Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Monitoring a Borehole Heat Exchanger Field of a Multifunctional Office Building

Alexander Michalski[1], Norbert Klitzsch[1], Darius Mottarghy[2], Christoph Clauser[1]

[1] Institute for Applied Geophysics and Geothermal Energy, E.ON ERC, RWTH Aachen University, Germany

[2] Geophysica Beratungsgesellschaft mbH, Aachen, Germany

AMichalski@eonerc.rwth-aachen.de

Keywords: Borehole heat exchanger, BHE, groundwater, numerical simulation, EGRT, Enhanced Geothermal Response Test

ABSTRACT

Heating and cooling account for large energy consumption in office buildings. Here, use of renewables may reduce CO_2 emissions significantly. We present the new energy concept of the E.ON Energy Research Center, a multifunctional building in Aachen. Its energy derives from a geothermal borehole heat exchanger (BHE) field with 40 double U-tube BHEs, each 100 meters deep, a gas-fired combined heat and power (CHP) unit, and photovoltaics. The working fluid is a 35 % glycol-water solution. The project aim is to ensure a sustainable and long-term operation responding the heating and cooling load from different types of space, such as offices, conference or server-rooms. We use different tools, such as Distributed Temperature Sensing (DTS) for monitoring temperature within the BHEs, Enhanced Geothermal Response Test for measuring the apparent thermal conductivity, and SHEMAT, a simulator for heat and mass transport for numerical simulation. Specific groundwater flow is an important process which affects strongly the long-term efficiency of a BHE field. For estimating specific discharge rate and direction of groundwater flow, temperature sensor-rings are placed within one of the BHEs providing information on the temperature distribution outside the BHE. We perform forward simulations for different discharge rates from 85 m a^{-1} to 0.85 m a^{-1}, inlet and outlet temperatures. Assimilation of this data serves for estimating groundwater discharge rate and direction, thus helping to optimize and calibrate the numerical sub-surface model of the BHE field. We calculate the temperature difference for a BHE with groundwater flow of 8.5 m a^{-1} which is in an order ΔT of 20 mK which can be resolved by actual digital temperature sensors.

1. INTRODUCTION

The E.ON Energy Research Center's multifunctional building is equipped with a borehole heat exchanger field (BHE). This BHE field consists of 40 PE-100 exchangers with a depth of 100 meters. The volumetric flow rate and inlet and outlet flow rate can be monitored and manipulate individually by the monitoring, control, and interface system (MCIS). This dynamic operation mode provides the opportunity for a sustainable use of the geothermal heat storage capacity by optimizing the heating and cooling periods. The thermal storage capacity of a borehole heat exchanger field depends strongly on the thermal interaction of the BHEs. Claesson shows that the BHE field geometry and the thermal interaction between the BHEs depend on the groundwater flow, Claesson & Eskilson (1988).

The Enhanced Geothermal Response Test (EGRT) is an established and useful method for determine groundwater flow rate and its influence on the apparent thermal conductivity is the Enhanced Geothermal Response Test (EGRT). Combining information derived from borehole measurements and from the EGRT one help determining regions with apparently high thermal conductivity. Regions with unexpected high thermal conductivity indicate possible groundwater flow within the layers. However, the EGRT data do not allow determining the flow direction and the exact discharge rate of the groundwater.

We present a new concept for a temperature recording system for determining the groundwater flow rate and its direction using temperature sensor rings installed within the BHE. This allows monitoring the temperature distribution in near and around the BHE. Additionally, we simulated the temperature distribution around the BHE for horizontal Darcy flow rates ranging from 0.85 m a^{-1} ($2.7\ 10^{-8}$ m s^{-1}) to 85 m a^{-1} ($2.7\ 10^{-6}$ m s^{-1}). Results indicate that flow rates as low as 8.5 m a^{-1} can be resolved by temperature measurement with a minimal resolution of 0.01 K The results serve for dimensioning a temperature sensor module for groundwater detection in direct vicinity of a BHE without using any geometrical correction factors or tracer tests (Morgenstern, 2005).

