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PRESSURE WAVES IN A GAS–LIQUID MEDIUM WITH A STRATIFIED LIQUID–BUBBLY MIXTURE STRUCTURE

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Evolution and decay of pressure waves of moderate amplitude in a vertical shock tube filled by a gas–liquid medium with a nonuniform (stepwise) distribution of bubbles over the tube cross section are studied experimentally. The gas–liquid layer has the form of a ring located near the tube wall or the form of a gas–liquid column located in the center of the tube. It is shown that the nonuniformity of bubble distribution over the tube cross section increases the attenuation rate of pressure waves.

Key words: *pressure wave, liquid, gas bubbles, attenuation.*

Propagation of pressure waves in a liquid with gas bubbles has been extensively studied both theoretically and experimentally [1–5]. In particular, it was shown that a nonlinear finite-length disturbance in a liquid with gas bubbles disintegrates into solitary waves called solitons; the evolution and structure of these waves were considered in detail. It was found that heat exchange of the gas in the bubbles with the ambient liquid in a wide range of parameters of the medium is the main mechanism of wave dissipation in bubbly media. The presence of a third phase significantly affects both the wave structure and its attenuation in three-phase media [6–9]. The structure and decay of moderate-amplitude solitary pressure waves in a liquid with gas bubbles of an identical size were studied experimentally in [10 11]. Allowance for polydispersion in the gas–liquid medium increases the attenuation rate of the pressure waves [12, 13]. A new type of wave structures, multisolitons in a liquid with gas bubbles of two different sizes with different relations of bubble radii, was found in [14]. The influence of inhomogeneity of the gas–liquid mixture and liquid compressibility on the pressure-wave structure was considered in [15, 16]. The structure of the downward and upward bubbly flows was considered experimentally in [17, 18]. It was shown that a significant redistribution of the gas phase over the tube cross section occurs even with low volume fractions of the gas. Almost all the bubbles are concentrated either in the central part of the tube (downward flow) or in the near-wall region (upward flow). It is shown that the structure of gas–liquid bubbly flows in vertical tubes is significantly inhomogeneous both in laminar and turbulent flows.

Evolution and decay of moderate-amplitude pressure waves in a liquid containing gas bubbles with a nonuniform distribution of bubbles in a cross section perpendicular to the wave-propagation direction are experimentally studied in the present work.

The experiments were performed on a setup of the shock-tube type. The test section was a vertically mounted thick-walled steel tube 1.5 m long, which had an inner diameter of 53 mm. Inside the test section, there was a thin-walled (wall thickness of 30 μm) Mylar tube 37.5 mm in diameter. The Mylar-tube diameter was chosen such that the cross-sectional area inside the tube was equal to the area of the ring between the Mylar tube and the test-section wall. The position of the Mylar tube was rigidly fixed by thin partitions. The test section was filled by a liquid and saturated by gas bubbles through a generator located in the lower part of the tube. The experiments were performed for three different structures of the bubbly medium. The bubbles were supplied uniformly over the cross section of the entire test section, over the ring between the Mylar tube and test-section wall (gas–liquid ring), or over the cross section of the Mylar tube (gas–liquid column). The bubble generator had 22 calibrated glass capillaries. More precise selection of capillaries in the generator was performed by the results of videofilming of gas bubbles. This allowed obtaining gas bubbles whose size varied within $\pm 5\%$. The mean bubble radius was 0.53 mm.

