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EVOLUTION OF PRESSURE WAVES IN A LIQUID WITH BUBBLES OF TWO DISSIMILAR GASES

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The structure and dissipation of moderate-amplitude pressure waves in a liquid with bubbles of two dissimilar gases (*freon and helium*) *are experimentally studied. It is shown that introduction of a small* (*by volume*) *quantity of helium bubbles with a high thermal conductivity into a liquid with poorly heat-conducting freon bubbles, sharply increases the rate of damping of solitary pressure waves.*

Evolution of pressure waves in a liquid with gas bubbles has been extensively studied both experimentally and theoretically (see [1, 2]). In particular, it was shown that an initial perturbation in a gas–liquid medium may decompose into solitary waves — solitons, whose properties have been studied in much detail. It was found that the main mechanism of wave dissipation in gas–liquid media is heat transfer between the gas in bubbles and the ambient liquid. In our previous works [3, 4], we experimentally studied the structure and dissipation of moderate-intensity solitary pressure waves in a gas–liquid mixture. Kedrinskii [5] and Shagapov [6] showed that the allowance for the polydisperse composition of a gas–liquid medium leads to an additional attenuation of pressure perturbations in it, the wave structure remaining unchanged. Effects of gas–liquid mixture nonuniformity and liquid compressibility on the structure of pressure waves was studied by Beylich and Gulhan [7] and Kameda et al. [8]. Gasenko et al. [9, 10] found that, in a bubbly liquid, oscillatory solitary waves (multisolitons) of two different sizes, related to two degrees of freedom in the medium, might exist. In [11, 12], we experimentally studied the structure and dissipation of oscillatory solitary waves in a liquid with gas bubbles for different ratios of bubble radii.

In the present paper, the structure and dissipation of moderate-amplitude pressure waves in a liquid with bubbles of two dissimilar gases (freon and helium) for the cases of identical and two different bubble sizes is experimentally studied.

The test were carried out on an experimental setup of the shock-tube type. The test section was a vertically installed thick-walled steel tube with a 0.053-m inner diameter and 1.5-m length. The test section was filled with a liquid saturated with gas bubbles produced by two independent generators located in the lower part of the tube. The bubble generators were calibrated glass capillaries. A more refined choice of capillaries in each generator was achieved using gas-bubble filming. The latter allowed us to obtain a bubbly liquid with bubble sizes identical within ±5%. As the working liquid, we used a 50% (by mass) glycerin solution in distilled water. The gas phase was either Freon 12 or helium. It should be noted that the thermal diffusivity of helium is fifty times that of freon. The gas bubbles, as they ascended to the free surface, had a spherical shape. The mean (over the length of the test section) volume fraction of the gas in the bubbles $\varphi_{\rm f,h}$ was determined from the rise of the liquid level in the test section after the liquid was saturated with bubbles of a certain diameter $d_{\rm f,h}$. Here the subscripts "f" and "h" refer to freon and helium, respectively. The tests were conducted at a static atmospheric pressure p_0 at the free surface of the gas–liquid mixture.

Domelike pressure waves were generated by an electromagnetic wave generator mounted at the bottom of the test section, owing to repulsion of a thin copper plate from an induction coil fed with electric-current pulses. The waveform of the pressure waves was measured by six piezoelectric sensors installed over the entire length of the test section. The signals from the piezoelectric sensors were fed to an analog-to-digital converter to be subsequently analyzed on a computer.

