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Long-term Performance of a Borehole Heat Exchanger Field Connected to a Multifunctional Office Building

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ABSTRACT

We present results of long-term numerical simulations of a large array of borehole heat exchangers (BHE) serving a multifunctional building. Automatically controlled heating and cooling operation has been monitored for a period of over two years. This data set, including groundwater flow, was used for a numerical simulation of the subsurface temperature over a period of ten years. Data from distributed optical temperature sensing (DTS) was used in some of the boreholes for calibrating the simulation results. We see different behaviours of BHEs depending on their specific position. We used the results on the variation of sub-surface temperature with time for optimizing the building's control regarding the management of the heating and cooling operation mode . With all monitoring and measuring systems in place at the E.ON ERC multifunctional building, the BHE array provides ideal ground-truth for testing long-term numerical simulations for a sustainable and cost reducing operation of such buildings..

1. INTRODUCTION

In modern energy concepts for heating and cooling operations, reduction of CO_2 emissions in multifunctional buildings is a big challenge. Additionally, integration of space for offices, laboratories, server and seminar rooms results in different load demands. Here, we present the new energy concept for 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 (Figure 1) and a gas fired combined heat and power (CHP) unit. in this contribution, we focus on the operation of the BHE array and its numerical simulation (Fütterer and Constantin, 2014).

Figure 1: E.ON ERC office building and geothermal array. Geophysical data are available from selected boreholes (red).

A main advantage of the E.ON ERC BHE array is that each single BHE can be switch on and off individually. This allows operation of single BHEs or BHE clusters depending on their spatial position and their long-term behaviour. Thus, we seek to ensure a sustainable and long-term operation, corresponding to the different heating and cooling loads from various 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 (EGRT) for measuring the apparent thermal conductivity, and SHEMAT-SUITE, a simulator for heat and mass transport for numerical simulation. We also present a new system for measuring minute groundwater flow rates in the direct vicinity of a BHE. This enables identifying the contribution of advective heat transport to and from a

BHE , an important process affecting the long-term efficiency of a BHE field significantly.

The heating and cooling loads of the building are managed by a simulation-based operation system. The numerical simulations of the BHE field account for the current and past energy loads of the buildings as variable input parameters. This allows calculating the possible heat storage capacity of the BHE-field for a sustainable use off the BHE field and hence an efficient long-term operation. We present results of long-term simulations of the BHE field and the resulting operation modes of the E.ON ERC building.

The challenge of long-term sustainable operation is to operate the geothermal field such that its energy use is balanced over one year. Our approach is to adjust the energy transfer between the building and the field accordingly to its energy balance. We achieve these adjustments by changing switching points and operation times of certain heating and cooling system modes within a mode-based control strategy. This strategy provides the required flexibility in operating the energy control of the building.

The main idea of the mode-based strategy is using an iterative process for simulating the geothermal field yielding the variation of the field's outlet temperature with time based on the thermal load transfer from the building to the field. Figure 2 shows the predictive control tuning process with its three main parts: initial calculations, energy and temperature profile calculation, and long-term field behaviour calculation.

Within this process, we first calculate the thermal load of the building by validated consumer models. The thermal load of the building and the field depends of the field's outlet temperature. In the first iteration, we use a temperature variation within the field simulated during the design phase of the building.

Then, we initialize the field simulation using the calculated thermal load as well as measured temperatures as initial values. This simulation yields a temperature variation for the field which is used as new input for calculating the thermal load. Once the new thermal load is calculated we run another field simulation and obtained an updated variation of the temperature variation with time within the BHE field. This iterative process is repeated until the thermal load over one year is balanced, i.e. its variation becomes negligible.

Finally, we use this balanced thermal load time series for calculating the long-term temperature variation of the field. A temperature increase of the field indicates a surplus of heat stored in the BHE field. If the temperature decreases, the field requires more heat for a sustainable operation. After achievement of a thermal balance for the field, we start another iterative process for calculating the final switching parameters which ensure an energy exchange over time between building and subsurface corresponding to a sustainable operation of the BHE field.

