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EFFECTS OF GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS ON THE PERFORMANCE OF VERTICAL GROUND COUPLED HEAT EXCHANGER SYSTEMS

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Abstract: Thermophysical properties of subsurface materials and groundwater flow strongly affect the heat exchange rates of ground coupled heat exchanger systems (GCHE). One popular method to estimate the mentioned thermal parameters is the interpretation of in situ thermal response test (TRT), but this method due to some simplifying assumptions could result in the overestimation of the number of needed heat exchangers. To overcome this problem, we propose to use finite element method to calculate the heat exchange rate of GCHE systems. Discrete Fracture Elements (DFE) has been integrated into the finite element matrix system to overcome the computational difficulties caused by the extreme disproportional geometries. To validate this method calculated data were compared with the data of a TRT and a cooling test measured at an implemented GCHE system. The correlation of calculated vs. measured data illustrate that the finite element model is able to better calculate the heat exchange rate than the TRT test. Next, we examined how the groundwater flow velocity (GWV), and the thermal properties in the grout affect the heat exchange rates of the GCHE. We concluded, that under 0.001 m/d GWV the effects are negligible, but over this value the heat exchange rates would increase rapidly, due to the advection effect of the groundwater motion.

Key words: Ground heat exchanger, finite element model, heat transport modeling

1. INTRODUCTION

The use of geothermal energy is gaining worldwide interest as a result of increasing demand for cleaner, accessible and more economical energy sources. Ground coupled heat exchangers (GCHE) have been recognized recently as being among the most energy efficient and cost effective systems for space heating and cooling in residential and commercial buildings.

In Hungary, despite the advantages of these systems, the use of GCHEs is still limited because of a lack of information, and because of their high initial cost. In some cases these costs may be the result of an oversized design of GCHEs, caused by that the theoretical understanding of the heat transfer process along the heat pipe and the surrounding soil mass is still lagging behind the manufacturing and installation technologies. The reason for this is the absence of a rigorous numerical technique for the practical simulation of the problem Al-Khoury et al., (2005).

Different types of vertical tubes are key components of these systems. It typically consists of high-density-polyethylene pipe U-tubes inserted into 30-120 m deep boreholes. A grout mixture is inserted into the borehole to fill the gap between the U-tube and the borehole wall.

The performance of GCHE systems mostly depends on the thermal parameters of soils (heat conductivity and heat capacity) and the borehole thermal resistance. The soils' thermal parameters can be guess-estimated based on known geology or better estimated by interpreting a thermal response test (TRT) Yavuzturk et al., (1999). In most TRT measurements energy is injected into the borehole by circulating a heated fluid in the collector. Borehole mean values of the effective ground conductivity and borehole thermal resistance, that is thermal resistance between fluid and borehole wall, are evaluated from this data Thomas et al., 2003, Marcotte & Pasquier,

2008) showed that the TRT leads to an overestimation of the borehole thermal resistance, because of the use of the average fluid temperature.

In several cases it is forgotten that the hydrogeological conditions (GW level and its fluctuation, GWV, effective and total porosity, etc.) may notably influent the GCHE performance.

One important research area for the GCHEs is modeling. Several analytical and numerical models have been developed (Sharkawy et al., 2009, Cui et al., 2007, Lamarche & Beauchamp 2007, Li & Zheng, 2009, Diersch et al., 2008), but these methods are based on some simplifications (the grout and soil are not taken apart, steady state process is assumed, simplified geometrical structure in the borehole).

In this study, the performance of a large-scale system installed in South Hungary has been simulated using the finite-element groundwater flow and heat transport simulation program, FEFLOW (Diersch, 2002). We integrated Discrete Fracture Elements (DFE) into the finite element matrix system to simulate the thermal behaviour of the GCHE. The model was developed on the basis of geological and groundwater data corresponding to the site on which the GCHE system is located. The model was validated using the results of a TRT and a following cooling test which was measured at the same hole (Napradean & Chira, 2006). We used the validated model, to calculate the effects of groundwater velocity, the geological background, the heat conductivity of the grout mixture and the type of the tube, on the performance of the system.

2. CASE STUDY (SZEGED)

The GCHE system was installed in the basement of the new building of the University of Szeged. Szeged is located at the south part of the Great Hungarian Plain (Fig. 1).

Figure 1. Location of the studied area

The Great Hungarian Plain belongs to the Pannonian Basin. It is an intermontane sedimentary depression, which has evolved during the Neogene as an integral part of the Alpine Carpathian and Dinaride orogenic system. During the Late Pliocene and Quaternary, alluvial plain, terrestrial, and fluviatile sediments were deposited, consisting silts, clay and sand. During the Quaternary, the depositional environment became terrestrial and over 1000 m of clastic sediments were accumulated (Tóth & Almási, 2001).

At the site, where the system was installed, the sedimentary sequence consist of grey clays, muddy clays and grey sands see figure 2.

The installed system was build to provide space heating and cooling for the building. Twenty-four 100 m deep boreholes with a diameter of 152 mm were drilled in the foundation of the building. The tubes are single U-shape polyethylene pipes with 40 mm inside, 32.6 outside diameter and 85 mm lag spacing. The grout mixture filling the hole has 1.15 W/mK heat conductivity.

