Explosive Eruptions of Volcanoes: Hydrodynamic Shock Tubes as Lab Method of Simulation

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1 Introduction

Obviously, it is beyond question that the explosive character of decompression during the volcanic eruption initiates a whole spectrum of phenomena in a pre-compressed magmatic melt containing large amounts of dissolved gases: homogeneous nucleation, bubbly cavitation, gas diffusion, and dynamically increasing viscosity of the melt. It is these processes that determine the eruption character, the magma state dynamics, and the flow structure in decompression waves as a whole. In the same time many aspects of their mechanisms remain unclear. The answers to these questions and, in particular, to the question about the mechanism of the cavitating magma transition to a state of an ash cloud cannot be simple because of extremely complicated and multiple-scale phenomena such as an explosive eruption [1]. In this connection, as it was noted by Gilbert and Sparks [2], laboratory experiments on the dynamics researches of volcanic flows and, in particular, the shock tube methods must become important components of simulation processes together with mathematical models and numerical analysis.

Indeed, the analysis of the pre-eruption hydrodynamic schemes of the St Helens and Kilauea volcanoes has shown that, in terms of structural features, they are similar to hydrodynamic shock tubes (HST) [3], [4]. The ”inversion” variant of the Glass-Heuckroth -scheme [3] turned out to be most close to the real scheme of the pre-eruption state of explosive volcanoes. It includes three basic elements: a high-pressure chamber (analogue of the system consisting of a volcanic chamber and a channel filled by compressed magma), a low-pressure chamber where the gas is under atmospheric pressure (analogue of the free portion of the volcanic conduit and/or a crater bordering with the atmosphere), and a diaphragm (plug) separating these two chambers. Thus, one can consider that pre-eruption schemes of explosive volcanoes have a common gas-dynamic sign.

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Prof.A. Lacroix (1908) proposed to classify volcanoes on the basis of the intensity of their explosive eruptions: *Hawaiian* - as rarely explosive, *Strombolian* - as moderately explosive, *Plinian*/*Vulcanian* - as strongly explosive, *Pelean* - as the greatest explosive. It meant that they were classified according to the principal types of behaviour that they exhibited. The magma properties were mainly determined as andesitic or rhyolitic ones.

Fig. 1 From left to right: Vertical and lateral eruptions of the St Helens volcano, successive vertical and lateral eruptions at shallow underwater explosions

An analogue to a similar spectrum of intensity can be found in processes inherent in underwater explosions. It is the field of hydrodynamics of high-velocity unsteady flows initiated by explosive sources of different intensity. The latter depends on the energy release rate, which is insignificant in the case of underwater explosions of wires or gaseous mixtures and reaches a maximum value in the case of explosions of condensed cast and pressed high explosives (HEs). As an example, we can mention directed "eruptions" in the form of jet flux (fountains) on the free surface of a liquid, which are observed during shallow underwater explosions and resembles volcanic eruptions (Fig. 1, [5]).

It should be noted that the mechanics of these phenomena has the same cumulative nature (both for wire and HE explosions) determined only by the interaction of the explosive cavity with the free surface and independent of the energy release rate of the explosive source. For some types of volcanoes of the explosive character from Lacroix's classification, the intensity may also be assumed to exert no significant effect on the mechanisms responsible for the processes inherent in explosive volcanic eruptions. Thus, the community of the mechanisms controlling the eruption process can be considered as the second common sign of processes inherent in examined phenomena.

Finally, the question about the so called M-liquid (a liquid analogue of magma) remains open. In this paper, the experimental results obtained for distilled water will be discussed. This choice is based on one of important common signs (features): the densities of the number of pores per unit volume for a solidified lava sample ($10^{10} - 10^{12} m^{-3}$) and of micro-inhomogeneities in distilled water ($10^{10} - 10^{11} m^{-3}$) have practically close orders.

2 HST-Methods and State Inversion Problem

An analysis of researches in the field of mechanics of liquid destruction under shock-wave loading [6] and data on volcanic eruptions (see, for instance, [2]) suggests that unsteady high-velocity processes initiated by pulsed loading of liquid media can be considered as analogues of natural volcanic processes in terms of both the probable mechanisms of their initiation and the flow state dynamics.

