In conclusion, we acknowledge useful discussions with Yu. D. Shmyglevskii and V. I. Maron.

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INTERACTION OF SHOCK WAVES AND PROTECTIVE SCREENS IN A LIQUID AND IN A TWO-PHASE MEDIUM

B. E. Gel'fand, A. V. Gubanov, and E. I. Timofeev

UDC 532.593:532.529

The significant, for practical applications, characteristics of changes in shock-wave parameters at boundaries separating a two-phase mixture and a continuous liquid are clarified by investigations of the propagation of pressure waves in two-phase gas—liquid media.

One of the often-discussed practical applications of the study of the dynamics of wave processes in a two-phase medium is related to the damping of pressure waves by bubble screens. However, almost any problem with damping of pressure waves in a two-phase medium separates into two independent, but closely related, problems of their attenuation and amplification on boundaries separating media with different acoustical impedance. Thus, the problem of amplification of pressure waves is encountered in analyzing their transition into a medium with a high acoustical impedance. It is well known that when shock waves are incident on a separation boundary in a two-phase medium, as the acoustical impedance increases, the pressure differential on the shock front increases by a factor of up to 5-7 [1-5]. When shock waves pass into a medium with a lower acoustical impedance, the pressures waves are observed to attenuate by a factor of 3-5 [1-5] or damping of short wavelength excitations in the gas—fluid medium becomes possible.

In this connection, depending on the specific conditions, it turns out that protective properties of water bubble screens in liquids begin to be determined by the ratios of the acoustical impedances of the liquid and the two-phase medium on both boundaries of the screen; on one of them, the pressure differential increases, while on the other it decreases. Therefore, the effectiveness of screens will depend on the pressure in the medium, the volume concentration of gas in the liquid, and the intensity of the wave. When the acoustical impedances of the continuous liquid and the two-phase medium approach one another, as noted, for example, with an increase in pressure or decrease in the volume concentration of gas in the liquid, the protective screens become transparent to shock waves and, therefore, become ineffective.

Computational data, indicating the low effectiveness of bubble screens for damping shock waves with pressure differential on the front exceeding 5 mPa with the volume concentration of gas in the liquid up to 10%, were already obtained in [6]. However, the computed

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 118-123, January-February, 1982. Original article submitted December 15, 1980.

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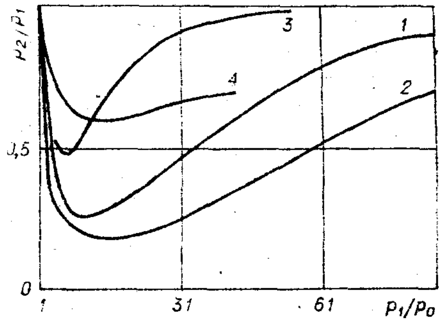

Fig. 1

characteristics in [6] do not reflect the influence of the starting pressure on the efficiency of lowering the amplitude of shock waves with the help of screens. Likewise, the illustration of strong damping action of water bubble screens for weak shock waves with pressure differential on the shock front below Δp = 0.1-0.2 MPa given in [6] is not adequate. As a result of the inadequacies noted, a sufficiently convincing proof of the effectiveness of water bubble screens in protecting underwater structures in water and water screens for protecting the same structures in a two-phase medium is not yet available in the literature.

We shall estimate from a unified point of view the possible situations that could be encountered in using different types of protective screens. This is all the more necessary, since papers periodically appear in the literature concerning both the successful application of screens [7] and the limitations of their protective properties [8].

Formulation of the Problem

We shall examine the interaction of an infinitely long shock wave with a gas–liquid screen with thickness l, placed in a volume of continuous liquid. The pressure on the leading edge of the wave is p_1. The wave propagates initially in the liquid, whose equation of state is described by Tait's equation in the form $p_1 - p_0 = B[(\rho_f \rho_{f0}^{-1})^n - 1]$, where B = 304.5 MPa; n = 7.15; p_0 is the initial pressure in the medium. The equation of state in the two-phase medium for isometric behavior of gas bubbles has the form

$$p\beta[(1-\beta)\rho_f]^{-1} = \text{const} = A,$$

where β is the volume concentration of gas in the liquid. On the front boundary of the water–two-phase medium, the starting wave attenuates to a magnitude p_1', while on the trailing boundary separating the two-phase medium and the water, the shock wave intensifies to a value p_2. The pressure wave reflected into the screen also has the same pressure. We shall write out a series of well-known relations for the pressures on shock wave fronts and the rarefaction wave on the first water–two-phase medium boundary:

