Article

Method of Averaging the Effective Thermal Conductivity Based on Thermal Response Tests of Borehole Heat Exchangers

Aneta Sapińska-Śliwa, Tomasz Sliwa *, Kazimierz Twardowski, Krzysztof Szyski, Andrzej Gonet and Paweł Żuk

Laboratory of Geoenergetics, Faculty of Drilling, Oil and Gas, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Krakow, Poland; ans@agh.edu.pl (A.S.-Ś.); twardowski@agh.edu.pl (K.T.); szyskikrzysztof@gmail.com (K.S.); gonet@agh.edu.pl (A.G.); pawel.zuk@vp.pl (P.Ż.)

* Correspondence: sliwa@agh.edu.pl; Tel.: +48-12-617-2217

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Abstract: This work concerns borehole heat exchangers and their testing using apparatus for thermal response tests. In the theoretical part of the article, an equation was derived from the known equation of heat flow, on which the interpretation of the thermal response test was based. The practical part presents the results of several measurements taken in the AGH Laboratory of Geoenergetics. They were aimed at examining the potential heat exchange capacity between the heat carrier and rock mass. Measurement results in the form of graphs are shown in relation to the examined, briefly described wells. Result analysis made it possible to draw conclusions regarding the interpretation of the thermal response test. The method of averaging the measurement results was subjected to further study. The measuring apparatus recorded data at a frequency of one second, however such accuracy was too large to be analyzed efficiently. Therefore, an average of every 1 min, every 10 min, and every 60 min was proposed. The conclusions stemming from the differences in the values of effective thermal conductivity in the borehole heat exchanger, resulting from different data averaging, were described. In the case of three borehole heat exchangers, ground properties were identical. The effective thermal conductivity λ_{eff} was shown to depend on various borehole heat exchanger (BHE) designs, heat carrier flow geometry, and grout parameters. It is important to consider the position of the pipes relative to each other. As shown in the charts, the best (the highest) effective thermal conductivity λ_{eff} occurred in BHE-1 with a coaxial construction. At the same time, this value was closest to the theoretical value of thermal conductivity of rocks λ , determined on the basis of literature. The standard deviation and the coefficient of variation confirmed that the effective thermal conductivity λ_{eff} , calculated for different time intervals, showed little variation in value. The values of effective thermal conductivity λ_{eff} for each time interval for the same borehole exchanger were similar in value. The lowest values of effective thermal conductivity λ_{eff} most often appeared for analysis with averaging every 60 min, and the highest—for analysis with averaging every 1 min. For safety reasons, when designing (number of BHEs), safer values should be taken for analysis, i.e., lower, averaging every 60 min.

Keywords: thermal response test; borehole heat exchangers; underground thermal energy storage; geoenergetics; geothermal heat pumps; geothermal energy; geothermics

1. Introduction

In the era of depleting conventional energy sources and increasingly pro-ecological policies, e.g., those of the European Union, it became natural to focus the attention on alternative energy sources.

Among them are not only those safe for the environment, but also those with renewable resources. New solutions in the field of heating and air conditioning were developed [1]. Due to the rapid growth of geothermal energy development, individual users gaining independency in acquisition and distribution of geothermal energy became common. Geothermal energy based on heat pumps can support traditional installations, or, in favourable conditions, entirely replace them on quite a large scale [2].

An example of such solutions are borehole heat exchangers (BHEs) [3]. This article concerns research conducted in the Laboratory of Geoenergetics, Department of Drilling, Oil and Gas AGH UST [4,5], which aimed to analyze thermal response tests (TRTs). Based on the tests performed, the potential for heat exchange in the BHE [6] could be estimated. As a result, rational design of an underground thermal energy storage (UTES) became possible, particularly the determination of the number of boreholes required [7].

Correct and most accurate determination of the ground parameters is a key element when designing the installation of the so-called shallow geothermal energy [8]. One of the methods of temperature change determination in the BHE is to introduce a thermometer [9] based on fiber optic links into the exchanger. Sensors measure the flowing medium at a fixed depth [10]. In a classic thermal response test (Figure 1), the working fluid is heated on the surface and injected into the borehole heat exchanger. Based on the temperature changes obtained over time, further parameters are determined. A slightly different method is to use heating cables directly in the borehole and then monitor the heat flow after heating the rock mass [11]. In many cases of using vertical exchangers, thermal parameters of the ground are also influenced by subsurface waters [12]. In the event of their intensive occurrence, BHEs may interact with one another in a way that impairs or improves the parameters of the system (depending on their distribution), which should be especially considered in the process of system design [13]. Currently, this interaction becomes an increasingly considered parameter when determining the thermal parameters of the ground. Measuring circulation parameters of the heat carrier is conducted by using appropriate temperature and flow sensors (Figure 1) on the BHE [14]. Such solution ensures the measurement of a fluid's temperature changes depending on the flow. The effect of the atmospheric environment in which the borehole heat exchanger is located is also worth noting (Figure 2). Temperature difference between the heat carrier in the connection pipes and atmospheric air can be significant. Depending on the method of averaging the results, the value of calculated effective thermal conductivity λ_{eff} in BHE may vary up to 10% from the value determined from tests [15]. The influence of atmospheric air on the TRT results depends on the length of the BHE's connection to the apparatus and its thermal insulation (Figure 3).

