the hydrostatic pressure. It follows from the second result, with allowance for the first, that in the case of sufficiently poor wetting an interval of equilibrium angles exists for which the microlayer enters the interval of unstable thicknesses during growth of the bubble and the contact angle begins to decrease. However, for large bubble diameters the hydrostatic repulsive forces play a definite role, elongating the bubble upward. The curvature of the bubble surface at its base increases, causing the pressure to increase and the microlayer to enter the interval ab of stable thicknesses for which an equilibrium contact angle is formed at the phase interface; this process appears to be confirmed by the high-speed motion pictures (see Fig. 1c).

The foregoing analysis has thus shown that the laws governing the variations of the size of the base and the contact angle in the quasistatic growth of vapor bubbles in a boiling liquid are qualitatively attributable to the specific properties of the liquid microlayer under the bubble.

NOTATION

θ, contact angle (angle formed by the surface of the bulk liquid with the surface coated by a thin liquid layer); $\bar{\theta}$, relative contact angle; d, diameter of bubble base; $\bar{d}$, relative diameter of bubble base; τ, relative bubble growth time; μ, excess chemical potential of microlayer per unit volume; ℓ, thickness of liquid microlayer under vapor bubble.

LITERATURE CITED

1. E. I. Aref'eva and I. T. Alad'ev, "Influence of wettability on heat transfer in boiling," Inzh.-Fiz. Zh., No. 7, 11-17 (1958).
2. S. B. Korotaev and K. P. Prokhorov, Growth and Breakoff of Vapor Bubbles from the Heating Surface in the Boiling of a Saturated Liquid [in Russian], JINR, Obninsk (1978), pp. 1-20.
3. W. Zijl, "Capillary-induced formation of a dry area in a thin liquid layer and adherence of a growing gas bubble at a horizontal wall," in: Two-Phase Momentum, Heat, and Mass Transfer in Chemical Processing and Energy Engineering Systems, Vol. 1 (1979), pp. 263-270.
4. L. M. Shcherbakov, "Contact angles and adsorption," in: Surface Phenomena in Melts and the Solid Phases Produced from Them [in Russian], Shtiintsa, Kishinev (1974), pp. 95-106.
5. T. S. Chigareva, "Cinemicrographic investigation of the mechanism of growth and breakoff of vapor bubbles in the boiling of liquids on horizontal surfaces and pores," Inzh.-Fiz. Zh., 11, No. 6, 773-778 (1966).
6. I. E. Dzyaloshinskii, E. M. Lifshits, and L. P. Pitaevskii, "General theory of van der Waals forces," Usp. Fiz. Nauk, 73, No. 3, 380-422 (1961).
7. A. N. Frumkin, "Bubble wetting and adhesion effects," Zh. Fiz. Khim., No. 12, 337-345 (1938).

HYDRODYNAMIC MECHANISM OF ABSORPTION-WAVE PROPAGATION IN A TRANSPARENT LIQUID UNDER THE ACTION OF A LASER PULSE

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UDC 621.378.385

The hydrodynamic approach is used to study the formation and movement of an absorption wave in water under the action of a pulse from a ruby laser.

The study of the effect of powerful laser radiation on a transparent liquid, begun in [1], is of considerable scientific and practical interest. Most recent studies of the absorption of radiation in transparent condensed dielectrics have been based on the notion

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that the decisive role in the initiation of this process is played by hard microscopic particles (irregularities) on the order of several microns in size [2, 3]. Given sufficient heating, an absorbed particle may generate an absorption wave which propagates from the particle surface into the dielectric. Thus, the initially transparent medium becomes an absorptive medium.

Previous studies have examined mainly breakdown [4] and heat-conduction [5-7] mechanisms of formation and propagation of a radiation absorption zone (RAZ). As regards the breakdown mechanism, it plays a significant role only in the case of very high power densities $I > 10^{11}$ W/cm^2. The heat-conduction mechanism of RAZ propagation, due to its great inertia, plays a significant role in the action of micro- and millisecond laser pulses ($I \sim 10^6$-10^9 W/cm^2). At the same time, there has been almost no study of the formation and propagation of an RAZ under the action of laser pulses of nanosecond duration (molecular-quality-factor regime). With satisfactory focusing, this regime can produce values of $I \sim 10^{10}$-10^{11} W/cm^2 with a pulse duration $\tau \sim 30$-40 nsec. In connection with this, it is interesting to investigate the dynamics of the formation and propagation of an RAZ in a condensed dielectric under the action of a laser pulse of nanosecond duration.

