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EXPERIMENTAL MODELING OF VOLCANIC EJECTION WITH FORMATION OF MINERAL FILAMENTS

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We consider the process of formation of mineral filaments as a result of volcanic ejection of lava. An experimental setup that models this process is described. A mathematical model of the motion of melt film in the skull layer of a cylindrical channel is constructed.

Skull formed by melted mineral appears on the walls of the crater in volcanic ejection. This can be accompanied by the formation of glassy filaments ("Pélé's hair") from the melt. This phenomenon was observed when a lava cauldron such as Kilauea volcano in Hawaii was active. The temperature deep inside the cauldron attains 1450 K. The liberated gases above the open surface of it attain a temperature of up to 1650 K (exothermic reactions of burning of hydrogen and other combustible gases). Here the appearance of mineral filaments (fibers) is governed by:

1) the presence of melted mineral material whose temperature interval of fiber formation is equal to the temperature of incandescent gases or smaller;

2) the thermophysical characteristics of the melt: viscosity (η) and surface tension (σ) and their ratio (η/σ) – all ensuring a stable possibility for formation of fibers from the given mineral;

3) the high-temperature gas flow, whose velocity is sufficient for drawing fibers from the melt (not lower than 50 m/sec), and the extent of the zone of its effect on the jets of the melt that preserves the viscosity, allowing the drawing of fibers.

An analysis of the processes of fiber formation from a melt of minerals shows that the main factor without which the process of the appearance of the fibers is impossible is not the drawing of the fibers themselves, but rather spouting of the melt and its separation into small jets formed on collision of a jet of an incandescent flow of gases with the melt of the mineral [1].

The preparation of a melt of rocks under laboratory conditions and its interaction with a high-temperature gas flow were realized on spaced portions of a single plasma flow.

Powdered materials of rocks were melted in the high-temperature (2500–3000 K) portion of a plasma jet and were fixed on the walls of the channel in the form of skull, whose melted portion, interacting with the plasma flow, moved to the exit from the channel.

After interaction with the powdered raw material, the temperature of the plasma jet was decreased to 1500–1700 K, and at the exit from the channel, interaction between the melt of rocks and the high-temperature gas flow was ensured; this interaction is adequate for the process of ejection of gas flows from the neck of a volcano, on whose walls skull from magma is formed.

The experimental setup is depicted in Fig. 1.

During the operation of the experimental setup a plasma-forming gas heated in a plasmatron to a temperature of 2500–3500 K enters a reactor into which mineral powder is fed by means of a transporting gas. The mineral powdered raw material was made of rocks ground to fractions of 30–100 μm of the main composition: dolerites, metadiabases, amphibolites available in the crystalline foundation of the South of Belarus – 69 kinds of specimens in all [2].

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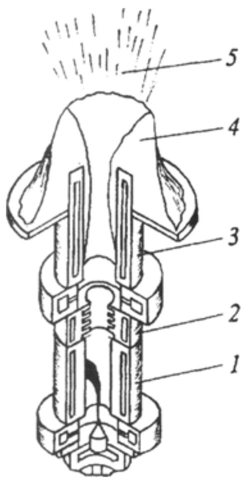


Fig. 1. Experimental setup to model volcanic ejection: 1) plasmatron; 2) turbulizer; 3) reactor; 4) melt; 5) fibers.

Fig. 2. Photograph of fibers produced from powdered raw material. ×1000.

The bulk of the powder melts and "freezes" on the inner surface of the reactor. The skull formed from the melt of the mineral is subjected to the effect of a high-velocity turbulent flow, as a result of which local instabilities appear on the surface of the melt in the form of waves and small jets, which subsequently, under the action of the same gas flow, are drawn as fibers.

The part of the melt that is not entrained by the plasma flow as separate fibers or drops flows out of the reactor nozzle and spreads over its outer surface, creating "skulls."

An analysis of the fibers, skulls, and nonfibrous inclusions obtained as a result of experiments showed that out of 69 specimens of various minerals of rocks only three of them did not form fibers (these were amphibolized dolerite, hornblendite, and microdiorite). In all remaining cases stable production of fibers was observed, both superfine (from 1 to 3 μm in diameter) and rough ones (with a diameter of 16–30 μm). The length of the fibers obtained was in the range from 0.5 to 250 mm (Fig. 2).

A study of the melt surface that comes in contact with the high-temperature gas flow shows the presence of transverse waves that are formed in the channel and precisely from which the drawing of fibers occurs (Fig. 3).