TRT was developed mostly in Sweden [16]. A TRT is an indirect (in-situ) measurement method, which is the simplest and most exact way to determine precise thermal properties [17]. Thermal response tests were first suggested at an international conference in Stockholm [18]. A simple system was suggested, in which thermal energy at constant heating power was injected into a BHE while the BHE temperature was measured. Thermal response tests with mobile measurement equipment were first introduced in Sweden and USA in 1995. Since then, the method has developed and spread to several other countries in North America and Europe [17].

Until now, several studies regarding TRT have been conducted, e.g., [19–23]. Multiple modifications have been proposed, e.g., [24–28]. Traditional TRT applies a constant heating power to the pumped heat carrier [29]. The newer method, which holds the outflow heat carrier at a constant temperature, was shown to have many benefits, including shortening the test time and improving the operating constance and test exactness [30]. TRT can also be conducted numerically by simulating it in mathematical models [3,31,32].

Increasingly, the literature mentions the use of old, decommissioned boreholes, mainly oil wells [33,34]. The development of deep BHE installations reduces the cost of internal, heat insulating pipe column [35]. So far, there is no information in the literature about the implementation of TRT in a deep borehole.

The purpose of this article is to determine the effect of temperature measurement frequency during the TRT on its results. Temperature measurements, as well as the measurement of other parameters during the test, e.g., differential pressure [36], can be recorded at different frequencies (averaged). The article analyzes how it affects the calculated value of effective thermal conductivity λ_{eff} in BHE, which is a basic parameter determined during TRT.

Figure 1. Schematic of thermal response test devices and operation. Legend: 1—thermometer with absolute error 0.1 °C, 2—flowmeter, 3—pump, 4—control computer (stabilization of thermal power and record the data), 5—set of heaters, 6—current source, 7—heater control signal, 8—borehole heat exchanger, Q —flow rate of heat carrier, P —heat flow rate (power), T_1 —temperature of heat carrier (outflow from BHE), T_2 —temperature of heat carrier (inflow to BHE), $\rho_f = f(T)$ —density of heat carrier as a function of temperature, $c_f = f(T)$ —specific heat of heat carrier as a function of temperature.

Figure 2. Thermogram of the borehole heat exchanger (BHE) connection to the thermal response tests (TRT) apparatus.

Figure 3. Thermal response test apparatus and its connection to the BHE.

Effective thermal conductivity λ_{eff} in BHE is not the same value like weighted average thermal conductivity of geological layers λ . Difference between λ_{eff} and λ is due to method imperfections. Basic TRT operational parameters are heating power and heat carrier flow rate. That values determine effective thermal conductivity λ_{eff} in BHE.

Different values of λ_{eff} are also observed in various BHE constructions when the geological condition is the same. Not only borehole thermal resistance R_b changes with various BHE constructions. One of the most important reasons are heat exchange area and velocity of heat carrier.

In the paper, only values of λ_{eff} in the function of measurement frequency are analyzed. Additional results are the comparison of values of λ_{eff} in different BHEs of Geoenergetics Laboratory.

The paper includes mathematical background of TRT. The described method is a classical/traditional method of effective thermal conductivity λ_{eff} in the BHE calculation. Next is the description of three different BHEs of Laboratory of Geoenergetics located at the Department of Drilling, Oil and Gas AGH UST. Next paragraph shows the results of TRT made on the BHEs. Interpretation of the results by different temperature measurement frequency during the TRT is described.

Many different commercial TRTs results are shown. On the basis of TRT data, the effect of frequency averaging of TRT results was determined. The paper finishes with conclusions and references.

2. Thermal Response Test

Thermal response test is based on Fourier's generally known differential heat conduction equation, which in cylindrical coordinates is as follows [37]:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{\rho C_p}{\lambda} \frac{\partial T}{\partial t} \quad (1)$$

where:

ρ —density of the medium, kg/m³,

c_p —specific heat of the ground, J/(kgK),

λ —thermal conductivity of the ground, W/(mK),

T —temperature, K,

t—time, s,
r—radius, m.