The hydrodynamic (photodetonation) mechanism is the most likely mechanism in this case. This mechanism ensures the formation and propagation of an RAZ in the volume of the liquid dielectric during a short period of time (on the order of the duration of the laser pulse). The action of this mechanism can be represented as follows. Rapid heating of the absorbing irregularity creates high pressure in the surrounding region, and this pressure sends a shock wave out into the medium. The dielectric is heated in the shock wave, and free electrons are generated in the heated dielectric (the generation mechanism will be described below). Since the free electrons efficiently absorb laser radiation, an energy release zone is formed behind the shock front. The formation of this zone leads to further intensive heating of the dielectric, its transition to the plasma state, and loss of transparency. An important parameter of the process which characterizes the energy-release zone is the coefficient of radiation absorption κ_e, which is determined by the concentration of free electrons. The two most likely mechanisms of free-electron generation in a condensed dielectric are the thermal and impact mechanisms. In the first of these mechanisms, bound electrons are thermally excited to the free state. As in [5], we will use Saha's equation to determine the density N_{eT} of the electrons generated in this manner.

In the shock mechanism of free-electron generation in a liquid dielectric (such as water), the following events take place. The passage of a shock wave in the liquid with a pressure on the order of several GPa or more increases the density and temperature of the liquid, which leads to appreciable dissociation: $H_2O \rightarrow H^+ + OH^-$. The electron associated with OH is weakly bound (bond energy no greater than 2 eV). This value is considerably less than the 12.6 eV required to ionize an H_2O molecule. It must also be taken into account that the dissociation occurs in a field of laser radiation. Since the energy bonding the electron to OH is about the same as the energy of a quantum of radiation from a ruby laser (1.78 eV), the electron is almost instantaneously changed from the bound to the free state. It can thus be inferred that the degrees of dissociation and ionization of the molecules coincide. It should be noted that the electron generation effect is very substantial in the case of the combined action of laser radiation and shock compression; for example, it was found in the passage of a shock wave with a pressure of 15 GPa in water that the degree of ionization $\alpha \sim 0.01$ and the temperature $T = 0.08$ eV. The degree of ionization is many orders of magnitude lower for the thermal mechanism of generation, i.e., at a low temperature the mechanism of electron generation by shock compression is predominant. Consequently, the density of free electrons and, thus, the coefficient of absorption of laser radiation depend significantly on the degree of compression of the liquid and its temperature. This means that the rate of energy release is heavily dependent on the hydrodynamic parameters.

Confirmation of the experimental fact that the breakdown threshold of water is markedly increased (by a factor of about two) in the transition from the radiation wavelength $\lambda_1 = 0.69$ μm to $\lambda_2 = 1.06$ μm [8] is obtained within the framework of this model. In fact, at least two quanta with $\lambda = \lambda_2$, in contrast to one quantum with $\lambda = \lambda_1$, are needed to change an electron associated with OH to the free state. Thus, the rate of generation of free electrons is lower at λ_2 than at λ_1, which leads to an increase in the breakdown threshold in the first case.

The study of two-dimensional liquid flow caused by absorption of radiation by an irregularity and the propagation of a shock wave in the liquid is a fairly complex matter. However, to explain the basic laws of RAZ propagation we need only examine the unidimensional case. The formulation of the problem consists of the following. A plate made of an absorbent material and having a thickness d is placed in water. The role of the plate is initiation of initial heating of the liquid. The absorber is rapidly heated by a laser pulse; an absorption wave is formed in the liquid, which is rapidly converted to the plasma state at high temperature. Study of the movement of this absorption wave is the subject of the present investigation.