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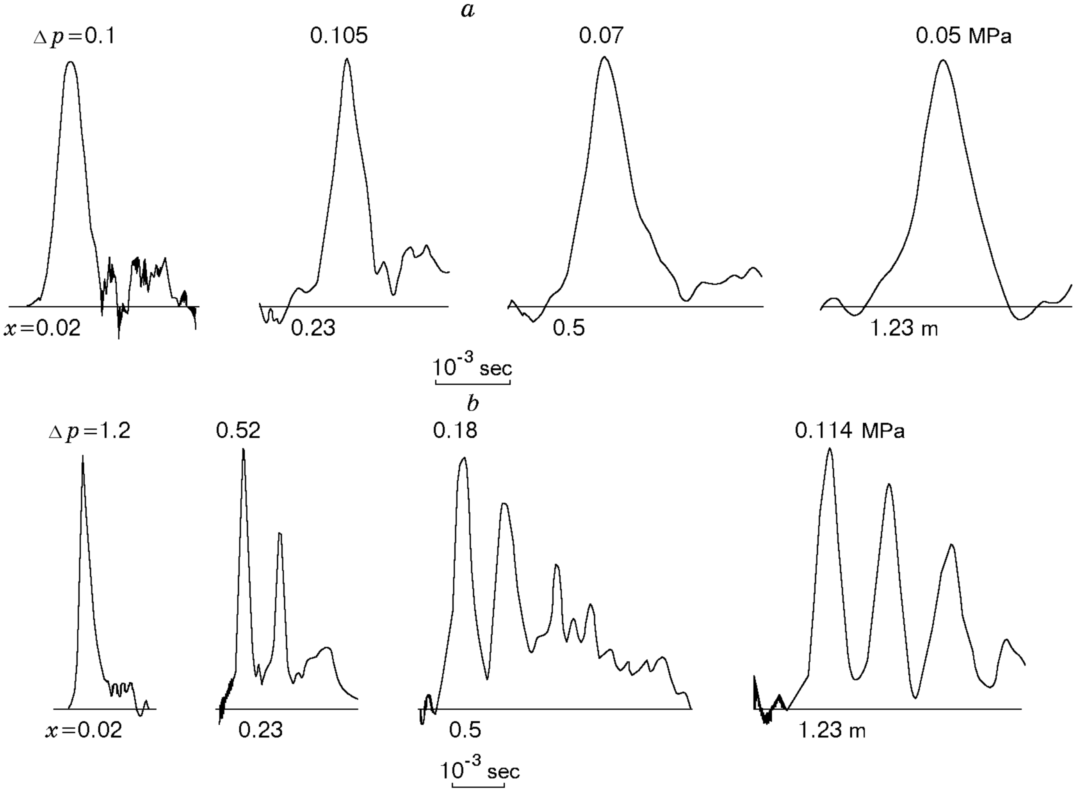

Fig. 1. Evolution of a pressure wave in a liquid with freon bubbles ($d_f = 2.3$ mm and $\varphi_f = 1.2\%$) for $\Delta p_0 = 0.1$ (a) and 1.2 MPa (b).

The experimental data showed that the proportion between the poorly heat-conducting freon bubbles and well hear-conducting helium bubbles in the gas–liquid mixture largely determined the wave structure in it and substantially influenced wave dissipation. Figure 1 shows the time evolution of pressure waves in the liquid with freon bubbles at various distances x from the place where the initially dome-shaped pressure waves were generated. These data were obtained for two initial wave amplitudes Δp_0 (Δp is either the wave amplitude or the first-oscillation amplitude in a train of solitary waves or oscillating shock waves). In the case of small wave amplitudes (Fig. 1a), the initial perturbation transforms into a solitary wave (soliton) ($x = 0.23$ m), which decays as it propagates in the medium owing to dissipative processes. As the amplitude of the input signal increases, two or more solitary waves emerge (Fig. 1b), which become independent at a distance $x = 1.23$ m.

The main mechanism of dissipation of solitary waves in a liquid with gas bubbles is heat exchange between the gas contained in the bubbles and the ambient liquid [1–3]. According to [3], the main parameters that govern the heat-transfer intensity during bubble compression in the wave are the thermal diffusivity of the gas, the bubble radius, the volume fraction of the gas in the liquid, and the amplitude of the solitary wave.

