DAMPING OF STRONG SHOCKS IN RELAXING MEDIA

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The expanded range of pulsed materials processing requires the development of means for localizing the effect of high-power energy sources used to excite shock waves in the surrounding medium. In addition to special chambers, recently multiphase media (bubble screens in liquids [1, 2], gas—liquid foams [3, 4], foam plastics [5, 6], etc.) have been used for damping of shock waves.

Studies have shown that the energy of explosions is most efficiently absorbed by water foams [3, 4]. Thus, for sufficiently large distances from an explosive charge ($R > 0.8$ m/kg$^{1/3}$, where $R = r_f/Q^{1/3}$; r_f is the distance from the center of the energy source (m), and Q (kg) is the mass of the charge for an energy of 5.4 MJ/kg; the pressure at a shock front falls to more than an order of magnitude below air pressure. At the same time, decreasing distance from the charge leads to a sharp reduction in the damping coefficient and, in particular, for $R < 0.5$ m/kg$^{1/3}$ the pressure impulse in the decaying wave becomes greater than in a gas.

A qualitative theoretical analysis of strong shock waves in two-phase media with a small volume fraction of condensed material showed that the potential ability of foams to damp shock waves is greater and that the parameters of shock waves at a fixed distance can be reduced below those obtained experimentally [4, 7]. It was noticed that the failure to reach the calculated damping parameters was apparently a result of the fact that the characteristic interphase relaxation times, which determine the conversion of energy from the medium into internal energy of the condensed phase (which has no role in the pressure), are substantially greater than the time required to reach the peak pressure at the shock front.

In this paper we analyze the dependence of the shock damping parameters on the thermal relaxation time in order to provide a deeper understanding of the damping of shock waves in such media and to determine their effectiveness as localizing media. On the other hand, the observed reduction in the damping coefficient for shocks in foam near the explosive charge requires an extension of the experimental investigation near the energy source.

CALCULATION OF THE PARAMETERS OF STRONG SHOCK WAVES GENERATED BY POINT ENERGY SOURCES

The occurrence of relaxation processes makes strong shock calculations in such media considerably more complicated because the flow is not self-similar. This means that a time-dependent system of differential equations must be solved. In analyzing shock flows in two-phase media the following assumptions are made: (a) the two-phase medium is homogeneous; (b) the volume fraction of the condensed phase is negligibly small and its density and specific heat are constant; (c) there are no phase transitions; (d) kinematic equilibrium exists between the phases at the shock front; and, (e) the gaseous phase obeys the ideal gas equation of state.

In Euler variables the basic hydrodynamic equations for the motion of a thermally nonconducting inviscous medium can be written in the form of an overall balance for the two phases in the continuity, momentum, and energy equations:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^{\nu-1}} \cdot \frac{\partial r^{\nu-1} \rho u}{\partial r} = 0, \tag{1a}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0, \tag{1b}$$

$$\frac{\partial}{\partial t}\left(\rho E + \rho\frac{u^2}{2}\right) + \frac{1}{r^{\nu-1}}\frac{\partial}{\partial r}\left[r^{\nu-1}u\left(\rho E + \rho\frac{u^2}{2}\right) + p\right] = 0. \tag{1c}$$

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Here ν is a parameter which takes the values 1, 2, or 3 for plane, cylindrical, and spherical symmetry, respectively; u is the mass velocity of the flow; ρ is the density of the mixture; p is the pressure; E is the internal energy per unit mass; r is the spatial coordinate; and t is the time. Treating the equations for the mixture as a whole allows us to avoid specifying the interphase interaction terms which unavoidably arise when the equations are written down separately for each phase [8].

The effect of shock wave damping associated with interphase interactions in which part of the energy that determines the pressure of the mixture is transformed to energy that makes no contribution to the pressure, can be described by the time-dependent parameter Γ which specifies at any given time the relationship between the internal energy E, the pressure p, and the mixture density ρ:

$$E = p/\rho(\Gamma - 1). \tag{2}$$

The thermodynamical basis for this type of dependence originates in ideas about nonequilibrium processes [9]. Suppose as a result of some process the change in the internal energy E causes a change in the quantity $p\rho^{-1}$. The magnitude of the latter quantity will vary depending on the extent of relaxation that has occurred. Following the formalism of [9], the dependence of $p\rho^{-1}$ on the energy can be written in operator form:

$$\left(\frac{\partial \widehat{p\rho^{-1}}}{\partial E}\right) = \left(\frac{\partial p\rho^{-1}}{\partial E}\right)_f + \frac{\left(\frac{\partial p\rho^{-1}}{\partial E}\right)_e - \left(\frac{\partial p\rho^{-1}}{\partial E}\right)_f}{1 + \tau_0 \frac{d}{dt}},$$

that is, the changes $\delta p\rho^{-1}$ and δE are related by

$$\delta p\rho^{-1} = \left(\frac{\partial \widehat{p\rho^{-1}}}{\partial E}\right)\delta E.$$

