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Tomasz Śliwa*, Andrzej Grygieńcza*, Anna Bieda*, Aneta Sapińska-Śliwa*, Andrzej Gonet*, Marek Jaszczur, Tomasz Kowalski***

THE ANALYSIS OF HEATING OUTPUT EVALUATION METHODS FOR BOREHOLE HEAT EXCHANGERS***

1. INTRODUCTION

Boreholes, which use rock mass as a heat reservoir, are increasingly made for heating and cooling systems [15]. This paper presents an analysis of the thermal behavior of borehole heat exchangers including the following parameters: effective thermal conductivity and thermal resistance of a borehole heat exchanger.

An important element of the work is to compare the methods of assessing the effective thermal conductivity, including:
– an analysis of the literature based on the lithological profile,
– a temperature profile analysis carried out with the use of a NIMO-T tool,
– a Thermal Response Test (TRT).

The measurements were realized in the Laboratory of Geoenergetics in Krakow. The installation is described by Śliwa and Gonet [15] and Śliwa et al. [17].

On the basis of the lithological profile, profiling the temperature or the thermal response, one may determine the mean value of the thermal conductivity of rocks or the effective conductivity (from TRT). Then, indicative values of the potential unit power exchanged with the rock mass are calculated from the formulas [2]:

$$q = 20 \cdot \lambda_{eff} \tag{1}$$

and:

$$q = 13 \cdot \lambda_{eff} + 10 \tag{2}$$

* AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland
** AGH University of Science and Technology, Faculty of Energy and Fuels Krakow, Poland
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In equation (1) and (2):

q – the unit heat flowrate in a borehole heat exchanger (unit thermal efficiency) [W·m^{-1}],

λ – the average thermal conductivity of rocks or the effective thermal conductivity in a borehole heat exchanger [W·m^{-1}·K^{-1}].

The value of the unit power of a borehole heat exchanger q from formulas (1) or (2) is a value appropriate for the operation of heat pumps for 2,000 hours [2] a year, only in the heating mode. The determined value can be used for designing only small installations up to 20 kW [2]. For more borehole heat exchangers, one must use specialized programs to evaluate their long term exploitation [14].

2. ANALYSIS OF THE LITHOLOGICAL PROFILE

The easiest way to estimate thermal parameters of rocks is to take the conductivity of rocks, as well as other values, from the literature [5].

Table 1

Thermal values of rocks for borehole heat exchangers [5]

<table>
<tr><th>Geologic period</th><th>Interval [m]</th><th>Rock</th><th>Thermal conductivity λ, [W·m^{-1}·K^{-1}]</th><th>Specific heat c_{vav}, [MJ·m^{-3}·K^{-1}]</th><th>Thermal diffusivity a, [10^{-6}m^2·s^{-1}]</th></tr>
<tr><td rowspan="5">Quaternary (Pleistocene, Holocene)</td><td>1.6–2.2</td><td>anthropogenic soils (dark-gray embankment with rubble)</td><td rowspan="7">2.039</td><td rowspan="7">2.309</td><td rowspan="7">0.883</td></tr>
<tr><td>2.2–2.6</td><td>silt (gray soil)</td></tr>
<tr><td>2.6–4.0</td><td>fine and dusty sand with a touch of clay</td></tr>
<tr><td>4.0–6.0</td><td>fine sand</td></tr>
<tr><td>6.0–15</td><td>sand and gravel mix</td></tr>
<tr><td rowspan="2">Tertiary (Miocene)</td><td>15–30</td><td>gray clay</td></tr>
<tr><td>30–78</td><td>gray shale</td></tr>
</table>

As indicated in Table 1, the average thermal conductivity of rocks lithological profile for BHE Laboratory of Geoenergetics University of Science and Technology in Krakow is λ = 2.039 W·m^{-1}·K^{-1}.

3. NIMO-T LOGGER

In geothermal installations, the heat source is, among others, the Earth's natural heat flux q. In the shallow layers of the lithosphere at the depth of 20–40 km, a stream is formed by heat conduction, whereas convection and radiation are less important [25].

The thermal conductive flow is described by the Fourier law, which states that the density of the conductive heat stream is directly proportional to the temperature gradient and the thermal conductivity through the rocks. The measure of this ability is the coefficient of thermal conductivity λ. The Fourier law has the form:

$$w = -\lambda \cdot T \tag{3}$$

where:

w – the density of the Earth's natural heat flux [$W \cdot m^{-2}$],
T – temperature [°C],
λ – the thermal conductivity of rocks [$W \cdot m^{-1} \cdot K^{-1}$].