$$p_1 - p_0 = \rho_{f0}\, cu_0,\ p_1 - p_0 = \rho_0 D_1 u_1,\ p_1 - p_1 = \rho_{f0}\ (c + u_0)(u_1 - u_0),$$

where ρ_{f0} and c are the density and propagation velocity of sound in the pure liquid; u_0 and u_1 are the velocity of the medium behind the shock wave in the liquid and the gas–liquid medium, respectively. The shock waves in the liquid are viewed in the acoustic approximation, while the compressibility of water must be taken into account only in studying the propagation of pressure waves in the two-phase medium. It can be shown that the velocity of the wave for $\beta > 0$, $\Delta p < 100$ MPa will constitute in this medium

$$D^2 = c^2 a[1 + a]\{(1-\beta)[(1-\beta p_0 p^{-1})a + \beta(1 - p_0 p^{-1})]\}^{-1},$$
$$a = \Delta p (Bn)^{-1}.$$

The density of the two-phase medium $\rho_0 = (1 - \beta_0)\rho_{f0}$, β_0 is the volume concentration of gas in the screen.

On the trailing boundary with the transition into water, the parameters of the incident and reflected waves are related by the relations

$$p_1' - p_0 = \rho_0 D_1 u_1,\quad p_2 - p_0 = \rho_{f0} c u_2,$$
$$p_2 - p_1' = \rho_0' (D_1' + u_1)(u_1 - u_2),$$

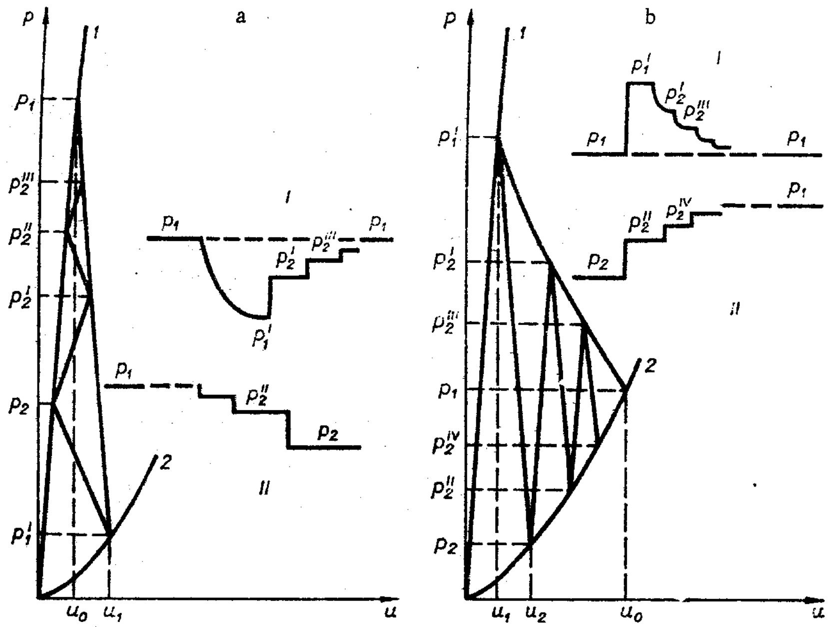

Fig. 2

where ρ_0' is the density of the two-phase medium behind the incident wave; D_1' is the velocity of the wave reflected into the screen; p_2 and u_2 are the pressure and velocity of the medium in the wave passing behind the screen.

Figure 1 shows the dependence of $p_2 p_1^{-1}$ as a function of $p_1 p_0^{-1}$ for different volume concentrations of gas β_0 and initial pressure p_0. Curves 1 and 2 were constructed for the case $\beta_0 = 5, 10\%$, $p_0 = 0.1$ MPa. Curve 3 was obtained for $\beta_0 = 5\%$, $p_0 = 0.5$ MPa and shows the effect of the starting pressure p_0 on the coefficient of attentuation of the wave $p_2 p_1^{-1}$. From a comparison of curves 1 and 3, it is evident that an increase in the starting pressure p_0 considerably worsens the damping action of the screen on the shock wave due to the convergence of the acoustic impedances of water and the gas—liquid medium. The existence of minima in the quantity $p_2 p_1^{-1}$ is related to the nonlinear pressure dependence of the wave velocity in the two-phase medium. Curve 4 corresponds to the case in which the gas—liquid screen with gas concentration β_0 is situated in a gas—liquid medium with concentration β_1, and in addition, $\beta_0 > \beta_1$. For the case examined, $\beta_0 = 10\%$, $\beta_1 = 1\%$, and $p_0 = 0.1$ MPa. The example presented indicates that the introduction of a small quantity of the gas into the liquid greatly decreases the damping action of the screen on the shock wave.

