ENERGY THRESHOLD FOR IMPULSIVE FAILURE OF A LIQUID VOLUME

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Several studies have examined the dynamic strength of a liquid. These studies have used static [1], ultrasonic [2, 3], and impulsive [4-8] methods of measuring the bulk strength of liquids. In every case the authors tried to find strength parameters for cleavage fracture in the liquid, i.e., they assumed that if a negative pressure of great amplitude were applied to the liquid, then a "crack" would be formed in the medium and part of the liquid volume would suddenly be separated from the rest of the volume, as occurs in the fracture of solids. However, it is known [9] that in a real liquid, containing bubble nuclei, such a large negative pressure can be reached only if the rise time of the tensile force behind the front of the unloading wave is on the order of 10^{-8}-10^{-9} sec. For this reason, to obtain cleavage fracture, methods were developed to generate very short waves with a steep leading edge in the liquid [7, 8].

However, failure of the liquid volume and the subsequent formation of a spray flow also take place after reflection of an unloading wave from a free surface in "normal" underwater explosions, in which the shock wave has a front with a rise time greater than 10^{-6} sec and the time of pressure decrease behind the front is tens or hundreds of microseconds. The question arises as to what kind of failure of the liquid volume will occur in this case.

The present study examines the failure of a liquid volume in an underwater explosion with a small pressure gradient on the front of the shock wave; the rise time of the leading edge is $(1\text{-}10)\cdot10^{-6}$ sec. The range of shock-wave amplitudes in the tests was chosen on the basis of the following considerations. As was shown in [10], after a shock wave with an amplitude of $(1\text{-}5)\cdot10^{8}$ Pa reaches a free surface, the liquid behind the front of the reflected unloading wave becomes opaque, i.e., in this case the liquid medium undergoes failure immediately behind the front of the unloading wave. On the other hand, it is obvious that a liquid medium will not fail in the sense of an irreversible loss of continuity behind the front if the unloading wave reflected from the free surface is very weak — there will be only a slight increase in the size of the cavitation bubbles followed by their collapse. Thus, there is a critical value of explosion energy below which cavitational flow behind the unloading-wave front will be of a reversible character, while at higher energies the cavitational processes will proceed without limit, i.e., the liquid will fail. Here we determine the energy threshold for explosive failure of the liquid, i.e., the minimum value of explosion energy necessary for the failure of a unit mass of liquid in the sense of an irreversible loss of continuity in the liquid.

Tests were conducted in accordance with the scheme shown in Fig. 1, where 1 is a cylindrical volume of water bounded on the outside by a thin, easily destroyed paper shell 2 with

