

# On the mechanism of explosive eruption of mount erebus volcano: the dynamics of the rupture structure in a cavitating layer

E S Bol'shakova<sup>1</sup> and V K Kedrinskiy<sup>1</sup>

<sup>1</sup> Lavrentyev Institute of Hydrodynamics, Siberian Branch of Russian Academy of Sciences, Lavrentyev prosp. 15, Novosibirsk, 630090, Russia

E-mail: [kedr@hydro.nsc.ru](mailto:kedr@hydro.nsc.ru)

**Abstract.** This paper presents the results of an experimental simulation of rupture development in heavily cavitating magma melt flow in volcanic conduits and its effect on the structure of explosive volcanic eruptions. The dynamics of the state of a layer of distilled water (similar in the density of cavitation nuclei to magma melt) under shock-wave loading was studied. The experiments were performed using electromagnetic hydrodynamic shock tubes (EM HST) with maximum capacitor bank energy of up to 100 J and 5 kJ. It was found that the topology of the rupture formed on the membrane surface did not change during its development. Empirical estimates were obtained for the proportion of the capacitor bank energy expended in the development of the rupture and the characteristic time of its existence. The study revealed a number of fundamentally new physical effects in the cavity dynamics in a cavitating medium: a cavitation “boundary layer” is formed on the surface of the quasi-empty rupture, which is transformed into a cluster of high energy density upon closure of the flow.

## 1. Introduction

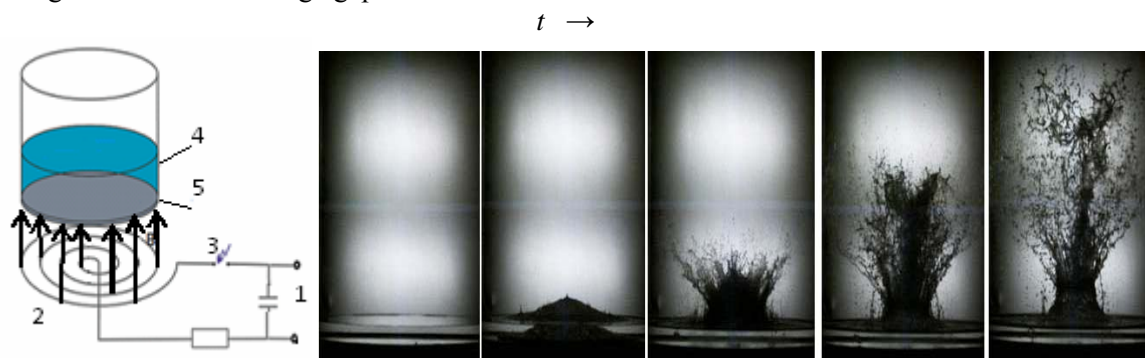
Comparing the flow characteristics and structure in liquids containing a high density of micro-inhomogeneities ( $10^{12} \text{ m}^{-3}$  in distilled water) under shock-wave (SW) loading with the natural processes occurring in volcanic conduits during explosive eruptions, it is easy to conclude that all of them are directly related to the hydrodynamics of high-velocity multiphase unsteady flows [1]. In many cases, the adequacy of their representation by mathematical models and experimental designs in simulations of large-scale natural processes becomes obvious through the analysis of the pre-explosion state of Mount St. Helens volcano in May 1980 made by an international team [2]. The authors have reconstructed a model of the volcano architecture, which has proved an analog of the well-known hydrodynamic shock tube of I. Glass [3]. Studies of the mechanisms responsible for the explosive nature of volcanic eruptions often focus on two fundamental problems. One is to find mechanisms that determine the dynamics of the magma state behind the decompression wave front and its transition from the liquid melt state to the gas-particle state with the emission of giant ash clouds into the atmosphere [4-6]. The second problem is the discreteness of the eruption, which is observed in both closed (Mount St. Helens volcano) and open (Mount Erebus volcano) volcanic systems [6-12]. Obviously, the explosive nature of the decompression wave may well initiate ruptures in heavily cavitating magma flow in volcanic conduits even before the eruption. This hypothesis was