2. EQUATIONS

Simulations are based on SHEMAT, a finite-difference simulator for heat and mass transport in porous media. (Clauser 2003). The combined flow and heat transport equations are solved on a Cartesian 2-D grid.

$$\nabla \bullet \left[\frac{\rho_W\, gk}{\mu} \left(\nabla h + \rho_r \nabla z \right) \right] + Q = S_s \frac{\partial h}{\partial t} \tag{1}$$

where ρ_W is the density of water [kg m^{-3}], μ_W the dynamic viscosity of water [kg $(m\ s)^{-1}$], g gravity [m s^{-2}], k permeability [m²], h the hydraulic head [m], z the vertical coordinate in space [m], and $\rho_r = (\rho_f - \rho_0)\ \rho_0^{-1}$ describes the relative change of water density towards a reference density ρ_0. Q is a specific flow source term and S_s the specific storage coefficient [m^{-1}].

In analog to the flow equation based on mass balance, the heat transport equation may be derived from Fourier's Law and energy balance:

$$\nabla \bullet \left(\rho_W\, c_W\, T\, v - \lambda \nabla T \right) + H = \left(pc \right)_e \frac{\partial T}{\partial t} \tag{2}$$

where T is the temperature [°C], c_w is the specific heat capacity of water [J(kg K)$^{-1}$], and H a heat source term [W m^{-3}]. The effective thermal conductivity of the fluid filled matrix, λ_e [W m^{-1} K^{-1}], c_w and c_e are the volumetric heat capacities of water and the fluid-saturated porous medium [J m^{-3} K^{-1}], respectively. ν is the Darcy velocity [m s^{-1}].

3. MODEL DESCRIPTION

Two 2-D models are set up in this work. In the first model the working fluids temperature is simulated for a single inlet and outlet tube. This cylindrical symmetrical model is a simplification of the real case. The simulation results provide the temperature of the working fluid as input parameters for the next 2-D model. Here we calculate the development of the temperature distribution in a horizontal cross section of a Double U-Tube BHE in a certain depth of interest.

3.1 Numerical simulation of working fluid temperature in a BHE

The temperature distribution in the vicinity depends strongly on the difference between inlet and outlet fluid temperature. In a first step, the temperature distribution of the working-fluid is calculated along the BHE. We consider the simplified case of a single inlet tube where the temperature of the fluid at the bottom of the tube is used as input parameter for the outlet temperature distribution. We consider a 100 meter long tube. The rotationally symmetric 2-D model consists of 30 × 120 × 1 cells. The cells representing the pipe are 16 millimeters thick and one meter long for a realistic description of the pipe. Further, the pipe's wall and the backfilling cement are also resolved. In z-direction the pipe is divided in 100 equidistant, one meter long sections while the entire model extends to 150 meters depth for avoiding boundary effects. Six geological layers are modeled according to drilled lithology. The different colors in Figure 1 denote different layers with varying parameters for porosity and thermal conductivity. . In this first period of operation where the working fluid just reaches the bottom of the pipe, the interaction between the inlet and outlet tubes can be neglected.

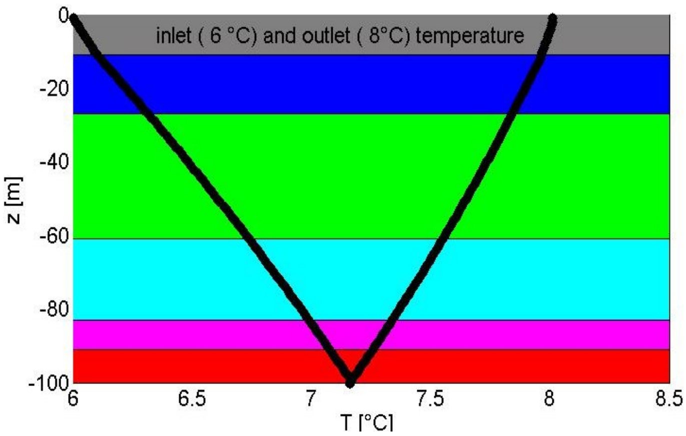

Figure 1: Simulation results for the cylindrically symmetrical 2-D model. The curves show the calculated inlet and outlet temperatures as a function of depth. Colored layers denote ground with different geophysical parameters.

