Interpretation of rock mass thermal conductivity at the design stage of heat pump installation and its impact on system efficiency (COP)

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Abstract. The recognition of geological and thermal conditions of the rock mass in the case of designing a vertical borehole heat exchanger as the ground source for heat pump installations is a key issue affecting the efficiency of the heating/cooling system operation. This is especially important for large-sized buildings with a high demand for thermal power, which affects into the size of the ground source installation. The aim of the article is to indicate the difference in the obtained results concerning thermal calculations at the design stage of the brine/water heat pump installation with the vertical heat exchanger, in relation to the theoretical values of the rock mass thermal conductivity and the real (measured) values obtained during the thermal response test (TRT). For this purpose, calculations of thermal efficiency from one meter of the current rock mass were made, with particular emphasis on the change in the value of the thermal conductivity coefficient in the tested drilling profiles. Correspondingly, heat pump coefficients of performance (COP) were calculated, which allowed to analyze the influence of the over/undersizing phenomenon of the ground source on the technical parameters of the heat pump's operation and the economic effect of the investment.

Keywords: heat pumps, thermal conductivity, thermal response test

1 Introduction

The heat pump market in Europe and in Poland develops dynamically, which is confirmed by statistical data published both by the European Heat Pump Association [1], as well as the Polish Association for Heat Pump Technology and Development [2]. It is especially important according to the importance of using the low temperature geothermal resources to the heat production [3–4]. When analyzing this data, attention should be paid at two main issues. The first one is the stability of the ground-source heat pumps market and its share in the total sales of heat pumps. The second issue is the percentage sales change each year, which indicates that while in the European market in the analyzed interval 2010–2015, there

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was a sale decrease in 2012 compared to 2011 by 7%, in Poland in the period of 2012–2017 the market was constantly growing at the level of 5–22% annually (Fig. 1, 2). In view of the above, it should be assumed that the heat pump sector will continue to develop, and hence requires a precise approach to the design of installations. This applies in particular to brine/water heat pumps with a vertical borehole heat exchanger (BHE), not only due to the fact that the implementation of the heat source is a significant contribution to the costs of the entire installation, but also due to the need of properly estimate the coefficient of thermal conductivity of the rock mass, which is crucial parameter for the proper design of the BHE.

To determine the correct configuration of the vertical borehole heat exchangers for the heat pump system, it is reasonable to conduct a thermal response test (TRT). The implementation of TRT is necessary especially in the case of locations with poorly recognized geological and hydrogeological conditions, and in the case of heat pumps with higher cooling power (i.e. over tens of kW) [5–10]. Unfortunately, in practice, the coefficient of thermal conductivity is often selected by the designer based on the theoretical values for individual layers in the lithological profile. This may lead to errors in the calculation the total length of BHE, and consequently to oversizing (much more common) or undersizing of the heat source. TRT allows for the empirical determination of the coefficient of thermal conductivity, thus obtaining precise information on the geological/hydrogeological conditions prevailing at the site of the planned installation [11–14].

The paper presents calculations for an exemplary vertical borehole heat exchanger for which a thermal response test was carried out and compared with the theoretical models for the selection of BHE, based on literature data [15]. Based on calculations, the consequences resulting from over/undersizing of the heat source were indicated, both from an economic point of view and the effects that such practice can cause at the heat pump's operating stage and the efficiency of its operation.