As is customary in hydrodynamic processes, it is assumed that viscosity, heat conduction, and external heat transfer are slightly dependent on the parameters of the resulting perturbations. We therefore describe their propagation by the system of equations for an ideal compressible fluid: the momentum equation in Eulerian form, and the continuity and energy equations with allowance for volumetric heat release. In a unidimensional approximation the system of initial equations takes the form:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho}\left(\frac{\partial P}{\partial \rho}\right)_T \frac{\partial \rho}{\partial x} + \frac{1}{\rho}\left(\frac{\partial P}{\partial T}\right)_\rho \frac{\partial T}{\partial x} = 0,$$

$$\frac{\partial \rho}{\partial t} + \rho\frac{\partial u}{\partial x} + u\frac{\partial \rho}{\partial x} = 0, \quad \frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + \frac{P}{C\rho}\frac{\partial u}{\partial x} = \tag{1}$$

$$= \frac{1}{C\rho}\frac{dQ}{dt}, \quad \frac{dQ}{dt} = I\varkappa_e(1-R)\exp\left(-\int_0^x \varkappa_e dx\right)\left[1-\exp\left(-\int_0^t \frac{dt}{\tau_p}\right)\right].$$

We augment system (1) by the equation of state of water in the form [9]:

1) $\rho > 1$ g/cm³

$$P(\text{bar}) = \frac{3050\,(\bar{\rho}^{7/3}-1)}{1+0{,}7\,(\bar{\rho}-1)^4}\,(1-0{,}012\bar{\rho}^2F) + 4{,}7\bar{\rho}F\,(T-273);$$

2) $0{,}8 < \rho < 1$ g/cm³,

$$P(\text{bar}) = \xi^4 - 470\bar{\rho}F\xi + 4{,}7\bar{\rho}F\,(T-273), \quad \xi = 10\,(1-\bar{\rho}) + 66\,(1-\bar{\rho})^2 - 270\,(1-\bar{\rho})^3;$$

3) $0 < \rho < 0{,}8$ g/cm³,

$$P(\text{bar}) = \xi^4 - 470\bar{\rho}F\xi + 4{,}7\bar{\rho}F\,(T-273), \quad \xi = 6{,}6\,(1-\bar{\rho})^{0,57}\bar{\rho}^{0,25},$$

where

$$F(\bar{\rho}) = \frac{1+3{,}5\bar{\rho}-2\bar{\rho}^2+7{,}27\bar{\rho}^6}{1+1{,}09\bar{\rho}^6}; \quad \bar{\rho} = \rho/\rho_0, \quad \rho_0 = 1 \text{ g/cm}^3.$$

The following assumptions were made in writing the source in the right side of the energy equation:

1. The approximation of geometrical optics is valid, which leads to an exponential dependence of the absorbed energy on the distance (the last term in Eq. (1)). As is known, this approximation satisfactorily describes the propagation of an absorption wave in an ionized dielectric under the condition $\kappa_e\lambda < 1$ ($\lambda = 0.69$ μm is the wavelength of the radiation from a ruby laser).

2. As is shown by estimates made on the basis of the Frenkel formula for the reflection coefficient and Eqs. (2), appreciable reflection of radiation in the ionized dielectric occurs only when the permittivity $\varepsilon < 0$. With a slight deviation of ε from 0 in the direction of negative values, the reflection coefficient for laser radiation R changes sharply from 0 to 1 (by analogy with the reflection of light from a metal surface). We therefore assume that $R = H(N_e - \bar{N}_e)$, where $\bar{N}_e$ is the critical electron density. We find the latter from the condition $\varepsilon(\bar{N}_e) = 0$. The quantity H is the Heaviside function. Consequently, we do not consider the additional heating of the plasma resulting from radiation penetrating beyond the plane $x = x_0$, where x_0 satisfies the condition $\varepsilon[\bar{N}_e(x_0)] = 0$. Also, dissipation of the energy of the laser radiation is determined by absorption only in a transmitted electromagnetic wave [10].