For simulating the inlet and outlet temperatures we assume a general working mode with an inlet temperature of 6 ° C for heating. As a result of the simulation the calculated outlet temperature on the top of the outlet tube is T = 8 °C. Both temperature profiles yield a realistic approximation of the temperature distribution as a function of depth as the outlet temperature fits well with the temperature (T = 8.1 °C) measured at the control temperature sensor. As Figure 1 shows, the temperature gradient is lower in the first 10 meters due to a lower thermal conductivity of 1.2 W m^{-1} K^{-1} comparised to the other layers (thermal conductivity of layer two to six in W m^{-1} K^{-1}: 2.6, 2.83, 3.01, 2.87, and 2.92). The depth where groundwater flow is expected was determined by an Enhanced Geothermal Response Test. With this Test variation of thermal conductivity with depth can be determine by heating the borehole and monitoring its cooling. In comparison with the stratigraphy porosity one can identify regions of unexpected high apparent thermal conductivity. The result of our EGRT indicates that an aquifer and related groundwater flow at a depth of around 75 to 90 meters. At this depth we calculated numerically a temperature difference between the inlet and outlet tubes in the range of 0.5 Kelvin and less.

As in the 2D cross section model of the BHE only the temperature changes are important. We suppose for further simulations an inlet temperature of 6.0 °C and 6.5 °C, respectively, and a temperature of the surrounding soil of 10 °C.

3.2 Numerical simulation of a cross-section of a BHE

In a second step we simulate a 2-D horizontal cross section of the borehole heat exchanger of one meter thickness. The model domain is discretized into 247 × 247 finite difference cells with different lengths depending on the distance to the area of interest. The simulated area is 18 × 18 meters long and wide with a refined discretization of 0.0032 meters in the direct vicinity of the borehole and of the borehole heat exchanger. This resolves single pipes of the BHE and the structure around it well. The borehole heat exchanger is a standard PE-100 Double U-Pipe of 100 meters depth with a diameter of 150 millimeters. The two inlet and two outlet pipes have a diameter of 32 millimeters. Figure 2 shows a sketch of the modeled BHE. The black dots denote the monitoring points in our simulations as well as the positions of the temperature sensors used in the real measuring system. The inlet tubes are marked with a cross while the outlet tubes are marked with a spot. The BHE is back-filled with a concrete suspension with a thermal conductivity of 2 W m^{-1} K^{-1}. The surrounding soil has a thermal conductivity of 2.6 W m^{-1} K^{-1} according to the data provided by the EGRT. This model is for simulating the ground water flow directions and groundwater flow velocities and their influence on the temperature distribution.

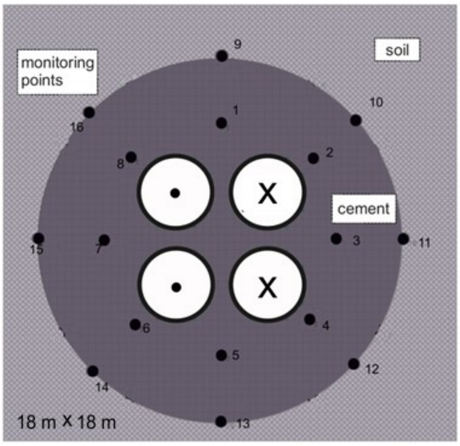

Figure 2: Schematic top view of the 2-D model for a horizontal cross section of a Double U-Tube BHE. The crosses indicate the inlet tubes, the dots indicate the outlet tubes. Black numbered dots show monitoring points for the inner and the outer ring.

