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Numerical Modeling of Geothermal Applications

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ABSTRACT

Geothermics has an increasing importance to energy supplies worldwide. Thus, there is also an increasing need to numerically model different geothermal scenarios. Depending on the type of problem, it may be necessary to take density coupled processes into account. Further, the thermal dependence of material properties should be considered. Special problems occur in the case of fractured flow, which can be of high importance with respect to productivity. In general, the simultaneous modeling of heat and mass transport processes is necessary. Several programs which apply different numerical methods are available, but the need to model 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 efficient numerical modeling of shallow ground heat exchanger arrays.

1. INTRODUCTION

Geothermal energy taps the heating and cooling capacity of the solid earth and its internal fluids. It has tremendous potential, which is only starting to be tapped by mankind for space heating, process heating, and the generation of electric power (Clauser 2006). One of the advantages of geothermal energy is that its use can reduce CO_2 emissions.

The efficient use of this natural resource can be optimized by applying numerical heat-transport models. Depending on the site, it may be necessary to take density-coupled processes into account. Furthermore, it may be crucial to consider the thermal dependence of material properties. Thus, the simultaneous modeling of heat and mass transport processes is necessary. Several simulation codes for flow and heat transport are available, featuring different numerical methods. However, the need to model complex subsurface geometries reduces this number substantially. An introduction on the modeling of different geothermal utilization scenarios using FEFLOW® is given in this report (Diersch, 2005; Trefry & Muffels, 2007).

2. 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 the sake of clarity, 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 in Equation 1 (Diersch 2005)

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

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}).

$\mathbf{K}$ represents the tensor of the hydraulic conductivity ($m\ s^{-1}$), defined in Equation 2

$$\mathbf{K} = \frac{\mathbf{k}\rho_f g}{\mu_f} \tag{2}$$

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 in Equation 3.

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

The heat transport with conductive and advective parts reads

$$(\rho c)_g \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T - (\rho c)_f \mathbf{q} T\right) + H \tag{4}$$

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

2.1 Temperature Dependence

Temperature dependence is introduced into the set of differential equations (Equations 1 and 4) on one hand by the hydraulic conductivity K ($m\ s^{-2}$). Due to the temperature dependence of the dynamic viscosity, the value of the hydraulic conductivity at 26°C is approximately 2/3 of the value at 10°C. Changes in the fluid density have an influence on this property, but this also has to be taken into account due to the buoyancy term. FEFLOW is able to take density variations due to heat and mass-transfer simultaneously into account.

In addition, the physical properties of the matrix, including the heat conductivity and specific heat capacity, are also temperature dependent (e.g. Clauser, 2006). However, in case of the latter, the temperature dependence is quite small. All of these temperature dependences can easily be taken into account by applying additional IFM modules.

3. GEOTHERMICS

Geothermal installations are generally distinguished between shallow (in Germany defined as boreholes with depths up to 400 m) and deep geothermics.

3.1 Deep Geothermics

Deep geothermics is sometimes defined by its direct usability, i.e. that it is not necessary to use heat pumps. 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, which is given in Equation 5, the rate of heat flow q (W m^{-2}) between two points is given by (e.g. Carslaw and Jaeger 1959):

$$q = -\lambda \cdot \frac{\Delta T}{\Delta z} \qquad (5)$$

Assuming an average thermal conductivity of $\lambda = 2.16$ W m^{-1} K^{-1}, an increase of temperature with depth of 0.03 K m^{-1} results. To operate a geothermal power plant, it is necessary to at least reach the boiling point of the working fluid. The required temperature of 100°C for water is therefore available at a depth of 3 km, assuming an average ground temperature of 10°C. However, due to advective processes, even higher temperatures might be achieved at lower depths.

A critical issue for open geothermal systems is the required flow rate. If heat pumps are used, the necessary flow rate depends on the utilization. In the case of power generation using an enhanced geothermal system, flow rates should be at least 180 m^3 h^{-1} (Clauser 2006). To achieve this, the flow rate can be increased by hydraulic fracturing or stimulation. Figure 1 shows the prototypical setup for a geothermal installation using a classical doublet of boreholes. In such a case, a typical question during project planning is the forecasted lifetime of the system, or the amount of time before the area of influence is cooled down to the minimum working temperature. The potential cooling of the system can be assessed using numerical simulations.