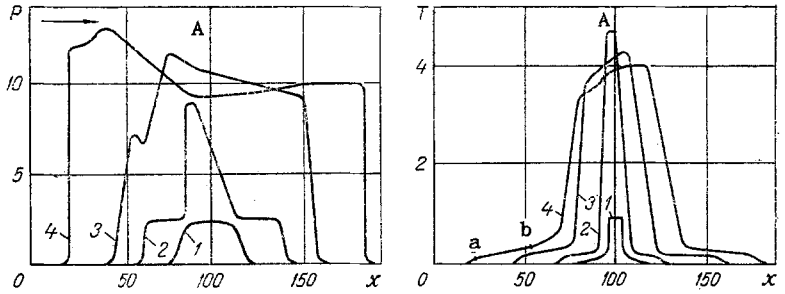

Fig. 1. Dependence of pressure P and temperature T on the coordinate x at different moments of time t: 1) t = 7.8; 2) 15.6; 3) 23.4; 4) 31.2 nsec. The arrow shows the direction of the laser radiation. A stands for the absorber. P is in GPa, T in eV, and x in μm.

The presence of the multiplier in square brackets in the right side of the energy equation is due to the following. Since laser radiation is absorbed by a subsystem of free electrons and heating of the molecular subsystems occurs with elastic collisions by means of energy transport from an electron gas, then in principle, it is possible for the electron temperature to deviate from the molecular temperature in the case of high radiation intensity. Thus, the transfer of the energy of laser radiation absorbed by an electron gas to a molecular subsystem occurs with a certain time lag $\tau_p = MN_0/2mN_e\nu$, where M is the mass of a molecule; N_0 is the volumetric density of the fluid molecules. In this case, the solution of the problem on the basis of the equations of two-temperature hydrodynamics is complicated considerably. System (1) was written with the assumption that the temperatures of the electronic and molecular subsystems are equal, but the source includes the relaxation-type multiplier $[1 - \exp(-\int_0^t \frac{dt}{\tau_p})]$. The latter accounts for the time lag in the transfer of absorbed laser-radiation energy from one subsystem to another.

Proceeding on the basis of the plasma model of the substance, we have the following relation for the radiation absorption coefficient κ_e [11]:

$$\varkappa_e = 2\frac{\omega}{c}\left\{-\frac{\varepsilon}{2}+\left[\left(\frac{\varepsilon}{2}\right)^2+\left(\frac{2\pi\sigma}{\omega}\right)^2\right]^{1/2}\right\}^{1/2}\left[1-\exp\left(-\frac{1{,}78}{T}\right)\right],$$
$$\varepsilon = 1{,}77-\frac{4\pi\sigma}{\nu},\quad \sigma = \frac{N_e e^2}{m}\frac{\nu}{\omega^2+\nu^2}, \tag{2}$$

where $\nu = \nu_0\bar{\rho}$ is the frequency of elastic electron-molecule collisions in a fluid with the density ρ ($\nu_0 = 10^{15}$ sec^{-1}). The dependence of N_{eT} on temperature T (eV) is determined by the Saha formula, which in the case of a low degree of ionization takes the form

$$N_{eT} = 7{,}75\cdot 10^{10}T^{3/4}N_0^{1/2}\exp\left(-\frac{E}{2T}\right). \tag{3}$$

Analysis of empirical data on electrical conductivity led to the following relation for the density of electrons $N_{es}(T, \rho)$ generated in the shock compression of water [12]

$$N_{es} = 6\cdot 10^{18}\bar{\rho}^{(7,2+2,5\bar{\rho})}\exp\left(-\frac{0{,}3}{T}\right)\ \text{cm}^{-3}, \tag{4}$$

where T is in eV. The resulting value of the density of free electrons $N_e = N_{eT} + N_{es}$. To simplify the solution of (1), we assume that the densities of the absorber and fluid are equal and have similar equations of state. We write the absorption coefficient of the absorber in the form $\kappa = \kappa_0\bar{\rho}$. To ensure sufficient initial heating of the absorber during the time of action of a laser pulse with the power density $I > 10^{10}$ W/cm^2, it is necessary that $\kappa_0 I \geqslant 5\cdot 10^{12}$ W/cm^3.