As was mentioned above, the closest example of explosive volcanoes with the pre-eruption state corresponding to the HST-scheme ("inversiion" GH-scheme) is the St. Helens volcano whose powerful eruption was initiated by a huge landslide, which cut off the plug covering the volcano vent, Fig. 2 ([7], [4]).

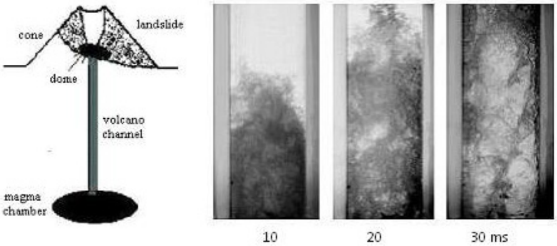

Fig. 2 From left to right: pre-eruption scheme of the St Helens volcano and experimental data on the flow structure simulation in a channel of the inversion GH-scheme.

It is considered ([8], [9]) that the density of cavitation bubbles formed in the magma as a result of explosive decompression is uniform. During cavitation development, the cavitating magma state through a stage of the foam structure is transformed to the gas-droplet state.

However, the experiments (Fig. 2, exposure time1 μs for each frame) shows that this ideal scheme of the transition of the cavitating magma to the state of an ash cloud can be rather far from real processes: the flow can be strongly inhomogeneous and, in particular, have a character of a "bubbly cluster - slug" regime (see Fig. 2).

Dynamic schemes of the HST (systems initiating a shock wave (SW) in a sample with the free surface) are most interesting for lab applications. An SW propagates within a liquid sample and compresses it, simulating the stage of the hydrostatic state of the compressed magma in a volcanic chamber and channel. Then the SW reflects from the free surface of the sample as a rarefaction (decompression) wave. Propagating over the compressed sample in the opposite direction, it performs the function of a decompression wave.

Figure 3 presents the HST scheme (a) and the scheme of magma state dynamics (b), [8], [9]: volcano chamber, nucleation zone, cavitation zone, foam state, fragmentation zone, and, as result of fragmentation, gas/particles system. In this figure, the diaphragms are indicated by d; and the elements of this scheme are the gas receiver (1), the vacuum channel with a piston p (2), the channel with the liquid

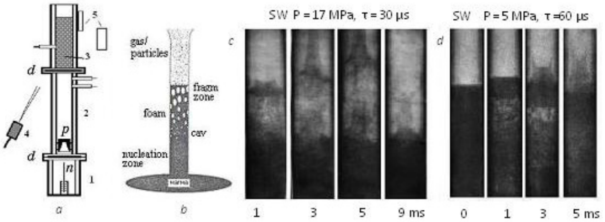

Fig. 3 Dynamic HST-scheme a; Dobran-Woods model of magma desintegration dynamics b and dynamics of intensive cavitation zone development (computer analogue of x-ray negatives) behind the decompression wave front c, d

sample (distilled water) studied (3), the pulse x-ray source (exposure time about 80 ns) (4), and the x-ray receivers (5).

As was noted above, the mechanism of the foam structure destruction or, in other words, ”the foam - gas-droplet inversion” is one of unsolved principal problems.

In mid-1990s, however, thanks to the application of the impulse x-ray method, laser scanning, and digital image processing of x-ray negatives, some progress has been achieved in understanding the specific features of the flow structure of a cavitating medium at the late stages of disintegration. According to the data presented in Fig. 3,c the effect of the ”foam - gas/droplet system” transition and the eruption of the gas-droplets flow can be realized in the case of sample loading by a strong SW (15 MPa amplitude and 30 μs duration). The intense cavitation development is also observed in the case of loading by a relatively weak SW (5 MPa amplitude and 60 μs duration). In this case, however, the cavitating sample (or at least its part) is also destroyed, but then (see instant $t \approx 5$ ms) it is restored again without eruption (see Fig. 3,d). It is interesting to note that this effect turns out to be close to H.M.Gonnermann’s, and M.Manga’s idea (Nature, 2003) that the magma deep within volcanoes can be repeatedly torn into fragments and then squeezed together again without an explosive eruption.

