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HEAT TRANSFER IN A GEOTHERMAL SYSTEM OF MUTNOVSKY VOLCANO: THE INFLUENCE OF THE FORM, DISCHARGE OF MAGMA CHAMBER DEGASSING AND ROCKS PERMEABILITY

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ABSTRACT

The process of heat transfer during the fluid filtration in rocks of magma-geothermal system of Mutnovsky volcano was studied by the method of numerical simulation. The distribution of temperature, pressure, fluid phase state and its phases' velocities were obtained. The character of dependence of the calculated geothermal gradient and geometry of supercritical fluid region on the form of magma chamber, the permeability of fluid-conductive zone and degassing discharge was determined.

INTRODUCTION

The processes of heat-and-mass transfer in geothermal systems in the zones of natural permeability and in the process of natural heat carrier extraction to obtain geothermal energy are the subject of studying of mining thermal physics.

Nowadays geothermal resources are used to get heat supply, produce electric power, and extract valuable mineral components (boron, zinc, silica, sodium chloride) and in balneology. In practice the overwhelming part of geothermal resources is used by means of the development of natural deposits of geothermal heat carrier as liquid, liquid-vapor mixture or dry and even superheated steam. During last 30 years the researchers from the USA, USSR, Great Britain and Japan have developed the technology to extract heat of so-called dry rocks (or petrageothermal resources) by means of circulating systems production of the exploitation and injection wells. Since 2002 Australian company Geodynamic Ltd. has been successfully developing petrogeothermal resources of Cooper Basin deposit which is the largest one of underground heat resources on the continent. It is one of the first world commercial projects of such kind. By the end of 2015 nine units of geothermal electric power plants with a total capacity 450 MW are planned to be set in operation. Each block will use well system of five exploitation and four injection wells with mean depth 4.2 km. The temperature of the bottom of drilled exploitation well is 250^0C.

Moreover the interest for potential use of heat and mineral resources of near-surface magma chambers has been increasing.

There are several magma-geothermal systems including near-surface magma chambers with considerable resources of heat energy in Kamchatka. Potential heat resources of Mutnovsky magma-geothermal system (Kamchatka) amount to 2 GW. Heat efflux by Mutnovsky volcano fumaroles is 1.2 GW. The prospects of the development of Mutnovsky volcano resources were considered in the project of geotechnological development of Mutnovsky magma-geotechnological system for commercial producing of chemical raw materials and ore constituents 20 years ago (Trukhin, 2003). Near-surface magma chamber is considered to be the source of Mutnovsky volcano heat activity. Recently Mutnovsky volcano is considered to be a potential object to obtain heat and electric power. Drilling and geophysical studying were not made within volcano edifice. There isn't any generally accepted conceptual model of Mutnovsky magma-geothermal system. Numerical simulation is one of the available methods to calculate key parameters of heat transfer and heat resources. In conditions of imperfection of initial information the simulation in possible range of input parameters and during different initial and boundary conditions allows to determine the range of the system full-sized characteristics. In (Pashkevich and Taskin, 2007; Pashkevich and Taskin, 2007; Pashkevich and Taskin, 2007) it was studied how calculated process characteristics depended on the following parameters: the type of magma chamber (cooling or constantly convecting), depth of its occurrence, configuration of initial geoisotherms configuration near its surface and dominant type of heat transfer (conductive, convective) in rocks surrounding fluid-conductive zone. Present paper is the continuation of (Pashkevich and Taskin, 2007;

Pashkevich and Taskin, 2007; Pashkevich and Taskin, 2007). The aim of the work is to determine the influence of magma chamber, permeability of fluid-conductive zone, rate of magma degassing on the process parameters in conditions where conductive heat transfer is dominant.

SET OF A PROBLEM (FORMULATION OF THE PROBLEM)

The object

Mutnovsky volcano is a large active volcanic edifice with 2323 m maximum height (Vakin et al, 1966). The fumarole fields – Donnoye and Verkhneye – are located in the south-western and north-eastern craters. The most intensive fumarole's activity is in the crater called Active crater.

Schematization of environmental conditions and geometry of model region

The fumaroles of Active crater, Donnoye and Verkhneye fields are located on the line coinciding with the line of proposed fracture of the north-eastern direction discovered by Ye.A. Vakin in 1966 (Vakin et al, 1966). Almost all hydrothermal manifestations of volcano region are located along the line of the fracture. This line goes along stretching fracture renewed during the irruption of 2000. On this basis Mutnovsky magma-geothermal system of Mutnovsky volcano is considered to be a fracture-and-porous flat vertical zone which thickness is equal to a lateral dimension of Active crater (150 m). The flat band stretches to the northern-east and passes through the centre of Active crater. The surface of Active crater is hydraulically connected with magma chamber with the help of fluid-conductive zone formed by the system of contraction fractures appeared as a result of crater cooling (Figure.1*a*).

