Numerical analysis of geothermal energy sources thermal regimes in the Tomsk region

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Abstract. Numerical analysis of thermal regimes of deposits of geothermal energy sources in the Tomsk region has been carried out. The nature of temperature distributions in the zone of location of a typical deposit of geothermal energy sources in the Tomsk region has been established. A significant influence of the non-stationarity of heat transfer processes on the temperature distribution in the considered solution region is shown. The obtained results testify to the expediency of further studies of the thermal regimes of deposits of geothermal energy sources in the Tomsk region.

1 Introduction

The use of geothermal resources is constantly growing. The world consumption of geothermal energy in 2020 was 107727 MW [1].

Technologies of creating enhanced geothermal systems [2, 3] and extracting heat from hot dry rocks [4, 5] are developing most intensively.

Technologies of low-temperature heat sources with the use of heat pumps are also being developed [6, 7]. At the same time, the use of downhole heat exchangers is being studied [8, 9].

The aim of the work is a numerical analysis of the thermal regimes of geothermal energy sources in the Tomsk region.

2 Problem statement

One of the most typical types of a two-string geothermal well in the Russian Federation is considered: the columns, conductor and directions of which are made of cement. Figure 1 shows a schematic representation of the object under consideration.

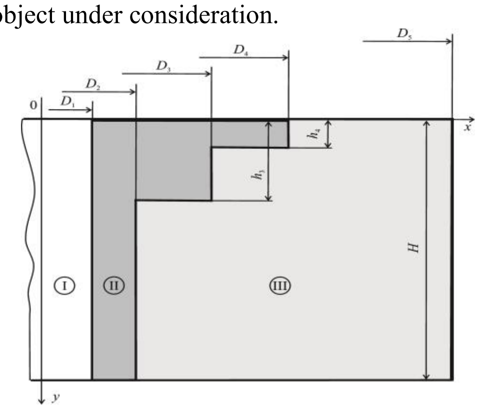

Fig. 1. Scheme of the solution area: I - energy carrier; II - columns, conductor and directions; III - rock.

Prior to the start of operation of a geothermal well, a constant temperature was maintained in the considered solution area (Fig. 1). At the initial moment of time, the energy carrier begins to be pumped through the system. A constant temperature is established on the inner surface of the object. This temperature is equal to the temperature of the energy carrier. Thus, the analysis of the thermal regimes of geothermal energy sources is reduced to solving the non-stationary problem of heat conduction in the "geothermal well - rock" system.

At the D_1 boundary, the temperature was equal to the temperature of the energy carrier. At the D_5 boundary, the temperature gradient was equal to zero. On the contact surfaces between the layers, the conditions of ideal thermal contact were introduced. On the surface $y = 0$, heat transfer occurs under conditions of natural convection. At $y = H$, the heat flux is zero.

The following basic assumptions have been made:

1) the thermophysical characteristics of materials are constant and known;

2) the conditions of perfect thermal contact are satisfied at the boundaries of the contact between the layers; and

3) heat-transfer process in a liquid heat carrier was not considered (see Fig. 1).

3 Equations and mathematics

The problem was solved in a cylindrical coordinate system, whose origin is at the symmetry axis of the pipe. The mathematical formulation of the problem has the next form:

$$c_i \rho_i \frac{\partial T_i}{\partial \tau} = \lambda_i \left(\frac{\partial^2 T_i}{\partial x^2} + \frac{1}{x}\frac{\partial T_i}{\partial x} + \frac{\partial^2 T_i}{\partial y^2} \right); i = \text{II, III}. \quad (1)$$

$$T_i = T_0 = \text{const}; i = \text{II, III}. \quad (2)$$

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$$T = T_{\mathrm{I}}, \tag{3}$$

$$\frac{\partial T_{\mathrm{III}}}{\partial x} = 0. \tag{4}$$

$$-\lambda \frac{\partial T_i}{\partial y} = \alpha \left(T_i - T_{ex} \right); i = \mathrm{II}, \mathrm{III}, \tag{5}$$

