MODELLING AND SIMULATION OF GROUNDWATER INFLUENCE ON BOREHOLE THERMAL ENERGY STORES

D. Bauer, W. Heidemann, H. Müller-Steinhagen
University of Stuttgart, Institute of Thermodynamics and Thermal Engineering
Pfaffenwaldring 6, D-70550 Stuttgart, Germany
Tel: +49-(0)711-685-69445
bauer@itw.uni-stuttgart.de

H.-J. G. Diersch
DHI-WASY GmbH
Berlin, Germany

ABSTRACT
Borehole thermal energy stores used for seasonal heat storage in solar assisted district heating systems are very sensitive to groundwater flow. A heat and mass transport model has been developed by the authors in order to simulate the influence of moving groundwater on borehole thermal energy stores. This was done by combining an advanced numerical strategy, where the borehole heat exchangers are modeled by one-dimensional finite-element representations with three-dimensional finite element modeling of the surrounding ground. Thus, the computation time is significantly reduced compared to fully discretized computations while precise results are still achieved. The model is used to investigate the efficiency of a borehole thermal energy store consisting of 80 borehole heat exchangers similar to the one that is currently built in Crailsheim, Germany.

1. INTRODUCTION
Borehole thermal energy stores (BTES) consist of a large number of borehole heat exchangers typically installed with spacing in the range of two to five meters (VDI 4640, 2001) as the thermal interaction of the individual borehole heat exchangers is essential for an efficient storage process. BTES can be a reasonable technical and economical alternative – depending on the local geological and hydrogeological situation – to other techniques of heat storage for the use in solar assisted district heating systems with seasonal heat storage (Bodmann et al., 2005). BTES are very sensitive to groundwater flow. Both, for permit procedures required by the authorities and for plant-engineering issues, a simulation tool is needed which is capable of predicting the three-dimensional temperature profile in the underground and the thermal efficiency of the store. However, no suitable simulation tool exists to predict the long-term performance of these systems in the presence of groundwater flow.

2. FINITE ELEMENT MODELING OF BOREHOLE HEAT EXCHANGERS
Due to their flexible mesh generation, finite element simulation programs are well suited when it comes to detailed modeling of geological and hydrogeological conditions. Despite modern and
powerful computers and the possibility of parallel computing, today it is not yet wise to model borehole heat exchangers in a fully discretized manner, as shown in Figure 1. The computation time for BTES consisting of various borehole heat exchangers would easily exceed the simulation time period and so foil a feasible application. Additionally, the effort in terms of time and modeling work would be substantial.

A more target-oriented manner is the modeling of borehole heat exchangers as one-dimensional line elements in the three-dimensional finite element model of the underground. As the surrounding ground can be discretized with a relatively coarse mesh compared to the geometry of a borehole heat exchanger, the number of finite elements can radically be reduced. Furthermore, the number of finite elements only slightly increases with an increasing number of borehole heat exchangers as the geometrical dimensions of the model area remain constant. BTES can be modeled and simulated in an efficient and variable manner with this technique. Figure 2 shows the implementation of a one-dimensional line element representing a borehole heat exchanger in the three-dimensional finite element modeling of the surrounding ground.

3. LOCAL HEAT AND MASS TRANSPORT IN THE BOREHOLE

The heat and mass transport process in the borehole can be described by simplified thermal resistance and capacity models. Figure 3 shows exemplarily the horizontal cross-section of a single U-tube borehole heat exchanger and a suitable thermal resistance and capacity model developed by the authors.
Figure 3: Horizontal cross-section of a single U-tube borehole heat exchanger and the corresponding thermal resistance and capacity model; $T_i$: fluid temperatures, $T_{gi}$: grout temperatures, $T_b$: temperature of the borehole wall, $q_i$: heat fluxes, $C_g$: thermal capacities, $R_{ii}$: thermal resistances

These simplified models can be solved numerically or analytically. One numerical approach was shown by Al-Khoury et al. (Al-Khoury et al., 2005 and 2006). For the fluid in each tube one node and for the grout one or several nodes are set in a horizontal cross section of the borehole. The borehole wall is represented by one single node. This node is the interface between the local process in the borehole and the three-dimensional finite element matrix of the surrounding ground.

Based on this procedure, the authors developed advanced thermal resistance and capacity models for different types of borehole heat exchangers. These models take care of a correct thermodynamical description of the heat transport processes between the heat exchanger tubes and the borehole wall as well as the internal heat transport between the tubes.

One of these two-dimensional models is set for every slice of the finite element matrix. Vertical linkages of the model nodes account for the heat and mass transport processes in vertical direction making a three-dimensional model out of several two-dimensional models (Figure 4). This approach allows a correct computation of the transport processes even at fast-changing boundary conditions. The moving temperature front in the fluid channels after a step of the fluid inlet temperature can be tracked. This solution procedure has shown very effective. Together with the correct consideration of the thermal capacity of the grout it makes short simulation time steps possible.