Transforming the formula (3) one obtains the thermal conductivity dependence:

$$\lambda = -\frac{w}{T} \tag{4}$$

A NIMO-T (Non-wired Immersible Measuring Object for Temperature) logger is used for temperature measurements in borehole heat exchangers (Fig. 1). A NIMO-T is a small, lightweight, wireless probe consisting of pressure and temperature recorders, as well as a programmed microprocessor. Everything is placed in a closed metal waterproof tube that can withstand pressure up to 100 bar. The sensor itself has a length of about 235 mm, a diameter of 23 mm and weighs 99.8 g. A NIMO-T probe, because of its weight, falls to the bottom of the borehole at a constant rate of about 0,2–0,3 $m \cdot s^{-1}$. The speed of descent can be adjusted by means of weights. The temperature is measured every 2, 4 or 6 seconds. This data is stored in a built-in memory inside the probe. Once the logger reaches the lowest point of the U-tube, a circulating pump is connected to the second arm. When enabled, the sensor is flushed out of the U-tube [10].

Fig. 1. NIMO-T logger [11]

Results and interpretation of the temperature profile from the NIMO-T

Temperature profiling was performed using a NIMO-T device in all the boreholes located on the premises of AGH University of Science and Technology in Krakow at the turn of June and July 2009.

The data read from the NIMO-T logger i.e. the pressure, the depth and the temperature are presented by means of diagrams (Fig. 2) for the temperature profiling of individual heat exchangers.

