SHOCK WAVES, EXPLOSIONS, AND DETONATIONS

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Relaxation Phenomena in a Foamy Structure

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Abstract

The gas-liquid foams, unlike the single-phase media of a gas and liquid type, display a number of relaxation properties that determine the structure and parameters of wave disturbances propagating in such a medium. The present work analyzes the effect of thermal and kinematic relaxation between phases on the shock wave parameters and wave reflection from the rigid wall. The problem of a peak stage of explosion in such a medium and the dependence of the generated shock wave parameters on explosion energy and medium density are considered. The estimated results are compared with the experimental data obtained with piezoelectric and electric pressure gages in foams with liquid mass concentration from 2 to 50 kg/m^3.

The theoretical analysis presented herein provides a physical explanation for the experimentally observed phenomena of the shock dispersion, pressure growth at the incident and reflected wave front with increasing duration of the wave disturbance, and the increase of the shock wave damping factor with distance in foam explosion.

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Nonmenclature

a_e = equilibrium sound velocity in a two-phase mixture
a_o = sound velocity of a gas filling the foam cells
C_p = specific heat of a gas phase at a constant pressure
D = shock wave velocity
d = density of a condensed phase
E = specific internal energy of a mixture
H = specific enthalpy of a two-phase mixture
k = pressure damping coefficient
P = pressure
q = mass of explosive charge
r = radius
T = gas temperature
t = time
t_o = characteristic time
u = gas phase velocity
v = condensed phase velocity
Γ = ratio of specific heats of a mixture
Γ_f = effective index of shock adiabat for gas-liquid foam
γ = index of adiabat of a gas
δ = ratio of specific heat of a condensed phase and specific heat of a gas phase at a constant pressure
ε = volume fraction of a condensed phase in a mixture
η = ratio of mass concentrations of condensed and gas phases
ρ = density of mixture
ρ_g = gas density
σ = mass concentration of a condensed phase
τ = temperature of a condensed phase

Introduction

Recent studies** of dynamic processes in gas-liquid foams have revealed that the phenomena of shock and detonation wave propagation in these systems differ significantly in the following way from the phenomena observed when these waves propagate in a homogeneous media of either gas or liquid:

(1) The structure of a shock wave in foam depends on velocity of their propagation. At $D < a_o$ the pressure

**See for example Borisov et al. (1978), Krasinski et al. (1978), Kudinov et al. (1976), Kudinov et al. (1977a, 1977b), Palamarchuk (1979), Palamarchuk et al. (1979), and Saint-Cloud et al. (1976).

profile of the wave has a two-front configuration.

(2) At a fixed shock wave velocity the amplitude of pressure depends upon a time of wave disturbance.

(3) The structure of shock wave front depends on the conditions of its excitation; shock waves of equal amplitude generated in the shock tube and by a charge explosion of explosives are significantly different.

(4) Damping of explosive waves occurs more rapidly in foams than in gas, liquid, or bubble media.

(5) Even though the detonation wave velocity is constant in detonable foams at from 2 to 15 kg/m^3, the pressure behind its front decreases as liquid concentration increases.

(6) Heterogeneous detonation waves in foam do not have clearly defined "chemical peaks;" the concentration limits of foam detonation considerably exceeding those in condensed gaseous media.

(7) The pressure generated by the reflection of a foam detonation wave from the rigid wall tends to the pressure in the incident detonation wave as liquid concentration increases.

Mathematical models for such media are substantially complicated by a variety of processes of interphase interaction. At the same time, Palamarchuk et al. (1979) have shown that the phenomena could not be explained within the scope of classical thermodynamics and that any mathematical model must account for the relaxation of detonation waves in foam. Analysis of the experimental data on detonation wave propagation in foams has led to the conclusion that the characteristic times for deformation and breakage of foam cells are considerably shorter than those for thermal and kinematic relaxation processes between gaseous and condensed phases. Palamarchuk (1979) has constructed a qualitative model which simulates the dynamic behavior of foam and explains the observed relaxation phenomena in the propagation of shock and detonation waves in foams.

For investigation of stationary and quasistationary waves in foams if an effective index of foam adiabat is defined:

$$\Gamma_f = \gamma \frac{1 + \eta\delta(\tau/T)}{1 + \gamma\eta\delta(\tau/T)}$$

then, mathematical the state equation for foam takes a form:

$$E = P(1-\varepsilon)(\Gamma_f - 1)\rho$$

Solution of the one-dimensional conservation equations across a discontinuity in the foam leads to a family of Hugoniot abiabats for a relaxing two-phase medium (Palamarchuk et al. 1980):

$$P^* = \frac{\Gamma+1}{\Gamma-1} - \frac{1-\eta_0}{\rho^*} + \frac{2\gamma}{\gamma-1} \times \frac{\eta_0-\eta}{1+\eta_0}(1-\varepsilon_0)Q^* - \varepsilon_0 \frac{2\Gamma}{\Gamma-1} \Big/$$

$$\frac{\Gamma_f+1}{\Gamma_f-1}\,\frac{1+\eta_0}{\rho^*} - 1 - \varepsilon_0 \frac{2\Gamma_f}{\Gamma_f-1}\,\frac{\eta}{1+\eta}\,\frac{1+\eta_0}{\eta_0}$$

$$\Gamma = \gamma \frac{1 + \eta d}{1 + \gamma\eta d}, \quad Q^* = \frac{Q}{C_p T_0}$$

$$\rho^* = \frac{\sigma + (1-\varepsilon)\rho_g}{(1-\varepsilon_0)\rho_{go}}, \quad P^* = \frac{P_1}{P_0}$$

The analysis of Rankine-Hugoniot relations for shock and detonation waves for foams showed that variation of volume fraction of a condensed phase did not result in a considerable change of the velocity of wave propagation and pressure in it. If the volume fraction is neglected, mass velocity and a density of the mixture are changed considerably.

