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PROPAGATION OF SHOCK WAVES IN A POROUS MEDIUM SATURATED BY A LIQUID WITH BUBBLES OF A SOLUBLE GAS

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UDC 532.529

The process of evolution and reflection of shock waves of moderate amplitude from a rigid boundary in a porous medium saturated by a liquid with bubbles of a soluble gas is studied experimentally. Experimental values of the amplitude and velocity of the reflected wave are compared with the calculated results obtained using mathematical models. The process of dissolution of gas bubbles in the liquid behind the shock wave is studied.

Based on numerical calculations of the process of collapse of a layer of cavitation bubbles near a solid wall, Kedrinskii [1] observed the appearance of a series of high-amplitude pressure pulses on the wall, which are caused by inertial effects of collective collapsing of the bubbles. A powerful secondary shock wave generated by the collapse of a single bubble in the liquid was observed in the experiments of [2, 3] by optical methods. Shima and Fujiwara [4] studied the interference of the neighboring bubbles on their disintegration and generation of secondary shock waves. Amplification of shock waves in a liquid with vapor bubbles or with bubbles of a readily soluble gas was studied experimentally in [5–9]. The amplification was observed both in the incident wave and in the wave reflected from the rigid boundary.

The evolution and structure of pressure perturbations in a suspension of a liquid with solid particles and gas bubbles and the reflection of perturbations from the rigid boundary was studied theoretically and experimentally in [10–12]. Shreiber [13] proposed a model of propagation of nonlinear acoustic waves in a three-phase mixture. Evolution equations were obtained, which explain some experimental data on wave dynamics in three-phase media. The effects of interphase interaction in multiphase disperse systems including phase transitions and chemical reactions were considered by Theofanous et al. [14] and Hanratty et al. [15]. The stability of interfaces in multiphase media and the dynamics of solid and gaseous inclusions were studied.

The evolution and structure of weakly nonlinear pressure waves in porous media saturated by a liquid or by a liquid with gas bubbles were investigated in [16, 17]. The existence of two types of longitudinal waves ("fast" and "slow" modes) caused by different compressibilities of the porous skeleton and saturating liquid was shown.

In the present paper, we experimentally studied the evolution and reflection of shock waves of moderate strength from the rigid boundary in a porous medium saturated by a liquid with bubbles of a soluble gas. The experimental data are compared with calculations performed using the models proposed by Lyakhov [18] and Nigmatulin [19]. The process of dissolution of gas bubbles in the liquid behind the shock wave is studied.

The experiments were conducted in a "shock-tube" facility [9]. The test section was a vertical thick-walled steel tube with an inner diameter of 0.053 m and a length of 1 m, which was bounded by a solid wall from below. The test section was filled by a saturated porous medium. The porous medium was a random packing of bulk polyethylene particles with a characteristic size of 3.5 mm (porosity $m_0 = 0.37$) or foam rubber ($m_0 = 0.98$). The working liquid was distilled water, and the gas phase was air or carbon dioxide.

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The porous medium was filled by the liquid at a static pressure P_0. The liquid was preliminarily saturated by the gas to the equilibrium state for a given value of P_0. After the decrease in pressure in the test section to the atmospheric value, the gas escaped from the liquid.

Assuming the process of nucleation of gas bubbles to be heterogeneous, which is valid for distilled water, we can estimate the critical radius of the nucleus from which the growth begins [19]: $a_* = 2\sigma/\Delta P_s$, where σ is the coefficient of surface tension of the liquid and ΔP_s is the static-pressure difference. In preparing porous media saturated by water with air bubbles, we have $\Delta P_s \geqslant 0.2$ MPa, and the size of the critical nucleus is $a_* \leqslant 10^{-6}$ m. Since the number of nuclei with the characteristic size $a \approx 10^{-6}$ m per unit volume of water is $n \approx 10^{12}$ m^{-3} [19], we can estimate the bubble radius R_0 reached by the nucleus with decrease in static pressure. For air bubbles, we have $R_0 \approx 50 \cdot 10^{-6}$ m within the range of examined volume contents of the gas.

In experiments with a porous medium saturated by water with carbon-dioxide bubbles, the decrease in static pressure was $\Delta P_s \approx 0.02$ MPa. In this case, the critical radius of the nucleus is $a_* \approx 10^{-5}$ m. A tenfold increase in a_* as compared to air bubbles dramatically decreases the number of nucleation centers of carbon-dioxide bubbles. Correspondingly, the size of carbon-dioxide bubbles after the pressure decrease is significantly greater than the size of air bubbles for identical values of the volume content of the gas. The estimates based on the measurement of the half-width of solitary waves in a porous medium saturated by water with carbon-dioxide bubbles yield the value $R_0 \approx 250 \cdot 10^{-6}$ m.

Changing ΔP_s, we can change the volume content φ_0 of the gas in the liquid. The value of the gas content averaged over the test-section length in a porous medium saturated by a liquid with gas bubbles was determined by the increase in volume of the liquid with decrease in initial static pressure in the medium [17].

Stepwise pressure waves were generated by breaking the diaphragm separating the high-pressure chamber and the test section. The profiles of the pressure waves were registered by piezoelectric pressure transducers located along the test section. The pressure transducers did not contact the skeleton of the porous medium and measured the pressure in the liquid phase. The signals from the transducers were fed to an analog-to-digital converter and processed on a computer.

The shock-wave amplitude was determined in the experiments using the mean pressure value behind the wave front. The shock-wave velocity was found from the time difference between wave registration at two neighboring transducers and the distance between them.

