

Structure dynamics of cavitative magma flow in a volcano channel at explosive eruption

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Abstract. The effect of the density of cavitation nuclei on the state and flow structure of the magma melt in the case of its explosive decompression is numerically studied within the framework of the gas-dynamic model of mechanics of multiphase media. It is demonstrated that a zone with anomalously high values of the basic characteristics of the magma state is formed in the vicinity of the free surface of the magma column as the density of cavitation nuclei increases. A drastic increase in the particle velocity up to 150 m/s on the lower boundary of this zone testifies to a high probability of its separation from the main flow. Within the framework of the numerical scheme, this separation is "realized," and the dynamic behavior of the magma column remaining in the conduit is analyzed. It is shown that the detected effects of anomalous zone formation and possibility of separation turn out to be fairly stable, which allows one to define them as a "self-sustained regime of cyclic ejections."

1. Introduction

A comparison of results of experimental studies and numerical models of the dynamics of the states of conventional fluids under shock wave (SW) loading [1] with numerous investigations of natural processes (detailed reviews [2] should be noted) accompanying explosive volcanic eruptions allows an important conclusion to be drawn. The fundamental problems of the dynamics of the magma state in decompression waves [3], its transition from the state of a single-phase melt to the gas-particle state (formation of ash clouds), and the cyclic character of ejections are directly related to high-velocity hydrodynamics of multiphase media. Previous investigations show that the dynamics of the state of the magma melt in the gravity field is characterized by intense development of the cavitation process [3]. However, the problem of modeling the final stage of the process (destruction of the flow), which was described in [4] for conventional fluids under SW loading and in [5,6] for open volcanic systems, is still far from being solved despite numerous experimental studies based on various models of the viscous magma. Another aspect (cyclic character of ejections) is also rather problematic; some of the solutions are obtained on the basis of studying physically obvious models of the slug mode, effects of slipping/adhesion of the cavitating flow on the conduit walls, and elastic properties of the system consisting of the volcanic chamber and the conduit [2, 7-9]. In the proposed paper, the challenge is to solve a more general problem, i.e., to find mechanisms responsible for the formation of discontinuities in the magma flow and, as a consequence, for the discrete character of ejection of ash clouds.



2. Two-phase mathematical model of state dynamics of cavitating magma

It is known that eruptions of closed volcanic systems can be initiated by a sudden decrease in pressure on the crater-conduit interface; as a result, a decompression wave (DW) starts to form in the high-pressure magma melt and propagates inward the conduit. As a consequence, the gas in the form of cavitation bubbles is released in the process of diffusion behind the DW front in the melt saturated by the gas: a cavitating magma flow is formed in the volcanic conduit. An interesting example for analyzing such systems is the St Helens volcano (eruption of May 1980). The point is that the scheme of its pre-explosion state reconstructed in [10] turned out to be absolutely adequate to the pulsed rarefaction tube (PRT) scheme. This fact is important, first of all, from the viewpoint of verification of results of experimental modeling of the magma state dynamics. It were the PRT-method that were used in the 1980s to study essentially nonlinear processes of cavitation destruction of distilled water under SW loading as a reference sample of heterogeneous media with free gas microbubbles. Experimental investigations by the diffraction-optical method of laser radiation scattering on microinhomogeneities combined with SW loading showed that their number contained in distilled water was of the order of 10^6 cm^{-3} [11]. A similar order ($10^{12-14} \text{ m}^{-3}$) of the density of micropores was observed in solidified lava samples.

Thus, unsteady high-velocity processes that occur under pulsed loading of distilled water [1, 11] can be considered under certain conditions as analogs of natural volcanic processes from the viewpoint of both possible mechanisms of their initiation and flow dynamics. In constructing the mathematical model of the magma state dynamics in the volcanic conduit, it is reasonable to take the basic model in the form of the Iordanskii-Kogarko-van Wijngaarden model [1,3] with the Navier-Stokes equation for the averaged velocity v , density ρ , and pressure p at a variable viscosity of the medium μ (more detailed see in [3]):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial z} = 0; \quad \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g + \frac{1}{\rho} \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} \right),$$

supplemented by the kinetics equations of dynamic processes inherent in volcanic eruptions:
by the Tait equation of state and by the definition of the magma melt viscosity

$$p = p_0 + \frac{\rho c^2}{n} \left\{ \left(\frac{\rho}{\rho_0(1-k)} \right)^n - 1 \right\}, \quad \mu = \mu^* \exp \{ E_\mu(C)/(k_B T) \}$$