Here the subscripts e and f mean that the derivatives are taken for equilibrium between the phases and for frozen thermal relaxation, respectively. τ_0 is the characteristic interphase relaxation time. Since a two-phase medium in equilibrium can be described by the equations

$$E = \frac{p}{\rho_0(\Gamma_0 - 1)}, \quad \left(\frac{\partial p\rho^{-1}}{\partial E}\right)_e = \Gamma_0 - 1, \quad \Gamma_0 = \gamma\frac{1+\omega}{1+\gamma\omega},$$

and since only the internal energy of the gaseous phase will change during instantaneous compression, i.e.,

$$\left(\frac{\partial p\rho^{-1}}{\partial E}\right)_f = \gamma - 1,$$

Eq. (3) yields

$$\hat{\Gamma} = \gamma + \frac{\Gamma_0 - \gamma}{1 + \tau_0 - \frac{d}{dt}}, \tag{4}$$

where $\gamma = c_p/c_V$; $\omega = c/c_p \cdot \sigma_s/\sigma_g$; c and c_p are the specific heats at constant pressure of the condensed phase and gas; and, σ_s and σ_g are the mass concentrations of the condensed and gaseous phases. Equation (4) is then substituted in Eq. (2).

We now specify Γ for a passing shock wave. The phase disequilibrium, as assumed, develops at the shock front. Equilibration of the parameters of both phases takes place behind the shock. Assuming in the first approximation that the characteristic relaxation time τ_0 is a constant and that the change in the flow parameters behind the shock front makes no additional contribution to the disequilibrium between the phases, Eq. (4) can be written in the analytic form

$$\Gamma = \Gamma_0 + (\gamma - \Gamma_0)\exp(-\tau/\tau_0), \tag{5}$$

where τ is the lifetime of a microscopic volume in the shock wave. Although this expression is only an effective index and not exact, it does make it possible to analyze the main features of shock wave propagation in the presence of nonuniformities.

In general τ is a function of the time and spatial coordinate, i.e., $\tau = \tau(r, t)$, and satisfies the differential equation

$$\frac{\partial\tau}{\partial t} + u\frac{\partial\tau}{\partial r} = 1, \tag{6}$$

with $\tau = 0$ for $t = 0$ and $r = r_f$. Supplementing Eqs. (1), (2), (5), and (6) with the overall energy balance equation for the volume occupied by the shock wave,

$$\mu\int_0^{r_f}\left(\rho E + \rho\frac{u^2}{2}\right)r^{\nu-1}dr = E_0 + E_{s0} + E_{g0},$$
$$\mu = 2(\nu-1)\pi + (\nu-2)(\nu-3), \tag{7}$$

we obtain a closed system of equations for the motion of a two-phase medium including the thermal disequilibrium behind the shock front. Here E_{go} and E_{so} are the initial energies of the gas and condensed phase.

We shall limit ourselves to considering a strong shock wave where the initial internal energy of the gas can be neglected in Eq. (7). Then the equations at the shock discontinuity (the boundary conditions) take the following form, given that the effects of thermal relaxation have not yet been able to appear:

$$p = 2/(\gamma+1)\cdot\rho_0 D^2,\ \rho = (\gamma+1)/(\gamma-1)\cdot\rho_0,\ u = 2/(\gamma+1)\cdot D,$$

where D is the shock speed. In the case of a point source of energy E_0 the initial conditions for the system of equations can be found from the self-similar solution of the problem [10, 11].

This system of differential equations was solved using a computer program. The method of solution was based on implicit finite-difference schemes analogous to those given in [12]. With an implicit scheme it is possible to avoid placing strict limitations on the time step. The unknown quantities at the nodes of the implicit scheme were found using the method proposed in [13] for solving problems with two independent variables. The machine time spent on the ES-1040 computer to calculate a single variant of the problem was 3-4 h.

