Simulation and Numerical Investigation of Temperature Fields in an Open Geothermal System

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Abstract. An open geothermal system consisting of injection and productive wells is considered. Hot water from production well is used and became cooler, and injection well returns the cold water into the aquifer. To simulate this open geothermal system a three–dimensional nonstationar mathematical model of the geothermal system is developed taking into account the most important physical and technical parameters of the wells to describe processes of heat transfer and thermal water filtration in a aquifer. Results of numerical calculations, which, in particular, are used to determine an optimal parameters for a geothermal system in North Caucasus, are presented. For example, a distance in the productive layer between the point of hot water inflow and of cold water injection point is considered.

1 Introduction

A geothermal system is a system used for heating that utilizes the earth as a heat source. Geothermal systems simply take advantage of the relatively constant temperature within the earth. For example, in North Caucasus the earth's temperature ranges 90–102°C at a depth of 900 m throughout the year.

Geothermal systems have the potential for significant savings in energy costs and for reducing of oil and natural gas consumption. However, some of these systems also have the potential for adverse environmental effects if installed or operated improperly or if they use inappropriate materials. It is also important to ensure a long-term service and appropriate heat efficiency of these installations.

Let consider an open geothermal system consisting of injection and productive wells. Hot water from production well is used and became cooler, and injection well returns the cold water into the aquifer. This cold water is filtered in porous soil towards the inflow of hot water of the production well. It is required to describe propagation of the cold front in the productive layer of water, depending on the different thermal soil parameters and initial data defined filtration rate in the productive layer, and to answer the question about the time of the system effective operation (operation of a geothermal system is stopped when the front of the cold water will reach the inflow of the production well).

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In simulations of underground flow, Darcy's law and law of mass conservation (continuity equation) are used [1]. A convection-diffusion equation with dominant diffusion is considered. A system of equations for temperature in aquifer is solved using a finite difference method based on an approach of works of A.A.Samarskii and P.N.Vabishevich [2].

Let note that the model and the numerical algorithms are convenient (with some adaptations) to simulate different problems of heat and mass transfer, for example, to find thermal fields of underground pipelines [3,4] and the problems related to phase transitions in the soil around engineering constructions [5–7] in permafrost.

2 Mathematical Model and a Method of Solving the Problem

Let consider a mathematical model of a Underground Water Source (Geothermal Open Loop) Heat Pump System. A geothermal open loop (GOL) consists of two wells: an injection well and a production well (Fig. 1), which are inserted into as aquifer Ω as the heat source and sink. Water is taken from the aquifer by a productive well (Ω_1), circulated to the individual pump, cooled, and returned via an injection well (Ω_2). Let injection well has a cold water with temperature $T_1(t)$, production well has a hot water with temperature $T_2(t)$.

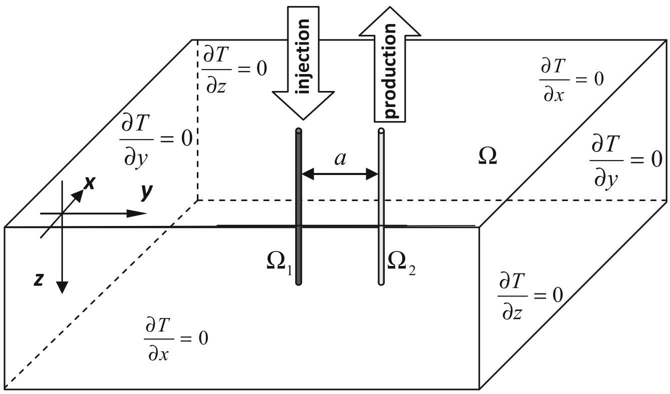


Fig. 1. A model of Geothermal Open Loop.

