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GAS CAVITY DYNAMICS IN A CONTACT UNDERWATER ELECTRICAL EXPLOSION

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UDC 532.528

A contact electrical explosion is often used for the electrohydroimpulse destruction of materials [1], when one of the electrodes is the workpiece. This means that the vapor–gas cavity which is formed develops directly on the object being processed (the solid wall), so the latter may affect both the pressure field formed in the liquid and the manner in which the electrical explosion develops.

In the majority of theoretical investigations on the dynamics of cavities in contact with a solid wall [2-5], the problem of the collapse of a spherical cavity [2, 3] or an ellipsoidal cavity [4, 5] is considered as the model problem. However, as experiment shows [6-10], because of the initial increase in the cavity under asymmetric boundary conditions it is subject to deformations. The changes in shape which therefore occur may be extremely important [6, 8], and, consequently, according to the results obtained in [4, 5], the nature of the collapse of the cavity becomes unpredictable. Hence, in this paper an attempt is made to investigate the dynamics of the cavity generated by a contact electrical explosion experimentally in order to clarify the contribution of this stage of the process to the mechanism of the destructive action of the contact electrical explosion, and to find ways of improving technological processes which use this sort of electrical explosion.

For convenience we varied the length of the discharge gap l while keeping the remaining parameters fixed, viz., the breakdown voltage $U_0 = 50$ kV, the capacitance of the capacitor battery $C = 10^{-6}$ F, the inductance $L = 4.3 \times 10^{-6}$ H, the conductivity of the liquid $\sigma = 0.005$ $(\Omega \cdot m)^{-1}$, and the equivalent resistance of the circuit $R_e = 0.1$ Ω, defined from the curve of the current for the short-circuited discharge gap. The process was stabilized by initiating a discharge with a copper conductor of diameter 0.05 mm. The dynamic pattern of the development of the cavities was recorded with an SFR-2M high-speed motion-picture camera in a time loop using the method described in [6, 8], and was represented by a series of photographs (Fig. 1) as a function of the length of the discharge gap (on the right of each photograph we show the spatial scale b = 94 mm, and the exposure time ~0.2-0.4 msec).

Whereas when there is no contact surface the disintegration of the plasma cylinder in water with similar energy parameters is accompanied by its conversion into a pulsating cavity of quasispherical form [11], in the case of a contact explosion the evolution of this process is more complex: The formation of cavities is observed in the form of a spherical segment (see Figs 1a and b), dome-shaped (Figs. 1c-f) or a quasicylindrical shape (Fig. 1g).

The extremal amplitude–frequency parameters of the process are shown in the table (the number of the row of the table corresponds to the outer number of the series of photographs in Fig. 1, i.e., 1 corresponds to a, 2 corresponds to b, etc.).

Nikolaev. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 115-119, September-October, 1982. Original article submitted August 19, 1981.

0021-8944/82/2305-0693$07.50

TABLE 1

No. of discharge mode	l, m	$\varkappa_*$	$T \cdot 10^3$, sec	$V_{max} \cdot 10^3$, m^3	No. of discharge mode	l, m	$\varkappa_*$	$T \cdot 10^3$, sec	$V_{max} \cdot 10^3$, m^3
1	0,01	1,92	10,0	0,7	5	0,10	0,98	15,0	3,3
2	0,025	1,72	12,0	1,0	6	0,15	0,72	14,8	3,4
3	0,05	1,28	12,7	1,6	7	0,20	0,60	15,6	—
4	0,075	1,11	13,9	2,0					

