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Thermal effects of natural convection in boreholes

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Abstract

Thermal regime in borehole is simulated by water-filled vertical channel passing through the rock massif. A constant temperature gradient is maintained at the external borders of the massif. Results of numerical simulation of natural thermal convection arising in the channel are presented. Analysis of the results shows the existence of two types of convective thermal effects disturbing the natural temperature field: transient effect, which manifests itself as temperature oscillations around the mean temperature value at a given depth, and quasi-stationary effect causing distortion of natural temperatures and temperature gradient. The obtained statistical relations for estimation of the characteristics of thermal effects and convection flow velocities agree with the data recorded in real boreholes.

Keywords: geothermy; Earth's temperature; natural thermal convection; borehole; numerical simulation

Introduction

High-precision temperature measurements in boreholes, including temperature monitoring, are increasingly used in hydrogeological research (Anderson, 2005; Lapham, 1989), in studies of the thermal field of the Earth (Beardsmore and Cull, 2001; Duchkov and Karchevskii, 2013; Duchkov and Kazantsev, 2007; Duchkov et al., 1987; Lyubimova, 1968), paleoclimatic changes (Bodri and Cermak, 2011; Demezhko, 2001), and geodynamic processes in seismically active regions (Buntebarth et al., 2005; Demezhko et al., 2012a,b; Shimamura et al., 1985), and on the exploration and exploitation of hydrocarbon fields (Aslanyan et al., 2016). This is favored by the appearance of modern sensors, equipment, and recording systems ensuring high accuracy, stability, and spatial and temporal resolution. As a result, it becomes possible to estimate rather weak temperature anomalies (hundredths and thousandths of a degree) and related processes in the geologic environment. This instrumental potential, however, is not always implemented completely because of the temperature noise caused by the natural thermal convection of fluid in boreholes.

Thermal effects of natural thermal convection are observed in many boreholes where temperature grows with depth (Devyatkin and Kutasov, 1973; Diment, 1967; Gretener, 1967; Sammel, 1968). For example, in boreholes with a diameter of 75 mm filled with water with a temperature of 20 ºC, convection arises at a temperature gradient of 8 K/km, and in boreholes with a diameter of 100 mm, at 2.5 K/km. In most boreholes the temperature gradient is much higher. The mechanism of convection is as follows: A colder and, hence, heavier fluid is localized over a warmer one because of a positive temperature gradient and determines the thermomechanical instability in the liquid column. As a result, ascending and descending flows arise, which tend to smooth out the density and temperature inhomogeneities. The thermal convection in a borehole causes small (a few hundredths of a degree) deviations of the fluid temperature from the unperturbed rock temperature, which limit the accuracy of measurements and thus are an obvious setback. The convective "noise" limits the minimum length of the interval of geothermal-gradient evaluation. This significantly reduces the resolution of logging detecting thermal physical inhomogeneities in rocks (Pfister and Rybach, 1995; Wisian et al., 1998). The unsteadiness of the convection process manifests itself during studies of the thermal regime in boreholes (Berthold and Börner, 2008; Cermak et al., 2008a; Eppelbaum and Kutasov, 2011). The problem of taking into account or suppressing the convective "noise" is especially important during borehole temperature monitoring in seismically active regions, when rather weak temperature signals related to deformation processes are studied (Demezhko et al., 2012a,b).

In this paper we quantitatively estimated the temperature effects (their amplitude and spatial and temporal dynamics),

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based on the results of numerical simulation of natural thermal convection and their statistical analysis. Earlier, numerical simulation of this process was made by Cermak et al. (2008b), Khoroshev (2012), and Mindubaev and Demezhko (2012). The former work was dealt with study of thermal convection in a vertical slit, and the other two focused attention on slightly supercritical convective regime.

Numerical simulation

We considered a model in which a vertical channel of square cross section with side $2r$, filled with fluid (water), is surrounded by a rock massif with temperature conductivity a_m different from that of the fluid, a_w. A constant temperature gradient is maintained at the external borders of the massif. Numerical simulation for this model is easier to implement. On the other hand, this model describes well a real borehole of diameter $2r$, because the "effective" cross section of the square channel is somewhat smaller than its true cross section as a result of the stabilizing effect of viscosity in the section corners (Gershuni and Zhukhovitskii, 1972). The fluid flow in this zone is described by a system of equations for natural thermal convection in the Boussinesq approximation (Gershuni and Zhukhovitskii, 1972):