Using the method proposed for the Theis equation in hydrogeology [38] to solve this type of differential equation, the substitution was used:

$$u = \frac{r^2 \rho C_p}{4t\lambda} \quad (2)$$

and

$$\rho C_p = \frac{\lambda}{\alpha} \quad (3)$$

which is

$$u = \frac{r^2}{4\alpha t} \quad (4)$$

After appropriate transformations, Equation (1) takes the form of:

$$u \frac{\partial^2 T}{\partial u^2} + (1 + u) \frac{\partial T}{\partial u} = 0 \quad (5)$$

After a series of transformations, a mathematical relationship is obtained:

$$T(r, t) = T_0 + \frac{q}{k\pi\lambda} \int_{\frac{r^2}{4\alpha t}}^{\infty} \frac{e^{-x}}{x} dx \quad (6)$$

where:

q—unit heat transfer coefficient of the BHE, W/m,

T_0 —initial temperature in the BHE, K.

Formula 6 is the basic equation on which the interpretation of the thermal response tests of the borehole heat exchangers is based. For a long time period further solution is possible. In the evaluations made of German TRTs, the minimum duration criterion as noted by [39] proved helpful:

$$t_{\min} = \frac{5 \cdot r_b^2}{\alpha} \quad (7)$$

with $t_{\min}$ —lower time limit of data to be used for analysis and r_b —borehole radius.

Considering the integral of the exponential function further:

$$\int_u^{\infty} \frac{e^{-x}}{x} dx \quad (8)$$

it can be represented using the additive property of the integral relative to the integration interval and the integral function as follows:

$$\int_u^{\infty} \frac{e^{-x}}{x} dx = - \left[\int_0^1 (1 - e^{-x}) \frac{dx}{x} - \int_1^{\infty} \frac{e^{-x}}{x} dx + \int_1^u \frac{dx}{x} - \int_0^u (1 - e^{-x}) \frac{dx}{x} \right] \quad (9)$$

By replacing the values of the integral with its approximate value, a relation is eventually obtained:

$$T(r, t) \cong T_0 + \frac{q}{4\pi\lambda} \left[\ln \left(\frac{4\alpha t}{r^2} \right) - \gamma \right] \quad (10)$$

Test results show the relation between the heat carrier temperature and time. This allows for calculation of the effective thermal conductivity λ_{eff} according to the formula [29]:

$$\lambda_{ef} = \frac{P}{4 \cdot \pi \cdot k \cdot H} \quad (11)$$

where:

P—mean heating power during the TRT, W,

H—depth of the borehole heat exchanger, m,

k—the slope of the trend line—a straight line determined as the ratio of the mean temperature to the logarithm of the natural test time.

According to the mathematical model, effective thermal conductivity is identical to the thermal conductivity of the medium (rock mass). In reality, this value also depends on:

- the design of the borehole heat exchanger,
- TRT parameters, and
- how the measurement results are averaged, as shown in this article. Its aim is to show the diversity of the final measurement results, which can be regarded as a manifestation of their uncertainty.

3. The Scope of the Conducted Research

Laboratory of Geoenergetics located at the Department of Drilling, Oil and Gas AGH UST contains borehole heat exchangers of different designs [4]. Three of them were subjected to the described research, short characteristics of which are given in Table 1. The location of aforementioned BHEs is shown in Figure 4. Similar studies for various BHE designs have already been described in literature [1,12,26].

Table 1. Characteristics of the researched borehole heat exchangers belonging to the Laboratory of Geoenergetics, Department of Drilling, Oil and Gas AGH UST [40].

BHE No.	Characteristics of the BHE Construction	Symbol
BHE-1	Depth 76.4 m, coaxial design (pipe in pipe). Outer diameter of the outer pipe equals 90 mm, wall thickness 5.4 mm. Outer diameter of the inner pipe is 40 mm, with wall thickness 2.4 mm	
BHE-3	Depth 76.4 m, design consisting of a single U-tube. Distance between pipe axes equals 80 mm. Outer diameter of the exchanger pipes is 40 mm. Wall thickness 2.4 mm. Heat-improved sealing material (thermocem) with heat conduction $\lambda = 2.0 \text{ W/(mK)}$	
BHE-5	Depth 76.4 m, system with double U-tube. Distance between the pipe axes is 70 mm. Outer diameter of the pipes equals 32 mm, wall thickness 2.4 mm	

The study consisted of determining the effective thermal conductivity λ_{eff} in the borehole, which depended primarily on the thermal conductivity of the rocks in the lithological profile. Drilled lithological profile is presented in Table 2 [40].