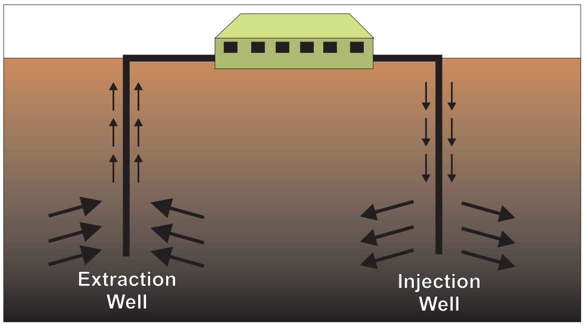

Figure 1: Schematic illustration depicting the classical configuration of a geothermal well installation

The application of 2D elements (called Discrete Feature Elements (DFE) in FEFLOW) allows the discrete modeling of fracture zones. Different approaches to the flow laws (Darcy, Hagen-Poiseuille, Manning-Strickler) can be applied.

3.2 Shallow Geothermics

Shallow geothermics are mostly utilized via heat pumps together with borehole heat exchangers (BHE) and take advantage of the temperature difference between the atmosphere and the ground. Different technical solutions are used for borehole heat exchangers: u-shaped heat pipes, double u-shaped heat pipes, coaxial heat pipes, and grounding stakes. The boreholes can be filled with grout. Such ground heat exchangers in most cases form a vertical borehole system, where a heat carrier fluid circulates in closed pipes and its heat exchange with the surrounding aquifer is driven only by thermal conductivity (a closed loop system).

A procedure of special interest is the combined use of solar energy and geothermics, i.e. the storage of solar energy in the ground.

Unlike closed systems, a combination of extraction and injection wells can be used in an open system, comparable to deep geothermal doublet systems.

In order to increase knowledge on these environmental matters, it may be necessary to model the impact of ground heat exchangers on the subsurface temperature. Summaries of introductive modeling scenarios follow.

3.2.1 Open Loop

Modeling results for combining an extraction and injection well are shown in Figure 2. At the injection well, a special module has been programmed to add a variable temperature difference to the temperature of the extracted water. Due to groundwater flow, the temperature at the extraction well increases with time.

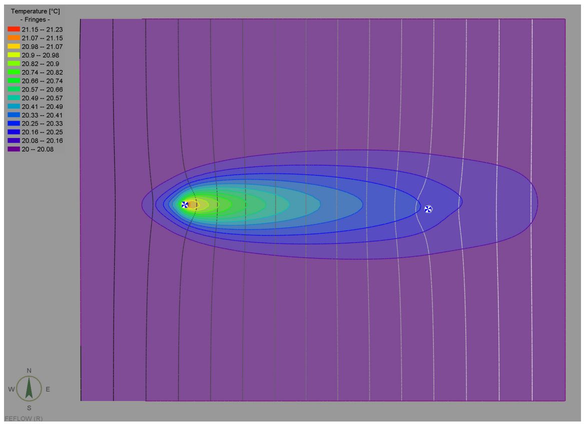

Figure 2: Modeled temperature distribution after 10 years at a geothermal well installation. Injection well is left, extraction is right. Size of the domain is 85 m x 70 m. Hydraulic conductivity is set to 1·10-4 m s-1, ground temperature is 20°C, and the head gradient is ~ 0.12, inducing a flow from left to the right

3.2.2 Discrete Modeling of Ground Heat Exchangers

The discrete modeling of a single double U-shape heat pipe is shown in Figure 3. In this case, the four pipes themselves are modeled using 1D vertical fracture elements. Such a modeling approach is required if the impact of groundwater flow on the subsurface temperature distribution is to be analyzed.

3.2.3 A new efficient Modeling Procedure for Ground Heat Exchanger Arrays

For large heat exchanger arrays consisting of numerous heat pipes, a fully discrete modeling system is no longer practical. The extreme geometrical aspect ratios require an advanced numerical strategy, in which the heat pipe exchangers are modeled by an appropriate 1D representation. For the most part, the ideas proposed by Al-Khoury et al. (2005) and Al-Khoury & Bonnier (2006), who firstly used 1D single and double U-pipe elements in the context of geothermal heating systems, are followed. The numerical strategy is further extended and adapted to the FEFLOW simulator with respect to the following:

- Generalization of the formulations for single and double U-shape configurations as well as coaxial pipe configurations.

- Improving pipe-to-grout approximation method by using multiple grout points in application to single and double U-shape pipe exchangers.

- Improving relationships for thermal resistances of BHE.

- Integrating the 1D BHE pipe elements into FEFLOW's finite-element matrix system similar to fracture elements.

- Direct and non-sequential (essentially non-iterative) coupling of the 1D pipe elements to the porous medium discretization.

- Extending FEFLOW's boundary conditions for BHE pipes similarly to multi-well borehole conditions.