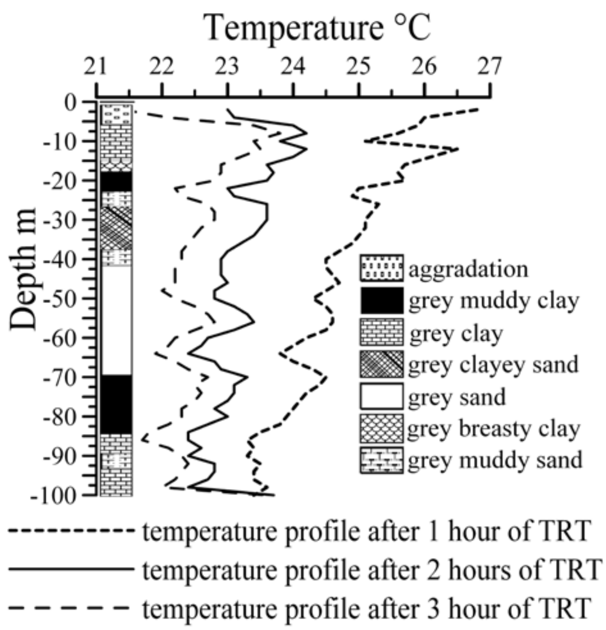

Figure 2. Sequence and temperature profiles after TRT along the U-tube

The horizontal distances between the boreholes are 5 m and 10 m, (see arrangement and tube geometry in figure 3.) All the U-tubes have the cooling and heating capacity of 85 kW and 110 kW respectively.

2.1. Thermal response and cooling tests

The TRT was carried out from 20 April 13:00 to 22 April 13:20 2010 by the Geort Ltd. To determine undisturbed soil temperature (T_0), the heat transfer was initially circulated through the system without heating. This was 15.8°C at each hole.

During the test inlet and outlet temperatures of the boreholes were measured in every 10 minutes. Although the flow rate was fixed at the constant value of 40.8 l/min, it was also checked in every 10 minutes. The average heating power of the circulating pump was about 5351 W.

After this procedure the equipment was switched off, and temperature profile along the tube was measured, in every 2 meters one, two, and three hours later.

2.1.1. Response analysis

The response analysis is widely accepted for simplicity and reasonable accuracy. This method is based on the solution of the Line Source problem. In this problem, the equation of the temperature field as a function of time and radius around a line source with constant heat injection rate is used to calculate the heat injected from the tested GCHE. (Esen & Inalli, 2009)

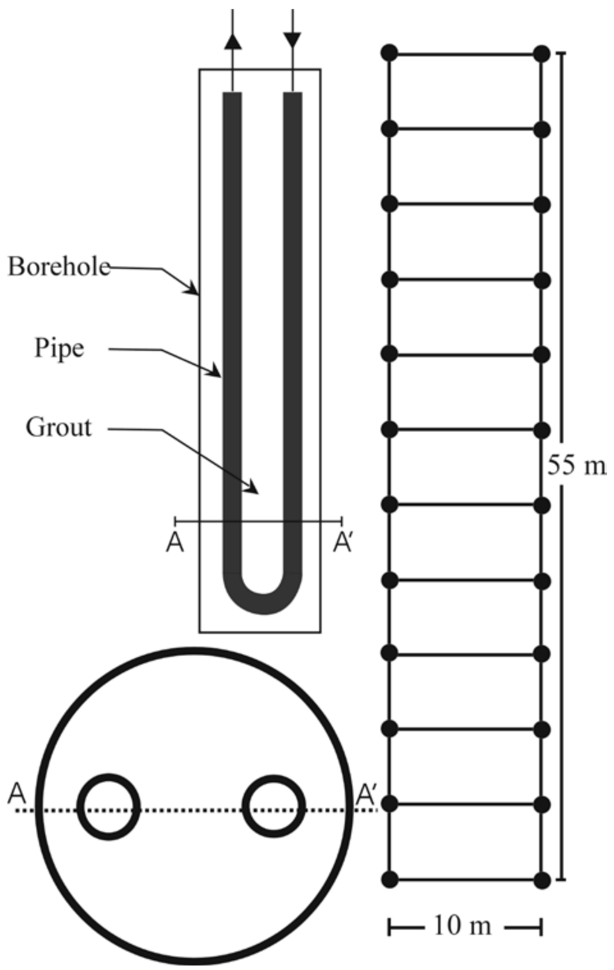

Figure 3. The geometry and arrangement of the U-tubes

2.1.2. Method for gaining thermal conductivity (λ) and thermal resistance (R_b)

Ingersol & Zobel (1954) gave the transient solution of the Line-Source model. The increment in temperature felt in the ground over time and distance from the borehole centre is given by Eq.1

$$\Delta T(r_b,t)=\frac{Q}{H\cdot 4\cdot\pi\cdot\lambda}\cdot\int_{r^2 4at}^{\infty}\frac{e^{-u}}{u}\cdot du=\frac{Q}{H\cdot 4\cdot\pi\cdot\lambda}\cdot E_1\left(\frac{r^2}{4at}\right) \quad (1)$$

If

$$\frac{r^2}{4at}\geq 5 \quad \text{then:} \quad E_1\left(\frac{r^2}{4at}\right)=\ln\left(\frac{4at}{r^2}\right)-\gamma \quad (2)$$

Where $\Delta T(r_b, t)$ Rock temperature variation at time t and distance r from the borehole wall, Q is heat injected rate, H is borehole depth, λ is thermal conductivity of soil, E is eexponential integral, and γ is Euler's constant (0.5772).

