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REFLECTION OF PRESSURE WAVES OF MODERATE INTENSITY AT A SOLID WALL IN A LIQUID WITH BUBBLES OF A READILY SOLUBLE GAS

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The present paper is concerned with an experimental study of the process of gas dissolution behind a shock wave in a liquid with bubbles of a readily soluble gas, the influence of gas dissolution on the wave evolution, and strengthening of the shock wave after reflection from a solid wall.

Reflection of high-amplitude pressure waves at a solid boundary in a liquid with gas bubbles has been investigated theoretically and experimentally [1–3]. It is found that the wave reflection has a substantially nonlinear character. Numerical calculations [4, 5] for the process of collapse of a layer of cavitation bubbles at a solid wall showed that the inertia effects of collective collapse of bubbles give rise to a series of high-amplitude pressure pulses at the wall. In the experiments of [6–8], it was established that in a liquid with vapor bubbles and in a liquid with bubbles of a readily soluble gas, shock-wave strengthening takes place both in incident waves and in waves reflected from a solid boundary.

The experiments described here were performed on a setup of the "shock tube" type [9]. The working section was a thick-walled steel pipe with inside diameter 0.053 m and length 2 m bounded from below by a solid wall and filled with a liquid. Gas bubbles were introduced in the liquid through holes of 0.2 mm diameter along the perimeter of the lower part of the working section. This method of introducing bubbles provided for a fairly high volumetric gas content. The average bubble size for different gas contents varied within 2–4 mm, and the difference in bubble size did not exceed 10–20%. As the working liquid we used distilled water saturated with carbon dioxide to the state of equilibrium under the initial conditions of the experiment (room temperature and atmospheric pressure). Carbon dioxide was used as the gas phase. The gas content averaged over the length of the working section was calculated from measurements of the rise of the liquid column in the working section due to the introduction of gas bubbles. The bubble size was measured by photographing through optical windows in the upper and lower parts of the working section.

Stepped pressure waves were produced by rupture of the diaphragm separating the high-pressure chamber and the working section. Pressure-wave profiles were recorded by six piezoelectric pressure gauges located along the working-section length and flush-mounted with the inner wall. Signals from the gauges were sent to an analog-to-digital processor and then processed on a computer.

Figure 1 shows the shock-wave speed U_1 in water with carbon dioxide bubbles versus the amplitude P_1/P_0. Here C_0 is the low-frequency speed of sound in the gas–liquid mixture and P_0 and P_1 are the pressures ahead of the shock wave and behind its front. Experimental points 1–4 correspond to the following values of the initial volumetric gas content of the medium: $\varphi = 0.05$, 0.10, 0.18, and 0.29. Calculations in the adiabatic approximation $U/C_0 = ((\gamma + 1)P_1/(2\gamma P_0) + (\gamma - 1)/2\gamma)^{0.5}$ [1] are shown by a solid curve; calculations using the approximation $U/C_0 = ((P_1/P_0 - 1)/(\gamma(1 - (P_1/P_0)^{-1/\gamma})))^{0.5}$ [10] are shown by a dashed curve; γ is the adiabatic exponent; gas dissolution behind the wave was ignored in the calculations.

It is obvious that the calculation results are fairly close to each other and describe the experimental data adequately. The results calculated in the isothermal approximation ($\gamma = 1$) lie somewhat above these

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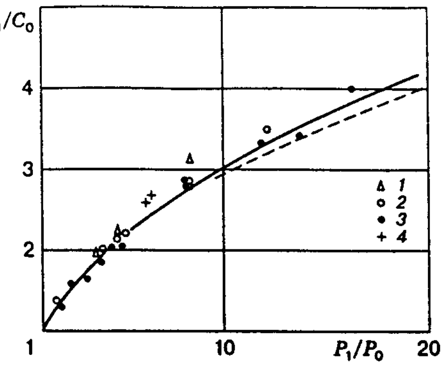

Fig. 1

curves. As will be shown below, intense dissolution of carbon dioxide in water proceeds behind the front of a shock wave of moderate amplitude. Hence, one can assert that the gas dissolution in the liquid behind the shock wave practically does not influence the speed of the wave leading edge in the investigated range of parameters of the waves and the medium. The experiments showed that the gas dissolution does not influence the shock-wave structure and does not lead to a change in its amplitude and shape in the investigated range of parameters of the wave and the medium.

