Numerical modeling of Geothermal Processes: Issues and Examples

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Abstract

Geothermics has an increasing importance for energy supply worldwide. Hence, there is also an increasing need to model different geothermal scenarios. Depending on the type of problem it may be necessary to take density coupled processes into account. Furthermore, thermal dependence of material properties should be considered. Special problems occur in cases of fracture flow, which can be of high importance with respect to productivity. Finally, the simultaneous modeling of heat and mass transport processes may be necessary. Several simulation codes are available which apply different numerical methods. However, the applicability for complex subsurface geometries reduces the number substantially. We will present modeling approaches with FEFLOW®. These will include applications for deep geothermics (enhanced geothermal systems), the use of mine-water for heating purposes and the numerically efficient modeling of shallow ground heat exchanger arrays.

Introduction

Geothermal energy is the heat contained in the solid earth and its internal fluids. This sets it apart from other terrestrial energy sources. It represents a vast supply which has only started to be tapped by mankind for space heating, process heat and generation of electric power. (Clauser, 2006)

The efficient use of this natural resource can be optimized by applying numerical heat-transport models. In the following we will give an introduction on the modeling of different geothermal utilization scenarios using FEFLOW® (Diersch, 2005; Trefry & Muffels, 2007).

Coupled modeling of flow and heat transport

The computation of heat transport within a porous medium requires the solution of a set of balance equations. For comprehensibility only flow in a saturated medium is discussed. Of course, advanced heat and groundwater modeling codes are also able to compute unsaturated flow, fracture flow and other special processes.

The mass conservation equation of a fluid in a saturated porous medium is given by (Diersch, 2005)

$$S_0 \cdot \frac{\partial h}{\partial t} = \nabla \cdot \left(\mathbf{K}\left(\nabla h + \chi \mathbf{e}\right)\right) + Q \qquad (1)$$

where S_0 is the specific storage due to fluid and medium compressibility (m^{-1}), h is the hydraulic head (m), t is time (s), χ is the buoyancy coefficient (/) and $\mathbf{e}$ is the gravitational unit vector (/). Q corresponds to sources and sinks (s^{-1}).

K represents the tensor of the hydraulic conductivity ($m\ s^{-1}$), defined as

$$\mathbf{K} = \frac{\mathbf{k}\rho^f g}{\mu^f} \qquad (2)$$

where $\mathbf{k}$ is the permeability tensor (m^2), ρ^f is the fluid density ($kg\ m^{-3}$), g is the gravitational force ($m\ s^{-2}$) and μ^f is the dynamic fluid viscosity ($kg\ m^{-1}\ s^{-1}$).

The Darcy velocity $\mathbf{q}$ ($m\ s^{-1}$) is given by

$$\mathbf{q} = -\mathbf{K}(\nabla h + \chi \mathbf{e}) \qquad (3)$$

The heat transport with conductive and advective parts reads

$$(\rho c)^g \frac{\partial T}{\partial t} = \nabla \cdot \left(\boldsymbol{\lambda} \nabla T - \rho^f c^f \mathbf{q} T\right) + H \qquad (4)$$

where T is the temperature (K), c is the specific heat ($J\ kg^{-1}\ K^{-1}$) and λ is the heat conductivity ($W\ m^{-1}\ K^{-1}$). $(\rho c)^g$ is bulk volumetric heat capacity ($J\ m^{-3}\ K^{-1}$). H refers to sources and sinks ($W\ m^{-3}$).

Geothermics

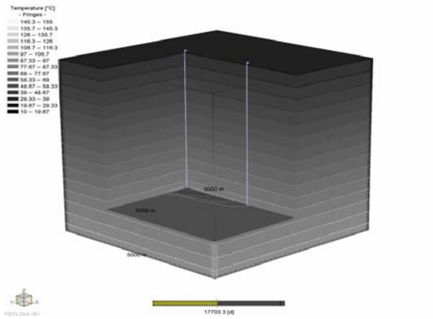
Geothermal installations are generally distinguished between shallow (using boreholes with depths up to 400 m) and deep geothermics. The latter is sometimes defined by its direct usability, i.e. that it is not necessary to use heat exchangers.