The present work, a continuation of the previous investigations, is concerned with the effect of kinematic and thermal relaxation and also the volume fraction upon the parameters of shock wave reflections in foam and a strong stage of explosion in foam. A model of the kinetics of relaxation processes in foams is proposed.

Experimental Equipment

Measurements of shock wave parameters in foam were performed in the following installations.

1) A horizontal shock tube of 67 mm i.d. 5.9 m long with a 2.6-m-long driver section separated by a diaphragm: In the end plate and in the walls of the shock tube, pressure transducers, whose characteristics will be given below, were located. The tube was filled with water foam, the liquid concentration in foam varying from 2 to 30 kg/m^3.

2) A 1600-mm diam cylindrical vessel: Spherical shock waves were generated by the explosion of bulk density

cyclotrimethylene trinitramine (RDX) charges, weighing from 0.5 to 2.8 kg.

3) 529-mm-diam steel cylinders: These were used to study shock waves in the nearest explosion zone.

Recording of the parameters of spherical shock waves was accomplished with the help of the piezoceramic transducer of the "knife" type, representing a flat steel rod, on which piezoceramic 15-mm elements were attached. In the shock tube shock waves with a gradual pressure rise were recorded by mass-produced piezoceramic transducers whose resonance frequency is 30 kHz. Reproducibility of the impulse shape of pressure by piezoceramic transducers is not possible because of the influence of blast furnace processes on the charge generated under ceramic compression (Khokhlov et al. 1978). Electret pressure gages were developed to measure the loading impulses on the rigid wall during the reflection of strong waves. The sensitive element of this gage was an electret rigid vinyl-plastic. These electrets are produced from rigid PVC by the application of an intensive electric field to the polymer, which is maintained at temperatures in access of the vitrification temperature for several hours, then removed from the electric fields and cooled. In a series of independent experiments, it was established that the piezomodule of rigid PVC electrets with one-sided axial loading depends on the polarization condition which remains unchanged during load increment from 10^{-7} to 10^{-3} s. Output characteristics of electret gages were linear at pressures up to 200 MPa. The piezomodule of electret PVC approaches piezomodules of the natural piezoelectrets: quartz and tourmaline. In this work electret gages with values of resonance frequencies 0.4 and 1.7 MHz were used. The gages were calibrated in the shock tube, and also with the explosions of spherical charges of explosives both in water and air. Correlation of the gage response was performed by the source repeater and matching coaxial cable. Recording of signals was made by the memory oscilloscope C 8 -2.

Reflection of Plane Shock Waves

Borisov et al. (1978) and Palamarchuk (1979) have shown that shock waves in foam had developed relaxation zones. To study shock wave reflection from a rigid wall, the characteristic dimension of the test section should be several times the length of the relaxation zone. The dimensions of relaxation zone depend on an intensity of wave and on a concentration of liquid and range from 0.5 to 1.0 m. The

test section length restricts the minimum possible lengths of the driver section, since a sufficiently long period of a stationary zone behind the wave front is needed to avoid interaction between the rarefaction wave from the driver and the developed relaxation zones. In this investigation, experimental data reported by Borisov et al. (1978) was used to select test and driver section lengths of 5.9 and 2.6 m, respectively.

The relationship between the propagation velocity of weak quasiacoustic pressure waves and the liquid concentration of the foam is shown in Fig. 1. Here, the calculated equilibrium sound velocity in foam (Rudinger 1965) is also shown by the solid line

$$a_e = \sqrt{\Gamma P_0/\rho_0(1-\varepsilon_0)}$$

As is seen, a good correlation is observed between the calculated and experimental data.

As in the previous investigations (Borisov et al. 1978), two types of shock waves were observed: a disperison wave with a two-front configuration at $D < a_0$ and a one-front one at $D > a_0$.

The calculated and experimental pressure ratios at the shock wave front for foams with different initial densities are plotted against the Mach value, $M = D/a_e$ in Fig. 2.

The data indicate that, within the measurement error, the observed velocity of incident shock waves agrees with predictions based on an equilibrium model whose parameters can be calculated through the model for dynamic behavior of foam (Palamarchuk 1979; Palamarchuk et al. 1979).

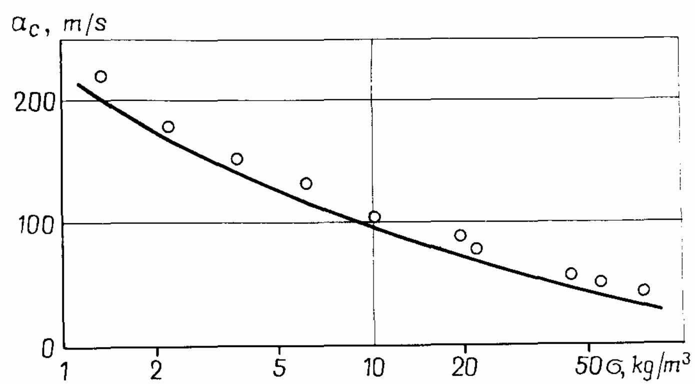

Fig. 1 Equilibrium sound velocity in foam.

