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INTERACTION OF PRESSURE WAVES WITH A WET FOAM

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The use of water foams as shields to effectively dampen shock waves and sound waves in various technological devices has stimulated major interest in research on processes of wave propagation in foam media. The dynamics of high-intensity shock waves and sound propagation in foam has been studied in detail both experimentally and theoretically [1-3]. In this article we report an experimental investigation of intermediate-amplitude disturbances with a wavefront gauge pressure in the range between shock wave and sound wave amplitudes.

The experiments were carried out in a vertical shock tube, the details of which are described in [4]. Here we note that the inner duct of the transparent Plexiglas tube was filled with a foam layer of height H, which was varied from 30 cm to 50 cm. The foam was prepared from a 3% aqueous solution of a surface-active agent and had a volume-average density of 50 kg/m^3 and a bubble diameter (determined from photographs) of 0.5 mm. To measure the pressure profile, miniature piezoceramic transducers were mounted on the end wall of the duct and at distances of 4, 15, 26, and 37 cm from it; their output signals were recorded by means of S9-8 oscilloscopes and were analyzed on a PC AT 286 personal computer interfaced with the oscilloscopes.

High-pressure (HP) chambers of various lengths were used to obtain waves with a constant peak pressure level (long waves) and waves having a bell-shaped (Gaussian) pressure profile. Figure 1 shows typical profiles of the gauge pressure; the time scale is shown in the upper right-hand corner and refers both to long waves (upper oscillogram) and to bell-shaped waves (lower oscillogram). In the case of long waves the pressure profile behind the wave in a foam is known to be formed by relaxation to equilibrium between the gaseous and liquid phases of the flow. The maximum of the gauge pressure P_f depends on the density of the foam and is related to the wave velocity by the equilibrium shock–adiabat equations. The bell-shaped waves are damped as they move through the foam, their peak pressure level decaying rapidly [1].

In the experiments both the long waves and bell-shaped waves acquired a prominent leading edge in the form of a small-amplitude jump in the gauge pressure P_p; this disturbance is called a precursor in [1]. Measurements using "fast" (in comparison with the two upper oscillograms in Fig. 1) sweeps of the oscillograph time scale show (see the lower oscillogram in Fig. 1, with the time scale indicated in the lower right-hand corner) that the pressure in the precursor grows in a time $\tau \geq 40$ μsec, i.e., the precursor itself has a fairly extended structure. A distinctive feature of the precursor is the fact that its amplitude, on the one hand, is approximately three times the amplitude of acoustic oscillations and, on the other, is smaller than the amplitudes of weak bell-shaped shock waves, whose propagation in wet cellular foams has been studied in [3, 5].

We note that a wave was generated in the foam layer when an air shock with Mach number $M_s \leq 1.5$ entered the layer from above. To diminish the influence of wave generation processes in the foam on the parameters of the precursor, measurements near the surface of the layer were also performed in experiments with the HP chamber in a low position, so that the wave was generated in the lower part of the layer and moved through the foam from the bottom toward the top.

Points 1 and 2 in Fig. 2 represent the results of measurements of P_p and τ, respectively, for downward motion of the precursor in the layer, points 3 represent experimental data from [5] for the peak pressure in bell-shaped shock waves, points 4 correspond to P_p for upward motion of the precursor in the layer, and x denotes the distance from the air–foam interface. It is evident from Fig. 2 that, when the precursor moves downward in the layer, a rapid increase in the value of τ is observed together with a slight reduction in the amplitude of the disturbance. The formation of a long, gradually sloping profile on the part of the pressure after the wave is attributable to the increase of τ in the precursor and not to the decrease in its amplitude. We know that the rise time of the pressure after the front in a two-phase medium is related to the penetration depth of the processes of relaxation to interphase velocity and temperature equilibrium [6]. The duration of these processes for weak shock waves in wet foams is usually $\simeq 1000$ μsec [4]. The rapid relaxation of the pressure at the leading edge of the wave ($\tau < 100$ μsec) indicates the termination of the first (rather short) stage in the evolution of the parameters, this being the stage associated

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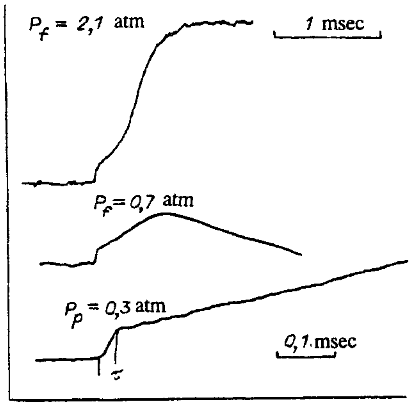