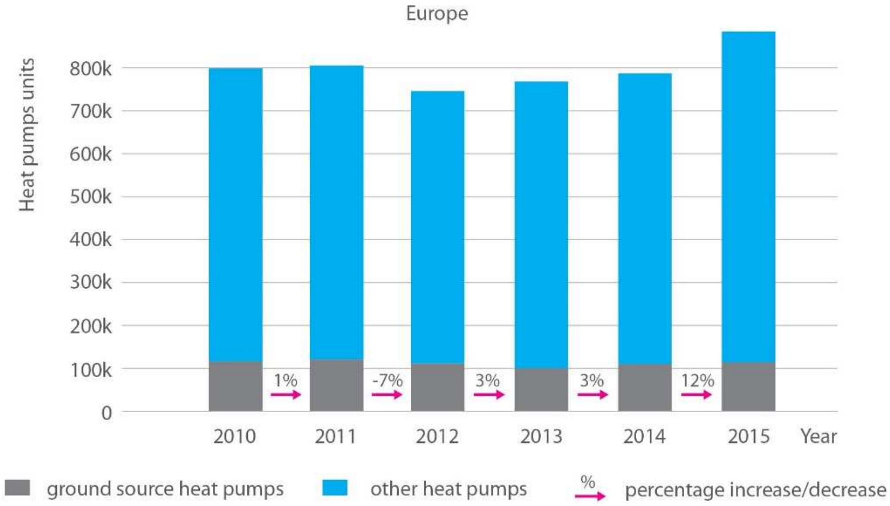

Fig. 1. Share of ground source heat pumps in total heat pump sales in Europe (based on [1]).

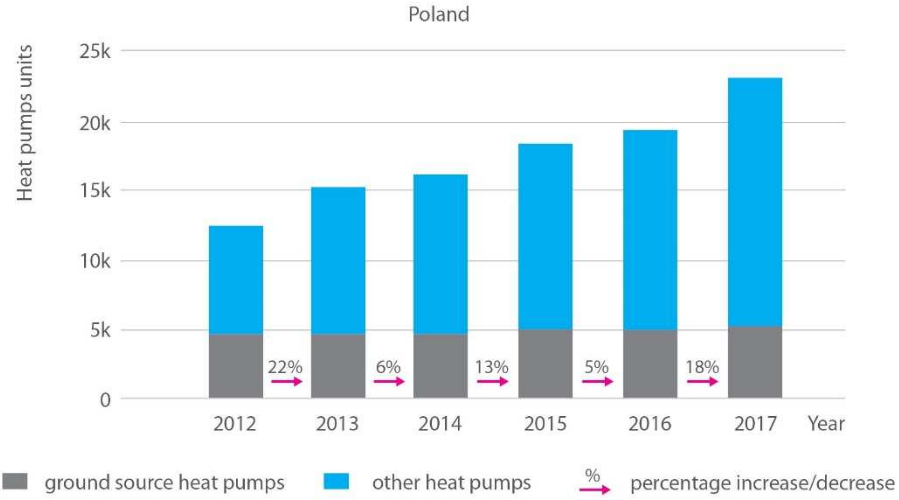

Fig. 2. Share of ground source heat pumps in total heat pump sales in Poland (based on [2]).

2 Analyzed vertical borehole heat exchanger

As mentioned in the introduction, the performance of the thermal response test is economically justified especially for large heat pumps installations. For this reason, a BHE was analyzed with a total depth of 210 m. The technical parameters of the BHE are listed in Table 1 and the lithological profile is shown in Figure 3. The theoretical values of the coefficient of thermal conductivity were assigned to each layers in the lithological profile [15], taking into account the minimum and maximum values. It allowed to calculate the average (based on weighted average) value of the coefficient of thermal conductivity in the whole profile of the tested borehole, which was assuming the minimum values of 0.96 W/mK, and for the maximum values 2.15 W/mK. It should be pointed out that the discrepancy depending on the adopted values is significant.

Table 1. Parameters of the analysed borehole heat exchanger.

Parameter	Value
depth of BHE	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
injected power (Q)	5.70 kW
ground temperature	12.99°C