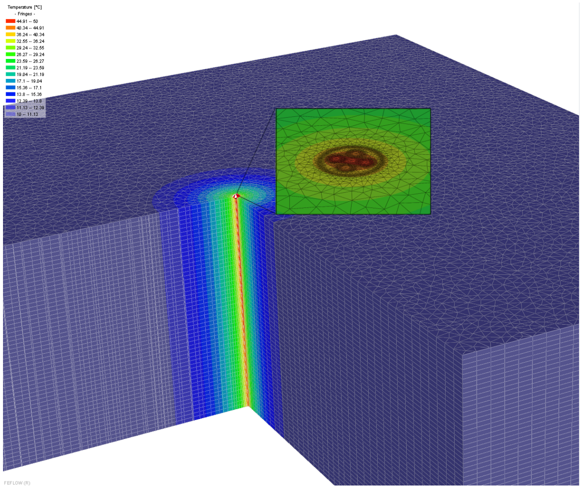

Figure 3: Discrete modeling of a double U-shape heat pipe using FEFLOW

The local processes within BHE can alternatively be modeled via an analytical technique under the major assumption that local conditions are at steady-state, where a thermal equilibrium immediately occurs between the inlet and outlet pipes for a given solid temperature at the borehole wall. This type of analytical solution was first introduced by Eskilson and Claesson (1988).

Their local analytical model is taken as an alternative to the general Al-Khoury et al.'s numerical strategy, particularly for long-term predictions. Al-Khoury et al.'s numerical strategies and Eskilson and Claesson's analytical strategies are compared and tested. While Al-Khoury et al.'s numerical approach has proven to be appropriate over all time ranges of processes, Eskilson and Claesson's analytical solution is not suited for short-term predictions (e.g. thermal responses in a time range smaller than a few hours). However, for long-term predictions, Eskilson and Claesson's analytical solution has been shown to have reasonable accuracy in comparison to Al-Khoury et al.'s general numerical strategy. In FEFLOW, both modeling approaches are available and can be chosen in accordance with the specific needs of modeling.

3.3 Geothermal Use of Mine Water

Mine water is the fluid that is produced during the operation or the later safeguarding of open or underground mining sites. These waters often have high enough temperatures to be feasible for heating purposes.

If the flow rate of mine water is high (up to some hundreds of liters per second), the use of the water's thermal energy might be possible. Depending on the temperature, either direct energy extraction or heat exchangers can be applied.

The potential use of underground mines for geothermics was first investigated in the 1970s. Water in the Springhill coal mines with a temperature of 18°C was used for geothermal energy production in Nova Scotia, Canada. Other sites include: Park Hills, USA; Follda, Norway; Shettleston, UK; and Ochil View, UK (Wolkersdorfer 2008). Recently, the geothermal energy in an abandoned coal mine in Heerlen, the Netherlands, has been tapped (Bazargan Sabet et al. 2008).

Depending on the available temperature, mine water can either be used directly for heating purposes or for use in heat pumps. Both closed loop and open loop systems can be used. In combined heating and cooling systems, extraction and injection boreholes are often switched seasonally to take advantage of the heat storage capacity of the mine.

<u>3.3.1 Particular Characteristics of Mine Water Models</u>

The movement of water in underground mining sites primarily takes place in the voids created during the mining activities. These are typically shafts, galleries, mined coal seams, and caverns.

The flow velocity within these voids exceeds the flow velocity within the host rock by several orders of magnitude. While the flow in the porous host rock can be described by a potential flow (where inertial energy is neglected), the flow in the voids is a free fluid movement where a linear scaling of velocity with head difference may no longer be realistic. Depending on the particular situation, different approaches such as laminar flow (Hagen-Poiseuille law) or turbulent flow (Manning's equation, Darcy-Weissbach law) can be chosen to model this kind of movement.

The voids of abandoned mines are in many cases not extended widely in all three dimensions. In comparison with the surrounding rock mass, shafts or tunnels can be considered as one-dimensional, while mined coal seams can be approximated in two dimensions. Such geometrical simplifications allow easier application of the empirical flow equations for turbulent fluid flow, such as Manning's equation. When reducing the mine models to one-dimensional structures, combined 1-D/3-D simulation models can be applied.

However, the reduction of flow geometry may not be suitable in all cases. At high Rayleigh numbers, the development of convection cells is possible, which can either support or inhibit heat transport within the system. In contrast to larger convection cells incorporating different shafts and tunnels, local convection cells cannot be simulated in 1-D or 2-D approximations of the workings.