Deep geothermics

Deep geothermal installations are primarily used for hydrothermal heating systems and for electric power generation. Mainly due to radiogenic heat production the earth's crust generates a continental average conductive heat flow of 65 mW m^{-2} (Beardsmore and Cull, 2001). Based on Fourier's law the rate of heat flow q (W m^{-2}) between two points is given by (Carslaw and Jaeger, 1959)

$$q = -\lambda \cdot \frac{\Delta T}{\Delta z} \tag{5}$$

Figure 1 *Temperature distribution along a horizontal fracture zone in 4 km depth after ~ 48.5 years. The right borehole extracts while the left one injects.*



Assuming an average heat conductivity of $\lambda \approx 2.16$ (W m^{-1} K^{-1}) an increase of temperature with depth of 0.03 (K m^{-1}) results. For operating a geothermal power plant it is at least necessary to reach the steam temperature of the used fluid. In case of water, assuming an average ground temperature of 10°C, a temperature of 100°C is therefore available at a depth of 3 km. However, due to advective processes even higher temperatures can be achieved at smaller depths.

Besides temperature, the flow rate is the most critical issue (min. 50 m^3 h^{-1}). For enhanced geothermal systems the flow rate can be increased by hydraulic fracturing/stimulating.

In Figure 1 a prototypical model for a geothermal installation using a classical doublet borehole is shown. A typical question is always how long the installation can be used until the subsurface is cooled down to a specific temperature. Based on this model the potential cooling of the system can be assessed.

Shallow geothermics

Shallow geothermics is mostly used via borehole heat exchangers, which utilize the temperature difference between the atmosphere and ground. Different technologies exist, e.g., U-shape heat pipe, double U-shape heat pipe, coaxial heat pipes and grounding stakes. Such ground heat exchangers form a vertical borehole system, where a refrigerant circulates in closed pipes exchanging heat with the surrounding aquifer driven alone by thermal conductivity (closed loop system). Unlike those closed systems a combination of extraction and injection wells can be used in an open system, see Figure 2. A procedure of special interest refers to the combined use of solar energy and geothermics, i.e,. the storage of solar energy in the ground. For instance, in order to give expertise on environmental matters it may be necessary to model the impact of ground heat exchangers on the subsurface temperature. In the following some introductive modeling scenarios are summarized.

Open loop

In Figure 3 modeling results for combining an extraction and injection well are shown. At the injection well a special module, which has been programmed for this purpose, adds a variable temperature difference on the temperature of the extracted water. Due to groundwater flow, the temperature at the extraction well increases in time.

Discrete modeling of ground heat exchangers

In Figure 4 the discrete modeling of a single double U-shape heat pipe is exemplified. In this case the heat pipes are modeled by using 1D vertical fracture elements. Such a modeling approach is required if the impact of groundwater flow on the subsurface temperature distribution has to be analyzed.

Figure 2 *Schematic illustration depicting the principle of a geothermal well installation.*

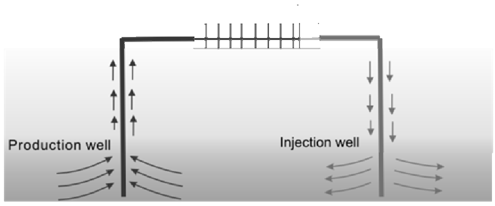
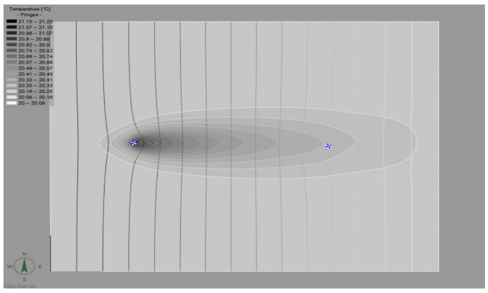


Figure 3 *Modeled temperature distribution after 10 years at a geothermal well installation. Injection well is left, extraction is right. Size of the domain is 85 m x 70 m. Hydraulic conductivity is set to $1 \cdot 10^{-4}$ m s^{-1}, ground temperature is 20°C, and head gradient is ~ 0.12 inducing a flow from left to the right.*