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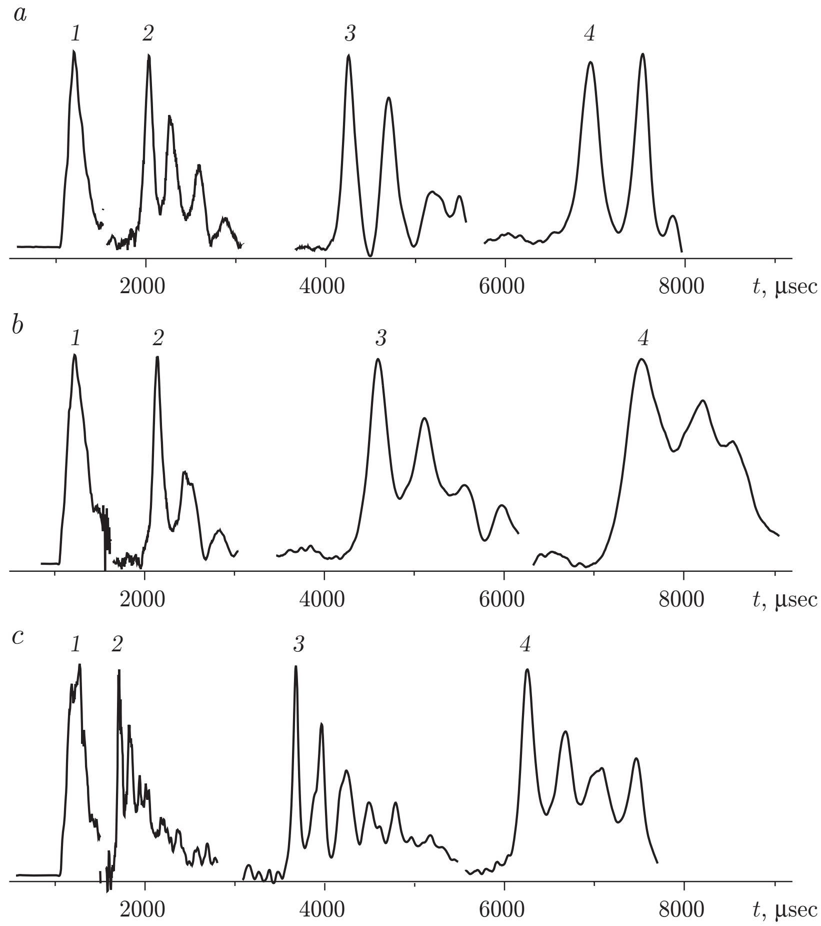

Fig. 1. Evolution of the pressure wave in the liquid with Freon bubbles for $X = 0$ (1), 0.25 (2), 0.76 (3), and 1.25 m (4): (a) homogeneous medium [$\Delta P_0 = 0.272$ (1), 0.172 (2), 0.117 (3), and 0.068 MPa (4)]; (b) gas–liquid ring near the wall [$\Delta P_0 = 0.219$ (1), 0.195 (2), 0.072 (3), and 0.031 MPa (4)]; (c) gas–liquid column in the center of the tube [$\Delta P_0 = 0.93$ (1), 0.53 (2), 0.28 (3), and 0.108 MPa (4)].

The test liquid was a 50-% (by mass) solution of glycerin in distilled water, and the gas phase consisted of Freon 12 and nitrogen whose thermal diffusivities were significantly different: $3.2 \cdot 10^{-6}$ and $2.2 \cdot 10^{-5}$ m^2/sec, respectively. When floating up in the liquid, the bubbles had a spherical shape. The fraction of the gas in the bubbles averaged over the cross section and length of the test section was determined by the increase in the liquid level in the test section after introduction of gas bubbles; its value was 0.5% in all experiments. The experiments were performed at room temperature and atmospheric static pressure P_0 above the level of the gas–liquid medium.

Bell-shaped pressure waves were generated by an electromagnetic emitter located at the bottom of the test section, owing to repulsion of a thin copper plate from an electromagnetic coil with a current pulse passing through the latter. The pressure-wave profiles were registered by six T-500-2 piezoelectric pressure gauges located along the test section. The systematic error of the gauges was smaller than 1%. The error of amplitude measurements by the pressure gauge was 2–3%. The signals from the gauges were fed to an analog-to-digital converter and then processed on a computer.

The test results showed that the nonuniform distribution of the gas phase over the tube cross section has a significant effect on wave evolution and decay in bubbly media. Figure 1 shows the pressure-wave profiles in time at different distances X from the place where the pressure wave entered the liquid with bubbles of a low-heat-conducting gas (Freon) for different structures of the medium and initial wave amplitudes ΔP_0 (ΔP is the wave amplitude or the amplitude of the first oscillation for a group of solitary waves and oscillating shock waves). A comparison of wave evolution in Fig. 1a and b shows that the displacement of gas bubbles from the central part of the tube to the near-wall region with an unchanged volume fraction of the gas averaged over the cross section leads to a significant increase in the attenuation rate and to a change in the wave structure. For a uniform distribution