The thickness of the skull layer along the length of the plasma reactor increases from the place of feeding of the powdered material to the exit nozzle of the reactor. But its magnitude depends on many factors, viz., the geometric parameters of the reactor and the plasmatron, electric-arc power, flow rate of the plasma-forming gas, temperature of the plasma flow, its velocity, consumption of powdered material, thermophysical characteristics of its melt, and the intensity of cooling of the reactor walls.

Analysis of the processes of heat and mass exchange in a plasma reactor with a skull layer when microfibers were obtained from powdered materials is considered in detail in [3].

In simulating the process of ejection of magma through the channels of magma ascent, it is necessary to take into account the effect exerted on the melt film by gravitational forces, which can substantially influence the thickness and configuration of the skull layer in the case of vertical positioning of the reactor.

To carry out calculations, we adopted the following model of flow in the near-nozzle zone of the plasma reactor: in the section of the channel of a vertically positioned cylindrical reactor with inner radius R_s turbulent discharge of a plasma flow occurs. Affected by friction and gravitational forces, the melt film moves over the wall of the reactor upward between the plasma flow and the surface of the melt. Here one observes the presence of large radial gradients of the temperature and, accordingly, the viscosity of the melt.

The stress on the surface of the melt as a result of the friction of the plasma flow is

$$\tau = \frac{\xi \rho_p \bar{\vartheta}^2}{8}, \tag{1}$$

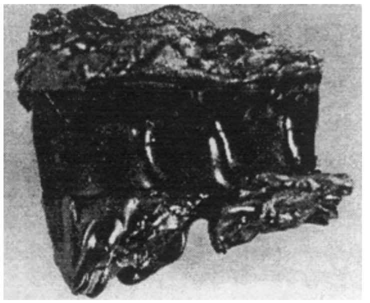


Fig. 3. Formation of transverse waves on the surface of the melt interacting with the plasma flow (the material is fine granular metadiabase).

where generally $\xi = 0.3164\mathrm{Re}^{-0.25}$ (Blasius equation). With account for the roughness of the channel wall we can assume [4] that $\xi = 0.03$ and that it is independent of the number Re.

The gravitational force that acts on the melt and is normalized to unit melt surface area is

$$K = \frac{\rho_{\mathrm{liq}} g \left(r^2 - R_1^2\right)}{2r}. \tag{2}$$

Comparing these two forces, normalized to unit melt surface area, it is possible to find conditions where the gravitational force exerts a substantial influence and where this effect can be neglected. Substituting into Eqs. (1) and (2) the characteristic parameters of the process, it is possible to conclude that gravitational forces start to exert a substantial effect on the motion of the melt film when the thickness of the film exceeds 0.1 mm. This effect can be neglected when the thickness of the melt film is smaller. When the film has a thickness of 2 mm or more, the gravitational effect becomes more substantial than the effect of the plasma flow.

The heat flux from the plasma to the coolant through an annular section of the reactor of length Δx [5] can be found from the formula

$$Q = \frac{2\pi \Delta x \left(T_{\mathrm{p}} - T_{\mathrm{c}}\right)}{\frac{1}{\alpha_1 R_1} + \frac{1}{\lambda_{\mathrm{liq}}} \ln \frac{R_{\mathrm{s}}}{R_1} + \frac{1}{\lambda_{\mathrm{s}}} \ln \frac{R_{\mathrm{w}}}{R_{\mathrm{s}}} + \frac{1}{\lambda_{\mathrm{w}}} \ln \frac{R_{\mathrm{c}}}{R_{\mathrm{w}}} + \frac{1}{\alpha_2 R_{\mathrm{c}}}}. \tag{3}$$

The heat exchange coefficients α_1 and α_2 are determined on the basis of a dimensionless expression taken from [6]:

$$\mathrm{Nu} = 0.021\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43} \left(\frac{\mathrm{Pr}}{\mathrm{Pr_w}}\right)^{0.25} \varepsilon_l\, \varepsilon_\varphi\, \varepsilon_t. \tag{4}$$

For air $p = 1$ bar, $T = 1400°\mathrm{C}$, $\mathrm{Pr}^{0.43}\left(\frac{\mathrm{Pr}}{\mathrm{Pr_{st}}}\right)^{0.25} \approx 0.86$, and therefore the following expression is quite acceptable for engineering calculations:

$$p = 1\ \mathrm{bar},\ T = 1400\ {}^{\circ}\mathrm{C},\ \mathrm{Pr}^{0.43}\left(\frac{\mathrm{Pr}}{\mathrm{Pr_w}}\right)^{0.25} \approx 0.86,$$

$$\mathrm{Nu} = 0.018\,\mathrm{Re}^{0.8}\, \varepsilon_l\, \varepsilon_\varphi\, \varepsilon_t. \tag{5}$$