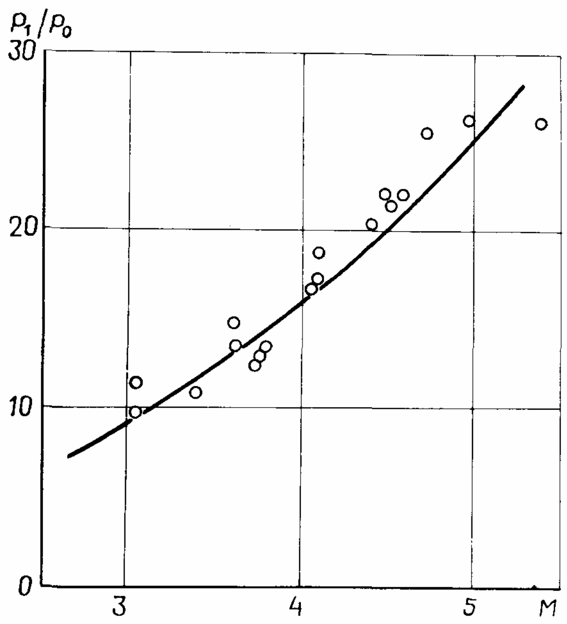

Fig. 2 Pressure behind incident shock wave in foam.

Figure 3 shows the evolution of the reflected shock wave for foam of σ = 27 kg/m^3 and the record of the incident shock wave. Locations of the pressure gages are also shown in this figure.

As seen in Fig. 3, qualitative changes occur in the pressure profiles of the reflected wave subsequent to reflection. The maximum pressure achieved in the wave, is 29 MPa, increasing during 2.5 ms. Unlike the incident shock wave, the reflected wave has a triangular pressure profile. The precursor wave before the sharp use in pressure is the incident wave; this wave decreases in amplitude as the wave approaches the end wall.

As a distance of 65 mm from the end, the precursor wave becomes shorter in time. Maximum pressure in the wave amounts to 23 MPa. Further on, the wave front becomes abruptly steeper and, at a 0.5 m distance from the end, the wave has a steep shock front, the decrease of pressure beyond the front becoming more flat. The wave amplitude drops, too. The reflected wave velocity D_r on the base of 0-65 mm is 95 m/s, decreases to 55 m/s on the base of 65-135 mm, and abruptly rises to 140 m/s between gages 3 and 4 and 470 m/s between gages 4 and 5.

Experimental and predictions of pressure data on reflection of shock waves from the rigid wall for foams with

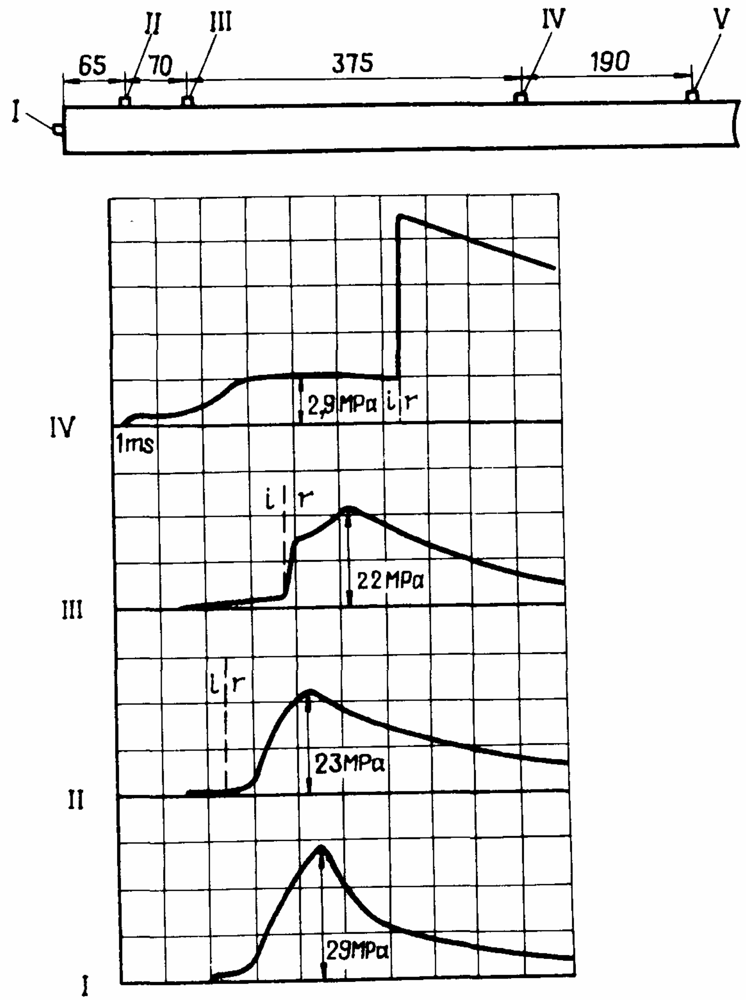

Fig. 3 Evolution of a reflected shock wave in foam.

different initial density and air are shown in Fig. 4. As this figure shows, the coefficient of reflection (P_2/P_1) of shock waves in foam exceeds the maximum possible for air.