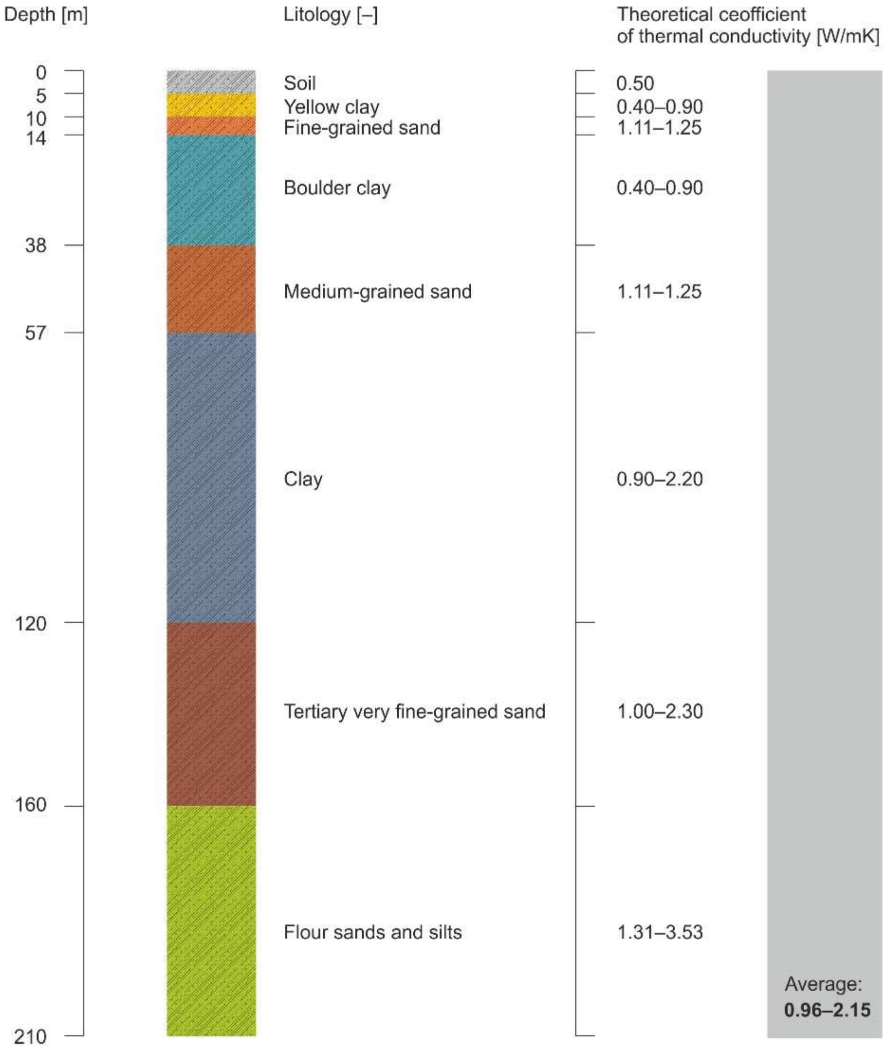

Fig. 3. Lithological profile with theoretical coefficient of thermal conductivity values (theoretical coefficient of thermal conductivity based on [15]).

3 Methodology and results of calculation

As mentioned above, the aim of TRT is to test the vertical borehole heat exchanger in order to determine in an empirical way, the amount of heat that can be obtained from the ground. To make calculations of the effective coefficient of thermal conductivity, during the thermal response test the following parameters were measured: fluid temperature (water/glycol) on input and output as a function of time (which allowed to determine the average value T_f) and unsettled ground temperature T_{ground} [16]. The change of temperature T_f in relation to undisturbed ground temperature T_{ground} allowed to determine the supplied thermal energy Q/H. The coefficient of the effective thermal conductivity λ_{eff} and the total thermal resistance of the heat exchanger R_b according to the linear model were described by the formula (1) [17]:

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

$T_f(t)$ – the average temperature of the fluid in the BHE [K]
Q/H – thermal power supplied [W]
λ_{eff} – effective coefficient of thermal conductivity [W/mK]
α – thermal diffusivity of the ground [m^2/s]
t – duration of the test [s]
γ – Euler constant, $\gamma = 0{,}5772$
r – radius of the borehole [m]
R_b – total thermal resistance of the BHE [m^2K/W]
T_{ground} – unsettled ground temperature [K]

The coefficient of thermal conductivity depends mainly on the thermal parameters of the rock mass surrounding the BHE, and thermal resistance of the BHE depends on the quality and technology of its implementation. Equation 2 is a simplified mathematical record of the logarithmic function of equation 1, where k parameter is the directional coefficient of the curve created by the semi-logarithmic presentation of the temperature changes of the medium during the heating phase of the test.