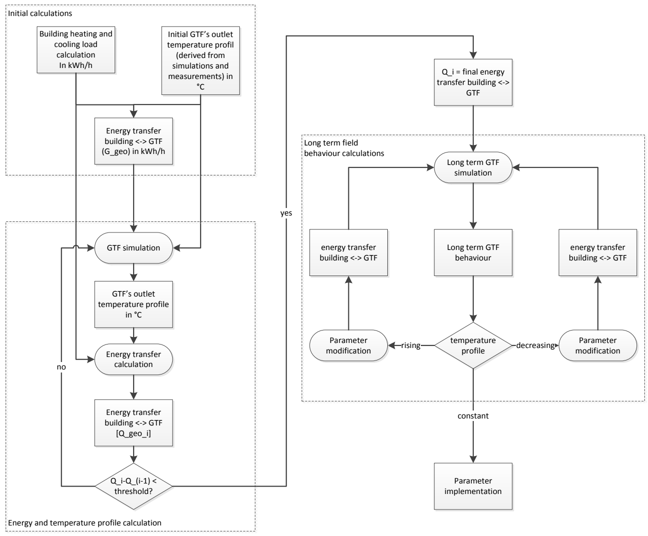

Figure 2: Iterative predictive control tuning process.

We developed and implemented this new control strategy to meet the demands of the predictive control tuning system. Fütterer and Constantin (2014) present this energy concept and the control strategy for buildings in detail.

2. METHODS

We focus on the long-term thermal simulation of the BHE array. These simulations are performed with SHEMAT-Suite, a finite-difference simulator for heat and mass transport in porous media. (Clauser 2006, Rath et al. 2006). The combined flow and heat transport equations are solved on a Cartesian, 2-D grid. We use the flow equation:

$$\nabla.\left[\frac{\rho_W g k}{\mu}\left(\nabla h+\rho_r \nabla z\right)\right]+Q=S_s\frac{\partial h}{\partial t},$$

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

Such as the flow equation is derived from Darcy's equation and mass balance, the heat transport equation is derived from Fourier's Law and energy balance:

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

where T is the temperature [°C], c_w the specific heat capacity of water [Jkg^{-1} K^{-1}], H a heat source term [W m^{-3}], , λ_e the effective thermal conductivity of the fluid-filled matrix [W m^{-1} K^{-1}], $(\rho c)_e$ the volumetric heat capacity of fluid-saturated porous medium [J m^{-3} K^{-1}], and v specific discharge or Darcy velocity [m s^{-1}]. Additionally, we use a semi-analytical FD approximation for calculating the thermal effect of the BHE (Mottaghy, 2012). The FD formulation considers the heating and cooling loads for the entire geothermal field and transfers it into an effective heat generation for an arbitrary number of BHEs. The BHEs can be arranged in any geometry within the field. Any of the BHEs may be switched on or off individually. This allows calculations of larger BHE fields, such as the E.ON ERC BHE array, within short time.

3. MODEL DESCRIPTION

We simulate numerically temperature variation in our BHE field of 40 double U-tubes, 100 meter deep each, and offset from each other by 10 meters. The simulated domain is 60 m × 120 m, discretised by cells size approximately 1 meter. To prevent boundary effects we add a 20 meters deep layer at the bottom with a heat production rate of 90 mW m^{-2} and a small top air layer for accounting the influences of long-term climate (Mann et al. 2009). The simulation domain is divided into seven layers of varying thickness. Each layer has specific properties, such as permeability, porosity, heat capacity and thermal conductivity. These properties are derived from ten test drillings (Mottaghy et al., 2012) and Enhanced Geothermal Response Tests (EGRT). Thermal conductivity in these layers varies from 1.5 W m^{-1} K^{-1} to 2.3 W m^{-1} K^{-1}. The BHE field serves as a capacitor for heating and cooling of the multifunctional building. In summer, the geothermal field is used mainly for cooling and heat is stored in the ground. During winter, in contrast,, heat is extracted from the ground for heating. We use the building's heating and cooling power, which is provided to the BHE array via a heat exchanger device, as input parameter for the numerical simulation of the BHEs. The power is related linearly to the flow rate and the differente ΔT between inlet and outlet temperature from the BHE array:

$$P = \left(\rho c\right)_f \dot{Q}\Delta T$$

Here, $(\rho c)_f$ is the volumetric heat capacity of the working fluid and $\dot{Q}$ is the volume flow rate of the fluid which, for a single BHE, is typically about 21 L s^{-1}. Figure 3 shows the power load data which we used for the numerical simulations over a period of 10 years. Here, heat extraction from the field is represented by positive values and heat injection is indicated by negative power values.

