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Thermal Stabilization Time of Borehole Heat Exchanger Due to the Drilling Process

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ABSTRACT

The implementation of a borehole heat exchanger for a heat pump consists of the following stages: drilling the borehole, running the probe, filling the borehole, Thermal Response Test execution and drilling of subsequent borehole heat exchangers depends on power and energy required. In this paper the effect of time on the thermal stabilization time borehole heat exchanger after the drilling process is evaluated. It should be emphasized that this time can be comparised with the period after the Thermal Response Test of the borehole heat exchanger can be performed. An estimate of this time is necessary because only after this time can a reliable TRT be made. The research used newly drilled borehole heat exchangers at the AGH University of Science and Technology and the NIMO-T device used to test both the pressure and the temperature of the heat carrier filling the heat exchanger tubes.

1. INTRODUCTION

The most commonly used method for exploitation of low-temperature geothermal heat are borehole heat exchangers. They can be used both to obtain heat from a rock mass as well as to obtain cold. The process of obtaining cold comes from the heat injection to the rock mass, most often from air conditioning. Such a process can be called the regeneration of heat resources in the rock mass or heat storage (Sliwa and Rosen 2015). The heat thus collected is not, however, geothermal heat. Regeneration may also involve the inflow of heat from the surrounding rock mass through conduction from the surrounding layers and advection related to the filtration of groundwater.

Energy from hole heat exchangers can be fully green. It occurs when the electric supply driving the geothermal heat pump compressor is generated in an ecological source (renewable energy sources) (Jastrzębska 2007, Sliwa et al. 2017, Chiasson 2016). If the electricity comes from traditional sources (coal, oil, natural gas), the environmental effect obtained is smaller than for electricity from renewable sources, e.g. geothermal energy (Bertani 2015) or solar energy (Shaikh et al. 2017) or wind energy (Ayee et al. 2009, Wagner 2017). In recent years, the production of electricity from renewable sources has been increasing (https://ourworldindata.org, Bertani 2015). The ecological effect of geothermal heat pumps includes energy losses during individual energy transformations resulting from the conversion of chemical energy in traditional fuels (i.e. stored solar energy reaching the planet's surface for billions of years) and from its network transport. Above a certain COP of a geothermal heat pump, there is a surplus in useful heat production compared to the calorific value of coal, oil or natural gas.

The most important parameter of BHEs is energy efficiency. It can be defined as the unit heating power exchanged between the rock mass and the heat carrier (total power of a single hole divided by its depth). Three methods can be used to determine this parameter (Gonet et al. 2011), which are based on the knowledge of ground heat conductivity λ. Indicative values (Barthel 2005) the potential power unit exchanged with the ground can be determined with the following formulas:

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

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

where if $1<\lambda_{eff}<3$, q is unit energy flux, $W\cdot m^{-1}$, and λ_{eff} is the effective thermal conductivity in the BHE, $W\cdot m^{-1}\cdot K^{-1}$.

As effective thermal conductivity in BHE can be also use average thermal conductivity of ground. There are three methods for ground heat conductivity define:

a) based on the literature data for individual lithological layers (e.g. Somerton 1992, Plewa 1994, Gonet et al. 2011) and weighted average,
b) based on thermal response test (TRT) described e.g. in (De Vries 1952, Austin 1998, Austin et al. 2000, Witte et al. 2002, Gehlin 2002, Gehlin and Hellström 2003),
c) by means of the natural rock mass temperature profile (Rohner et. al. 2005, Sliwa 2012).

Ground thermal conductivity of rocks λ in lithological profile is not the same as effective thermal conductivity λ_{eff} measured in BHE by thermal response test making. The difference due to the fact that value of effective thermal conductivity depend on parameters of TRT (Gonet et al. 2012).

The most popular way to determine the thermal parameters of rocks is to perform a thermal response test at the test site. This test is performed on a previously made hole heat exchanger (Sliwa et al 2016b, Gonet and Sliwa 2010). The thermal response test of the hole exchangers consists in measuring changes in the temperature of the heat carrier during its circulation in a closed circuit with the supply or receipt of thermal energy with a constant heating power. This is a particularly important issue in order to be able to properly select the design, number and arrangement of orifice heat exchangers. The TRT test is especially recommended for large investments (Gehiln 2002, Gonet and Sliwa 2008, Gonet et al. 2012, Rolando et al, 2017). The topic of thermal response testing is becoming more and more popular (Liebel et al. 2011, Wilke et al. 2019, Chae et al. 2020). Tests, besides the hole heat exchangers, are also recommended for energy piles (Loverdige et al. 2015, Franco et al. 2016, Jensen-Page et al. 2020). The scheme of TRT execution is shown in Fig. 1.