However, the wave pattern changes qualitatively when the shock wave is reflected at a solid wall in a liquid with bubbles of a readily soluble gas. Figure 2a shows the evolution of the incident shock wave 1 and the wave reflected at the solid wall 2 in water with carbon dioxide bubbles (x is the distance from the entry of the wave to the gas–liquid medium to the point of measurement of the wave profile). It is evident that the shock wave is significantly strengthened upon reflection from the solid wall. In addition, the stepped shape of the reflected shock wave practically does not change until the arrival of the rarefaction wave 3 reflected from the free surface of the gas–liquid medium.

The amplitude P_2/P_1 of the shock wave reflected at the solid wall in water with carbon dioxide bubbles versus the amplitude P_1/P_0 of the shock wave incident on the wall is shown in Fig. 2b (the points are experimental data for different values of the initial volumetric gas content of the liquid). Curves 1–10 show results of calculations using different models for the following values of volumetric gas content: curves 1, 4, and 7 for $\varphi = 0.05$, curves 2, 5, and 8 for $\varphi = 0.10$, curves 3, 6, and 9 for $\varphi = 0.18$, and curve 10 for $\varphi = 0.29$. Curves 1–3 correspond to calculations using the adiabatic model of Lyakhov [10], and curves 4–6 correspond to calculations by the isothermal model of Nigmatullin [11] taking into account the compressibility of the liquid but ignoring the gas dissolution in the liquid behind the wave. Curves 7–10 refer to calculations of the reflection of a shock wave of condensation (dissolution) [11]. It is assumed that the gas is completely dissolved in the shock wave incident on the wall and the reflected shock wave propagates in the pure liquid.

Beginning with wave amplitudes $P_1/P_0 \approx 4$, significant strengthening of reflected shock waves is observed, unlike in the calculations (curves 1–6), which ignore gas dissolution in the liquid behind the wave. With increase in the volumetric gas content, the strengthening of the reflected waves becomes more considerable. This agrees with the mechanism for shock-wave strengthening in gas–vapor–liquid media proposed in [6, 7]. This wave strengthening mechanism involves conversion of the kinetic energy of the radial motion of the liquid to the potential energy of the liquid pressure upon bubble collapse [4, 7]. For the occurrence of this mechanism, it is necessary that the gas dissolution in bubbles due to diffusion proceed in a time of the order of the duration of the shock-wave leading edge. Otherwise, the regime of accelerated bubble collapse, leading to occurrence of pressure jumps in the liquid, will not be observed [7]. One factor that accelerates the interphase mass exchange is an increase in the interface, which is possibly caused by breaking of bubbles in the wave. From Fig. 2b it is evident that the threshold for the amplitude P_1/P_0 of the beginning of the wave strengthening due to reflection ($P_1/P_0 \approx 4$) corresponds to the threshold of intense breaking of 2–4-mm bubbles in shock waves [12]. Indeed, at pressures higher than the threshold ones, bubble breaking behind the