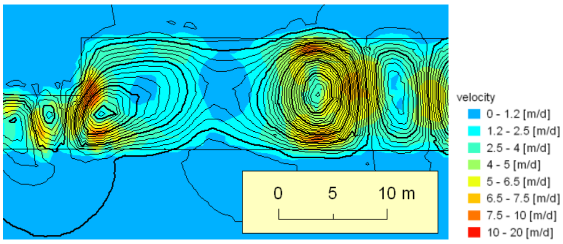

Figure 4 Convection Cells shown by streamlines and velocity distribution (Renz et al. 2009)

3.3.2 Numerical Modeling of Heat Transport in Mine Workings

No standard approach has emerged yet, though the strong influence of pre-existing simulation codes on the simulation strategies can be noted.

In previous studies, a number of different approaches have been used to simulate fluid flow within mine workings. Representations of mining voids in the literature range from 3-D Navier-Stokes calculations (cited in Wolkersdorfer 2008) to different 3-D porous media approaches combined with 1-D pipe flow (Adams and Parkin 2002; Reymond and Therrien 2008), and from hybrid finite element mixing cell approaches (Brouyère et al. 2008) to Darcy flow for both host rock and mine workings (Malolepsy 2003). To choose an appropriate simulation strategy for mine voids, it is important to decide on the flow equation and the required dimension (1-D, 2-D, or 3-D) based on the physical properties of the system in question.

An example of a type 3D model is shown in Figure 5. The volume of the water-filled mine workings in this particular system is approximately $2.18{\cdot}10^6$ m^3. One pair of extraction and injection wells was used on different horizons, and the pumping rate was set to 300 m^3 d^{-1} (this equals a theoretical complete exchange of the mine water during a pumping time of 20 years). The dimension of the model is 5 km in the x-direction and 5 km in the y-direction, as shown in Figure 5. The depth extends from -750 m up to the variable level of topography (approximately 70 m above sea level). The model uses a temperature dependent density for computations. Further details are given in Renz et al (2009).

The heat transfer resulting from the geothermal operation can be calculated based on Equation 6

$$Q = (T_{out} - T_{in}) \cdot (\rho c)_f \cdot q \qquad (6)$$

where Q is the amount of heat transferred (W), T_{out} and T_{in} are the temperatures (°C) at the extraction and injection wells, respectively, $(\rho c)_f$ is the volumetric heat capacity of the fluid (typically $4.2{\cdot}10^6$ J m^{-3} K^{-1}), and q is the flow rate (m^3 d^{-1}).

3.4 Geochemical Reactions

Another important aspect that has to be regarded in geothermal modeling is the influence of geochemistry. Especially in case of deep geothermal energy facilities, operations lead to significant changes in the chemical milieu of the aquifers, including changes in temperature, salinity, and acidity level. These factors can have a critical impact on the hydraulic conductivity of the hydrothermal reservoir. Especially borehole clogging can significantly decrease the available flow rate in the facility. On the other hand, geochemical stimulation can be used to maximize these flow rates (Wagner et al., 2005). When coupled with sound understanding of these processes, codes capable of simulating chemical processes (e.g. SHEMAT, FEFLOW) can therefore be a valuable tool to minimize economic risk and optimize profitability.

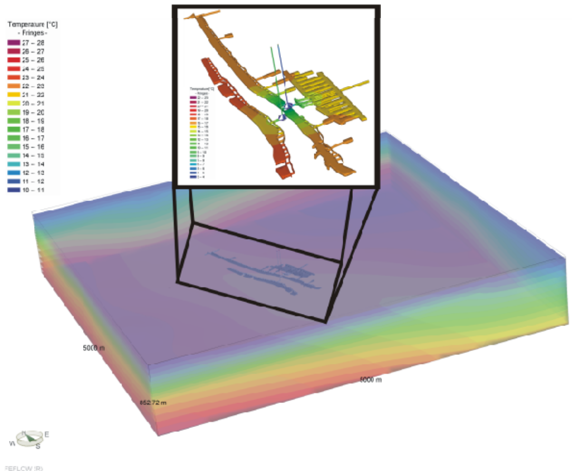

Figure 5 :3D model showing the calculated temperature. In a magnified image, the temperature in the centrally positioned mine workings is displayed (Renz et al., 2009)

DISCUSSION AND OUTLOOK

Numerical simulation can be a powerful tool for designing and planning purposes in geothermal applications. The computations require the availability of subsurface temperature measurements and additional parameters such as thermal conductivity and thermal capacity. In addition to the evaluation of geothermal installations, these data can give substantial new information about the flow fields (Anderson, 2005).

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