EXPERIMENTAL STUDY OF EXPLOSION CAUSED BY FOCUSING MONOPULSE LASER RADIATION IN WATER

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When powerful laser radiation is focused in a liquid the electromagnetic radiation energy is transformed into mechanical work, into the energy of motion of the medium. The question of how the energy transformation process takes place and the effectiveness of this process has not yet been entirely clarified in spite of the fact that the process is of definite scientific and practical interest. The high concentration of the laser radiation luminous energy and the short duration of its release make it possible to examine the phenomena taking place in the liquid from the viewpoint of explosion physics.

In the following we present the results of an experimental study of the hydrodynamic processes which take place when monopulse ruby laser radiation is focused in water. The data obtained are used as a basis to establish the degree of correspondence between the nature of this phenomenon and that observed in chemical explosions or an electric discharge in water. The values of the photohydrodynamic coefficient of the process is determined, i.e., the fraction of the radiation energy which is transformed into mechanical work.

EXPERIMENTAL SETUP

The experiments were conducted on a setup shown schematically in Fig. 1. The ruby laser (1) light pulse passed through the system of focusing lenses with overall focal length 20-30 mm (2) and entered the cell (3) filled with water. In the first series of experiments we studied the development of the cavitational bubble when the laser beam was focused in tap water. To this end we photographed the process using the SFR-IM high-speed camera (4), operating both in the single-frame scan mode and in the photorecorder mode. The optical system of the setup made it possible to observe the shadow pattern of the propagation in the liquid of the compression waves caused by the pressure pulse at the focus of the laser beam. Illumination was provided by the pulsed gas discharge lamp (5), which was synchronized with the laser radiation pulse and with the SFR-IM camera control system.

In this same series of experiments records were made of the pressure pattern in the shock waves generated at the laser beam focus with the aid of the piezoelectric pressure sensors (6). The pressure sensors were located so as to measure the pressure at distances from 10 to 60 mm from the focus in the direction normal to the radiation axis. In this series of experiments the average radiation energy, determined using a calorimeter, was about 0.5 J with a pulse duration of 50-60 nsec.

In the second series of experiments we studied the pressure variation in the shock wave as a function of the direction relative to the location of the focal spot and the optical axis. To this end the pressure sensors were located in the cell filled with distilled water so that simultaneous recordings were made of the pressure in the direction normal to the laser optical axis and along this axis. In this series of experiments the radiation energy was about 1.5 J with a pulse duration of 30 nsec.

Pressure sensors of two types were used in both series of experiments. The sensitive element of the probes of the first type was made from a plate of polarized barium titanate ceramic, bonded to an acoustic waveguide – a small zinc rod embedded in wax [1]. When recording the pressure in the wave propagating perpendicular to the optical axis of the laser system these sensors had a resolution time of

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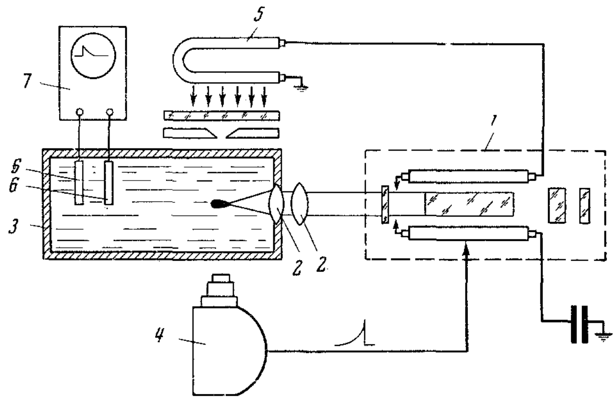

Fig. 1

0.25 μsec, and when recording the pressure along the radiation axis the figure was 0.8 μsec. The sensors of the second type were a needle with a tourmaline piezocrystal bonded to the tip. When the sensors of this type were installed in the first or second location their resolution was 0.8 and 2.5 μsec respectively. The signals were recorded on oscillographs of the OK-17M type (7) with high impedance preamplifiers which were free of frequency distortion up to 6 MHz. The sensors were calibrated in a high-pressure shock-detonation tube using the calculated gasdynamic relations connecting the pressure at the shock wave front with its velocity, and in an explosion tank using standard charges – the ED-8E type commercial electrical detonators.

