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Analysis of the Thermal Conductivity of a Borehole Heat Exchanger Measured during TRT Compared with Theoretical Calculations and its Impact on the Installation Parameters

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ABSTRACT

To determine the proper system design using a borehole heat exchanger, it is appropriate to implement a thermal response test (TRT), which gives the averaged values. Though it provides the average, it is still sufficient to quantify the performance of a heat exchanger. The implementation of TRT is needed for sites with poorly recognized geological and hydrogeological conditions and have higher power heat pumps (i.e. over tens of kW heating/cooling) installed. In such cases, the cost of the TRT can be paid back when the test results show that the system can be modified with less borehole heat exchangers than the original design based on the average values of the thermal conductivity coefficient of the ground. This study presents the calculations for borehole heat exchanger installations for which the thermal response test has been applied and compared with the theoretical borehole heat exchanger selection models (based on literature data). The analysis of the thermal conduction parameter measured during the TRT compared to the theoretically calculated one clearly indicate the amount of errors that can be committed during calculations and the possibility of having an imprecise interpretation of literature data.

1. INTRODUCTION

For heat pump operations, except the electricity necessary to the compressor working, a low-temperature heat source is needed. Selection of the heat source system parameters is derived from the building's thermal energy demand (heating, domestic hot water production) and the analysis of the thermal capacity and conductivity of the ground. Special attention should be directed to the temperature of the heat source and its changes, which are crucial for the performance of the heat pump. The use of heat pumps is directly related to the possibility of obtaining thermal energy from a heat source (e.g. ground), which should have a constant temperature throughout the year to allow the economic recovery of heat, recover the energy potential capacity at a certain time, and operate the system smoothly. Therefore, it is important to choose the appropriate installation parameters for the heat source.

The thermal response test (TRT) is used for testing of borehole heat exchangers, where the working fluid absorbs heat from a low-temperature heat source for the GSHP (ground source heat pump). The most widely used type of vertical heat exchanger is the U-tube heat exchanger. Depending on the heat demand of a building, the length and circuit number of the low-temperature heat source system for the heat pumps can be determined. These settings are mostly based on the theoretical calculation of the possible amount of heat that can be received from the ground. In contrast, TRT allows the determination of thermal parameters empirically for the proposed installation place. The current state of knowledge shows that, for a system based on borehole heat exchangers consisting of 10 or more vertical heat exchangers, TRT execution may reduce overestimation of a system nominal power, and thus achieve savings in the investment stage (Wajman, 2011).

2. TRT: METHODOLOGY OF CALCULATION

TRT is used to test the installation of borehole heat exchangers (which is the source for brine/water heat pump), allowing the determination of the maximum amount of heat that can be received from the ground in an experimental way, instead of a theoretical one. During first phase of the TRT, which is precirculation, the undisturbed ground temperature (T_{ground})is measured. In the heating phase, temperatures of the fluid at the inlet and the outlet are measured as a function of time (Acuña, 2010). It should be noted that the measuring sensors used in the equipment are located on the ground surface, which means that the results obtained are average values.

The T_{ground} shows the average temperature of the ground in which the borehole is made. From the measured temperatures at the inlet and outlet, the average value for T_f can be determined. Changing the T_f value according to the T_{ground} allows one to determine the thermal energy supplied q (Q/H). With these values, one can find the coefficient of effective thermal conductivity (λ_{eff}) and the total thermal resistance of the borehole heat exchanger (R_b) according to Equation 1 (Eklöf and Gehlin, 1996):

$$T_f(t) = (Q/H\pi 4\lambda_{eff})\ \ (\ln(4\alpha t/r^2) - \gamma) + (Q/H)R_b + T_{ground} \qquad (1)$$

where,

r is the radius of the borehole [m]

α is the thermal diffusivity of the ground [m2•s-1]

t is the duration of the test [s]

γ is the Euler constant, γ=0,5772

Q is the heat/power injection rate [W]
H is the depth of the borehole [m]

The ability of the rock to exchange heat determines the capability for thermal conductivity, while the heat transfer rate is determined by the coefficient of thermal conductivity (λ). These parameters result from the geological and hydrogeological parameters of the ground. The installation is characterized by the thermal resistance of the borehole heat exchanger (Rb).