$$T_f(t) = k \cdot ln(t) + m \tag{2}$$

From equations (1) and (2) results that:

$$k = Q/(4 \cdot \pi \cdot H \cdot \lambda_{eff}) \tag{3}$$

and

$$m = R_b \cdot (Q/H) + T_{ground} \tag{4}$$

The coefficient of effective thermal conductivity was calculated from the formula (5):

$$\lambda_{eff} = Q/(4 \cdot \pi \cdot H \cdot k) \tag{5}$$

From the logarithmic curve fit to TRT measurements (Tf(t)), k and m parameters were obtained. The effective coefficient of thermal conductivity λ_{eff} calculated using the above methodology was 2.19 W/mK. The heat exchanger efficiency per meter length was obtained considering the dependence of the λ on the performance specified in SIA 384/6 (Fig. 4), for the curve 2,0 MJ/m^2 on the assumption that working time of the BHE is 1850 h/year.

Calculations concerning the selection of the total length of the vertical borehole heat exchanger were carried out with the assumption of 3 variants of the heat pump cooling capacity: 9, 18 and 40 kW. Calculating total length of BHE is the result of the quotient of heat pump cooling capacity and performance based on SIA 386/4. Calculating heat pump capacity based on theoretical values of thermal conductivity is the result of the multiplication of total length of BHE and measured coefficient of thermal conductivity. The obtained results are presented in Table 2 and indicate that in the analyzed lithological profile, regardless of whether the designer adopts the theoretical values of the coefficient of thermal conductivity at the minimum level (0.96 W/mK) or maximum level (2.15 W/mK), will be lower than the value calculated on the basis of measurements from the thermal response test – 2.19 W/mK. It has to be mention that it is not recommended to choose the maximum values [15] which gave a result close to the calculated one. This results in oversizing the heat source in each of the analyzed cases. In the case of a 9 kW heat pump, instead of the total length of the exchanger of 257 m, the length of 474 m (for the minimum theoretical value of the coefficient of thermal conductivity) and 272 m (for the maximum value) were calculated. This is an error at the level of 6–84%. Consequently the power that the heat source will have can be sufficient for a heat pump with a cooling capacity of 9.5–16.5 kW.

For heat pumps with 18 and 40 kW cooling capacity, the total length values of the vertical borehole heat exchanger obtained in the calculations change proportionally in relation to the increase of the cooling power. Designed powers of the heat source based on the theoretical parameters are respectively: instead of 18 kW – 19–33 kW, instead of 40 kW – 42.5–73.5 kW (in both cases an error at level 6–84%).

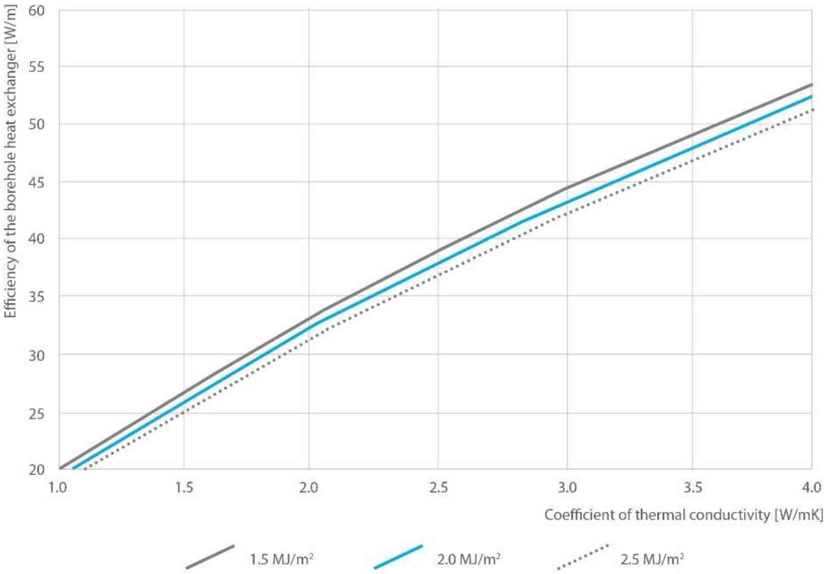

Fig. 4. Dependence of the borehole heat exchanger performance per 1 length meter and coefficient of thermal conductivity (based on [18]).