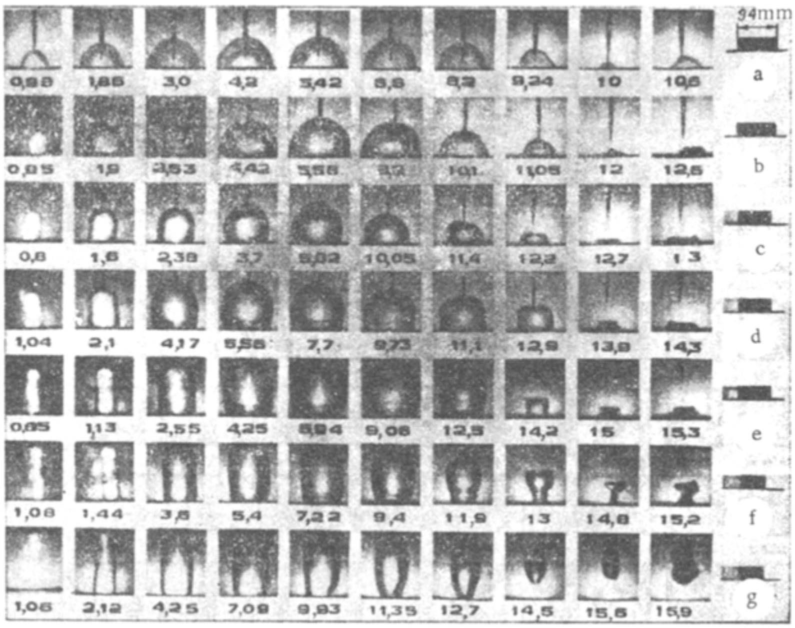

Fig. 1

We chose as the generalized parameter representing the form of the cavity, as in [4, 5, 9, 10], its deformation coefficient $\varkappa = 2a/h$ (h is the length of the axis perpendicular to the plane, i.e., the axis of symmetry [8], and $2a$ is the length of the axis parallel to the plane).

Analysis of the time dependence of the degree of deformation (Fig. 2, the numbers on the curves correspond to the order number of the electrical explosion mode in the table) shows that only in the region of extremely oscillatory modes (for small l) of the electrical explosion do the bubbles have a quite definite (quasi-hemispherical) geometrical form. As the discharge approaches the critical mode ($l \to 0.2$ m) the shape of the cavity is deformed and recalls rather a circular cylinder distorted from the side wall in a radial direction with an upper cap in the form of a spherical segment (see also Fig. 1). It is not possible in this case, as in [3], to distinguish the angle of contact of the vapor–gas cavity with the solid wall due to distortions connected with the effect of the viscosity of the liquid and the asymmetry of the flow. There is a preferential radial expansion of the cavities (the first increasing part of the $\varkappa(\bar{t})$ curves) which is common for all electrical explosion modes. Then, as l increases, the region of stability of the shape decreases, and in the concluding stage there is accelerated axial compression. An obvious exception to this behavior of $\varkappa(\bar{t})$ is only observed in the case of curve 7, when during the closure of the cavity there is an appreciable drop in the coefficient $\varkappa$ (a tendency to drop is already obvious in curve 6), and then towards the end of the pulsation an extremely rapid increase, due to overcompression of the cavity in the region of the neck. It is characteristic that $\varkappa$ for an electrical explosion of a cavity of ellipsoidal form (the broken curve for the electrical explosion energy per unit length of channel is 7.4 kJ/m) when there is no solid wall differs from the explosion mode close to it shown in curves 5 and 6 solely in the concluding stage of the collapse, which is connected with the more rapid axial compression of the cavity (from both ends, unlike a contact electrical explosion).

We will denote by $\varkappa_*$ the degree of deformation at the instant when the cavity reaches its maximum volume V_{max}, which represents the stage of collapse. Qualitatively, the nature of the collapse of the cavity in the contact electrical explosion (particularly when $\varkappa_* \leq 0.7$) recalls the collapse of oblate ellipsoidal cavities (with

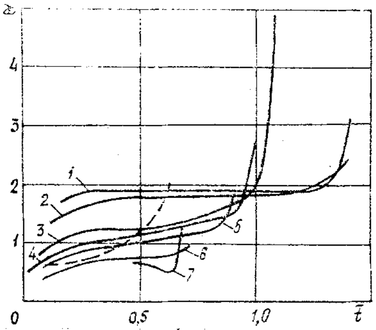

Fig. 2

$\varkappa_* > 1.3$), which are in contact with a solid wall [5, 9]. However, in this case the length of the neck is much greater and extends practically to the walls, and its rate of contraction is less. In addition, for a contact electrical explosion the main part of the bubble splits off, and its small part touches the wall.

When $\varkappa_* > 0.72$ the cavity collapses on an obstacle and is broken by the flow only in the concluding stages, and when $\varkappa_* = 0.72$ the cavity, as it approaches minimum volume, becomes extended along the axis of symmetry and during this period the cumulative jet (the formation of the latter was recorded from the bending of the surface of the cavity) penetrates into the cavity. When $\varkappa_* < 0.72$ the cavity is already collapsed not on the solid wall but in the space between the wall and the positive electrode, which on the one hand, may lead to an increase in the intensity of the action on the wall of the secondary shockwave radiated when collapse occurs, and a considerable attenuation of the force of the liquid flow at the collapse stage, on the other. When the deformation coefficient reaches a value $\varkappa_* = 0.62$ the main jet formed from the end of the cavity does not reach the obstacle; the maximum velocity of this jet recorded in the experiments was 32 m/sec and occurred at $t = 0.8T$, where T is the pulsation period of the cavity.