Figure 2 illustrates the evolution of a pressure wave in a liquid that contains freon bubbles with only a small (by volume) admixture of helium bubbles of the same size. In the case $\Delta p_0/p_0 \approx 1$, addition of a small amount of helium bubbles into the medium without changing its total gas content sharply increases the attenuation factor for solitary waves (Fig. 2a). The latter is caused by the fact that the wave structure is mainly determined by freon bubbles, whereas the predominant contribution to wave attenuation is due to helium bubbles. As the input wave amplitude increases, the dissipative losses also grow in value, which leads to the formation of an oscillating shock wave from the initial signal (Fig. 2b). The increase in the dissipative losses with increasing wave amplitude is caused by enhanced heat transfer between the gas bubbles and the liquid due to a more intense compression of bubbles in the wave. The change in the wave structure, in turn, weakens wave attenuation because of the additional energy supply to the leading front of the oscillating shock wave. As a consequence, the wave dissipation due to helium bubbles added into the medium turns out to be less pronounced for waves with a high amplitude. A considerable increase in the damping rate of high-amplitude waves due to addition of a small amount of helium bubbles may be

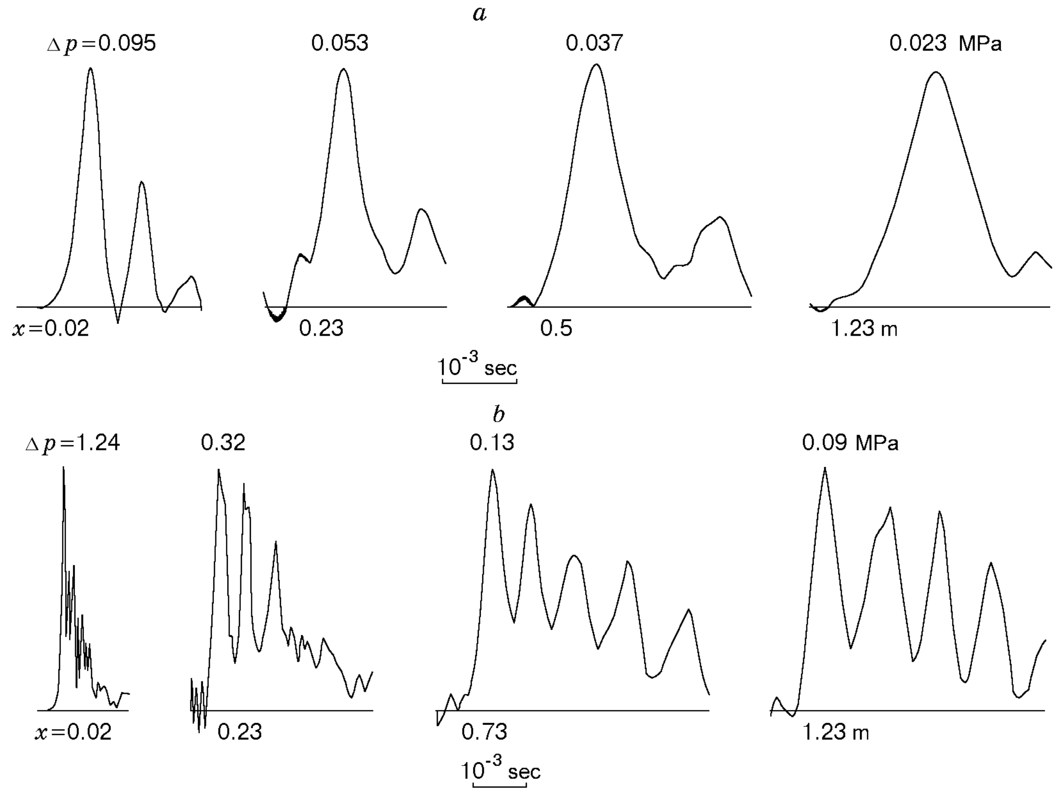

Fig. 2. Evolution of a pressure wave in a liquid with freon and helium bubbles ($d_f = d_h = 2.3$ mm, $\varphi_f = 1\%$, and $\varphi_h = 0.2\%$) for $\Delta p_0 = 0.095$ (a) and 1.24 MPa (b).

obtained in a liquid with larger bubbles. An increase in the gas-bubble size allows one to transform the initial signal into a train of independent solitary waves. Since the damping rate for independent solitary waves is substantially higher than that for an oscillating shock wave, the effect here will be quite appreciable.