4. SIMULATIONS

The temperature difference, ΔT between inlet and outlet tubes at a depth of 80 meters is 0.5 Kelvin. Hence the inlet temperature is set to T = 5.9 °C, the outlet pipe temperature is calculated to be 6.4 °C while the underground has a temperature of 10 °C. Three different groundwater specific discharge rates are considered for a realistic range of flow velocities (v in m a^{-1}: 0.85, 8.5, and 85). These values had been measured in pumping tests in the local area. Additionally, the flow direction varies from 0° to 180° in 22.5° steps of 22.5° with respect to the positions of the inlet tubes. The flow direction is varied because the model is asymmetric due of the arrangement of the PE-100 tubes. The groundwater flow is simulated from the inlet side (0°) to the outlet side (180°). Therefore nine different scenarios for temperature distributions are generated depending on the groundwater flow direction. Each of the nine scenarios is calculated for the three different discharge rates varying from 0.85 m a^{-1}, 8.5 m a^{-1} and 85 m a^{-1}. Figure 3 shows calculating results for a flow velocity of v = $3x10^{-6}$ m s^{-1} from left to right. This means heat is transported towards the BHE at with a temperature of 10 °C at the up-flow side while on the down-flow side the BHE is cooling the underground to the right side.

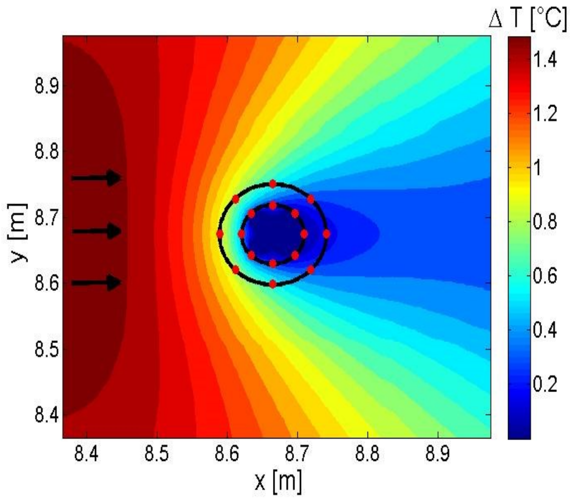

Figure 3: Simulated specific discharge of temperature differences around a BHE. Black arrows indicate the groundwater flowing direction v = 85 m a-1.

The temperature distributions of each scenario are calculated and temperatures are monitored at the sensor positions labeled with "1" to "8" for the inner ring and "9" to "16" for the outer ring.

The simulation shows that the influences of groundwater flow on the sensors on the inner ring are small due to the thermal resistance of the grout. However, the inner ring is essential for determining the sensor's position relative to the BHE tubes. As the double U-tube heat exchanger is not a symmetrical problem, the temperature shift resulting from BHE layout has to be accounted for. Depending on the groundwater flow azimuth the distorted temperature distribution differs with the relative position of the inlet and outlet tubes, (provided that both differ in temperature)..

4.1.1 Results for the inner ring

The four curves in Figure 4 represent the monitoring points on the inner ring. They represent four different time steps (time step of eight hours, one day, five days and 30 days). After five days the temperature distribution reaches a quasi-static level and do not change significantly for a flow velocity of 85 m a^{-1}. For smaller velocities it takes longer until a static state is reached. The effect of the orientation and the temperature of the BHE tubes show a significant impact on the measured or calculated temperature data. In this example the both inlet tubes with colder working fluid are near to the sensor position two and four, while the outlet tubes are in the vicinity of sensor positions five and seven. The inner ring serves for the exact estimation of the relative orientation of the two fixed rings to the position of the inlet and outlet tubes of the BHE. Based on this data the monitoring data information from the outer ring, which will be discussed further below can be interpreted, as the relative orientation of the BHE and of the tubes also influence the temperature distribution on the exterior wall of the BHE.