Figure 4. Layout of the borehole heat exchanger field in the Laboratory of Geoenergetics, Department of Drilling, Oil and Gas AGH UST. BHE-1 is a coaxial system, BHE-2, BHE-3, and BHE-4 are boreholes with a single U-pipe design and various sealing, BHE-5 has a double U-tube design [3].

Values of the thermal conductivity of rocks were determined based on literature data [12,41,42].

The measuring apparatus (Figure 3) consisted of two modules together with a computer controlling and recording data (Figure 5). It corresponds to the schematic of thermal response test devices and operation from Figure 1. The first module included electric heaters and a circulation pump, the second consisted of flow meters and thermometers. The computer program recorded all data necessary to calculate subsequent parameters. These data included the exact date and time from the start of the measurement, the temperature of the heating agent at the inflow and outflow of the borehole heat exchanger, the outside temperature, the difference in pressure at the inflow and outflow of the borehole heat exchanger, and the accumulated electricity.

Figure 5. Modules of the TRT apparatus together with a power generator (corresponds to Figure 1).

Measurement results were recorded every second with time stabilization provided by the computer processor. The precision of the measurement time recording was high and equaled 0.2 milliseconds. Temperature measurements were performed with thermometers with an accuracy class of 1%. Flow meters had an average accuracy of 5%, up to 2% in an optimal operating range.

Table 2. Stratigraphic lithological profile of the LG-2a borehole together with selected thermal parameters of rocks [40].

No. of Layer	Top of the Layer, m	Bottom of the Layer, m	Thiciness of the Layer, m	Lithology	Stratigraphy	Thermal Conductivity, λ , $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$	Volumetric Heat Capacity, c_v , $\text{MJ}\cdot\text{m}^{-3}\text{K}^{-1}$
1	0.0	2.2	2.2	Anthropogenic soil (dark gray bank with debris)	Quaternary (Pleistocene, Holocene)	1.600	2.000
2	2.2	2.6	0.4	Silt (gray soil)		1.600	2.200
3	2.6	4.0	1.4	Fine and dusty sand, slightly argillaceous		1.000	2.000
4	4.0	6.0	2.0	Fine sand		1.200	2.500
5	6.0	15.0	9.0	All-in aggregate and gravel		1.800	2.400
6	15.0	30.0	15.0	Gray loam	Tertiary (Miocene)	2.200	2.300
7	30.0	78.0	48.0	Gray shale		2.100	2.300
Weighted average						2.039	2.309

Data from TRT were obtained by summing all the records from every second and dividing by their number every 1 min, 10 min, and 1 h, which is a classic arithmetic mean. It was originally assumed that the median was an average value, but such averaging was more time consuming. Due to the very small differences between the median and the arithmetic mean, and a significantly shorter time of determining the latter estimator, it was decided to calculate the arithmetic mean. Data recording on the disc was carried out with precision to two decimal places.

4. Measurement Results

Presented results include measurements for three boreholes of the Laboratory of Geoeenergetics (number 1, 3, and 5). Each time, the test was preceded by a 24-h rinsing period without heating the heat carrier in order to effectively vent the system and equalize the temperature in the rock mass. In the next stage, heaters were started with a set power and worked for 100 h. This time ensured the stabilization of the effective thermal conductivity value, which is a basic parameter in the BHE measurements. On this basis, the ability of the rock mass to dissipate/store heat could be determined. The assumed heating power with which the heaters heated the working fluid was 2.8 kW. The heat carrier flow capacity was 20 dm³/min.

Effective thermal conductivity was calculated from Formula 10. The slope factor of the straight line k was determined with Microsoft Excel using the REGLINP function. It uses the least squares method.

The distribution of the average temperature in the graphs according to the time intervals of data averaging (every 1 min, 10 min, and 1 h) are shown in Figures 6–11. Figure 6 shows the measurement results for the borehole No. 1, with the measurement data averaging every 1 h. Figure 7 shows the same relationship but in a semi-logarithmic plot. Figure 8 shows the measurement results for borehole No. 3, with the measurement data averaging every 10 min. Figure 9 shows the same relationship but in a semi-logarithmic plot. Figure 10 shows the measurement results for borehole No. 5 with the measurement data averaging every 1 min. Figure 11 shows the same relationship but in a semi-logarithmic plot.

The curves are so wobbly (identically wobbly) because of no ideal thermal insulation. As shown in Figure 5, thermal insulation of pipes is used. Figure 2 (thermogram) shows the need for even better thermal insulation.