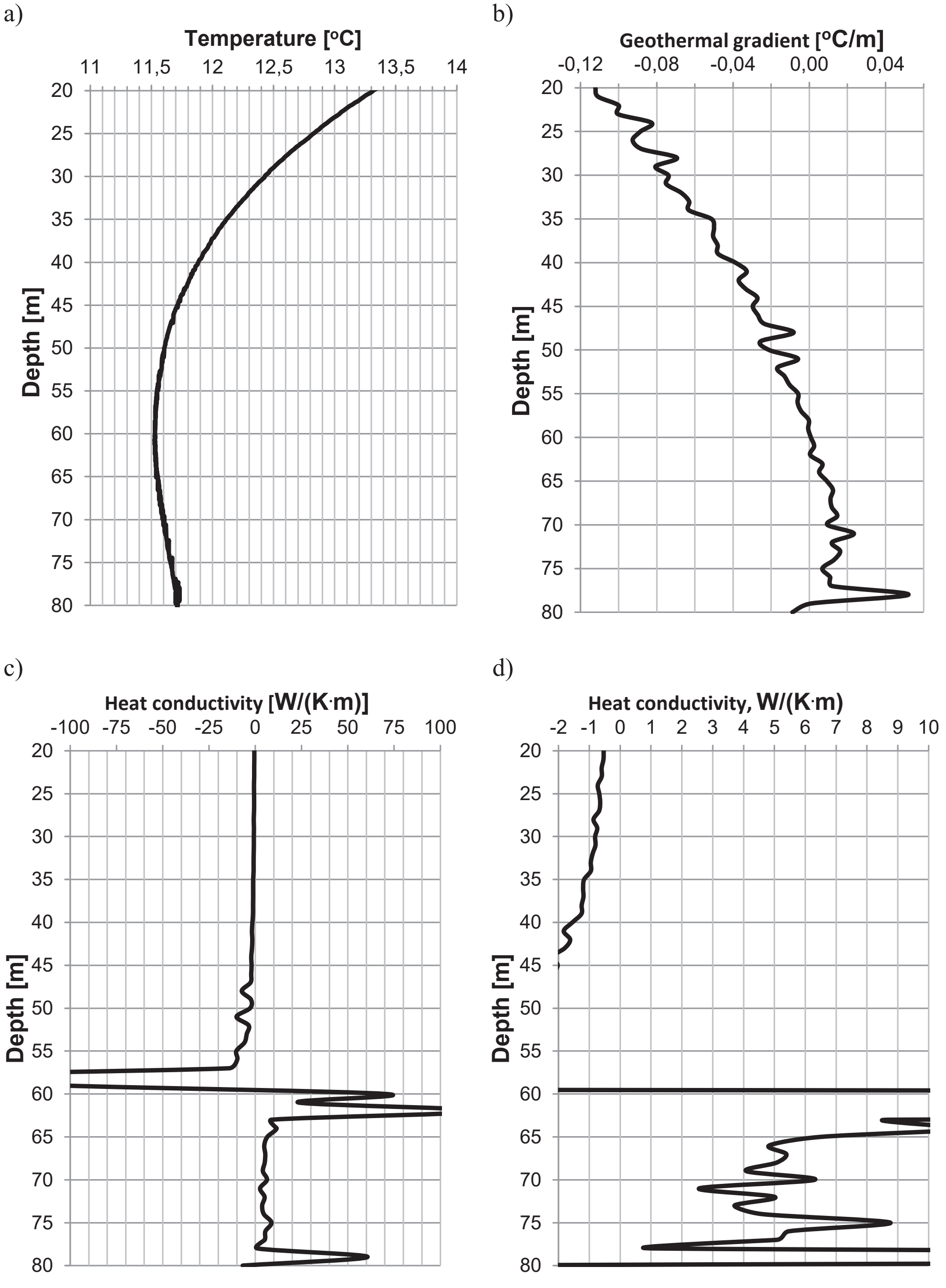


Fig. 2. Borehole heat exchanger temperature profiling:
a) temperature; b) gradient; c) thermal conductivity;
d) thermal conductivity with more accurate scale

The figures show that all temperature profiling studies are approximate. At the initial depth of 0 to 20 meters, the temperature measured during the test is influenced by the temperature of air. However, below 20 meters, the remaining heat exchangers are influenced only by the rock mass. The fluid injected into the heat exchangers was water.

From the curves of temperature profiling for the university's exchangers, one may also know how long the season was during the research. The nature of the curves corresponds to summer time (June, July), which is proven by initial profiled temperature values.

An unusual temperature increase was observed to a depth of about 60 m (Fig. 2a). It results from the urban infrastructure, where in the case of the Laboratory of Geoenergetics it is influenced by the municipal pipeline of district heating.

Determination of conductivity from the temperature profiling

For the calculation of the temperature gradient from the temperature profiling the following formula (5) was used:

$$G = \frac{T(h_{\max}) - T(h_{\min})}{h_{\max} - h_{\min}} \tag{5}$$

where:

$T(h_{max})$, $T(h_{min})$ – temperature at the maximum and the minimum depth respectively [°C],

h_{max}, h_{min} – maximum and minimum depth respectively [m].

Having the value of the Earth's natural heat flux, taken from the map of the density distribution of the Earth's natural heat flux in Poland [25] based on the Fourier law (3), one may determine the thermal conductivity coefficient value λ [5].

The resulting values were averaged for depth ranges successively every 1 m, and then, based on such conditions, the temperature gradient in borehole heat exchangers and its behaviour was calculated (Fig. 2b).

It was found that values of individual gradients at various heat exchangers do not differ much from each other. Only no. 5 was affected at a depth of 31 to 32 m.

At the bottom of each borehole it was observed that in some places the gradient was near 2°C/100 m.

For the same conditions as in the case of the determination of the temperature gradient, i.e. after the rejection of 20 m of overburden rocks from the Fourier law, knowing the density of the heat flow q for Krakow 60 $mW \cdot m^{-2}$, the converted formula enables calculation of the thermal conductivity coefficient λ for each depth. This dependence is shown in Figure 3.

Similar conditions occurred during the calculation of the thermal conductivity of the heat exchangers 1, 2 and 5, but different for 3 and 4. Sam as in the case of the temperature gradient, in some 1 meter thick intervals, negative values of thermal conductivity were obtained. This fact should not be surprising because the coefficient λ depends on the temperature gradient.

To sum up, the data obtained from the tests using a NIMO-T probe indicates that temperature profiling for all heat exchangers was executed without complications. In its initial phase, to a depth of approx. 20 m, air temperature impact occurs. Below 60 m, temperature is rising along with the depth.