An increase in the volume fraction of helium bubbles in the gas–liquid mixture increases the damping rate of pressure waves. If the volume fraction of helium bubbles is large ($\varphi_h = 1\%$ and $\varphi_f = 0.2\%$), the initial signal immediately transforms into shock waves whose oscillations rapidly die away, and dissipative processes prevail over nonlinear and dispersive processes even for large wave amplitudes, which results in rapid smoothing of oscillations and formation of a monotonic shock wave.

Figure 3 shows the attenuation factor for a pressure wave in a liquid with freon and helium bubbles versus the wave amplitude. At the distance $x = 0.23$ m (Fig. 3a), the helium-bubble content of the gas–liquid mixture has a strong impact on wave dissipation, which is most pronounced at $\Delta p_0/p_0 \approx 1$ (points 1 and 2). With increasing volume fraction of helium bubbles in the medium (without changing the total volume gas content in it), the attenuation factor increases and the effect of helium bubbles on wave damping decreases markedly. As the amplitude of the wave entering the medium increases, the effect of the helium-bubble concentration on the wave attenuation factor decreases. As is shown above, the latter is caused by aggregation of solitary waves and formation of an oscillating shock wave. The considerable scatter of experimental data in Fig. 3a is caused by inhomogeneity of the medium and by the fact that the region where the initial signal transformed into solitary waves was quite comparable with the distance between the wave entry point and the measurement point.

With increasing distance x (Fig. 3b), the most appreciable influence of the helium-bubble concentration on wave damping is observed for $\Delta p_0/p_0 \approx 1$; in this case, the solitary waves are not yet aggregated in an oscillating shock wave. As the volume fraction of helium bubbles in the gas–liquid medium increases, the attenuation factor versus wave amplitude dependence becomes weaker due to waveform restructuring.

We showed previously [4, 11] that the damping rate for solitary waves in a liquid with gas bubbles of two different sizes is greater than in a liquid with gas bubbles of identical sizes if all the other medium and wave parameters are unchanged. The reason for this fact is resonant oscillations of the bubbles of both types, which

