SHOCK WAVE ASSOCIATED WITH OPTICAL BREAKDOWN IN WATER

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When the ray of a laser operating in the Q-switched mode is focused in water, a breakdown occurs [1-3] just as in the case of focusing in a gas. At the lens focus there develops a region filled with plasma, which absorbs the radiant energy and continues to expand after termination of the radiation pulse. Like the explosion or electrical discharge, optical breakdown is accompanied by the emission of a compression pulse (shock wave); the bubble which forms in the focal region pulsates after the breakdown.

In the present study we investigated shock waves which form during breakdown of water when a ruby laser operating in the Q-switched mode is focused in the water. The experimental setup is shown in Fig. 1. The ray of the laser 1, after passing through the system of neutral filters 3, entered the cuvette 2 filled with water, where the ray was focused by the lens 7. The pressure sensor 6 (the sensor was fabricated and made available for the experiment by N. A. Roe, to whom the authors are very grateful) was introduced into the cuvette; the flat, sensitive surface of the sensor was perpendicular to the direction of propagation of the wave formed during breakdown. The energy meters 8 (E') and 9 (E") made it possible to measure the energy of the ray entering and leaving the cuvette. At the same time, part of the laser radiation was diverted to the coaxial photocell 5 from which the signal was fed to the time interval meter 10 (I-2-7) and photographed.

We used a ruby laser which provided light pulses with energy up to 2 J and duration at the half-height of about 20 nsec; the filters 3 made it possible to reduce the focused energy to practically any value.

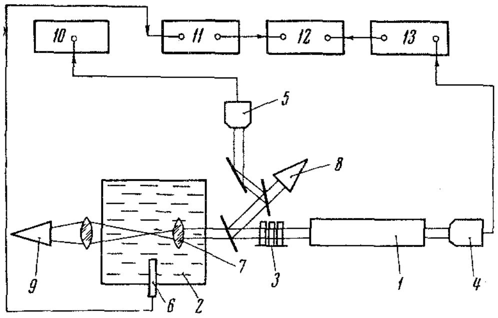

Fig. 1

The pressure sensor 6 had a passband on the order of 10 MHz. The passband was estimated on the basis of the thickness of the receiving element, which in our case was 0.1 mm. The sensor was calibrated in steps using compressed air. The voltage pulse from the sensor passed through the preamplifier 11 (S-1-15/1) to the dual-beam oscillograph 12 (OK-21). The OK-21 oscillograph was triggered with the required delay by a pulse supplied by the pulse generator 13 (G5-3B), which in turn was triggered by a pulse from the photocell 4. This circuit made it possible to determine the time for pulse passage in the water from the point of breakdown to the sensor.

The breakdown was studied in tap water which had been allowed to settle. The focus region was photographed and we

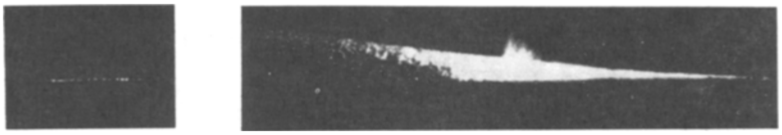

Fig. 2a, b

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 11, No. 3, pp. 125-127, May-June, 1970. Original article submitted May 29, 1969.

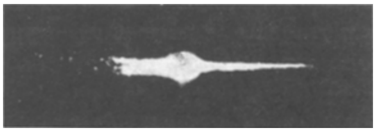

Fig. 3

see from the resulting pictures that breakdown in water appeared when focusing a light pulse with energy exceeding 0.06 J. The shape of the spark occurring during breakdown varied as a function of the pulse energy. As examples Fig. 2a shows a picture of the spark for an energy of 0.13 J, while Fig. 2b shows an energy of 1.76 J. We see that for the high energies breakdown takes place not only in the focal region but also ahead of this region; however for pulse energies less than 0.2 J the spark breaks up into individual spots, which confirms the hypothesis that breakdown takes place on nonhomogeneities [4]. The spot size is on the order of a hundred microns. The focal region dimensions in this experiment were determined basically by beam divergence and amounted to $\phi \sim 1$ mm, $l \sim 10$ mm.

