State dynamics of bubbly cavitation in a vicinity of quasi-empty rupture at its collapse

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Abstract. The presentation deals with one of the experimental models of a quasi-empty rupture which is formed in the liquid layer of a distilled cavitating fluid under shock loading. It is shown that the rupture is shaped as a spherical segment, which retains its topology during the entire process of its evolution and collapsing. The dynamic behavior of the quasi-empty rupture and of the structure of cavitating flow on its surface are analyzed. It is shown that rupture implosion is accompanied by the SW radiation and a transformation of the bubble boundary layer to a cavitating cluster, which takes the form of a ring-shaped vortex floating upward to the free surface of the liquid layer.

1. Introduction

Explosive volcanic processes have been intensely investigated in both experiments and numerical multi-phase models [see, for example, 1, 2]. It’s well known that magma melt is saturated by a high-pressure gas. The formation of rarefaction waves induced by conduit opening violates the thermodynamic equilibrium state: diffusion processes behind the fronts of these waves arise, and intense development of bubble cavitation is observed, which can lead to magma melt rupture. An experimental model of rupture formation in a liquid layer was proposed in [3]. Those experiments were performed in electromagnetic hydrodynamic shock tubes (EM HSTs) with the diapason of storage energies up to 1.2 kJ [3]. It was shown that the shock wave generated in the liquid layer by a membrane under the action of a pulsed magnetic field initiates the development of intense cavitation processes in the liquid layer after SW reflection from its free surface. The pulsed motion of the membrane leads to the formation of a quasi-empty rupture already (in 10 µs) on the motionless membrane. The dynamics and structure of this rupture can be considered as a qualitative model of the above-mentioned process. Distilled water is a multiphase medium with very small gas bubbles, solid micro-particles, and their combinations with sizes of about 1.5 µm and densities of the order of 10^6 cm^-3 [4]. New experimental data on the dynamics of the state of the bubble boundary layer on the rupture interface and on its transformation to a cavitating cluster at the rupture implosion “point” are reported below.

2. Statement of experiments

The test section of the small experimental setup (EM HST) includes a transparent cuvette 4 cm in diameter, which is filled with distilled water [4]. The bottom of the cuvette is a conducting Duralumin membrane, which is placed directly onto a flat helical coil connected via an electronic switch to a high-voltage capacitor bank. When the switch is closed, a pulsed magnetic field is generated on the coil,
which pushes the membrane due to the skin effect, thus, generating a powerful SW in the liquid (the SW amplitude is of the order of 10 MPa). The process is recorded by a high-speed video camera with a frequency up to $10^5$ frames/s.

![Figure 1. Principle scheme of EM HST: (4) – cuvette, high-voltage capacity bank - (1), (3) – electronic switch, (2) - flat helical coil, (5) – liquid layer. Characteristic dynamics of eruption (experimental model).](image)

3. Experimental results.
When the electronic switch is closed, an SW is generated in the liquid layer. This SW is reflected from the free surface of the layer in the form of a rarefaction wave and leads to the formation of an intense cavitation region (Fig. 2a). In 0.5 ms, a maximum size of rupture is formed on the membrane (Fig. 2, b). A bubble boundary layer on the surface, which covers the entire rupture interface, is clearly visible. The next two frames (Figs. 2, c and 2, d) demonstrate the dynamics of the collapsing rupture and SW radiation.

![Figure 2. Rupture dynamics. The loading energy 32 J, at t = a) 0.1; b) 0.5;c) 1.04;d)1.1ms.](image)

