UNDERWATER EXPLOSION OF A RING CHARGE NEAR A FREE SURFACE

V. K. Kedrinskii and V. T. Kuzavov

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A number of works are devoted to the study of effects accompanying the underwater explosions of lumped charges near a free surface, in which the process of directional ejection-plumes [1-4] and the development of cavitation and the wave field structure [5, 6] are investigated. It is shown in [4] that, depending on the depth of the explosion, distinctive types of plumes occur, a hollow cylindrical vertical ejection-wall of an open cavern being formed during depressurization of the explosive cavity (its subsequent closure results in the development of an axial jet flow), and several continuous vertical and radial plumes. As a result of an analysis of the process of formation of one of the kinds of vertical ejections during the underwater explosion of large charges of around 100 kg and more in weight at depths of several tens of meters the assumption is expressed in [4] that the mechanics of their development is associated with the flow singularities that occur during pulsations of a toroidal cavity with detonation products.

A torus is formed surfacing in a heavy liquid, with deformation of the initially spherical explosive cavity having maximum radius on the order of 10 m. The sequence of such a transformation is determined by the vertically upward development of a cumulative flow in the lower part of the collapsing cavity during its first pulsation and the disappearance of the simple-connectedness of the domain during closure of the cumulative jet apex at the upper part of the cavity.

The process of formation of vertical plumes of the type mentioned was demonstrated experimentally in explosions of ring charges (mainly from detonation cords DC) for a broad range of their radii a_0 (from several centimeters to several meters), energies, and depths of the explosion. Naturally, additional effects associated with the radiation of the shock that has an almost toroidal shape, is propagated in a domain exterior to the ring, and is focused in the area of its axis, occur here. Since the velocity of the detonation wave D in the explosive material of the DC is approximately five times greater than the velocity of the weak shock front 1 in water, this latter converges in the domain 3 shifted somewhat relative to the ring axis 4. The shape of this domain is somewhat complex spatially (Fig. 1). Three successive locations of the wave front in the exterior domain of a ring charge are represented in Fig. 1, up to the time the detonation front completes a revolution around the ring.

The interaction between the shock and the free surface and the expanding cavity with the detonation products results in the intensive development of bubble cavitation. Frames

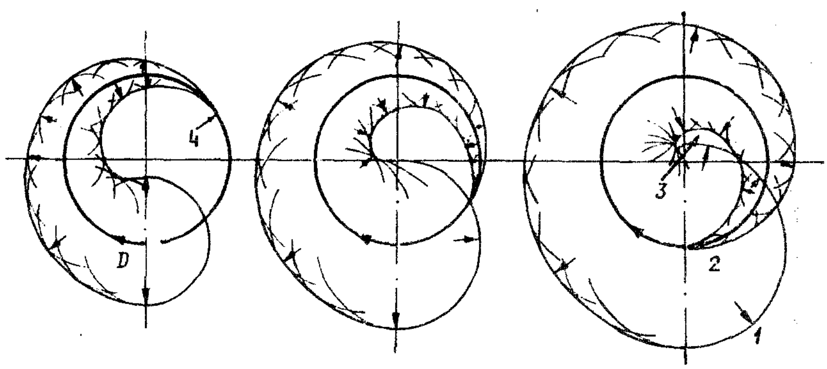

Fig. 1

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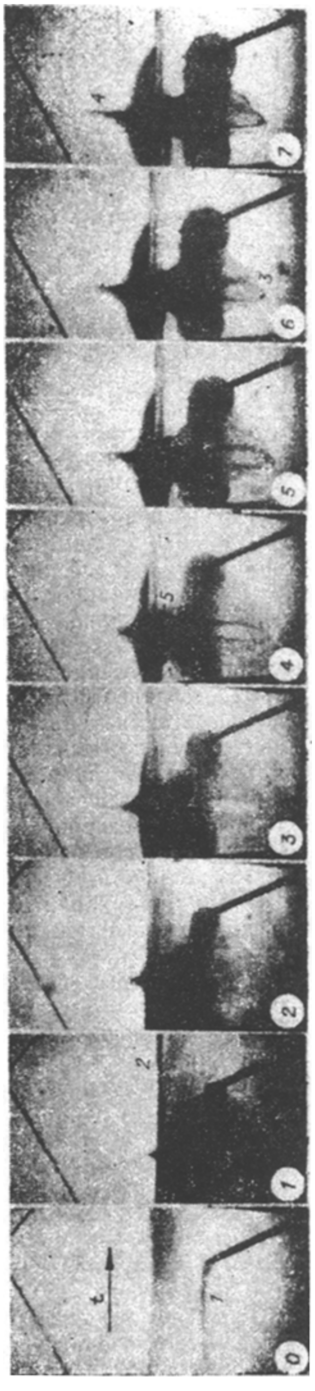