The study of evolution of shock waves of moderate strength in a saturated porous medium shows that the initial signal entering the porous medium is divided into the "fast" and "slow" modes, which is caused by different compressibilities of the porous skeleton and the gas–liquid mixture saturating it [17]. The "slow" wave decays rather rapidly owing to the interphase friction at the liquid–solid skeleton boundary. The "fast" wave retains an almost stepwise shape. In our experiments, we studied the evolution and reflection of a "fast" pressure wave from the solid wall (hereinafter the term "fast" is omitted).

Figure 1 shows typical profiles of shock pressure waves at different distances X from the entrance to the saturated porous medium. The incident (1) and reflected (2) shock waves retain an almost stepwise shape. In the case of rather high amplitudes ($P_1/P_0 \geqslant 10$), significant pressure oscillations are observed at the leading front of the shock wave, which is caused by strongly nonlinear oscillations of the bubbles.

Figure 2 shows the dependence of the shock-wave velocity U_1 in foam rubber saturated by water with gas bubbles on the wave amplitude P_1/P_0 for different parameters of the medium (P_0 is the pressure ahead of the shock wave and P_1 is the pressure behind the shock-wave front). The experimental data lie in the interval between the adiabatic and isothermal approximations for the corresponding parameters of the medium. This is due to the fact that the time of thermal relaxation of the gas in the bubbles $\tau_h = R_0^2/(\pi^2 a_0)$ (a_0 is the temperature diffusivity of the gas in the bubbles) is close to the duration of the leading front of the shock wave, especially for air bubbles of radius $R_0 \approx 50 \cdot 10^{-6}$ m. In addition, some increase in the shock-wave velocity with increasing wave amplitude P_1/P_0 is observed in experiments as compared to calculations (points 2 and curves 5 and 8; points 3 and curves 6 and 9 in Fig. 2). The reason is the decrease in the initial volume content

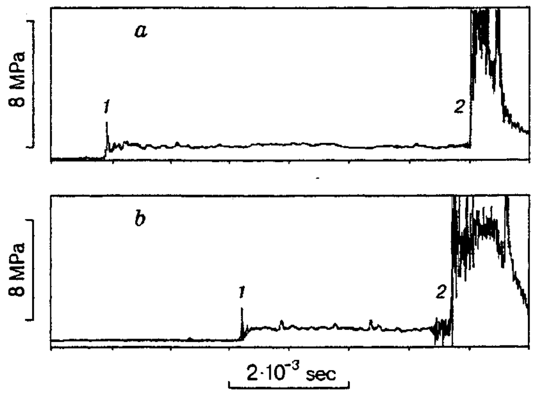

Fig. 1

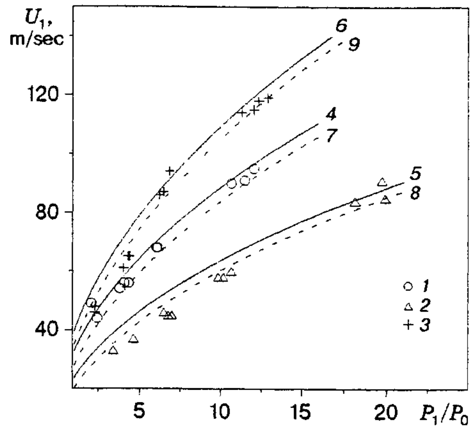

Fig. 2

Fig. 1. Profiles of the incident pressure wave (1) and that reflected from the rigid boundary (2) in foam rubber saturated by water with air bubbles ($m_0 = 0.98$, $\varphi_0 = 0.18$, $P_0 = 0.104$ MPa, and $P_1/P_0 = 10.9$) for $X = 0.38$ (a) and 0.59 m (b).

Fig. 2. Shock-wave velocity versus amplitude ($m_0 = 0.98$): 1–3) experiment; 4–6) calculation by the adiabatic model of [12, 18]; 7–9) calculation by the isothermal model (the ratio of specific heats is $\gamma = 1$) [12, 19]; points 1 and 2 and curves 4, 5, 7, and 8 refer to air ($\varphi_0 = 0.18$ and $P_0 = 0.104$ MPa for points 1 and curves 4 and 7, and $\varphi_0 = 0.19$ and $P_0 = 0.056$ MPa for points 2 and curves 5 and 8); points 3 and curves 6 and 9 refer to carbon dioxide ($\varphi_0 = 0.105$ and $P_0 = 0.104$ MPa).

of the gas in the medium after the passage of the shock wave, since part of the gas leaves the porous medium and the value of φ_0 changes when a shock wave (especially, a strong one) passes over the medium.

Note that these and subsequent calculations of shock-wave velocities in saturated porous media took into account the compressibility of the solid phase, and the modulus of volume elasticity of the porous skeleton was assumed to be equal to zero. The compressibility coefficient of the solid phase was determined experimentally from the measured velocity of sound in the porous medium saturated by a liquid without gas bubbles using Wood's formula [11].

The dependence of the amplitude P_2 of the shock wave reflected from the solid wall in a saturated porous medium on the amplitude P_1 of the wave incident onto the wall for different initial parameters of the medium is shown in Fig. 3. Points 1 and 2 show the experimental data for foam rubber saturated by water with rather small air bubbles ($R_0 \approx 50 \cdot 10^{-6}$ m). Because of the low rigidity and large porosity, the porous skeleton does not exert a significant effect on the process of shock-wave reflection from the solid wall but only confines gas bubbles in the liquid.

