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PRODUCTION OF PHREATIC EXPLOSIONS IN THE INTERACTION OF LAVA AND ICE

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A mathematical model is given of the formation of phreatic explosions in lava flows coming into contact with ice formations. Quantitative characteristics are derived for the various stages in the development of the explosion, by means of which its strength and other parameters may be evaluated. The theoretical calculation results are in agreement with empirical data.

The formation of numerous secondary explosions is one of the main consequences of direct contact between lava flows and bodies of ice during volcanic eruptions. In the classification of Vlodavets [5] these are phreatic contact explosions.

Qualitative descriptions of phreatic explosions recorded in the course of an eruption in the snow and ice zone of the Klyuchevskoi group of volcanoes are to be found in [2 - 4]. Analysis of the data shows that conditions are most favourable to the formation of secondary explosions when lava flows more than 5 m thick overlay small isolated volumes of ice.

The course of a phreatic explosion is a complicated process definable in terms of many factors such as water and the thickness of the lava flow, the size and shape of the ice body, the presence of moraine and pyroclastic interlayers in it etc. Various regimes, ranging from the gentle emission of vapor through fissures to powerful explosions accompanied by the ejection of crust lava, are possible, depending on the relationship of these factors (Fig. 1). Powerful explosions obviously occur when the conditions exist for fairly lengthy accumulation of vapor in a cavity under increased pressure. The increasing mass of the vapor must, in the absence of escape, lead to an increase in pressure or in volume, or in both at once. When vapor accumulates under a plastic lava roof there is little probability of an appreciable increase in pressure, and the dominant process should be an increase in volume due to deformation of the roof.

Let us, as a first approximation, consider the following simple model of the formation of a phreatic explosion and its course, dividing the process into three successive stages: (1) the melting of ice and the heating of the melt water to boiling point without any appreciable increase in the volume of the submerged mass; (2) evaporation of the water, accompanied by a considerable increase in volume; (3) breaching of the lava sheet and escape of the steam-and-water mixture - the phreatic explosion proper.

Such a model will make it possible to find some quantitative relationships for comparison with observations. It will be considered as a first approximation that pressure in the chamber beneath the lava is constant throughout all the stages of the secondary explosion and is $P_* = g\rho_0 H + P_{atm}$, where g is gravity acceleration, ρ_0 is lava density, P_{atm} is atmospheric pressure. Let us designate the mean temperature of the lava flow in ^oC at a distance from the contact with the ice body by t_0, and the area in plane

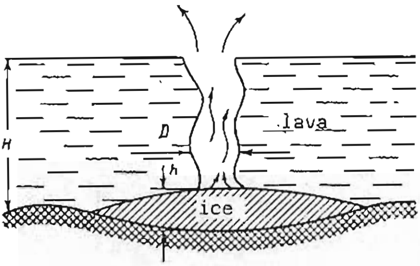

Fig. 1

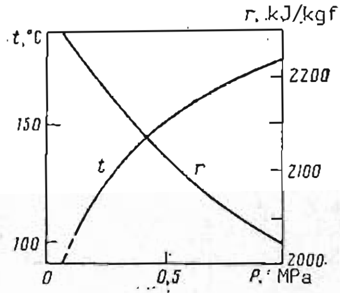

Fig. 2

Fig. 1. Interaction of a lava flow with a buried ice body. Symbols explained in text.

Fig. 2. Thermodynamic properties of water and water vapor on the saturation line according to data in [6].

section over which the mass of the ice (M) is distributed by S.

Ice melting. Let r_i be the latent heat of melting of the ice, and let r_* and t_* be the latent evaporation heat and the boiling point of water at the pressure P_*. At moderate pressures $P_* < 5$ MPa, the quantity t_* does not exceed 250°C (Fig. 2) and is considerably lower than the lava temperature t_0. Consequently, the variation of temperature in the course of the melting of the ice and subsequent heating may be disregarded by comparison with t_0, and the heat flux q reaching a buried volume of ice (water) may be calculated on the basis of solving the problem of heat transfer in the layer of lava, regarded as a semi-bounded mass [9]:

$$q=\frac{\lambda_0 t_0 S}{\sqrt{\pi a_0 \tau}}, \quad (1)$$

where λ_0 and a_0 are the coefficients of the heat conductivity and temperature conductivity of the lava.