We shall examine the history of the motion of the shock wave reflected from the trailing separation boundary. Figure 2a shows qualitatively the p—u diagram (the pressure—velocity diagram) for the case of interaction of a shock wave and a gas—liquid screen, situated in the liquid. Curves 1 and 2 are the shock adiabats of the liquid in the two-phase medium. The shock wave reflected into the screen with pressure p_2 on the front falls on the front boundary and is amplified, after interacting, to some quantity p_2'. Returning to the rear boundary, this wave is amplified on interacting to a magnitude p_2''. The process of successive reflections continues until a disturbance passes behind the screen with pressure at the front equal to the initial disturbance p_1. Figure 2 shows qualitatively the increase in pressure inside the screen (I) and behind it (II). Apparently, three to four passages of the wave along the screen are sufficient for practically complete equalization of pressure behind and in front of the screen. By this time, both boundaries of the screen will be moving with a velocity close to u_0.

Let us examine the interaction of a shock wave, propagating in a gas—liquid medium with water interlayer with thickness l (inverse screen). For the starting disturbance of the transmitted and refracted waves, we retain the same notation as for the normal screen. The gas concentration is β_0. Here it is no longer necessary to write out the well-known shock relations, and we shall only examine the features related to the rarefaction wave in the gas—liquid medium for the case when, instead of the water layer, there is a bubble screen, which has a volume concentration β_1, and, in addition, $\beta_1 < \beta_0$. If in the water the rarefac-

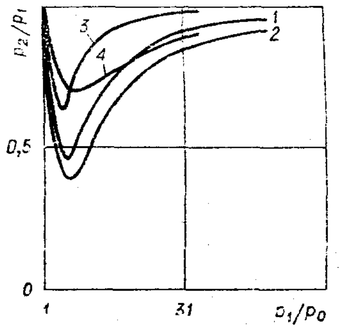

Fig. 3

tion wave can be described in the acoustical approximation, then in the two-phase medium this cannot be done. It is necessary to carry out a complete calculation of the wave profile using Riemann invariants for the compressible medium. It can be shown that for a gas–liquid medium in the isothermal case, taking into account the compressibility of the liquid, the relation between the velocity of the medium and the pressure has the form $u \pm \{b - 0.5d \times \ln[(d = b)(b - d)^{-1}]\}(\rho_f c)^{-1} = \text{const}$, $b^2 = p^2 + A\rho_f c^2$, $d^2 = A\rho_f c^2$, where A is a constant from the equation of state in the two-phase medium. Using this expression and the shock-wave relations written out previously, we shall find the ratio $p_2 p_1^{-1}$ behind the water layer in the gas–liquid medium as a function of the same parameters as for a normal screen, as in Fig. 3. Curves 1 and 2 in Fig. 3 are constructed for $\beta_0 = 5$, 10% and, correspondingly, $p_0 = 0.1$ MPa. Curve 3 is constructed for $\beta_0 = 5\%$, $p_0 = 0.5$ MPa. As for normal screen, an increase in the starting pressure worsens the damping action of the inverse screen. Curve 4 corresponds to the case in which the gas–liquid layer with gas concentration β_1 is situated in a two-phase medium and, in addition, $\beta_1 < \beta_0$, $\beta_1 = 1\%$, $\beta_0 = 10\%$, and $p_0 = 0.1$ MPa. Introduction of an insignificant amount of gas into the water layer ($\beta_1 = 0$) led to a significant worsening of the damping properties of the screen.