Fig. 2

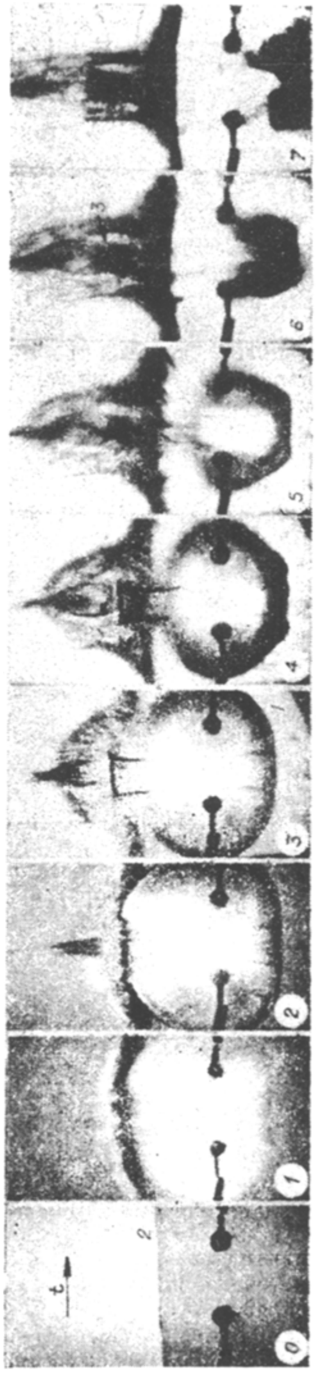

Fig. 3

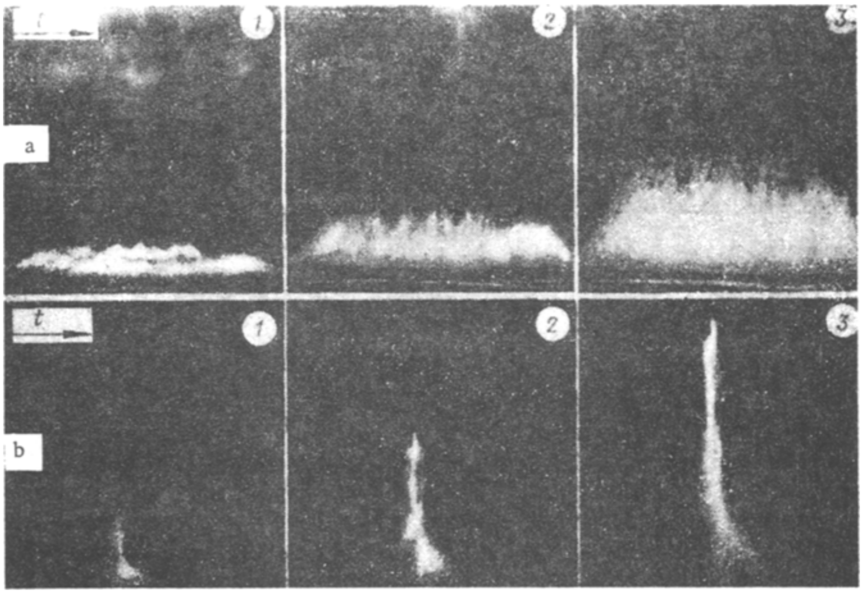

Fig. 4

of high-speed photography of the process are shown in Fig. 2 for the explosion of a DC semiring 1 (explosive charge radius a_* =0.0325 cm) of 18-cm diameter at a 9-cm depth from the free surface 2. The plane of the semiring was parallel to the liquid surface, and the ends of the charge were on a transparent vertical wall. In particular, such a formulation affords the possibility of observing the flow development in the central domain of the ring. The moving picture frames are presented at 0.5-msec intervals. They permit noting two features of the process: a cylindrical wake 3 in the cavitation zone (axis of symmetry domain) and a thin vertical ejection 4 on the surface at the center of the dome. The beginning of the formation of this latter practically agrees with the origination of the intensive cavitation whose front is propagated downward from the surface and, therefore, is associated with the result of shock interaction with the free surface, i.e., with the development of the dome. As is shown in [4], the dome consists of split-off cavitating liquid layers. The structure of the split-off (with the formation of a "fountain" nature ejection 4) is determined in experiments with ring charges by the shape of the wave front and its focusing.

To confirm this effect, an experiment was performed which permitted excluding the dynamics of the cavity with the detonation products from the process. A detonation cord with a_* = 0.0825-cm radius was placed inside an anechoic container, a ring of metallic pipe containing water. The plane of the ring was in the liquid at an appropriate depth under the free surface. The pipe parameters were chosen in such a manner that the sealing of the container and its dimensions were conserved during the experiment.

Because of the explosion, the pipe turned out to be the source of a quasitoroidal acoustic wave whose interaction with the free surface qualitatively duplicated completely the pattern of intensive cavitation zone and "fountain" ejection formation represented in Fig. 2. However, the cylindrical wake noted above in the experiments with the container did not develop. This feature of the process is, from our viewpoint, a confirmation of the jet nature of the flow being developed in the domain of a ring charge axis of symmetry during expansion of a toroidal cavity with detonation products.