To analyze the stationary of reflected shock waves in foam, calculations were made of the effect of the volume fraction of liquid on the values of the reflection coefficients, on the velocity of the reflected wave, and on its other conditions. In this case it was assumed that 1) gas was considered as an ideal one; 2) pressure in the mixture was determined by the gas only; 3) flow was one-dimensional

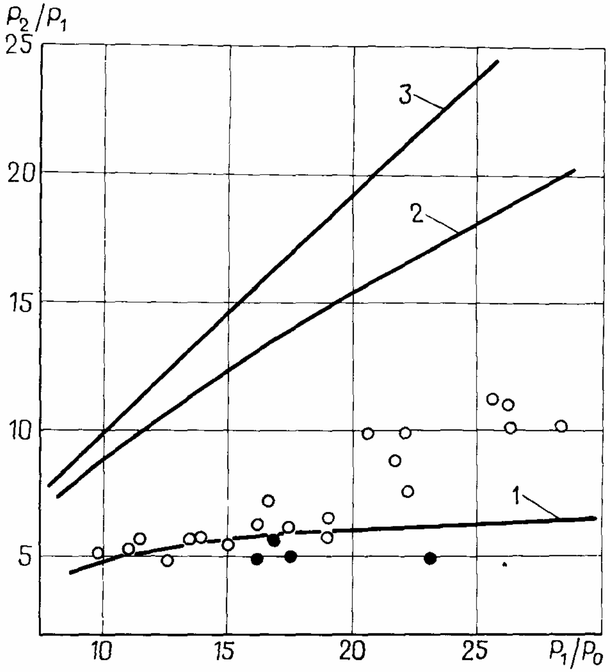

Fig. 4 Pressure behind reflected shock waves in foam and air. Curves 1,2,3: prediction for air and foam with σ = 2.5 and 27 kg/m^3, respectively; o: this investigation; o: observations due to Borisov et al. (1978).

and the effects of the wall boundary layer are neglected; 4) a condensed phase with a constant heat capacity is supposed to be incompressible; and 5) no mass exchange exists between the phases.

The calculations indicated that the pressure in the reflected wave did not, in fact, depend on the volume fraction of the condensed phase. However, if this fraction is ignored, the predicted velocity of the reflected wave decreases considerably (see Fig. 5). A qualitative difference in the relationship between the velocity of the reflected wave and that of the incident one then results. For sufficiently strong shock waves, when the volume fraction is ignored, the velocity of the reflected wave drops as the intensity of the incident wave increases and, if the volume fraction is considered, the velocity rises.

In Fig. 4, the calculated curves of the reflection coefficients (P_2/P_1), are plotted for foams at σ = 2.5 and 27 kg/m^3. Closed circles indicate the results of Borisov et al. (1978) obtained on shock tube with a 1.5-m-long test section. As is seen, the calculated curves lie considerably higher than the experimental data. At the same time, the increase of test and driver section lengths led to the

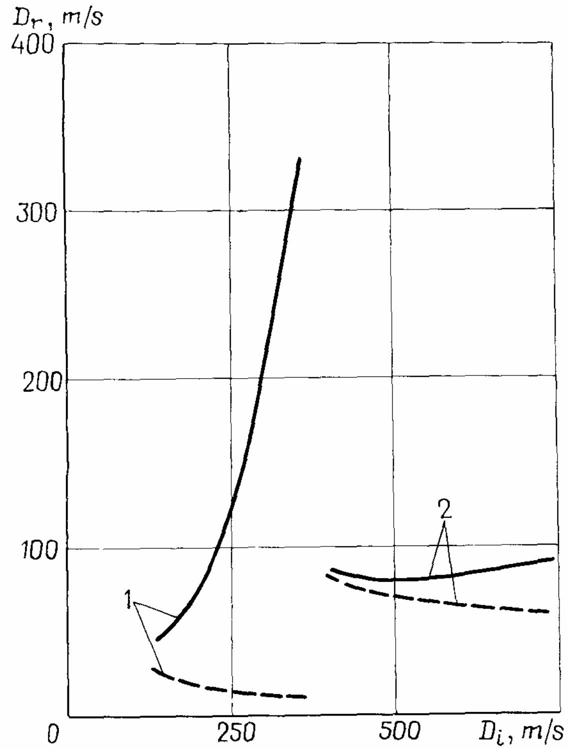

Fig. 5 Prediction of reflected shock wave velocity in foam. (——): taking into consideration the volume fraction of liquid; (---): without taking into consideration the volume fraction of liquid. For curve 1, σ = 27 kg/m^3; for curve 2, σ = 2.5 kg/m^3.

increase of both the absolute pressure value and the reflection coefficients as compared to the data obtained earlier.

The difference is not directly associated with the volume fraction of the liquid. Instead, the source of this difference should be found in the nature of the reflection of the waves, which have developed relaxation zones.

To date, it is remarkable to date that in all experiments stationary reflected waves have not been attained. The profile variation of a reflected shock wave in foam suggests that at a distance of 0.3-0.5 m from reflection the wave propagates not in foam, but in a pushing gas which is attributed to an abrupt wave front characteristic for the shock waves in gases.

The formation of the reflected wave occurs in a narrow zone near the test section end plate, and is complicated by the superimposed disturbances, which are generated at the contact surface and which should be, in view of the acoustic impedances of foam and gas, rarefaction waves. The decrease of pressure beyond the front of the reflected wave suggests the existence of rarefaction waves. Analysis shows these interactions can be minimized if the test section is 30 m long or more.