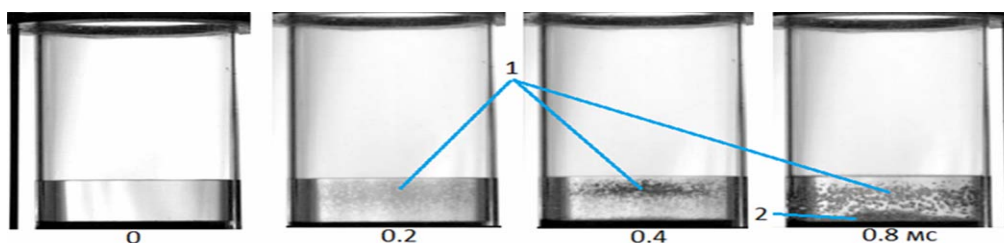
made in [7], but the authors suggested that such processes could be characteristic of great depths and would not lead to an explosive eruption. Of interest is the architecture of Mount Erebus volcano – an open volcanic system of the explosive type with a lava lake on the crater floor, through which eruptions occur. The dynamics of tens of cyclic eruptions in the discharge zone has been studied using a radar system and the Doppler effect has been studied experimentally [2]. It has been shown that gas bubbles in the cavitating flow do not oscillate and thus cannot affect the cyclicity of eruptions of Mount Erebus volcano or similar systems. The aim of the present study was to experimentally simulate the development of a rupture in a cavitating liquid layer under SW loading in order to analyze the effect of the rupture dynamics on the cavitating flow structure.

## 2. Experimental setup

In the study we used an experimental setup based on SW loading of a liquid layer to produce rupture under conditions of rapidly developing bubble cavitation. The experiments were performed using electromagnetic hydrodynamic shock tubes (EM HST) with maximum capacitor bank energies of up to 100 J and 5 kJ, which makes it possible to analyze scale factors. A schematic diagram of the EM HST with the capacitor bank used and a general view of the formation dynamics of a characteristic eruption in a cavitating layer are presented in figure 1. The parameters of the electromagnetic unit provide an aperiodic discharge. Upon ignition of the discharge gap 3, the capacitor bank 1 (figure 1) is discharged into the flat spiral coil 2 placed under the conductive membrane 5, which serves as the bottom of the cell 4. The resulting current in the coil generates pulsed magnetic field  $B$ . The membrane 5 gains momentum as a result of the skin effect. The movement of the membrane generates a shock wave (SW) in the liquid layer 4 (distilled water). A high-speed “Photron FASTCAM SA 5” digital video camera (recording speed of up to 700 thousand frames per second) is synchronized with the ignition of the discharge gap 3.



**Figure 1.** Schematic diagram of the EM HST (4) with the high-voltage capacitor bank (1); characteristic dynamics of eruption (experimental model).

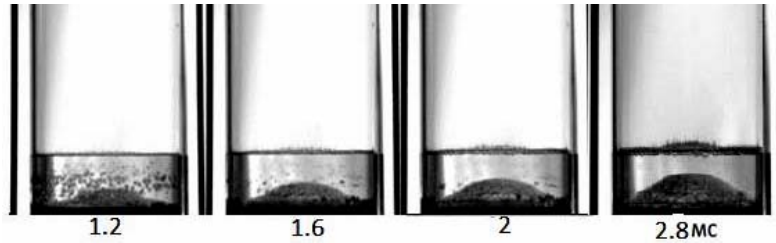


**Figure 2.** Development of cavitation in a layer under SW loading (1) and rupture nucleation (2) for a membrane diameter of 12 cm, a layer height of 4 cm, and a capacitor bank energy of 0.8 kJ.