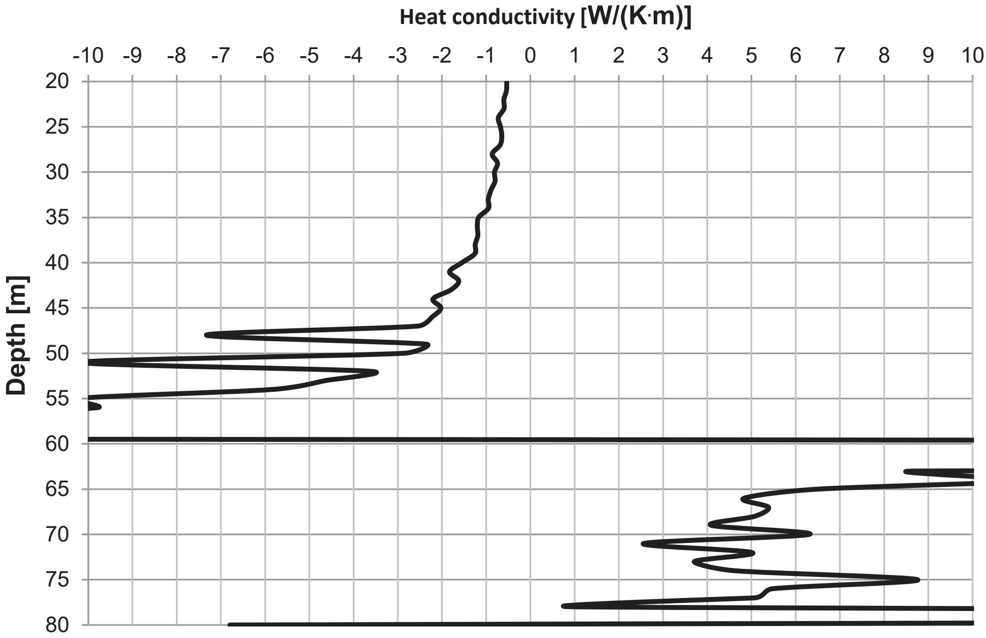


Fig. 3. The values of thermal conductivity in the borehole heat exchanger no. 4

Having determined the thermal conductivity from the temperature profiling data, it was concluded that the test method is not effective. Only the thermal conductivity from exchanger no. 5 may be considered as properly determined.

4. THERMAL RESPONSE TEST

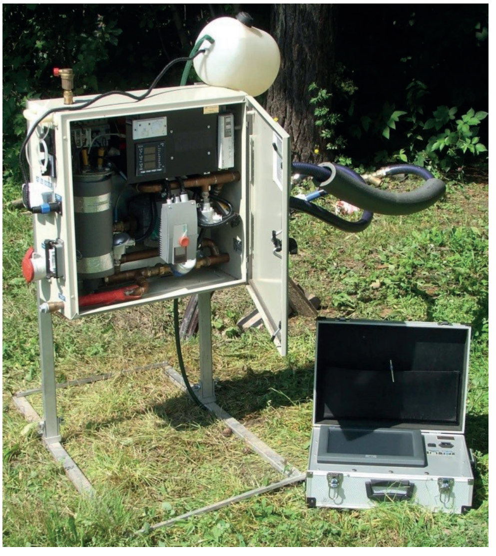
The first independent devices for thermal response tests (TRT, also GeRT – Geothermal Response Test) were the solutions constructed in 1995 in Sweden, and the United States. The Swedish instrument was installed at the University of Technology, Lulea, whereas the American one was at the University of Oklahoma. After these tests, many countries have introduced their own constructions for TRT [6].

TRT equipment has various structures in different countries. They may be either mounted on trailers or in special portable boxes (Fig. 4).

A TRT instrument includes flowrate and temperature sensors, a circulation pump and an electric furnace. The system allows for the to performance of tests to determine the effective conductivity of rocks and the thermal resistance of a borehole heat exchanger. Thanks to these values, it is possible to properly design the number and the location of borehole heat exchangers and to determine the temperature characteristic of operation of the heat exchange system [15].

Tables 2 and 3 show data that can be used in the design of the borehole heat exchanger's unit power with the use of the effective thermal conductivity λ measured during the thermal response test.

a)



b)

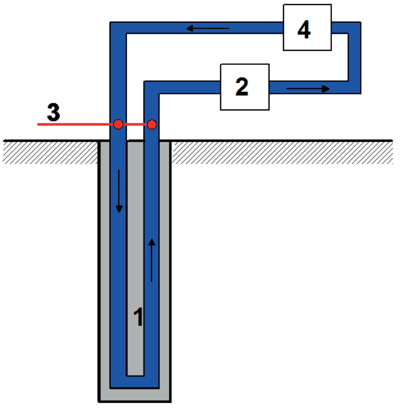


Fig. 4. Idea of Thermal Response Tests (a) equipment for TRT: 1 – BHE, 2 – flow rate meter, 3 – thermometers, 4 – electric heater and circulation pump (b)

Table 2

Unit thermal output of a single u-tube borehole heat exchanger determined using the effective thermal conductivity measure by TRT [7]

The effective thermal conductivity by TRT [W·m^{-1}·K^{-1}]	Unit power of a borehole exchanger [W·m^{-1}]
to 1.5	to 40
from 1.5 to 2.0	to 50
from 2.0 to 3.0	to 55
more than 3.0	to 80

Table 3

Unit thermal output of a single u-tube borehole heat exchanger determined using the effective thermal conductivity measure by TRT [26]

The effective thermal conductivity by TRT [W·m^{-1}·K^{-1}]	Power output borehole heat exchanger [W·m^{-1}]
to 1.5	to 30
from 2.0 to 3.0	from 50 to 55
more than 3.0	to 80

Results

The study was conducted for borehole heat exchangers numbered 1 to 5 located in the area of AGH University of Science and Technology in Krakow. The conducted TRT provided the following results:

- the amount of seconds from the beginning of heating [s],
- the temperature of the fluid which powers the heat exchanger [°C],
- the temperature of the fluid that returns from the heat exchanger [°C],
- the outdoor temperature (atmospheric temperature) [°C],
- the momentary flowrate [dm^3min^{-1}].

