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ARTICLE

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THE INFLUENCE OF THE TRAJECTORY OF A BOREHOLE HEAT EXCHANGER ON THE POWER EXCHANGED WITH THE ROCK MASS

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Abstract: The article presents the influence of the trajectory of a borehole heat exchanger on the power exchanged with the rock mass. The focus is on the thermal parameters of rocks, which include thermal conductivity. This parameter can be determined using literature, laboratory tests or in-situ using a thermal response test. The design of the borehole heat exchanger as an inclined borehole maximizes the power exchanged with the rock mass by increasing the length of the borehole exchanger in the layer with the best thermal parameters. Mathematical calculations and thermal response tests show the advantage of inclined wells over vertical borehole heat exchangers in terms of the amount of power obtained from the rock mass.

Keywords: borehole heat exchangers, inclined borehole, thermal conductivity, geoenergetics, drilling wells

1. Introduction

The term "borehole heat exchanger (BHE)" refers to a borehole equipped with heat exchanger pipes (usually U-shaped). A heat transfer medium flows through these pipes. The space between the pipes and the well's wall should be sealed with cement grout. The basic designs of BHE include: single U-tube, double U-tube, multi-U-tube, and centric systems [1–3]. To 200 m in depth, single U-tube systems are most frequently applied, while deeper installations are coaxial. The coaxial system is most profitable in the view of exploitation costs and the highest heating power. Any kind of construction can be applied in boreholes purposed for producing heat [4]. Many factors influence the correct design of ground heat pump systems (with BHEs). Important factors affecting the effectiveness of this system are presented in Table 1. Economic and energy factors are presented.

Table 1. Factors affecting the efficiency of BHEs heating or cooling installations [1]

Construction parameters	Natural parameters	Production parameters
– depth of the installation	– geothermal gradient	– basic heating loads
– diameter of the borehole	– thermal conductivity of rocks	– basic cooling loads
– diameter of pipes	– specific heat of rocks	– peak load value
– thermal resistivity of pipe materials	– porosity and saturation of rocks	– peak load time
– distance between pipes in the exchanger	– hydrogeodynamic conditions	– time in which heat sources regenerate in the rock mass
– thermal conductivity of cement slurry	– local climatic conditions	– temperature of the heat carrier

Most often, borehole heat exchangers are made as vertical wells. However, there is a technique that allows borehole heat exchangers to be made at an angle known as Geothermal Radial Drilling (GRD). It is characterized by drilling multiple diagonal boreholes from a single location. A specialized drilling rig is used to drill this type of borehole, which has its limitations. The drilled boreholes are diagonal (angle of 30 to 65 degrees), usually between 40 and 60 m long, whereas classic borehole heat exchangers are usually around 100 m or more. Another difference between GRD and conventional drilling (vertical heat exchangers) is the need to construct a start chamber. Its depth is usually between 1 and 2 m. The basics of this method were developed by Tracto-Technik in the late 1970s [5] and in 2006 the company developed a modern tool with intelligent solutions for this type of installation. It was Tracto-Technik that named this method Geothermal Radial Drilling [4, 6, 7]. Such an installation is located in the C research field of the Geoenergetics Lab (Faculty of Drilling, Oil and Gas, AGH University of Krakow).

This work involves comparing the works of borehole heat exchangers, both vertical and inclined boreholes (drilled individually, unlike GRD technology). BHEs made as inclined boreholes, each drilled from a separate station, are located in research field B of the Geoenergetics Lab. The Geoenergetics Laboratory has heat exchangers of the same design made as vertical exchangers in research field A.

2. Method section

The BHEs located in research fields A and B at the Geoenergetics Lab (Faculty of Drilling, Oil and Gas, AGH University of Krakow) will be analyzed. A sample vertical BHE was selected, while the other was constructed as an inclined borehole. Both boreholes have the same lithological profile, as shown in Table 2.

The comparative analysis was performed in two stages. The first stage consisted of an analysis of literature data. The second stage consisted of in-situ measurements performed as a thermal response test (TRT).