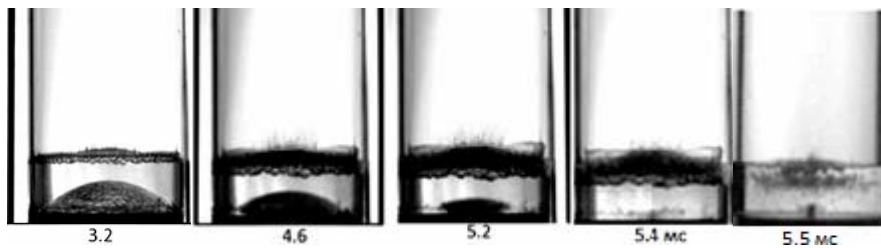
## 3. Rupture dynamics in the cavitating liquid

The experiments showed that the shock wave reflected from the free surface of the layer initiated a rapid cavitation process in the layer (1) (figure 2). The initial position of the membrane is restored

within a few microseconds for the small EM HST or within 10  $\mu$ s for the large EM HST. The inertial motion of the impacted liquid leads to the formation of a rupture (2), whose dynamics and structure can be treated as a qualitative model of the initial stage of the Mount Erebus eruption process [13].



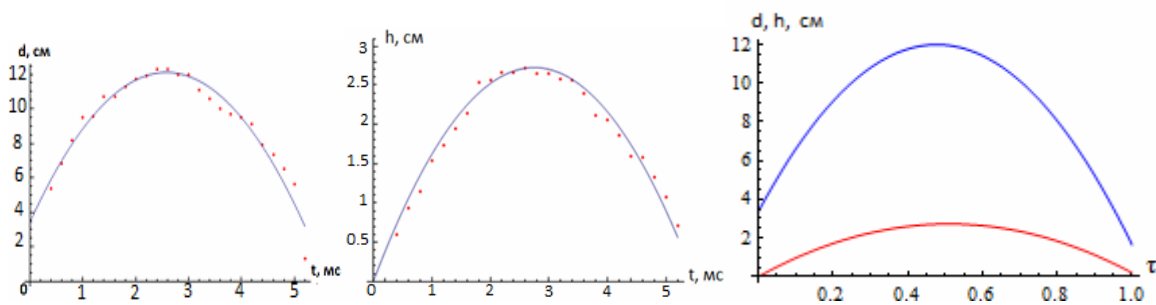
**Figure 3.** Development of rupture; the maximum volume is reached at  $t = 2.8$  ms.



**Figure 4.** Closure of the rupture ( $t = 3.2 - 5.2$  ms), the formation of a cluster ( $t = 5.4$  ms), and the initial stage of its expansion ( $t = 5.5$  ms).

A detailed analysis of the rupture structure (figures 3 and 4) shows that for different scales of SW loading of the layer, the rupture has the shape of a spherical segment and retains its topology throughout the period of existence. It is found that the collapse of the rupture on the membrane surface (solid wall) in the cavitating liquid does not produce a cumulative jet. The definition of the rupture as a spherical segment makes it possible to estimate its volume and potential energy  $Q = VP_0$  at the time it reaches the maximum size. This result allows us to evaluate the proportion  $\alpha$  of the capacitor bank energy  $E$  expended in the development of the rupture  $Q = \alpha E$ . It was found that  $\alpha \approx 2\%$ . It is assumed that the rupture is quasi-empty and the internal energy of the possible vapor-gas mixture in it is much less than the potential energy. A formula for the characteristic time of existence (formation–collapse) of the rupture was derived based on a combination of the determining parameters (the density  $\rho$  and the hydrostatic pressure  $P_0$ ) within dimension theory:

$$T = \alpha^{1/3} \frac{E^{1/2} \rho^{1/2}}{P_0^{5/6}} \quad (1)$$



**Figure 5.** Dynamics of rupture parameters. In a dimension time – (a) width  $d(t)$ , (b) height  $h(t)$  of rupture, at  $E = 0.8$  kJ, and in a dimensionless time (c) –  $d(\tau)$  (blue),  $h(\tau)$  (red).