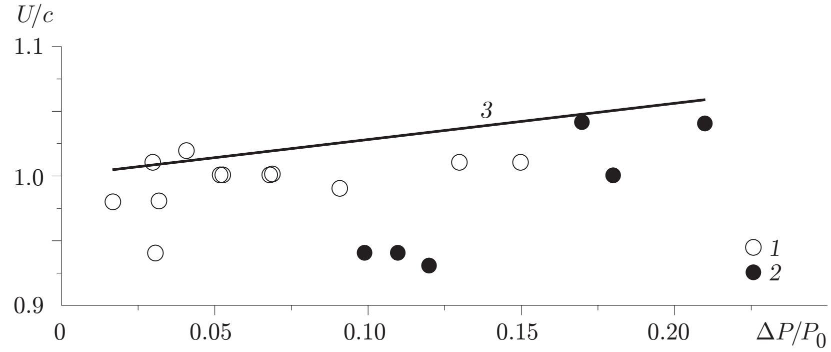

Fig. 2. Velocity of small perturbations in an inhomogeneous gas–liquid medium: the points refer to the experiment [gas–liquid ring near the wall (1) and gas–liquid column in the tube center (2)] and curve 3 refers to the calculation by the homogeneous model.

of bubbles over the tube cross section, solitary waves (solitons) were formed from the initial signal at a distance $X = 0.76$ m (curve 3 in Fig. 1a); in the case of a gas–liquid ring near the tube wall, an oscillating shock wave is formed (curve 3 in Fig. 1b). The formation of an oscillating shock wave is caused by the increase in dissipative losses in the medium. It should be noted that the redistribution of the gas phase over the tube cross section does not alter the frequency of oscillations in the wave. As in the case of a homogeneous medium, the duration of the first oscillation corresponds to resonant oscillations of gas bubbles in the wave.

With increasing wave amplitude, its attenuation rate increases. As a result, oscillating shock waves are formed from the initial signal for all structures of the gas–liquid medium (Fig. 1c).

Figure 2 shows the experimental data on the velocity U of low-amplitude pressure waves in a liquid with a gas–liquid ring near the wall and a gas–liquid column in the center of the tube. The amplitude of the first oscillation of the wave was measured in the experiments; the velocity was determined by the difference in arrival times of the peak of the first oscillation to two neighboring gauges. The wave amplitude ΔP was assumed to be the averaged value of the amplitude from the neighboring gauges. Curve 3 shows the calculated velocity of solitary waves (solitons) by the Korteweg–de-Vries equation [3] in a liquid with a uniform distribution of bubbles (c is the low-frequency velocity of sound in the gas–liquid medium). Within the measurement error (5%), the wave velocity in the gas–liquid medium is independent of the distribution of gas bubbles over the tube cross section and is determined by the volume fraction of the gas averaged over the cross section.

Figure 3 shows the experimental data on the attenuation rate of the pressure wave (first oscillation) in the liquid with different distributions of bubbles in the medium for two characteristic amplitudes of the initial signal. For low amplitudes of the waves ($\Delta P_0/P_0 \approx 2$), significant differences are observed in wave attenuation rates in the liquid with Freon bubbles with uniform and ring-type distributions of gas bubbles in the medium (points 1 and 3 in Fig. 3a). At large distances from the place of wave entrance into the medium ($X \geqslant 0.5$ m), the wave attenuation rate in the case of a nonuniform distribution of bubbles over the tube cross section is higher than that in the case of a uniform distribution. At small distances ($X \approx 0.25$ m), however, the experimental points 3 in the case of the ring-type distribution of bubbles are higher than points 1 corresponding to the uniform distribution. Apparently, this is caused by the fact that dispersion and nonlinear effects in the ring-type mode lead to a more rapid formation of the solitary wave from the initial signal (curve 2 in Fig. 1b). In the case of formation of the solitary wave (oscillating shock wave), its amplitude is higher than the amplitude of the initial signal [3, 10, 11]. In the case of the uniform distribution of bubbles, the solitary wave is formed at a greater distance (points 1 in Fig. 3a), which leads to a decrease in the wave attenuation rate at the interval $X = 0.25$–0.50 m. Note, in the case of the uniform distribution of bubbles, a nonmonotonic behavior of the attenuation curve is observed at a distance $X \approx 1$ m (points 1 in Fig. 3a), which can be caused by wave re-formation in the course of its evolution. In the case of high wave amplitudes ($\Delta P_0/P_0 \approx 10$), the attenuation rate in the liquid with Freon bubbles is independent of the distribution of bubbles over the tube cross section (points 2 and 4 in Fig. 3a almost coincide).