This means that accuracy increases as thermal front reaches further beyond the borehole wall Roth et al., (2004). In the model, mean-fluid temperature is obtained by first computing the ground temperature at the borehole wall and then adjusting for the borehole thermal effective resistance:

$$T_f(t)=T_0+\Delta T(r_b,t)+\frac{Q}{H}\cdot R_b=$$
$$=T_0+\frac{Q}{H\cdot 4\cdot\pi\cdot\lambda}\cdot\left(\ln\left(\frac{4at}{r^2}\right)-\gamma\right)+\frac{Q}{H}\cdot R_b \quad (3)$$

The temperature of the fluid entering the borehole and leaving the borehole is monitored continuously during the test. Then, it is usually assumed:

$$T_m(t)\approx T_f(t)=\frac{T_{in}(t)+T_{out}(t)}{2} \quad (4)$$

Eq. (3) can be rewritten in a linear form:

$$T_f(t)=k\cdot\ln(t)+m \quad (5)$$

Where $T_f(t)$ and $T_m(t)$ is fluid temperature, T_0 is undisturbed soil temperature, R_b is borehole effective thermal resistance, $T_{in}(t)$ is temperature at the borehole entrance, $T_{out}(t)$ is temperature at the borehole exit, and *m* and *k* are constants. In Eq. (5) *k* is determined from the slope of the line in the semilog plot of time versus mean fluid temperature. From these equations thermal conductivity (*λ*) and thermal resistance (R_b) can be calculated.

2.1.3. Results of the TRT test, approximations

The results of the TRT test are plotted on the semilog graph (Fig. 4).

Using the determined k=3.056 and m=8.76 values from Eq. 5 for thermal conductivity and the borehole thermal resistance 1.56 W/mK and 0.133

mK/W were calculated respectively. Based on this TRT twenty-four U-shaped pipe was considered to absolutely fulfil the heating needs, and almost fulfil the cooling needs of the building.

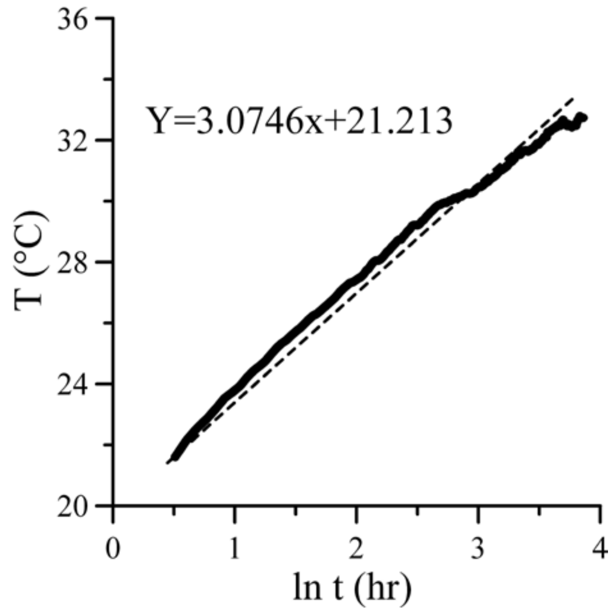

Figure 4. The mean fluid temperature data versus natural log of time in hour.

The method contains heavy approximations which leads to an overestimation of borehole thermal resistance (Cui et al., 2007, Marcotte & Pasquier, 2008, Zanchini et al., 2010).

- The Eqs. (2) and (3) are valid only if the time elapsed from the beginning is greater then 15 h respectively.
- The grout is regarded as an infinite medium, and the borehole as an infinite line source.
- The thermal capacitance of the borehole elements such as pipe wall and grout are neglected, which plays a role, especially when computing short term fluid temperature.
- It is assumed that T_m and T_f are equal Eq. (4), but it is valid only when the heat flux is constant along the entire borehole.

Therefore, we used the 3D dimensional model FEFLOW (Diersch, 2002) calculate more precisely the performance.

2.2. The 3D numerical model

The modelling of the transient heat-transport in a GCHE system and the surrounding rock bodies, especially in a short time period is a complex mathematical problem. This is because it involves extreme disproportional geometries. There are thermodynamic interactions between the few cm diameter thin pipe components and the vast surrounding soil mass. Therefore simplifying assumptions are needed Al-Khoury, et al., (2005).

2.2.1. Theoretical background

The mathematical modelling of heat transfer in a GCHE system involves the simulation of flow, heat conduction and convection processes. We used the 3D finite element numerical model FEFLOW (Diersch 2002) to simulate the groundwater flow and the heat transport processes in the soil and the grout. If the standard 3D formulation would be made to describe heat flow in the tubes and the surrounding soil mass, the required number of finite elements will be enormous. So we used 1D Discrete Fracture elements (DFE), to represent the pipe elements (pipe in, and pipe out).

The 1D pipe components transfer heat across their cross sectional areas, and exchange fluxes across their wall surface area. Fluid mass flow is considered to be large enough to fully develop turbulent flow. To simulate the quick heat propagation to the borehole wall, expected in turbulent regimes, we used an anisotropic fluid thermal conductivity tensor. The anisotropy ratio between horizontal plane and axial direction was calculated from the convective heat transfer coefficient (α) and from the heat conductivity (λ). For these, the convective heat transfer coefficient can be obtained as (Al-Khoury et al., (2005):

$$\alpha = \frac{1}{\dfrac{2}{r_0 \cdot Nu \cdot \lambda_{ref}} + \dfrac{r_0 \cdot \ln\left(\dfrac{r_0}{r_i}\right)}{\lambda_p}} \tag{6}$$

Where α is convective heat transfer coefficient, r_0 is outer radius of pipe, Nu is Nusslet number, λ_{ref} is thermal conductivity of refrigerant, r_0 outer radius of pipe, r_i is internal radius of pipe, λ_p is thermal conductivity of pipe material.