$$\frac{\partial T_i}{\partial y} = 0; i = \mathrm{II}, \mathrm{III}. \tag{6}$$

$$\lambda_i \frac{\partial T_i}{\partial x} = \lambda_j \frac{\partial T_j}{\partial x}; T_i = T_j; i, j = \mathrm{II}, \mathrm{III}; \tag{7}$$

$$\lambda_i \frac{\partial T_i}{\partial y} = \lambda_j \frac{\partial T_j}{\partial y}; T_i = T_j; i, j = \mathrm{II}, \mathrm{III}. \tag{8}$$

Notation: α is the heat transfer coefficient, $W/(m^2 \cdot K)$; λ is the thermal conductivity, $W/(m \cdot K)$; ρ is the density, kg/m^3; τ is the time, s; T is the temperature, K; c is the heat capacity, $J/(kg \cdot K)$; the following indices stand for: 0, for the initial moment of time; and I, II, III are the numbers of the boundaries of domains (see Fig. 1); 0, for internal, and ex, for external.

4 Method of solution and initial data

The system of equations (1)–(8) was solved by the finite element method [10], using the Galerkin approximation [11]. The investigations were carried out on a nonuniform finite-element mesh having 36544 nodes and 94018 elements. The number of elements was chosen from conditions of convergence of solution, the mesh was made denser by the Delaunay method [10, 11].

The peculiarity of the solution of the problem was the discontinuity of thermophysical characteristics at the interfaces (Fig. 1). At nodal points belonging to several regions, the thermophysical characteristics were calculated as arithmetic mean. The grid parameters were chosen from the conditions of convergence and stability of solutions.

Numerical analysis was carried out for a geothermal well with the following geometric characteristics: D_1=168 mm; D_2=299 mm; D_3=473 mm, D_4=630 mm, D_5=50 m, h_3=650 m, h_4=10 m, H=2500 m (Fig. 1). The geometry of the well corresponds to one of the most common types of geothermal wells in the Russian Federation, the columns, conductor and directions of which are made of cement.

The table 1 shows the values of thermophysical characteristics used in the numerical analysis of the thermal regimes of geothermal energy sources in the Tomsk region.

Table 1. Thermophysical characteristics.

Characteristic	λ, $W/(m \cdot K)$	c, $J/(kg \cdot K)$	ρ, kg/m^3
Cement	0,99	1830	1900
Rock	2,35	952	2100

The temperature value in the considered solution area at the initial moment of time was assumed to be T_0 = 272.7 K and corresponded to the typical temperature of permafrost in Eastern Siberia. The ambient temperature was T_{ex} = 273.15 K, and the heat transfer coefficient was α = 20 $W/(m^2 \cdot K)$. The energy carrier temperature inside the T_1 tube was 343.15 K.

5 Results and discussion

The main results of numerical modeling of thermal regimes of deposits of geothermal energy sources in the Tomsk region are shown in fig. 2, 3.

The studies were carried out for a period of time corresponding to 30 years of continuous operation of a geothermal well in the Tomsk region. When carrying out numerical simulation, the main attention was paid to the analysis of the non-stationarity of heat transfer processes in the considered solution area (Fig. 1).

Since the authors do not have data on temperature fields at the locations of geothermal wells in the Tomsk region, therefore, the validity and reliability of the research results follows from the checks of the methods used for the convergence and stability of solutions on a set of grids and the fulfilment of the energy balance conditions at the boundaries of the calculation area. The energy balance error in all variants of the numerical analysis did not exceed 1%, which can be considered acceptable in the study of heat transfer in geothermal systems under long-term operation. Comparison of the results of numerical simulation with the known data [12–16] on the study of thermal regimes of deposits of geothermal energy sources allows us to speak of their good qualitative agreement.

The figures 2, 3 show the temperature distributions in the considered solution area at different depths at different times. The temperature distributions (Fig. 2, 3) in the considered solution region (Fig. 1) show the expected dependence on the depth of the considered section.