In the case of more "heat-conducting" nitrogen bubbles of the same size with the same volume fraction of the gas with the uniform distribution of bubbles, the attenuation rate of waves with close initial amplitudes appreciably increases (points 1 and 2 in Fig. 3b). The reason is that the main mechanism of wave dissipation in a homogeneous bubbly medium is heat transfer between the gas in the bubbles and the ambient liquid [3, 10]. At the same time, in

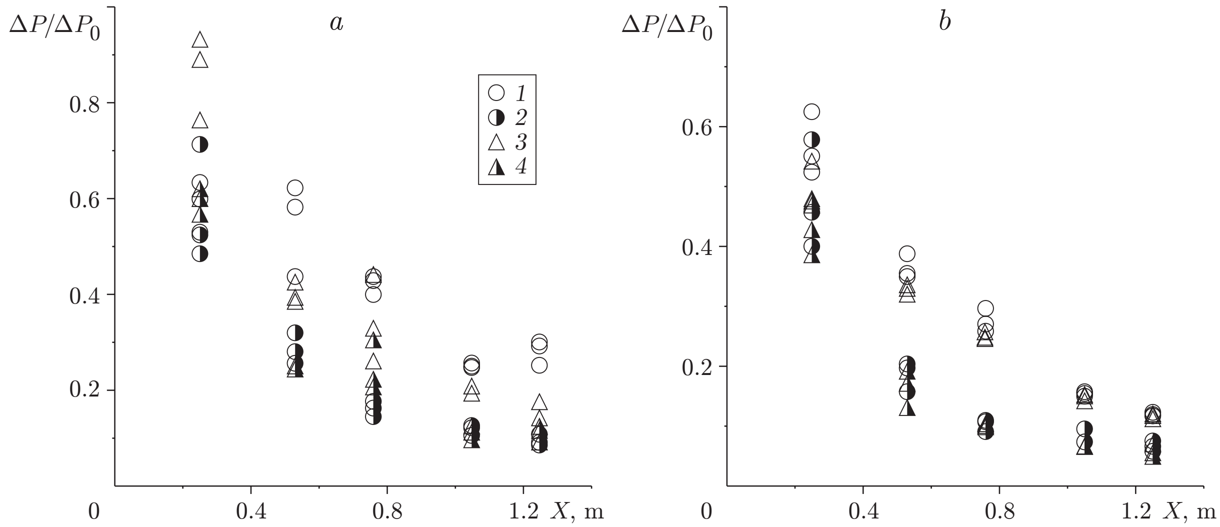

Fig. 3. Decay of the pressure wave along the test section for Freon bubbles (a) and nitrogen bubbles (b): (a) points 1 and 2 refer to the homogeneous structure of the medium for $\Delta P_0/P_0 \approx 2.5$ and 9.5, respectively, and points 3 and 4 refer to the gas–liquid ring near the wall for $\Delta P_0/P_0 \approx 2.1$ and 8.5, respectively; (b) points 1 and 2 refer to the homogeneous structure of the medium for $\Delta P_0/P_0 \approx 1.9$ and 14, respectively, and points 3 and 4 refer to the gas–liquid column at the center of the tube for $\Delta P_0/P_0 \approx 1.8$ and 14, respectively.

