For any t and z, expressions (2.4) satisfy the last equation of (2.3) and all the boundary conditions exactly, while the first equation of (2.3) is satisfied approximately since as $t \to \infty$ and $z \leq h$

$$\mathbf{L}_1(c_1, c_2) \leqslant c_0\sigma(Ut - h)^{-1/2} \exp\{-2\sigma U^{-1}(Ut - h)^{1/2}\} \to 0.$$

It is seen from (2.4) that the reagent concentrations in the phases near the reactor entrance equalize with the lapse of time, reaching the value $c \approx c_+ \approx 0$.

Let us note that the approximate expression for the concentration $c(x, t)$ in the continuous phase (2.4) yields the exact value at the reactor entrance for $z = 0$. This is proved by direct integration of the first equation in (2.3) for $z = 0$ with the equality $c_+(t, 0) = 0$ taken into account.

LITERATURE CITED

1. Yu. P. Gupalo, A. D. Polyanin, and Yu. S. Ryazantsev, "On diffusion to a chain of drops (bubbles) for high Péclet numbers," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1 (1978).
2. A. D. Polyanin, "On the diffusion interaction between drops in a fluid," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2 (1978).
3. Yu. P. Gupalo, A. D. Polyanin, and Yu. S. Ryazantsev, "Moving particle interaction effects in the mass transfer in reacting dispersed systems," in: Sixth Int. Colloq. on Gasdynamics of Explosions and Reactive Systems, Stockholm Sweden, AIA (1977).
4. S. Waslo and B. Gal-Or, "Boundary-layer theory for mass and heat transfer in clouds of moving drops, bubbles or solid particles," Chem. Eng. Sci., 26, No. 6 (1971).
5. B. P. Leclair and A. E. Hamielec, "Viscous flow through particle assemblages at intermediate Reynolds numbers. Steady-state solutions for flow through assemblages of spheres," Ind. Eng. Chem. Fundam., 7, No. 4 (1968).

LASER CAVITATION IN LIQUID NITROGEN

P. I. Golubnichii, P. I. Dyadushkin,
G. S. Kalyuzhnyi, S. D. Korchikov,
and V. G. Kudlenko

UDC 620.193.6

Since the first discovery of laser cavitation in liquids [1] a large number of studies of this phenomenon have appeared. The problem is of interest because this is in practice the only way of producing an isolated cavitation bubble within a liquid (with electrical discharges distortions are produced by the presence of the electrodes) and also because of the uncertainty surrounding the state of the material realized when such a cavity collapses. Studies have been made of the dynamics of bubbles formed by laser breakdown in a liquid using a technique based on recording of acoustical and light impulses produced during bubble formation and collapse [1], with high-speed photography [2], and by the shadow method with background illumination by a gas laser [3].

The goal of the present study is to investigate the laser cavitation in a most-simple cryogenic liquid — liquid nitrogen. Due to the closeness of the liquid nitrogen temperature to the boiling point, the pressure within the cavitation cavity at the latter's maximum dimensions, determined basically by the saturated nitrogen vapor pressure, will differ only insignificantly from the external pressure and the degree of bubble compression R/r will be small (here R is the maximum; r, the minimum bubble radius, respectively).

The temperature T within the bubble at maximum bubble compression can be written in the adiabatic approximation as

$$T = T_0(R/r)^{3(\gamma-1)},$$

Voroshilovgrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 103-106, September-October, 1979. Original article submitted October 10, 1978.