Figure 4: Connection of several 2D models to a 3D thermal resistance and capacity model capable of describing transient heat transport processes in horizontal direction and heat and mass transport processes in vertical direction.
In addition to the described numerical method the calculation of heat and mass transport processes can be carried out in an analytical way. This has been shown by Eskilson and Claesson for a Delta-circuit at stationary conditions (Eskilson et al., 1988). More complex models such as shown in Figures 3 and 4 can still be solved by this method using a set of coupled linear differential equations. One equation of the set describes the vertical temperature distribution of the fluid in one tube. For a borehole heat exchanger consisting of two fluid channels (single U-tube and coaxial) the set of differential equation complies with the following expressions:

\[
\frac{dT_1(z)}{dz} = a \cdot T_1(z) + b \cdot T_2(z) + c \cdot T_b(z) \quad L \leq z \leq 0
\]

\[
-\frac{dT_2(z)}{dz} = a \cdot T_2(z) + b \cdot T_1(z) + c \cdot T_b(z) \quad L \leq z \leq 0
\]

The coefficients \(a\), \(b\) and \(c\) can be derived from the thermal resistances and the heat capacity flows in the tubes. If the temperature of the borehole wall \(T_b(z)\) is known, the temperature distribution of the fluid inside the tubes and afterwards the heat flow between the fluid and the borehole wall can be calculated as a function of the depth \(z\). This method features short computation times compared to the numerical method. Especially waiving the computation of the convective heat and mass transport in the heat exchanger tubes via finite element method leads to an increased stability and hence significantly less numerical effort. On the other hand, one disadvantage of the analytical method is the assumption of stationary conditions of the grout. Furthermore, the outlet temperature of the borehole heat exchanger cannot be calculated after a step change of the inlet temperature until the fluid has passed the complete length of the heat exchanger tubes at least once. For these reasons, this method is only suitable for simulation time periods of several hours or more.

4. IMPLEMENTATION AND VERIFICATION OF THE SIMULATION MODEL

Both described methods were implemented in the finite element subsurface flow and transport simulation program FEFLOW (FEFLOW, 2007). For first model verification purposes comparative calculations were carried out with the analytical method and the Superposition Borehole Model (SBM) (Eskilson, 1986), the Duct Ground Heat Storage Model (Pahud et al., 1996) and additionally an in-house developed finite difference solver (FDS) (Heidemann, 1995).

For a 100 meter long DN32 single U-tube heat exchanger in a 130 mm borehole two comparative calculations between SBM, DST and the FEFLOW model were performed. After a step of the inlet temperature from 10°C to 40°C the inlet temperature was kept constant for a time period of 90 days. The mass flow rate was assumed constant during the simulation. The initial ground temperature was set to 10°C. Figure 5 shows the resulting outlet temperatures for two different mass flow rates (run 1: 0.05 kg/s, run 2: 0.2 kg/s) and the deviation and accumulated deviation regarding the transferred heat amounts of the FEFLOW model compared to the DST model. While the DST and SBM model nearly show the same results, the FEFLOW model shows a deviation in the range of 3% to almost 0% (run 1) and 8% to 6% (run 2) during the simulation period.

To check if the FEFLOW model gets inaccurate for high mass flow rates a comparison with a finite difference solver was conducted. This program gives the opportunity to build up fully discretized models as long as they can be described in cylinder coordinates. The comparison had to be made for a coaxial borehole heat exchanger installed in a 100 m deep borehole with 100 mm in diameter. The
mass flow rate was kept constant at 0.25 kg/s during the complete simulation time while the inlet temperature was prescribed by a periodical function. At time zero the inlet temperature is raised from 10°C to 80°C and at 90 days it is reduced from 80°C back to 10°C. So in addition to the comparisons with the DST and SBM models a storage effect could be included. Figure 6 shows the resulting outlet temperatures and deviations. During the heat injection process (day 0 to 90) the deviation is below 1% and during the following heat extraction period (day 90 to 180) it still remains below 2%.

