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DYNAMICS OF EXPLOSIVE LOADING FOR A FINITE VOLUME OF A DENSE TWO-PHASE MIXTURE

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UDC 532.528+539.375

This work is devoted to the problem of breakdown of a finite volume of liquid with explosive loading concentrated at its center. It is often assumed [1] that this type of process in liquids is identical to phenomena occurring in solid bodies from the point of view of their final effect, i.e., formation of spalled layers close to the free surface with reflection from it of a strong shock wave (SW). By analogy the concept is introduced of critical tensile stresses which are accommodated by the material and which when exceeded lead to formation, for example, in the case of plane shock waves, of plane separation surfaces. In [2], on the basis of analyzing work for studying critical stresses, it was shown that experimental data often differing by an order of magnitude may be explained by the nature of loading if a liquid which always contains microinhomogeneities in the form of free gas microbubbles is considered as a two-phase material and an appropriate mathematical model is applied to it. However, as noted in [3], this approach is inadequate in order to describe the breakdown process. It is also shown there that behind a propagating rarefaction wave front there is intense development of bubble cavitation. This type of volumetric cavitation boiling embraces a significant part of the liquid, the medium becomes optically opaque, and, as can be seen from calculations, it retains hardly any tensile stresses which relax in a time of the order of 1 μsec. Nonetheless, cases are possible when within the volume of a cavitating liquid conditions are created leading to occurrence of spalling phenomena [3]. The explicit cavitation (frothy) structure of these layers only underlines the indeterminate nature of the mechanism of their formation.

The main features of the breakdown process for a finite volume of liquid with a free surface under explosive loading may be described as follows. Reflection of a strong SW from a free surface leads to formation of an unloading wave behind the front of which intense development of bubble cavitation is observed at nuclei whose role is played by microinhomogeneities: their density is of the order of 10^5-10^6 cm^{-3} [4], i.e., the process of damage initiation typical for brittle fracture dynamics [5, 6] is absent in a liquid in view of the features of its original structure. Unlimited development of cavitation bubbles leads to formation in the "boiling" liquid of a foam structure [7]. The latter, during inertial expansion, is finally transformed into a gas-droplet structure. Naturally, in each specific case, the duration of this or another stage of the breakdown process may be different and it depends markedly on loading dynamics. Nonetheless, on the basis of already known experimental and numerical studies (e.g., [2, 5, 8]) it is possible to note these typical times for the process: of the order of a microsecond for relaxation of tensile stresses, tens of microseconds for development of a cavitation zone (cavitation cluster), hundreds of microseconds for formation of a foam structure, and of the order of milliseconds for its breakdown into liquid fragments.

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Results are presented in this paper for numerical analysis of the final stage of the explosive breakdown process for a spherical layer of liquid starting from a certain intermediate instant. It is assumed that cavitation breakdown has physically occurred. The medium is a dense package of elastic spherical liquid droplets. It is assumed that during reaction droplets do not flow together.

Statement of the Problem and a Mathematical Model. A spherical charge of explosive substance (ES) with density ρ_0 and radius r_1 is surrounded by a shell with internal radius r_2, which is a two-phase mixture of particles, i.e., air with a volume fraction of dispersed phase of 74% equal to the concentration of densely packed spheres. Detonation of the ES charge is modeled by an instantaneous explosion with a constant volume with some average value for pressure in the detonation products having the same density ρ_0.

Spherically-symmetrical movement of this two-phase mixture may be described by means of equations for heterogeneous medium mechanics [9]:

$$
\begin{aligned}
&\frac{\partial}{\partial t}\rho_1 + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho_1 u_1) = 0,\\
&\frac{\partial}{\partial t}\rho_2 + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho_2 u_2) = 0,\\
&\frac{\partial}{\partial t}(\rho_1 u_1) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho_1 u_1^2) + \alpha_1\frac{\partial}{\partial r}p_2 + \frac{\partial}{\partial r}\alpha_1(p_1 - p_2) = -f,\\
&\frac{\partial}{\partial t}(\rho_2 u_2) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho_2 u_2^2) + \alpha_2\frac{\partial}{\partial r}p_2 = f,\\
&\frac{\partial}{\partial t}(\rho_2 e_2) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho_2 e_2 u_2) = \frac{\alpha_2 p_2}{\rho_2^0}\left(\frac{\partial}{\partial t}\rho_2^0 + u_2\frac{\partial}{\partial r}\rho_2^0\right),\\
&\frac{\partial}{\partial t}(\rho_1 E_1 + \rho_2 E_2) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho_1 u_1 E_1 + r^2\rho_2 u_2 E_2) +\\
&+ \frac{1}{r^2}\frac{\partial}{\partial r}(r^2(\alpha_1 u_1 p_1 + \alpha_2 u_2 p_2)) = 0, \quad \rho_i = \rho_i^0\alpha_i \quad (i = 1, 2), \quad \alpha_1 + \alpha_2 = 1,\\
&f = 0.75\,\alpha_2\rho_1^0 C_d\,|u_1 - u_2|\,(u_1 - u_2)/d,
\end{aligned}
\tag{1}
$$