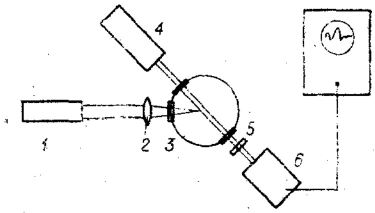

Fig. 1

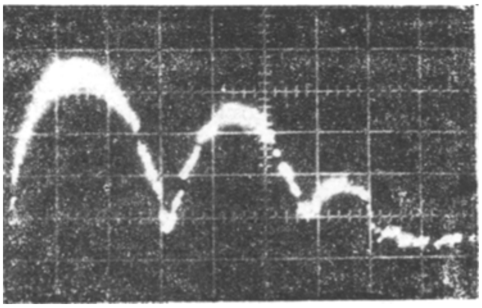
Fig. 2

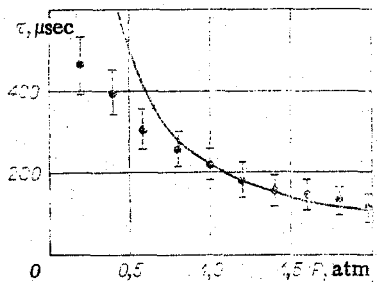

Fig. 3

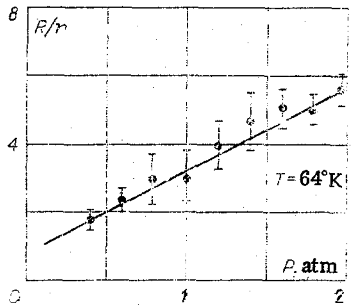

Fig. 4

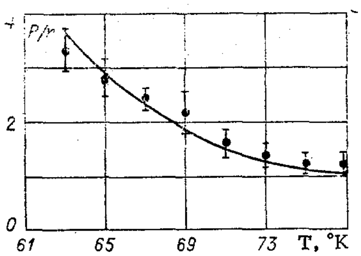

Fig. 5

where T_0 is the initial temperature; $\gamma = 4/3$ is the adiabatic index. As will be shown below, at atmospheric pressure $R/r \simeq 3$. In this case the temperature within the bubble does not exceed 240°K. Thus there will be no light radiation at the moment of bubble collapse.

Registration of acoustical pulses developed upon bubble collapse is complicated by strong reflections from the cryostat walls of the acoustical radiation generated during breakdown.

Thus, it is desirable to use either high-speed photography or the shadow method to study cavitation bubble dynamics. The latter technique is methodologically simpler and generates sufficient information on the cavity (value of the ratio R/r and cavity pulsation period), so it was chosen for the present study.

A block diagram of the equipment used is shown in Fig. 1. The beam from neodymium laser 1 is focused by lens 2 with focal length 25 mm to a point within the liquid nitrogen, located in optical cryostat 3. The laser pulse length was 10 nsec, with a maximum energy level of $\sim 3 \cdot 10^{-2}$ J. The system was adjusted so that breakdown occurred on the straight line connecting the helium–neon laser 4, used for background illumination, and the FÉU-13 photomultiplier 6, in front of which a KS-13 red filter 5 was installed. The light filter was needed to attenuate the light radiation from the breakdown spark incident on the photomultiplier.

A typical oscillogram of cavity pulsations is shown in Fig. 2. Since the cavity dimensions were much larger than the gas laser wavelength, the effective light scattering section may be considered equal to πl^2, where l is the bubble radius. Then the value of the ratio R/r may be obtained from the expression

$$R/r = (A/a)^{1/2},$$

where A is the maximum and a, the minimum, signal amplitude on the shadowgram.

This relationship may be verified in the following manner. It is known that the bubble pulsation period τ depends on the value of the maximum radius R as [4]

$$\tau = 1.83\, R(\rho/P)^{1/2},$$

where ρ is the liquid density and P is the surrounding pressure. Then for the ratio of the periods of the first and second bubble pulsations we obtain

$$\tau_1/\tau_2 = (A_1/A_2)^{1/2},$$

where the index 1 refers to the first pulsation and 2, to the second. This relationship proved valid for all shadowgrams.

Figure 3 shows the dependence of the period of the first pulsation upon the external pressure. The solid line shows the theoretical function $\tau \sim P^{-5/6}$, valid for the condition of constant energy expended by the cavity [4]. It is evident that in the pressure range above 1 atm the experimental data agree well with theory. Below 1 atm there is significant divergence between theory and experiment, which can be explained by the deviation of the cavity from a spherical shape. The amount of such distortion increases with reduction in pressure, due to increase in cavity dimensions, and consequent reduction in the stability of its form. This conclusion may also be confirmed by analysis of shadowgrams, which show significant distortions in pulsation form at low pressures.