To evaluate the effect of kinematic and thermal nonequilibrium between the two phases on the parameters of the reflected wave, the jump equations, the laws of conservation of mass, momentum, and energy, the equation of state for each of the phases, and the equation for a mixture density was solved for two-velocity and two-temperature media. The suppositions about the mixture properties are similar to those indicated for the equilibrium waves. The shock wave conditions were assumed to be stationary in time. The system of equations in a coordinate system fixed on the shock front is

$$\frac{\rho_o}{I+\eta_o} u_o = \frac{\rho}{I+\eta} u$$

$$\frac{\rho_o \eta_o}{I+\eta_o} v_o = \frac{\rho\eta}{I+\eta} v$$

$$P + \frac{\rho}{I+\eta}(u^2 + \eta v^2) = P_o + \frac{\rho_o}{I+\eta_o}(u_o^2 + \eta_o v_o^2)$$

$$\frac{u_o^2}{2} + C_p T_o + \eta_o \frac{v_o}{u_o}\left(\frac{v_o^2}{2} + \delta C_p \tau_o + \frac{P_o}{d}\right)$$

$$= \frac{u^2}{2} + C_p T + \eta_o \frac{v_o}{u_o}\left(\frac{v^2}{2} + \delta C_p \quad + \frac{P}{d}\right)$$

$$\frac{1}{\rho} = \frac{P_o T}{P T_o} \frac{1}{\rho_{go}} + \frac{\eta}{d}$$

The system of equations of stationary equilibrium discontinuities is obtained from this system at equal temperatures and velocities of the phases on both sides of the discontinuity.

Numerical solutions indicate that small deviations from kinematic equilibrium in the incident wave cause significant

reductions of the reflection coefficient. As an example, if the mass velocity of the condensed phase is 10% less than the gas velocity, in laboratory coordinates for a wave of 2 MPa intensity for air foam at σ = 27 kg/m^3, the reflection coefficient is 60% smaller than that of equilibrium foam at the same conditions. Differences in the temperature of the phases in the incident wave also lead to a decrease of the reflection coefficient. In the extreme case of the absence of initial heating of liquid in the incident and reflected shock waves, its value corresponds to the reflection coefficient for gas filling foam cells.

A further study of the complete reflection of shock waves in foams should be conducted at higher shock wave intensity, when the waves have narrower relaxation zones.

Blast Waves in Foam

For prediction of the parameters of shock waves generated by the ignition of explosives in foam the nature

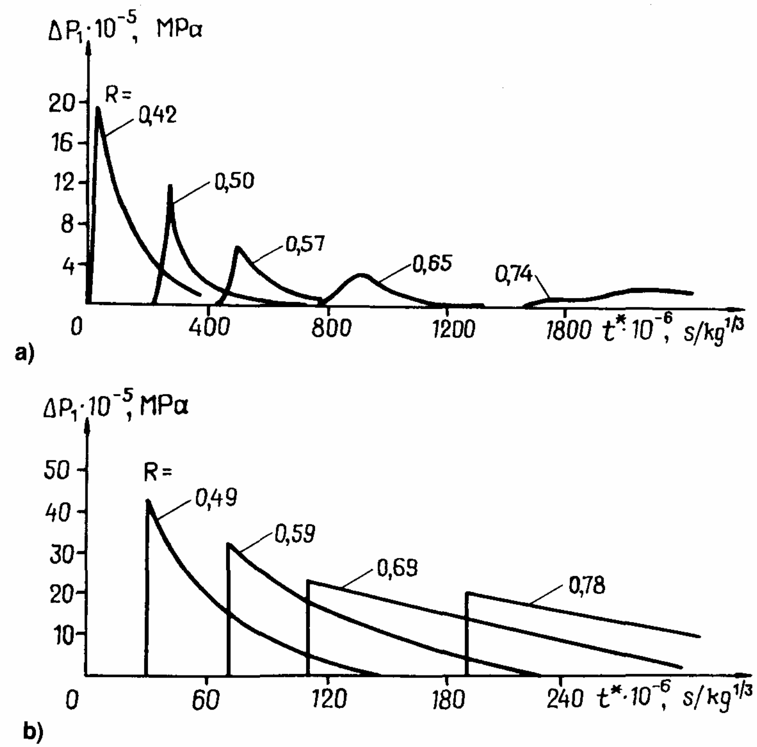

Fig. 6 Blast wave decay: a) in foams and b) in air.

of the relaxation interaction between gas and liquid must be understood. At the explosion in foam, the degree of completion of relaxation processes depends both upon thermophysical properties of phases and the energy of the explosion determining the period of wave disturbance.

To find the nature of the relaxation interaction between the phases, the conditions of shock waves excited by the explosion of 0.5-28-kg mass RDX charges were experimentally investigated.

Figure 6 shows the evolution of a shock wave in foam. The abscissa is the relative time; t^* is s/kg$^{1/3}$ from the moment of the wave entering the relative distance R = 0.42 m/kg$^{1/3}$.

For comparison the similar diagram has been plotted for air as reported by Adushkin (1963). The blast wave quickly damped more rapidly in foam than in air; the pressure profile decays from a triangular wave to a two-front dispersed wave similar to that observed in the shock tube.