The application of the HST- and x-ray methods, Fig. 3, unfortunately gives no idea about the physical mechanism of the transition itself. A new experimental approach makes it possible to considerably restrict the disintegration zone. Recall that $1cm^3$ of a distilled water drop contains about 10^6 micro-inhomogeneities. Hence, water drops of such volume can be considered as the main elements of the flow structure. In this case, it is principally important that the shock wave penetrating into the drop should be ultrashort to result in the cavitation development in small drops. An electromagnetic hydrodynamic shock tube (EM HST) was designed for generation of ultra-short (microsecond duration) shock waves in a liquid.

The experiments, [10], have shown that a dense cavitation zone is formed inside the drop already at the initial stage. During the following inertial development of the cavitation zone to the instant $t \approx 1500 \mu$s, the drop takes a cupola shape as a system of small spatial grids. The elements of the liquid grid under further stretching are gradually separated into individual fragments; due to instability, small jets

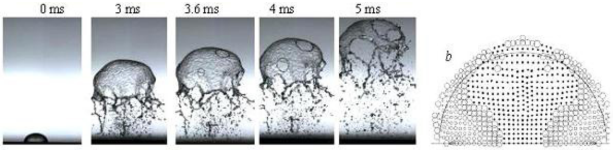

Fig. 4 Transformation of the cavitating drop into a cupola of a grid honeycomb structure and the zone of ”cavitative explosion” in the center of the drop (b)

disintegrate into individual drops [10]). As it follows from Fig. 4, the subsequent fracture of the liquid sample is determined by the inversion mechanism, which is related to the dynamically growing zone of disintegration on the ”cupola” surface forming the inversion front.

To understand the nature of a rather unbelievable transformation of the liquid drop to the cupola shape, Davydov [11] performed a numerical analysis of the state dynamics of a semispherical drop under ultrashort shock-wave loading within the framework of the IKvanW-model and the model of the ”frozen” profile of mass velocities. According to the calculation results, the dynamics of the cavitation zone structure inside the drop confirms that the drop transformation to a cupola shape as a system of grids is a result of a ”cavitation explosion” at the drop center: fast growth of bubbles, their coalescence, and inversion of states inside the drop. Figure 4,*b*, for the time $t = 145$ μs presents the distribution of visible (sizes from 0.1 to 2 mm) cavitation bubbles and the coalescence zone (symbols) occupying the central part of the drop.

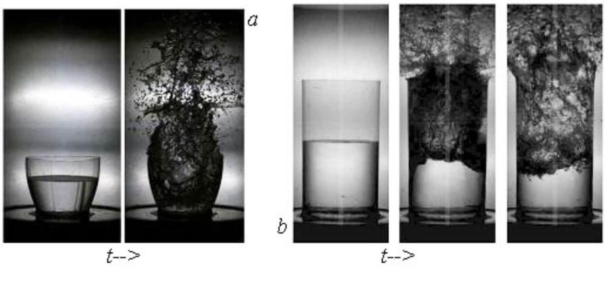

Fig. 5 Two experiments on destruction and eruption of liquid samples under shock-wave loading in the 5kJ of EM HST scheme

The recently created new electro-magnetic HST allows capacity bank to accumulate energy up to 5 kJ (which is approximately equivalent to 1 g of HE). The setup can be used for carrying out more precision experiments for larger-scale samples. First experiments have confirmed the possibility of the 5 kJ EM HST-scheme (Fig 5) to provide loading of samples that will be sufficient for destruction and eruption of a large volume of the examined liquid.

3 Conclusion

The studies have shown that , a number of explosive volcanic systems are close in terms of the structural features of the pre-eruption state to the scheme of the hydrodynamic shock-tube (HST). This fact confirms that the experimental settings for simulating magma behaviour under a decompression wave can be realised within the framework of the HST-scheme. A comparison of characteristic features of state dynamics of distilled water samples under shock-wave loading (studied by the HST-methods) with known existent models of magma behaviour during the eruption shows that high-speed processes in the liquid can be considered as analogues (in terms of some signs) of natural volcanic processes. Thus, one can assume that, independent of the eruption activity, the explosive volcanic processes (at least for some volcanoes from A. Lacroix's classification) are developed according to general gas-dynamic signs and kinetics determining the flow structure.

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