As the electrical explosion mode changes (as $\varkappa_*$ is reduced) a neck is clearly formed in the lower part of the cavity (~0.1h*), due to the action of the forces of viscosity, which slow down the flow of the liquid in the region of the obstacle. At the cavity compression stage a ring jet is formed which moves with a velocity of ~25-30 m/sec, during the collapse of which more intense closure of the neck occurs compared with the general radial compression of the cavity. The maximum value of the excess of the velocity of the neck over the radial velocity $\dot{a}$ recorded in the experiment was five and was observed for a value of $\varkappa_* = 0.72$.

A characteristic feature of the development of the cavity for a contact electrical explosion is a phase lag between the displacement of the side surface of the cavity and the end surface (Fig. 3a, b, where curves 1-4 correspond to $\varkappa = 1.9$, 1.3, 0.6, and 1). It can be seen that at the instant when V_{max} is reached not all parts of the free surface are displaced in the same directions (the instant when V_{max} is reached is indicated on the curves by the vertical bar). Hence, such ideas as expansion and contraction of the cavity only makes sense as they apply to changes in volume and not to its individual linear dimensions. This situation is also observed in electrical explosions in an open volume [8], but with a much lower energy capacity, when the cavities have an ellipsoidal form.

An analysis of the $\dot{a}(t)$ and $\dot{h}(t)$ curves confirms that these curves are not symmetrical with respect to the time axis, and also that the curves of $a(t)$ and $h(t)$ are not symmetrical with respect to their maxima. In addition, a simple comparison of the families of curves of $\dot{a}(t)$ and $\dot{h}(t)$ shows that at the stage of expansion the value of these velocities for the different electrical explosion modes differs slightly (the curves are densely situated), whereas the compression stage there is a considerable difference between the values of the velocities (a similar pattern is also observed for the velocities of the necks). Consequently, the collapse of cavities in the case of a contact electrical explosion depends much more on the initial degree of deformation $\varkappa_*$ than the expansion. Thus, a small change in $\varkappa_*$ (particularly in the region of $\varkappa_* \approx 1$) leads not only to an appreciable change in intensity, but also of the collapse mechanism, whereas in the expansion scheme no appreciable change occurs. In fact, for a contact electrical explosion, as follows from Fig. 4, in which we show the positions of the boundary of the bubble at successive instants of time $\bar{t} = t/h_* \sqrt{\Delta p/\rho}$ (ρ is the density of the liquid, and Δp is the difference between the hydrostatic pressure and the pressure in the cavity at the maximum $\Delta p \approx 10^5$ Pa) for various degrees of deformation ($a - \varkappa_* = 1.92$, $\bar{t} = 0.71$, 1.11, 1.24, 1.37, 1.44, lines 1-5, respectively), b $- \varkappa_* = 0.98$, $\bar{t} =$ 0.47, 0.67, 0.78, 0.85, 0.92, lines 1-5, respectively), c $- \varkappa_* = 0.72$, $\bar{t} = 0.34$, 0.57, 0.64, 0.67, 0.71, lines 1-5, respectively, d $- \varkappa_* = 0.62$, $\bar{t} = 0.35$, 0.54, 0.61, 0.64, 0.67, lines 1-5 respectively), two features are observed: The region occupied by the cavity remains simply connected (i.e., the bubble does not split into parts) during