Fig. 1

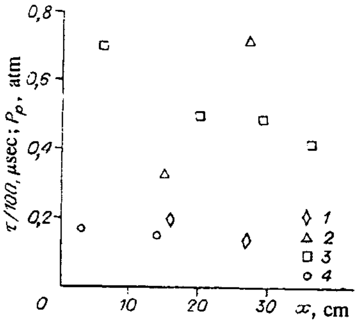

Fig. 2

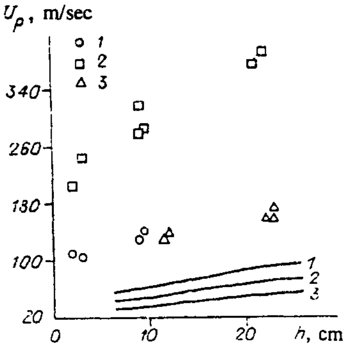

Fig. 3

with transmission of the precursor through the foam. By analogy with dry foams [7], it is reasonable to assume that the initial relaxation stage reflects the process of breakdown of the foam films by the precursor.

The precursor velocity was measured by the baseline method for air shock waves incident on the foam layer with wavefront gauge pressures of 0.3 atm to 1.6 atm. Despite the wide variation of the wave intensities, the parameters of the precursor remain virtually unchanged in this case. For a foam layer of height 50 cm the velocity of the precursor in the middle part of the layer does not exceed U_p = 140 ± 10 m/sec, and the amplitude is P_p = 0.30 ± 0.03 atm. Some of the experiments in the same series were carried out with a foam of a water—glycerin solution of surface-active agent. The volume–average density of the foam and the bubble diameter were kept the same as in the water foam, but now the viscosity of the solution was eight times that of water. However, the amplitude and velocity of both the precursor and the primary wave in these experiments scarcely differed from the corresponding values in the water foam, consistent with the conclusion of [8].

Summarizing, we note that the parameters of the precursor depended only slightly on the intensity of the primary wave itself and the velocity of the foam solution under the stated conditions, but changed considerably during the motion of the precursor through the layer. This motion is known to take place in the presence of a gravity-induced nonuniform (in height) profile of the local density of the foam layer [9]. Measurements of the precursor velocity show (Fig. 3, where points 1 and 3 indicate the results of measurements of U_p for downward and upward motion of the precursor in the layer, respectively, and h is the distance from the lower edge of the layer) that, irrespective of its direction of motion, the velocity is greater in the upper (drier) part of the layer and decreases in the lower (wetter) part. Consequently, despite the influence of dissipative processes on the parameters of the precursor, the velocity distribution along the layer reflects the variation of the local density of the foam.

In this series of experiments we also measured the distribution of the precursor velocity U_p along a layer of "slightly dried out" foam (the results of these measurements of U_p are represented by points 2 in Fig. 3). Its volume-average density was lowered by letting the foam stand for 3 min prior to burst, during which time the bubble diameter increased ≃ 1.5-fold. The velocity of the precursor in these experiments also decreased in the direction of increasing local density of the foam, but was still twice the value in the wet foam.