The calculations show that at the initial time $t < \tau_0$ the flow parameters deviate linearly, with an accuracy of 15%, from the self-similar parameters of a flow in a nonrelaxing medium. The more rapid damping of the shock velocity in the presence of thermal relaxation found in this case leads to an increase in the relative velocity u/D compared to the self-similar solution. Because of this the relative fraction of the mass in the central region decreases, but increases near the front. The pressure at the shock front decreases monotonically. The deviations from the self-similar parameters, given by the formulas (the self-similar variables are denoted by subscript a)

$$\delta_u = \frac{u-u_a}{u_a}\frac{t}{\tau_0},\quad \delta_p = \frac{p-p_a}{p_a}\frac{t}{\tau_0},\quad \delta_\rho = \frac{\rho-\rho_a}{\rho_a}\frac{t}{\tau_0},$$

are shown in Fig. 1.

The effect of relaxational heat exchange on the pressure damping in the shock wave is conveniently characterized by the parameter s which relates the pressure at the shock front, p, to the distance from the center of the energy source by $p \sim r_f^{-s}$. When kinematic equilibrium exists we have

$$s = -\frac{d\ln p}{d\ln r_f} = -2\frac{d\ln D}{d\ln r_f}.$$

It should be noted that for strong shocks, in which the relaxation processes occur within the shock front, s is a constant that for spherical symmetry, in particular, has the value $s_0 = 3$. Then the reduction in the pressure drop with distance is related only to the geometric divergence of the flow. At the same time, for a medium in which the shock is damped more rapidly than in a uniform medium, the parameter s must exceed s_0, the value in the self-similar solution.

The deviation from the self-similar value s_0 for $t < \tau_0$ is conveniently characterized by the quantity

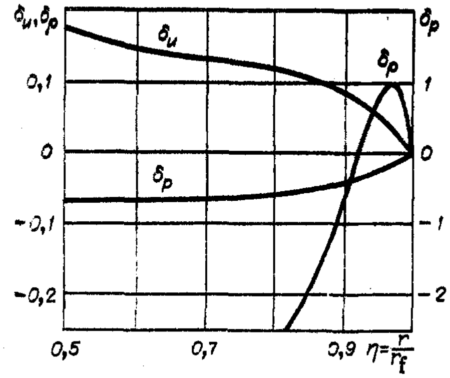

Fig. 1. Distributions of the corrections to the self-similar solution for the density δ_ρ, mass velocity δ_u, and pressure δ_p.

TABLE 1

Γ_0	δ_s for γ			
	2,1	1,2	1,4	5/3
1,2	—	0,0	0,505	0,655
1,1	0,0	0,560	0,760	0,800
1,05	0,610	0,840	0,885	0,870
1,01	1,095	1,065	0,985	0,925
1,001	1,205	1,115	1,010	0,940

$$\delta_s = (s - s_0) \cdot t/\tau_0. \tag{8}$$

Table 1 shows the computed corrections δ_s for spherical symmetry. We note that the correction δ_s characterizes the rate of damping of the shock with time.

Introducing the dimensioned parameter τ_0 into the problem (i.e., letting thermal relaxation occur) makes the flow non-self-similar. In this case the extent of pressure damping at the same relative distances $R^* = r_f/E_0^{1/3}$ is different. Thus, the reduction in the pressure at the shock front with distance depends on the parameters ρ_0, E_0, γ, Γ_0, and τ_0. These dependences are shown in Fig. 2.

From Fig. 2a it follows that for τ_0 = const the reduction in Γ_0 by changing the mass concentration of the condensed phase leads to a substantially more rapid damping of the wave than for the same values of Γ_0 at lower mass concentrations, even though in the limiting case of no heat exchange ($\tau_0 \to \infty$) the shock parameters are the same in both cases. This effect is explained by the fact that, despite the heat exchange, the enhanced concentration of the condensed phase leads to a reduction in the shock speed. When heat exchange occurs in the medium there is an increase in the time required for the shock to travel a given distance and this leads to more complete heat transfer between the phases.

For given ρ_0, γ, Γ_0, and τ_0 (see Fig. 2b) an increase of 10 and 100 times in the energy causes a reduction by factors of 1.2 and 1.45, respectively, in the distance over which a pressure of 5 MPa is reached. The effect of the characteristic heat-exchange time on the pressure variation with distance is shown in Fig. 2c. As is to be expected, with more intense heat exchange and all other conditions the same, damping should occur more rapidly. Variations in the initial value of γ (the adiabatic index of the gaseous phase) lead, on one hand, to different initial pressures and, on the other, to more rapid damping for smaller γ (see Fig. 2d).