by the definition of the frequency of homogeneous spontaneous nucleation and by the Rayleigh equation describing the dynamics of a single bubble in a viscous liquid

$$J = J^* \exp(-W_*/(k_B T)), \quad R\ddot{R} + (3/2)\dot{R}^2 = \rho^{-1}(p_g - p) + 4\nu R^{-1}\dot{R},$$

by the equations of state of the gas in the bubble (the gas is assumed to be ideal) and of the gas diffusion in the melt

$$(4/3)p_g R^3 = (m_g/M)k_B T, \quad \frac{dm_g}{dt} = 4\pi R^2 \rho D \left(\frac{dC}{dr} \right)_R = 4\pi R \rho D (C_i - C^{\text{eq}}(p_g)),$$

The effect of the density of cavitation nuclei on the state and flow structure of the magma melt in the case of its explosive decompression behind the DW front is numerically studied in a 1-km column of the compressed magma melt saturated by the gas. At the lower boundary of the magma column the pressure is set and maintained at a constant value of 170 MPa; the dissolved gas concentration is assumed to be 5.2 % wt. The distributions of these variables along the column (z axis) are determined by hydrostatics. At the time $t = 0$, the pressure on the upper boundary of the magma column is instantaneously reduced to 0.1 MPa.

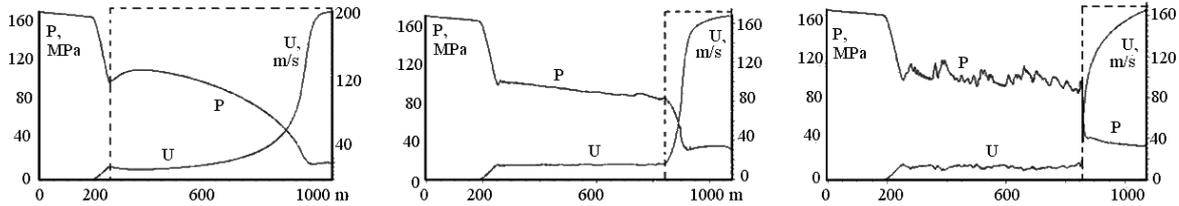


Figure 1. Profiles of decompression wave $P(z)$ and structures of mass velocity field $U(z)$ at $t=0.5$ s. Effect of the density of cavitation nuclei saturation $N_b, m^{-3} = 10^9, 10^{11}$ and 10^{13} on the anomalous zone formation (from left to right, correspondingly).

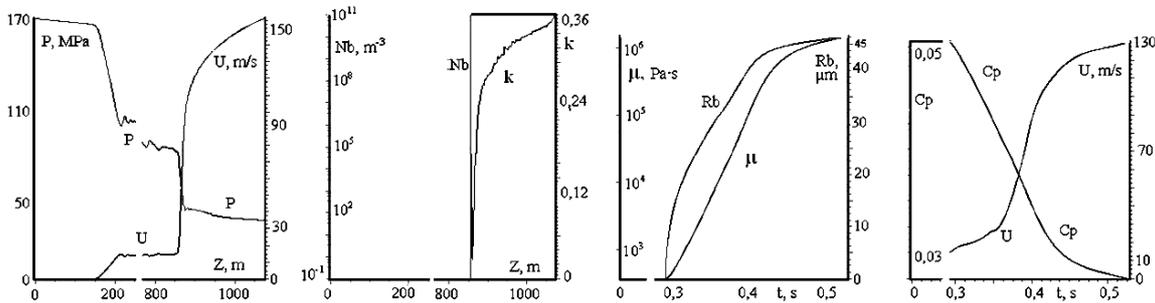


Figure 2. Decompression wave $P(z)$, mass velocity $U(z)$, density of cavitation nuclei $N_b(z)$ and gas phase concentration $k(z)$ distributions at $t=0.54$ s. Dynamics of bubble radii $R_b(t)$, viscosity $\mu(t)$, Pas, mass velocity $U(t)$ and losses of dissolved gas $C_p(t)$ by melt in a Lagrange-cross section.