In this stage of the underwater explosion, the dynamics of the cavity will clearly result in accumulation of the liquid stream in the area of the ring axis. The finiteness of the detonation rate of the explosive evidently plays no noticeable role here: It is shown in [7] that in this case the explosion products form a ring cavity which has the shape of a regular torus and is conserved throughout at least the first pulsation (the expansion-collapse time interval) if the ring radius is $a_0 \geqslant 150\ a_*$. It can be expected that the jet flow in the domain of the axis in an unbounded liquid should be symmetric relative to the plane of the charge. But the flow in the area between the charge and the free surface under the conditions of the experiments being discussed is distorted considerably because of the substantial disturbance of the continuity of the liquid: A dense dark domain 5 connected to

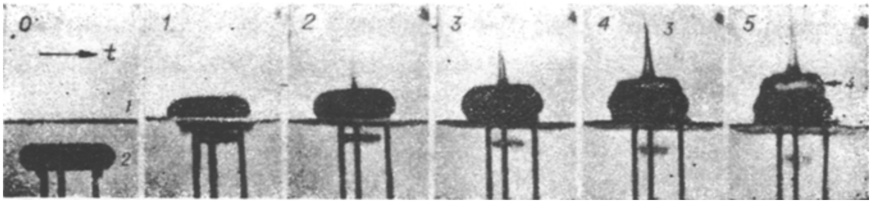

Fig. 5

the central area of the ring by the cavitation zone (see Fig. 2) is distinguished under the dome.

In order to analyze the flow configuration in the area of the ring axis in a formulation analogous to the above, experiments were conducted on exploding wires. This method permits concentrating battery energy mainly in the explosion products, weakening the shock, and, thus, determining the influence of the dynamics of the toroidal cavity on the nature of the flow.

The sequence of flow development on the free surface 2 and the dynamics of cavity 1 is represented in Fig. 3 for the underwater explosion of a nichrome wire semiring of 5-cm diameter at a 4-cm depth. Starting with the first, the time between frames is 4/3 msec. It is seen that for the conditions of this experiment the energy of the explosion per unit length of the conductor is sufficiently large: The cavity shape differs from a regular toroid, its maximum dimension is on the order of the depth of the explosion, and hence, the cavity is strongly deformed at the center. Intensive expansion of the cavity with explosion products results in the development of a vertical plume on the free surface. A moving picture defining the process in cross section permits consideration of its origin. This is the hollow ring jet 3 whose nature is, however, determined not by depressurization of the explosive cavity, as in the case of the explosion of a lumped charge at a depth of several radii, but by the initial shape of the charge. The flow geometry represented in frames 5-7 recalls the case of a cavity due to the explosion of a spherical or cylindrical charge whose collapse near the free surface is accompanied by the development of a cumulative jet flow directed deep into the liquid.