Two-dimensional (profile) model covering 18 km in plan is used. The depth of model region is 2 km.

The surface form of magma chamber of Mutnovsky volcano is unknown. The surface of cooling and constantly convecting chambers is defined by coupled processes of heat transfer, filtration, evaporation, condensation, melting, degassing, magma crystallization and forming of contraction fractures. Three probable chamber forms are mostly considered in publications. They are horizontal (lens), vertical ellipsoid (diapir) and sphere (Fedotov, 2006). In calculations the chamber was assigned as horizontal and vertical ellipse with semiaxes 2.5 and 1.5 km respectively and its area was close to a sectional area of sphere with the volume equal to the volume of sphere chamber calculated in work (Utkin et al, 2005). Prescribed fluid rate appearing as a result of magma degassing at the point of entry into the fluid-conductive zone was distributed in accordance with a number of grid layers in fluid-conductive zone in direction of *y* axis.

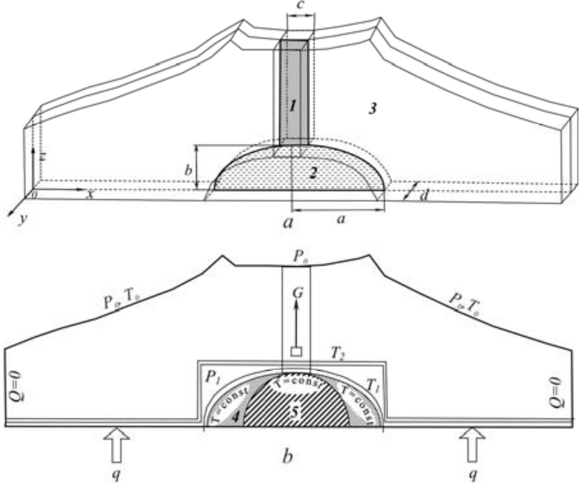

Figure 1. Schematization of model region and boundary conditions. *1* – fluid-conductive zone; *2* – magma chamber; *3* – surrounding rocks; *4* – magma chamber in a form of horizontal ellipse; *5* – magma chamber in a form of vertical ellipse; *a* and *б* – long and short semiaxes of magma chamber; *c* – width of fluid-conductive zone; *d* – model thickness; *q* – regional thermal flow; *Q* – mass fluid rate on the side boundaries; *G* – fluid rate at the point of entry into fluid-conductive zone as a result of magma degassing; P_0 – atmospheric pressure; T_0 – temperature on the edifice surface (10°C); P_1, T_1 and T_2 – initial isobars and geoisotherms in vicinity of magma chamber.

Mathematical model

Recently numerical simulation of hydrothermal systems forming over intrusions and also of volcano-geothermal systems has been carried out with the help of software system (computer model) HYDROTHERM (Hayba and Ingebritsen, 1994; Hayba and Ingebritsen, 1997; Hurwitz et al, 2003). The software was specially worked out for three-dimensional simulation of multiple flow of water and heat in permeable mediums with a temperature and pressure range of 0–1200°C and 0.05–1000 MPa respectively; this range is appropriate to the conditions of such geosystems. HYDROTHERM was used to simulate magma-hydrothermal and volcano-hydrothermal systems of the Cascade Range volcanoes (USA) (Hurwitz et al, 2003). In the whole model region the equations of mass and energy conservation in permeable mediums are solved by the method of finite difference (Hayba and Ingebritsen, 1994):

$$
\frac{\partial(n\rho_f)}{\partial t}-\nabla\cdot\left[\frac{kk_{rs}\rho_s}{\mu_s}(\nabla p-\rho_s g)\right]-
\nabla\cdot\left[\frac{kk_{rw}\rho_w}{\mu_w}(\nabla p-\rho_w g)\right]-q_m=0 \qquad (1)
$$

$$
\frac{\partial}{\partial t}\left[n\rho_f h_f+(1-n)\rho_r h_r\right]-\nabla\cdot\left[\frac{kk_{rs}\rho_s h_s}{\mu_s}(\nabla p-\rho_s g)\right]-
\nabla\cdot\left[\frac{kk_{rw}\rho_w h_w}{\mu_w}(\nabla p-\rho_w g)\right]-\nabla\cdot K_m\nabla T-q_h=0 \qquad (2)
$$