The structures of the wave fields $P(z)$, MPa, and particle velocity fields $U(z)$, m/s, formed by the time $t=0.5$ s are shown in Fig. 1 for three limiting values of the cavitation nuclei density N_b, m^{-3} (from left to right) : 10^9 (spontaneous nucleation), 10^{11} , and 10^{13} (homogeneous-heterogeneous nucleation). Here z , m is the abscissa axis; the values of the pressure (z) and particle velocity $U(z)$ are plotted on the ordinate axes. The value $z=0$ corresponds to the lower boundary of the magma column. The dashed curves in each of the plots $P(z)$ - $U(z)$ show the saturation zones where the density of cavitation bubbles reaches the above-given limiting values.

It can be easily seen that the saturation zone size becomes substantially smaller (owing to redistribution of diffusion flows). The particle velocity distribution in the saturation zones becomes essentially different: from its gradient growth in the case of spontaneous nucleation to a jump in the particle velocity gradient ($N_b = 10^{13} m^{-3}$).

The data in Fig. 2 are presented in the distributions form of $P(z)$, $U(z)$, $N(z)$, and $k(z)$ at the time $t=0.54$ s and in the dynamic form as the cavitation bubble radii $R_b(t)$, melt viscosity $\mu(t)$, loss of the dissolved gas from the melt $C_p(t)$, and particle velocity $U(t)$ in the Lagrangian cross section of the flow with the initial coordinate $z = 900$ m in the time interval up to 0.54 s. For a more compact presentation, the plots have breaks approximately 500 m long over the z axis and 0.1 s over the t axis.

The results obtained show that an increase in the cavitation nuclei density by 3-4 orders of magnitude with respect to spontaneous nucleation data leads to the formation (in the vicinity of the free surface of the magma column) of a saturation zone with anomalously high parameters (SZ) of the basic characteristics determining the state of the cavitating magma flow. In the SZ the gas mass in cavitative bubbles becomes stable, the diffusion processes come to a stop (see function $C_p(t)$, Fig.2), the pressure reaches 30-40 MPa magnitude.

The presence of a drastic jump of velocity on the lower boundary gives grounds to say that

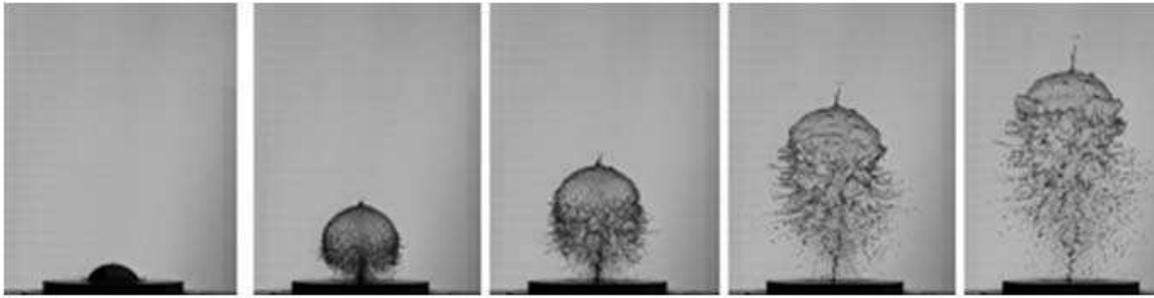


Figure 3. Cavitative explosion of 1 cm size drop at SW-loading (amplitude about 10 MPa, duration 5 μ s): droplets cloud formation, $t=0.15, 1.2, 2.0, 3.3$ and 4 ms.

the formation of a discontinuity on this boundary and a new free surface is fairly realistic. A numerical analysis (with software implementation of "separation") of the dynamics of the state of the magma column remaining in the conduit shows that the formation of the anomalous zone with jumps of the values of the basic characteristics is a repeated process. The latter allows one to define the regime found as a "self-sustained regime of cyclic ejections."

3. Experimental simulation

The processes behind the DW-fronts are experimentally modeled in a dynamic statements at SW-loading of liquid samples with a free surface. SW-loading can be considered as a dynamic analogy of explosive volcanic eruption initiation: SW-compression of a sample simulates its pre-explosion state, and the rarefaction wave reflected from its free surface simulates the decompression wave inducing an intense cavitation process in a sample [1].

One can assume that the SZ mentioned above after the separation from main flow will have to be sprayed on the droplets cloud by the internal cavitative explosion. This effect is simulated on the electro-magnetic ST by SW-loading of 1 cm size drop of the distilled water (remind, that its 1 cm^3 contains about 10^6 microinhomogeneities). Ultra-short SW (microseconds duration) in a drop is generated by duralumin membrane under pulse magnetic field (description can be found in [3]).

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