Figure 3 shows a spark photograph obtained during breakdown in the case in which the laser pulse consisted of two spikes. The difference in the form of the spark obtained in the 1-spike and 2-spike modes is explained by the fact that the light of the second spike is absorbed in the heated plasma over a shorter distance than for absorption of the first spike.

We noted previously that one of the consequences of liquid breakdown is the emission of compression waves. Figure 4 shows a typical pressure-time oscillogram obtained by a pressure sensor (timing marks every 100 nsec). The sensor was mounted at distances of 1.7-5.0 cm from the point of breakdown. The durations of the recorded compression pulses amounted to times on the order of hundreds of nanoseconds and increased with increase of the focused energy. The average compression pulse propagation velocity at distances on the order of a few centimeters was close to the sonic speed in all the cases investigated.

As an example we shall present some results of measurements obtained when focusing laser radiation by a lens with focal length equal to 25 mm in air. When focusing a radiation pulse with energy $E' \approx 0.6$ J ($E'-E'' \approx 0.4$ J is absorbed) the compression pulses Δp_Φ recorded by the sensor had pressure amplitudes of 30 and 100 atm at distances of 50 and 17 mm respectively, and when focusing $E' \sim 0.1$ J ($E'-E'' \approx 0.015$ J is absorbed) the values of Δp_Φ were 17 and 45 atm.

With increase of the focused energy the pulse became more diffuse (double peaked), which was probably a consequence of merging of pulses arriving from different segments of the breakdown.

The high energy release rate in the vicinity of the point where the liquid breakdown occurred led to considerable local increase of the pressure and emission of an intense shock wave.

For the description of the shock wave it is natural to use the known solutions of the strong point explosion problem. Specifically, it is convenient to use the approximate interpolational equation obtained in [5], which becomes the known solution for the strong explosion at small distances from the source and corresponds to the asymptotic shock wave decay laws at large distances. The equation is applicable for $\Delta p_\Phi / p_0 > 0.03$, where Δp_Φ is the pressure jump across the shock wave, p_0 is the characteristic pressure in the medium. In application to a liquid described by an equation of state of the form

$$p = A\left(\frac{\rho}{\rho_0}\right)^n - B \tag{1}$$

this equation can be written as follows

$$\frac{\Delta p_\Phi}{A} = \frac{8}{25}\,\frac{n}{n+1}\left\{0.611\left[\left(1 + 0.16\,\frac{nA}{E}\,r_\Phi{}^3\right)^{5/8} - 1\right]\right\}^{-1} \tag{2}$$

where E is the energy released in the explosion, r_Φ is the shock wave front radius, A = 3001 atm, B = 3000 atm, n = 7 for water.

An estimate using this equation shows that when releasing 0.6 J at a distance of 1.7 cm from the explosion point a shock wave is formed with pressure jump $\Delta p_\Phi = 150$ atm, which agrees in order of magnitude with the experimental result presented above.

Better agreement of the theoretical and experimental data is obtained for the case studied in [2], in which the shock wave amplitude was measured at a distance of 0.3 cm from a breakdown with release of energy $E \sim 0.1$ J. From the measurement data $\Delta p_\Phi \approx 500$ atm, an estimate using (2) yields $\Delta p_\Phi \approx 500$ atm.

The authors wish to thank N. F. Pilipetskii and Yu. P. Raizer for their interest in the study, and also Yu. A. Sidorin for assistance in carrying out the experiment.

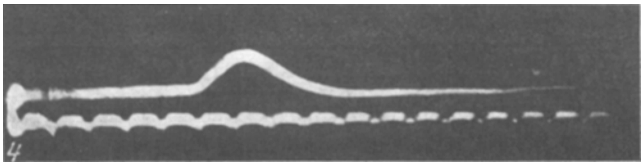

Fig. 4

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