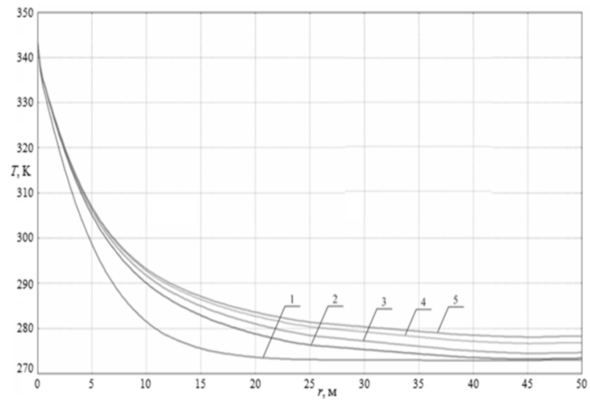

Fig. 2. Temperature distribution in the considered solution area at a depth of 5 m: 1 - 1 year, 2 - 5 years, 3 - 10 years, 4 - 20 years, 5 - 30 years.

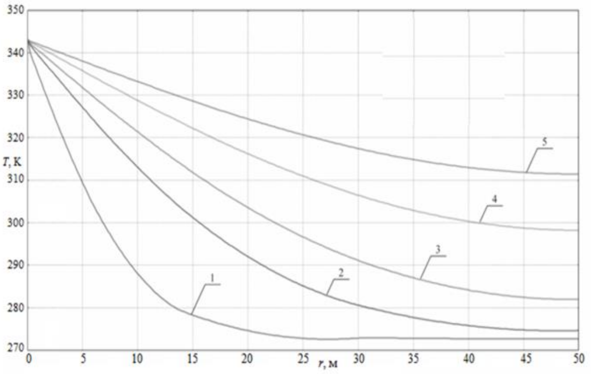

Fig. 3. Temperature distribution in the considered solution area at a depth of 2500 m: 1 - 1 year, 2 - 5 years, 3 - 10 years, 4 - 20 years, 5 - 30 years.

In the immediate vicinity of the well, the temperature values are higher. When moving away from it, the opposite is true. This corresponds to the concept of heat conduction processes in solids.

The results of numerical simulation shown in Fig. 2, 3 indicate a significant influence of the nonstationarity of heat transfer processes on the temperature distribution in the considered solution region. An analysis of the temperature fields indicates that they level out over time. During the considered period of time (30 years), the stationary mode of heat conduction does not yet occur.

One more important circumstance should be noted: the influence of heat removal at the upper boundary of the system under consideration (Fig. 1) affects the thermal regimes of deposits of geothermal energy sources in the Tomsk region to a depth of 50-70 meters (comparison of Fig. 2 and Fig. 3). This result is important primarily in practical terms, since it allows you to choose options for drilling wells (vertical, horizontal or inclined).

The results obtained also make it possible to reasonably choose the distances between adjacent geothermal wells. A geothermal well placement grid based on such calculations will help optimize site construction costs.

It should be noted that the results presented are estimates, since this study did not take into account the decrease in the temperature of the energy carrier during long-term operation due to a decrease in the thermal flow rate of geothermal wells and a number of other factors.

6 Future research

Directions for further development of the research topic are reduced to taking into account the following factors:

- decreased heat output of geothermal wells.
- the presence of temperature distribution in depth.
- influence of initial operating conditions.
- heterogeneity of thermophysical characteristics of rocks in the solution area.
- seasonal change in external conditions of heat transfer.

7 Conclusion

Numerical analysis of thermal regimes of deposits of geothermal energy sources in the Tomsk region has been carried out.

The nature of temperature distributions in the zone of location of a typical deposit of geothermal energy sources in the Tomsk region has been established.

A significant influence of the non-stationarity of heat transfer processes on the temperature distribution in the considered solution region is shown.

The obtained results testify to the expediency of further studies of the thermal regimes of deposits of geothermal energy sources in the Tomsk region.

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