Consequently, the heat received by the mass of ice and water over the time τ will be

$$Q=\frac{2\lambda_0 t_0 S}{\sqrt{\pi a_0}}\sqrt{\tau}. \quad (2)$$

The heat energy required to complete the first phase, i.e. to melt the ice and heat the water to the temperature t_*, will be

$$Q_1 = M(r_i + C_w t_*). \tag{3}$$

Equating expressions (2) and (3), we find the moment of time τ_1 that is the end of the first stage.

$$\tau_1 = \frac{\pi a_0 M^2 (r_i + C_w t_*)^2}{4\lambda_0^2 t_0^2 S^2}. \tag{4}$$

In formulas (3) and (4) C_w is the specific heat capacity of the water. The temperature t_* may always be calculated at an assigned pressure P_* from the data in [6] depicted in Fig. 2.

Steam generation. By virtue of the similar densities of ice and water, the first stage takes place practically under isochoric conditions. On completion of the first stage all the heat Q reaching the steam-and-water volume is expended on the generation of steam. When P < 5 MPa the density of the steam generated ρ_s may be approximated calculated by the formula

$$\rho_s = \rho_w P/(1650\ P_{atm}), \tag{5}$$

where ρ_w is water density (a constant), P_{atm} is atmospheric pressure. It may readily be seen that ρ_s is 10-100 times less than ρ_w. As a result the generation of steam results in a considerable increase of the volume V occupied by the steam-and-water mixture. This volume may be depicted in the form:

$$V = \frac{M}{\rho} \equiv M\left[\frac{1}{\rho_w} + x\left(\frac{1}{\rho_s} - \frac{1}{\rho_w}\right)\right], \tag{6}$$

where ρ is the density of the steam-and-water mixture, x is the mass content of the steam.

Between the time τ_1 and the time $\tau > \tau_1$, the volume of steam and water additionally receives the following amount of heat:

$$\Delta Q = \frac{2\lambda_0 t_0 S}{\sqrt{\pi a_0}}\left(\sqrt{\tau} - \sqrt{\tau_1}\right),$$

and the corresponding mass of steam is $xM = \Delta Q/r_*$. Consequently

$$x = \frac{2\lambda_0 t_0 S}{\sqrt{\pi a_0}\, M r_*}\left(\sqrt{\tau} - \sqrt{\tau_1}\right), \quad \tau > \tau_1. \tag{7}$$

The mean thickness of the volume occupied by the steam-and-water mixture is

$$h = M/(S\rho).$$

All the water will be converted to steam by the moment τ_s defined by the condition $x = 1$. We find from (7)

$$\tau_s = \tau_1 \left(1 + \sqrt{\frac{\pi a_0}{\tau_1}} \frac{Mr_*}{2\lambda_0 t_0 S}\right)^2.$$

The deformation of the layer of lava that acompanies the considerable increase in volume in the second stage of a phreatic explosion may result in the formation of fissures and channels in the lava with the result that the third stage of the process, escape of the steam-and-water mixture from beneath the lava into the atmosphere evidently commences when $\tau = \tau_2 < \tau_s$.

Phreatic explosion. The escape time is considerably shorter than τ_1 and τ_2. It is therefore possible to disregard the additional supply of heat from the lava to the steam-and-water mixture in the course of the explosion. Let D be the mean equivalent diameter of the channel formed in the layer of lava, and let x_2 be the mass content of steam in the steam-and-water mixture beneath the lava mass at the moment of breakout τ_2 (the escape period). Let us additionally introduce further notations: G, the mass discharge of the steam-and-water flow; x_{atm}, the mass content of the steam in the flow at the outlet of the escape channel; W_{atm}, the rate of escape of the steam-and-water flow into the atmosphere; r_{atm}, the latent heat of evaporation under atmospheric conditions; t_{atm}, the boiling point of water at atmospheric pressure P_{atm}. Disregarding the kinetic energy of the steam-and-water mixture in the chamber beneath the layer of lava, let us write the equation for the conservation of the total energy of the flow [8, 10] in a form that relates the characteristics of the two-phase mixture in the chamber and at the outlet from the escape channel:

$$C_w(t_{atm} - T_{atm}) + x_{atm} r_{atm} - x_2 r_* + \frac{W^2_{atm}}{2} = 0. \qquad (8)$$