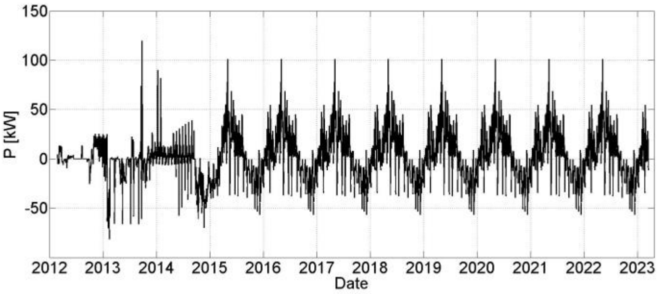

Figure 3: Extrapolated power demand scenario for 10 years office building operation. It consists of the first part of manual operation (2012 - 2014), followed by automated operation (2014 - 2015) and hypothetic data, deduced from the automated operation period (2015 - 2023).

Due to operation mode optimization, the building had not been managed automatically until May 2014. This is indicated by the non-sinusoidal shape in Figure 3 until May 2014. From May 2014 to the end of 2015, the operation mode was managed automatically by the building operation system. Power demand for the long-term numerical simulations was deduced from the automated operation until 2023. Additionally, we integrated groundwater flow into the numerical simulation. Specific discharge was assumed to be between 0.8 meters per year and 80 meters per year. Corresponding to Darcy's Law, this corresponds to a head difference in our model between 0.3 m and 30 m. First we simulated a steady-state subsurface temperature distribution under variable groundwater flow, without BHEs. Then, we used these data as initial condition for the subsurface temperature (T_0 = 10 °C) in the numerical simulations of the BHE field. The power load demand shown in Figure 3, is used for the heating and cooling injection or extraction power. For monitoring of the temperature field distribution, we use the position of BHEs 8, 32 38, and 39. We calibrate the BHE field temperature with the DTS monitoring data. For this propose, the BHEs are set as inactive.

4. RESULTS

In a first step, we use DTS data to calibrate the numerical simulation of the BHE field. The temperatures are measured along the BHE in an optical fibre with a spatial resolution of 0.1 m. and an accuracy of 0.1 K. Figure 4 shows DTS temperatures for a short period of time from several BHE s. The blue and green lines represent the inlet and outlet temperature of the BHE 33, respectively. They are logged via PT 100 platinum resistance temperature sensors with a accuracy of 0.1 K. The inlet temperature (blue) is slightly higher than the outlet temperature (green) in cooling operation mode. On June 21th, the heat pump was switched off. The corresponding DTS data for an active BHE 33 (blue +) in 80 meters depth are in good agreement with the measurements. The magenta crosses show the overall BHE field inlet temperature at the heat exchanger. The magenta crosses represent the measured average temperature for the inactive BHE 32 at a depth of 80 meters.

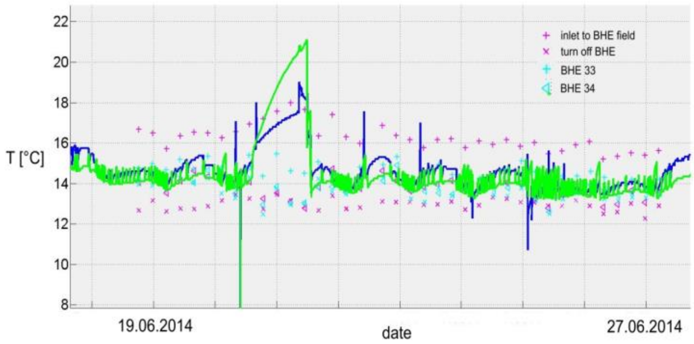

Figure 4: Inlet (blue) and outlet (green) temperatures for BHE 33. The symbols represent measured DTS temperature for different BHEs (magenta and cyan).

Figure 5 shows the numerical calculated results of the long-term temperature distribution for the BHE field at a depth of 80 meters. The monitoring points are at the positions of the inactive BHE 8, 32 and 38. Those positions are representative for three cases: (1) inside a smaller array of BHEs (BHE 8); (2) BHE inside a larger BHE array (BHE 32) and (3) BHE at the periphery of a BHE array (BHE 38).

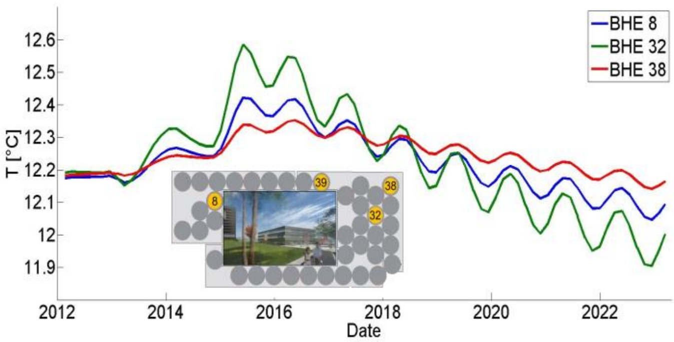

Figure 5: Time dependence of simulated temperature data at the position of the inactive BHE 8, 32 and 38 at a depth of z = 80 m and different positions within the BHE array.