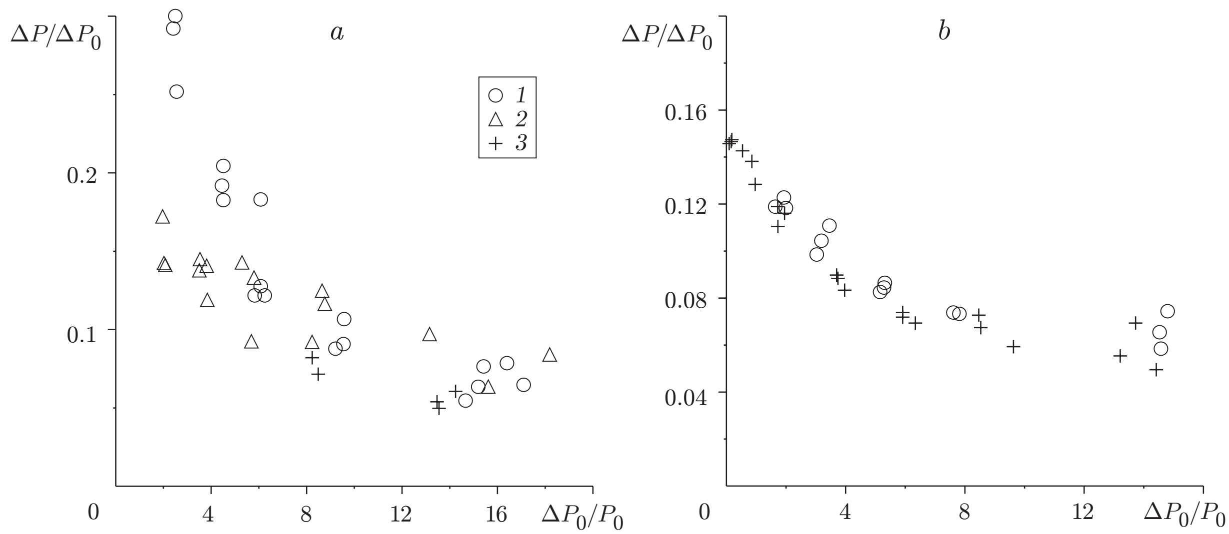

Fig. 4. Attenuation rate of the pressure wave in the liquid with gas bubbles versus wave amplitude: Freon bubbles (a) and nitrogen bubbles (b); points 1 refer to the homogeneous structure of the medium, points 2 to the gas–liquid ring near the wall, and points 3 to the gas–liquid column in the center of the tube.

the case of the nonuniform distribution of bubbles, the attenuation rate for waves with an amplitude $\Delta P_0/P_0 \approx 2$ in the liquid with Freon and nitrogen bubbles differs insignificantly (points 3 in Fig. 3a and b). This indicates the increase in the wave attenuation rate in the liquid in passing to the nonuniform distribution of gas bubbles, which is comparable to thermal dissipation.

Figure 4 shows the attenuation rate of the pressure wave (first oscillation) in the liquid with gas bubbles versus the wave amplitude at the distance $X = 1.25$ m from the point of wave entrance into the medium. At high wave amplitudes, the attenuation rate is independent of the distribution of bubbles over the tube cross section. Stratification of points 1 and 2 is observed in Fig. 4a with decreasing wave amplitude. Hence, for Freon bubbles, the nonuniformity of the gas-phase distribution in the liquid leads to an increase in the attenuation rate, which is comparable to thermal dissipation. For the liquid with nitrogen bubbles (Fig. 4b), stratification of points 1 and 2 with decreasing amplitude is smaller because of the predominant role of thermal dissipation. Additional dissipation due to inhomogeneity of the bubbly medium can be caused by the relative motion of gas bubbles in the liquid. The influence of the relative motion of bubbles in the liquid on propagation of shock waves in homogeneous bubbly media was first considered in [19]. In the case of homogeneous bubbly media, however, thermal dissipation almost always prevails over viscous dissipation because of the relative motion of the bubbles [3, 4]. In the case of bubbly media significantly inhomogeneous over the cross section, the bubbles in the wave move relative to the liquid not only in the wave-propagation direction but also perpendicular to it, in the direction of increasing compressibility of the medium. This leads to an increase in the relative velocity of the bubbles and a change in its direction, as compared to the case of a homogeneous medium, and correspondingly, to an increase in the attenuation rate. In addition, owing to the liquid motion, vortex structures can be formed in the pressure wave because of the transverse component of liquid velocity and the presence of the solid test-section wall. The presence of vortex structures also involves an increase in the attenuation rate of the pressure wave.

Thus, it is shown that the nonuniform distribution of gas bubbles in the cross section perpendicular to the wave-propagation direction can lead to an increase in the wave attenuation rate. The mechanism of decay caused by the relative motion of gas bubbles in the liquid and formation of vortex structures in the wave is considered.

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