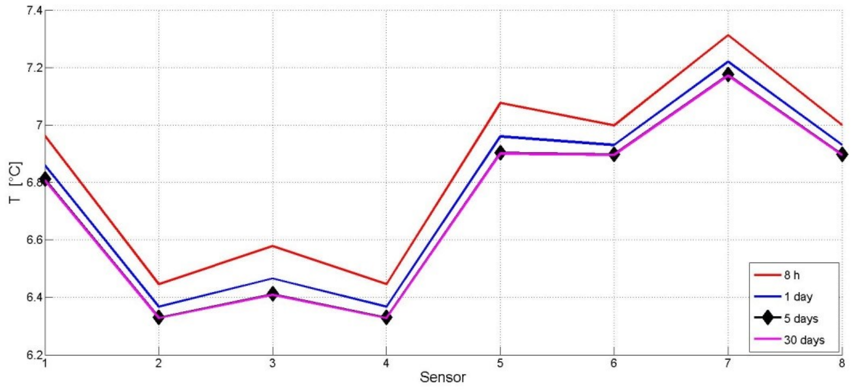

Figure 4: Simulated data for monitoring points on the inner ring at four different times.

Figure 5 shows the temperatures at the monitoring point for tree different flow azimuths. Azimuths of 0°, 90°, and 180° correspond to the temperature data calculated for groundwater flow from left, top, and right, respectively. One can see that the groundwater flow for fast groundwater flow velocity v = 85 m a^{-1} has a strong effect on the temperature distribution of the inner ring. This effect decreases rapidly for lower velocities. In the case of v = 0.85 m a^{-1} the temperature difference for each sensor for opposite flow directions is about 2 mK.

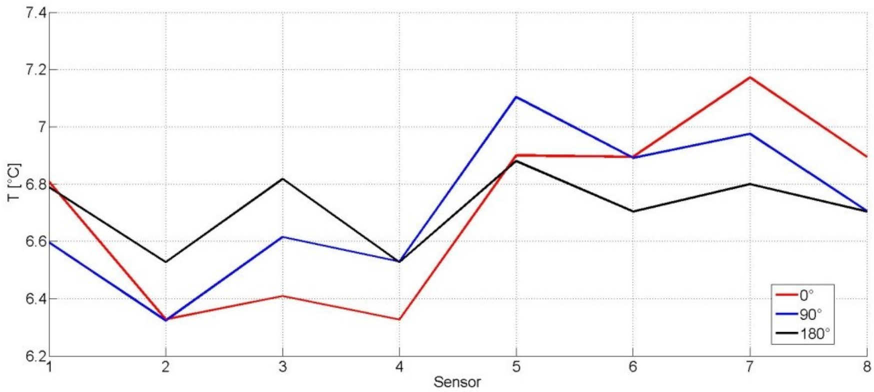

Figure 5: Influence of groundwater flow direction on the temperature at the monitoring points on the inner ring for 3 different flow azimuths.

4.1.1 Simulation results for the outer ring

Measuring the direct groundwater flow and its magnitude require a second monitoring ring. For precise measurements the sensors must be in direct contact with the surrounding ground. The curves for the outer monitoring data points are plotted in Figure 6. Again for a groundwater flow velocity of 85 m a^{-1} and identical times as before a quasi-steady state starts after day five. Here, the maximum and minimums peak of the temperature distribution are clearly visible.

Using the monitoring points at senor position on the outer ring, groundwater velocities down to 0.85 m a^{-1} can be resolved, with a difference in temperature of about 0.2 K between sensors on opposite sites along the flow direction. This means, that using an outer ring of temperature sensors measuring temperature distribution in the direct vicinity of a heat exchanger can be directly used to determinate the velocity and direction of the ground water flow can be determine for velocities of 0.85 m a^{-1} up to 85 m a^{-1}.

Figure 7 shows a comparable data set as in Figure 5 for the exterior ring. We have phase shifted temperature curves for groundwater flow direction change from left to right. The temperature curves are not equal because of the asymmetric design of the Double U-tube BHE. As a result the monitoring of the temperature data provides a very good tool to determine the groundwater flow direction.