Every graph (Figures 6–11) was based on the same TRT. The precision of the temperature time recording with the use was the current computer science standard, equal to 0.2 milliseconds. Different results were based only on different averaging intervals.

Figure 6. TRT results with the measurement data averaging every 1 h.

Figure 7. TRT results with the measurement data averaging every 1 h in a semi-logarithmic plot, together with the linear regression equation.

Figure 8. TRT results with the measurement data averaging every 10 min.

Figure 9. TRT results with the measurement data averaging every 10 min in a semi-logarithmic plot, together with the linear regression equation.

Figure 10. TRT results with the measurement data averaging every 1 min.

Figure 11. TRT results with the measurement data averaging every 1 min in a semi-logarithmic plot, together with the linear regression equation.

5. Interpretation of TRT Results

Values of the effective thermal conductivity λ_{eff} based on the conducted thermal response tests are presented in Table 3. Start time of calculation of λ_{eff} corresponded with Equation (7). End time corresponded with the end of heating time (end of TRT). The highest values are marked in red and the lowest in green. There is no correlation to be seen from the presented results.

Table 3. Effective thermal conductivity values in BHEs (highest values in red, lowest in green), taking into consideration sensors uncertainty the values of λ_{eff} has uncertainty equals $\pm \Delta\lambda_{eff} = 0.032 \text{ Wm}^{-1}\text{K}^{-1}$.

BHE No.	Value of λ_{eff} with Interval of 1 min, $\text{Wm}^{-1}\text{K}^{-1}$	Value of λ_{eff} with Interval of 10 min, $\text{Wm}^{-1}\text{K}^{-1}$	Value of λ_{eff} with Interval of 1 h, $\text{Wm}^{-1}\text{K}^{-1}$	Volatility * of the λ_{eff} Value, $\text{Wm}^{-1}\text{K}^{-1}$
BHE-1	1.585	1.613	1.610	0.028
BHE-3	1.540	1.539	1.529	0.011
BHE-5	1.516	1.515	1.579	0.064

* Maximum value (red) minus minimum one (green).

The variability of the heat conduction value for borehole No. 1 is $0.028 \text{ Wm}^{-1}\text{K}^{-1}$, for borehole No. 3 it is $0.011 \text{ Wm}^{-1}\text{K}^{-1}$, and for borehole No. 5 it is $0.064 \text{ Wm}^{-1}\text{K}^{-1}$. The relative error resulting from the method of averaging equals 1.74%, 0.71%, and 4.05%, respectively.

Table 4 shows different statistics. As presented, the volatility factor is less than 2.5%. With the same geology (the distance between the boreholes is shown in Figure 4), the value of this factor is quite high. This is due to the fact that the effective thermal conductivity λ_{eff} is not the same as the average thermal conductivity of the rock mass λ , which, according to Table 2, equals $2.039 \text{ Wm}^{-1}\text{K}^{-1}$, which is the weighted average conductivity according to literature data. The accuracy results from averaging. Literature data is based mostly on the measuring dry samples. Is-situ measurements are not applicable in the presented research, because coring is too expensive. Real values of rocks heat conductivity in rock mass varies in high range. The reason is, for example, saturation, underground water filtration, and conductivity anisotropy.

Table 4. Statistics of effective thermal conductivity λ_{eff} values in BHEs.

BHE No.	Average λ_{eff} , $\text{Wm}^{-1}\text{K}^{-1}$	Standard Deviation λ_{eff} , $\text{Wm}^{-1}\text{K}^{-1}$	Coefficient of Variation, %
BHE-1	1.603	0.015	0.94
BHE-3	1.536	0.006	0.39
BHE-5	1.537	0.037	2.40

Table 4 shows that the most advantageous design is the coaxial BHE, while single and double U-pipe exchangers are identical. The basic indicator that shows BHE quality is borehole thermal resistance R_b . It will be described in a separate paper. The same influence on BHE quality also shows effective thermal conductivity λ_{eff} . This value depends to some extent on the heat transfer from the carrier to the pipes. The heat penetration, however, also depends on the heat carrier's flow velocity. Heat penetration through the inner pipe and outer pipe is also of a different nature with U-pipe BHEs constructions.

For the latter case, the highest value of the coefficient of variation can be observed for different methods of the measurement results averaging. The value closest to the theoretical $\lambda = 2.039$ was measured in BHE-1, but it is not necessary that the effective thermal conductivity λ_{eff} measured will match an average textbook rock mass thermal conductivity λ .