Let $T(t, x, y, z)$ be temperature in the aquifer, $p = p(t, x, y, z)$ — pressure field. Thermal exchange is described by equation

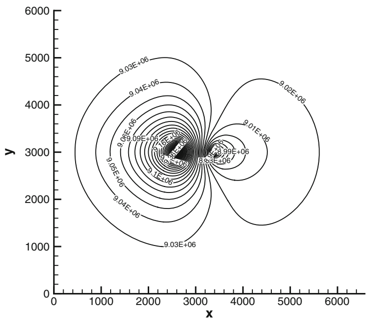
$$\frac{\partial T}{\partial t} + b\left(\frac{\partial T}{\partial x}u + \frac{\partial T}{\partial y}v + \frac{\partial T}{\partial z}w\right) = \lambda_0 \Delta T, \tag{1}$$

here $b = \dfrac{\sigma \rho c_f}{\rho_0 c_0 (1-\sigma) + \rho c_f \sigma}$, $\lambda_0 = \dfrac{\kappa_0}{\rho_0 c_0 (1-\sigma) + \rho c_f \sigma}$, ρ_0 and ρ_f are density of aquifer soil and of water, c_0 and c_f are specific heats of aquifer soil and of water, κ_0 is thermal conductivity coefficient of soil, σ is porosity, (u, v, w) is vector of velocity of water filtration in the soil.

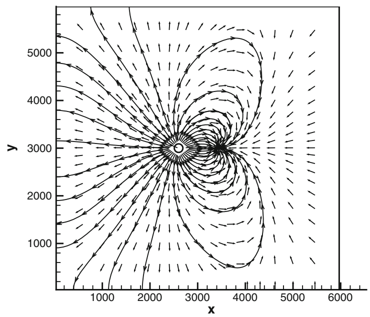
This equation is necessary to be considered with the following system, describing the water filtration:

$$\begin{aligned} \frac{\partial u}{\partial t} &= -\frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{g\sigma u}{k}, \\ \frac{\partial v}{\partial t} &= -\frac{1}{\rho}\frac{\partial p}{\partial y} - \frac{g\sigma v}{k}, \\ \frac{\partial w}{\partial t} &= -\frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{g\sigma w}{k} - g, \\ \frac{\partial u}{\partial x} &+ \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \end{aligned} \tag{2}$$

In simulations described by Eq. (1) and (2) it is necessary to estimate a distance a between the injection and productive wells due to the temperature in the productive well be appropriate for the considered system.



(a)



(b)

Fig. 2. (a) — density, (b) — velocity.

After transformation of system (2) we get Laplace equation for pressure

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0 \tag{3}$$

with corresponding boundary conditions. Pressure may be computed by method Fig. 2 shows pressure distribution in an aquifer.

Let consider an exact solutions, which satisfy equations of water filtration in the aquifer. For the surfaces Ω_1 and Ω_2 let conside the given pressure

$$P(t, x, y, z)\Big|_{\Omega_1} = P_1 - \rho g z, \tag{4}$$

and

$$P(t,x,y,z)\Big|_{\Omega_2} = P_2 - \rho g z. \tag{5}$$

Let find the solution in the form

$$p = b_1(t)x - \rho g z + b_0(t), \tag{6}$$

where $b_1(t)$ and $b_2(t)$ are unkown functions. Taking into consideration (4) and (5) this function has the form

$$p = -\frac{P_2 - P_1}{a}x - \rho g z + P_1. \tag{7}$$

Then, for the velocity u we get an ordinary differential equation

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{P_1 - P_2}{a} - \frac{g\sigma u}{k}, \tag{8}$$

with the zero boundary condition $u(0) = 0$. Then the solution of Eq. (8) has the form

$$u = \frac{k(P_1 - P_2)}{\rho g \sigma a}\left(1 - e^{-\frac{g\sigma t}{k}}\right). \tag{9}$$

Thus, a partial solution of system (2) has a solution (9) and $v = w = 0$. We have to note, that when the time tends to infinity, the solution tends to the stationary

$$u^* = \frac{k(P_1 - P_2)}{\rho g \sigma a}, \tag{10}$$

Naturally, the resulting partial solution does not satisfy all the boundary and initial conditions of the problem, but suggests that over time the problem under consideration is a stationary regime. So in the model we can use a steady-state flow to describe convective transport terms in Eq. (1).

After finding the pressure field, a vector of velocity of filtered water is determined in the aquifer.