In all heat exchangers the diameter of the borehole is $d = 0.143$ m. The temperature profile can be determined by recording the temperature of the circulating fluid before the heating process. The value of this temperature can be determined by profiling the temperature. In the case of heat exchangers at AGH University of Science and Technology the profile temperature was determined with a NIMO-T probe. If the thermal output Q and the depth H of an exchanger is known then the unit thermal output q can be calculated. The results of the determined temperature, the depth and the unit thermal output of each exchanger are provided in Table 4.

Table 4

Values of the set temperature profile and the depth of exchangers

BHE no.	1	2	3	4	5
Heating power, Q [W]	4,000				
Depth, H [m]	78				
Unit heating power, q [$W \cdot m^{-1}$]	51.28				

Based on the TRT results, graphs showing the dependence between temperatures of the powered fluid and the returning fluid and the time of heating were designed. This method illustrates how the temperature of a fluid injected in the borehole changes over time. For this case, the outdoor temperature was also given (Fig. 5).

As seen in Figure 5, it was concluded that during the initial stage of this test, the temperature of supply and return of the heating medium circulating in the heat exchanger suddenly rises. However, after exceeding the specified time, both temperatures are almost parallel. For the heat exchangers 1, 2, 3, 4 and 5 it was noted that during heating an abrupt rise and fall in the temperature of the heating medium occurred in certain areas. The reason for these results was the rapid increase of the outdoor temperature, which exceeded the temperature of fluid circulating in the heat exchanger during TRT. The end of the test at a constant heating power for each exchanger was different. According to the condition determining thermal parameters of heat exchangers, the duration of the test proposed by the International Energy Agency (IEA) should be more than 50 hours (Tab. 5).

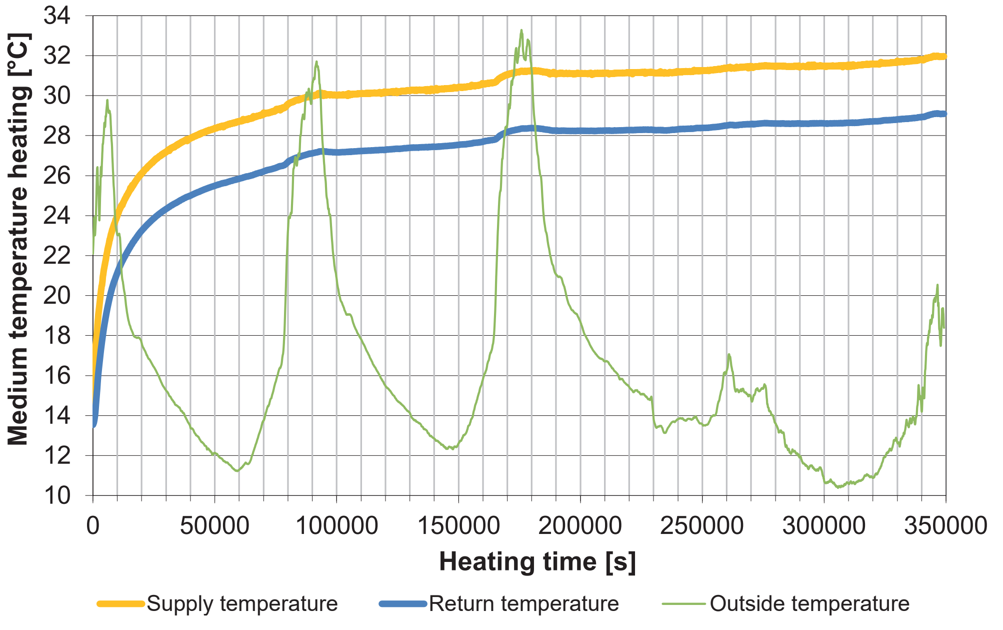


Fig. 5. Dependence between the temperature of the heating medium and the heating time in the heat exchanger no. 1