$$
C_d = \begin{cases} C_1 = 24/\mathrm{Re} + 4.4/\mathrm{Re}^{0.5} + 0.42, & \alpha_2 \leqslant 0.08,\\ C_2 = \dfrac{4}{3\alpha_1}\left(1.75 + \dfrac{150\alpha_2}{\alpha_1\,\mathrm{Re}}\right), & \alpha_2 \geqslant 0.45,\\ \dfrac{(\alpha_2 - 0.08)\,C_2 + (0.45 - \alpha_2)\,C_1}{0{,}37}, & 0.08 < \alpha_2 < 0.45, \end{cases}
$$

$$
\mathrm{Re} = \frac{\rho_1^0\,|u_1 - u_2|\,d}{\mu_1},
$$

$$
p_1 = F(\rho_1^0, e_1, r) = \begin{cases} (\gamma - 1)\,\rho_1^0 e_1, & r > r_d,\\ F_d(\rho_1^0, e_1), & r < r_d, \end{cases}
$$

$$
p_2 = p_T\left((\rho_2^0)^{7.15} - 1\right).
$$

Here ρ_i, ρ_i^0, α_i, u_i, p_i, E_i, and e_i are average and true densities, volume concentration, velocity, pressure, total and internal energy of the i-th phase (i = 1 is a gas; i = 2 is the dispersed phase); d is particle diameter; μ_1 is viscosity of air; γ is adiabatic exponent for air; r_d is boundary of the detonation products; $F_d(\rho_1^0, e_1)$ determines the state of the detonation products [10]. Equations for calculating resistance factor C_d were taken from [11].

In order to close this system it is necessary to introduce a condition of combined deformation of phases by means of which it would be possible to determine, for example, α_2. We make the following assumptions:

1) if $\alpha_2 \leq 0.74$, then particles have a spherical shape and their radius is determined from the condition for equality of pressures $p_2 = p_1$ with an unchanged particle mass;

2) with $\alpha_2 > 0.74$, particle deformation is considered so that: a) particles are packed at the tips of regular tetrahedra; b) outside the points of contact they have a spherical shape, and the radius is determined as in paragraph 1 without considering deformation; c) the contact surface of two particles is flat.

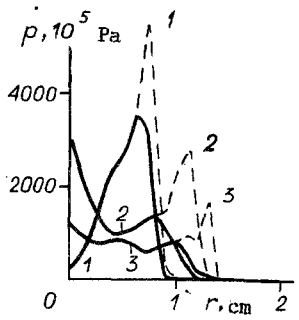

Fig. 1

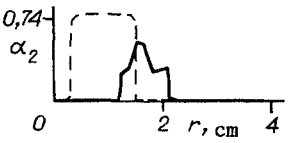

Fig. 2

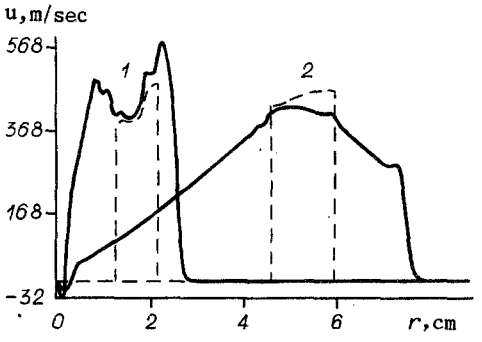

Fig. 3

By using these conditions it is possible to write an implicit equation $\alpha_2 = G(\alpha_2, \rho_1, e_1, \rho_2, r)$, where

$$G(\alpha_2, \rho_1, e_1, \rho_2, r) = \begin{cases} \rho_2/\rho_2^*, & \rho_2/\rho_2^* \leqslant 0.74, \\ \rho_2/\rho_2^* \left(9 \left(\dfrac{0.74\rho_2^*}{\rho_2} \right)^{1/3} - 3\dfrac{0.74\rho_2^*}{\rho_2} - 5 \right), \end{cases}$$

$$\rho_2^* = (F(\rho_1^*, e_1, r)/p_T + 1)^{1/7.15}, \quad \rho_2/\rho_2^* > 0.74, \quad \rho_1^* = \rho_1/(1 - \alpha_2).$$