Formulas (4) and (5) contain coefficients that take into account the initial portion of the flow, flow twisting, and the temperature factor, which respectively are equal to [5, 7, 8]

$$\varepsilon_l = \left(0.86 + 0.54 \left(\frac{2R_1}{x}\right)^{0.4}\right),\quad \varepsilon_\varphi = \left(1 + 0.58\left(\tan\varphi - 0.1\right)^{0.8}\right)^{0.8} \quad \text{and} \quad \varepsilon_t = \left(\frac{T_{\mathrm{p}}}{T_1}\right)^{0.36},$$

with decay of twisting along the channel length being taken into consideration [7]:

$$\frac{\tan \varphi}{\tan \varphi_0} = \exp \left(- (0.44 + 0.03 \tan \varphi_0) \left(\frac{x}{2R_1} \mathrm{Re}^{-0.25} \right) \right) .$$

It is noted in [7] that the degree of twisting leads to a decrease in Re_{cr} of transition to a turbulent flow: when $\tan \varphi_0 = 1$, $\mathrm{Re}_{cr} = 800$; when $\tan \varphi_0 = 10$, $\mathrm{Re}_{cr} = 100$.

Based on expression (3), the temperature T at an arbitrary point r of the melt is equal to

$$T = T_1 - \frac{\Delta Q}{2\pi \, \Delta x \, \lambda_{\mathrm{liq}}} \ln \left(\frac{r}{R_1} \right) . \tag{6}$$

According to Newton's law of friction

$$\tau - K = - \mu \frac{du}{dr} . \tag{7}$$

For reasons given in [2], the dependence of the viscosity of the mineral on the temperature is approximated by the expression

$$\mu = 0 \quad \text{when} \quad T \le T_s , \quad \mu = A \exp(- BT) \quad \text{when} \quad T > T_s , \tag{8}$$

where A and B are empirical coefficients that depend on the kind of material.

We introduce the notation

$$C = \frac{\Delta Q B}{2\pi \, \Delta x \, \lambda_{\mathrm{liq}}} .$$

Then, on the basis of Eqs. (8) and (6) we have

$$\mu = A \exp(- BT_1) \exp \left(C \ln \left(\frac{r}{R_1} \right) \right) .$$

The term $A \exp(-BT_1) = \mu_1$ is equal to the viscosity of the melt on the surface of the film, i.e., on the interface between the plasma flow and the melt film at the temperature T_1. Hence

$$\mu = \mu_1 r^C R_1^{-C} . \tag{9}$$

The velocity of the moving melt at an arbitrary point r with account for Newton's law of friction is determined from the expression

$$du = - \frac{\tau - K}{\mu} dr . \tag{10}$$

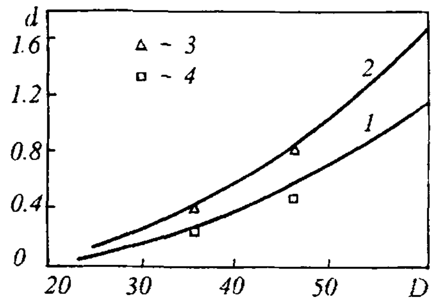
Substituting the relation for viscosity (9) into Eq. (10), we obtain

$$du = - \frac{\tau - K}{\mu_1} R_1^C r^{-C} dr . \tag{11}$$

Having integrated Eq. (11) with account for the boundary condition $u = 0$ at $r = R_s$, we find

$$u = \frac{R_1^C}{\mu_1} \left(\frac{\tau_1}{1 - C} (R_s^{1-C} - r^{1-C}) - \frac{\rho_{\mathrm{liq}} g}{2} \left(\frac{R_s^{2-C} - r^{2-C}}{2 - C} + R_1^2 \frac{R_s^{-C} - r^{-C}}{C} \right) \right) , \tag{12}$$

where $\tau_1 = \xi \rho_p \bar{\vartheta}^2 / 8$ is the shear stress on the surface of the melt film [4].



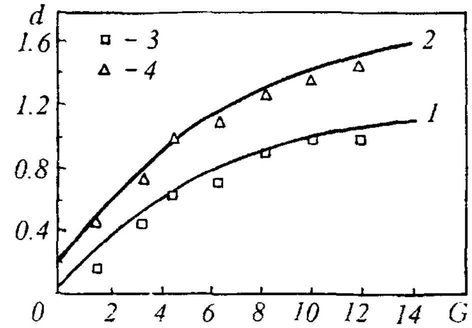


Fig. 4. Thickness of the melt film vs. discharge of powder for different diameters of the reactor: 1, 2) calculation, $D = 30$ and 40 mm; 3, 4) the same, experiment. d, mm.