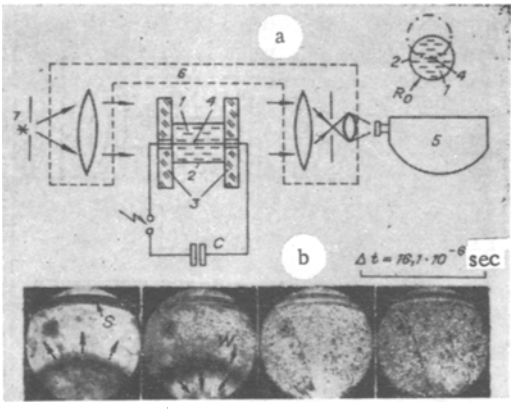

Fig. 1

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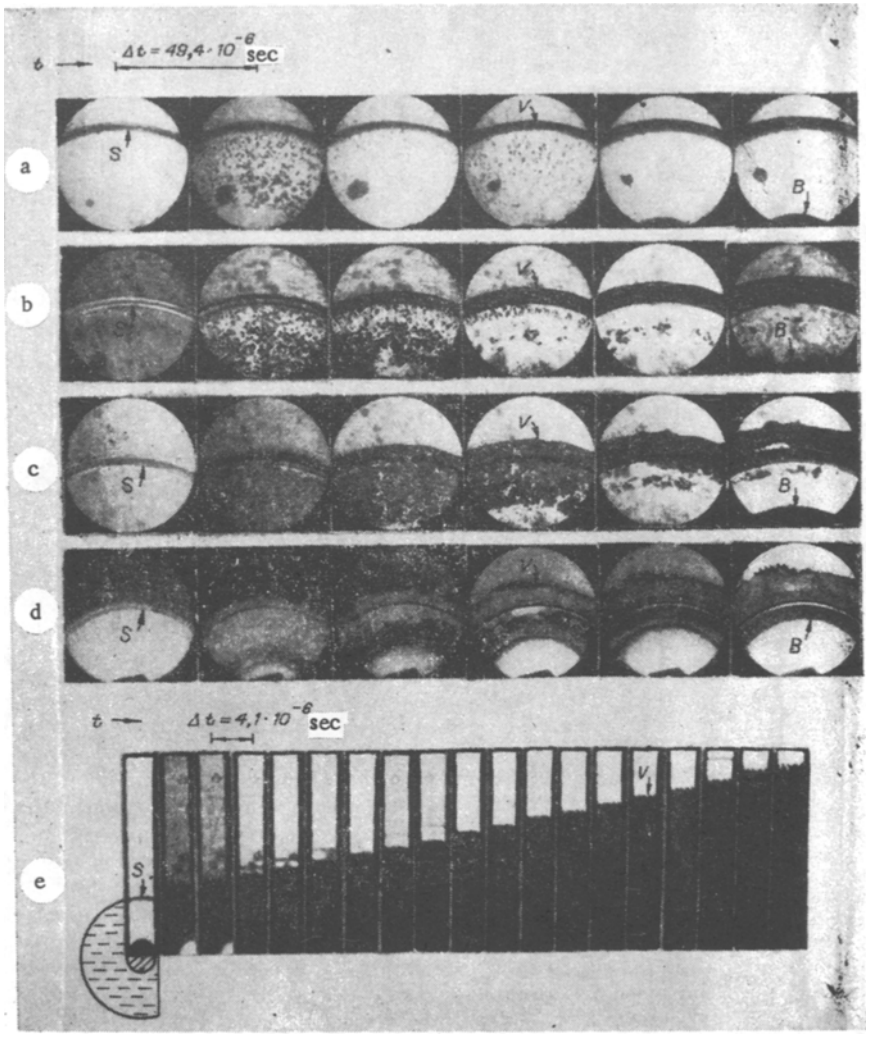

Fig. 2

incisions. The ends of the liquid volume are bounded by massive plane-parallel plates of organic glass 3. The plates are rigidly secured in a metal mounting to prevent their movement along the symmetry axis of the system. As the cylindrical source of the explosion we used a wire 4 located on the symmetry axis. The wire exploded when an electrical capacitor C discharged onto it. The process was recorded on a high-speed photographic recorder 5 with the aid of a shadow instrument 6 equipped with a pulsing lamp 7. The dot–dash circle in Fig. 1a shows the optical field in the recording of the process.

A cylindrical geometry was chosen for the liquid volume due to the need to visualize the process, while the use of an exploding wire provided a cylindrical low-power explosion source with energy parameters that could be regulated within a broad range. Thus, by changing the capacitance of the capacitor C or the charging voltage U, it was possible to vary broadly the energy of the electrical discharge $E = CU^2/2$ and its duration and, hence, the energy and parameters of the shock wave and explosive bubble in the liquid [11].

It is known that a subsurface explosion in a liquid releases the energy $E_e = E_1 + E_2$, where in the case of a cylindrical explosion

$$E_1 = \frac{2\pi rL}{\rho_0 c_0} \int_0^\tau p^2(t)\, dt$$

is the energy of the cylindrical shock wave (r is the distance from the center to the front of the wave; L is the length of the cylindrical surface of the wave front; p(t) is the pressure in the shock wave; τ is the duration of the compression phase in the wave; ρ_0 is the density of the liquid; c_0 is the speed of sound in the liquid); $E_2 = \pi R_*^2 L p_0$ is the energy of the explosive bubble (R_* is the maximum radius of expansion of the bubble; L is the length of

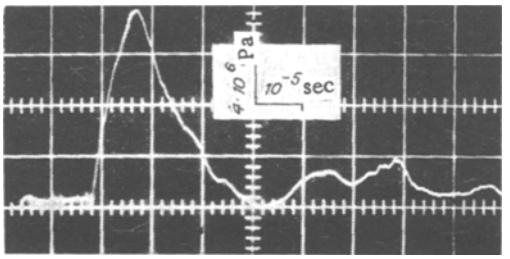

Fig. 3

the bubble; p_0 is the hydrostatic pressure in the liquid). The pressure in the shock wave p(t) was determined with piezoelectric transducers, while R_* was determined by high-speed photographic scanning. To do this, we placed two parallel, rigidly secured Plexiglas plates 100 × 100 cm in a tank with water equipped with transparent windows. The distance between the plates L = 3 cm. An explosive wire was placed in the center of the region between the plates perpendicular to their surface. Thus, in recording R_*, we practically excluded the effect of the boundaries of the tank on the process of full expansion of the explosive bubble. Experimental measurements of E_1 and E_2 with electrical explosion of the wire in water produced results which agree well with the data in [11]: The energy of the shock wave and the energy of the bubble are equal to 20 and 25-30% of the energy of the electrical discharge, respectively.

We will henceforth characterize the intensity of the explosion by the specific explosion energy $e_e = E_e/M$, where $M = \pi R_0^2 L \rho_0$ is the mass of the failed cylindrical volume of liquid.