RESULTS OF CINEMATOGRAPHIC OBSERVATIONS

Study of the high-speed movie data shows that the energy release process when a powerful monopulse laser beam is focused in water has an explosive nature and is accompanied by the same hydrodynamic phenomena which arise during the explosion of chemical explosive charges or during electrical discharges in water.

Figure 2a shows single-frame shadow scan of the development and pulsations of the cavity from breakdown at the focus; only typical frames are shown; the frame speed was 62,500 per sec.

It is easy to see from the pictures the features which are characteristic for all underwater explosions; the formation and expansion of the cavity, the cavity reaching its maximal size, collapse and subsequent pulsations of the vapor-gas bubble.

If the focal spot is close to the free surface of the water, a cavitation zone is formed, just as in the case of the underwater explosion near the surface, and a water spout develops.

Figure 2b shows single-frame shadow pictures of the explosive process when the laser beam is focused near the free surface; only typical frames are shown; the frame speed was 62,500 per sec.

The cavity shape when it reaches its final size is nearly spherical, just like the shape of the cavity which forms in water during the explosion of a concentrated chemical charge. However, the initial stage of cavity development is not characterized by spherical symmetry of the motion. The cavity is elongated along the radiation axis. This nature of the initial stage of cavity development corresponds to the explosion of a cylindrical charge of finite length.

A more detailed study of the initial cavity development stage, made photographically using a shadow setup, shows that the formation of the disturbing centers along the radiation axis in the region of the focal spot is not simultaneous, rather the duration of their formation exceeds by several fold the duration of the radiation input. Initially, very small vapor-gas bubbles arise at the center of the focal spot, then the bubble formation phase displaces rapidly in both directions along the radiation axis. As the vapor-gas bubbles approach and merge with the central formation, they create after a few microseconds the nucleus of the cavitation bubble – a cavity which is elongated along the radiation axis. It is significant that the formation of individual bubbles along the radiation axis, which pulsate independently of the central cavity, continues right up to the time when the central cavity reaches its maximal size.

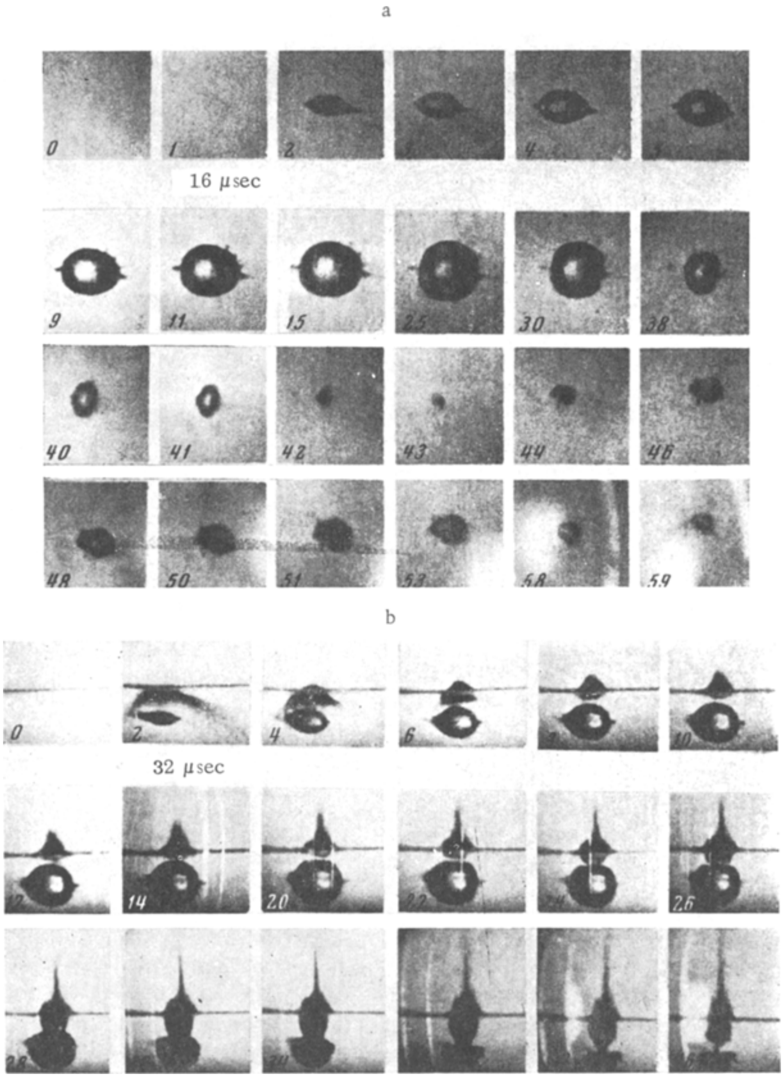

Fig. 2

Measurement of the maximal cavity radius makes it possible to estimate directly the absolute magnitude of the kinetic energy E_r of the radial motion of the liquid, which in turn characterizes quantitatively the value of the photohydrodynamic coefficient. To this end we use the relation for calculating the potential energy stored by the bubble during its expansion to the maximal size [2]