The second equation in determining G holds true with $\rho_2/\rho_2^* \leq 1.13$, which was controlled in the course of numerical experiments.

Numerical calculations were carried out by the method of coarse particles with unconsolidation of the two-phase region boundary and the boundary between detonation products and air. In view of the considerable velocity imbalance for phases, in order to achieve stability for the calculation the right-hand part in pulse equations, depending on the square of the difference of phase velocities, it was approximated as follows: one factor was taken from the lower (with respect to time) layer of the difference network, and the other was taken from the upper layer.

Hexogen was taken as a specific ES with a density of $\rho_0 = 1.65$ g/cm^3 and a calorific value of 1.32 kcal/g. Thus, the initial conditions for the set of differential equations (1) takes form with $r < r_d = r_1 = 0.3$ cm, $\alpha_2 = 0$, $\rho_1 = 1.65$ g/cm^3, $u_1 = 0$, $e_1 = 5526$ J/g; with $r_1 < r < r_2 = 1.5$ cm, $\alpha_2 = 0.74$, $\rho_2{}^0 = 1$ g/cm^3, $u_2 = 0$, $e_2 = 0$, $\rho_1{}^0 = 0.001$ g/cm^3, $u_1 = 0$, $e_1 = 250$ J/g; with $r_2 < r$, $\alpha_2 = 0$, $\rho_1 = 0.001$ g/cm^3, $u_1 = 0$, $e_1 = 250$ J/g. Calculations were made for three sorts of particles (d = 1, 6, and 60 μm).

Results. Analysis of numerical studies showed that it is possible to separate three stages of process development. First, disintegration of the separation at the inner boundary of the two-phase region leads to occurrence of an SW in the gas phase and a rarefaction wave in detonation products. A compression region forms ahead of the SW in the dispersed phase with a volume concentration of more than 74% with a pressure exceeding the pressure of the gas phase, and a clearly defined drop in pressure at the leading front. Presented in Fig. 1 for instants of time 3, 6, and 9 μsec (lines 1-3) are data for pressure distribution in the gas and dispersed (broken lines) phases. As a result of passage of this SW through particles the dispersed phase acquires a greater velocity than the gas and, therefore, the boundary of the detonation products lags behind the inner edge of the two-phase cloud. After passage of the SW in particles at the outer boundary of the dispersed zone a departing SW forms in air, and in the two-phase region a rarefaction wave forms which together with the divergence caused by the spherical symmetry of flow leads to a rapid drop in the volume concentration of particles below the level of dense packing; shown in Fig. 2 is the distribution of dispersed concentration through the thickness of the layer for two instants of time (t = 0 and 20 μsec, solid line). In our calculations the processes listed end toward 15 μsec. In this stage, particle diameter (within the limits in question) affects very weakly pressure and mass velocity of both components.

In the second stage the gas phase starts to transmit its kinetic energy to the dispersed phase [broken lines in Fig. 3 correspond to particle velocities, data are provided for particles with d = 6 μm and two instants of time: 20 and 100 μsec (profiles 1 and 2)]. Since the force of resistance is inversely proportional to inclusion diameter, fine particles ac-