In the tube, the velocity vector of the refrigerant fluid (V), which is 25 mass percent of ethylene-glycol, was calculated from the Hagen-Poiseuille low (Diersch, 2002):

$$\bar{V} = \frac{r_{hydr}}{2 \cdot \mu} \cdot \left(\frac{dp}{dz} - \rho \cdot g\right) \tag{7}$$

For this, at first the hydraulic aperture of the refrigerant can be obtained as:

$$r_{hydr} = 1.224745 \cdot r \cdot \sqrt{\frac{f}{f_0}} \tag{8}$$

Where $\bar{v}$ is average refrigerant velocity, r_{hydr} is hydraulic aperture, μ is dynamic viscosity, p is fluid pressure, z is axial coordinate, ρ is mass density, g is gravity velocity, r_{hydr} is hydraulic aperture, f is specific rate of temporary production:

$$f = \frac{\rho \cdot g}{\mu} \tag{9}$$

and f_0 is standard parameter factor for water:

$$f_0 = \frac{\rho_0 \cdot g_0}{\mu_0} = 7.55 \cdot 10^6 \tag{10}$$

2.2.2. Numerical modelling

A 3D single pipe model was constructed to simulate the performance of the GCHE system within the FEFLOW. The model extended over a 5 m diameter circle. It consists of the soil, the 152 mm diameter grout, and the pipe elements which were modelled like 1D DFE element.

The outer boundary of the model, where the undisturbed temperature boundary is assumed, is determined so that it does not feel the influence of the thermal performance produced by the U-tube.

The surrounding soil mass was fully saturated and unconfined. During the TRT, the flow rate was fixed at the constant value of 40.8 l/min, so we applied this data as well boundary condition. The T_{in}, which was measured during the test in every 10 minutes, was applied like time-dependent temperature boundary condition.

Because the temperature gradient between the pipe surfaces and the far field undergo a course of gradual change from big to small, therefore the mesh density should be changed opposite way. In addition, the thermophysical and hydrogeological parameters due to the properties of the grout are generally different that those of the soil, we refined the mesh inside the grout, and around the borehole. Figure 5 shows the finite element discretization of the model.

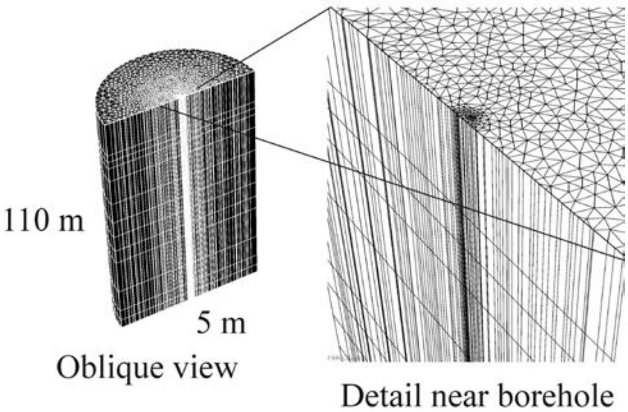

Figure 5. The finite element discretization of the model.

Vertically, thirteen layers were used, with the total thickness of 110m. The calibration of the model shows, that it was necessary, to insert a layer under the heat exchanger.

The thermophysical and hydrogeological parameters of the surrounding rock bodies were evaluated from the boring silt, and they were corrected from the recooling measurement, and from the calibration of the model. Based on the data of the nearest groundwater monitoring wells, the hydraulic gradient was 100 cm/km.

2.2.3. Validation of the numerical model

The GCHE model was validated using the results of the TRT test and the cooling test. First we considered the entering and exiting temperatures of the GCHE during the TRT. The entering water temperature was used as the input variable of our model, and the measured exiting water temperatures were compared with the model predictions. Figure 6 shows a comparison of the measured and calculated exiting water temperatures.

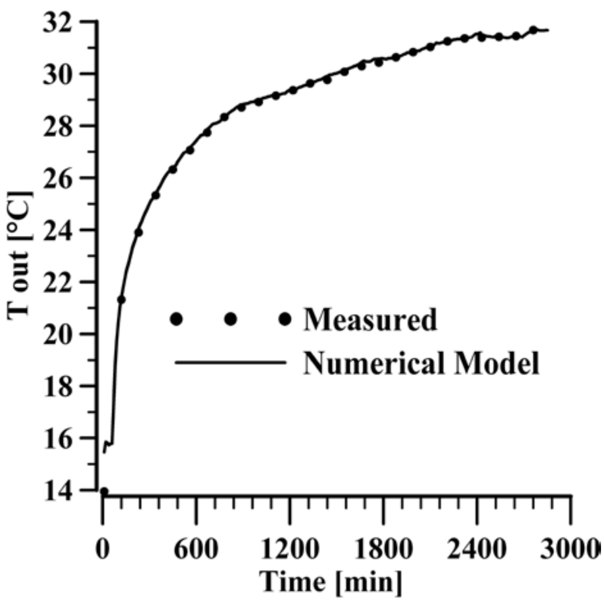

Figure 6. Comparison of the measurements and the value of the numerical model

It can bee seen, that good agreement was achieved. The maximum deviation (absolute error) appears at the start of the simulation (first half an hour), but speedily decrease in time (Fig. 7). To better analyse the difference between the two data row, the relative error which is defined in Eq. (11) is also calculated and depicted in figure 7. It can bee seen that the relative error is always smaller than 0.1, and after half on hour, it is smaller than 0.01.

$$\text{Relative error} = \frac{|measured\ value - calculated\ value|}{|measured\ value|} \tag{11}$$

