# Photoacoustic cavitation in water

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A new effect, photoacoustic cavitation in water, has been observed when $10^2$–$10^3$ J millisecond laser radiation pulses ($\lambda = 1.06\ \mu$) are focused into the interior of distilled water. The effect consists in the creation of acoustic cavitation by the laser radiation and in the intense scattering of the incident radiation by the caviation. The cavitation region is the result of the simultaneous heating and sound pressure produced by radiation absorption in the water. The process has a threshold with respect to the radiation energy (for pulse durations of $t \approx 10^{-3}$ sec).

The propagation of a laser beam in a liquid has been studied in[1]. A millisecond ruby laser was used in the investigations. The possibility of boiling liquids in the intense light beam was studied qualitatively. For sufficiently high light flux densities, the formation of bubbles was observed in ordinary tap water and previously aerated water. An increase in the scattering of the beam in the liquid was observed, and also a change in the character of the scattering with time of action of the light pulse and an attenuation of the light passing through the liquid upon aeration of the liquid when the light was focused within the liquid. In[1], different photohydraulic effects were first observed upon focusing of the light on a plate immersed in the liquid, and also explosive ejection of liquid from a vessel following propagation of a focused beam in an aqueous solution of copper sulfate.

In the present paper we have studied the propagation of a laser beam in pure distilled water. A new physical effect was observed experimentally—photoacoustic cavitation: the light beam of a millisecond neodymium laser focused inside a volume of the water created a region of acoustic cavitation near the focus of the lens and underwent strong scattering from it. The experiments described below were performed in 1969.

The experiments were carried out with a neodymium laser ($\lambda = 1.06\ \mu$), operating in the regime of a millisecond pulse ($t = 10^{-3}$ sec) with a characteristic spiked modulation of the radiation amplitude. An active element of 4.5 cm. diameter and length about 60 cm was pumped by a four-lamp illuminator placed inside a plane-parallel resonator. The energy of the radiation pulse at the input of the laser changed within the range $E \approx 10^2$–$10^3$ J. The radiation of the laser was focused in the center of a cylindrical glass cell of length and diameter $\approx 10$ cm. The entire volume of the cell was filled through a top opening with distilled water previously prepared by double distillation. The amount of water in the vessel was monitored by measurement of its electric resistance, and was not changed during the series of experiments. The radiation was brought inside the vessel through glass windows at the ends of the cell. For focusing of the beam, we used planoconvex lenses with $F = 10$ cm and $F = 15$ cm, located on the outside. With account of the refraction of the beam at the boundary with the water, their focal lengths were $F = 12$ cm and $F = 17$ cm, respectively. The minimum transverse size of the focusing region, determined from the measured divergence of the beam, amounted to 0.6–0.9 mm; the corresponding area of the minimum focusing spot was $(3–6) \times 10^{-3}$ cm$^2$, the longitudinal dimension 0.3–0.6 cm and the volume of the focusing region was $(1–4) \times 10^{-3}$ cm$^2$. The range of the light flux density in this volume was $(0.3–3) \times 10^8$ W/cm$^2$.

High-speed photography of the focal volume shows that at laser pulse energies greater than 100 J a region of scattering of the laser light arises in threshold fashion, consisting of bubbles of size 0.3–0.5 mm (Fig. 1). This region does not possess natural luminescence and the bubbles are seen only by applying the visible radiation of the laser pumping light. Longitudinal illumination of the cell with the water showed that its transparency in the focusing region falls off rapidly with increase in the energy of the laser pulse (Fig. 2).

Oscillograms of the scattered, incident, and transmitted signals at the laser radiation wavelength are shown in Fig. 3. It is seen that scattering arises with a delay of 0.2 $\mu$sec after initiation of the laser pulse. During this time, radiation is incident on the vessel with an energy of 64 J and the transmitted energy is 9 J, at a total incidence of 400 J, which corresponds to an energy release in the focal region of $64 \exp(-0.18 \times 5) [1 - \exp(-0.9 \times 0.3)] \approx 1.2$ J $\approx 0.3$ cal. For an estimate, data on the absorption $\alpha$ were used (Fig. 2), according to which $\alpha \approx 0.18$ cm$^{-1}$.1) By virtue of the low temperature-conductivity of water ($\sqrt{\chi t} \sim 10^{-3}$ cm) and the absence of mixing during the time of the pulse, the focal volume should be regarded as thermally isolated from the surrounding mass of water. Therefore, the estimated value of the energy release at the focus should be compared with that expended in heating the water and its transformation into vapor. These expenditures at $V = 10^{-3}$ cm amount to $(540 + 80) \times 10^{-3} \approx 0.62$ cal.