System (1) was solved numerically together with Eqs. (2)-(4) and the equation of state of water for different values of radiation power density I in the range 10^{10}-10^{10} W/cm^2. The solution yielded profiles of the hydrodynamic parameters (pressure, temperature, density, velocity) and the radiation transmission factor $k = \exp(-\int_0^x \kappa_e dx)$ at different moments of

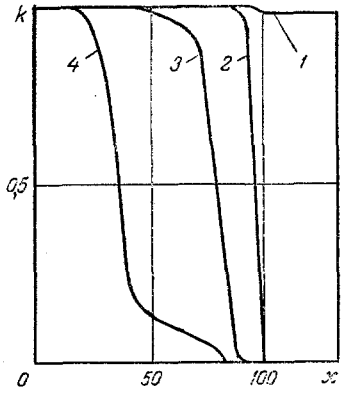

Fig. 2. Dependence of the radiation transmission factor k on the coordinate x at different moments of time t: 1-4) see Fig. 1.

time t. Figures 1 and 2 show typical curves depicting the spatial distribution of pressure P and temperature T as well as the transmission factor k at $I = 3.4 \cdot 10^{10}$ W/cm^2 and d = 3 μm.

The physical picture of the process of RAZ formation and propagation appears as follows [13]. With rapid heating (over several nanoseconds) of the absorber to T ~ 1 eV, absorption is also initiated in the layers of liquid adjacent to it on both sides. Since the density of free electrons N_{eT} and, thus, $\varkappa_e$ are exponentially dependent on temperature, there is a sharp increase in energy release in the liquid. This leads to an increase in temperature (to 3-4 eV) and pressure, which reaches several tens of GPa at $I \sim 10^{11}$ W/cm^2. A shock wave is propagated in the liquid, and temperature increases in this wave due to compression (the temperature increase at $\rho = 1.75$, for example, is $\Delta T \sim 600°K$). In accordance with (4), free electrons are generated in the shock-compressed water and radiation is absorbed in it, which leads to an increase in pressure. Thus, the three-dimensional pressure distribution is the result of two simultaneously competing processes: the occurrence of a shock wave due to energy release in the absorber and liquid; decay of the wave, accompanied by the propagation of shocks in opposite directions.

Analysis of the temperature and transmission-factor profiles (Fig. 2) established that absorption of radiation occurs at the initial moments of time on the high-temperature section of the RAZ (T > 1 eV). There is subsequently an increase in the fraction of energy absorbed on the low-temperature section of the RAZ (T < 0.4 eV), and nearly all of the radiant energy has been absorbed in this section by the end of the pulse (section ab in Fig. 1). Absorption on this section of the RAZ is the result of the generation of free electrons due to compression of the liquid. The width of the low-temperature section of the RAZ increases with an increase in the duration of the laser pulse. Thus, we have the effect of low-temperature displacement of the absorption-wave front counter to the light flux. Solution of the problem also yielded values of the velocity of the front D. For example, with $I = 3.4 \cdot 10^{10}$ W/cm^2, the velocity D reaches about 4 km/sec by the end of the laser pulse. As in the case of the heat-conduction regime of absorption-wave propagation, the velocity D is slightly dependent on the intensity of the laser radiation.

Analysis of the results obtained shows that the liquid loses its transparency when the degree of compression reaches about 1.7. For this to occur, it is necessary that $I > I_s \sim 2.5 \cdot 10^{10}$ W/cm^2, where I_s can be interpreted as the threshold for optical breakdown of water. The experimental value $I_s = (3.8 \pm 1.0) \cdot 10^{10}$ W/cm^2 [8]. Thus, there is satisfactory agreement between the experimental value of I_s and the value obtained from the model examined here. In comparing these values, it must be kept in mind that a significant part of the energy released is transferred to the surrounding layers of liquid under the conditions of the experiment, due to the lateral removal of liquid from the discharge channel. It should be expected that allowing for this fact by means of a two-dimensional approximation will lead to a higher value of I_s, i.e., to more satisfactory agreement between the calculated and experimental values of the breakdown-threshold power density.