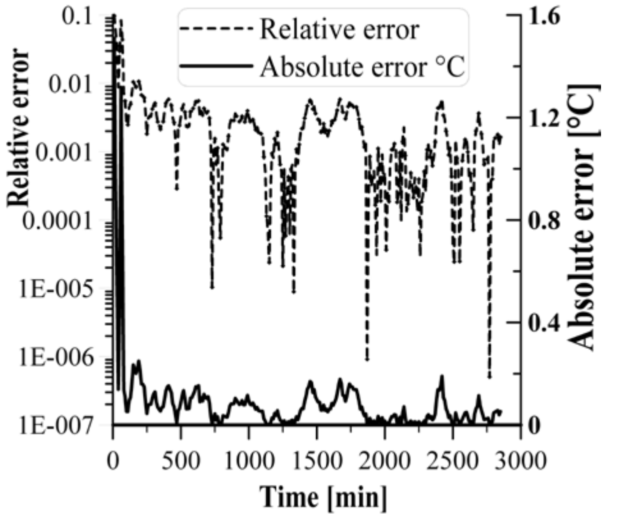

Figure 7. The absolute and relative error of the modelled the TRT.

Then we considered the temperature profile along the tube, which was measured (cooling test), in every 2 meters by the Geort Ltd. It was assumed that the temperature distribution after 3 hours follows the geological-hydrogeological conditions of the subsurface material. Figure 8 shows a comparison of the measured and calculated temperature distribution. We calculated also the relative error along the tube, which is everywhere smaller than 0.015.

3. RESULTS

3.1. Comparison the analytically and numerically predicted GCHE performance

In accordance with the predictions of the TRT, twenty-four U-shaped pipes had been inserted under the building. It was assumed, that one U-shaped pipe is able to produce approximately 3.5 kW in heating, and 4.6 kW in cooling mode. This means, that the temperature difference between the entering and exiting temperature has to be at least 2.95°C in heating mode, and 3.83°C in cooling mode.

To compare the analytical (TRT-test) and numerical predicted U-shaped number, we calculated, by the validated numerical model, the entering temperature.

We have devised an IFM (interface manager) module, and used it in the model as a refrigerant. By switching on boundaries, it keeps constant the temperature difference between T_{in} and T_{out} during the on-time, and switches off the boundaries during the off-time since the GCHE was stopped at night.

It can be seen, that in heating mode at the end of the operation times the entering temperature, is always higher than 7.8°C. Taking into account that the refrigerant is able to supercool under about -4°C, it can be stated that the GCHE performance is bigger than 3.5 kW figure 9.

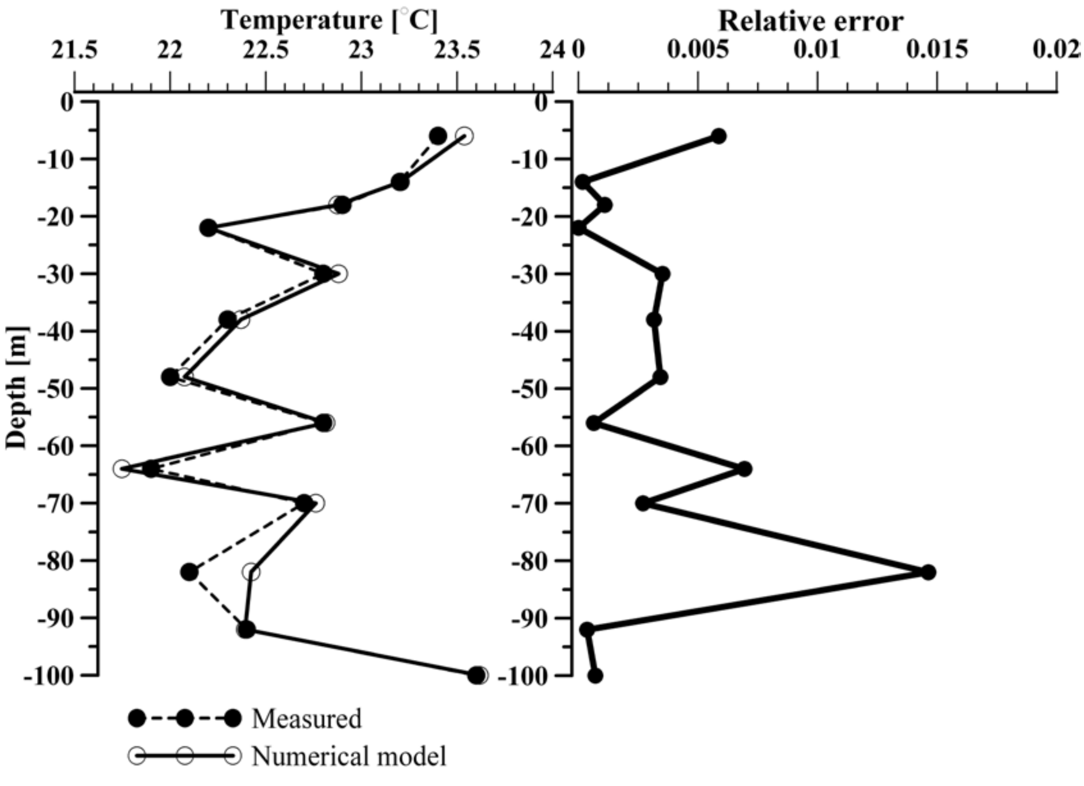

Figure 8. The absolute and the relative error of the modelled cooling test.