Table 2. Results of the TRT calculation in comparison to theoretical values.

	Lowest theoretical coefficient of thermal conductivity, 0.96 [W/mK]	**Highest theoretical coefficient of thermal conductivity, 2.15 [W/mK]**	**Measured coefficient of thermal conductivity (TRT), 2.19 [W/mK]**	***Calculating heat pump capacity based on theoretical values of thermal conductivity***
Performance based on SIA 386/4 [W/m]	19.00	33.00	35.00	–
Calculating total length of BHE for **9 kW** cooling power [m]	474	272	257	*9.5–16.5 kW*
Calculating total length of BHE for **18 kW** cooling power [m]	947	545	514	*19.0–33.0 kW*
Calculating total length of BHE for **40 kW** cooling power [m]	2105	1212	1143	*42.5–73.5 kW*

4 Summary and conclusions

Presented results of the calculations indicate that in the tested lithological profile of a vertical borehole heat exchanger, the value of the coefficient of thermal conductivity calculated on the basis of the thermal response test performed is significantly different from the theoretical values given in the literature. The real value is 2.19 W/mK, while the literature values range from 0.96–2.15 W/mK. In this particular case, the coefficient of thermal conductivity is underestimated at 2% to 228%. The consequence resulting from the selection of the heat source based on theoretical data will be its oversizing. The natural effect of oversizing the heat source will be higher investment costs.

The cost of realization the 1 meter of the vertical borehole heat exchanger depends on the geological structure in the location where the investment is being made. However, it can be assumed that the average cost of the BHE in Poland is 100 PLN per 1 meter (ca 23.5 EUR). As a consequence in the analyzed case the investor would pay more in a variant with a 9 kW pump by 1,500–21,700 PLN (ca 64–923 EUR), for a 18 kW pump, between 4,000–40,600 PLN (ca 170–1,728 EUR), and for a 40 kW pump by 6,900–96,200 PLN (ca 294–4,094 EUR).

It should be pointed out, that oversizing of the BHE causes, that too little heat load makes the compressor work in short periods of time. Lowering the assumed temperature in building activates the heat pump which due to the high installed capacity quickly heats the building. Therefore, it is switched off in a short time. Such cycles forcing the continuous start and stop, the compressor is strained. This process is accelerated by the fact that the start-up is accompanied by increased mechanical stress. Moreover, any such start-up brings with it an abrupt increase in energy consumption, which results from the necessity to overcome inertia of moving parts. It results in a greater electricity intake, and the heat pump's coefficient of performance (COP) decreases, which results from the change in the proportion of electric energy taken by the compressor to heat energy taken from the ground.

Despite the fact that in the analyzed case study there was no situation in which the heat source is undersizing, it should be added that such a situation would also causes decrease of the COP. Undersizing of the BHE results in longer compressor working time, which shortens the service life and the investor is exposed to additional costs. It is recommended to assume that the compressor will operate during the year between 1800 and 2500 hours, so that it does not wear out after 20 years of use. The heat pump works longer during the day to provide the required amount of heat which increases operational costs. During cold winters this effect is intensified, because the insufficient power of the device is supported by an electric heater. COP is lower than expected. In addition to extending the compressor's work cycle, the consequences is also that the ground around the heat exchanger cools down so much that it can't provide the designed cooling power. Such a situation can lead to emergency shutdowns of the device as a result of the evaporator low temperature. During mild winters this defect may not be revealed immediately.

The basic conclusion that should be emphasized from the analyzed example is that on the basis of literature data, for a brine/water heat pump is unable to precisely determine the total length of the vertical borehole heat exchanger. As a result of such a procedure, the investor incurs additional costs both at the investment and operational stages, and the efficiency of the heat pump's decrease. Therefore, especially in the case of large investments, the TRT method should be used as a means of obtaining information about the coefficient of thermal conductivity in an empirical way. In addition, it is worth considering adding information from the TRT to the results of i.e. electrical resistivity method, which may be an interesting implementation of geophysical methods to the field of heat pumps.

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