It is seen in Fig. 3 that the experimental data (points 1 and 2) are well described by the isothermal model (curves 5 and 6) for the corresponding parameters of the medium. At high amplitudes, the experimental points 2 deviate from the calculated dependence 6, which is caused by the decrease in the initial volume content of the gas in high-amplitude waves (curve 7). In addition, for high wave amplitudes, the process of reflection from the solid wall may approach an adiabatic process due to the decrease in time needed for the formation of a reflected shock wave, which becomes smaller than the time of thermal relaxation of the gas in bubbles [points 1 become closer to the results of adiabatic calculation (curve 3) for $P_1/P_0 \geqslant 10$].

The calculation results with complete dissolution of the gas behind the shock wave incident onto the wall taken into account (curves 8 and 9) are located significantly higher than the experimental data. Thus, the processes of gas dissolution in the liquid behind the shock wave are weak and exert no significant effect on the law of reflection from the solid wall.

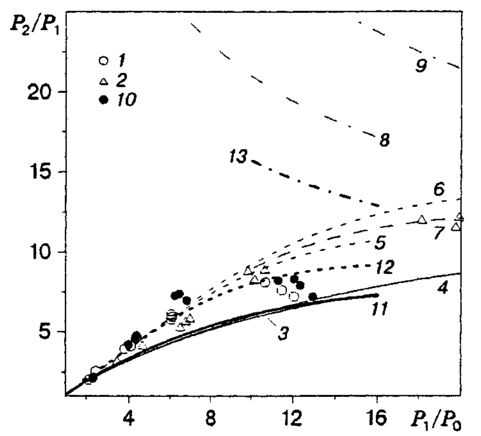

Fig. 3

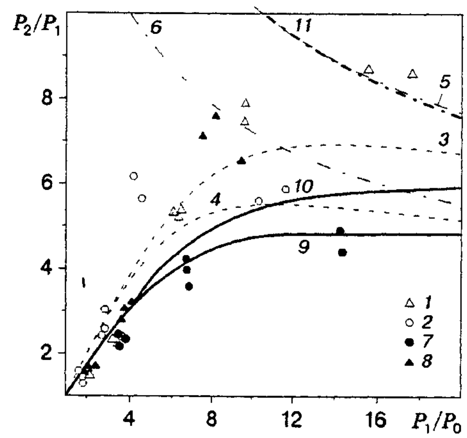

Fig. 4

Fig. 3. Amplitude of the shock wave reflected from the solid wall in a porous medium saturated by water with gas bubbles ($m_0 = 0.98$): 1, 2, 10) experiment; 3, 4, 11) calculation by the adiabatic model of [12, 18] (solid curves); 5–7, 12) calculation by the isothermal model of [12, 19] (dashed curves); 8, 9, 13) calculation of the reflection of the shock wave of complete condensation (dissolution) [12, 19] (dot-and-dashed curves); points 1 and 2 and curves 3–9 refer to air ($\varphi_0 = 0.18$, $P_0 = 0.104$ MPa for points 1 and curves 3, 5, and 8; $\varphi_0 = 0.19$ and $P_0 = 0.056$ MPa for points 2 and curves 4, 6, and 9; $\varphi_0 = 0.14$ and $P_0 = 0.056$ MPa for curve 7); points 10 and curves 11–13 (filled points and bold curves) refer to carbon dioxide ($\varphi_0 = 0.105$ and $P_0 = 0.104$ MPa).

Fig. 4. Amplitude of the shock wave reflected from the solid wall in a porous medium saturated by water with gas bubbles ($m_0 = 0.37$): 1, 2, 7, 8) experiment; 3, 4) calculation by the isothermal model of [12, 19] (dashed curves); 5, 6, 11) calculation of the reflection of the shock wave of complete condensation (dissolution) [12, 19] (dot-and-dashed curves); 9, 10) calculation by the adiabatic model of [12, 18] (solid curves); points 1 and 2 and curves 3–6 refer to air ($\varphi_0 = 0.105$ and $P_0 = 0.103$ MPa for points 1 and curves 3 and 5; $\varphi_0 = 0.095$ and $P_0 = 0.203$ for points 2 and curves 4 and 6); points 7 and 8 and curves 9–11 (filled points and bold curves) refer to carbon dioxide ($\varphi_0 = 0.05$ and $P_0 = 0.103$ MPa for points 7 and curve 9; $\varphi_0 = 0.10$ and $P_0 = 0.103$ MPa for points 8 and curves 10 and 11).

In the case of reflection of shock waves from the solid wall in a porous medium composed of densely packed particles of polyethylene, the pattern becomes qualitatively different. Points 1 and 2 in Fig. 4 show the experimental data for the amplitude of the shock wave reflected from the solid wall in a dense porous medium saturated by water with air bubbles. Beginning from certain values of the wave amplitude P_1/P_0, a significant amplification of reflected shock waves is observed (points 1 and 2) as compared to isothermal calculations (curves 3 and 4), which do not take into account the process of gas dissolution in the liquid behind the wave. Hence, the presence of a dense porous medium and a strongly developed gas–liquid interface intensifies the process of gas dissolution behind the shock wave and, hence, amplifies the reflected shock wave. The mechanism of wave amplification is based on the transition of the kinetic energy of radial motion of the liquid upon bubble collapsing into the potential energy of pressure in the liquid [1, 5, 9]. For implementation of the mechanism of shock-wave amplification, the dissolution of the gas in the bubbles due to the diffusion processes should occur during a time of the order of the duration of the leading front of the shock wave. Otherwise, the regime of accelerating collapse of the bubbles, which leads to the appearance of pressure peaks in the liquid and, hence, to the amplification of the reflected shock wave, is not observed [5].