From an analysis of experimental data on the main geometrical characteristics of the rupture (diameter  $d$  and height  $h$ ), we obtained semi-empirical relations of their dynamics:

$$d(t) = 3.45 + 6.71t - 1.3t^2, \quad h(t) = 1.98t - 0.36t^2. \quad (2)$$

Introducing the dimensionless time ( $\tau = t/T$ ), we obtain formulas in which  $d$  and  $h$  are in centimeters:

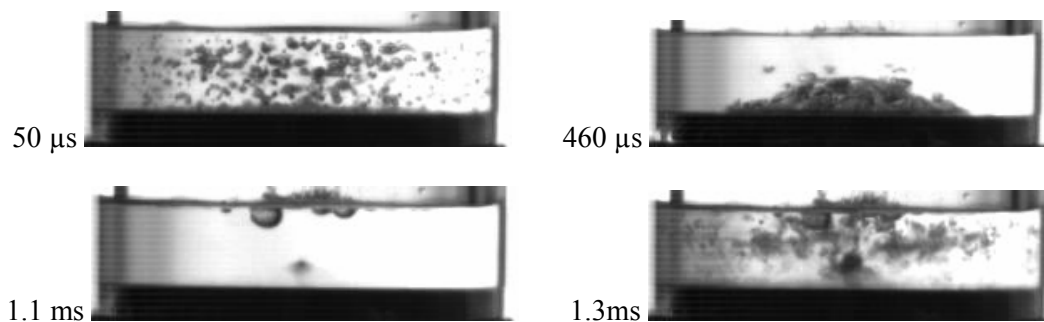
$$d(\tau) = 3.45 + 36.2\tau - 37.9\tau^2, \quad h(\tau) = 10.7\tau - 10.5\tau^2, \quad (3)$$

which adequately describe the state of the rupture parameters throughout the range of its existence (figure 5).

Experiments with the small EM HST (membrane diameter of 4 cm, layer height ranges from 0.5 to 1.5 cm), with a capacitor bank energy less by more than an order of magnitude, show that the flows are practically similar and differ only in the characteristic linear and time parameters of rupture dynamics. It is found that the proportion of the energy expended in the development of rupture under these conditions is significantly lower  $\alpha \approx 0.6\%$  due to the higher stiffness of the membrane.

One of the principal factors determining the characteristic rupture dynamics (unchanged topology, absence of cumulative flow) is the cavitating state of the surrounding liquid. In particular, the rupture development is accompanied by the formation of a kind of bubbly boundary layer on the surface (figure 6). The reason is obvious: the rupture is assumed to be quasi-empty and, hence, maintains low pressure throughout the period of development and closure up to the final phase. In this state, the rupture initiates the growth of microbubbles in the boundary layer.

Figure 6 shows an intermediate frames of the rupture initiated on a 4 cm membrane at a shock-loading energy below 100 J, proving that the scale factor does not affect the characteristics of the process studied.



**Figure 6.** Structure of the rupture (membrane diameter of 4 cm, layer height of 1 cm):  $t = 50$  and  $460 \mu\text{s}$  (about  $V_{\text{max}}$ ),  $t = 1.1 \text{ ms}$  – at the collapse time (loading energy of 32 J);  $t = 1.3 \text{ ms}$  – initial explosion.



**Figure 7.** Rupture structure ( $t = 0.77 \text{ ms}$ ) in the experiment using small EM HST for a cell diameter of 4 cm and a layer height of 1.5 cm. Right picture – the initial stage of cluster explosion (normal EM HST,  $t = 5.5 \text{ ms}$ ).

Analysis of the experimental data on the state dynamics of the rupture and boundary layer shows that the closure of the rupture in the cavitating liquid results in the formation of a highly compressed bubble cluster upon collapse of the boundary layer (figure 4, time  $t = 5.4$  ms, the small dark area at the center of the membrane). The state of the bubble cluster at the time of closure of the rupture can be defined as a state with high internal energy. This is confirmed by experimental data on the generation of a fairly powerful secondary SW by the cluster at the initial stage of expansion. Radiation is detected from the formation of a secondary cavitation zone (figure 7,  $t = 5.5$  ms) after the closure.

### Acknowledgments

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