Table 1. Technical parameters of the borehole heat exchanger

Parameter	Value
depth of BHE (H)	210 m
type of BHE	U-tube
tube	fi 40 x 3,7 mm
material of BHE	PE HD, gravel filling
borehole diameter	70 mm
test duration	49 h
fluid	water
injected power (Q)	5.70 kW
ground temperature (T_{ground})	12.99 °C

2.1 Coefficient of thermal conductivity

From the data measured during the thermal response test, the coefficient of thermal conductivity (λ) was chosen according to the formula and methodology by Eklöf and Gehlin (1996). The relationship shown in Equation 1 may be represented as a linear as a linear function as shown in Equation 2.

$$Tf(t) = k \cdot \ln(t) + m \quad (2)$$

From Equations 1 and 2, $k = Q/(4 \cdot \pi \cdot H \cdot \lambda_{eff})$. Thus, the coefficient of effective thermal conductivity can be calculated from Equation 3.

$$\lambda eff = Q/(4 \cdot \pi \cdot H \cdot k) \quad (3)$$

2.2 Analyzed case study

return temperatures on the measurment time (natural logarithm), and a trend line and its equation.

Using Equation 3, parameters from Table 1, and the parameter k = 0,985; the coefficient of thermal conductivity (λ_{eff}) was calculated to be 2.1946.

The temperature of the fluid at the inlet and outlet are measured by sensors in the equipment located on the surface of the ground. Thus, these values are average values because these are impacted by the lithology of the layers, borehole profiles, and the presence of groundwater. Because the temperature measurement gives the average values for the entire BHE, the value of λ is also the average since it takes into account all these factors. Therefore, it is called the coefficient of effective thermal conductivity.

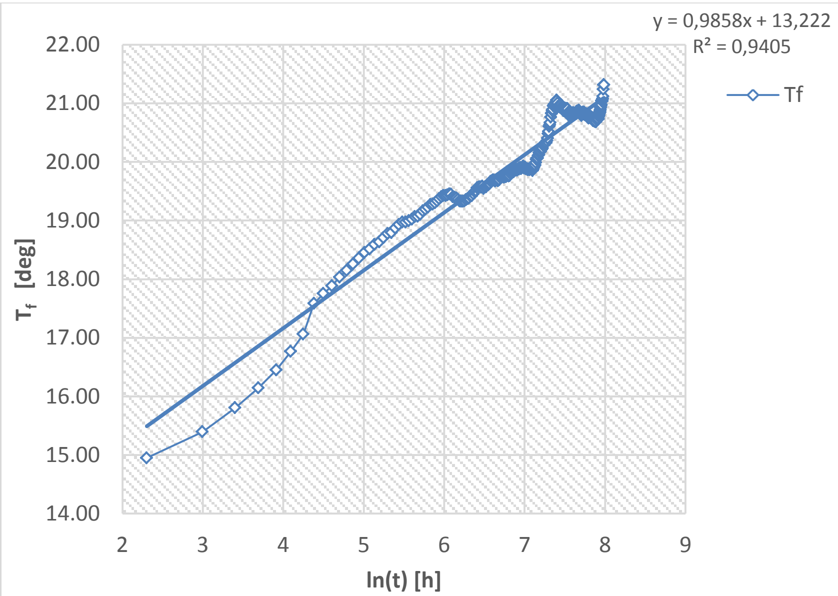

Figure 1. Dependence of the average temperature Tf obtained from the inlet and

The theoretical coefficient of thermal conductivity was calculated on the basis of the lithological profile of the vertical borehole heat exchanger and literature values of λ assigned to the type of surface. This method is based on the calculation of the weighted average of the coefficients of thermal conductivity, attributing to them the weight that is based on the thickness of the layer in the profile.

Table 2. Coefficient of thermal conductivity distribution in geological profile

Depth range [m]	**Lithology**	**Coefficient of thermal conductivity [W/mK]**	**Layer thickness [m]**
0-5	soil	1.20	5
5-10	yellow clay	0.75-1.25	5
10-14	very fine-grained sands	1.05-1.80	4
14-38	boulder clay	0.75-1.25	24
38-57	medium-grained sands	1.05-1.80	19
57-120	clay	1.05-1.25	63
120-160	tertiary very fine-grained sandstone	1.05-1.80	40
160-210	flour sands and silts	1.05-1.80	50