Experiments performed on ring charges of up to 2-m diameter from standard DC in a natural basin under natural conditions confirmed that for small depths of submersion relative to the diameter, the explosion of a ring charge whose plane is parallel to the free surface will result in the development of a ring plume (Fig. 4a). The mechanics of its formation and the structure of the ejection conform completely to plumes from the explosion of spherical or linear charges [4]. Three successive times from the high-speed motion photography of the development of a ring ejection are presented in Fig. 4a for the explosion of a 2-m-diameter charge from DC at a 30-cm depth. It should be noted that the maximal radius of the cavity with the detonation products is approximately 20 cm for a linear charge from the same DC (0.15-cm initial radius). As the size of the ring diminishes and the depth of the explosion is conserved, the nature of the surface ejection changes: Fig. 4b demonstrates the development of the central plume in an experiment with a 0.4-m-diameter ring charge.

The data of such a formulation are naturally inadequate for the assertion that the internal structure of this plume (Fig. 4b) is analogous to that in Fig. 3 or that this is a continuous jet. Consequently, the possibility of the development of a continuous vertical jet, together with the ring plume, was investigated in model experiments on the formation of jet flows on a free surface during pulsed motion of a solid preliminarily submerged in a liquid. As is known [4], this model was produced to describe the jet nature of the flow during the explosion of spherical and cylindrical charges near an initially plane free surface. It was shown here that if a solid sphere, say, placed in a liquid near a free surface receives an impulse vertically upward, then the velocity field and the main nature of the flow with a free surface are thereby modeled in the liquid as for pulsations of an explosive cavity.

It is naturally considerably more difficult to model the axisymmetric flow of a fluid bounded by a free surface and a pulsating ring cavity in the same manner. It turns out, however, that if dimensions on the order of the maximum size of the cavity with detonation products are given to the solid torus, then the effect expected can be obtained. Frames of

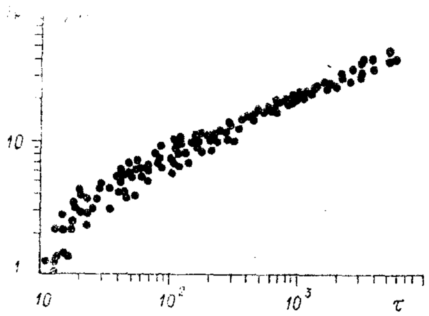

Fig. 6

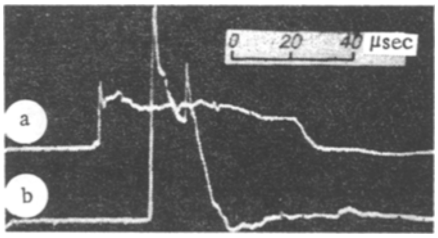

Fig. 7

the high-speed moving picture of the development of the ring 4 and the central 3 jet are represented in Fig. 5 for the motion of a solid torus 2 that has received an impulse from the free surface 1. The impulse is communicated because of the explosion of an auxiliary charge under a special apparatus connected rigidly to the torus and located at a depth of several diameters. The time interval between the frames 0 and 1 is 4 msec, and between the rest is 4/3 msec.