Comparison of the obtained figures leaves open the question of the physical mechanism of formation of the scattering region. We therefore performed the following experiment: We focused the radiation into previously

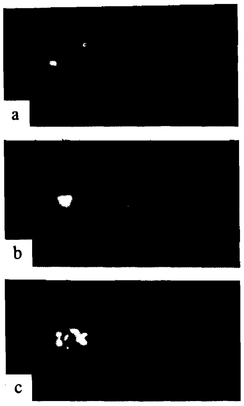

FIG. 1. Frames of high-speed photographs (with added illumination) of the focal region for a laser pulse energy of 180 J. Exposure time $\approx 1$ millisec; the beam is incident from right to left. Frames a and b show the beginning of the process, frame c refers to the middle of the laser pulse. The linear scale is 1:1.

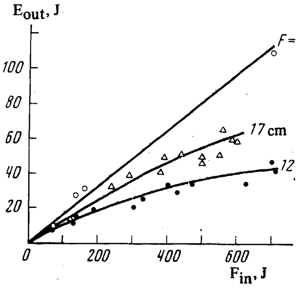

FIG. 2

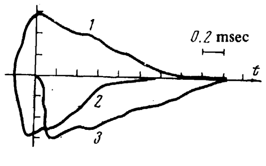

FIG. 3

FIG. 2. Dependence of the energy of the laser pulse transmitted through a cell on the energy $E_{in}$ at the input to the cell in the absence of focusing (F = ∞) and with focusing of the radiation by lenses with F = 17 cm and F = 12 cm.

FIG. 3. Oscillograms of the pulses (the envelopes of the pulses with spiked modulation are shown): 1–incident radiation (energy 400 J), 2) transmitted through cell, 3) scattered radiation. The gains are different in the oscillograms.

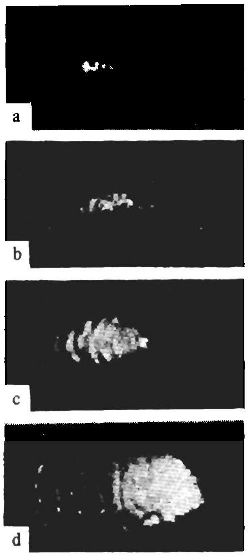

FIG. 4. Frames of high-speed photographs of the scattering region for a pulse energy of 1 kJ (the ray is incident from the right to left). The beginning of the pulse is shown (a, b), then the development of the cavitation region (c) and its maximum volume (d). Linear scale 1:1.

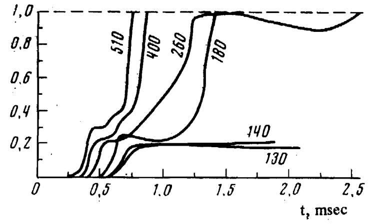

FIG. 5. Change in the transparency of the cavitation region with time in the direction perpendicular to the beam, for the following pulse energies: 1) E = 130 J, 2), E = 140 J, k 3) E = 180 J, 4, E = 260 J, 5) E = 400 J, 6) E = 510 J. Level 1 along the ordinate corresponds to the absence of transmission of the light.

heated (to a temperature of 80–90°C) distilled water. A sharp decrease in the threshold of the effect was observed, as well as an increase in the dimensions of the scattering region. Formation of bubbles took place over almost the entire volume of the light cone of the focusing lens. Estimates show that in this case the absorption of the light energy is clearly insufficient to produce boiling or bubble formation in such a large volume of water. There should be another factor along with the heating, which explains the observed effects. Such a factor, in our opinion, is the generation of sound as a result of heating of the water by laser radiation, leading to the generation in the water of acoustic cavitation (formation of bubbles on motes at the minimum of the sound-wave pressure as a result of rupture of the liquid[2]).

Let us estimate the sound amplitude generated in water in the focal region in a time $t \sim 10^{-6}$ sec, which corresponds, on the one hand, to the duration of a one-microsecond burst of laser radiation, and, on the other, to the characteristic time of oscillations of the focal volume $t_0 \sim \phi/c \sim 10^{-6}$ sec ($\phi \sim 10^{-1}$ cm is the size of the focal volume, $c \sim 10^5$ cm/sec is the sound velocity in water). Within the time $t \approx t_0/3$, one can assume that no relaxation takes place in the focal volume, so that the pressure amplitude $\Delta P$ corresponds to the energy density absorbed in the focal region and amounts to, at least,

$$\Delta P \approx \Gamma \alpha I t \approx 30 \text{ atm}$$

at[2)] $\alpha = 0.18$ cm$^{-1}$, $I \approx 10^8$ W/cm$^2$, $t = 0.3 \times 10^{-6}$ sec and at the Grüneisen coefficient $\Gamma \approx 0.4$ for $T \approx 80–100°C$, which appreciably exceeds the acoustic resistance of distilled water at 1.7 atm and at a frequency of 1 MHz.[2] The simultaneous action of the sound pressure and of the heating, which raises the pressure of the saturated vapor, explains the described effects qualitatively.