Based on the lithological profile, values of thermal conductivity λ for particular rock layers can be assumed based on literature. Next the average λ can be calculated. The next step is to calculate the values of the indicators [9] of unit power exchanged between the working medium and the rock mass based on the following formulas:

$$q = 20 \cdot \lambda \tag{1}$$

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

where:
- q – unit energy flow rate [$W \cdot m^{-1}$],
- λ – thermal conductivity of the rock (effective) [$W \cdot m^{-1} \cdot K^{-1}$].

For the above case, the value of the unit power exchanged between the working medium and the rock mass calculated using formula 1 is 40.78 $W \cdot m^{-1}$, and using formula 2 is 36.51 $W \cdot m^{-1}$. Therefore, the average power exchanged with the rock mass, calculated on the basis of literature data, is 38.65 $W \cdot m^{-1}$

Table 2. Lithological profile for fields A and B of the Geoenergetics [8]

Length of the inclined borehole depending on the drilling angle [m]					
No.	**Top [m]**	**Bottom [m]**	**Thickness [m]**	**Lithology**	**Thermal conductivity [W·m⁻¹·K⁻¹]**
1	0.0	2.2	2.2	Anthropogenic ground (dark grey filled with debris)	1.600
2	2.2	2.6	0.4	Aggregate mud	1.600
3	2.6	4.0	1.4	Slightly and dusty clayey sand	1.000
4	4.0	6.0	2.0	Fine Sand	1.200
5	6.0	15.0	9.0	Sand and slag mix, slag	1.800
6	15.0	30.0	15.0	Grey clay	2.200
7	30.0	78.0	48.0	Gray clayslate	2.100
–	–	–	–	Average	2.039

In the case of borehole heat exchangers, the main parameter is the thermal conductivity of the layers in which the heat exchanger is installed. Each layer has a thermal conductivity coefficient within a defined range. The thermal conductivity values of rocks can be found in literature or specialized software. Table 3 presents selected thermal conductivity values of rocks based on the Earth Energy Designer industry software.

Table 3. Thermal conductivity of various minerals and rocks based on specialized Earth Energy Designer software

Name	**Minimum thermal conductivity [W·m⁻¹·K⁻¹]**	**Maximum thermal conductivity [W·m⁻¹·K⁻¹]**	**Recommended thermal conductivity [W·m⁻¹ · K⁻¹]**
Amphibolite	2.14	3.55	2.90
Andesite	1.73	2.22	2.20
Arkose	2.54	3.73	2.90
Basalt	1.33	2.29	1.70
Breccia	2.26	4.11	2.80
Clay - dry	0.40	0.90	0.40
Clay - wet	0.90	2.22	1.60
Claystone	1.05	3.02	2.20
Coal	0.26	0.63	0.30
Conglomerate	1.35	3.70	2.80
Diorite	1.97	2.87	2.60
Dolomite	2.83	4.34	3.20
Dunite	3.98	4.73	4.20
Eclogite	2.32	4.19	2.90
Gabbro	1.72	2.53	1.90
Gneiss	1.89	3.95	2.90
Granite	2.10	4.07	3.40
Granodiorite	2.03	3.34	3.30
Gravel - dry	0.39	0.52	0.40
Gravel - saturated	1.80	1.80	1.80
Gypsum	1.29	2.80	1.60
Lamprophyre	2.43	3.41	2.60
Limestone - massive	2.46	3.93	2.80
Marble	1.28	3.08	2.60

Table 3. cont.

Name	Minimum thermal conductivity [W·m⁻¹·K⁻¹]	Maximum thermal conductivity [W·m⁻¹·K⁻¹]	Recommended thermal conductivity [W·m⁻¹ · K⁻¹]
Marl	1.75	3.46	2.10
Marl – clayey	1.46	2.52	2.00
Marl – dolomitic	1.89	3.90	1.89
Pegmatite	2.89	3.31	3.00
Peridotite	3.79	5.27	4.00
Quartzite	3.60	6.62	6.00
Rhyolite	3.06	3.37	3.30
Salt	5.28	6.38	5.40
Sand – dry	0.27	0.75	0.40
Sand – dry – compacted	1.11	1.25	1.20
Sand – moist	0.58	1.75	1.00
Sand – saturated	1.73	5.02	2.40
Sandstone	1.28	5.10	2.30
Serpentinite	2.30	4.31	3.00
Shale	1.50	2.60	2.10
Silt – dry	0.38	1.00	0.40
Silt – wet	1.00	2.30	1.80
Siltstone	1.31	3.52	2.40
Syenite	1.70	3.48	2.60