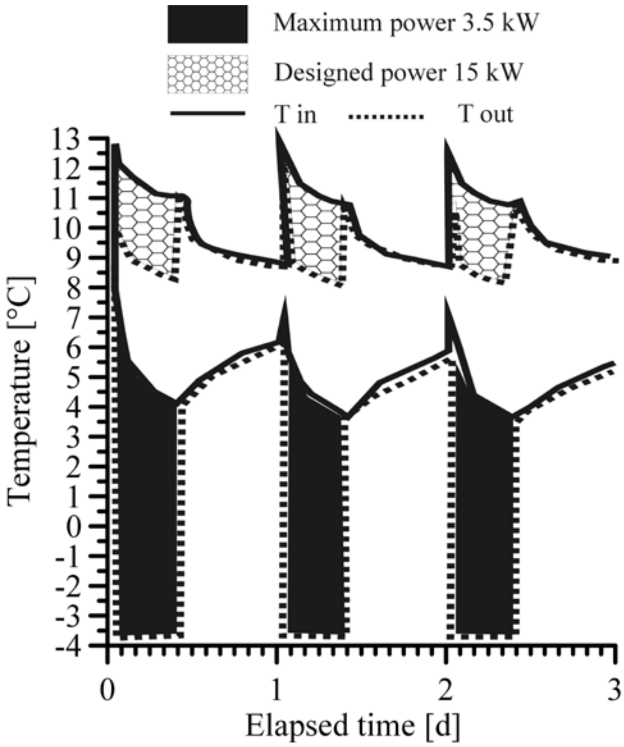

Figure 9. The difference between the maximum and the designed average power of the system.

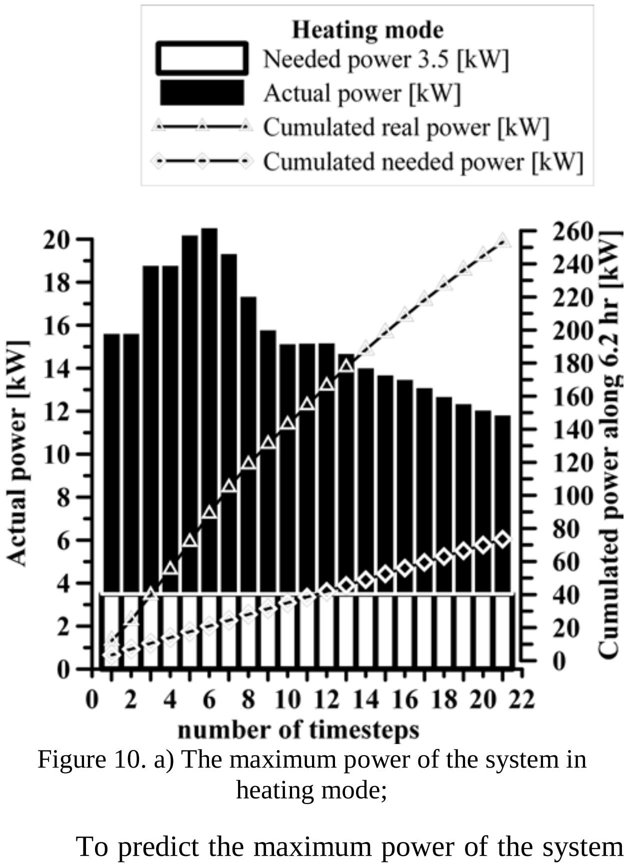

Figure 10. a) The maximum power of the system in heating mode;

To predict the maximum power of the system we have developed another IFM module, called "maximum demanding refrigerant", which is able to supercool the refrigerant temperature down to -4°C in heating mode, and to heat the refrigerant temperature up to 30°C in cooling mode. It switches off the boundaries during the off-times too.

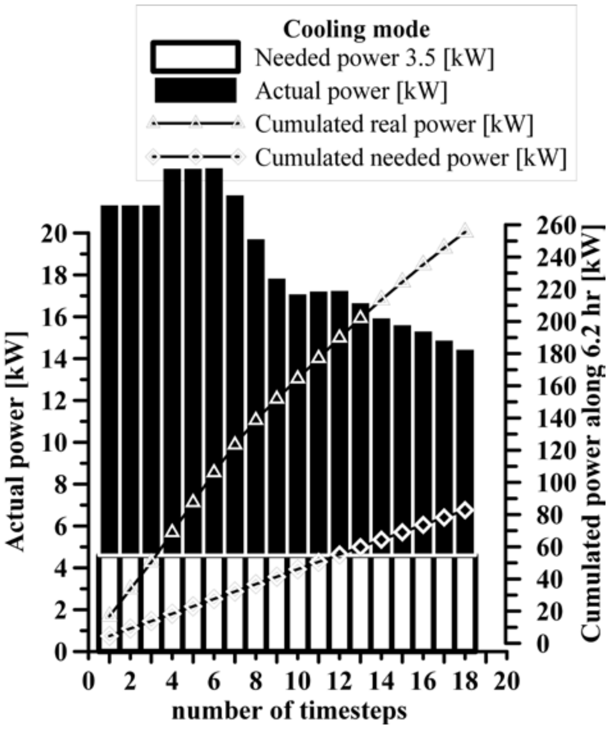

Figure 10. b) The maximum power of the system in cooling mode.