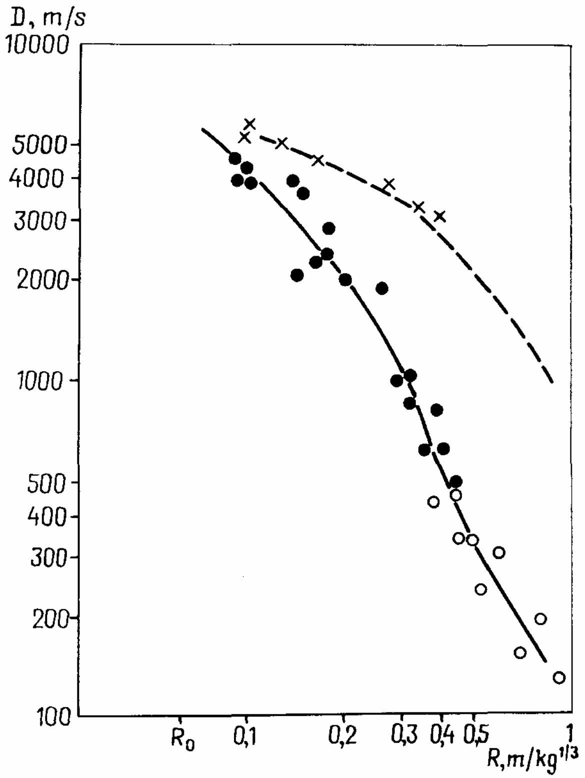

Fig. 7 Spherical shock front propagation velocity. (---): air; (——): foam; •: q = 0.5 kg, o: q = 0.5-2.8 kg.

Near the point of explosion an abrupt rise of pressure in foam was observed. In the explosive wave with a pressure drop of 2 MPa for R = 0.42, the time of pressure increase is a maximum, i.e. of the order to 20 µs. The relaxation zone of a stationary shock wave of the same amplitude generated on the shock tube has a period of about 2-3 ms.

Figures 7 and 8 show the relationships between the velocity and the pressure drop for spherical shock waves in foam and air.

Analysis of the experimental data indicates that the relationship between the maximum pressure ratio at the of a shock wave is

$$P_1/P_0 = M^2$$

where $M = D/a_e$, and a_e is the equilibrium sound velocity in foam. In the zone nearest to the explosion site the pressure ratio at the wave front is close to the ratio for kinematic equilibrium between the phases (Palamarchuk et al. 1979).

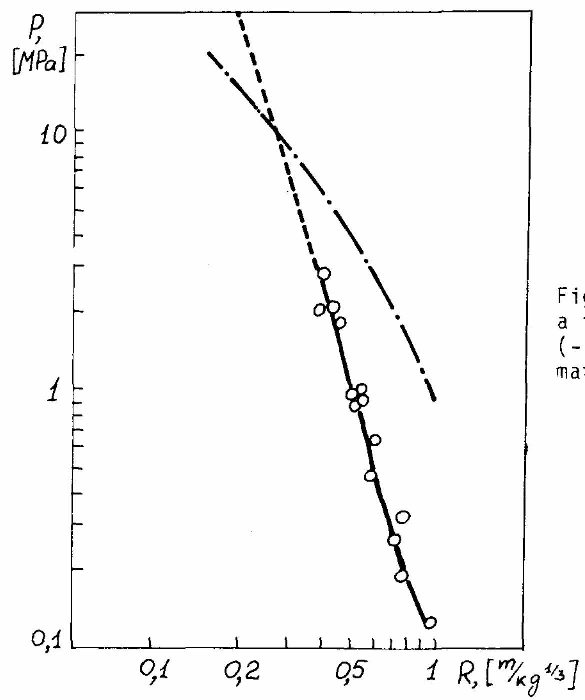

Fig. 8 Pressure drop as a function of a radius. (-·-·-·): air, (---): estimated values for foam.

Direct measurements of pressure were not made for $R < 4$. Extrapolation of the data for $R > 4$ indicates that in the nearest zone the pressure at the front in foam exceeds that at the wave front in air. The data obtained agree with the predictions of the initial parameters of a shock wave at the interface explosion products of RDX-foam. From the analysis of shock abiabat for foam at $\sigma = 15\ kg/m^3$ and isentrope of the expansion of the RDX explosion products for $D = 6000$ m/s and $P = 500$ MPa, the conditions of the wave weakly depend upon a degree of the completion of heat relaxation between the phases.

The abrupt reduction of the wave parameters in foam observed, as compared to a gas, is associated with the processes of heat exchange between liquid and gas (Palamarchuk et al. 1979). In this case the increase of the coefficients of damping of shock wave parameters, depending on a distance, leads to the conclusion that the course of the heat relaxation occurs more slowly than in the instance for which the two phases are kinematic equilibrium.

For a further theoretical analysis of the explosive waves in foam it should be noted that for the conditions of this experiment, the thermophysical properties of water, particularly the heat capacity, do not change significantly and evaporation of liquid between the phases is insignificant.

A Model of Foam Blast Waves

Analysis of the experimental data suggests the following assumptions in theoretical studies of relaxation processes of a strong blast wave:

1) A gas-liquid foam consists of a gas phase with liquid particles distributed in it.
2) No mass transfer takes place between the gas and the liquid particles.
3) The velocities of gas and condensed phase are equal.