We note that the process of amplification of reflected shock waves is not related to splitting of bubbles behind the shock wave, as was observed in the case of wave evolution in the liquid with rather large bubbles [9, 12]. The Weber number, which determines the instability and splitting of bubbles in the shock wave, in these experiments was significantly lower than the critical value ($\mathrm{We} = \rho_g R_0 V^2/\sigma \ll \mathrm{We}^* \sim 2\pi$, where ρ_g is the gas density and V is the relative velocity of gas bubbles in the liquid behind the wave).

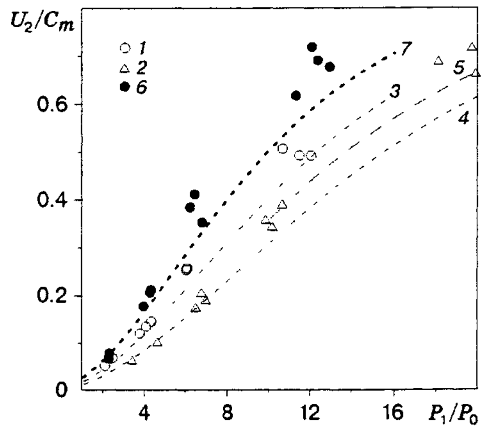

Fig. 5

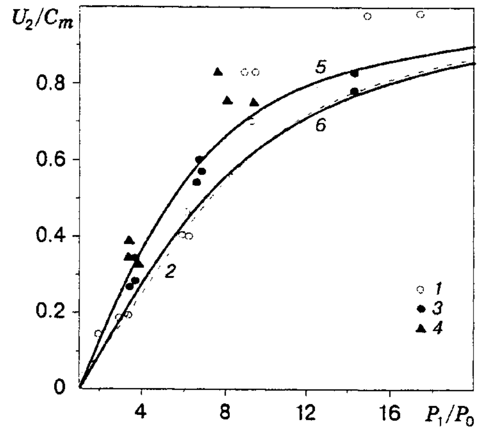

Fig. 6

Fig. 5. Velocity of the reflected shock wave in a porous medium saturated by water with gas bubbles ($m_0 = 0.98$): 1, 2, 6) experiment; 3–5, 7) calculation by the isothermal model of [12, 19]; points 1 and 2 and curves 3–5 refer to air ($\varphi_0 = 0.18$ and $P_0 = 0.104$ MPa for points 1 and curve 3, $\varphi_0 = 0.19$ and $P_0 = 0.056$ MPa for points 2 and curve 4, and $\varphi_0 = 0.14$ and $P_0 = 0.056$ MPa for curve 5); points 6 and curve 7 (filled points and bold curve, respectively) refer to carbon dioxide ($\varphi_0 = 0.105$ and $P_0 = 0.104$ MPa).

Fig. 6. Velocity of the reflected shock wave in a porous medium saturated by water with gas bubbles ($m_0 = 0.37$): 1, 3, 4) experiment; 2, 5, 6) calculation by the isothermal model of [12, 19]; points 1 and curve 2 refer to air ($\varphi_0 = 0.105$ and $P_0 = 0.103$ MPa); points 3 and 4 and curves 5 and 6 (filled points and bold curves) refer to carbon dioxide ($\varphi_0 = 0.05$ and $P_0 = 0.103$ MPa for points 3 and curve 5 and $\varphi_0 = 0.10$ and $P_0 = 0.103$ MPa for points 4 and curve 6).

A comparison of the experimental data 1 and 2 in Fig. 4 shows that an increase in the initial static pressure in the medium P_0 leads to an increase in the amplitude of the reflected shock wave (points 2) as compared to the calculated dependence (curve 4) for lower wave amplitudes P_1/P_0. This is caused by the decrease in the bubble radius with increasing P_0 and, hence, by the increase in the interface area for a constant value of φ_0. In addition, an increase in P_0 leads to an increase in the concentration of the dissolved gas on the bubble surface (an increase in the rate of dissolution of the gas in the liquid).

With increasing P_1/P_0, points 1 and 2 approach the corresponding calculated curves 5 and 6 taking into account the complete dissolution of the gas in the liquid behind the shock wave incident onto the wall. However, the measurements of the velocity of the reflected shock wave show that complete dissolution of the gas in the liquid behind the incident shock wave does not occur. Nevertheless, at high wave amplitudes, satisfactory agreement of experimental data and calculations taking into account the complete dissolution of the gas behind the shock wave is observed.

Points 1 and 2 in Fig. 5 show the experimental dependences of the velocity U_2 of the shock wave reflected from the solid wall in foam rubber saturated by water with air bubbles on the amplitude of the shock wave incident onto the wall P_1/P_0 (C_m is the low-frequency velocity of sound in a porous medium saturated by a liquid without gas bubbles).

Points 1 and 2 in Fig. 5 are well described by the isothermal approximation (curves 3 and 4), which does not take into account the process of gas dissolution behind the shock wave incident onto the wall for the corresponding parameters of the medium. For high wave amplitudes, points 2 deviate from the calculated dependence 4, which is caused by the decrease in the initial volume content of the gas in high-amplitude waves (curve 5). Hence, the process of gas dissolution in the liquid behind the incident shock wave in media in which the effect of the porous skeleton may be ignored is insignificant and does not lead to an increase in the velocity of the reflected shock wave.