Similarly, averaging the hydraulic losses along the canal we may write, in accordance with [10]:

$$P_* - P_{atm} = \frac{G}{f}\left[1 + \frac{\zeta H}{4D}\right] W_{atm}, \tag{9}$$

where ζ is the coefficient of hydraulic resistance in the generalized formula of Darcy and Weisbach [6], $f = \pi D^2/4$ is the mean cross-sectional area of the channel.

Under atmospheric conditions it follows from formulas (5) and (6) ($P = P_{atm}$) that:

$$\rho_s = \rho_w/1650, \quad \rho \approx \rho_w/1650 x_{atm}).$$

Consequently

$$W_{atm} = (1650\, x_{atm} G)/f_{w}). \tag{10}$$

Equations (8) - (10) are a system of three equations with respect to the three unknowns G, W_{atm}, x_{atm}. Its solution may readily be found

$$G = f(P_* - P_{atm})/[W_{atm}(1 + 0{,}25\,\zeta H/D)];$$

$$W_{atm} = \sqrt{C_w(t_* - t_{atm}) + x_2 r_*} \Bigg/ \sqrt{\frac{1}{2} + \frac{\rho_w r_{atm}(1+0{,}25\zeta H/D)}{1650\,(P_* - P_{atm})}}; \tag{11}$$

$$x_{atm} = [C_w(t_* - t_{atm}) + x_2 r_*] \Bigg/ \left[\frac{1650\,(P_* - P_{atm})}{2\rho_w(1+0{,}25\zeta H/D)} + r_{atm}\right].$$

Using the calculation formulas (11) the duration $\Delta\tau_{exp}$ of the phreatic explosion may immediately be calculated by the obvious relationship

$$\Delta\tau_{exp} = M/G. \tag{12}$$

This concludes the approximate mathematical description of all the stages of a phreatic explosion.

It should be noted that the time of the commencement of escape τ_2 is the main undetermined quantity in the calculation formulas derived, and that its precise value is dependent on a great many random factors. It is evident that τ_2 must be greater than τ_1 and can scarcely exceed τ_s. Another quantity that is difficult to predict is the diameter of the escape channel D and the coefficient of hydraulic resistance ζ. Admittedly, it may be assumed from the data of actual observations [2] that $D \lesssim H$, and it may be found from [1] that the most probable values of the coefficient ζ are in the range 0.04 - 0.06. Consequently, in (11) the ratio $(\zeta H)/(4D) > 0.01$, and the effect of possible errors in its calculation on calculation of the quantities G, W_{atm} and x_{atm} is evidently negligible.

The plane sectional area S may also alter during the second stage. At this time τ_s should decrease. The proposed model also does not make allowance for the fact that the steam-and-water flow ejected may be loaded with ash and lava fragments. Naturally, an enclosed chamber beneath lava is not the only condition in particular cases for the formation of phreatic explosions. For example, there might not be any melting of the ice during the first stage of the explosion should there be an inflow of water from outside. In such a case the hermetic sealing of the chamber will be created by hydrostatic pressure in the channel where the stream passes beneath the lava flow.

Let us now consider a specific example of the calculation of a phreatic explosion. Let us take as input data quantities similar to those previously discussed in [2]: P_{atm} = 0.01 MPa (1 atm); g = 9.81 m/s^2; M = 5000 kg; S = 20 m^2; H = 10 m. That these values are realistic is confirmed by our observations during the eruption of the Forecast outbreak of Klyuchevskoi Volcano in 1983; the dimensions of the ice bodies are typical for a zone of "dead" and buried ice of a volcanic structure; in a number of cases the lava flows are 10 m or more thick.