$$E_r = {}^4/_3 \pi r_m{}^3 P_0 \tag{2.1}$$

where r_m is the maximal cavity radius, P_0 is the hydrostatic pressure in the medium.

Analysis of the series of photographs showed that in the case in question the average value of E_r amounts to 4% of the total radiation energy.

Figure 3 shows as an example a continuous schlieren photorecording of the initial cavity development stage, the shock waves from the breakdown at the focus, and the waves reflected from the free surface.

Important characteristics of the explosion process in a liquid are the coefficients which characterize the energy loss of the radial motion of the liquid during sequential pulsations of the bubble. The reduction of the oscillation period and the maximal cavity dimensions during its pulsations is connected uniquely with the intensity of the compression waves which form as the cavity collapses. It is known [2] that the ratio of the energy E_k stored in the kth bubble pulsation to the energy E_{k+1} of the bubble of the (k + 1)st pulsation obeys the relation

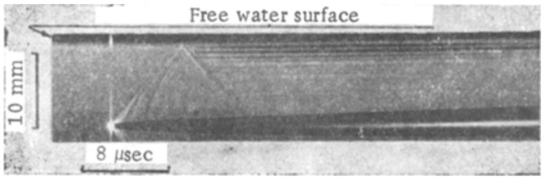

Fig. 3

$$\eta_k = \frac{E_k}{E_{k+1}}\eta_{k+1} = \left(\frac{T_k}{T_{k+1}}\right)^3 \eta_{k+1} \quad (2.2)$$

where T is the period of the corresponding cavity pulsation.

The measurements made in performing the described series of experiments yield the following cavity pulsation characteristics: the maximal cavity diameter in the first, second,and third pulsations is 6.3, 2.9, and 1.6 mm. The periods of successive pulsations are $T_1 = 590$ µsec, $T_2 = 240$ µsec, $T_3 = 130$ µsec. Hence we can obtain the relationships between the energy loss coefficients $\eta_2 = 0.07\eta_1$, $\eta_3 = 0.016\eta_2$.

Comparing these values with the known data [2] for the case of underwater TNT explosions $\eta_2 = 0.34\eta_1$, $\eta_3 = 0.54\eta_2$, we can conclude that there is a faster loss of the liquid radial motion energy in successive pulsations of the cavity caused by laser radiation in a liquid. This is explained to a considerable degree by the deviation of the oscillation process from the centrally symmetric type, which leads to rapid destruction of the cavity. But the primary reason for the intense energy loss in successive pulsations of the cavity is the radiation of comparatively powerful compression waves during cavity collapse. The absence of detonation products in the cavity creates conditions for more complete cavity collapse than is observed during underwater explosion of a chemical charge.

The determination of the dynamic characteristics of cavity development makes it tempting to try to determine the pressure at the focal spot of the laser beam with the aid of the familiar hydrodynamic relations connecting the thermodyanmic parameters of the detonation products in a cavity and the kinetics of the liquid motion. For example, we shall use the relation [3, 4] describing the expansion of a spherical cavity filled with a gas with adiabatic exponent 1.33 in an ideal incompressible liquid as a function of the initial cavity radius r_0, hydrostatic pressure P_0 at the depth of the explosion, and the initial pressure P_1 in the embrionic cavity.

$$P_1 = \frac{P_0\,[1-(r_0/r_m)^3]}{3\,(r_0/r_m)^3\,(1-r_0/r_m)} \quad (2.3)$$

Assuming that the initial radius of the cavity in which the sought pressure P_1 is given is determined by the beam divergence and in the described series of experiments amounts to 0.1 mm, and using the data of the experiments conducted, we can find that this pressure amounts to $10^4 - 10^5$ bar. However this estimate will be extremely rough, even if we consider the water compressibility, which in itself introduces significant corrections into the computational results.