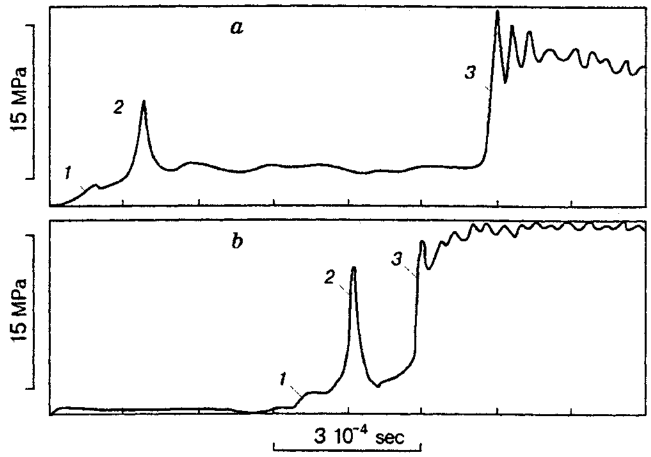

Fig. 7. Evolution of a high-amplitude pressure wave in a porous medium filled by water with air bubbles ($m_0 = 0.37$, $\varphi_0 = 0.05$, $P_0 = 0.1$ MPa, and $P_1/P_0 = 28$): 1) incident shock wave; 2) wave of condensation (dissolution); 3) shock wave reflected from the solid wall; $X = 0.49$ (a) and 0.69 m (b).

Points 1 in Fig. 6 correspond to the experimental values of the velocity of the shock wave reflected from the solid wall in a densely packed saturated porous medium. Curve 2 shows the calculation by the isothermal model of [12, 19]. With increasing wave amplitude, the experimental values of the velocity of the shock wave reflected from the solid wall 1 deviate from the calculated curve 2. Hence, gas dissolution in the liquid occurs behind the shock wave incident onto the wall, which leads to a decrease in the volume content of the gas behind the wave and, consequently, to an increase in the velocity of the reflected shock wave. In the case of $P_1/P_0 > 10$, the experimental values of the velocity of the reflected shock wave significantly deviate from the calculated curve, i.e., the process of gas dissolution determines to a large extent the behavior of the gas behind the shock wave. In the case of propagation of shock waves in three-phase suspensions with rather large bubbles [12], the process of gas dissolution in the liquid behind the shock wave is caused by bubble splitting. As is shown below, the intense mass transfer behind the shock wave in these experiments is caused by the turbulent motion of the liquid behind the shock wave in dense porous media.

For high-amplitude waves in a porous medium saturated by a liquid with gas bubbles, in the case of a rather developed interface surface, the shock-wave amplification occurs not only upon reflection from the solid wall but also behind the front of the incident shock wave. Figure 7 shows typical structures of a high-amplitude shock wave at different distances X from the entrance to the porous medium, which are formed from the initial stepwise signal. As the shock wave 1 propagates over the medium, a high-amplitude pressure pulse 2 is formed behind the shock-wave front. The velocity of this pulse is close to the velocity of the leading front of the shock wave, and the amplitude reaches the value of the amplitude of the shock wave reflected from the solid wall 3. The mechanism of formation of a powerful pressure pulse behind the shock-wave front is related to the origination of pressure oscillations in the liquid upon collapsing of gas bubbles due to their intense dissolution. Because of the large area of the gas–liquid interface and intensification of mass transfer by the turbulent motion of the liquid behind the wave, wave amplification is observed even in media with bubbles of air, which is poorly soluble in water. The process of shock-wave amplification in liquids with bubbles of a readily soluble gas and vapor–liquid media was previously noted in [6, 7].

We consider the reflection of a shock wave from the solid wall in a porous medium saturated by water with bubbles of carbon dioxide, which is readily soluble in water. The solubility of carbon dioxide is 40 to 50 times greater than the solubility of air in water at room temperature. Hence, we can expect a dramatic amplification of carbon-dioxide dissolution in water behind the shock wave and, correspondingly, a stronger amplification of the shock wave reflected from the wall. However, the size of carbon-dioxide bubbles is five times the size of air bubbles. An increase in the bubble size decelerates the process of dissolution. As a result, the amplitudes of reflected shock waves in a porous medium saturated by water with bubbles of carbon dioxide and air differ insignificantly for identical values of the initial volume content of the gas and the amplitude of the shock wave incident onto the wall.

The values of P_2/P_1 for foam rubber saturated by water with carbon-dioxide bubbles are plotted in Fig. 3. For experimental points 10, the time of thermal relaxation of the gas in bubbles is $\tau_h \sim 0.6$ msec. Hence, the heat losses should be insignificant in the course of shock-wave reflection from the solid wall, and the reflection law is close to adiabatic. Nevertheless, a stronger shock wave is observed in experiments as compared to calculations (curve 11). As for air bubbles (see Fig. 4), the amplification of the reflected shock wave is not related to splitting of gas bubbles in the shock wave ($\mathrm{We} \leqslant \mathrm{We}^*$). As is shown below, the intense mass transfer, which leads to the amplification of reflected waves, may be caused by convective diffusion due to the relative motion of gas bubbles in the liquid behind the shock wave.

The decrease in P_2/P_1 for $P_1/P_0 \geqslant 10$ is caused by the decrease in the initial volume content of the gas in strong shock waves, which is confirmed by the increase in velocity with increasing amplitude of the shock wave incident onto the wall (see Fig. 2). The calculation results taking into account the complete dissolution of the gas behind the shock wave incident onto the wall (curve 13 in Fig. 3) are considerably higher than the experimental values, which indicates a moderate process of gas dissolution behind the shock wave.