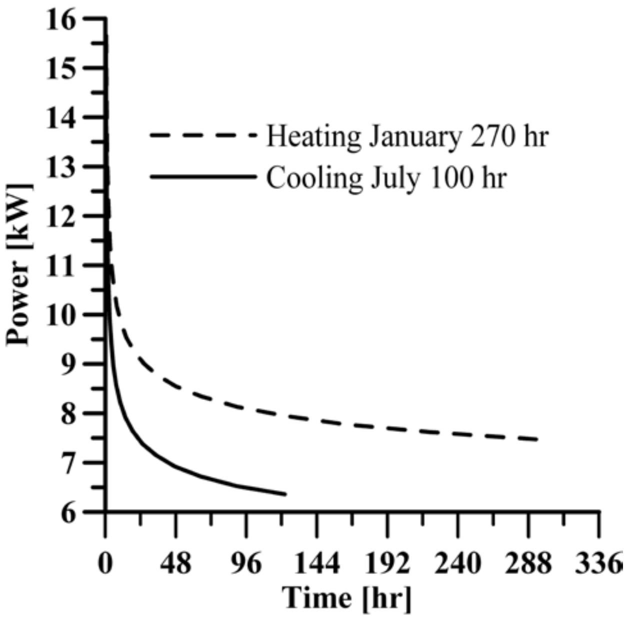

Figure 11. The power of the system quickly decrease with operating time.

It can be seen in figures 10a and 10b, that this way the average power of one U-tube, along the nine hour long heating period could be risen over 11- 16 kW in heating mode, and 10-18 kW in cooling mode. Taking into account, that the heating power quickly decrease with operating time (Fig. 11), we calculated the minimum number of U-shapes as the function of the number of operating intervals, during the maximum power demanding winter season and summer season (Fig. 12).

According to the simulation we can state, that only seventeen U-shapes are able to absolutely fulfil all the heating and cooling needs of the building.

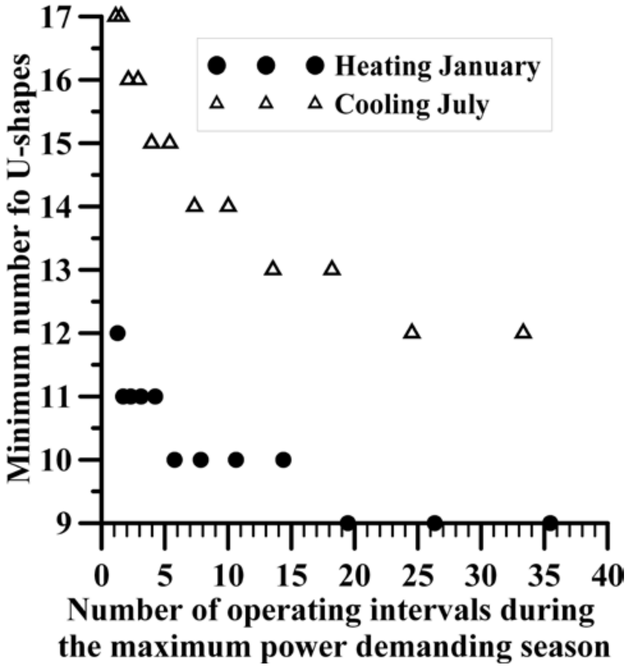

Figure 12. The minimum number of U-shapes as the function of the number of operating intervals, during the maximum power demanding winter season and summer season.

3.2 Geological and technical effects

Using the GCHE model we have evaluated how the heat exchange rate is affected by the groundwater flow velocities (GWV) and the geological background. Rates after three, six and nine hours of work under different GWVs are given in figure 13.

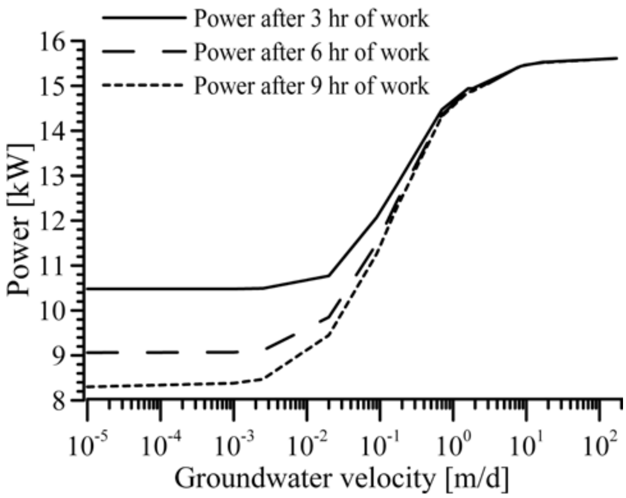

Figure 13. Rates after three, six and nine hours of work under different groundwater velocities.

The GWVs along the horizontal axis are calculated from the hydraulic conductivity and from the hydraulic head boundaries.

The maximum and minimum values of GWV in different geologic formations can bee seen in table 1. The ratio of powers at GWV= $5\cdot10^{-10}$ m/d and 10^{-4} m/d was 1.001, indicating, that small groundwater velocities have negligible effect on heat exchange rate. If the GWV is larger than 0.001 m/d, power would increase due to the advection effect of the flowing groundwater.

We have seen, that the heating power quickly decreases with operating time, but we can state that, if the GWV is larger than 0.1 m/d, the power of the GCHE does not decrease and it is almost the same after three or eight hours of work (Fig. 14).