In addition, it is assumed that the density and a specific heat of liquid are constant, the volume fraction of liquid phase and liquid particles partial pressure are negligibly small, and the gas is described by the equation of state for a perfect gas with constant specific heats. With these assumptions, the wave processes beyond the shock wave front are described by hydrodynamic equations (Baum et al. 1975; Sedov 1972) and the equations of a total balance of complete energy (Sedov 1972; Kastenboim et al. 1974):

$$\frac{\partial\rho}{\partial\tau} + u\frac{\partial\rho}{\partial r} + \rho\left(\frac{\partial u}{\partial r} + \frac{2}{r}u\right) = 0$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r}\right) + \frac{\partial P}{\partial r} = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\rho E' + \frac{\partial}{\partial r}\rho u E' + P\left(\frac{\partial u}{\partial r} + \frac{2}{r}u\right) = 0$$

$$4\pi \int_0^{r_\phi} (\rho E' + \tfrac{1}{2}\rho u^2) r^2\, dr = q_o$$

Here, the state equation for foam can be reduced to

$$E' = P/\rho(\Gamma_f' - 1) \qquad (2)$$

where Γ_f' is the effective index of shock abiabat of foam

$$\Gamma_f' = \gamma\,\frac{1 + \eta\delta(\tau - T_o)/T}{1 + \gamma\eta\delta(\tau - T_o)/T} \qquad (3)$$

On the front of the strong shock wave at "freezing" ($\tau = T_o$) of relaxation processes $\Gamma_f' = \gamma$, while at thermodynamic equilibrium ($\tau = T$) between the phases $\Gamma_f' = \Gamma$. Here, for concentrations of a condensed phase corresponding to foams, Γ is close unity.

Model kinetics of Γ_f' time variation were used as

$$\Gamma_f' = \Gamma + (\gamma - \Gamma)\exp(-\theta'/t_o) \qquad (4)$$

The exponential relationship was based on the assumption that energy transfer to the liquid phase occurs through heat conduction which follows the exponential law.

The residence time θ' of a microvolume in the wave is described by the differential equation

$$\frac{\partial\theta'}{\partial t} + u\frac{\partial\theta'}{\partial r} = 1 \qquad (5)$$

At the shock front, owing to "freezing" of the relaxation processes

$$\theta'(r_\Phi) = 0 \quad (6)$$

From the Rankine-Hugoniot conditions the relations for the leading front at the strong explosion limit are as follows

$$\rho = \frac{\gamma+1}{\gamma-1}\rho_o \qquad u = \frac{2}{\gamma+1}D \qquad P = \frac{2}{\gamma+1}\rho_o D^2 \quad (7)$$

where D is the velocity of shock front. At the center for all t

$$u = 0 \quad (8)$$

As at the initial moment the medium does not display relaxation properties, the system of the differential equations has a similarity solution (Sedov 1972; Kastenboim et al. 1974).

The system of Eqs. (3-5) is transformed through variables $\xi = r/r_\Phi$ and χ where χ is determined by the equation $d\chi/dt' = 1-Z$ and $\chi = 0$ at $t' = 0$.

$$\Phi = \frac{\rho}{\rho_o} \qquad V = \frac{U}{D} \qquad P = \frac{P}{\rho_o D^2} \qquad \theta = \frac{\theta'}{t_o} \qquad t' = \frac{t}{t_o} \quad (9)$$

to the form

$$\chi(1-Z)\frac{\partial\Phi}{\partial\chi} + (V - \xi)\frac{\partial\Phi}{\partial\xi} + \Phi(\frac{\partial V}{\partial\xi} + \frac{2}{\xi}V) = 0$$

$$\Phi[\chi(1-Z)\frac{\partial V}{\partial\chi} + (V - \xi)\frac{\partial V}{\partial\xi} + ZV] + \frac{\partial P}{\partial\xi} = 0$$

$$\chi(1-Z)\frac{\partial P}{\partial\chi} + (V - \xi)\frac{\partial P}{\partial\xi} + 2ZP + \Gamma'P(\frac{\partial V}{\partial\xi} + \frac{2}{\xi}V) + \frac{\Gamma'-\Gamma}{\Gamma'-1}\chi = 0$$

$$\psi = \int_0^1 (\frac{P}{\Gamma'-1} + \frac{V^2}{2})\xi^2 d\xi \quad (10)$$

$$\chi(1-Z)\frac{d\psi}{d\chi} + \psi(2Z + 3) = 0$$

$$\chi(1-Z)\frac{\partial\theta}{\partial\chi} + (V - \xi)\frac{\partial\theta}{\partial\chi} = \chi$$

$$\Gamma'_f = \Gamma + (\gamma-\Gamma)\exp(-\theta)$$

where $Z = (r_\Phi/D^2)(dD/dT)$ and, at $t'=0$, $Z = -1.5$. The boundary conditions then take the form $V = 0$ at $\xi = 0$:

$$\Phi = \frac{\gamma+1}{\gamma-1} \qquad V = \frac{2}{\gamma+1} \qquad \theta = 0 \text{ at } \xi = 1 \quad (11)$$

At the initial moment $\chi = 0$, system (10) has a similar solution (Sedov 1972; Kastenboim et al. 1974).

The system of nonlinear differential equations (10) is hyperbolic (Godunov 1979; Rozhdestvenskii and Yanenko 1978) for $\chi > 0$, $0 < \xi < 1$. The characteristic roots of the determinant whose coefficients are the partial derivatives with respect to ξ are real. In spite of the fact that there are multiple roots, there still exists the transformation with the determinant differing from zero, which reduces the system of the differential equations to a canonic form. In this case, the necessary condition of the uniqueness of the solution requires

$$\Gamma'_f > 1 \qquad \frac{\partial\Gamma'_f}{\partial t} \leq 0 \quad (12)$$

To find the solutions of the quasilinear partial differential equations, numerical methods must be used.

At the symmetry center and at the initial moment, the system of differential equations (10) has some difficult limit points. At the center, a saddle point is observed and causes difficulty in calculations of this region. At the initial moment the order of the equation system increases and complicates the calculations.