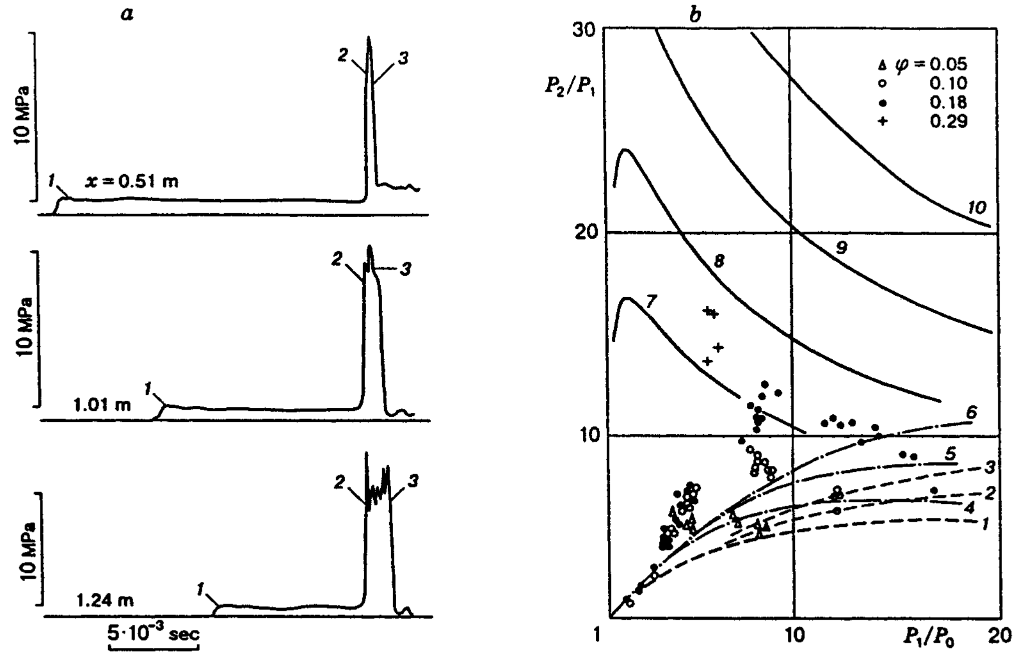

Fig. 2

shock wave incident on the wall leads to a considerable increase in the interface. Hence, the reflected shock wave propagates in the medium with a well developed interface, and the bubble gas dissolves during the time of passage of the front of the reflected shock wave. In the last stage of bubble collapse, powerful pressure pulses arise in the liquid, resulting in strengthening of the reflected shock wave.

Calculations taking into account complete condensation (dissolution) in the incident shock wave (curves 7–10) give only qualitative agreement with the experiment. This is due to the fact that in these calculations, gas dissolution proceeds instantaneously behind the shock wave incident on the wall, and this leads to strengthening of waves with a rather low amplitude $P_1/P_0 \approx 1$. In the experiments, "shock" dissolution, leading to a strong increase in pressure in the medium, occurs only in the presence of a fairly developed interface and, as a result, the strengthening in the experiment begins with wave amplitudes of $P_1/P_0 \approx 4$.

We note that the shock-wave strengthening due to reflection from the wall is observed for a rather narrow range of wave amplitudes P_1/P_0. With increase in P_1/P_0, the experimental points for the first three values of φ fall, respectively, on curves 1–3, calculated in the Lyakhov adiabatic approximation ignoring the dissolution process. This is apparently due to the fact that behind incident shock waves with amplitude $P_1/P_0 \geqslant 10$, the volumetric gas content decreases considerably (owing to both adiabatic compression of the bubble gas and dissolution). As a result, the kinetic energy of the radial motion of the liquid decreases considerably due to bubble collapse in the reflected shock wave, and the process of "shock" dissolution proceeds only slightly.

We consider the process of gas dissolution in the liquid behind the shock wave incident on the wall using results from measurements of the amplitude and speed of the reflected wave. Figure 3 shows experimental curves of the speed of the shock wave reflected from the solid wall U_2 (curves 1–3) and the speed of the rarefaction wave reflected from the free surface of the gas–liquid mixture C_2 (curves 7 and 8) versus the amplitude of the shock wave incident on the wall (C_1 is the speed of sound in the liquid). Curves 1 and 7 correspond to initial volumetric gas content $\varphi = 0.05$, curves 2 and 8 correspond to $\varphi = 0.10$, and curve 3 corresponds $\varphi = 0.18$. Curves 4–6 show results of calculations performed in the Lyakhov adiabatic approximation [10] ignoring gas dissolution in the liquid for different volumetric gas contents ($\varphi = 0.05$, 0.10, and 0.18).

It is evident that for wave amplitudes $P_1/P_0 \geqslant 2$, the experimental speeds of the shock wave reflected from the solid wall (curves 1–3) deviate considerably from the corresponding calculated curves 4–6. Hence,

