Influence of flow rate and heating power in effective thermal conductivity applied in borehole heat exchangers

T Śliwa¹, A Sapińska-Śliwa¹, R Wiśniowski¹, Z Piechówka¹, M Krzemień¹, D Pycha¹ and M Jaszczur²

¹AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland
²AGH University of Science and Technology, Faculty of Energy and Fuels, Krakow, Poland

E-mail: sliwa@agh.edu.pl

Abstract. In borehole heat exchanging systems one of the most important parameters necessary to estimate its efficiency is the effective thermal conductivity. One of the methods for determining it is thermal response test. Such a test may be performed with respect to various parameters. The most important ones include flow rate and heating power. The article summarizes the results of TRT research in Pałecznica village, Poland which was performed in boreholes located there in the already operating installation. It presents the established methodology. Also, there is an attempt to determine the relation between the mentioned parameters and the effective thermal conductivity. The research indicates the dependence of the conductivity with the test parameters.

1. Introduction

In the last years in Poland, apart from the efficiency of energy collection, there has been an interest in its method and the influence on the environment [1]. The main factors are not only economic but also ecologic and environmental [2]. Because of that, unconventional sources of energy are becoming popular. One of the sources of clean energy is the rock mass [3]. One of the methods of energy collection from the rock mass is the application of a heat pump and borehole heat exchangers (BHE) [4].

BHEs harvest energy from the rocks of the Earth’s crust, which is used for heating. Heat pumps are reverse devices. After reversing the operation of the system, they may be used for cooling (air conditioning) [5].

Using the rock mass for heating by heat pumps and BHEs is burdened with a high initial cost of the installation. However, exploitation costs are low; there is no purchase of fuel and cost of transport, and what is most important, there is a lack of emission of combustion products to the atmosphere. Locally clean energy is received [6]. The emission is transferred to plants producing electric energy, which in Poland is mostly produced from coal [7].

The goal of installing BHEs is the acquisition of appropriate heating power, capable of heating a given facility [8]. Installations always comprise of many exchangers located in a given area, in a certain layout. The depth and the layout of boreholes depend on the lithology of the area and the properties of the rock mass [9]. The number of boreholes is selected in a way that secures a proper heating power [10].
The aim of the paper was to test the effective thermal conductivity of a BHE installation in the Pałecznica village (Małopolskie voivodeship). Furthermore, dependence between TRT parameters (temperature of the heat carrier/heating power and the volumetric flow rate) and the value of the conductivity was determined. A thesis that the value of the effective thermal conductivity $\lambda_{\text{eff}}$ changes with the varying TRT parameters in a BHE was made.

The tested BHE has a single U-pipe structure. The diameter of the borehole is 140 mm, and the diameter of the polyethylene U-pipe is 40 mm. The BHE is sealed with loam-cement mixture [11].

The average value of the thermal conductivity of the rocks in the profile was determined based on data from the literature and amounts to $1.70 \text{ Wm}^{-1}\text{K}^{-1}$. The average specific heat is $2030 \text{ Jkg}^{-1}\text{K}^{-1}$.

2. Methodology

There are three methods of determining rock thermal conductivity:

Method 1 based on data from the literature, dependent on the lithological profile [1] [12]. The thermal conductivity is determined based on values of conductivity for certain rocks forming the profile that are taken from literature. The weighted average is estimated, where the weight is the thickness of layers.

Method 2 based on the temperature profile of the borehole (temperature gradient $\nabla T$). It uses Fourier equations in the form:

$$ q = -\lambda \cdot \nabla T $$ (1)

Knowing the local value of the Earth natural heat flow rate $q$, the thermal conductivity $\lambda$ is estimated [13] with the following formula:

$$ \lambda = -\frac{q}{\nabla T} $$ (2)

Method 3. Using TRT, which uses a linear heat source [14] [15] dependence:

$$ T(r, t) = T_0 + \frac{q_0}{4\pi\alpha} \left[ \ln \left( \frac{4\alpha t}{r^2} \right) - C \right] $$ (3)

where $\alpha$ – average thermal diffusivity of the rocks in the drilled through profile ($\alpha = 1.10 \times 10^{-6} \text{ m}^2/\text{s}$), $r$ – radius of the borehole ($r = 0.07 \text{ m}$), $q_0$ – unit power, $\text{Wm}^{-1}$, $T(r, t)$ – dependence between temperature and the radius and time, $K$, $T_0$ – initial temperature, $K$, $t$ – test time, $s$, $C$ – constant.