The same values are shown on below diagrams. For BHE-1 in Figure 12, for BHE-3 in Figure 13 and for BHE-5 in Figure 14. The number of significant digits results from averaging. One digit less gives the same averages in one case.

Figure 12. Effective thermal conductivity λ_{eff} depending on time interval for BHE-1 (coaxial).

Figure 13. Effective thermal conductivity λ_{eff} depending on time interval for BHE-3 (single U-pipe).

Figure 14. Effective thermal conductivity λ_{eff} depending on time interval for BHE-5 (double U-pipe).

The diagrams of effective thermal conductivity λ_{eff} for individual heat exchangers depending on the time interval of measurement averaging, illustrate the differences between the values obtained for different boreholes with the same parameters, such as the flow rate of the heat carrier and the set heating power. For the sake of a more thorough statistical analysis on the impact of measurement averaging on TRT results, data from commercial thermal response tests were used [43]. Borehole and test data, as well as the interpretation results, are presented in Tables 5–9.

Table 5. Parameters of the tested exchangers, with the interval of every 1 min.

Location of the Exchanger	Average Heating Power during TRT, W	Standard Deviation of Heating Power, W	Coefficient of Variation, %	Borehole Depth, m	Average Unit Heating Power, W/m	Slope of the Regression Line in a Semi-Logarithmic Plot
Łódź	6645	127.36	1.92	120	55.38	1.8632
Szczecin	10,008	60.24	0.60	191	52.40	1.5816
Polkowice	7800	24.52	0.31	153	50.98	1.8542
Rawa Mazowiecka	2509	26.03	1.04	48	52.27	1.7100
	7009	56.61	0.81	140	50.06	1.4352
Kraków I	7823	383.32	4.90	150	52.15	1.9694
Wolsztyn	9523	86.99	0.91	200	47.62	2.1722
Goła Dzierżoniowska	7014	226.90	3.23	150	46.76	1.2513
	6000	79.97	1.33	120	50.00	1.5873
Żarów	5997	124.74	2.08	120	49.98	1.4193
Białystok	4390	245.75	5.60	100	43.90	1.4745
Wrocław	4072	141.12	3.47	133	30.62	1.4139
Kraków II	4813	154.05	3.20	150	32.09	1.2354
Niepołomice	4007	100.27	2.50	140	28.62	0.8564
Kraków III	8892	288.36	3.24	200	44.46	1.8384

Table 6. Parameters of the tested exchangers, with the interval of every 10 min.

Location of the Exchanger	Average Heating Power during TRT, W	Standard Deviation of Heating Power, W	Coefficient of Variation, %	Borehole Depth, m	Average Unit Heating Power, W/m	Slope of the Regression Line in a Semi-Logarithmic Plot
Łódź	6648	28.28	0.43	120	55.40	1.8463
Szczecin	10,008	14.87	0.15	191	52.40	1.4713
Polkowice	7799	38.83	0.5	153	50.97	1.8620
Rawa Mazowiecka	2509	12.13	0.48	48	52.27	1.4534
	7008	24.28	0.35	140	50.06	1.8801
Kraków I	7824	68.32	0.87	150	52.16	2.0785
Wolsztyn	9523	54.65	0.57	200	47.62	2.134
Goła Dzierżoniowska	7014	39.13	0.56	150	46.76	1.2995
	6000	39.06	0.65	120	50.00	1.4714
Żarów	5998	73.58	1.23	120	49.98	1.4543
Białystok	4387	137.96	3.15	100	43.87	1.3974
Wrocław	4071	176.86	4.34	133	30.61	1.4834
Kraków II	4813	121.38	2.52	150	32.09	1.2582
Niepołomice	4007	158.25	3.95	140	28.62	0.8629
Kraków III	8890	273.58	3.08	200	44.45	1.9976

Table 7. Parameters of the tested exchangers, with the interval of every 60 min.

Location of the Exchanger	Average Heating Power during TRT, W	Standard Deviation of Heating Power, W	Coefficient of Variation, %	Borehole Depth, m	Average Unit Heating Power, W/m	Slope of the Regression Line in a Semi-Logarithmic Plot
Łódź	6636	106.70	1.61	120	55.30	1.8421
Szczecin	10,009	4.01	0.04	191	52.40	1.8276
Polkowice	7800	2.18	0.03	153	50.98	1.8430
Rawa Mazowiecka	2508	10.42	0.42	48	52.25	1.4979
	7009	5.38	0.08	140	50.06	2.0205
Kraków I	7794	14.71	0.19	150	51.96	2.2584
Wolsztyn	9523	28.45	0.30	200	47.62	2.1623
Gola Dzierżoniowska	7014	14.19	0.20	150	46.76	1.4956
	6000	17.29	0.29	120	50.00	1.593
Żarów	5996	33.78	0.56	120	49.97	1.4702
Białystok	4390	99.77	2.27	100	43.90	1.3912
Wrocław	4077	227.82	5.59	133	30.65	1.484
Kraków II	4810	102.54	2.13	150	32.07	1.3227
Niepołomice	4008	130.54	3.26	140	28.63	0.9115
Kraków III	8889	242.48	2.73	200	44.45	2.0555

Table 8. Summary of the heating power of borehole exchangers for which a thermal reaction test was performed.