Table 5

The duration of TRT

No.	Author	Time [h]	Bibliography
1	Austin W. et al. 2000	50	[1]
2	Gehlin S. 2002	min. 60, recom. 72	[3]
3	Gehlin S. and Austin W. 2006	45–60	[4, 28]
4	Mands E. and Sanner B. 2001	48	[8, 9]
5	Sanner B. et al. 2005	30	[11]
6	Skouby A. 1998; Spitler J. et al. 1990	50	[13] [23]
7	Spitler J. et al. 2000	50	in order to obtain reasonably accurate results, a 50 hour test duration is recommended [24]
8	The International Energy Agency (IEA)	50	[28]
9	Złotkowski A., Śliwa T., Gonet A. 2011	100	[27]

Interpretation

For each borehole a curve was provided, presenting the average value of the heating temperature (temperature from the feed and the return), for the common logarithm of the heating time. The next step was to determine an appropriate time interval, which will be necessary to properly determine the parameters of a heat exchanger. In fact, the duration of the test for calculating the appropriate values should begin with $t \geq 5 \cdot r^2/a$ for an error of 10%. However, in order to obtain a more accurate value, the designated time begins with $t \geq 20 \cdot r^2/a$ for an error of 2.5%. Then the average temperature intervals of the heating medium and the time can be displayed on a graph setting for it a linear equation. The following parameter values are for an error of 2.5% (Tab. 6). It was established that alpha is $0.883 \cdot 10^{-6}$ m²/s.

Table 6

TRT time for borehole heat exchangers [h:min]

No.	1	2	3	4	5
$t \geq 20 \cdot r^2/a$	29:28				
End of test	96:59	70:10	68:52	66:13	160:31

Using the formula for temperature between the hole and the surrounding rocks, depending on the time and the radius, at a constant heating power, and substituting it for the thermal resistance of the hole $T_f - T_b = R_b \cdot q$, the temperature of the fluid circulating in the exchanger is obtained (6):

$$T(r,t) = T_o + \frac{q}{4 \cdot \pi \cdot \lambda} W(u) \cong T_o + \frac{q}{4 \cdot \pi \cdot \lambda}\left[\ln\left(\frac{4a \cdot t}{r^2}\right) - \gamma\right] \tag{6}$$

where:

$T(r,t)$ – temperature at any point around the opening [K],
T_o – average temperature in profile [K],
q – unit thermal efficiency [W·m⁻¹]:

$$q = \frac{Q}{H},$$

Q – heating power [W],
H – borehole's depth [m],
λ – thermal conductivity coefficient of the rock [$W \cdot m^{-1} \cdot K^{-1}$],
a – temperature conductivity coefficient of the rock [$m^2 \cdot s^{-1}$]:

$$a = \frac{\lambda}{\rho \cdot c},$$

ρ – rock density [$kg \cdot m^{-3}$],

c – specific heat of the rock [$J \cdot kg^{-1} \cdot K^{-1}$],
r – radius [m],
γ – Euler's constant = 0.5772,
u – substitution $u = \frac{r^2}{4a \cdot t}$.

$$T_f(t) = \frac{q}{4 \cdot \pi \cdot \lambda}\left[\ln\left(\frac{4a}{r_o^2}\right) - \gamma\right] + q \cdot R_b + T_o \tag{7}$$

where:

T_f – average temperature of the fluid [K]:

$$T_f = \frac{T_{in} + T_{out}}{2}$$

T_{in} – supply temperature [K],
T_{out} – return temperature [K],
q – unit thermal efficiency [$W \cdot m^{-1}$]:

$$q = \frac{Q}{H},$$

Q – heating power [W],
H – borehole's depth [m],
R_b – thermal resistance of the borehole [$K \cdot m \cdot W^{-1}$],
T_o – average temperature in profile [K],
λ – thermal conductivity coefficient of the rock [$W \cdot m^{-1} \cdot K^{-1}$],
t – heating time [s],
a – thermal diffusivity of rock [$m^2 \cdot s^{-1}$],
r_o – radius [m].

Because the unknown factor is the temperature conductivity of rocks, the calculations also need the values of the weighted average of thermal conductivity coefficient of rocks, as well as the volumetric specific heat. These values were collected from the literature. In this case, the mean parameters for borehole heat exchangers 1, 2, 3, 4 and 5 are summarized in Table 1. It is important that properties of thickness of 1.6 meters were omitted. The reason is that the heat exchanger is not placed at 0 m, and is recessed in a suitable well.

Based on previous conclusions and the calculated values shown in Tables 4 and 6 linear equations were set taking into account the time and error level of 2.5% and the average temperature of the fluid. The linear equation for a borehole heat exchanger is shown in Figure 6.