Table 1. The typical value of groundwater velocity at the case of different formations and different hydraulic gradient

Groundwater velocity (m/d)						**Hydraulic gradient (m/km)**
Gravel (coarse)	***Gravel (fine)***	***Sand (coarse)***	***Sand (fine)***	***Silt***	***Clay***	1
8.5	0.7	0.09	0.001	0.00007	$5\cdot10^{-11}$	2
16.9	1.6	0.17	0.0025	0.00015	$1\cdot10^{-10}$	20
170	18.1	1.85	0.02	0.001	$1\cdot10^{-9}$	1

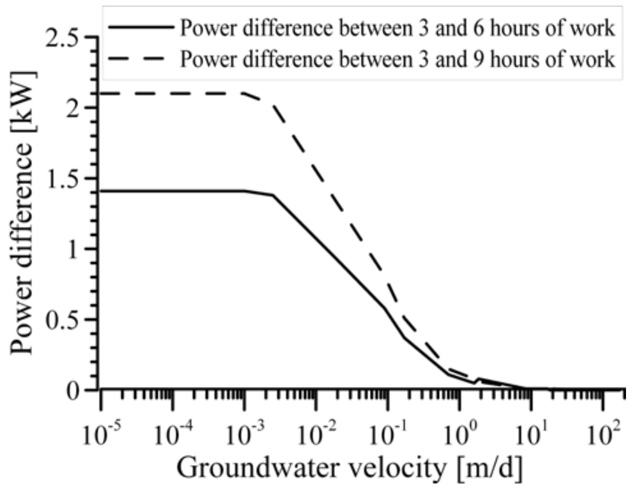

Figure 14. Power difference between working time as a function of groundwater velocity.

To evaluate the effect of the heat conductivity of the grout material, we calculated the heat exchange rate, in different values of GWV. The difference between the power of the GCHE, is 6 % for the GWV of 0.001 m/d, and almost 20% for the GWV of 6 m/d.

In the first case the heat conductivity of the grout material was 1.15 W/mK, in the second case it was 2.5 W/mK. In figre 15 it can bee seen, that the impact of the grout material's heat conductivity is growing with the value of the GWV.

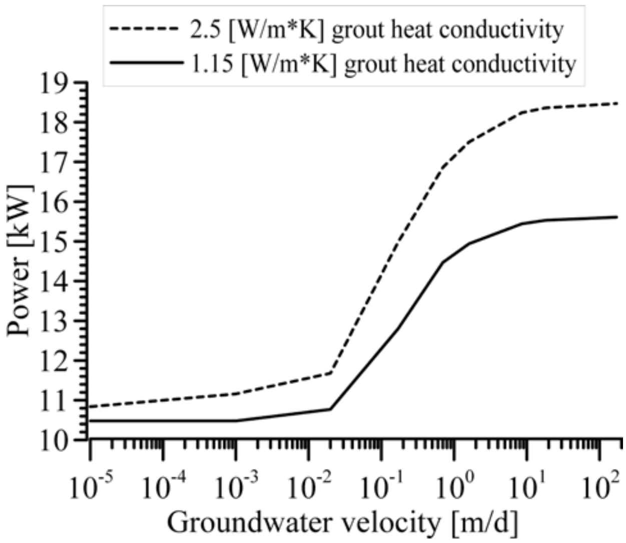

Figure 15. The effect of the heat conductivity of the grout material as a function of the groundwater velocity.

To determine the effect of some technical conditions we evaluated the performance of four types of GCHEs (Fig. 16).

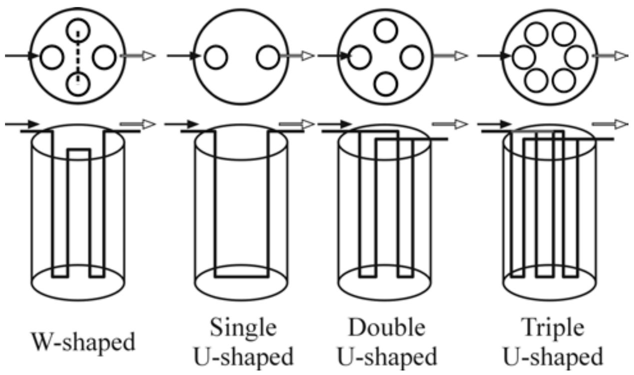

Figure 16. The geometry of the different type of tube shape.

Table 2. Energy output as a function of tube shape and working time

Type	Energy output after 3 hours (kW)	Energy output after 9 hours (kW)	Energy output after 24 hours (kW)	Energy output after 48 hours (kW)
Single U-shaped	11.6	9.7	8.9	8.4
Double U-shaped	12.9	9.6	7.8	7
Triple U-shaped	12.4	9.2	8	7.4
W-shaped	14.9	12.1	10.8	10

The results can be seen in table 2. We can conclude, that in this site, all the Double and Triple U-shaped types have the same, or lower performance after nine or more hours of work than the simple U-shaped type.

Only the W-shaped type is able to produce 19% more energy output after twenty-four hours of continuous work than that of the U-shaped type. This is due to the thermal interactions between the pipe legs.

4. CONCLUSIONS

Thermophysical and geological properties of subsurface materials and groundwater flow strongly affect the heat exchange rates of ground coupled heat exchanger systems (GCHE). A 3D single pipe model was constructed to simulate the performance of the GCHE system within the FEFLOW. Using the GCHE model we have evaluated how the heat exchange rate is affected by the groundwater velocities and the geological background. We can conclude that small groundwater velocities have negligible effect on heat exchange rate. If the groundwater velocity is larger than 0.001 m/d, power would increase due to the convective fluxes caused by the groundwater flow. We evaluated the effect of the heat conductivity of the grout material. It can bee seen, that the impact of the grout material's heat conductivity is growing with the value of the groundwater velocity. Although the soils' thermal parameters can be guess-estimated based on known geology or better estimated by interpreting a thermal response test, but we can conclude that our method is the most effective way to calculate the heat exchange rate, and to avoid an oversized design which can result in reducing installation costs.

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