BHE Location	Heating Power for an Interval of 1 min, W	Heating Power for an Interval of 10 min, W	Heating Power for an Interval of 60 min, W	Average Heating Power, W	Standard Deviation of Heating Power, W	Coefficient of Variation, %
Łódź	6645	6648	6636	6643	5.10	0.077
Szczecin	10,008	10,008	10,009	1008.33	0.47	0.005
Polkowice	7800	7799	7800	7799.67	0.47	0.006
Rawa Mazowiecka	2509	2509	2508	2508.67	0.47	0.019
	7009	7008	7009	7008.67	0.47	0.007
Kraków I	7823	7824	7794	7813.67	13.91	0.178
Wolsztyn	9523	9523	9523	9523	0.00	0.000
Gola Dzierżoniowska	7014	7014	7014	7014	0.00	0.000
	6000	6000	6000	6000	0.00	0.000
Żarów	5997	5998	5996	5997	0.82	0.014
Białystok	4390	4387	4390	4389	1.41	0.032
Wrocław	4072	4071	4077	4073.33	2.62	0.064
Kraków II	4813	4813	4810	4812	1.41	0.029
Niepołomice	3998	4007	4008	4007.33	0.47	0.012
Kraków III	8892	8890	8889	8890.33	1.25	0.014

Table 9. Summary of the effective thermal conductivity λ_{eff} of the borehole heat exchangers for which the thermal reaction test was performed (green—the lowest, red—the highest value of λ_{eff}).

BHE Location	BHE Design	λ_{eff} for an Interval of 1 min, $\text{Wm}^{-1}\text{K}^{-1}$	λ_{eff} for an Interval of 10 min, $\text{Wm}^{-1}\text{K}^{-1}$	λ_{eff} for an Interval of 60 min, $\text{Wm}^{-1}\text{K}^{-1}$	Average λ_{eff} , $\text{Wm}^{-1}\text{K}^{-1}$	Standard Deviation of λ_{eff} , $\text{Wm}^{-1}\text{K}^{-1}$	Coefficient of Variation, %
Łódź	2-U-tube	2.37	2.39	2.39	2.38	0.010	0.42
Szczecin	1-U-tube	2.63	2.83	2.28	2.58	0.230	8.91
Polkowice	1-U-tube	2.19	2.18	2.20	2.19	0.010	0.46
Rawa Mazowiecka	1-U-tube	2.33	2.12	1.97	2.14	0.150	7.01
	1-U-tube	2.90	2.86	2.77	2.84	0.050	1.76
Kraków I	1-U-tube	2.11	2.00	1.83	1.98	0.120	6.06
Wolsztyn	1-U-tube	1.74	1.78	1.75	1.76	0.020	1.14
Gola	1-U-tube	2.97	2.86	2.50	2.78	0.200	7.19
Dzierżoniowska							
Żarów	1-U-tube	2.50	2.70	2.50	2.57	0.090	3.50
	1-U-tube	2.80	2.74	2.70	2.75	0.040	1.45
Białystok	1-U-tube	2.53	2.50	2.39	2.47	0.060	2.43
Wrocław	1-U-tube	1.72	1.64	1.64	1.67	0.040	2.40
Kraków II	2-U-tube	2.07	2.03	1.93	2.01	0.060	2.99
Niepołomice	1-U-tube	2.66	2.64	2.50	2.60	0.070	2.69
Kraków III	2-U-tube	1.92	1.77	1.72	1.80	0.080	4.44

In Table 9, the lowest values are marked in green and the highest values in red. It can be seen that most often the lowest values occur for analysis with averaging every 60 min, and the highest for averaging every 1 min. For design safety reasons (designing the number of BHEs), averaging every 60 min should be used for analysis.

Due to the analysis of the commercial thermal response tests data, the effective thermal conductivity λ_{eff} for borehole heat exchangers located throughout Poland was determined. Calculations were made for three time intervals of measurement results averaging: 1 min, 10 min, 60 min, in each individual case.