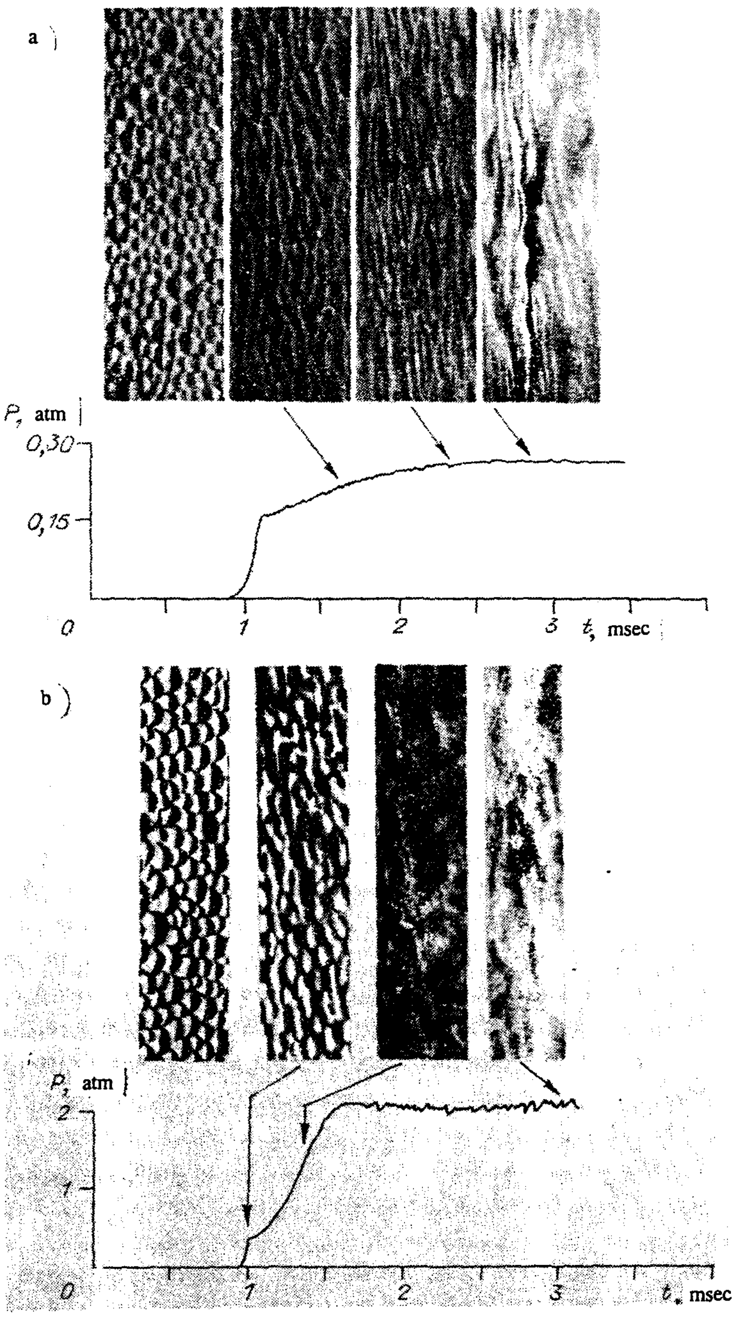

Fig. 4

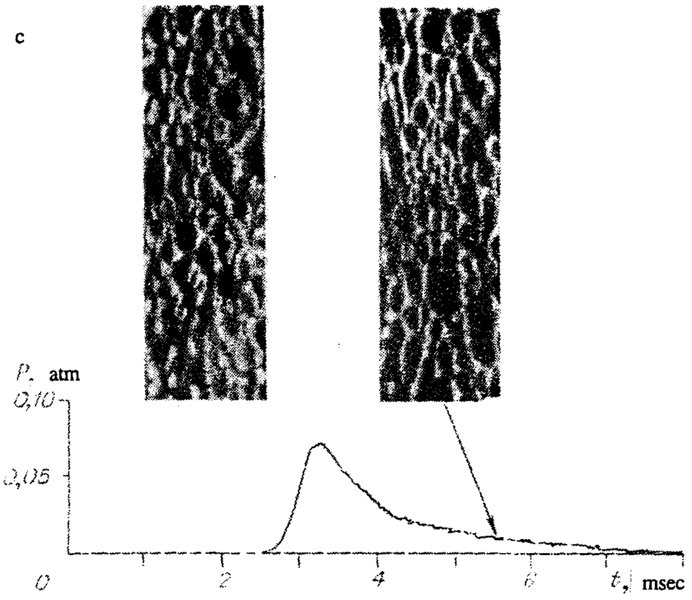

Fig. 4c

In Fig. 3 the experimental values of the precursor velocity in a wet foam are compared with the values calculated according to equations in [5]. The following equation was used for the equilibrium (between the velocities and temperatures of the gaseous and liquid phases of the flow) wave velocity U_e:

$$U_e = (P_1/P_0)^{0.5}\{P_0/(\alpha[\alpha\rho_g + (1 - \alpha)\rho_l])\}^{0.5},$$

and the adiabatic (velocity equilibrium without interphase heat transfer) wave velocity U_a was given by the equation

$$U_a = (P_1/P_0)\{[\gamma + 1 + (P_0/P_1)(\gamma - 1)]/2\gamma\}^{0.5}\{\gamma P_0/(\alpha[\alpha\rho_g + (1 - \alpha)\rho_l])\}^{0.5},$$

where P_0 is the initial atmospheric pressure, P_1 is the peak pressure in a bell-shaped wave, α is the volume fraction of gas in the foam, ρ_g is the density of the gas, ρ_l is the density of the liquid, and γ is the adiabatic exponent of the gas. The standard expression was used for the sound velocity: $U_s = (\Gamma P_0/\rho_f)^{0.5}$ [Γ is the effective adiabatic exponent of the two-phase medium, and $\rho_f = \alpha\rho_g + (1 - \alpha)\rho_l$ is the density of the foam].

The analytical equations for the velocity of weak bell-shaped shock waves in a foam as a function of the density of the foam and the peak pressure in the wave have been derived on the assumption that the foam structure is indestructible. The authors of [5] state that the calculated results agree satisfactorily with experimental data obtained over a wide range of foam densities. Velocity calculations for a nonuniform layer require knowledge of the density distribution along the height of the foam column. In the present study we have investigated the wave velocities U_e and U_a for three different cross sections of the foam layer, in which estimates [4] give local densities of 114, 68, and 37 kg/m^3 at distances of 4, 15, and 26 cm, respectively, from the lower boundary of a layer of height 30 cm. The calculated velocities were interpolated by splines. Curve 1 in Fig. 3 represents U_a for $P_1/P_0 = 1.5$, Curve 2 for $P_1/P_0 = 1.2$, and Curve 3 gives the equilibrium sound velocity U_s in the foam. The fact that the experimental data exceed the results of the calculations (even when the calculations are carried out for the "fastest" adiabatic wave with an amplitude twice that of the precursor) can be linked to several effects disregarded in the theory. One instance is the failure to allow for fluid motion along the channeled structure of the foam in the analytical equation; this effect (according to [3]) will necessarily increase the velocity at which the wave propagates. Another factor is possible breakdown of the foam by the motion of the precursor through it.