Figures 4 and 5 show the dependence of the ratio R/r upon external pressure and temperature. According to [5], the value of the ratio R/r is determined by the gas content parameter $\delta = p/P$, where p is the pressure within the cavity at maximum bubble radius, namely

$$R/r = (1 + 3\delta - \delta^{1.6})/3\delta. \tag{1}$$

In a first approximation one may consider the pressure within the cavity at its maximum dimensions to be equal to the pressure of saturated nitrogen vapor. Results of calculations with Eq. (1) and this assumption are shown by the lines in Figs. 3-5. It is evident that the experimental data agree well with Eq. (1).

Thus, we may conclude that the dynamics of a cavitation cavity in liquid nitrogen are described well by the known expressions for a conventional liquid, with the exception of the low-pressure range, in which non-spherical cavity form begins to play a role. The degree of compression (ratio R/r) in liquid nitrogen is low, not exceeding a value of six (at an excess pressure of 2 atm and temperature of 65°K), as a consequence of which bubble compression is not of a severe character (collapse), leading to the emission of an acoustical pulse, comparable in magnitude to the pulse produced at breakdown. To increase the degree of compression it is necessary to decrease the value of the gas content parameter, which can be done by increasing the external pressure.

LITERATURE CITED

1. A. A. Buzukov and V. S. Teslenko, "Sonoluminescence upon focusing of laser radiation within a liquid," Pisma Zh. Eksp. Teor. Fiz., 14, No. 5 (1971).
2. A. A. Buzukov, Yu. A. Popov, and V. S. Teslenko, "Experimental study of the explosive process generated by focusing a laser monopulse in water," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1969).
3. A. G. Akmanov, V. G. Ben'kovskii, P. I. Golubnichii, S. I. Maslennikov, and V. G. Shemanin, "Laser sonoluminescence in liquids," Akust. Zh., 19, No. 5 (1973).
4. K. A. Naugol'nykh and N. A. Roi, Electrical Discharges in Water [in Russian], Nauka, Moscow (1971).
5. M. G. Sirotyuk, "Experimental studies of ultrasonic cavitation," in: High-Power Ultrasonic Fields [in Russian], Nauka, Moscow (1968).

STRUCTURE OF A SHOCK WAVE FRONT IN A POROUS SOLID

S. Z. Dunin and V. V. Surkov

UDC 534.222.2

The investigation of the nature of wave propagation in substances with a disruption of continuity is important for several reasons: The study of shock heating of a porous material in high-intensity waves makes it possible to deduce the equation of state of the continuous material under anomalous conditions (megabar pressures and temperatures of the order of the melting point) [1]; the majority of materials are not continuous in nature, and the wave propagation process is largely determined by the actual structure of the solid.

In the investigation of shock waves in solids with a disruption of continuity it is essential to take the following considerations into account. First, as in the analysis of a shock front in gases with retarded excitation of certain degrees of freedom [1], the structure of the shock transition in porous solids must be investigated with regard for the inertial properties of the medium [2-4]. Thus, in the shock loading of a porous solid to pressures in the tens of kilobars (such that the influence of heating of the substance can be neglected), the structure of the wave front is affected by the pore-selection dynamics [2-4]. An investigation of this type indicates that the pressure in the substance depends not only on the density of the substance, but also on its derivatives. Second, a number of theoretical and experimental studies [3-8] suggest an appreciable influence of the viscous properties of the porous material on the nature of the propagation and attenuation of shock waves. Third, estimates [2-4, 9] show that the porosity changes significantly only when the entire mass of the solid substance enters into the ductile state.

In the present study we discuss the characteristics of low-intensity shock wave propagation, where the influence of heating of the substance can be neglected (tens of kilobars), but the actual nature of wave propagation is largely determined by the behavior of the porous solid in the ductile state, viz., the pore-selection dynamics exerts a strong influence on the wave structure.

1. The shock profile is investigated in the example of a plane stationary wave propagating with velocity D. In this case all physical quantities (density, particle velocity, etc.) turn out to depend only on one variable $\zeta = x - Dt$, and the equations of mass and momentum conservation are easily integrated. Considering media of low porosity, we can neglect the dependence of the stress deviator on the porosity factor [10] and regard it as constant, with a value close to the yield point of the solid. Then in a coordinate system attached to the shock wave the equations are written in the form

$$\rho_0 D = \rho(D - v),\ p - p_0 = \rho_0 v D, \tag{1.1}$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 106-114, September-October, 1979. Original article submitted September 27, 1978.

0021-8944/79/2005-0612 $07.50