By selecting the average or recommended value for a given layer, one can calculate the weighted average thermal conductivity along the length of the BHE installed in that rock mass. By making an inclined borehole, the thermal conductivity is improved by increasing the apparent thickness.

The next stage of research was the TRT. This test should be understood as a measurement method used for the evaluation of factual thermal properties of a rock mass in the tested area. The test is carried out in in-situ, on borehole heat exchangers for a test well. Thanks to it, it is possible to determine a proper amount of vertical borehole exchangers and their placement according to the set temperature conditions of work of a system. A TRT of BHEs measures changes of temperature of a fluid during its circulation in a close circuit in the event of supplying or collecting thermal energy of a steady heating power [8, 10–12].

The TRT is performed on a previously drilled and cased borehole. The borehole is considered to be cased by a system of exchanger pipes located in the borehole, with the space between the borehole wall and the exchanger pipes injected, if possible, with a special sealing grout.

The thermal conductivity of rocks at the location and the thermal resistance of the exchanger can be determined using mathematical methods of interpreting TRT results. In order to determine these correctly, it is necessary to perform an adequate duration test. The recommended duration of TRT varies greatly depending on the literature [13–15]. Minimum duration of the TRT given in most studies is approximately 50 hours. However, in Poland, tests lasting approximately 100 hours are most commonly performed [14]. These tests were also performed for this duration. Methods for interpreting TRT results are described in [1, 8].

3. Results and discussion

The first part of the analysis involving the interpretation of literature data is presented below. In order to calculate the actual length of the inclined BHE, the relationship presented in Table 4 was used. The increase in the length of the inclined borehole depending on the angle for 1 m of the drilled layer is presented in Table 5.

The change in the length of the exchanger is presented below, and thus the increase in the power exchanged between the working medium and the rock mass, assuming the same borehole depth (TVD – True Vertical Depth). The weighted average thermal conductivity per thickness should then be calculated for both the vertical and inclined boreholes. Table 6 shows the determination of the length of the vertical and inclined boreholes.

Table 4. Increase in the length of the inclined borehole depending on the drilling angle, assuming the length of the vertical borehole as *H*

Length of the inclined borehole depending on the drilling angle [m]					
10°	**20°**	**30°**	**40°**	**45°**	**50°**
$\frac{H}{0.985}$	$\frac{H}{0.940}$	$\frac{H}{0.866}$	$\frac{H}{0.766}$	$\frac{H}{0.707}$	$\frac{H}{0.643}$

Table 5. Increase in the length of the inclined borehole depending on the angle for 1 m of the drilled layer

Increase in the length of the inclined borehole depending on the angle for 1 m of the drilled layer [m]					
10°	**20°**	**30°**	**40°**	**45°**	**50°**
0.015	0.064	0.155	0.305	0.414	0.556

Table 6. Lithological profile for fields A and B of the Geoenergetics Lab

Determining the length of the vertical and inclined boreholes (10°) [m]					
No.	**Top [m]**	**Bottom [m]**	**Thickness – vertical borehole [m]**	**Thickness – inclined borehole [m]**	**Thermal conductivity [W·m⁻¹·K⁻¹]**
1	0.0	2.2	2.2	2.23	1.600
2	2.2	2.6	0.4	0.41	1.600
3	2.6	4.0	1.4	1.42	1.000
4	4.0	6.0	2.0	2.03	1.200
5	6.0	15.0	9.0	9.13	1.800
6	15.0	30.0	15.0	15.23	2.200
7	30.0	78.0	48.0	48.73	2.100
Total			78.0	79.18	–

When analyzing the above case, it can be seen that the average conductivity values for the profile are the same, and therefore the average unit power exchanged with the rock mass is also constant. Assuming the same borehole depth (TVD), the length measured in the case of an inclined wells for a borehole exchanger changes. The total power exchanged with the rock mass in a vertical hole is 3014.70 W, while in the case of a diagonal hole (drilled to the same depth but at an angle of 10°) it is 3060.31 W. Other cases were also analyzed. For a borehole drilled at an angle of 30°, the total power exchanged with the rock is 3480.82 W. It should therefore be noted that as the angle of the inclined well increases, the total power exchanged with the rock increases.