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\,\mathbf{u} = -\frac{1}{\rho_0}\nabla P + \nu \nabla^2 \mathbf{u} - \beta\,\mathbf{g}\,(T - T_0), \tag{1.1}$$

$$\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla)\,T = a_w \nabla^2 T, \tag{1.2}$$

$$\nabla \cdot \mathbf{u} = 0, \tag{1.3}$$

$$\rho = \rho_0 (1 - \beta (T - T_0)),$$

where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$, T_0 is the equilibrium temperature distribution; $\mathbf{u}$ is the fluid flow velocity; $\mathbf{g}$ is the gravity vector; ν is the kinematic viscosity; β is the thermal-expansion coefficient; P is the pressure; and ρ and ρ_0 are the density and the equilibrium density distribution, respectively. There is no flow in the enclosing massif. A corresponding equation for the propagation of heat in this zone is

$$\frac{\partial T}{\partial t} = a_\mathrm{m} \nabla^2 T.$$

We used the following measurement units: length—the half-width of the horizontal section, r; time—r^2/a_w; velocity—a_w/r; and temperature—Gr, where G is the temperature gradient. To eliminate the pressure gradient from the equation, the velocity is usually expressed in terms of the velocity potential (Mallinson and de Vahl Davis, 1977):

$$\mathbf{u} = \nabla \times \boldsymbol{\psi}. \tag{2}$$

In this case, Eq. (1.3) is automatically satisfied. A vorticity vector is also introduced:

$$\boldsymbol{\omega} = \nabla \times \mathbf{u}. \tag{3}$$

The corresponding substitutions of (2) and (3) into (1) gives the following system of equations with variables ($\boldsymbol{\omega}$, $\boldsymbol{\psi}$, T) (Mallinson and de Vahl Davis, 1977):

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + \nabla \times (\boldsymbol{\omega} \times \mathbf{u}) = \mathrm{Pr}\,\nabla^2 \boldsymbol{\omega} - \mathrm{PrRa}\,(\nabla \times T\mathbf{e}_z), \tag{4.1}$$

$$\nabla^2 \boldsymbol{\psi} = -\boldsymbol{\omega}, \tag{4.2}$$

$$\frac{\partial T}{\partial t} + (\mathbf{u} \times \nabla)\,T = \nabla^2 T, \tag{4.3}$$

where $\mathrm{Ra} = \frac{\beta g G r^4}{a\nu}$ is the Rayleigh number, $\mathrm{Pr} = \frac{\nu}{a}$ is the Prandtl number, and $\mathbf{e}_z$ is the unit vector. After nondimensionalization, the heat conductivity equation for the enclosing massif is as follows:

$$\frac{\partial T}{\partial t} = b \nabla^2 T, \tag{5}$$

where $b = a_\mathrm{m}/a_\mathrm{w}$. The horizontal borders are taken to be isothermal: $T = 0$, $z = \lambda_z$, $T = \lambda_z$, and $z = 0$, where $\lambda_z = L_z/r$ is the aspect ratio characterizing the ratio of the vertical length of the zone, L_z, to the half-width of the horizontal section, r. The temperature distribution at the lateral vertical borders of the massif is maintained linear: $T(z) = \lambda_z - z$, $x = -\lambda_x/2$ and $x = \lambda_x/2$, and $y = -\lambda_y/2$ and $y = \lambda_y/2$, where λ_x and λ_y are the ratios of the corresponding horizontal dimensions of the massif, L_x and L_y, to r.

Simultaneous solution of Eqs. (4) and (5) permits one to take into account the conditions of a thermal contact between the two zones and to consider cases intermediate between the two extreme ones, when the channel boundaries are an ideal conductor (Mindubaev and Demezhko, 2012) or an isolator, i.e., to consider the thermal effect of flows on the temperature distribution in the surrounding massif.

According to Hirasaki and Hellums (1968), the components of the vector velocity potential $\boldsymbol{\psi}$ at the boundaries are expressed as

$$\frac{\partial \psi_x}{\partial x} = \psi_y = \psi_z = 0, \text{ at } x = -1, 1;$$

$$\frac{\partial \psi_y}{\partial y} = \psi_x = \psi_z = 0, \text{ at } y = -1, 1;$$

$$\frac{\partial \psi_z}{\partial z} = \psi_x = \psi_y = 0, \text{ at } z = 0, \lambda_z.$$

According to Aziz and Hellums (1967), the boundary conditions for the vorticity vector $\boldsymbol{\omega}$ at the solid lateral boundaries are as follows:

$$\omega_x = 0, \quad \omega_y = \frac{\partial^2 \psi_y}{\partial x^2}, \quad \omega_z = \frac{\partial^2 \psi_z}{\partial x^2} \quad \text{at} \quad x = -1, 1;$$

$$\omega_x = \frac{\partial^2 \psi_x}{\partial y^2}, \quad \omega_y = 0, \quad \omega_z = \frac{\partial^2 \psi_z}{\partial y^2} \quad \text{at} \quad y = -1, 1;$$