A peripheral BHE is clearly affected less by the BHE field. The overall variation of the subsurface temperature is small. We attribute the increase of the subsurface temperature until 2016 to the overall higher amount of cooling power. During this period, about 3200 kW of heat from the building where stored in the ground while in the time period between 2016 and 2023 approximately 7000 kW of geothermal heat will be produced from the ground. For the soil in the position of a peripheral BHE, this yields a nearly zero heat balance. For the BHE position inside a BHE array, the temperature decrease is stronger due to the influence of the neighbouring BHEs. In summary, the numerical simulation shows that the operation of the building must be switched to a “less heating” operation mode.

Then, we compared the simulated temperature of the inactive BHE 39 (cf. Figure 1) at a depth of z = 80 m for different flow conditions. The simulation results assuming groundwater flow confirms qualitatively earlier simulations with completely deactivated flow (cf. Figure 5). The increase in temperature until 2016 corresponds to the manual building operation period. The following automated operation is characterized by a superposition of seasonal sinusoidal variation and a decreasing long-term trend. This general behaviour is still present under the different applied flow velocities. After a period of negligible unsystematic differences before 2015, results for different flow rates with corresponding head differences $\Delta h > 0$ do not differ considerably. Compared to the no-flow situation, the groundwater flow yields a temperature offset. Figure 6, shows an example for the variation with time of the offset between no-flow and maximal flow ($\Delta h = 30$ m:There is a slight decreasing difference, i.e. $\Delta T_{2012} - \Delta T_{2023} \approx 0{,}02$ K over 11 years of simulation.

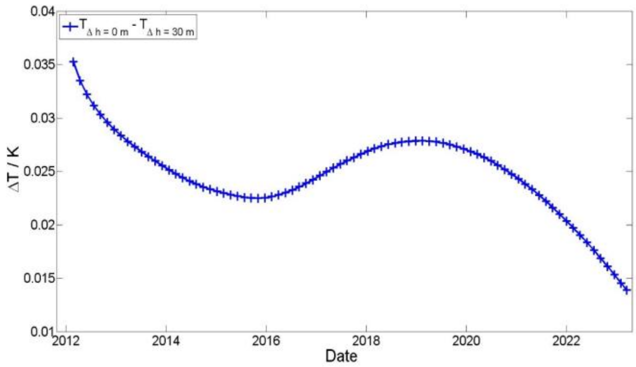

Figure 6: Time dependence of simulated temperature difference between the two cases with hydraulic head Δh = 0 m (no flow) and Δh = 30 m (maximum value) at the position of the inactive BHE 39 at a depth of z = 80 m.

5. CONCLUSIONS

We evaluated a first scenario for a sustainable operation of BHE arrays using a simulation-based control strategy of heating and cooling loads under the above mentioned groundwater flow conditions. In future studies, it would be a promising to quantify a corresponding threshold value for groundwater influence depending on the distance between active or inactive BHEs in relation to groundwater velocity. In the current operation scenario, the groundwater flow provides additional cooling. This and the effect of different spatial positions of the BHEs may be considered already for specifically adapted BHE array operation and building operation procedures.

Additionally, one should consider extending the simulation time period for quantification of a good estimator for a sustainable use of the BHE array.

REFERENCES

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

Fütterer J, Constantin A.: *Energy concept for the E.ON ERC main building*. Aachen: E.ON Energy Research Center; 2014. (E.ON Energy Research Center Series; vol 4,9).

Mottaghy, D., Pechnig, R., 2012. Erstellung und Kalibrierung eines numerischen geothermischen Modells für das E.ON-ERC Erdwärmesondenfeld. Erläuterungsbericht der Geophysica Beratungs-gesellschaft mbH.

Mottaghy, D., Dijkshoorn, L., 2012. Implementing an effective finite difference formulation for borehole heat exchangers into a heat transport code, Renewable Energy 45, 59-71, DOI:10.1016/j.renene.2012.02.013.

Mann, M.E., Z. Zhang, S. Rutherford, R. Bradley, M.K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. Ni, 2009: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. Science, 326, 1256-1260, doi:10.1126/science.1177303.

Rath, V., Wolf, A., & Bücker, M., 2006. Joint three-dimensional inversion of coupled groundwater flow and heat transfer based on automatic differentiation: sensitivity calculation, verification, and synthetic examples, *Geophysical Journal International*, **167**, 453-466.