In considering the damping of shock waves generated by nonpoint energy sources, such as solid explosives, it should be noted that increasing the density of the condensed phase in order to reduce the shock wave parameters must cause a reduction in the shock formation region as well as an increase in the shock parameters at the interface between the two-phase medium and the explosion products. It is natural to assume that in some region of shock wave forma-

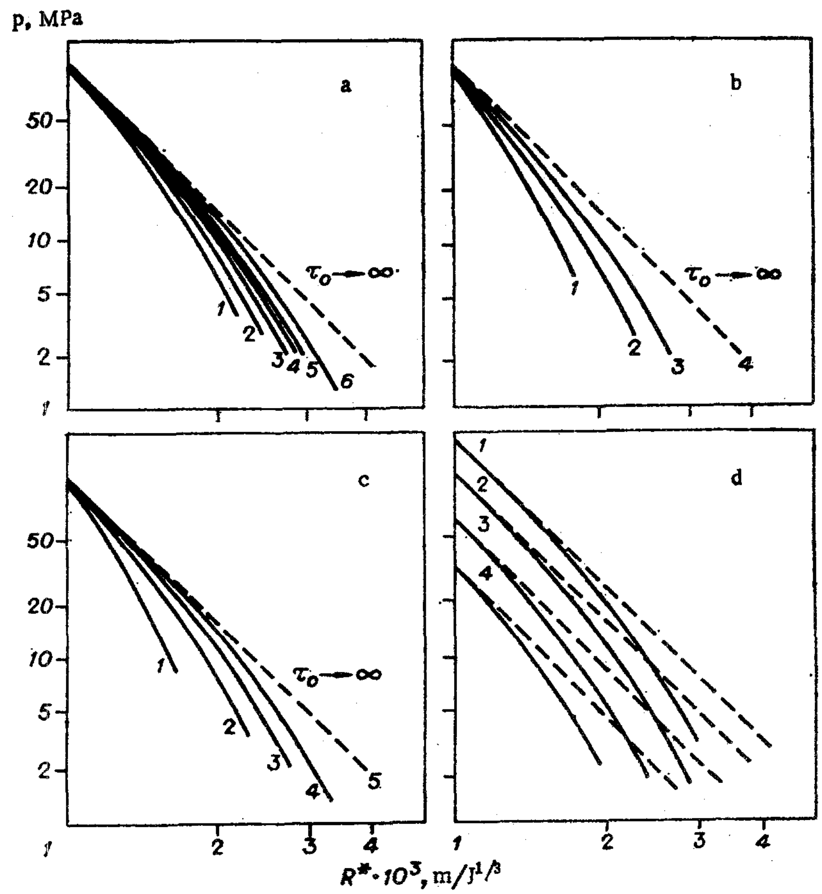

Fig. 2. Dependence of the pressure damping on the relative distance when Γ_0, ρ_0, E_0, τ_0 and γ are varied. a) $\gamma = 1.4$, $E = 10^7$ J, $\tau_0 = 150$ μsec, 1) $\Gamma_0 = 1.01$, $\rho_0 = 50$ kg/m^3, 2) $\Gamma_0 = 1.01$, $\rho_0 = 20$, 3) $\Gamma_0 = 1.001$, $\rho_0 = 10$, 4) $\Gamma_0 = 1.01$, $\rho_0 = 10$, 5) $\Gamma_0 = 1.1$, $\rho_0 = 10$, 6) $\Gamma_0 = 1.01$, $\rho_0 = 2$ kg/m^3; b) $\gamma = 1.4$, $\rho_0 = 10$ kg/m^3, $\Gamma_0 = 1.01$, $\tau_0 = 150$ μsec, E_0, J: 1) 10^9, 2) 10^8, 3) 10^7; c) $\gamma = 1.4$, $E_0 = 10^7$ J, $\rho_0 = 10$ kg/m^3, $\Gamma_0 = 1.01$, τ_0, μsec: 1) 30, 2) 80, 3) 150, 4) 300; d) $E_0 = 10^7$ J, $\rho_0 = 10$ kg/m^3, $\Gamma_0 = 1.01$, $\tau = 150$ μsec, γ: 1) 1.67, 2) 1.4, 3) 1.2, 4) 1.1.