In the Thermal Repose Tests, the analyzed object is the inclination of the curve in temperature over time of heating the heat carrier at a constant heating power.

3. Thermal response test

The thermal response test is carried out to estimate the value of the thermal conductivity and the thermal resistance in a BHE. This parameter is site- specific and cannot be modified or influenced by engineering [16]. Knowledge about this coefficient is crucial to evaluate the usability of a rock mass in the view of building BHEs. The method is simple, but quite time-consuming and it requires certain conditions to be met.

The basis for the described test is the working medium, which normally is a properly selected glycol solution. The medium should circulate in the system consisting of a BHE and measuring equipment at a constant volumetric outgo. It should be heated at a constant heating power. These are the most significant parameters in the execution of the test. Sustaining constant heating power, the working fluid is being heated during circulation. The temperature of the fluid is registered at the inflow and at the outflow from the BHE. Based on the data, it is possible to estimate the value of the effective thermal conductivity. For the results to be reliable, a few rules need to be followed. It is important to carry the test out for proper duration, 48 hours minimum (100 hour long test is advisable). It is essential to keep the whole system sealed, so the volume of the circulating medium does not change.

Taking the (eq. 3), after transformations, calculations are done based on the dependence of the temperature of the working medium returning from the BHE.
4. Test evaluation
The result of the TRT is a set of data, which allows for generating a plot exhibiting the dependence between the supply and the return temperatures of the heating medium over time (see figure 1).

The value of the effective conductivity $\lambda_{eff}$ can be estimated based on the dependence between the temperature of the returning fluid and time. Semi-log scale (time axis) needs to be applied in order to obtain the linear form (figure 2). Then the slope $k$ is determined.

![Figure 1. Dependence between supply and return temperatures of the heating medium and the time of TRT.](image)

![Figure 2. Dependence between return temperature of the heating medium and the log of TRT time.](image)

Knowing the slope, it is possible to estimate the effective thermal conductivity $\lambda_{eff}$ from the following dependence:

$$\lambda_{eff} = \frac{P}{4\pi H k}$$  \hspace{1cm} (4)

where $\lambda_{eff}$ – effective thermal conductivity, Wm$^{-1}$K$^{-1}$, $P$ – heating power, W, $H$ – depth of the borehole ($H = 30$ m), $k$ – directional coefficient of the regression line of the temperature course in the natural logarithm of time.

**Table 1.** List of beginnings and endings of intervals for evaluation of effective thermal conductivity.

| No. of interval | Beginning of interval | End of interval |
|-----------------|-----------------------|-----------------|
| 1               | $t_0$                 | $t_5$           |
| 2               | $t_1$                 | $t_5$           |
| 3               | $t_2$                 | $t_5$           |
| 4               | $t_0$                 | $t_2$           |
| 5               | $t_0$                 | $t_3$           |
| 6               | $t_2$                 | $t_3$           |
| 7               | $t_1$                 | $t_4$           |
| 8               | $t_3$                 | $t_5$           |

$t_0$ – beginning of the heating phase, $t_1$ – point of deviation of the line $T_{in}(t)$, $t_2$ – time corresponding to $t = 5r^2\alpha^{-1} = 22223 \text{ s} = 6.17 \text{ h}$, $t_3$ – time corresponding to $t = 20r^2\alpha^{-1} = 88892 \text{ s} = 24.69 \text{ h}$, $t_4$ – middle of the heating phase duration, $t_5$ – end of the heating phase.
Calculations may be carried out for different time intervals, taking into consideration the whole duration of the test e.g. the time from the point of deviation of the line in the chart. Further calculations were made for 8 time intervals. They are defined in table 1. TRT results averaged every 1 minute were used.

The equipment used for field work consists of three main modules for: a) controlling and registering results, b) sustaining circulation and heating power, c) measuring the temperature and the volumetric flow rate, which is presented in figure 3. The control module is an industrial computer fitted with a touchscreen and placed in a metal case fit for work in the field. It is a significant issue, given the fact that one may not always expect a sustained power supply in the place of tests, leading to complications during the test itself and while analyzing the data.