It is seen that a ring jet is formed from the liquid layer remaining on the torus which is left on the liquid surface because of natural deceleration. This layer on the fixed torus evidently possesses a definite momentum. Because of the inertial properties, it tends to be separated from the surface, resulting in the appearance of tensile stresses that are most intense in the zone of the maximal mass flow rates. Under these conditions the fluid clearly changes the direction of the mass flow rates towards the oncoming rarefaction zone and shrinks into a ring with circumference along the radial direction on the torus surface "more easily" than it can be separated from this surface over the ever greater area of contact. The process of ring jet formation, which will have a definite velocity gradient in the vertical direction, continues until the liquid–solid contact surface is converted into a thin ring. And if the jet possesses sufficient impulse, it can separate from the torus. This effect and the fracture of the jet into parts because of the velocity gradient was observed in the case of hurling a solid sphere from a liquid in experiments to model plumes during the explosion of spherical charges.

As is seen from Fig. 5, the process of central jet formation under investigation is simulated to a definite extent by the motion vertically upward of a solid torus for which radial mass flow rates are communicated to the liquid in the central part of the torus. It was noted above that this flow developed in the explosion experiment because of squeezing of the liquid by the detonation products being expanded.

Results of experimental investigations of the dependence $h(\tau)$, the height of the rise of the central jet, are presented in Fig. 6 for the underwater explosion of 40-80-cm-diameter ring charges at depths H from 20 to 80 cm relative to the free surface. The radius of the explosive charge is 0.15 cm. Here $\tau = (EQ\rho_*^{-1}H^{-5})^{1/2}t$ is the dimensionless time, E is the energy of the explosion per unit mass of the explosive, Q is the mass of the explosive, ρ_* is its density, and t is the time. Despite the noticeable spread in the experimental data in the initial stage of the plume rise, which can be associated with the superposition of the "fountain" ejection of the split-off dome, a hypothesis can be made about the similarity of the processes for central jet flow development as a whole for different parameters of linear charge and depth of explosion. The dependence $h(\tau)$ is exponential in the fundamental time interval and is determined by the expression

$$h/H \simeq \tau^{1/2}$$

or

$$h \approx (EQ\rho_*^{-1}H^{-1})^{1/4}t^{1/2}.$$

Data on the near wave field parameters for ring-type charges are of interest for a number of hydroacoustic problems. These materials are presented partially in [7], where the strong dependence of the wave shape and the pressure amplitude in the front on the location of the sensor relative to the detonation initiation point is noted. Two oscillograms, recorded at the center of the ring (a) and at the focusing point (b), are represented in Fig.

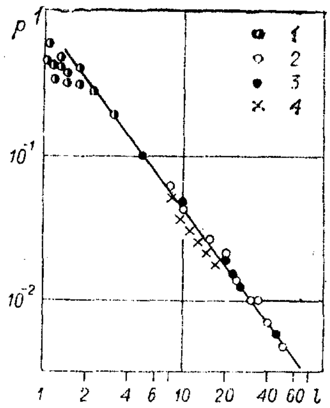

Fig. 8

7. The oscillogram at the focusing point (see Fig. 1, the center of domain 3 is determined from optical recording data) has the form of a "shelf," and indicates a definite "stationarity" of the process in this time interval; at the center of the ring the sensor records a double wave; the first front belongs to the convergent shock, and the second is a pressure wave reflected after focusing in zone 3 (see Fig. 1). This wave reaches the center more rapidly than the wave front 2 which is generated in the liquid by the detonation wave traveling over the final section of the ring charge.

Presented in Fig. 8 is the distribution of the experimental data on the pressure in the front of the convergent shocks on the axis of the ring charges with radii $a_0 = 10$ cm (DC radii $a_* = 0.0825$ cm and 0.15 cm correspond points 1, 2) and 20 cm and 30 cm (points 3, 4) for $a_* = 0.15$ cm. It turns out that in the range of values 5-50 for the relative distance $l = [(z/a_0)^2 + 1]^{1/2}$, these data satisfy the dependence

$$p_{max} = Al^{-0.65},$$

where z is the distance along the axis from the plane of the charge, in cm, and the coefficient

$$A \approx \frac{2}{3} a_* \left(\frac{a_*}{a_0}\right)^{1.4} 10^7$$

depends on the charge parameters and is referred to atmospheric pressure. The noticeable spread in the experimental data on the pressure in the area at the center of the ring is associated with the inhomogeneity of the copper jacket of the special thin DC which were used for the investigations under laboratory conditions.

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