Tests were conducted with cylindrical volumes of water of a length L = 3 cm and an initial radius (see Fig. 1a) R_0 = 1-3 cm. The electrical parameters of the discharge circuit: C = 2 μF, U = 5-15 kV. In each case, the length of the shock wave at the moment it reached the free surface was equal to the radius of the liquid volume R_0.

The following was established from analysis of films of the failure of cylindrical of water (Fig. 1b and Fig. 2a-d). After the wire explodes and the triangular shock wave (Fig. 3) reaches the free surface S (see Fig. 1b), cavitation flow develops behind the front of the convergent unloading wave W (see Fig. 1b), i.e., the continuity of the liquid is disturbed. In the case of low values of specific explosion energy (Fig. 2a, e_e = 0.11 J/g), the disturbance of continuity is reversible: Over time, atmosphere pressure collapses the cavitation bubbles, the annular layer of liquid expands, and perturbations develop simultaneously on its free surface (in Fig. 2, S is the free surface, B is the explosive bubble, and V represents perturbation on the free surface). The perturbations are unstable in this flow regime [10], which leads to depressurization of the explosive bubble. An increase in e_e (Fig. 2b, c, where e_e = 0.2 and 0.4 J/g, respectively) is accompanied by an increase in the intensity of the cavitation flow: Bubbles are collapsed at later stages of expansion of the liquid ring by atmospheric pressure. Finally, at $e_e \gtrsim 1$ J/g (Fig. 2d, e_e = 2 J/g), there is an irreversible loss of continuity by the liquid: Atmospheric pressure is no longer capable of suspending the increase in the volumetric concentration of cavitation bubbles, so that the liquid fails. Thus, the value $e_e \approx$ 1-2 J/g is the threshold value of specific explosion energy. For comparison, Fig. 2e shows a film of the failure of a liquid volume with e_e = 360 J/g (detonation of a charge of explosives in a cylindrical water ring [10]), where e_e was two orders of magnitude greater than the threshold value of specific explosion energy.

In conclusion, we thank V. K. Kedrinskii for his discussion of the results of the work.

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STATIONARY FLOWS IN CHANNELS DURING SIMILARITY WAVE PROPAGATION OF A CHEMICAL REACTION WITH AN ABRUPT CHANGE IN VISCOSITY

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The channel flow of reacting media with a viscosity which increases sharply with the degree of chemical conversion is accompanied by adhesion of the product to the channel wall and the formation of a stream of unreacted substance along the axis [1-6]. This phenomenon was studied numerically in [2, 3] and experimentally in [4] using the example of a polymerization in the continuous tube reactor. An analytic description was given in [5, 6] of the dynamics of the process with the condition that the viscosity and density of the medium is unambiguously dependent on the time of the reaction. This condition is satisfied in the absence of heat transfer in the medium (for example, in the isothermal flow of a medium with negligible diffusion). However, many chemical reactions are accompanied by intensive heat release and heat transfer, and the results obtained in [5, 6] are inapplicable in these cases. This pertains particularly to the practically important phenomenon of similarity wave propagation of a reaction, which was examined in [7-11] for the case of polymerization in a stationary medium. To allow for molecular heat transfer – which is important in this case – the method developed in [5, 6] was modified in [12]. However, the authors could not obtain an analytic description of flow in this case and instead presented results of numerical calculations of some of its characteristics.

Here we examine stationary flows of a reacting medium in plane and cylindrical channels during the similarity wave propagation of the reaction accompanied by a sharp increase in viscosity. The study will be based on the method of calculating laminar flows in a boundary layer with a surface of discontinuity. This method was developed in [13].

Within the framework of the assumptions made in [12], we obtained an analytic solution to the problem and found the form of the reaction wave in explicit form. The flow-rate – pressure characteristics of the channel were determined. It is shown that a small parameter of the problem – the ratio of the viscosities of the medium before and after the wave – introduces a singular perturbation into the solution which results in a sharp distortion and extension of the wave profile and the profile of the longitudinal velocity component near the axis, i.e., it leads to the formation of an axial jet. As a consequence of this, the condition of uniform smallness of the angle of inclination of the wave to the axis that was adopted in [12] is not satisfied, and the stationary reaction wave ceases to exist away from the axis. The region of existence of the wave becomes smaller with a decrease in the ratio of viscosities on the wave, which may lead to destabilization of the steady-state process.

1. We are examining stationary flows in plane and cylindrical channels in the presence of a chemical reaction wave. The medium is assumed to be incompressible, and heat release due to dissipation of mechanical energy is not considered. The thickness of the wave is assumed to be small in comparison to the characteristic cross-sectional dimension of the channel.

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