Near the center, beginning from some ξ, pressure P was kept constant, along the coordinate, while the change of velocity and density follows the asymptotic formulas

$$V \sim \xi \qquad \Phi \sim \xi^s$$

where $s > 0$. The error caused by this approximation is not significant, since a contribution of the central region to the energy integral is small.

The method of solution used to overcome the singularity associated with the disappearance of terms involving partial derivatives with respect to x is as follows: At the initial moment, when the relaxation processes have little effect on the flowfield as compared to its initial value, all changes in the dependent variables can be considered as small disturbances. The unknown variables can be written as

$$\Phi = \Phi_1(1 + \delta_\Phi x) \qquad V = V_1(1 + \delta_V x) \qquad P = P_1(1 + \delta_p x)$$

$$\Gamma_f' = \Gamma + (\gamma - \Gamma)\exp(-\delta_\Gamma x) \qquad \theta = \delta_\Gamma x \tag{13}$$

$$\psi = \psi_1(1 + \delta_\psi x) \qquad Z = -1.5 + \delta_Z x$$

where variables δ_Φ, δ_V, δ_p, δ_Γ depend on the coordinate only, while δ_ψ and δ_Z are constants, the initial values of the variables of the flow being designated by index I.

If the expressions (13) are substituted into the equation system, the resulting equations are expanded into a series with respect to a small parameter, $\delta \cdot x$, and if only first-order terms are retained; a linear system of differential equations results.

This system was solved by a finite-difference scheme which approximates differential equations within the second order of accuracy.

When the condition $\delta_x \ll 1$ is not satisfied, the system (10) must be solved subject to boundary conditions (11). Implicit difference schemes used for flow computer calculations are approximated by the first-order system of Eqs. (10).

It is necessary to note that Z both in the method of calculation at the initial time moment and at successive times is determined by the method of successive approximations. The chosen value Z_0 is substituted for the equation, and density, velocity, and pressure are calculated. Substitution of these values permits the calculation of energy integral ψ and, consequently, a new value of Z_1. This iteration scheme quickly converges. For times $t \sim t_0$, Z is linear in x, with

$$\delta_Z = -0.199 \tag{14}$$

The parameter Z characterizes a degree of wave damping, since

$$Z \frac{r_\Phi}{D^2}\frac{dD}{dt} = \frac{1}{2}\frac{d \ln P}{d \ln r_\Phi} \tag{15}$$

So, at propagation of a strong shock wave in a nonrelaxing medium we have $Z = -1.5$, which characterizes the rate of damping because of the geometric divergence of the wave. In a relaxing medium which obeys the kinetic model equations (2, 4), the shock wave damps faster and at the initial moment the degree of damping is expressed as

$$\frac{d \ln P}{d \ln r_\Phi} = 2Z = -(3 + 5\delta_Z \frac{t}{t_0}) = -(3 + 0.995 \frac{t}{t_0}) \tag{16}$$

With this relationship a characteristic time t_0 may be determined from the slope of the curve in Fig. 8. For the charges of explosives with mass of 0.5-2.8 kg, t_0 is approximately 150 μs.

It is interesting to compare the change in a pressure drop in a passing wave for a relaxing medium, foam, and for a nonrelaxing one, for example, air. The coefficient of damping is defined as the pressure as a relation of the pressure in a nonrelaxing medium P_n to that in a relaxing medium P_f at the same relative distance from the point explosion:

$$k = P_n/P_f \tag{17}$$

The pressure damping coefficient is shown in Fig. 9. For distance $R \approx 0.4$ m/kg$^{1/3}$, the explosion in air can be considered point explosion (Adushkin 1973). Analysis of the damping coefficient for a point explosion yields

$$k = \exp(-2\delta_Z t/t_0) \tag{18}$$

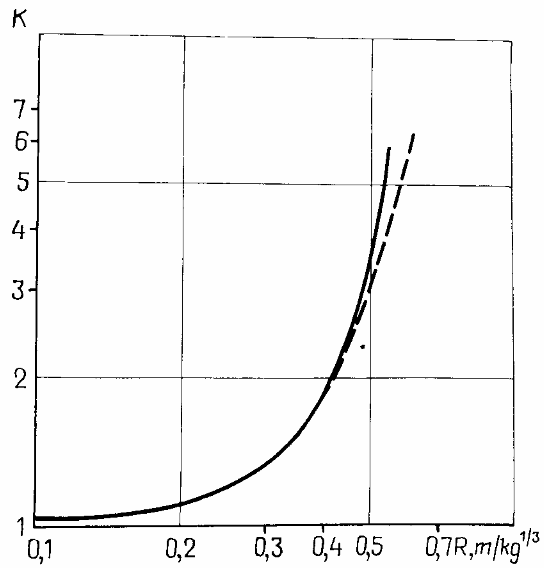

Fig. 9 Pressure damping coefficient for a blast wave in foam. (---): experimental values; (——): estimated values.

A better agreement between the pressure damping coefficients calculated from the experimental results, Fig. 18, and estimated from the ratio (18) is observed for t_0 = 180 μs (Fig. 9).

Since the thermal relaxation times obtained by two independent methods agree, it appears that an adequate description of the relaxation processes in foam is possible within the framework of the proposed theory.

Conclusions

The results of the experimental and theoretical investigations of the relaxation phenomena which accompany the propagation of shock waves in foam indicate that within the scope of relaxation gasdynamics it is possible to explain the phenomena observed. Further investigations of the kinetics of relaxation processes in foams will allow construction of strict mathematical models.

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