Coefficient of determination R^2 (the correlation coefficient to the second power) can assume values between 0 and 1. Values closer to 1 denote a good fit of the model to real data. Among the linear charts of average temperatures of the heating medium, only heat exchanger 4's determination coefficient differs from others, but, because they have the value of $R^2 = 0.8678$, both lines were accepted as complying with the matching data. Table 7 collects the gradients of lines for particular heat exchangers.

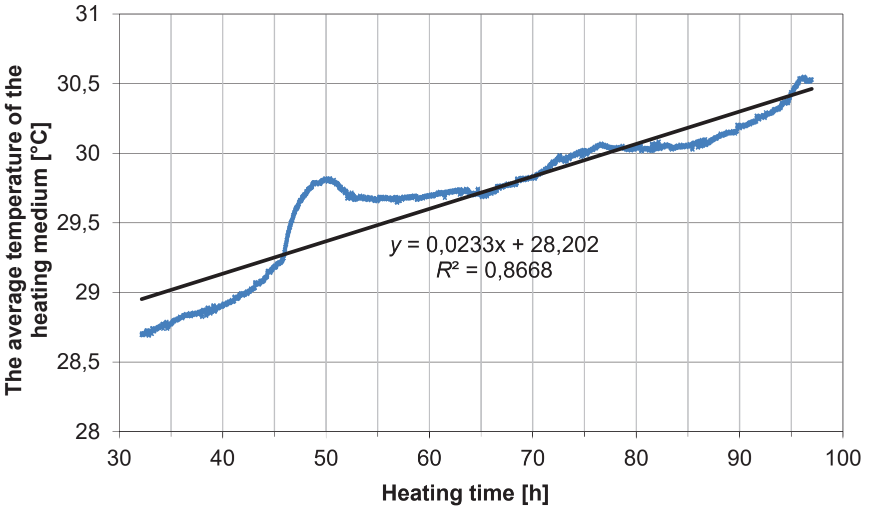


Fig. 6. Line of the average temperature of the heating medium for borehole heat exchanger no. 1

Table 7

Gradient from TRT with an error of 2.5%

No. BHE	1	2	3	4	5
Slope *k*	1.446	2.1606	1.9091	1.4886	1.8071

Determination of parameters and the heating output

The heating output on the TRT device testing borehole heat exchangers at AGH was fixed at a constant level $Q = 4000$ W. In the analytical method for the linear source at a constant heating power, the value of the slope k of the linear equation is taken into account to determine the effective thermal conductivity. For such a case, the effective thermal conductivity is calculated with the equation (8). The slope k can be used to assess the efficiency of heat conduction:

$$\lambda_{eff} = \frac{q}{4 \cdot \pi \cdot k} \tag{8}$$

where:

λ_{eff} – effective thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$],
q – unit thermal efficiency [$W \cdot m^{-1}$]:

$$q = \frac{Q}{H},$$

Q – heating power [W],
H – depth [m],
k – slope.

In order to determine the thermal resistance R_b, it is necessary to know the borehole's depth and its diameter, the thermal properties of the rock and the determined temperature profile (Tabs. 1 and 4). All the necessary values for thermal resistance were substituted into the formula (8). The behavior of the determined thermal resistance for a given heat exchanger for an error of 2.5% is shown in Figure 7. The remaining values and the effective thermal conductivity are provided in Table 8.

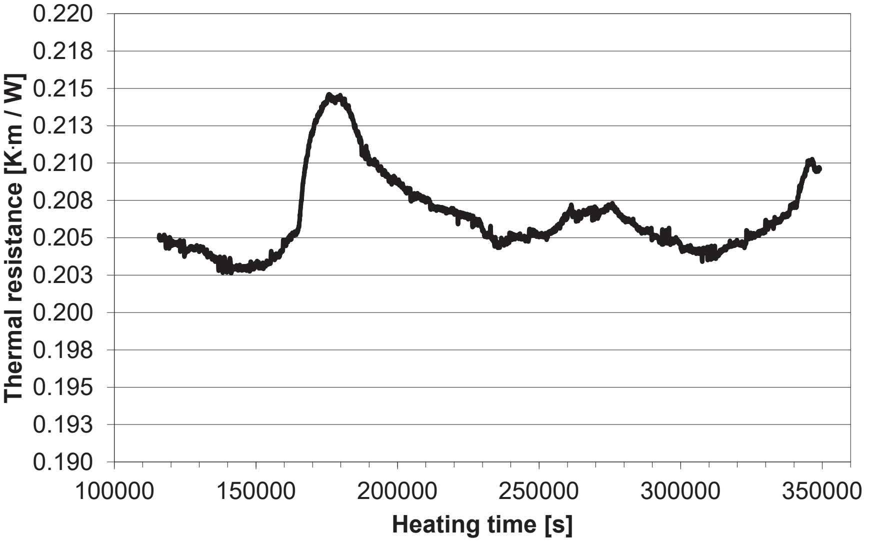


Fig. 7. Thermal resistance over the heating time for the borehole heat exchanger no. 1