The module sustaining the heating power and the circulation of the working medium is in the form of a case mounted on a rack. Inside, apart from a series of valves, there is an electric furnace, which can operate in several modes, depending on the demanded working parameters (the heating power). Moreover, this module includes a pump sustaining the pumping outgo of the working fluid. It is this element which is responsible for key test parameters, thanks to which reliable results can be obtained. Furthermore, the module comprises a valve which facilitates venting of the whole installation. It is the highest point of the installation. This process needs to be repeated every time after the apparatus is filled with the working fluid (glycol), because an air lock may greatly constrict the acquisition of the set flow rate parameters (the pumping outgo), and in extreme cases prevent the testing.

![Diagram](image)

**Figure 3.** Field work set, a) block schematics, b) photograph of the set; 1 – controlling and registering module (computer), 2 – module for sustaining heat power and circulation, 3 - module measuring the temperature and the volumetric flow rate of the heat carrier, 4 - U-pipe in the testing borehole.

The measuring module is a smaller case, and in concord with its name, it contains a series of valves, two flow rate meters of different ranges and thermometers. This part of the installation is connected directly to the underground borehole heat exchanger through hydraulic hoses. The valve module is necessary for proper setting of parameters ordered by the two other modules.

The modules are connected with each other with flexible hydraulic hoses. Such a set should form a sealed unit, which imposes control of the tightness of hoses and seals on threaded joints.

### 5. Experiment – performed measurements
Within the research, a number of TRT tests were conducted in Palecznica village. Since 2014, a heating installation has been operating there based on a heat pump and borehole heat exchangers. The research was carried out in 5 testing single U-pipe BHEs that are 30 m deep. The BHE installation operates in a direct steam system. 5 testing BHEs were made for monitoring the work of a system made of almost 40 operating exchangers. The paper presents results from the borehole no. 5.

Each measurement consisted of 6 hours of setting the flow rate and 48 hours of heating, which amounts to 54 hours of testing. To be able to witness changes in the value of the thermal conductivity
coefficient depending on the TRT parameters, research was conducted with varying parameter values. Parameters of each test are presented in table 2.

For the temperature of the rock mass to return to its initial value prior to the test, a 54 hour long waiting period was applied. At that time, other borehole exchangers were tested.

To observe how the temperature in the exchanger returns to its primary value after heating, temperature profiling was conducted. They were done with a NIMO-T device [13], which was inserted into the U-pipe. The device registered the temperature and the location every 2 seconds (about 2 m single reading). The results of the measurements are presented in figure 4.

![Figure 4](image_url)

**Figure 4.** Dependence between the temperature and the depth after a different period of time after TRT.

The chart presents the dependence between the temperature in the exchanger and the depth for measurements done both prior to and after the TRT. Before the connection to the apparatus, one profiling was done. After the TRT, 16 measurements were done. Initially, they were conducted every 1 hour, then every 6 hours. The last measurement, carried out 54 hours after the heater was turned off, was conducted before another test. It is visible in the chart that the temperature did not return to its previous value but it is very similar.

6. Results and analysis

The value of the effective thermal conductivity for particular TRT parameters and time intervals is presented in table 2.

In order to observe the correlation between parameters, selected results from table 4 were exhibited in figures 5 and 6. Figure 5 shows the dependence between the effective conductivity and the heating power which was put to the test. Figure 6 presents the dependence between the effective conductivity and the volumetric flow rate of the heat carrier.

The value of the effective thermal conductivity in the BHE is quite even for all intervals except the 8th, in which the value deviates greatly from others. This value results in an increase in the arithmetic mean and the standard deviation. In the 8th interval, significant fluctuation in the temperature of the heat carrier occurred.

Figure 6 presents the dependence between the effective conductivity and the heating power during a TRT. The highest value was determined at 1.5 kW. Simultaneously, it was noticed that higher
conductivity occurs at lower flow rates of the heat carrier. It is also proved by the chart in figure 7. Increase in the flow rate of the heat carrier results in a decrease in the value of the effective conductivity $\lambda_{\text{eff}}$. At a higher value of the volumetric flow rate, higher speed of the heat carrier is observed. Heat transfer is also higher. However, the increase in speed of the carrier results in the shortening of the contact between the carrier and the wall of the U-pipe. The time in which the heat carrier exchanges the heat with the surroundings is shorter. This factor has a significant influence on the value of the effective conductivity in the borehole exchanger.

![Figure 5](image_url)

**Figure 5.** Dependence between the effective thermal conductivity and the heating power for two different values of the volumetric flow rate of the heat carrier.