Points 7 and 8 in Fig. 4 show the experimental data for a dense porous medium saturated by water with carbon-dioxide bubbles. For $\varphi_0 = 0.05$, the experimental data (points 7) are in good agreement with the calculated curve 9, which does not take into account gas dissolution in the liquid behind the shock wave. With increasing initial volume content of the gas ($\varphi_0 = 0.10$), the mass-transfer processes behind the shock wave lead to the amplification of the reflected shock wave (points 8) as compared to calculations (curve 10). As in Fig. 3, the experimental data in Fig. 4 are located significantly lower than the calculated curve, which takes into account the complete dissolution of the gas behind the shock wave incident onto the wall.

Figure 5 shows the experimental values (points 6) of the velocity U_2 of the shock wave reflected from the solid wall in foam rubber saturated by water with bubbles of carbon dioxide readily soluble in water. With increasing wave amplitude P_1/P_0, the experimental values of U_2 deviate from the calculated curve 7. Hence, gas dissolution in the liquid occurs behind the shock wave incident onto the wall, which decreases the volume content of the gas behind the wave and, hence, increases the velocity of the reflected shock wave. The process of gas dissolution behind the shock wave, as is shown below, is brought about by convective diffusion due to the relative motion of gas bubbles in the liquid behind the shock wave.

Figure 6 shows the experimental values (points 3 and 4) of the velocity U_2 of the shock wave reflected from the solid wall in a dense porous medium saturated by water with bubbles of carbon dioxide readily soluble in water. For $\varphi_0 = 0.05$, the experimental data for the shock-wave velocity (points 3) are in good agreement with the calculated curve 5, i.e., gas dissolution in the liquid behind the shock wave is negligibly low. With increasing φ_0, the dissolution becomes considerable, and the experimental points 4 deviate from the calculated curve 6.

A comparison of Figs. 3 and 4 and also Figs. 5 and 6 allows us to conclude that the presence of a dense porous medium has an insignificant effect on the process of carbon-dioxide dissolution behind the shock wave and, hence, on shock-wave amplification upon its reflection.

We consider the process of gas dissolution in a liquid behind the shock wave incident onto the wall in a saturated porous medium on the basis of measurement of the amplitude and velocity of the reflected wave. Substituting the experimental values of the amplitude and velocity of the reflected shock wave into the numerical model of [12, 19], we can calculate the volume content of the gas behind the incident shock wave taking into account the process of gas dissolution in the liquid φ_1^*. From the velocity of the reflected shock wave in individual sections, we calculate the values of φ_1^* for various residence times of the gas phase behind the front of the incident shock wave. Correspondingly, we can determine the relative volume concentration of the dissolved gas behind the shock wave: $\varphi^* = (\varphi_1 - \varphi_1^*)/\varphi_1$, where φ_1 is the calculated value of the volume content of the gas behind the shock wave with ignored gas dissolution for $\gamma = 1$.

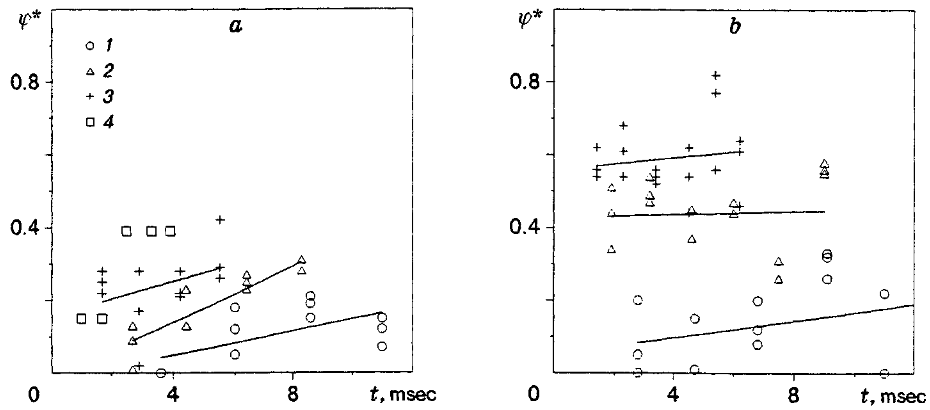

Fig. 8. Relative volume content of the gas dissolved in water behind the shock wave ($m_0 = 0.98$) for air ($\varphi_0 = 0.18$ and $P_0 = 0.104$ MPa) (a) and carbon dioxide ($\varphi_0 = 0.105$ and $P_0 = 0.104$ MPa) (b): $P_1/P_0 = 4$ (1), 6 (2), and 12 (3); $P_1/P_0 = 24$ for $\varphi_0 = 0.114$ (4).

The points in Fig. 8 show the values of φ^* calculated using the above-described technique as a function of the residence time of the gas phase behind the wave front (the porous medium is foam rubber). The solid curves average the calculated values of φ^* for the corresponding parameters P_1/P_0 and φ_0. The calculation was performed using the experimental values of the amplitude and velocity of the reflected shock wave obtained at different sections. The reason for the large scatter of the points is the measurement error for a large number of the medium and wave parameters, which are used in calculations (P_1/P_0, φ_0, U_2, and P_2), and also the nonuniform distribution of φ_0 along the test-section. In a wide range of wave amplitudes P_1/P_0, the relative volume concentration of air dissolved in water depends weakly on the wave amplitude and time and is slightly greater than the measurement error (Fig. 8a). The reason for the weak dependence of φ^* on P_1/P_0 may be the decrease in φ_0 caused by the fact that part of the bubbles leave the porous medium after the passage of the shock wave. A nonuniform distribution of the bubbles along the test-section may lead to a weak dependence of φ^* on time. Thus, diffusion processes in foam rubber saturated by water with air bubbles do not lead to a noticeable change in the volume content of the gas behind the shock wave for $t \sim 10$ msec.