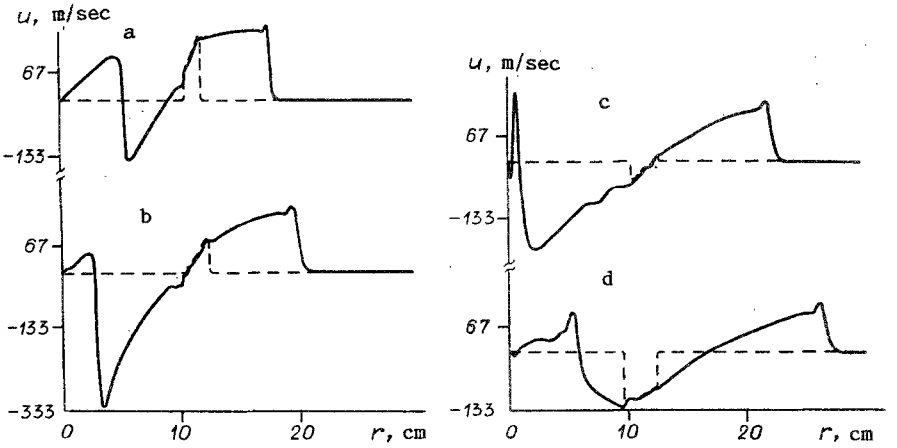

Fig. 4

TABLE 1

d, μm	r_1, cm	r_2, cm	r_2-r_1
1	4,9	8,1	3,2
6	6,3	10,8	4,5
60	47,0	56,0	9,0
Starting parameters			
1; 6; 60	0,3	1,5	1,2

quire considerable velocity and they outstrip coarser particles. The behavior of the detonation product boundary in this stage depends on particle diameter: for d = 1 and 6 μm it lags a little behind the inner edge of the heterogeneous zone, and for d = 60 μm it easily goes deeper into the two-phase layer.

The second stage ceases toward 60-70 μsec when pressure in the two-phase cloud becomes equal to atmospheric pressure. Depending on diameter, the particles start to slow down to a greater or lesser degree by entraining gas (Fig. 3). Dispersed clouds with a particle diameter of 1-6 μm move as weakly permeable pistons and, therefore, toward 400-500 μsec when in the internal cavity pressure drops to $1.5 \cdot 10^4$ Pa for d = 6 μm ($2 \cdot 10^3$ Pa for d = 1 μm), the powerful reverse gas flow occurring stops particles and their movement commences toward the center of symmetry. Development of this process is reflected in Fig. 4, where the broken line is velocity of a dispersed phase with a particle diameter d = 1 μm for t = 300, 350, 400, and 500 μsec (a-d, respectively). Shown in Fig. 5 is pressure distribution in the gas phase with t = 400 μsec.

Thus, pressure in the internal cavity increases anew, particles stop, and they are entrained by the gas flow with positive velocity. As a result of this damping oscillatory movement of the two-phase cloud occurs whose boundary dynamics are noted in Fig. 6. The amplitude and frequency of disperse zone oscillation with d = 1 μm (lines 4 and 4') in view of its lower permeability is greater than with d = 6 μm (lines 3 and 3'). Asymptotic values of the internal edge radius for a two-phase cloud (curves 1'-4') and the outer edge are given in Table 1.

A different situation arises in the case of coarse particles with d = 60 μm. The resistance of this cloud appears to be quite small, so that although it also creates rarefaction in the inner cavity ($p_1 \approx 5 \cdot 10^4$ Pa) reverse gas flow does have a great effect upon its move-

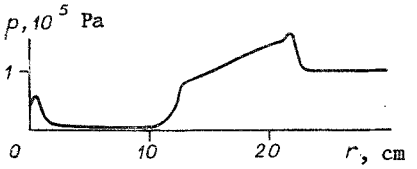

Fig. 5

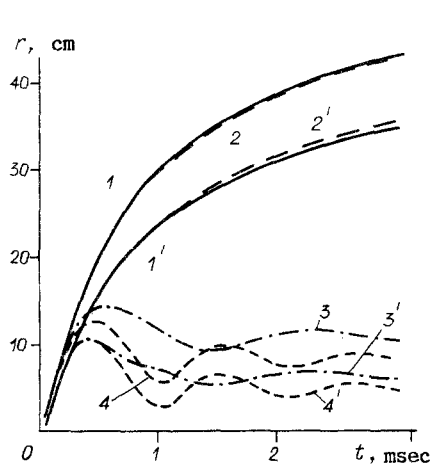

Fig. 6

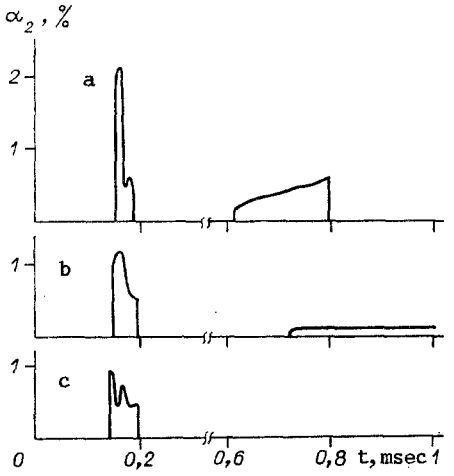

Fig. 7

ment (curves 1 and 1'). Starting from 500-μsec displacement of the dispersed zone differs little (≈2%) from the movement of individual particles of the same diameter in quiescent air (in Fig. 6 their trajectories are given by lines 2 and 2').