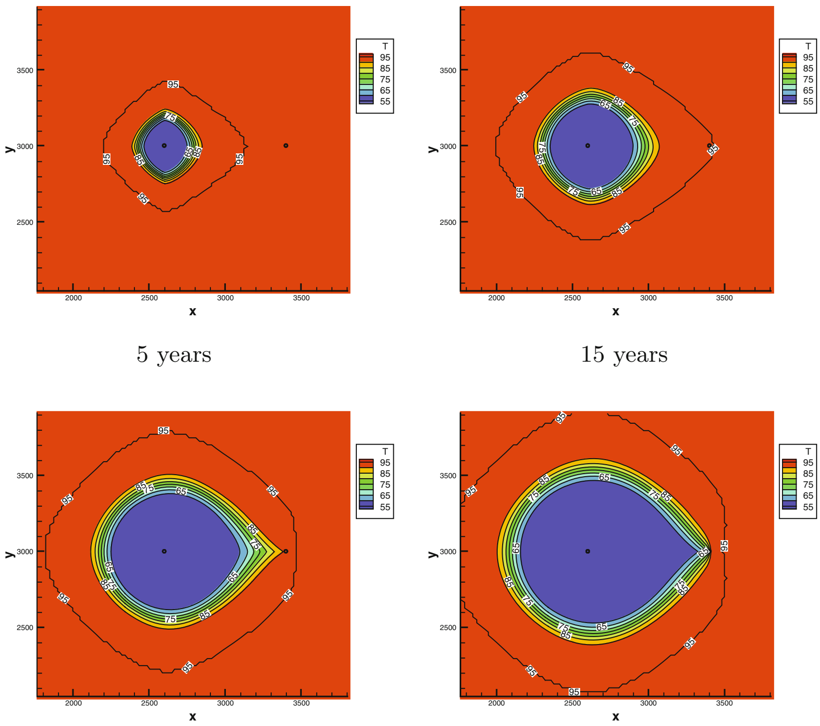
On the base of ideas in [2] a finite difference method is used with splitting by the spatial variables in three-dimensional domain to solve the problem (1)–(5). We construct an orthogonal grid, uniform, or condensing near the ground surface or to the surfaces of Ω_1 and Ω_2. The original equation for each spatial direction is approximated by an implicit central-difference scheme and a three-point sweep method to solve a system of linear differential algebraic equations is used.

3 Numerical Results

Let a computational domain be a parallelepiped 6000 m·6000 m·50 m size (Fig. 1). The choice of such large computational domain is related with decreasing the influence of boundary conditions. Mesh size is $201 \cdot 201 \cdot 51 = 2060451$ nodes. Injection well is in point (2600 m, 3000 m), productive — in (3400 m, 3000 m). The distance between the wells is 800 m. Soil thermal parameters correspond to Hankal geothermal fields in the North Caucasus. The initial temperature of water in the aquifer at a depth of 950–1000 m is 95°C, temperature of the injected water is 55°C.

Computations are carried out with 1 day time step for 50 years and for various pressures difference.

We present the results of calculations for the differential pressure between production and injection wells 420000Pa. Figure 2 shows a typical pressure (a) and velocity (b) distribution in the aquifer.



5 years 15 years

30 years 50 years

Fig. 3. Temperature in aquifer for years of exploitation, °C.

The transition of filtered water allow to compute temperature in the aquifer and to determine how the a cold injection well influences to the productive well. Figure 3 shows a temperature distribution in (x, y)-plane after 5, 15, 30, and 50 years of exploitation of the system.

Figure 4 is an average temperature in productive well during the time.

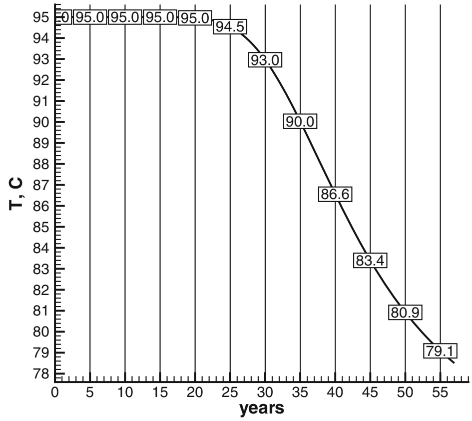


Fig. 4. Temperature in productive well during the time of exploitation, °C.

4 Conclusion

Computations alows to choose an optimal parameters of an open geothermal systems, in particular to determine an appropriate distance between injection and production wells depending on the operating conditions of the geothermal system. Taking into consideration a geothermal gradient allows to increase time of the system operation. Note that many researchers do not consider this factor in the simulation, although the results obtained, for example, in [8] are in qualitative agreement with our results.

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