where n is porosity; ρ_f, ρ_s, ρ_r are density of fluid, steam and rocks; k is an intrinsic permeability tensor, k_{rs} is relative permeability to steam, k_{rw} is relative permeability to liquid water, μ_s, μ_w are dynamic viscosity of steam and water; K_m is thermal conductivity; h_f, h_r are enthalpy of fluid and rocks; q_m and q_h are mass flow rate per unit volume and heat flow per unit volume respectively. The last two values are used to assign an explicit rate of magma degassing at the point of entry into fluid-conductive zone and regional heat flow on a lower boundary of the model region.

The fumarole's fluid of Active crater has mainly aqueous composition (98-99 mole % H_2O) (Trukhin, 2003). The geothermal fluid within the volcano edifice and fluid degassing from magma are also considered to be close to clear water in accordance with their thermophysical properties. In the HYDROTHERM model the properties of clear water in areas of saturated liquid, wet and superheated steam and also in supercritical region were tabulated.

Initial and boundary conditions

An average geothermal gradient 30^{o}C/km and hydrostatic distribution of fluid pressure were assigned in rocks surrounding magma chamber as initial condition.

On upper boundaries outside of Active crater atmospheric pressure and 10^{o}C temperature were assigned. On the surface of Active crater atmospheric pressure was given. On lower boundary of simulation area outside of the chamber a regional heat flow 80 mW/m^2 was given. On the model sides the flow absence was maintained. The temperature 900^{o}C of a constantly convecting magma in the chamber was assigned, that corresponds to the conditions accepted in (Utkin et al, 2005). Near the chamber surface initial rectangular geoisotherms and isobars (Figure 1*b*, T_1 and P_1) with numerical values equal to initial calculated ones outside of the chamber were given. This type of initial conditions corresponds to one of the possible cases of forming rectangular surface (lens) of chamber at initial time with further fusion of edge parts up to isometric – ellipsoid. Such initial conditions can be applied because melting rate of rocks of chamber surface is lower than geoisotherms rate.

Model parameters

Main parameter determining the dynamics of heat and hydrodynamic fields is permeability of the rocks of fluid-conductive zone and rocks surrounding this zone. Hydrogeological situation of volcano edifice has been studied insufficiently. Real values of rocks permeability and porosity are unknown. Rocks permeability of fluid-conductive zone varied from 0.001 up to 1 mD. Taking into account that vertical direction of fractures of fluid-conductive zone is more probable the permeability of its rocks in vertical direction was assigned some higher then in horizontal one (Table 1). The permeability of rocks surrounding fluid-conductive zone was assigned 0.001 mD. As it was shown in (Cathles, 1977), when rocks permeability is less then 0.05 mD we can ignore an influence of fluid convection and consider conductive heat transfer to be dominant. Density, heat capacity and thermal conductivity of rocks were given constant and equal to averaged values for volcanic and metamorphic rocks: 2500 kg/m^3, 1 kJ/kg·K, 2 W/m·K, porosity 10%.

Table 1. Models parameters

Model	Permeability of fluid-conductive zone, mD		Chamber form	Fluid rate, kg/s
	In horizontal direction	In vertical direction		
B13	0.1	1.0	Horizontal ellipse	3
B14	-«-	-«-	-«-	600
B15	-«-	-«-	Vertical ellipse	3
B16	0.001	0.001	-«-	-«-

Fumarole gases rate of Active crater is 500 kg/s (Vakin et al, 1966). Though the fraction of magma components in total fumarole rate was not determined magma fluid rate at the point of entry into fluid-conductive zone varied from 3 up to 600 kg/s. Fluid enthalpy at the point of entry into fluid-conductive zone was determined in accordance with the diagram of water steam under the temperature of 900^{o}C and it was 4400 kJ/kg in calculated pressure range.

RESULTS

Influence of rate of magma degassing

The calculations in accordance with the models of equal rocks permeabilities but different degassing rates were made for magma chamber in a form of horizontal ellipse (Figure 2). Figure 2 shows if degassing rate increases the zone of rocks heated up to 400^{o}C and more becomes wider; supercritical fluid region and calculated geothermal gradient in the rocks surrounding fluid-conductive zone increases too. The zone of high pressure (ellipse closed isobar, Figure 2*b*) is formed under a high (600 kg/s) degassing rate in fluid-conductive zone and its environs. Under a low rate (3 kg/s, Figure 2*a*) in a lower part of fluid-conductive zone there is the flow of supercritical fluid changing in a flow of superheated steam owing to filtration loss and heat transfer into surrounding rocks. Under a high rate (Figure 2*b*) the flow of supercritical fluid spreads along the whole fluid-conductive zone.