Fig. 5. Thickness of the melt film vs. diameter of the reactor for different discharges of powdered raw material: 1, 2) calculation, $G = 2$ and 7 g/sec; 3, 4) the same, experiment.

The flow rate of the material through the melt film in the horizontal section of the reactor is determined by the integral

$$G = 2\pi \rho_{\text{liq}} \int\limits_{R_1}^{R_s} u r dr \,. \tag{13}$$

Substituting Eq. (12) into Eq. (13) and integrating, we find

$$G = 2\pi \rho_{\text{liq}} \frac{\tau_1 R_1^C}{\mu_1 C} \left(\frac{R_s^{2-C} - R_1^{2-C}}{2 - C} - \frac{R_s^2 - R_1^2}{2} R_s^{-C} \right) - \frac{\pi \rho_{\text{liq}}^2 g R_1^C}{\mu_1} \times$$
$$\times \left(\frac{R_s^{2-C} (R_s^2 - R_1^2)}{2 (2 - C)} - \frac{R_s^{4-C} - R_1^{4-C}}{(2 - C)(4 - C)} + R_1^2 \left(\frac{R_s^{-C} (R_s^2 - R_1^2)}{2C} - \frac{R_s^{2-C} - R_1^{2-C}}{C (2 - C)} \right) \right) . \tag{14}$$

Having supplemented Eq. (14) with the relations $\lambda_p = f(p, T)$, $\mu_p = f(p, T)$, and $\rho_p = f(p, T)$, taken from [9], and having solved the resulting system of equations for the variable R_1, we can determine the thickness of the melt on the inner surface of the reactor for a given flow rate of the material G and known geometric parameters. Having substituted the value obtained into Eq. (3), we find the distribution of the temperatures in the melt film.

Comparing the results of numerical calculation with experimental data shows their good coincidence in the range of the parameters investigated (Figs. 4 and 5).

The results obtained can be used in analysis of the processes of ejection of magma and determination of the temperature fields of the neck of a volcano to perform predictive calculations.

The investigations carried out also have a purely applied aspect, namely, testing of the indicated rocks to find the possibility of their application as a single-component raw material for producing high-temperature fibrous heat-insulating materials.

On the basis of the work carried out at the Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute" of the National Academy of Sciences of Belarus a pilot plant is being constructed to obtain mineral ultra- and superfine fibers from powders of rocks by means of an electric-arc plasma.

It is advantageous to continue experimental modeling of volcanic ejection of glassy filaments ("Pélé's hair") from magma melt in the direction of increasing the power of the setup, more detailed study of the processes of formation of glassy fibers, and extension of the region of investigations.

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NOTATION

Q, heat flux in the radial direction, W; T_p, mean temperature of the plasma flow averaged over the radius of the reactor, K; T_l, T_s, T_c, temperature of the surface of the melt film, on the solid material–melt interface, and of the cooling liquid, K; α_1, heat transfer coefficient on the interface between the plasma flow and the melt film, W/(m^2·K); α_2, heat transfer coefficient on the boundary between the reactor wall and the cooling liquid, W/(m^2·K); λ_{liq}, λ_s, λ_w, coefficients of heat conduction of the melted material, the solid material, and the reactor wall, J/(m·sec·K); R_l, R_s, R_w, R_c, radial coordinates of the surface of the melt film, the interface between the solid phase of the material and the melt, the inner wall of the reactor, and the boundary between the reactor wall and the cooling liquid, m; μ, μ_l, dynamic viscosity of the melt at an arbitrary point of the melt r and on the surface of the film, N·sec/m^2; u, velocity of the melt flow, m/sec; τ, surface tension, kg/(m·sec^2); K, gravitational force normalized to unit film surface area of the melt, kg/(m·sec^2); g, free-fall acceleration, m/sec^2; ρ_{liq}, density of the melt, kg/m^3; p, static pressure in the plasma flow, N/m^2; ρ_p, density of the plasma, kg/m^3; $\bar{\vartheta}$, plasma flow velocity averaged over the reactor cross section, m/sec; ξ, friction factor of the plasma flow in the cylindrical channel; tan φ, tangent of the angle of twisting of the plasma flow, equal to the ratio of the circumferential to the axial velocity; tan φ_0, tangent of the angle of twisting of the plasma flow at $x = 0$; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number; Pr_w, Prandtl number at the temperature of the reactor wall; G, flow rate of the material through the melt film, kg/sec; x, axial coordinate, m; r, radial coordinate, m. Subscripts: p, plasma; l, surface of the melt film; liq, melt; s, melt–skull interface; w, steel wall–skull interface; c, cooling liquid.

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