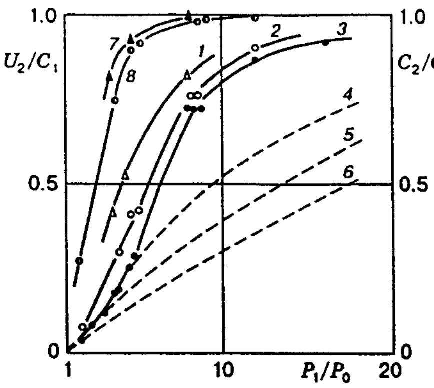

Fig. 3

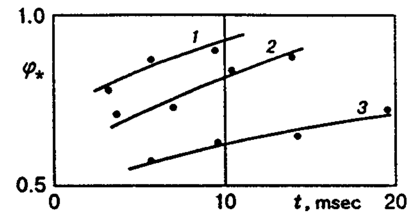

Fig. 4

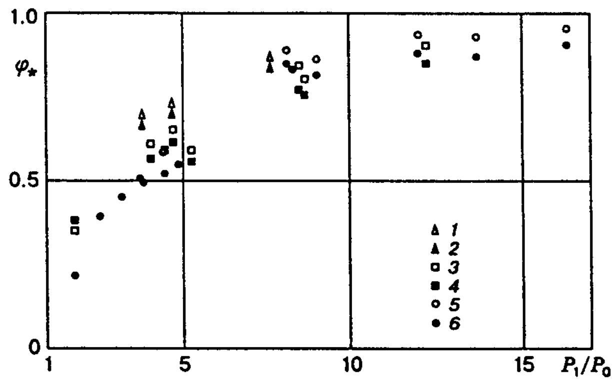

Fig. 5

behind a shock wave with amplitude $P_1/P_0 \geqslant 2$ that is incident on the wall, gas dissolution in the liquid proceeds, leading to a considerable decrease in the volumetric gas content behind the wave and, hence, to an increase in the speed of the reflected shock wave.

Thus, substituting the experimental amplitude and speed of the reflected shock wave at given initial φ into the formula for calculating the speed of the reflected shock wave [10], one can calculate the volumetric gas content behind the incident shock wave with allowance for gas dissolution in the liquid φ_1^*. Accordingly, it is possible to calculate the relative amount of the gas dissolved behind the shock wave: $\varphi_* = (\varphi_1 - \varphi_1^*)/\varphi_1$, where φ_1 is the calculated volumetric gas content behind the shock wave ignoring the dissolution process.

Figure 4 shows calculated curves of the relative amount of carbon dioxide dissolved in water behind the incident shock wave versus the time of stay of the gas phase behind the incident shock wave (time of dissolution) for initial volumetric gas content $\varphi = 0.1$ and for $P_1/P_0 = 12.2$, 8.5, and 4.8 (curves 1–3). The calculation was performed using reflected shock wave speeds measured on certain segments of its propagation, and the dependence for the speed of the shock wave reflected from the solid wall, calculated by the adiabatic Lyakhov model [10].

It can be seen from the curves that the rate of gas dissolution behind the wave decreases with increase in the time of dissolution and, apparently, has a maximum value at the initial moment of bubble dissolution. The slight change in φ_* in the later stage of bubble dissolution allows one to estimate dependences of φ_* on the parameters of the waves and the medium at times $t \approx 10$ msec.

Figure 5 shows calculated dependences of the relative amount of carbon dioxide dissolved in water behind the incident shock wave φ_* on P_1/P_0. Points 1 and 2 correspond to volumetric gas content ahead of the wave $\varphi = 0.05$, points 3 and 4 correspond to $\varphi = 0.10$, and points 5 and 6 correspond to $\varphi = 0.18$. The values at points 1, 3, and 5 are calculated from reflected shock wave speeds measured on a segment of the order of 0.5 m at the entrance to the gas–liquid mixture, and the values at points 2, 4, and 6 are calculated from the speeds measured on a segment of the order of 1 m. Therefore, because of the dependence of the speed of the reflected shock wave on P_2/P_1 and the volumetric content φ_1^*, the times of stay of gas bubbles behind the incident shock wave (times of dissolution) are different for all points. In the present experiments, the times of dissolution vary within 6–15 msec. However, despite the sufficiently approximate representation, the dependence obtained allows one to judge the process of gas dissolution behind the shock wave. It is obvious that for wave amplitudes of $P_1/P_0 \approx 5$, the changes in the volumetric gas content behind the shock wave due to adiabatic compression and dissolution become comparable in time $t \approx 10$ msec. For $P_1/P_0 \geqslant 10$, the main process determining the gas content behind the wave is the gas dissolution in the liquid.

In the calculation of φ_* (Figs. 4 and 5), we used the adiabatic Lyakhov model [10]. It was assumed that the dissolution process behind the reflected wave does not significantly affect its speed. However, this may not be true for waves of high amplitude. From Fig. 3 it can be seen that for $P_1/P_0 \geqslant 10$, the speed of the rarefaction wave reflected from the free boundary of the gas–liquid mixture is practically equal to the speed of sound in the liquid. Hence, the shock wave reflected from the solid wall is a wave of complete condensation (dissolution), and in calculations of φ_*, one must use the model of complete condensation in a shock wave [11]. But the difference between values of φ_* obtained using the model of complete condensation and the adiabatic Lyakhov model is less than 10% for amplitudes of $P_1/P_0 \geqslant 5$ and less than 2% for $P_1/P_0 \geqslant 10$. This allows one to use the Lyakhov model with a certain degree of accuracy over the entire interval of wave amplitudes.

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