Let us examine the wave motion along the screen. In contrast to the preceding case, in which only shock waves moved along the screen, for a water layer alternating refraction and compression waves will be observed. Figure 2b shows qualitatively the p–u diagram of the interaction of shock waves, propagating along a two-phase medium, with a water screen. The notation is the same as in Fig. 2a. Initially, a shock wave with pressure p_1 along the front and velocity of the medium u_0 moves along the two-phase medium. On the first separation boundary, on crossing into the water, the wave is amplified to a pressure p_1' and, in passing behind the screen, it weakens to a magnitude p_2. At the same time, a rarefaction wave, moving toward the front boundary, propagates in the water. As a result of the interaction of the rarefaction wave with the front boundary, the rarefaction wave penetrates into the two-phase medium, while the shock wave with pressure p_2' on the front penetrates into the water. For the case of a water layer, this process of alternation of the pressure and rarefaction waves will continue until the pressure behind the screen equals the initial pressure p_1. The explanatory diagram in Fig. 2b shows qualitatively the pattern of the flow in front of (I) and behind (II) the water screen. In front of the screen a shock wave initially propagates along the medium under a pressure p_1, and then a series of rarefaction waves propagates. A series of shock waves moving along and catching up with one another is observed behind the screen.

Let us examine the effect of the gas concentration β_0 outside the screen on the attenuation coefficient $p_2 p_1^{-1}$. In the screen, the volume concentration is β_1. Figure 4 shows the dependence of $p_2 p_1^{-1}$ on β_0 for the case $p_0 = 0.1$ MPa, $p_1 p_0^{-1} = 10$. Curves 1-3 are constructed for $\beta_1 = 0.1$, 1, and 10%. All curves have a contact point with the straight line $p_2 p_1^{-1} = 1$. In this case, there are no separation boundaries. To the left of the contact point $\beta_0 < \beta_1$, and we have the case of a normal screen. For $\beta_0 > \beta_1$, the inverse screen is realized.

Discussion of Results

Analysis of the computed characteristics displayed in Figs. 1-4 shows that the shock-wave parameters may be expected to decrease only for a shock wave whose pressure differential on the front falls in the interval above $p_1 p_0^{-1} = 3$-5 and $p_1 p_0^{-1} = 30$-40 for $p_0 = 0.1$ MPa and with a very significant volume concentration of gas in the liquid ($\beta_0 = 5$-10%). Even

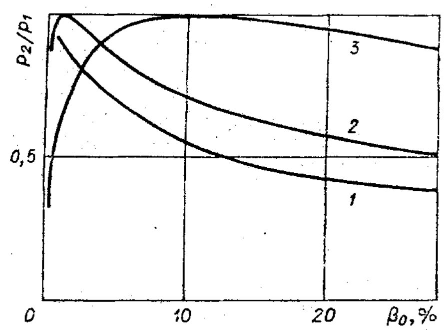

Fig. 4

with such high volume fractions of gas in the liquid, an increase in pressure to a magnitude of the order of $p_0 \geqslant 0.5$ MPa, equivalent to placing the double screen at a depth exceeding 50 m, limits the damping property of the screen even more sharply and narrows the range of transparency of the screen to the pressure differential interval $3 < p_1 p_0^{-1} < 20$. As can be seen, an increase in the initial pressure weakly affects the transparency of the screen with respect to weak pressure disturbances. At the same time, the nontransparency range with respect to strong shock waves narrows from $p_1 p_0^{-1} = 30\text{-}40$ to $p_1 p_0^{-1} = 15\text{-}20$.

There is also a definite difference between the estimate of the damping action of bubble screens for weak waves [6] and that in Figs. 1-4. Thus, according to the data in [6], bubble screens with volume gas concentration in the liquid of 1-10% decrease the wave parameters with pressure differential $p_1 p_0^{-1} \sim 1.7$ for $p_0 = 0.1$ MPz by almost a factor of 10. However, actually, when a pressure wave incident on the screen is attenuated, the pressure differentials in front of the screen and behind it must converge. Indeed, in [6], a relation is shown between the quantities p_2 and p_1 in the acoustical case in the form $p_2 p_0^{-1} - 1 = (p_1 p_0^{-1} - 1) 4 z_1 z (z_1 + z)^{-2}$, where z and z_1 are the acoustical impedances of water and of the two-phase medium $\rho_0 c_0$, respectively. It can be verified, therefore, that for $p_1 p_0^{-1} \to 1$, $p_2 p_0^{-1} \to 1$. Thus, the relations and illustrations presented reflect more realistically the protective properties of a screen with respect to weak waves.