The relationship of the parameters of a foam-destructive wave to the initial structure and density of the foam has been all but ignored to date. Borisov et al. [1] have noted that the foam remained in the tube after an experiment with very strong shock waves. The destruction of dry foams by weak shock waves has been investigated only in [7].

The state of the foam was monitored in the present study by open-shutter photography of the foam layer; this technique is described in detail in [7]. The source of illumination was second-harmonic emission from a pulsed NiG laser with a 20-nsec flash. The strong light-scattering properties of the foam were exploited to obtain photographs limited to the part of the layer adjacent to the inner surface of the transparent duct. A piezoelectric transducer and an adjustable-delay line were used to synchronize the flash with the investigated process.

Photographs of the foam before the burst (column height 50 cm) and at various times after passage of the precursor are shown in Fig. 4. The position of each photograph corresponds to the time of the light flash in which the photograph was taken. The delay time T was counted relative to the arrival of the leading edge of the precursor at the pressure transducer. The experimental pressure oscillograms (pressure transducer situated at a distance of 26 cm from the end wall of the duct) are shown with scale preservation. It is evident from Fig. 4 (left photograph) that the average size of the foam shells changed very little from one experiment to another, so that the differences in the behavior of the foam after the precursor leading edge are determined by the intensity and profile of the pressure wave. (The frame height is 9 mm, and the direction of motion of the wave is downward in the photographs.) In the first series of experiments (Fig. 4a, T = 0.8, 1.7, and 2.2 msec) an air shock with a constant pressure amplitude and a gauge pressure of 0.30 atm at the shock front was incident on the foam layer. Here the foam structure was remained intact throughout the entire observation time. The foam cells began to be deformed well within the limits of the relaxation zone, becoming elongated in the direction of wave motion. Only in the last photograph do cell discontinuities and voids in the form of "pockets" begin to appear at the wall of the tube. The emergence of such "pockets" can be attributed to the initial inhomogeneity of the foam.

In the next series of experiments (Fig. 4b, T = 0.05, 0.4, and 2.1 msec) the gauge pressure at the front of an air shock incident on the foam increased to 0.96 atm. Here the foam begins to break up well within the limits of the pressure relaxation zone. A slight deformation is observed in the precursor, where the cells lose their spherical geometry. The dark spots in the photograph indicate the possible presence of liquid droplets or films on the inner wall of the tube. We note that in both cases the amplitude of long air waves approximately doubled upon refraction into the foam. The photographs show that this growth effect is associated with foam deformation and breakdown processes, in which the gaseous phase of the flow is retarded both by foam structural elements and by liquid droplets formed in the flow.

The motion of a bell-shaped wave through the foam layer with a peak amplitude smaller than that of the precursor was also photographed. An oscillogram from the pressure transducer and photographs of the foam for such a wave are shown in Fig. 4c (T = 3 msec). In these experiments the wave decayed rapidly as it moved through the foam. Despite the deformation of the foam cells, a destructive process similar to that noted in the preceding series was not observed even 1.5–2 msec after arrival of the pressure maximum. A detailed analysis of the foam breakdown conditions as a function of the intensity and other governing parameters of the waves is planned for a later time. We note here that the results of the reported experiments suggest a relationship of the wave dynamics to processes of change in the foam structure behind the wavefront.

We have thus investigated the propagation of weak pressure waves in a wet cellular water foam. Such disturbances are accompanied by the formation in the foam of a leading edge of the wave, or so-called precursor, whose amplitude lies in the range between well-studied shock and acoustic waves. It has been established on the basis of the experimental results that: 1) the velocity of the precursor depends on the density of the foam in the investigated range of parameters, while the amplitude of the shock wave itself and the viscosity of the foam solution have scarcely any influence on the parameters of the precursor; 2) the velocity of the precursor exceeds the calculated velocity of weak shock and acoustic waves in a foam, and the propagation of the precursor itself can be accompanied by breakdown of the initial foam structure; 3) the governing parameter of foam destruction for long waves is the initial intensity of the pressure wave; 4) the decay of weak bell-shaped waves is accompanied by deformation of the cells with preservation of the foam structure. Long waves refracted into the foam are amplified upon destruction of the foam in the relaxation zone of rising pressure after the leading edge of the precursor.

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