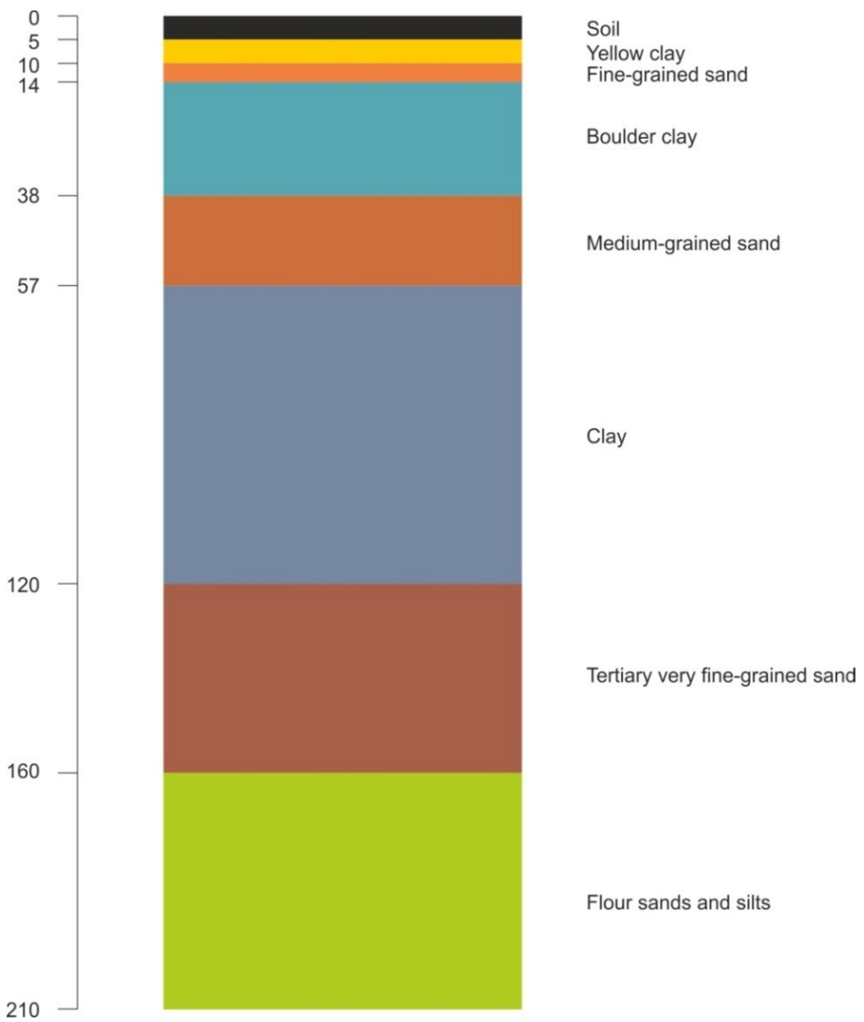

Figure 2. Geological profile of the analyzed case study area

The theoretical coefficient of thermal conductivity (λ) was calculated as a weighted average using the highest range values of the coefficient for every layer and it was found to be equal to 1.54.

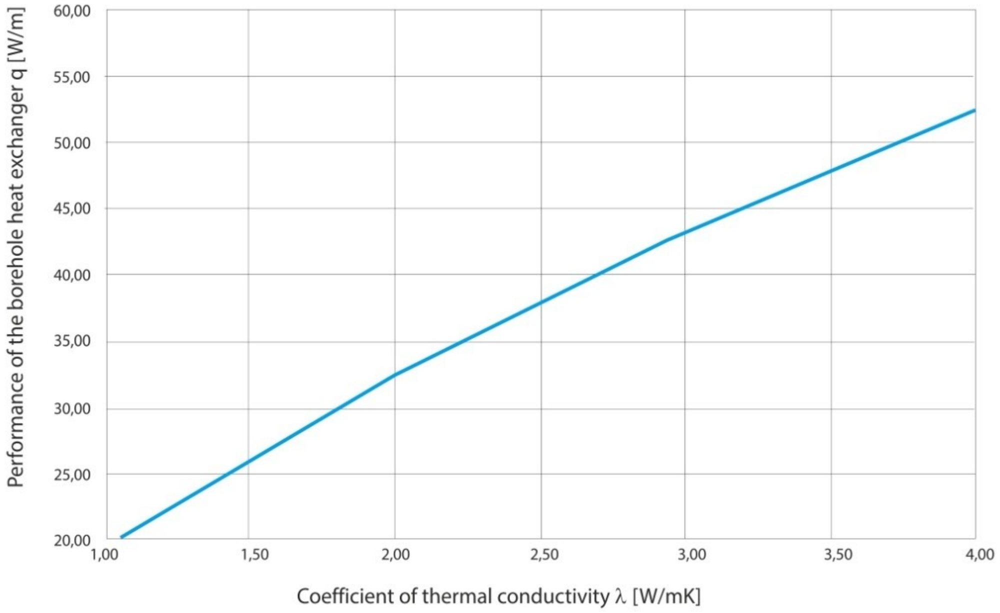

Figure 3. Dependence of the borehole heat exchanger performance per 1 length meter and coefficient of thermal conductivity (based on SIA 384/6, 2009, modified)