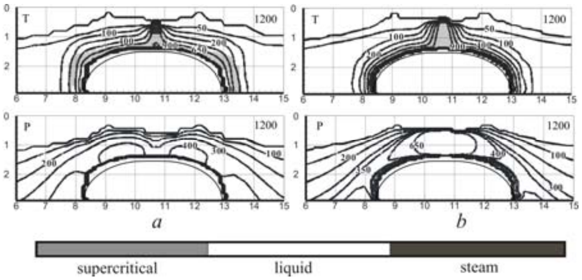

Figure 2. Calculated distribution of temperature (T, ^{o}C), pressure (P, bar) and phase state (color) with different fluid rate: *a* – model B13; *b*– model B14. The time (years) from the beginning of calculation is presented in upper right corner. The depth (km) is shown along the vertical axis, the width (km) of model region is shown along the horizontal axis.

Influence of chamber form

Though a real form of magma chamber surface is unknown the form of magma chamber was changed from horizontal into vertical ellipsoid in two models with low fluid rate B15 and B16 in comparison with the models B13 and B14 (Table 1). At the same time the initial isotherm configuration near magma chamber in a form of vertical ellipse was the same as in models magma chamber in a form of horizontal ellipse B13, B14 (Figure 1, T_1). Isotherm T_1=800^{o}C (fusion solidus) goes along the outer boundary of crystallizable crust of magma chamber in a form of horizontal ellipse. Such initial temperature conditions correspond to an intrusion of a new portion of magma material along vertical fracture «magmafracture» into partially cooled magma chamber in a form of horizontal ellipse. Such renewal of magma chamber material can occur on the third evolution stage of peripheral quasi-stationary magma chamber (Fedotov, 2006).

Comparing Figure 2*a* with Figure 3 we can conclude that temperature distribution in fluid-conductive zone and rocks surrounding it and magma chamber outside the initial isotherm T_1 is practically the same in both models. In the model with vertical magma chamber in a zone between the surface and isotherm T_1 temperatures are lower then in the model with horizontal magma chamber. The calculated gradient of pressure in the model with horizontal magma chamber (Figure 2*a*, 1.2 thou. years) is higher then in the model with vertical magma chamber (Figure 3*b*, 1.2 thou. years). Therefore the process of heat-and-mass transfer in the system is substantially defined by the initial temperature distribution, at least during 2.2 thou. years.

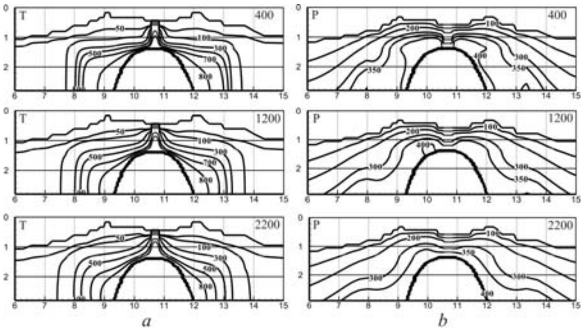

Figure 3. Calculated distribution: *a* – temperature, ^{o}C; *b* – pressure, bar. Model B15.

Isobars' form both of the model with vertical (Figure 3*b*) and horizontal magma chamber (Figure 2*a*) is typical for the conditions of fluid drainage. The depression zone in fluid-conductive zone and its environs is clearly observed.

A wide zone of supercritical fluid is formed near a chamber surface (Figure 4).