At the focal zone of the laser beam there is formed a superheated vapor-gas medium containing partially ionized products of decomposition of the water. For such a medium we cannot use the relations of the form (2.3), since they were obtained for a sphere filled with an ideal gas with known thermodynamic characteristics. In addition to the uncertainty in the state of the matter at the focal spot in the initial development period of the phenomenon the initial cavity radius, which is not identical with the radius of the focal spot, will also be uncertain. Moreover, the initial disturbances when focusing the laser beam in water does not develop with spherical symmetry and the formation of the individual disturbing centers will not be simultaneous.

Piezoelectric Measurements of the Pressure Field. The complex nature of the development of the explosion process in the focal zone of the laser beam has a unique influence on the pressure field which develops in the region of this spot. Figure 4a, b shows typical oscillograms of the pressure recorded in the first series of experiments at a distance of 30 mm from the laser beam focus.

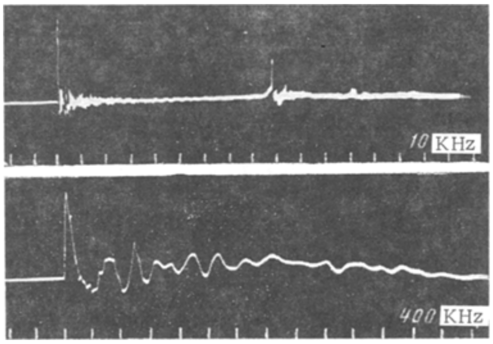

Fig. 4

We see from the record in Fig. 4a (timing marks 10 KHz) that the pressure pulse caused by laser radiation creates in the liquid a series of compression waves corresponding both to the time of beginning of the formation of the cavity and to the times of cavity collapse during its subsequent pulsations. The first compression wave is characterized by an abrupt pressure rise; as a rule the subsequent pulses have a gradual pressure rise.

Shock waves and the series of compression waves which are formed during pulsations of the gaseous sphere are also observed during underwater explosions of concentrated chemical charges. However, the nature of the pressure change behind the shock wave front in the case studied here is significantly different from that in the shock wave of the underwater chemical charge explosion.

The record shown in Fig. 4b, where the pressure pattern of the first pulse is shown stretched out considerably in time (timing marks 400 KHz), shows that immediately behind the first pressure pulse there follows a group of intense compression waves, which are not observed in underwater chemical explosions. The slight subdividing of the compression wave in the experiments described was also recorded for the pressure pulses corresponding to the cavity pulsations.

The formation of such a complex pressure field can be explained by the nonsphericity of the hydrodynamic flow in the vicinity of the focal spot in the initial cavity development period and the nonsimultaneity of the occurrence of the disturbing centers in the focal spot region.

In fact, the photorecording shown in Fig. 3, where the disturbance propagation is clearly recorded with the aid of the shadow photographic technique, shows that the initial disturbance corresponding to the bow shock wave propagates with a velocity close to the speed of sound. But the initial slope of the traces of the subsequent disturbances corresponds to a velocity exceeding the speed of sound in water by 2-3 times. This is explained by the fact that the disturbances visible on the photorecording are radiated by points located on the optical axis of the laser beam but outside the plane of the photorecorder slit. Therefore disturbances having velocities close to the speed of sound and crossing the slit plane at an angle leave on the film a trace whose slope corresponds to its high propagation velocity.

Thus it becomes obvious that the formation of the group of compression waves which follow immediately behind the bow shock wave owes its appearance to the nonspherical nature of the development of the central cavity when the laser radiation is focused in the water and to the independent formation and pulsations of individual vapor-gas bubbles near the central cavity on the optical axis of the laser beam. The conclusions obtained in the oscillographic measurements correspond to the conclusions drawn in optical observations of hydrodynamic processes in the focal point region.

We note that the general qualitative nature of the development of the hydrodynamic processes remains the same when focusing the radiation in distilled water, but the number and intensity of the high-frequency compression pulses accompanying the first disturbances are reduced.

Figure 5 shows on a logarithmic scale the results of analysis of the experimental data for $E = 0.5$ J. Lines 1 and 2 were obtained by measuring the pressures along lines at angles of 45 and 90° to the radiation axis, respectively. Lines 1 and 2 show the amplitudes of the pressure p at the shock wave front as a function of the focal spot distance R, recorded during the first series of experiments. Lines 3 and 4 are the values of p as a function of the distance to the focal point, recorded during the second series of experiments for $E = 1.5$ J in the direction normal to the radiation axis and along this axis, respectively. Comparison of lines 3 and 4 shows that the waves propagating along the normal to the radiation axis exceed in amplitude by more than a factor of two the waves propagating along the optical axis for the same radiation energy.