In our experiments, the sound was not recorded directly. However, subsequent experiments on the time development of the observed processes completely verify the proposed physical mechanism. Actually, for sufficiently high energy of the laser pulse (above the threshold of the effect), it can be expected that after formation of a large number of bubbles in the caustic of the focusing lens and after the "collapse" of its transparency, the light energy will be scattered sideways and absorbed in the surrounding volume of the water, heating it. The corresponding generation of the sound leads to propagation of the cavitation region from the focus to the surrounding volume of water with the predominant direction of propagation towards the laser by virtue of the decrease in the transparency, because of the increase in the dimensions of the region). After the lapse of a certain time (which is smaller the greater the power of the laser radiation), a "collapse" of the transparency of the cavitation region should be observed in the transverse direction (relative to the laser beam). The results of observation confirm this expected picture of the process (Figs. 4, 5).

High-speed photographs (Fig. 4) show the emergence of the cavitation region to the outside of the focal volume, as well as its predominant growth in the direction toward the laser, with mean speed ≈10 m/sec. The results of irradiation of the cavitation region by a red neon-helium laser beam (with aperture ≈1 mm) are represented in Fig. 5. For energies in the laser pulse of E = 130–140 J, the effect of cavitation arises within 0.5 millisecond after the initiation of the pulse, and the attenuation of the probing beam in the transverse direction amounts to ≈20%. For E = 180 J, the process begins somewhat earlier, the damping of the beam reaches ≈25%, and within a time ≈0.5 millisecond a "collapse" of the transparency of the cavitation region takes place, brought about by heating of the water outside the focal volume. With increase in the energy, both the delay time of the appearance of the effect at the focus of the lens relative to the beginning of the pulse, and the delay time connected with the propagation of the cavitation zone to the surrounding volume of water, are decreased. We note that the non-transparency of the water as a result of the intense scattering by the cavitation bubbles persists for $\sim 10^{-1}$ sec, a time much greater than the duration of the pulse of laser radiation ($10^{-3}$ sec).

Thus, a new physical effect of photoacoustic cavitation in water has been established in the experiments just described. The effect consists in the creation of acoustic cavitation and intense scattering of radiation by a laser beam.

When radiation with energy of several kilojoules was focused in an open vessel with distilled water, with the focal region located near the surface of the water, we observed a photohydraulic effect accompanied by intense upward ejection of the liquid.[1,3] From the height of the upward jet, $h \simeq 1$–$5$ m, one could also, just as in[3], estimate the amplitude of the pressure near the surface, $P \sim \rho c v/2$, where $\rho = 1$ g/cm$^3$ is the water density, $c \approx 10^5$ cm/sec, and $v = \sqrt{2gh}$. The value $h = 1$ corresponds to $P \simeq 25$ atm. The pressure in the interior of the medium on the beam axis should be somewhat higher. This estimate does not contradict the value given above for the amplitude of sound generated on the axis of the beam in the focal region.

In conclusion, the authors express their gratitude to G. A. Askar'yan for remarks made in discussions of the research at a seminar at the Oscillations Laboratory of the Lebedev Physical Institute.

Brief results of this research were reported at the VII All-Union Conference on Nonlinear and Coherent Optics.[4]

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[1] It should be noted that for water with temperatures t = 20° and 90°C one obtains $\alpha = 0.140$ and $0.135$ cm$^{-1}$, respectively, from measurement of the absorption in water at a wavelength $\lambda = 1.06\mu$ with a spectrophotometer.

[2] The intensity average over the millisecond pulse is shown; the intensity in an individual microsecond burst is in fact somewhat larger.

[1] G. A. Askar'yan, A. M. Prokhorov, G. F. Chanturiya, and G. P. Shipulo, Zh. Eksp. Teor. Fiz. 44, 2180 (1963) [Sov. Phys.-JETP 17, 1463 (1963)].
[2] Moshchnye ul'trazvukovye polya (High-Intensity Ultrasonic Fields) (L. D. Rozenberg, ed.) Nauka, 1968.
[3] A. A. Buzukov, Yu. A. Popov, and V. S. Teslenko, Prikl. Mekh. Tekh. Fiz. No. 5, 17 (1969).
[4] F. V. Bunkin, V. I. Konov, A. M. Prokhorov, V. V. Savranskiĭ, and V. B. Fedorov, Reports of papers at the VII All-Union Conference on Nonlinear and Coherent Optics, 1974, Tashkent; p. 234.

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