NOTATION

P, ρ, u, and T, pressure, density, velocity, and temperature of the liquid; C, specific heat; x, distance along the laser beam; t, time; I, ω, power density and frequency of laser radiation; σ, conductivity of the plasma; c, speed of light; κ_e, R, radiation absorption and reflection coefficients; m, electron mass; e, electron charge; E = 9.0 eV, energy of electron transition from bound state to free state.

LITERATURE CITED

1. G. A. Askar'yan, A. M. Prokhorov, G. F. Chanturiya, and G. P. Shipulo, "Laser beam in a liquid," Zh. Eksp. Teor. Fiz., 44, No. 6, 2178-2183 (1963).
2. S. I. Anisimov and B. I. Makshantsev, "Role of absorbent irregularities in the optical breakdown of transparent media," Fiz. Tverd. Tela, 15, No. 4, 1090-1095 (1973).
3. Yu. K. Danileiko, A. A. Manenkov, V. S. Nechitailo, et al., "Role of absorbent inclusions in the failure of transparent dielectrics due to laser radiation," Zh. Eksp. Teor. Fiz., 63, No. 3, 1030-1035 (1972).
4. Yu. P. Raizer, "Heating of a gas under the influence of a powerful light pulse," Zh. Eksp. Teor. Fiz., 48, No. 5, 1508-1519 (1965).
5. I. E. Poyurovskaya, M. I. Tribel'skii, and V. I. Fisher, "Ionization wave subjected to powerful monochromatic radiation," Zh. Eksp. Teor. Fiz., 82, No. 6, 1840-1852 (1982).
6. I. V. Aleshin, S. I. Anisimov, A. M. Bonch-Bruevich, et al., "Optical breakdown of transparent media containing microscopic irregularities," Zh. Eksp. Teor. Fiz., 70, No. 4, 1214-1224 (1976).
7. E. L. Klochan, S. P. Popov, and G. M. Fedorov, "Transient absorption wave in a transparent solid dielectric," Inzh.-Fiz. Zh., 42, No. 4, 633-639 (1982).
8. V. N. Pozhidaev and A. I. Fedorov, "Thresholds of optical breakdown of liquid water and micron-size droplets under the action of single laser pulses," Kvantovaya Elektron., 8, No. 1, 119-123 (1981).
9. N. M. Kuznetsov, "Equation of state and heat capacity of water in a broad range of thermodynamic parameters," Zh. Prikl. Mekh. Tekh. Fiz., No. 1, 112-118 (1961).
10. V. I. Myshenkov and Yu. P. Raizer, "Ionization wave propagating due to the diffusion of resonance quanta and sustained by superhigh-frequency radiation," Zh. Eksp. Teor. Fiz., 61, No. 5, 1882-1890 (1971).
11. V. L. Ginzburg, Propagation of Electromagnetic Waves in a Plasma, Pergamon (1971).
12. W. B. Holzapfel, "Effect of pressure and temperature on the conductivity and ionic dissociation of water up to 100 kbar and 1000°C," J. Chem. Phys., 50, No. 10, 4424-4428 (1969).
13. E. A. Romashko, G. I. Rudin, and S. I. Shabunya, "Propagation of an absorption wave in a transparent liquid under the action of a laser pulse of nanosecond duration," Pis'ma Zh. Tekh. Fiz., 11, No. 8, 455-459 (1985).

EXPERIMENTAL INVESTIGATION OF THE GAS PERMEABILITY OF SHIELD-VACUUM HEAT INSULATION

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UDC 536.248.1:536.21

This is an experimental and theoretical study of the longitudinal and transverse permeability to gas of screen-vacuum heat insulation.

The level of vacuum and the intensity of molecular heat transfer in layers of shield-vacuum heat insulation (SVHI) are determined both by its gas separation and its permeability to gas, which has been studied extremely insufficiently, both theoretically and experimentally [1-4].

The present work reports on the experimental study of the effect of the structure of shields and interlayers (riffled, crumpled, corrugated, type of perforation, diameter of fibers, thickness, and porosity) and of the density of packing of the layers of SVHI on its longitudinal and transverse permeability to gas in the molecular regime of gas flow and on the verification of the possibility of describing it theoretically on the basis of the diffusion model. The diffusion approach to the description of molecular flows was suggested by

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