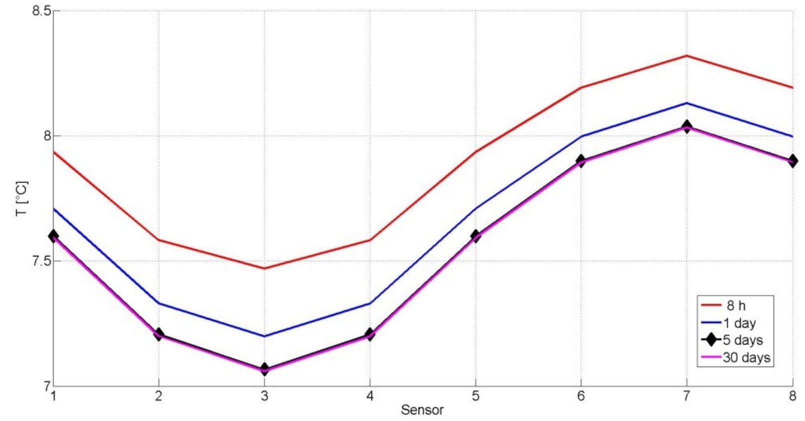

Figure 6: Simulated data for monitoring points on the external ring at four different times.

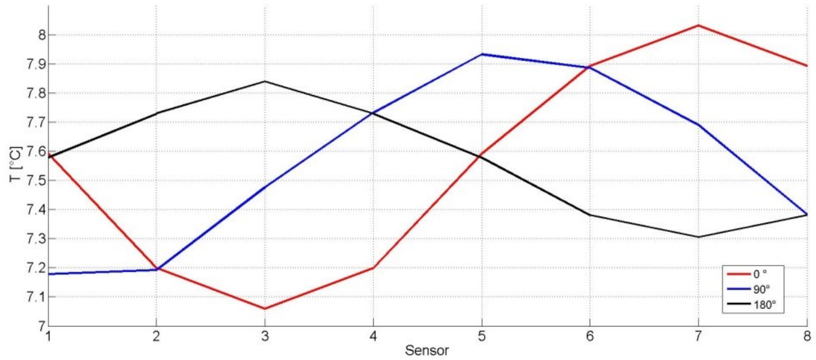

Figure 7: Influence of groundwater flow direction on the temperature at the monitoring points on the outer ring for 3 different flow azimuths.

5. CONCLUSION

We performed numerical simulations on groundwater flow in the direct vicinity of a borehole heat exchanger during operation. The specific simulated BHE is an asymmetric Double U-Tube P-100 of 100 meter length. The simulations where performed with SHEMAT a simulator for heat and mass transport in porous media.

Using a simplified model of a linear tube allowed us simulating the temperature distribution of the working fluid along the BHE as a function of depth. This gives the possibility for further simulations on the horizontal temperature distribution in the vicinity of the BHE as a function of underground temperature, specific parameters like thermal conductivities, working fluid temperature and most important as function of the groundwater flow.

In a second step we analyze the effect of groundwater flow on a BHE in a specific discharge interval and by varying groundwater flow direction. The temperature distribution changes from a nearly symmetrical distribution as a function of the radius to an aciniform distribution. Depending on the ground temperature water transports heat to or away from the BHE. The simulations show that in an interval from 85 to 8.5 m a^{-1} of the flow velocity, the changes in temperature which arise from the groundwater flow are in the order of 0.02 K or greater. This temperature changes can be detect or monitored by technical digital sensors. For slower flow velocities the changes are less than 0.005 K, hence too small to resolve them technically. We present this as a possible new application tool for groundwater measurements near and around a BHE. This allows direct measurements of the undergrounds temperature and the effect of groundwater flow on the temperature distribution without using correction factors or tracer tests.

REFERENCES

Claesson, J. and P. Eskilson, 1988: Simulation Model for thermally interacting heat extraction boreholes. - Numerical Heat Transfer, 13, 149-165.

Clauser, C., 2006.: Numerical Simulation of Reactive Flow in Hot Aquifers. SHEMAT and processing SHEMAT, Springer, Heidelberg.

Morgenstern, A., 2005.: Entwicklung einer Einbohrloch-Messsonde zur Bestimmung der horizontalen Fließparameter ohne Störung des Strömungsfeldes, Dissertation, Technische Universität Cottbus.