Let us take the properties of the lava (basalt) from [7]: ρ_0 = 2800 kg/m^3; λ_0 = 2/5 W(m.$^\circ$C); C_0 = 0.8 kJ/(kg.$^\circ$C); $a_0 = \lambda_0/(\rho_0 C_0) = 1.1 \times 10^{-6}$ m^2/s; t_0 = 1200° C.

Consequently, P_* = 0.37 MPa ($\approx$ 3.7 atm); t = 140° C; r_* = 2150 kJ/kg.

In addition, P_{atm} = 0.1 MPa; t_{atm} = 100° C; r_{atm} = 2260 kJ/kg; C_w = 4.2 kJ/kg; ρ_w = 1000 kg/m^3. The latent heat of melting of the ice r_i = 335 kJ/kg.

From formula (4) we find $\tau_1 = 553$ s (9.2 min). The time taken for conversion of all the water into steam is $\tau_s = 4480$ s (75 min). The estimate $9.2 < \tau_2 < 75$ min agrees in order of magnitude with the data in [2, 4] to the effect that explosions were observed within a few tens of minutes after submergence of the ice by the lava, although such a comparison is no more than provisional in the case under consideration.

Let us provisionally assume for the subsequent calculations that $\tau_2 = 40$ min (2400 s). Let us find $x_2 = x(\tau_2) = 0.15$ by formula (7).

Let D = 1.5 m, and $\zeta = 0.06$. In that case

$$\frac{\zeta H}{4D} = 0.1; \quad f = 1.77 \text{ m}^2,$$

and, in accordance with the formulas (11), $W_{atm} = 284$ m/s; $G = 1.53 \times 10^3$ kg/s; $x_{atm} = 0.2$. The escape time $\Delta\tau_{exp} = 3.3$ s.

Some results of the calculation of the dependence of W_{atm} and G/f on the thickness of lava flows are given in Fig. 3. Similar graphs may also be compiled for calculation of the other parameters of a phreatic explosion.

A mathematical model has been constructed and some of the quantative characteristics of secondary explosions arising when a lava flow covers small isolated masses of ice have been calculated. The basic assumption was that the interaction of the lava with the ice takes the form of three successive and independent stages: melting of the ice, evaporation of the water at constant pressure, and escape of the steam-and-water mixture along a channel developing in the lava roof.

The model makes it possible to estimate the energy of the explosion, and the rate and duration of the escape of the steam-and-water mixture as a function of the size and shape of the isolated mass of ice and of the characteristics of the lava flow covering it, and to estimate the delay of the phreatic explosion relative to the time when the ice covered the lava. The theoretical estimate of the delay is in satisfactory agreement with the results

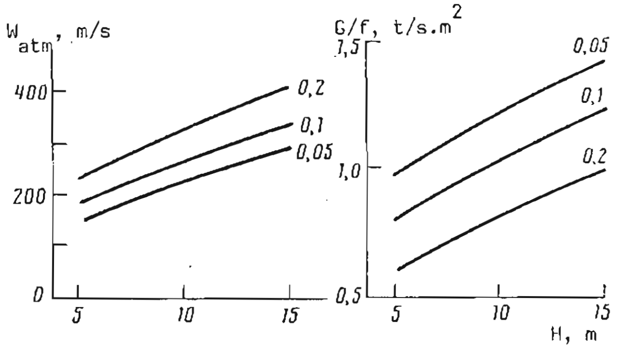

Fig. 3. Dependence of the rate of escape of vapor into the atmosphere (W_{atm}) and of the specific mass flow of water vapor (G/f) on the thickness of the ice cover (H).

of observations. It is desirable that subsequent trials of the model should be based on observational data on the height and power of secondary outbursts, having first established the theoretical connection of these parameters with the rate of escape of the steam-and-fluid mixture. Verification of the other conclusions may need special research.

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