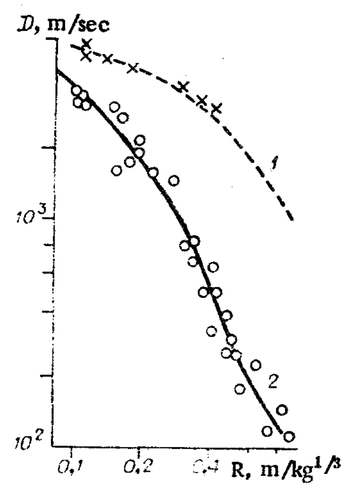

Fig. 3. Variation in the shock front velocity with the reduced distance for air (1) and foam (2).

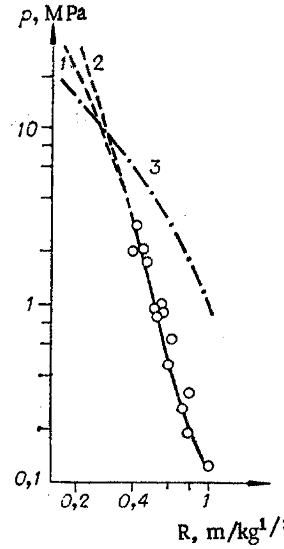

Fig. 4. Pressure variation with distance for foam (1, 2) and for air (3) [14].

tion the pressure amplitude at the shock front in the two-phase medium will also be greater than in a gas.

EXPERIMENTAL STUDY

In order to obtain quantitative estimates of shock damping in the formation region for shock waves generated by solid explosives, we have studied experimentally the velocity field of shock waves in an air foam with a mass concentration of liquid of 10-15 kg/m^3. The experiments were conducted with spherical explosive charges having a bulk mass of 0.5 kg (E_0 = 2.7 MJ) and using electrical contact probes.

Figure 3 shows the observed variation in the shock speed with the reduced radius $R = r_f/Q^{1/3}$ in foam and in air [14]. It can be seen that at closer distances from the charge, there is a sharp reduction in the differences between the shock speeds in the foam and gas. Figure 4 shows the variation in the pressure drop at the shock front in foam calculated from these data assuming kinematic equilibrium between the phases at the shock front (curve 2).

For $R > 0.4$ m/kg$^{1/3}$, where direct measurements of the pressure were made (continuous curve in Fig. 4), with charges having a mass of 0.5-2.8 kg the difference between the measured values of the pressure drop [4] and those calculated from the velocity lies within the measurement error of 20-30%. Thus, we may assume to this accuracy that kinematic interphase equilibrium exists in the shock front. Since direct pressure measurements were not made there, the calculated dashed curve 2 should be regarded as the upper limit of the possible pressure drop at the shock front in foam because a given shock speed would correspond to a lower pressure in the absence of kinematic equilibrium. Curve 1 of Fig. 4 represents the pressure field of a point explosion in foam taking thermal relaxation into account. As can be seen in Fig. 4, when $R \approx 0.3$ m/kg$^{1/3}$ the pressure in a foam becomes comparable to the pressure at a shock front in air and sharply increases on approaching the charge, at the boundary of which, judging from the shock speed, the pressure must be $p \simeq 500$ MPa. These data agree with estimates obtained from the decay of the discontinuity between the explosion products and foam (D = 6000 m/sec, p = 500 MPa). Thus, attenuation does not occur near the explosive charge, but rather an increase in the shock parameters in foam compared to air. This must be taken into account when using foam as a damping medium.

The characteristic time for heat exchange between the gas and liquid in a foam can be estimated by determining the parameter s from the slope of the pressure vs. distance curve (see Fig. 4). For $R = 0.5$ m/kg$^{1/3}$, when the wave can still be regarded as strong, we have $s = 4$. Given that $\delta_s \approx 1$ for a gas-water foam with the above mass concentrations of the condensed phase ($\gamma = 1.4$, $\Gamma_0 = 1.01-1.001$) and knowing the time for the shock to propagate from the surface of the explosive charge to the specified distance, Eq.(8) can easily be used to estimate the characteristic heat exchange time, which is τ_0 = 150-180 μsec in this case.

This analysis shows that heat transfer significantly changes the flow pattern and makes it more difficult to describe the damping of strong shock waves in two-phase media. The coupling of the time-varying heat-exchange parameters with changes in the shock damping coefficients has been demonstrated. It has been found that the parameters of shock waves in foams are enhanced compared to those in gases near nonpoint energy sources because of the conditions under which energy is transferred from the source to the medium.

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