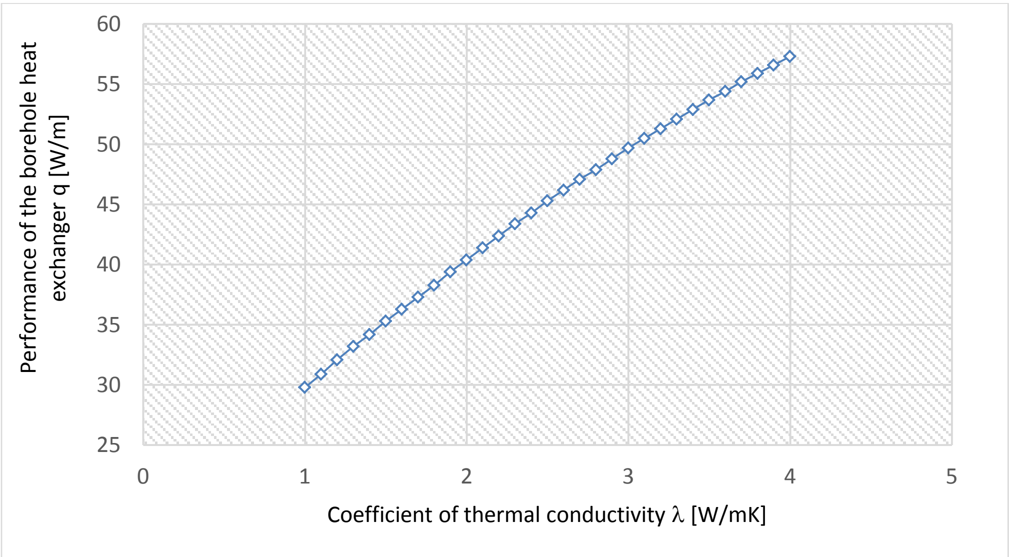

Figure 4. Dependence of the borehole heat exchanger performance per 1 length meter and coefficient of thermal conductivity (based on Sanner, 1996)

The borehole heat exchanger performance per length was calculated for the previously determined coefficients of thermal conductivity, taking into account the dependence of λ on the performance specified in the SIA 384/6 norm by Sanner (1996). In the case of the standard SIA 384/6 from 2010, the dependence described in the BHE chart for 100 m with an average soil temperature equal to 10°C and 1850 hours of heating was used. The dependence described by Sanner, based on the standard VDI 4640 from 1998, corresponded to the conditions of 2100 hours of heating (with the preparation of hot water) and no groundwater flow. Calculations were performed for two standards to illustrate the difference between the more stringent requirements of the standard SIA 384/6 compared to the VDI 4640, due to the development of the branch.

Assuming 9 kW and 20 kW cooling capacity values for the planned system of brine/water heat pump, the obtained the results for the total length of the vertical heat exchangers are shown in Table 3.

3. CONCLUSIONS

The purpose of the article was to confirm the existence of differences between measured coefficient of thermal conductivity at the site of planned installation and the coefficient calculated on the basis of literature data and the impact of this difference on the system parameters. In this case study, the theoretical coefficient of thermal conductivity was 1.54 [W/mK] while the coefficient of effective thermal conductivity was 2.19 [W/mK].

Table 3. Results of the calculations

		coefficent of thermal conductivity	
		λ = 1.54 W/mK	**λ_{eff}= 2.19 W/mK**
performance [W/m]	SIA 386/4	26.4	35
	B. Sanner for 2100h	35.8	41.8
calculating total length of the vertical heat exchanger [m] for the 9 kW cooling power	perf. by SIA 386/4	341	257
	perf. by B. Sanner	251	215
calculating total length of the vertical heat exchanger [m] for the 20 kW cooling power	perf. by SIA 386/4	757	571
	perf. by B. Sanner	559	478

As can be seen in the results (Table 3), the SIA 386/4 norm is much more restrictive. For instance, when the value of λ_{eff} = 2.19 is assumed, the performance is 35 W/m while the Sanner value is 41.8 W/m. In addition, there is a difference in the required length for the borehole heat exchanger in both cases. The SIA 386/4 norm requires 257 m while the Sanner norm requires 215 m for a system with a 9 kW cooling capacity. However, these results are even more important in systems with large planned installed capacity values. With the installation of a 20 kW cooling capacity, SIA 386/4 requires 571 m while Sanner requires 478 m.

Calculations show that the discrepancy of the coefficient of thermal conductivity gives an impact to the installation parameters of the borehole heat exchanger length. However, aside from the difference in the coefficient of thermal conductivity, there is also a difference in the selection of standards to calculate the performance, which significantly affects the determination of the length of the planned heat exchangers. Using literature data, the calculated heat exchanger length values are higher than the results obtained from the implementation of TRT. Longer heat exchangers are more expensive which lead to higher investment costs. A much worse situation, however, is to have an undersized heat source. The installation will not operate efficiently in the winter, which in Polish conditions is essential.

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