Table 8

Thermal properties of exchangers determined by the thermal response test

No. BHE	1	2	3	4	5
Average temperature in BHE, T_o [°C]	12.68	12.73	12.72	12.69	12.71
Slope, k	1.446	2.1606	1.9091	1.4886	1.8071
Effective thermal conductivity, λ_{eff} [$W \cdot m^{-1} \cdot K^{-1}$]	2.824	1.890	2.139	2.743	2.259
BHE thermal resistance, R_b [$K \cdot m \cdot W^{-1}$]	0.206	0.127	0.102	0.033	0.123

Considering the effective thermal conductivity coefficients, it may be concluded that all the obtained values differ from each other. For borehole heat exchangers located within AGH, the weighted average value of the thermal conductivity is equal to 2.039 $W \cdot m^{-1} \cdot K^{-1}$ which shows that for borehole 3 λ_{eff} coefficient is very close. However, small differences in the effective thermal conductivity were observed for numbers 2 and 5, and large for 1 and 4, which may result from a different construction of borehole heat exchangers.

The determined thermal resistance of the borehole also has variable values. With the increase of the heat conductivity of the filler used to seal the borehole heat exchanger thermal resistance R_b decreases. Using a normal filling material, it was concluded that its thermal resistance will have a value above 0.1 K·m·W^{-1}, while for thermal material it will be less than 0.1 K·m·W^{-1}.

In heat exchanger no. 1 having a coaxial structure a high heat resistance value was observed. The reason may be a change in the flowrate velocity of the fluid from the inner tube heat exchanger into the annular space due to the different cross-sectional area. Another condition may be the fact that the circulating fluid in the borehole has direct contact with rocks. In this case, the calculated value of the thermal resistance of the borehole equals 0.206 K·m·W^{-1}. It is important to point out that heat exchanger no. 1 is sealed with cement, which confirms that the resistance value is greater than 0.1 K·m·W^{-1}.

For TRT on single u-tube heat exchangers and received resistivity values slightly higher and lower than 0.1 K·m·W^{-1} it was stated that thermal cement might have been used for sealing in both boreholes 3 and 4. Cement of this kind has been introduced in borehole no. 3. The thermal resistance of borehole 2 amounts to 0.127 K·m·W^{-1}, which proves the use of gravel as the filling material. In the case of a double-tube (borehole 5), the thermal resistance of the borehole for sealing with gravel and Hekobentonite respectively has a consistent value. The shape of the curves of thermal resistance with respect to the heating time for borehole heat exchangers 1, 2 and 4 was influenced by a higher external temperature of supply and return of the circulating liquid medium.

5. CONCLUSIONS

1. Thermal conductivity λ can be determined in a laboratory using a rock originating from the borehole, but may also be determined in field conditions by the so-called thermal response test. Since both methods are time consuming and sometimes require special equipment, in which case a the simpler technique can be used to determine the thermal conductivity λ, namely a wireless NIMO-T probe, which runs down into the inoperative borehole heat exchanger and measures the pressure and the temperature.
2. TRT is a method determining thermal parameters of rocks. In this method, the fluid circulates in a (e.g. U-tube) borehole heat exchanger. The heat pump working medium is heated / cooled, which then determines its flow and return temperature. In this manner, rock parameters are important in planning the output of large quantities of heat in a specific area of their construction. The model line-source analytical method is one of the easiest ways to determine the effective thermal conductivity and the thermal resistance of the borehole tested with a thermal reaction.
3. For heat exchangers at AGH University of Science and Technology, determining the thermal conductivity coefficient from the temperature profiling data, the calculation method is stated not to be effective. The reason is that there are inflated or negative values λ. Only in the case of heat exchanger no. 5, the thermal conductivity can be accepted as correct.
4. The average thermal conductivity λ literature data is lower than the effective thermal conductivity λ_{eff} based on the calculation from the thermal response tests. Only the heat exchanger 2 has lower effective thermal conductivity λ_{eff}. The thermal resistance of the BHEs in all wells corresponds to the proper values for the filler material.

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