An estimate of the time of collapse of gas bubbles in the case of a stepwise variation of pressure due to the diffusion process $\tau_d = R_0^2/(2D_1(\varphi_R - \varphi_\infty))$ (D_1 is the diffusion coefficient of the gas in the liquid and φ_R and φ_∞ are the volume concentrations of the gas dissolved in the liquid at the bubble boundary and far from it) [20] confirms the insignificant variation of φ^* behind the shock wave with decreasing bubble radius relative to $R/R_0 = (1 - t/\tau_d)^{0.5}$ [20] (Fig. 8a). For example, for $P_1/P_0 = 10$ and $P_0 = 0.1$ MPa, we have $\tau_d \sim 1$ sec. Convective mass transfer due to the relative motion of air bubbles in water is also insignificant, since the time of equalization of phase velocities $\tau_\mu = R_0^2/(18\nu)$ (ν is the kinematic viscosity of the liquid) [19] is dozens of microseconds.

Calculations of the relative concentration of air dissolved in water behind the shock wave in a dense porous medium ($m_0 = 0.37$, $\varphi_0 = 0.105$, and $P_0 = 0.103$ MPa) showed that, for $t = 1$–2 msec, we have $\varphi^* \approx 0.6$ for $P_1/P_0 = 9.2$ and $\varphi^* \approx 0.95$ for $P_1/P_0 = 16.5$. Thus, the presence of a dense porous medium leads to a dramatic intensification of mass transfer at the gas–liquid interface. With increasing wave amplitude, the process of gas dissolution in the liquid is amplified. Assuming that the number of bubbles per unit volume of the medium is constant, we can obtain an expression for the mass-transfer coefficient per unit surface of the bubble behind the shock wave $\beta_t = (d\varphi^*/dt)R/(3(\varphi_R - \varphi_\infty))$. Using the expression for the mass-transfer coefficient in the diffuse regime of bubble dissolution in the boundary-layer approximation $\beta_d = D_1/R$ [21], we obtain the coefficient of mass-transfer enhancement caused by the dense porous medium: $\beta_t/\beta_d = (d\varphi^*/dt)R^2/(3D_1(\varphi_R - \varphi_\infty))$. For a wave amplitude $P_1/P_0 = 16.5$ at the initial stage of bubble collapsing ($R \approx R_0$), the estimate yields $\beta_t/\beta_d \sim 100$. This dramatic increase in mass transfer may be caused by turbulent oscillations of the liquid velocity behind the shock wave in a porous medium. Indeed, the Reynolds number based on the diameter of solid particles of the porous medium d and the relative velocity of the liquid and solid phases W behind the shock wave is $\mathrm{Re}_d = dW/\nu \gg 100$; hence, the liquid-flow regime in the porous medium is turbulent [22]. Note that the time of equalization of velocities of the solid and liquid phases behind the shock wave is considerably greater than the examined shock-wave length.

The calculations of the relative concentration of carbon dioxide dissolved in water behind the shock wave in saturated foam rubber are plotted in Fig. 8b. With increasing wave amplitude, the amount of the gas dissolved in water increases, and the calculated values of φ^* are greater than the calculation error. The calculations for the case of a dense porous medium ($m_0 = 0.37$, $\varphi_0 = 0.10$, and $P_0 = 0.103$ MPa) showed that $\varphi^* \approx 0.6$ for $t = 1$–2 msec and $P_1/P_0 = 8.2$. The calculated values of φ^* in porous media with $m_0 = 0.37$ and 0.98 are rather close for identical wave parameters. Hence, in experiments with carbon-dioxide bubbles, the porous medium has no significant effect on the process of gas dissolution in the liquid behind the shock wave, and the diffusion due to the turbulent motion of the liquid behind the shock wave is not the main mechanism of mass transfer.

Using the dependence for the mass-transfer coefficient for a gas bubble floating up in the liquid in the diffusion boundary-layer approximation [21], we can obtain the expression for the mass-transfer coefficient per unit surface of the bubble due to its relative motion in the liquid behind the shock wave $\beta_c = (2D_1V/(\pi R))^{0.5}$. To estimate the time of collapse of gas bubbles upon a stepwise variation of pressure in the wave due to convective diffusion, we have $\tau_c = 3\sqrt{\pi}/(2\sqrt{2})R_0^{3/2}/((\varphi_R - \varphi_\infty)(D_1V)^{0.5})$. The bubble radius varies in accordance with the relation $R/R_0 = (1 - t/\tau_c)^{2/3}$. For a shock-wave amplitude $P_1/P_0 = 12$ in foam rubber filled by water with carbon-dioxide bubbles, the estimates obtained yield the value of the ratio of the actual mass-transfer coefficient to the convective mass-transfer coefficient at the initial stage of bubble collapse $\beta_t/\beta_c \sim 1$. It was assumed in the calculations that the velocity of the relative motion of the gas bubble in the liquid V equals the velocity of the liquid behind the wave (this is valid for $t \ll \tau_\mu$). Hence, convective diffusion due to the relative motion of gas bubbles in the liquids makes the main contribution to mass transfer behind the shock wave.

An estimate of the time of collapse of carbon-dioxide bubbles behind the shock wave due to convective diffusion for the same parameters yields the value $\tau_c \approx 1$ msec. Taking into account that the time of equalization of velocities of carbon-dioxide bubbles and the liquid behind the shock wave is $\tau_\mu \approx 1$ msec, we can state that the dependences plotted in Fig. 8b are caused by convective diffusion due to the relative motion of gas bubbles and the liquid behind the shock wave. The weak dependence of φ^* on time in Fig. 8b (points 2 and 3) for $t > \tau_\mu \approx 1$ msec also confirms indirectly the action of the convective mechanism of mass transfer behind the shock wave.