It should be noted that the results obtained concerning the weak attentuation of waves with small and large pressure differential are partly confirmed in the experiments in [8], where it is also noted that a pressure wave with pressure differential on the front 0.14 MPa with $p_0 = 0.1$ MPa, i.e., for $p_1 p_0^{-1} = 2.4$, attenuates when crossing a bubble screen by only a factor of 2. The pressure wave with pressure differential 1.2 MPa with $p_0 = 0.1$ MPa, i.e., for $p_1 p_0^{-1} = 13$, is attenuated by not more than 20-30%. Both of these results are described quite well by the calculations that were carried out. Comparison with the experiments in [8], where the passage of short wavelength disturbances through the screen was investigated, shows that in order to estimate the attenuation of the parameters on the front of a pressure wave, it is completely possible to use the relations presented and the proposed model of the change in the parameters of long waves traversing a water–bubble screen, since in this case repeated reflections of shock waves will no longer occur in the screen.

The calculations carried out illustrate the poor universality of the water bubble screens as a medium for attenuating pressure waves in a liquid. In each specific situation, depending on the pressure wave parameters, the average pressure in the medium, and the technical possibilities for providing a given volume of gas concentration in the liquid, it is useful to estimate the effectiveness of a screen before it is installed. In addition, when installing protective screens, it is necessary to take into account the possibility of a considerable decrease in their effectiveness when even a small quantity of gas enters into the medium surrounding the screen.

The analysis carried out above also showes the greater effectiveness of normal screens than inverse screens in changing the parameters of shock waves. In connection with the fact that the velocity of sound in a gas–liquid medium is much smaller than the velocity of sound in a liquid, in using normal screens for waves with moderate intensity and sufficiently extended screens, it is possible to achieve significant stretching of the passing wave pulses with time. For the inverse screen, this cannot be done due to the strong dependence of the velocity of propagation of the waves on their intensity. The rapid process of multiple passage of waves inside the inverse screen and their mutual superposition outside the screen in the two-phase medium make inverse screens ineffective for decreasing the parameters of shock waves.

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STRUCTURE OF COMPRESSION AND RAREFACTION WAVES IN A VAN DER WAALS GAS WITH CONSTANT SPECIFIC HEAT

A. A. Borisov and G. A. Khabakhpashev

UDC 532.592+534.222+536.441

It is known [1] that the change in entropy in shocks of weak intensity is proportional to the change in specific volume to the third power: $S_2 - S_1 = (\partial^2 p/\partial V^2)(V_1 - V_2)^3/12T_1$, where p is the pressure, V is the specific volume, T is the temperature, and the subscripts 1 and 2 denotes values of the quantities in front of and behind the front, respectively. In an ideal gas, as well as in the majority of actually realizable situations, $(\partial^2 p/\partial V^2)_S > 0$. Therefore, the condition of entropy growth allows the existence of compression shocks and forbids the existence of rarefaction shocks (Zemplen theorem).

However, Zel'dovich [2] has shown that near the fluid—vapor critical point, $(\partial^2 p/\partial V^2)_S$ can be less than zero under definite conditions. In this domain of anomalous thermodynamic properties, compression waves should be spread out in time, while rarefaction waves are propagated in the form of (rare) shocks. A more complex case, in which the unperturbed state is in the domain of anomalous thermodynamic properties while the perturbed state is outside (or conversely), has been considered theoretically in a number of papers, a detailed summary of which is given in [3]. The main attention in these papers is given over to an analysis of the wave adiabats of such media. The question of the existence of exact self-similar solutions of the problem under consideration has not yet been investigated. An evolutionary equation has been obtained in [4] for long-wave perturbations of finite amplitude which can be used to explain the possible multiwave structure of rarefaction waves.

The first experiment to study the propagation of finite-amplitude perturbations in the critical domain was performed on a "shock tube" type apparatus [5]. The rarefaction wave profiles were determined in this experiment, hence it is desirable to obtain the theoretical results also in analogous form. In this connection, the question of the pressure wave structure near the fluid—vapor critical point is investigated in this paper by using a numerical solution of the problem of the dissociation of an arbitrary discontinuity.

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 123-128, January-February, 1982. Original article submitted January 9, 1981.

0021-8944/82/2301-0115$07.50