It follows from the oscillographic measurements that the duration of the bow pressure pulse in the case of the measurements along the normal to the radiation axis is shorter than the wave duration recorded by the sensor along the radiation axis by nearly a factor of two. From this we can conclude that the bow shock wave pulses at the same distance from the focus are nearly similar, regardless of the wave propagation direction.

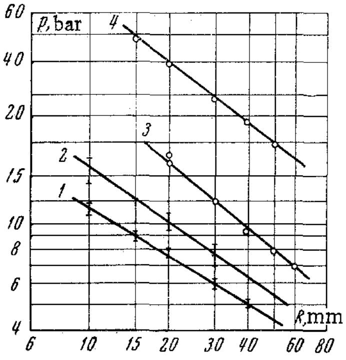

Fig. 5

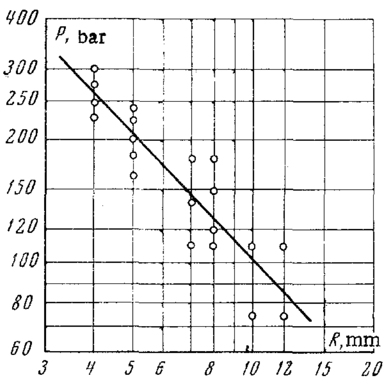

Fig. 6

An essential characteristic of the bow shock wave is the fact that its duration amounts to only 2-3 μsec. Hence it becomes obvious that the resolution of the pressure piezosensors used in this study is not adequate for proper recording of the amplitude at the shock wave front.

Therefore the values shown in Fig. 5 are too low. The correction of the oscillograms by extrapolation of the pulse amplitude [5], which is the method usually used in such cases, will not be applicable here in view of the fact that the shock waves have too steep a pressure dropoff behind the front.

The results of a special series of experiments to determine the pressure on the shock wave front by the "spall" method [2] can serve to illustrate what has been said above.

It is known that the initial rate of rise U of the surface layers of the water in the case of normal incidence of a shock wave on the free surface in the acoustic approximation is defined by the relation

$$U = \frac{2P}{\rho c} \tag{3.1}$$

where ρc is the acoustic resistance of the water.

Figure 6 shows the experimental values of the pressure p as a function of distance for the immediate breakdown zone for E = 0.5 J, calculated from the liquid "spalling" velocity using (3.1); here we have used the measurements of the initial rate of rise of the water dome directly above the focal spot. Figure 2b shows an example of a cinegram of the process. However we note that the conditions for the formation of the "spall" zone in the considered case of a microexplosion have several specific peculiarities. These include the brevity of the action of the compression phase in the shock wave and the large curvature of the shock wave front at the moment it leaves the free surface. These characteristics make it impossible to take the data presented here as absolutely accurate, considering the present status of our knowledge of the "spall" problem in a liquid.

The nature of the relations in Figs. 5 and 6 make it possible to assume that the propagation of the shock wave which forms when monopulse laser radiation is focused in water obeys the energetic similarity principle, which is well satisfied in the case of underwater chemical explosions [2]. In fact, in logarithmic coordinates these relations are straight lines; therefore they can be approximated by the expression

$$P = A\,(E^{1/3}/R)^{\alpha} \tag{3.2}$$

Here E is the laser radiation energy, R is the distance from the measurement point to the focus, A and α are empirical coefficients.

However, analysis of the data showed that while the value of the coefficient α varies in different series of experiments from 0.65 to 0.82, i.e., by only 20%, which can be explained by the pressure measurement errors noted above, the value of the coefficient A changes by 3-4 times, which cannot be explained by any systematic procedural deficiencies. Therefore it is not possible to establish a generalized relation of the form (3.2) on the basis of the described experimental data, particularly since the amplitude of the pressure at the shock wave front depends on the direction of its propagation relative to the radiation axis. The following situation may be the reason for this.

In the underwater chemical charge explosion case, the initial intensity of the shock wave depends only on the parameters of the detonation wave as it approaches the charge—water interface and not on the total amount of charge. However, the dependence of the pressure at the shock wave front on the explosive energy reflects the process of superpositioning of the rarefaction wave, defined by the thermodynamic state of a definite amount of the detonation products contained in the cavity, on the bow shock wave.