Thus, the amplification of shock waves in a porous medium saturated by a liquid with gas bubbles upon wave reflection from the solid wall, which is caused by accelerating collapse of gas bubbles behind the shock-wave front, has been experimentally studied. It is shown that, in the case of small bubble radii ($R_0 \approx 50 \cdot 10^{-6}$ m), the amplification of the reflected shock wave may occur in a medium with bubbles of air, which is poorly soluble in the liquid. Experimental data on shock-wave reflection are compared with calculations.

It is shown that the main mechanism of mass transfer behind the shock wave in porous media saturated by a liquid with small gas bubbles may be diffusion due to the turbulent motion of the liquid behind the shock wave.

For rather large bubbles, in the case of relative motion of gas bubbles in the liquid but without splitting of the bubbles, the main mechanism of mass transfer behind the shock wave is convective diffusion.

REFERENCES

1. V. K. Kedrinskii, "Shock waves in a liquid with gas bubbles," *Fiz. Goreniya Vzryva*, No. 5, 14–25 (1980).
2. W. Lauterborn and A. Vogel, "Modern optical techniques in fluid mechanics," *Annu. Rev. Fluid Mech.*, **16**, 223–244 (1984).
3. Y. Tomita and A. Shima, "High-speed photographic observations of laser-induced cavitation bubbles in water," *Acustica*, **71**, 161–171 (1990).
4. A. Shima and T. Fujiwara, "The behavior of two bubbles near a solid wall," *Arch. Appl. Mech.*, **62**, 53–61 (1992).
5. B. E. Gel'fand, V. V. Stepanov, E. I. Timofeev, and S. A. Tsyganov, "Amplification of shock waves in a nonequilibrium system liquid–bubbles of a dissolving gas," *Dokl. Akad. Nauk SSSR*, **239**, No. 1, 71–73 (1978).
6. V. E. Nakoryakov, B. G. Pokusaev, and I. R. Shreiber, *Wave Dynamics of Gas- and Vapor–Liquid Media* [in Russian], Énergoatomizdat, Moscow (1990).
7. V. E. Nakoryakov, E. S. Vasserman, B. G. Pokusaev, and N. A. Pribaturin, "Amplification of the amplitude of pressure waves in a vapor–liquid medium with a bubbly structure," *Teplofiz. Vys. Temp.*, **32**, No. 3, 411–417 (1994).
8. W. Tepper, "Experimental investigation of the propagation of shock waves in bubbly liquid–vapor mixtures," in: *Proc. of the 14th Int. Symp. on Shock Tubes and Shock Waves* (Sydney, Australia, Aug. 19–22, 1983), New South Wales Univ. Press, Sydney (1983), pp. 397–404.
9. V. E. Dontsov, "Reflection of pressure waves of moderate strength at a solid wall in a liquid with bubbles of a readily soluble gas," *Prikl. Mekh. Tekh. Fiz.*, **39**, No. 5, 19–24 (1998).
10. V. E. Nakoryakov, V. E. Dontsov, and B. G. Pokusaev, "The propagation of pressure waves in a liquid with solid particles and gas bubbles," *Russ. J. Eng Thermophys.*, **4**, No. 2, 173–188 (1994).
11. V. E. Nakoryakov, V. E. Dontsov, and B. G. Pokusaev, "Pressure waves in a liquid suspension with solid particles and gas bubbles," *Int. J. Multiphase Flow*, **22**, No. 3, 417–429 (1996).
12. V. E. Dontsov, "The interaction of a shock wave with a rigid wall in a three-phase suspension," *Russ. J. Eng. Thermophys.*, **7**, Nos. 3/4, 125–139 (1997).
13. I. R. Shreiber, "Bulk viscidity model in acoustic of bubble water saturated soil," *Acustica*, **83**, 430–435 (1997).
14. T. G. Theofanous, W. W. Yuen, and S. Angelini, "The internal dynamic structures of a class of transient dispersed flow with phase change," in: *Book of Abstr. of 3rd Int. Conf. on Multiphase Flow*, Lion, France, June 8–12 (1998), p. 3.6-1.
15. T. J. Hanratty, I. Iliopoulos, and B. Woods, "The roles of interfacial stability and particle dynamics in multiphase flow," *ibid.*, p. 0.1-3.
16. V. E. Nakoryakov, V. V. Kuznetsov, and V. E. Dontsov, "Pressure waves in saturated porous media," *Int. J. Multiphase Flow*, **15**, No. 6, 857–875 (1989).
17. V. E. Dontsov, "Structure and dynamics of pressure perturbations of finite amplitude in a porous medium saturated by a liquid with gas bubbles," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 1, 80–83 (1992).
18. G. M. Lyakhov, *Waves in Soils and Porous Multispecies Media* [in Russian], Nauka, Moscow (1982).
19. R. I. Nigmatulin, *Dynamics of Multiphase Media*, Part 1 and 2, Hemisphere Publ., New York (1991).
20. P. S. Epstein and M. S. Plesset, "On the stability of gas bubbles in liquid–gas solutions," *J. Chem. Phys.*, **18**, No. 11, 1505–1509 (1950).
21. S. S. Kutateladze and V. E. Nakoryakov, *Heat and Mass Transfer and Waves in Gas–Liquid Systems* [in Russian], Nauka, Novosibirsk (1984).
22. M. E. Aérov and O. M. Todes, *Hydraulic and Thermal Fundamentals of Operation of Apparatus with a Stationary and Boiling Granular Layer* [in Russian], Khimiya, Leningrad (1968).