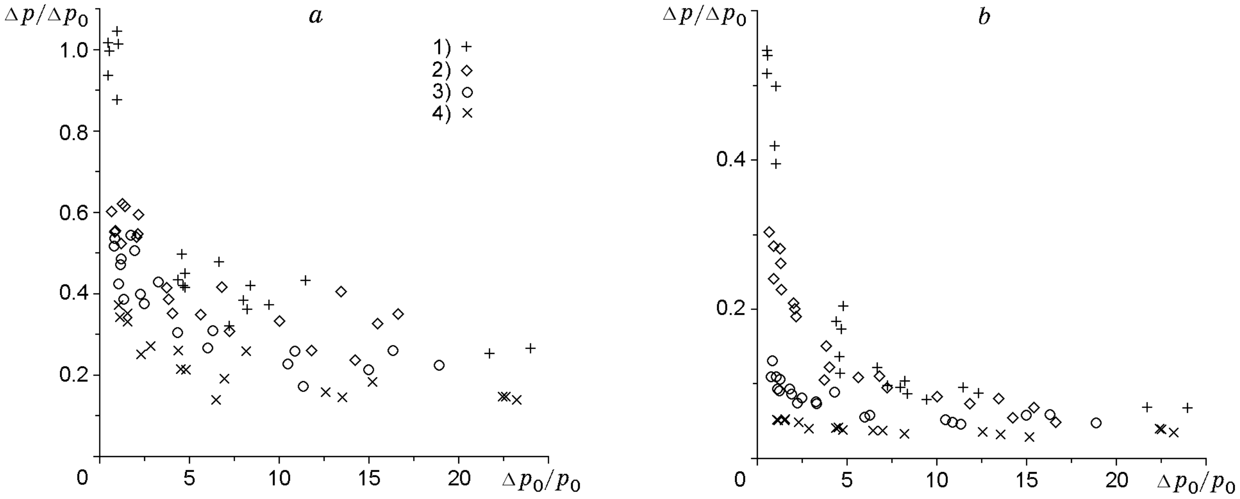

Fig. 3. Attenuation factor of a pressure wave in a liquid with freon and helium bubbles versus the wave amplitude ($d_f = d_h = 2.3$ mm) for $x = 0.23$ (a) and 1.23 m (b): points 1 refer to $\varphi_f = 1.2\%$ and $\varphi_h = 0$, points 2 to $\varphi_f = 1\%$ and $\varphi_h = 0.2\%$, points 3 to $\varphi_f = 0.4\%$ and $\varphi_h = 0.8\%$, and points 4 to $\varphi_f = 0$ and $\varphi_h = 1.2\%$.

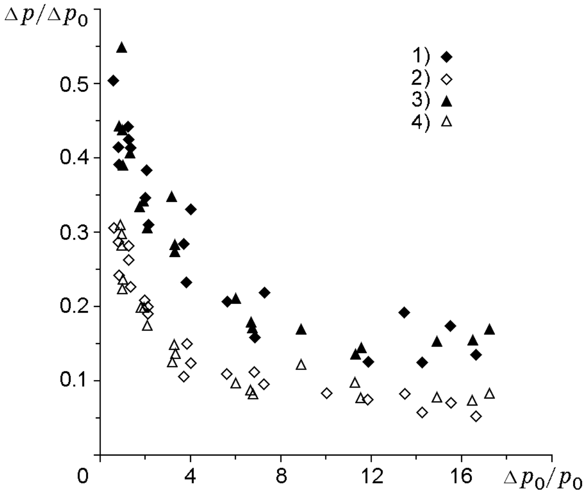

Fig. 4. Attenuation factor for a pressure wave in a liquid with freon and helium bubbles versus the wave amplitude ($d_f = 2.3$ mm, $\varphi_f = 1.0\%$, and $\varphi_h = 0.2\%$): points 1 and 3 refer to $x = 0.5$ m and $d_h = 2.3$ (1) and 1.1 mm (3) and points 2 and 4 refer to $x = 1.23$ and $d_h = 2.3$ (2) and 1.1 mm (4).

form an oscillating solitary wave — multisoliton. In the present study, we obtained experimental data concerning the structure and dissipation of moderate-amplitude pressure waves in a liquid with freon bubbles with a small (by volume) admixture of smaller helium bubbles. It was found that a more than twofold change in the helium-bubble size exerted practically no influence on the wave structure and attenuation factor. Apparently, the dissipative losses during compression of small helium bubbles are very high, and the bubbles cannot exert oscillations at their resonant frequency and form, together with freon bubbles, an oscillating solitary wave. The helium bubbles just "trace" the pressure in the wave formed by freon bubbles. For this reason, a decrease in the helium-bubble size in a liquid with a mixture of freon and helium bubbles does not cause any further increase in the rate of wave damping.

Figure 4 shows the attenuation factor for a pressure wave in a liquid with freon and helium bubbles of identical sizes (points 1 and 2) and in a liquid with freon and helium bubbles of two different sizes (points 3 and 4) versus the wave amplitude at different distances x from the entry point. Points 1 and 3 ($x = 0.5$ m) and 2 and 4 ($x = 1.23$ m) are practically coincidental in a wide range of wave amplitudes $\Delta p_0/p_0$. Hence, introduction of small-size bubbles of a highly heat-conducting gas (helium) into a gas–liquid mixture causes no increase in the rate of wave attenuation.

It seems that an increase in the rate of wave attenuation may be achieved in a liquid with larger bubbles, in which the overall dissipation is lower, by introducing gas bubbles of two different sizes.

Thus, in the present work we showed the possibility of increasing the attenuation factor for moderate-amplitude pressure waves in a liquid with gas bubbles by introducing a small volume fraction of well heat-conducting gas bubbles into the medium.

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