The second part of the interpretation analyzes the results obtained during the TRT. The tests were performed using a specialized device shown in Figure 1.

The first stage of installing the device is to correctly connect the tubes of the BHE to the valve module. Using the tubes of the borehole heat exchanger plugged in to the valves, to start the circulation of the working medium. The start of the test is considered to be the point at which a constant heating power is set on the heater. During heating, data such as the supply and return temperature of the working medium, instantaneous flow, and atmospheric (outside) temperature are recorded.

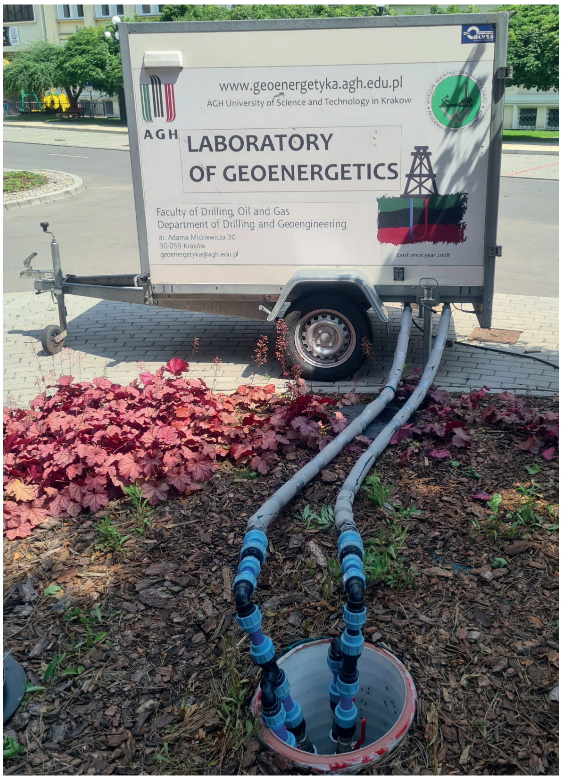

Fig. 1. TRT Equipment (photo Geoenergetics Lab team)

These values are stored in the memory of the computer connected to the device. The data obtained from TRT in the BHEs were interpreted using the classical method [1].

Borehole heat exchangers were tested: vertical and inclined, made at an angle of 10°. After conducting laboratory tests, necessary computer studies, analyses and calculations, the following results were obtained:

- for a vertical borehole heat exchanger, measured and calculated the effective thermal conductivity was 1.47 $W \cdot m^{-1} \cdot K^{-1}$,
- for a inclined borehole heat exchanger, measured and calculated the effective thermal conductivity was 1.69 $W \cdot m^{-1} \cdot K^{-1}$.

When analyzing the above results, it can be seen that real effective thermal conductivity occurs for the inclined borehole. It is recommended to perform a TRT for each new investment for which a field of BHEs is planned. This test should be completed after drilling the first well in order to determine the actual thermal parameters of the rocks, which is necessary for the proper selection of the number of heat exchangers for the investment.

4. Conclusions

Borehole heat exchangers are increasing in popularity because they fit perfectly into the trend of renewable energy sources and can be installed anywhere, regardless of lithology. The development of cities and buildings requires unconventional solutions, such as the installation of borehole heat exchangers in inclined boreholes. This procedure allows for a reduction in the distance between boreholes on the surface without causing heat transfer between nearby boreholes (with depth, the inclined boreholes move further apart). The use of diagonal borehole heat exchangers also allows for maximizing the power exchanged with the rock mass by increasing the length of the borehole in the layer with the highest thermal conductivity. When drilling BHEs, it is recommended to prepare a TRT each time in order to determine the actual parameters of the ground since this allows for the appropriate selection of the size of the BHE installation.