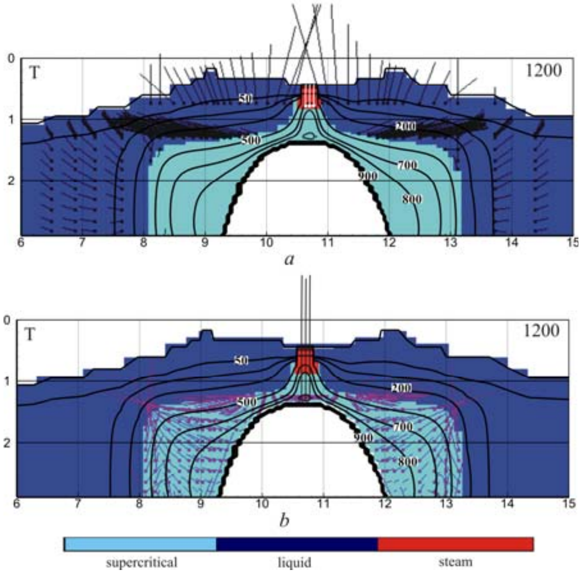

Figure 4. Calculated distribution of temperature (T, ^{o}C), phase state (color) and phases velocities in model B15 (arrows): *a* – vectors of water mass velocity (black arrows), 1 km = 2·10^{-5} kg/s·m^2 and steam (white arrows), 1 km = 3·10^{-4} kg/s·m^2; *b* – vectors of mass velocity of supercritical fluid, 1 km = 6.25·10^{-7} kg/s·m^2.

A flow of supercritical fluid is in a lower part of fluid zone, a flow of superheated steam is in an upper part. The zone of water free convection is formed outside the zones of supercritical fluid and superheated steam (Figure 4*a*). The flow of supercritical fluid in a lower part of model region goes to the sides from the chamber surface.

Influence of rocks permeability of fluid-conductive zone

To study the influence of rocks permeability of fluid-conductive zone on intensity of heat transfer we used the model B16 where fluid-conductive zone permeability was reduced twofold in comparison with other models. At the same time initial hydrostatic pressure and initial temperature gradient (30^{o}C/km) were assigned in the whole model region. Initial isobar P_1 and isotherms T_1, T_2 were not given.

In this case the thermal conduction is the dominant mode of heat transfer in fluid-conductive zone. Calculated geoisotherms near the chamber have the same form but outside they are practically equal to initial geoisotherms till the end of 2.2 thou.years (Figure 5*a*).

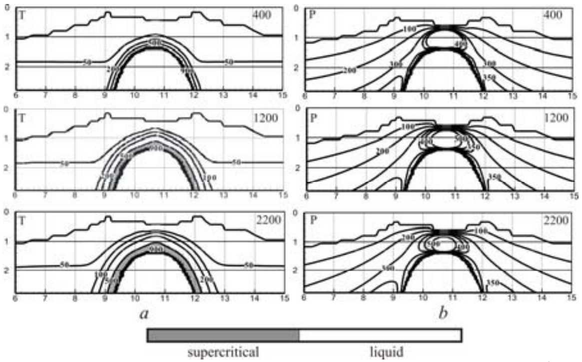

Figure 5. Calculated distribution: *a* – temperature, ^{o}C; *b* – pressure, bar. Model B16.

The zone with the temperature higher then 400^{o}C is confined by a narrow region with 200 m width near the chamber surface. As a result of low rocks permeability of fluid-conductive zone the high-pressure region (closed ellipse isobars, Figure 5*b*) is formed within fluid-conductive zone and its environs during the assigned rate of fluid degassing in apical part of chamber. This case corresponds to a small line density of contraction fractures of fluid-conductive zone and can be realized during the first stages of volcano fumarole's activity forming and also before the beginning of phreatic and phreatic-and-magmatic eruptions which happen on volcano periodically. Supercritical fluid region is also confined by a narrow region near chamber surface and has the same form (Figure 5*a*). Supercritical fluid region increases temporally with the course of time.

CONCLUSION

As a result of simulation the following conclusions were obtained:

1. Magma degassing rate defines the following parameters of heat transfer of Mutnovsky magma-geothermal system: the width of rocks zone heated up to 400^{o}C and more; calculated geothermal gradient; depth of supercritical fluid region.
2. The depth and width of supercritical fluid region are defined by the form of chamber surface. At the same time temperature distribution is mainly controlled by configuration of initial geoisotherms near chamber surface.
3. Rocks permeability of fluid-conductive zone defines the width of supercritical fluid region. At the same time the form of mentioned zone has the form like chamber. When rocks permeability is low high-pressure region is formed in the environs of fluid-conductive zone.
4. Minimal calculated temperature of system rocks at 2.5 km from the center and at the depth up to 1.5 km is 400^{o}C during a dominant conductive heat transfer. Calculated temperatures will be higher during a convective heat transfer.
5. Mutnovsky magma-geothermal system is suitable for practical use. Relief regions acceptable for riggings are located at the mentioned distance from the center of system. There is a great experience of holes drilling up to 2.0 km in depth in similar mining conditions in Kamchatka. The development of heat resources of Mutnovsky magma-geothermal system can be carried out in accordance with the technology of geothermal circulating systems.

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