![Figure 6](image_url)

**Figure 6.** Dependence between the effective thermal conductivity and the volumetric flow rate of the heat carrier for two values of the heating power.

| No. of time interval | Flow rate, $Q$ (dm$^3$min$^{-1}$) | Heating power, $P$ (kW) | Maximum difference, (Wm$^{-1}$K$^{-1}$) |
|---------------------|----------------------------------|-------------------------|----------------------------------------|
|                     | 6.5                              | 10                      |                                        |
|                     | 6.5                              | 10                      |                                        |
|                     | 6.5                              | 15                      |                                        |
|                     | 10                               | 15                      |                                        |
|                     | 15                               | 15                      |                                        |
| 1                   | 1.66                             | 1.52                    | 0.19                                   |
| 2                   | 1.66                             | 1.52                    | 0.19                                   |
| 3                   | 1.81                             | 1.61                    | 0.44                                   |
| 4                   | 1.80                             | 1.69                    | 0.44                                   |
| 5                   | 1.69                             | 1.62                    | 0.32                                   |
| 6                   | 1.93                             | 1.54                    | 0.32                                   |
| 7                   | 1.61                             | 1.59                    | 0.74                                   |
| 8                   | 5.96                             | 1.37                    | 4.79                                   |
| Average             | 2.27                             | 1.47                    | 1.08                                   |
| Standard deviation  | 1.50                             | 0.116                   | 0.139                                  |
The lowest differentiation of the value of the thermal conductivity was found in the 5th interval, i.e. just over the 24th hour of the test. Similarly to the charts, the highest values were observed for low flow rates of the heat carrier.

7. Problems and limitations

A TRT set is relatively easy in operation. A person who had no previous contact with such a measuring device can be trained in a few hours. Despite the simplicity in handling, a series of obstacles and complications were met during the tests, which hampered obtaining the results. The causes of these complications can basically be divided into categories described below.

A. Differences in the voltage – the research was conducted in July and August, which is a season of violent storms accompanied by heavy rainfall and lightning in the southern Poland. Seldom strong winds also occur. All of the above contribute to differences in voltage in the electric grid. The measuring equipment used for the described research was not fitted with a stabilized power system, which in addition to the aforementioned differences in voltage resulted in changes of the ordered parameters or in extreme cases – the equipment turning off (e.g. at a flow rate of 6.5 dm³/min and a power of 1 kW, which is especially visible for the conductivity determined in interval no. 8).

B. Problems considering the automatic parameter control mode – it is a complication related directly to the aforementioned problems with the electric grid. In a laboratory the apparatus could be switched to the automatic mode after selecting the flow rate and heating power parameters, whereas in the case of uncertain power conditions this mode was inefficient. The equipment had to be constantly controlled in respect to the heating power, even at night, which forced shift work for at least two operators.

C. Tightness of the installation – given the age and the wearing of the equipment, prior to each test, the system had to be inspected for leaks with utter care, especially seals, threaded joints and hydraulic hoses. The majority of repairs could be made with the use of simple elements such as a Teflon tape, tow or spare seals. Spare equipment parts were also of use.

D. Logistic problems – the last but not least obstacle in realizing the measurements were the size and the weight of each module. The equipment used for the research was not fitted with any driving system, which results in moving it manually to another testing borehole. It had to be done deftly, sometimes at night, in unfavorable atmospheric conditions.

It needs to be said that the equipment used for the described research is a unit that has been utilized by the Laboratory of Geoenergetics at the Faculty of Drilling, Oil and Gas for the recent years [17]. Lately, a new measuring unit has been designed and constructed, which eliminates all of the aforementioned hindrances. Thanks to this, conducting next research will be improved significantly, which will facilitate acquisition of more reliable data.

8. Conclusions

8.1. The thermal response test is the most precise method of determining the thermal conductivity in a borehole exchanger. Given the nature of the test, the value of the thermal conductivity is variable and depends on TRT parameters (the heating power and the volumetric flow rate of the heat carrier). Therefore, the effective conductivity from TRT needs to be differentiated from the heat thermal of rocks.

8.2. In the case of TRTs conducted in on borehole, the received values of the thermal conductivity are maximal at the minimal value of the volumetric flow rate of the heat carrier. Longer contact of the heat carrier with the wall of the U-pipe is the cause.

8.3. Time intervals between tests amounted to over 50 hours. This period of time allows for reaching the initial temperature in the rock mass and starting a new TRT.

8.4. The influence of measurement conditions on the effective thermal conductivity should be further researched.

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