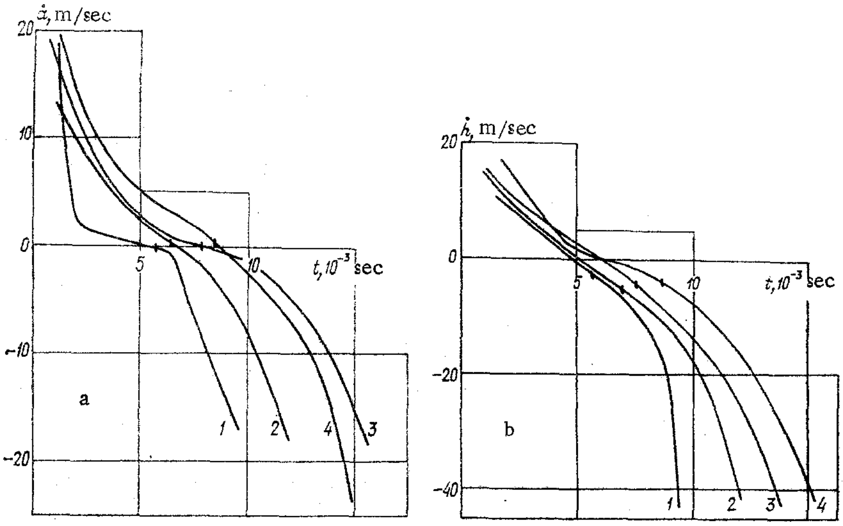

Fig. 3

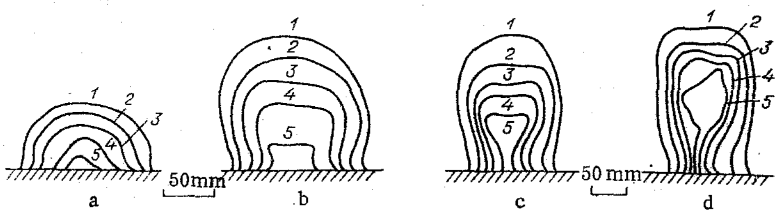

Fig. 4

the whole collapse process ($\varkappa_* < 1$) — division of the bubbles occurs. As the degree of deformation $\varkappa_*$ is reduced, the process by which a ring jet is formed and division of the cavity occurs into parts is shifted towards lesser times, and the volume of an individual bubble and its distance from the walls increase, the maximum velocity of the ring jet is reached at the end of the closure process, and increases somewhat as the degree of deformation is reduced. On passing through $\varkappa_* = 1$ the type of cavity collapse changes and, consequently, for cavities induced in the contact electrical explosion, $\varkappa_* = 1$ is the critical value of the degree of deformation.

The nature of the collapse of a quasihemispherical bubble on a solid wall (see Fig. 1a) differs to a considerable extent from the collapse of a spherical or quasispherical bubble [4-6]. In particular, unlike [4, 5], in this case no cumulative jet is observed at an earlier collapse stage, and the process of collapse of a quasihemispherical bubble occurs mainly as a result of its uniform compression, and the asymmetry of the liquid flow is due solely to the concluding stages of the collapse.

Comparison of the values of the velocity of motion of the side and end surfaces obtained, and also of the ring jet, shows that in practice for all the modes considered (with the exception of the mode with $\varkappa_* = 0.62$) maximum velocity is reached in a direction perpendicular to the solid wall.

It should be noted that at the beginning of each cycle of cavity pulsation volume acoustic cavitation of the liquid is observed, produced by the radiation of primary and secondary shock waves. However, for the oscillatory modes of the discharge, in view of the considerable brightness of the plasma channel, pulsating cavitational bubbles are not observed in practice, whereas for discharge close to critical, cavitation is quite clearly observed (see Figs. 1e-g).

Hence, the experimental results obtained enable us to clarify the dynamic features of the development of the cavities generated by a contact electrical explosion and to explain three characteristic types of collapse: collapse of the cavities on a solid wall ($\varkappa_* \geq 0.8$), splitting off of a considerable part of the cavity from the solid wall while maintaining contact via a connection neck ($0.6 < \varkappa_* < 0.8$) and collapse of the cavity outside the solid wall ($\varkappa_* \leq 0.6$).

In addition, in view of the qualitative analogy between the collapse of cavitational bubbles on a solid wall and cavities in a contact electrical explosion the latter can be used as a convenient model for studying cavitation on solid surfaces because of the rapidity and ease with which the power and the cavity geometry can be controlled, and also the number of times it repeats itself.

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ENERGY TRANSFER TO A PLANE INCOMPRESSIBLE PISTON UNDER DETONATION LOADING

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Among the problems of explosion-produced acceleration, a special place is occupied by the problem of the one-dimensional projection of a flat plate or piston. One-dimensional problems are of interest because they are relatively simple to investigate theoretically. Moreover, one-dimensional projection is a method that lends itself to direct practical realization and constitutes a simplified model of many actual problems of explosive propulsion.

The analytic approach to the solution of one-dimensional problems is usually based on the following assumptions: The piston material is incompressible; the shock waves in the explosion products (EP) are weak; and the EP formally satisfy the equation of state of a perfect gas with adiabatic exponent $k=3$. The last two assumptions imply that the characteristics of the equations of motion of the gas are linear and do not change their slope on intersection with shock waves moving in the opposite direction (compression waves), and that throughout the process the pressure and speed of sound in the gas are related by the expression

$$p = Ac^3,$$

where the constant A is determined by the initial thermodynamic state of the EP.

These assumptions have been used to obtain analytic solutions to a number of problems of the motion of a plane piston propelled by the explosion of a layer of explosive of finite thickness. The situation where a detonation wave impinges on the piston was considered in [1, 2]. A similar problem, with the difference that detona-

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 120-126, September-October, 1982. Original article submitted November 4, 1981.