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References

[1] Gonet A., Śliwa T., Stryczek S., Sapińska-Śliwa A., Jaszczur M., Pająk L., Złotkowski A.: *Metodyka identyfikacji potencjału cieplnego górotworu wraz z technologią wykonania i eksploatacji otworowych wymienników ciepła*. Wydawnictwa AGH, Kraków 2011.

[2] Kovacevic M. S., Bacic M., Arapov I.: *Possibilities of underground engineering for the use of shallow geothermal energy.* Gradevinar, vol. 64, no. 12, 2012, pp. 1019–1028.

[3] Aydin M., Sisman A.: *Experimental and computational investigation of multi U-tube boreholes*. Applied Energy, vol. 145, 2015, pp. 163–171.

[4] Śliwa T., Sapińska-Śliwa A., Knez D., Bieda A., Kowalski T., Złotkowski A.: *Borehole Heat Exchangers, Production and storage of heat in the rock mass*, 1st ed. Drilling, Oil and Gas Foundation, Krakow 2016, pp. 1–177.

[5] Bayer H.J.: *Effektive oberflächennahe erdwärmenutzung mit dem Geothermal Radial Drilling (GRD) verfahren*. Acta Montanistica Slovaca, vol. 12, 2007, pp. 162–170.

[6] Sanner B.: *Shallow geothermal drilling*. In: *International Geothermal Days*. Chapter 2.3, Romania 2012, https://pangea.stanford.edu/ERE/pdf/IGAstandard/ISS/2003Germany/II/4_1.san.pdf.

[7] Śliwa T., Kucper M.: *Accesing Earth's heat using Geothermal Radial Drilling for borehole heat exchangers*. AGH Drilling, Oil, Gas, vol. 34, no. 2, 2017, pp. 495–512.

[8] Śliwa T., Gonet A., Złotkowski A., Sapińska-Śliwa A., Bieda A., Kowalski T.: *Laboratorium Geoenergetyki 10 lat działalności*. Wydawnictwo Fundacji "Wiertnictwo – Nafta – Gaz. Nauka i Tradycje", Laboratorium Geoenergetyki AGH, Kraków 2017, pp. 1–183.

[9] Barthel P.: *Grundsätliche Überlegungen zur regionalen hydrogeologischen Beurteilung von Standorten für den Eisatz von Erdwärmepumpen*. Doctoral Thesis, Hydrogeologie und Umwelt, der Bayerischen Julius-Maximilians-Universität Würzburg, Würzburg 2005.

[10] Aydin M., Dolcek A.O., Onur M., Sisman A.: *Flow-controlled thermal response test and its comparison with the conventional test methods.* Geothermics, vol. 120, 2024, 103011.

[11] Aydin M., Gultekin A.: *Effect of test parameters on the recovery of underground after a Thermal Response Test and optimum waiting time between tests.* Renewable Energy, vol. 239, 2025, 122090.
[12] Galgaro A., Da Re R., Carrera A., Di Sipio E., Dalla Santa G.: *Comparison between new enhanced thermal response test methods for underground heat exchanger sizing.* Geomechanics for Energy and the Environment, vol. 40, 2024, 100613.
[13] Gehlin S.E.: *Thermal response test*. *Method development and evaluation*. Doctoral Thesis, Department of Environmental Engineering, Luleå University of Technology, Luleå 2002.
[14] Martin C.A., Kavanaugh S.P.: *Ground thermal conductivity testing. Controlled site analysis*. ASHRAE Transactions, vol. 108, no. 1, 2002, pp. 945–952.
[15] Złotkowski A., Śliwa T., Gonet A.: *Otworowe wymienniki ciepła istalacji grzewczo-klimatyzacyjnej Ekologicznego Parku Edukacji i Rozrywki OSSA*. Wiertnictwo, Nafta, Gaz, vol. 28, no. 1–2, 2011, pp. 475–482.