delta v(a)\,da. \tag{3}$$

Here c is the speed of sound in the liquid; $L_{\max}$, $L_{\min}$ are the maximum and minimum distances from the energy liberation point to the recording point; V is the volume of the energy liberation region; $f(a)$ is the probability density for the particle distribution. In the first approximation we neglect the dependence of bubble lifetime on bubble size ($\tau \sim W^{1/3}$, where W is the energy stored in the bubble [6]).

The volume of the bubble formed about the absorbing particle can be written in the form

$$\Delta v(a) = \frac{\pi a^2}{q}\left(\frac{E}{S} - \frac{4}{3}C\rho a\Delta t\right) \quad \text{at} \quad \frac{E}{S} \geqslant \frac{4}{3}C\rho a\Delta t, \tag{4}$$

where q is the energy required to heat to the boiling point and evaporate a unit volume of liquid; C, ρ are the specific heat and density of the liquid; $\Delta t = t_b - 20$°C.

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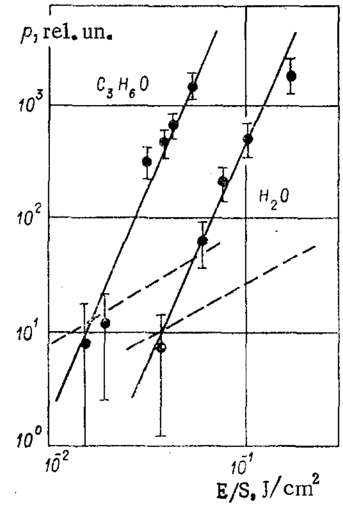

Fig. 1

We will limit ourselves to laser beam energy values at which bubble formation does not occur at particles with dimensions $a \geqslant a_m = 7$ µm. Substituting Eq. (4) in Eq. (3) and considering that the upper integration limit is the variable $a = (3/4)(E/S)(C\rho\Delta t)^{-1}$ and $f(a) \simeq 1/a_m$, we obtain

$$p \sim \frac{\rho_l \omega^3 \tau V N}{R a_m} \frac{1}{q (C\rho\Delta t)^3} \left(\frac{E}{S}\right)^4. \tag{5}$$

We note that this same dependence of acoustical signal amplitude on beam energy density and liquid and particle thermodynamic parameters is maintained for stable bubbles (in this case $dp_\omega \sim (\rho_l/r)\omega\Delta v$ [5]).

Experiments were performed with two liquids — water and acetone. The particle concentration in the water was 10^5 cm^{-3}, and in the acetone, $0.4 \cdot 10^5$ cm^{-3}. The bubble lifetime, estimated with shadow methodology, proved equal to $\sim 10^{-6}$ sec (the lifetime of refracting aureoles around inhomogeneities in the optically perturbed medium [2], which also attenuate the probe ray, comprises $\tau_0 \sim a^2/\chi \sim 10^{-4}$–$10^{-5}$ sec, where χ is the thermal diffusivity coefficient of the liquid). For this reason the acoustical channel passband was chosen to be $\Delta f \sim (2\pi\tau)^{-1} \simeq 160$ kHz $< f_{coh} \simeq 300$ kHz. The maximum laser beam energy density at which the absorbing particle size distribution could still be considered uniform was equal to $\sim 10^{-1}$ J/cm^2 for water and $\sim 5 \cdot 10^{-2}$ J/cm^2 for acetone. Figure 1 shows the dependence of the excess of acoustical signal p_p over the signal produced by the thermal generation mechanism p_t ($p = p_p - p_t$) on laser beam energy density for both liquids. The thermoacoustical signal level was determined from the approximation $p_t \sim E/S$ at low energy densities, and coincided with the signal in the pure liquid to an accuracy of $\sim 10\%$. The solid lines correspond to an analytical dependence $p \sim (E/S)^4$. The dashed lines show the level of the thermoacoustical signal. Estimates of the experimental exponent using the method of least squares give values of 4.1 ± 0.6 for water and 4.4 ± 0.5 for acetone. The distance between the straight lines (i.e., the ratio of the energy densities for identical absolute signal levels) is equal to $2.1^{+1.3}_{-0.8}$. Calculation with Eq. (5) gives a value of 1.8. It can be concluded from the data obtained that the model of sound generation by a set of microbubbles considered here, although quite coarse, truly reflects the basic features of the process.

The presence of acoustical radiation from bubbles formed upon absorption of laser energy by natural impurities which are always present in liquids should be considered in designing opticoacoustical experiments, especially in cases where the level of the signal to be studied is low. This is true, in particular, in measurements in water near 4°C. As was noted in [7, 8], in this case distortions of the acoustical signal appear which can be explained by microbubble radiation.

The effect considered here can be used to increase the amplitude of an acoustical signal without a significant change in laser radiation absorption coefficient, and also to monitor the presence of mechanical impurities in liquids. We will note also the possibility of studying nonlinear effects in sound generation in liquids (related, for example, nonlinearity of the thermal expansion coefficient) at relatively low values of laser beam energy density.

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DISTURBANCE OF THE BOLTZMANN POPULATION DISTRIBUTION OF ROTATIONAL LEVELS IN A FREE NITROGEN JET

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Inelastic collisions with exchange of the energy of rotational motion of molecules are being intensively investigated theoretically and experimentally (see [1, 2], for example). Supersonic expansion of gas in nozzles or in free jets is one of the most convenient subjects for the investigation of rotational relaxation, which is due to the large amount of experimental work performed in this field in recent years. In particular, in free jets one can attain controlled values of the translational temperature in the range from fractions of a degree Kelvin (at a high gas density such low temperatures cannot be obtained by other means) to several thousand degrees.

In experiments on rotational relaxation in jets various diagnostic methods are used, yielding information not only on the macroscopic parameters but also on the population distribution of rotational levels. Despite the evident progress in research, however, a number of fundamental problems still remain unsolved.

In the interpretation of results, certain authors [3, 4] state that the transition from the equilibrium state in rotational degrees of freedom in a gasdynamic source to a nonequilibrium state at a certain distance from it takes place through a succession of Boltzmann population distributions of rotational levels, whereas others [5, 6] find a disturbance of the Boltzmann distribution. The question of the form of the population distribution is important in a theoretical description of rotational relaxation. In the case of a Boltzmann distribution one can introduce a rotational temperature for which the relaxation equation

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