In the case of monopulse laser focusing in water, the initial pressure at the focus is determined by the radiation energy and power and this, in turn, leads to dependence of the pressure at the compression bow wave front in the initial stage of its development and, therefore, of the coefficient A on the radiation energy. Hence it becomes obvious that an attempt to estimate the pressure at the focus of the laser beam on the basis of data on the pressure at the shock wave front, using the available hydrodynamic relationships which are valid in underwater explosion physics, may lead to questionable results.

It appears that at present the most reliable estimate of the initial pressure at the center of the focal spot can be obtained using the electrodynamic characteristics of the phenomenon. The excess electrostriction pressure is described by the formula [6]

$$P = \frac{E^2}{8\pi} \rho \left(\frac{\partial \varepsilon}{\partial \rho} \right)_S \tag{3.3}$$

Here E is the intensity of the electric component of the electromagnetic radiation, ε is the dielectric permeability of the medium, ρ is the density of the medium. The electric field intensity [7]

$$E = 1.1 \cdot 10^4 \frac{\sqrt{W}}{a} \qquad (a = \beta f) \tag{3.4}$$

Here W is the laser radiation power, a is the radius of the focal spot, determined by the beam divergence β and the system focal length f.

Assuming that $\rho(\partial\varepsilon/\partial\rho)_s$ is a constant quantity and equal for water to 0.9 [8], and using (3.3), (3.4), we find that the pressure developed at the focus of the laser beam used reaches $10^5 - 10^6$ bar.

The experimental data obtained in this study make possible an estimate of the compression energy of the medium in the shock wave. This estimate does not contradict the previously noted incompatibility of the phenomenon with the principle of energetic similarity which is used in underwater explosion physics. If we take as the time τ of action of the shock wave compression phase the duration of the existence of the first compression wave group, then the shock wave energy is easily calculated from the formula [2]

$$E_p = \frac{4\pi R^2}{\rho c} \int_0^\tau P^2(t)\, dt \tag{3.5}$$

Here R is the distance from the center of the explosion to the measurement point, P(t) is the pressure at the shock wave as a function of time, ρc is the acoustic resistance of water.

From analysis of the piezoelectric measurement data it follows that the quantity E_p is equal to 0.015 J for industrial water (first series of experiments), which amounts to about 3% of the total radiation energy, and 0.045 J for distilled water (second series of experiments). This value of the energy E_p also corresponds to about 3% of the total radiation energy. We assume that these values of E_p were determined at the lower limit, since the peak pressure is quite low.

Moreover, in the calculations it was not always possible to account for the energy of the high-frequency pressure pulses formed by individual gas-vapor bubbles which follow immediately behind the first group of waves. If in computing the energy E_p we take as the pressure the value measured by the "spall" method, then the coefficient of conversion of radiant energy into compression energy in the shock wave increases and in many cases reaches 20%.

Photohydrodynamic Coefficient. In the case of an underwater explosion of a concentrated chemical explosive charge, the charge energy is transformed into two forms of mechanical motion of the medium: into the energy E_r of radial motion of the liquid and into the energy E_p' which is carried away by the shock wave. It has been shown that in the case of underwater TNT explosion these two forms of energy are similar in absolute magnitude and amount to $E_r = 0.47Q$ and $E_p' = 0.53Q$, where Q is the energy of the explosive charge. It follows from the experiments performed in the course of this study that the fraction of the laser radiation energy which is converted into the energy of radial motion of the medium amounts to about 4%, while the fraction of the shock wave compression energy measured in these same experiments is no less than 3%. This implies that the value of the photohydrodynamic coefficient, i.e., the fraction of the total radiation energy converted into energy of mechanical motion of the medium, amounts to no less than 7%. We note that in the case in question E_p and E_r are quantities of the same order.

The experiments conducted show that a significant increase of the magnitude of the photohydrodynamic coefficient in the case of laser radiation focusing in water can be achieved if the ray is focused on the point of a needle or on foil placed in the water. As a rule, in this case the dimensions of the cavitation bubble for the same radiation energy are larger and the bubble acquires a more regular, spherically symmetric form. Calculation using (2.1) shows that the fraction E_r of the energy of the radial motion of the liquid increases to 8-10% when the radiation is focused onto foil.

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