An important element for the analysis of the measurements was the rejection of the results recorded before and after conducting the test, as well as any anomalies, which could have been affected by external factors such as voltage drops, start-up and stabilization periods of the circulation pump operation, or the influence of atmospheric air temperature.

The output data of the conducted and analyzed tests were spreadsheets with a summary of all the parameters of the heat carrier flowing in the circulating system, recorded by the TRT device. For further analysis, additional calculations in the form of an average heat carrier temperature and the time from the beginning of the test and its natural logarithm were necessary.

By obtaining such data, it was possible to create appropriate graphs showing the relationship between the average temperature of the heat carrier, time, and the logarithm of time. A graph depicting the relationship between heating power, flow rate, and time was presented in order to determine their possible impact on the measurement process.

Slope factors were determined based on regression equations. The average heating power was calculated by summing the values recorded for each measurement and dividing it by the number of measurements. The depth of the exchanger, originating from the technical documentation, was given as additional information for each test.

The presented values of the effective thermal conductivity coefficient λ_{eff} for each exchanger are similar and show no significant differences between each other. Only in four cases a discrepancy in results of more than 5% can be noticed, which may have been caused by external factors.

The calculated standard deviation and coefficient of variation values confirmed that the set heating power showed constancy and that any deviations from the average were small (less than 10%). The same is true for the effective thermal conductivity factor (the variability of this parameter is only a few percent), which indicates small differences in conductivity depending on the sampling rate of the test. The heating power shows a small dispersion of values over the measurement process.

It has been confirmed that the directional coefficient of the regression line affects the value of effective thermal conductivity, but these are not very large discrepancies. This is due to the number of results making up the graph of the average temperature dependency on the logarithm of time. More data allow for more accurate determination of the parameters, however it makes it easier to disrupt the correctness of the measurement process, affecting the final result.

6. Conclusions

The thermal response tests were performed for 100 h in BHEs of different design and identical lithology. TRT data averaging intervals of every 1 min, 10 min, and 60 min were analyzed. Heat carrier temperature changes in time were recorded. The program used for the conversion of data from TRT apparatus were calculating the averages by an arithmetic mean method. It can be concluded that the most reliable (accurate) result would be reflected by a measurement with a time interval of every 1 min. Such data will be the largest in quantity. Rock mass properties were identical. The effective thermal conductivity λ_{eff} is dependent on various BHEs designs, heat carrier flow geometry, as well as sealing slurry parameters. The position of the pipes in relation to each other also seems important to consider. As shown on the graphs, the best effective thermal conductivity λ_{eff} has occurred in BHE-1 with a coaxial design. At the same time, this value is closest to the theoretical value of thermal conductivity of the drilled rocks λ .

By analyzing the results of the thermal response tests, the value of effective thermal conductivity can be easily determined. For this purpose, it is necessary to create a graph of the relation between the average temperature of the heat carrier and the logarithm of the working time of the TRT apparatus. Then, a regression line of this function and its directional factor should be determined.

The directional factor of the regression line shows different values, depending on the time interval for the considered BHE. As a result, the final value of the effective thermal conductivity coefficient λ_{eff} for this BHE is slightly different. It is influenced by the method of averaging the obtained results during the thermal response test. In the majority of described cases, these differences are not very significant, and the values are comparable. In two cases, they are slightly larger, possibly because it is easier to miss the moment of the ground thermal saturation and the temperature graph smoothing at intervals of 60 min. It therefore appears that the interval of 1 min is more accurate for correct determination of the thermal parameters of the rock mass.

The results of the conducted analysis of the thermal response tests for the borehole heat exchangers located in Poland allowed to determine the directional coefficient of a regression line, and its influence on the effective thermal conductivity for individual exchangers, which was presented in Table 9.

Standard deviation and coefficient of variation values have confirmed that there were no significant deviations from the set value of heating power. They also showed that the effective thermal conductivity calculated for different time intervals shows little value variability.

Thermal conductivity values for each time interval, for the same exchanger, were similar in value. Investigated media have shown good potential for extensive installations acquiring heat from low temperature sources.

As shown in Table 9, the lowest values most commonly appear for analysis averaging every 60 min, and the highest—for analysis averaging every 1 min. For design safety reasons (designing the number of BHEs), safer values can be taken for analysis, i.e., averaging every 60 min. A better way is to use the most accurate estimate (1 min averaging) and then simply include a safety margin for design safety reasons. Adding safety should be a quantifiable adjustment, which can be based on the lowest (safer) value of averaging, sensors uncertainty, and the impact of ambient temperature.

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