Figure 5: Comparative calculations of the DST, SBM and FEFLOW models for two different mass flow rates

Figure 6: Comparative calculation between a fully discretized finite difference model and the FEFLOW model
Both, the analytical and the numerical local borehole model do not account for convective groundwater influence. This could be done as typically used grout materials can be considered as nearly groundwater impermeable. The global model of course is able to account for convective groundwater influence. Because the combined convective-conductive driven heat and mass transport in FEFLOW has been validated in many cases, the authors did not go for validating it again. Instead of that, a validation against measured thermodynamical and hydrogeological data of a BTES realized in Crailsheim, Germany, is planned as soon as measured data from Crailsheim are available. FEFLOW offers several types of upwinding to stabilize numerical results if both relatively coarse meshes and convection-dominated transport processes lead to wiggles in the results. These upwinding methods can generate a certain amount of spurious numerical dispersion which is difficult to quantify. Possible distortion of the results could be avoided by using no upwind (Galerkin FEM). This made short time steps and a small error tolerance necessary.

Showing very good accuracy during this first verification process, the model seems to be well suited to be used for the purpose it has been developed: The investigation of the influence of moving groundwater on BTES.

5. SIMULATION OF A REAL BTES

To investigate the influence of moving groundwater on BTES of real dimensions, the recently built BTES in Crailsheim, Germany was simulated. This BTES consists of 80 double U-tube borehole heat exchangers with 55 m in length installed on a circular area with 30 m in diameter. The BTES is situated in a geology comprising two aquifers (Table 1). More details concerning the BTES in Crailsheim can be found in (Bauer et al., 2007), (Bauer et al., 2008) and (Rieger, 2008).

Table 1: Hydrogeological data of the two aquifers

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Aquifer 1</th>
<th>Aquifer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic gradient [-]</td>
<td>0.01</td>
<td>0.0045</td>
</tr>
<tr>
<td>Transmissivity [m²/s]</td>
<td>1·10⁻⁴</td>
<td>5·10⁻³</td>
</tr>
<tr>
<td>Porosity [-]</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Extent below top ground surface [m]</td>
<td>6 - 22</td>
<td>62 - 103</td>
</tr>
</tbody>
</table>

The simulation was conducted for a time span of five years featuring an alternation between one heat inserting period and one heat extracting period of six months per year. Figure 7 shows the resulting temperature profile of the underground after the heat inserting period in the fifth year. At the top of Figure 7 a reference temperature profile is depicted which is related to the case without groundwater flow. On the bottom the temperature profile with moving groundwater in both aquifers is shown. It can be seen that especially the aquifer below the store due to higher groundwater velocities has a significant effect on the temperature profile outside the store (black box or circle, respectively). The temperature profile inside the store only differs slightly.

Table 2 lists the heat amount injected and extracted as well as the utilization ratio defined in (VDI 4640, 2001) obtained by this simulation for the five simulation years. Only a small decrease of performance due to the groundwater movement can be observed. In the first year the utilization ratio with groundwater movement even reaches a higher value by reason of enhanced heat transport (conductive plus convective) in the storage medium. More details on this investigation can be found in (Bauer et al., 2008).
Figure 7: Simulated temperature profile of a BTES with and without moving groundwater. The horizontal cuts on the right show the temperature 15 m below ground surface (~ middle of upper aquifer)

Table 2: Calculated injected and extracted heat amount and resulting utilization ratios for the five simulation years

<table>
<thead>
<tr>
<th></th>
<th>inserted heat without/with moving groundwater [MWh]</th>
<th>extracted heat without/with moving groundwater [MWh]</th>
<th>utilization ratio without/with moving groundwater [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st year</td>
<td>1538 / 1534</td>
<td>-691 / -698</td>
<td>44.9 / 45.5</td>
</tr>
<tr>
<td>2nd year</td>
<td>1350 / 1352</td>
<td>-762 / -752</td>
<td>56.5 / 55.6</td>
</tr>
<tr>
<td>3rd year</td>
<td>1308 / 1312</td>
<td>-781 / -783</td>
<td>59.8 / 59.7</td>
</tr>
<tr>
<td>4th year</td>
<td>1293 / 1303</td>
<td>-799 / -780</td>
<td>61.8 / 59.9</td>
</tr>
<tr>
<td>5th year</td>
<td>1289 / 1291</td>
<td>-808 / -786</td>
<td>62.7 / 60.9</td>
</tr>
</tbody>
</table>

6. CONCLUSION

The influence of moving groundwater on borehole heat exchangers as well as borehole thermal energy stores can be investigated by implementation of the depicted heat and mass transfer processes in the simulation program FEFLOW. The resulting simulation tool provided good agreement with comparative calculations. The proposed implementation method provides the possibility of a dynamic coupling with energy simulation programs, e.g. TRNSYS (TRNSYS, 2000). Hence, it can be used to simulate the interaction of borehole thermal energy stores and the connected systems technology even with groundwater movement. Currently ITW and DHI-WASY GmbH are working on a user-friendly, commercially available simulation program based on the described approach. This program will come with a TRNSYS interface. Extensive validation work is in progress, including validation against measured data of the BTES in Crailsheim.
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REFERENCES