In addition, in this stage a marked increase is observed in the radial thickness of the two-phase layer. It is laid down on the first stage when as a result of passage of the SW through particles the outer boundary of the dispersed zone acquires a greater velocity. Subsequently, this effect is reinforced due to reverse gas flow, mainly retarding particles located at the inner edge of the dispersed phase.

From the data in Table 1 and Fig. 6 it is possible to suggest that, with presence of particle distribution over the diameter within the limits in question, the transverse size of the two-phase zone increases approximately up to 50 cm with an initial value of 1.2 cm in the computed problem.

The boundary of the detonation products in this stage definitely lags behind the two-phase layer. However, it should be noted that the dispersed phase hardly reacts with the hot detonation products (an exception is the case of d = 60 μm, but here also the reaction lasts about 40 μsec in a small volume).

Figure 7 represents the dynamics of dispersed phase concentration behavior at a distance of 8 cm from the center of the charge for d = 1, 6, and 60 μm (a-c, respectively). It can be seen that at instants of time close to 0.2 msec at a given point there are all types of particles, actually with a marked difference in values of α_2. In the time range from 0.6 to 0.8 msec, due to reverse movement at first particles appear with d = 1 μm, and then with d = 6 μm. After 0.8 msec a dispersed phase only with a particle size of 6 μm stabilizes at this point.

It is evident that consideration of heat and mass transfer and the effect of droplet breakage in a stream, even in the case of the original monodispersed structure of a dense two-phase layer, leads to occurrence of polydispersivity and those features which have been noted above.

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MECHANISM OF PULSED BREAKDOWN OF A LIQUID VOLUME

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UDC 532.528

From numerous experiments it is well known [1, 2] that with pulsed loading for liquid volumes of finite dimensions there is partial or complete breakdown of the liquid medium followed by formation of a spray stream. Until recently, the physical mechanism of this breakdown process had not been studied. In [3] the energy threshold was determined for pulsed breakdown of a water volume with shock-wave loading. In [4] it was demonstrated that if the loading time t_* is much greater than the time for unloading wave propagation through the liquid t_0, then breakdown is due to development of perturbations in the mobile boundaries of a liquid volume, and if $t_* \lesssim t_0$, then the breakdown stage is preceded by unlimited development of cavitation flow in the medium. In the latter case, the question remains open of the breakdown mechanism since it is not clear how, in the process of cavitation development, there is formation of discontinuities in a bubble medium and decomposition of it into individual fractions. Below this type of liquid breakage will be called cavitation breakdown.

1. In the present work, a phenomenological approach is suggested toward constructing a physical model of cavitation breakdown of a liquid medium taking account of the analysis of experimental results for axisymmetrical shock-wave loading of a cylindrical water volume.

Experiments were carried out in water specimens 1 (Fig. 1) with initial dimensions $R_0 = 2$ cm, $H_0 = 3$ cm. In the original condition the outer surface of the liquid was bounded by a thin paper shell 2 and with the ends rigidly clamped by plane-parallel plates of organic glass 3. A shock wave was generated as a result of an electrical explosion located along the axis of symmetry of the liquid volume by a manganin wire 4 in which a bank of high-voltage condensers with a capacitance of 1 μF was discharged. The explosive energy somewhat exceeded the threshold value [3]. The loading time (duration of shock-wave emission in the liquid, depending on the electrical discharge circuit parameters) is close to $t_0 = R_0/c_0$ (c_0 is sound velocity in water). According to [4] the process occurs in the following sequence: generation of a diverging cylindrical shock wave due to the electrical explosion of the wire; reflection of the wave from the free surface $r = R_0$ (Fig. 1); development behind the unloading wave front of cavitation flow with an unlimited increase in the volume concentration of bubbles; breakdown of the radially expanding cavitating volume into individual fractions. Optical recording of the process was carried out by means of a high-speed photorecorder SFR-1 (the field of exposure in Fig. 1 is marked with a broken circle).

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