A new efficient modeling procedure for ground heat exchanger arrays

For large heat exchanger arrays consisting of numerous heat pipes, a fully discrete modeling is not practical any more. The extreme geometrical aspect ratios require an advanced numerical strategy, where the heat pipe exchangers are modeled by appropriate 1D finite-element representations. We have included this approach into FEFLOW mainly following the ideas proposed by Al-Khoury et al. (2005, 2006). Al-Khoury et al.'s numerical strategy is further modified and adapted to FEFLOW with respect to the following (Diersch, 2008):

- Integrating the 1D heat pipe elements into FEFLOW's finite-element matrix system similar to so called discrete feature elements.
- Generalization of the formulations for single and double U-shape as well as coaxial heat pipe exchangers.
- Direct and non-sequential (essentially non-iterative) coupling of the 1D heat pipe elements to the porous medium discretization.
- Extending FEFLOW's boundary conditions for heat pipes similar to multi-well borehole conditions.

  First results show a sufficient agreement with fully discretized heat pipes. However, primarily due to the dimensional reduction the short-term behavior may be different in case of large variations of input temperature.

Mine water geothermics

If the flow rate of mine water is high (up to some hundreds of liters per second) the energetic use of the waters might be possible (PK Tiefe Geothermie, 2007). Depending on the temperature either a direct energy extraction or heat exchangers can be applied.

In Figure 5 a conceptual example based on an existing mining facility in Germany is shown. The mining space is assumed to be filled with water, whose temperature is in equilibrium with the surrounding rocks. Extraction and injection wells are simulated. The figure displays the temperature distribution after approximately 118 d. Using an appropriate numerical simulation code, it is possible to model different scenarios to optimize the heat transfer rate. Commonly, the temperature dependence of water density and viscosity (see Eq. 1 and Eq. 2) can be neglected in cases of low temperature gradients. However, as shown in Figure 6 the simulated heat transfer is apparently different in variable-density and viscosity-dependent computations although the maximum temperature difference is below 13 K.

Figure 4 *Discrete modeling of a double U-shape heat pipe using FEFLOW*

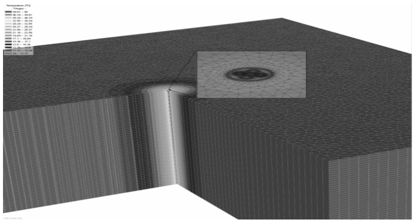


Figure 5 *Temperature distribution after 118 days due to geothermal operation in a conceptual mining facility.*

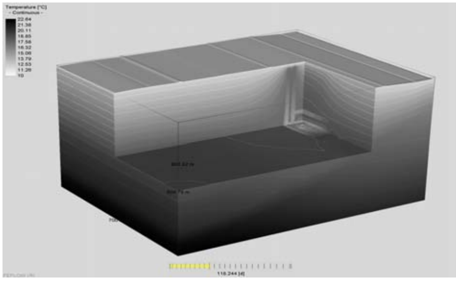
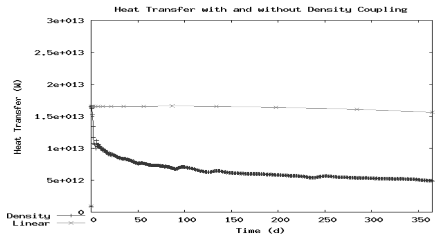


Figure 6 *Difference between the heat-transfer rates resulting from the consideration of temperature dependence of water density and viscosity.*



Discussion and outlook

Numerical simulation can be a powerful tool for designing and planning purposes of geothermal applications. The computations require the availability of additional parameters such as thermal conductivity and thermal capacity as well as the availability of subsurface temperature measurements. Besides the evaluation of the geothermal installation these data can give substantial and new information on the flow field (see Anderson, 2005). Due to the restricted length of this paper the important subject of geothermal chemical reactions could not be discussed. However, using the FEFLOW simulator such type of modeling can be easily performed.

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