The analysis of the rupture state dynamics shows that it acquires a shape close to a spherical segment. It is known that an implosion of an empty cavity in a homogeneous liquid near a solid wall is accompanied by the formation of a vertical cumulative jet. In the present case, however, such a situation is not observed: the rupture implodes without changing its topology. It is of interest that the liquid flow on the membrane in the course of the rupture implosion forms a ring-shaped flow of a homogeneous liquid, which is closed under the rupture with a high velocity (Fig. 2, c). At the end of the rupture
Implosion, a dense core is formed, and the bubble boundary layer transforms to a bubble cluster surrounding the rupture. The state of the rupture surrounded by a dense bubble cluster at the instant of the implosion can be defined as a state with a high internal energy. This is confirmed by generation of a sufficiently powerful secondary SW after the rupture implosion (Fig. 2d). Propagation of this SW and its interaction with the free surface leads to the formation of the secondary cavitation region (Fig. 2d). It was demonstrated earlier that the rupture retains its topology, i.e., a shape similar to a spherical segment. Based on this fact, we use the dimensional method, assuming that the basic parameters of the liquid state are the hydrostatic pressure $p_0$ and density $\rho$ of the liquid, the storage energy $E$, and the coefficient $\alpha$ characterizing the ratio of the maximum potential energy (see Fig. 2b) of the rupture to the loading energy $\alpha = Q/E$. Let us find a combination of parameters that yields the time characteristics of the examined process:

$$T = \alpha^{1/3} E^{1/3} \rho^{1/2} p_0^{-5/6} \quad (1)$$

The formulas of the rupture dynamics have the form: for its radius $r \approx 13.4 + 6.4 \cdot t - 19 \cdot t^2$, and for its height $h \approx 0.3 + 14 \cdot t - 1t^2$.

The value of $\alpha$ predicted by Eq. (1) allows to determine the value for the maximum potential energy: $\alpha = 0.0032$ or $Q \approx 0.1$ J (at loading $E= 32$ J) and $\alpha = 0.02$ or $Q \approx 25$ J (at loading $E= 1.25$ kJ). It is of interest that the experimental results obtained for identical storage energy, but for different heights of the water layer in the cavity are close to each other. Thus, it is confirmed that the dynamics of cluster formation depends to a greater extent on the loading energy and is almost independent of the water layer height. Fig 3 illustrates the cluster dynamics after the rupture implosion and generation of the secondary SW. Fig 3a show the secondary cavitation zone near free surface of liquid layer as result of SW- reflection.

Figure 3. Dynamics of the bubble cluster. The loading energy is 32 J; the time instants are 1.1 (a), 1.3 (b), 1.7 (c), 2.1 (d), 2.7 (e), and 3.1 ms (f).
Figure 4. Dynamics of bubble cluster emergence for different loading energies. The water layer height is 1.5 cm. The loading energy is 32 (blue), 24.5 (red), and 18 J (green).

It is seen that the cluster emerges to the water layer surface and possesses a sufficient amount of the initially stored energy to move to the liquid layer surface almost uniformly (1.5 cm in 2 ms). The character of the bubble cluster motion and the fact that a ring-shaped flow along the membrane is formed due to the rupture implosion allow us to assume that the bubble boundary layer transforms after the closure of the quasi-empty rupture to a ring-shaped cluster (vortex).

The results of the experimental analysis for the cuvette (membrane) diameter of 4 cm, water layer height of 1.5 cm, and loading energy of 18, 24.5, and 32 J are shown in Fig. 4. It is seen that the plot of motion is an almost straight line for the greatest energy examined in this study. As the energy decreases, the plot becomes curved, and the emergence velocity becomes smaller. The bubble cluster velocity is approximately equal to 7.5 m/s for the storage energy of 32 J.

Figure 5. Dynamics of vertical coordinate of center cluster (mm). Diameter of cuvette (membrane) - 12.5 cm, energy of loading (permanent) - 0.8 kJ. Height of water layer - red 3 cm, blue – 4 cm, green – 5 cm.
4. Conclusions

The analysis of the experimental data shows that shock wave loading of the liquid layer leads to the rupture development on the bottom of the cuvette. The rupture shape is close to a spherical segment, and there is a bubble boundary layer on the rupture interface. After the implosion, this boundary layer transforms to a bubble cluster. The rupture implosion generates the secondary shock wave, which is confirmed by the formation of the secondary cavitation region and which forms the cluster structure. After shock wave generation, the bubble cluster emerges to the liquid layer surface. The character of the cluster dynamics indicates the formation of a ring-shaped vortex moving upward to the liquid surface. It is shown that the cluster motion is almost independent of the liquid layer height and is mainly determined by the loading energy.

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