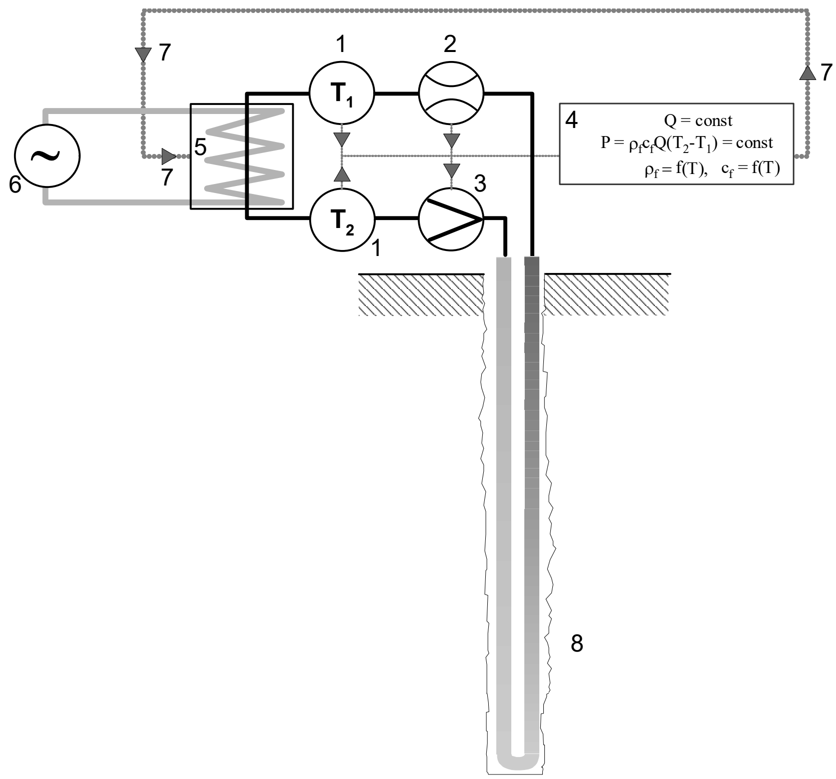

Figure 1: Schematic of thermal response test devices and operation. Legend: 1 – thermometer, with absolute error 0.1°C, 2 – flowmeter, 3 – pump, 4 – control computer (stabilisation of thermal power and record the data), 5 – set of heaters, 6 – current source, 7 – heater control signal, 8 – borehole heat exchanger, Q – flow rate of heat carrier, P – heat flow rate (power), T1 – temperature of heat carrier (outflow from BHE), T1 – temperature of heat carrier (inflow to BHE), ρ_f=f(T) – density of heat carrier as a function of temperature, cf=f(T) – specific heat of heat carrier as a function of temperature (Sapińska-Sliwa et al. 2019).

Temperature profiling is also an important issue, which can be made with a variety of devices. One of them is the NIMO-T (Non-wired Immersible Measuring Object for Temperature) instrument, which you can measure the temperature and pressure in the borehole heat exchanger (www.geowatch.ch). The literature also provides information on other systems used to perform well temperature profiles (Vojciniak et al. 2013, Aranzabal et al. 2019a, Aranzabal et al. 2019b). Temperature profiling is cheaper than thermal response tests (Sliwa and Rosen 2017). Numerous publications have been published on the subject of temperature profiling as a method of assessing the energy efficiency of borehole heat exchangers, e.g. Sliwa et al. 2016b. The topic of temperature profiling quality in determining energy efficiencies of borehole heat exchangers were moving Sliwa et al. 2019. The ground temperature profile achieves a stable profile at a time around five months after borehole insertion. It is recommended to perform temperature profiling before, during and after TRT (Montero et al. 2013a, Montero et al. 2013b).

Before the main TRT test, the heat carrier is circulated without heating. This is to determine the average temperature at the well. The consequence of performing such a circulation in unstable conditions is incorrectly determined thermal resistance of the hole exchanger R_b. Its value is determined by the formula:

$$R_b = \frac{1}{q} \cdot \left[T_f(t) - T_{av} \right] - \frac{1}{4\pi\lambda} \cdot \left(\ln \frac{4\alpha t}{r_b^2} - \gamma \right) \tag{3}$$

where T_{av} is the average profile temperature obtained in the bore with full thermal stabilization.

This value can be obtained in two ways:
- by circulation of the heat carrier before the TRT test,
- from hole temperature profiling.

The time of temperature stabilization in the borehole is related to the term known as a neutral surface (or the depth of periodic heat penetration) h_0 and the temperature of this surface (at this depth) T_0. It is the depth, which is the boundary between the zone of daily and seasonal temperature fluctuations and the zone where a constant temperature is observed - regardless of the measurement time (Plewa 2000). Most often, when increasing the depth, an increase in the temperature of the rock mass is observed. In engineering practice, the temperature of the neutral surface means the average local annual temperature of the atmospheric air (Plewa 2000). According to Gonet et al. (2011) the temperature of this surface is higher than the average by about 0.8°C. In Poland, the temperature of the neutral layer varies 6°C and 9°C. This area in Poland is at a depth of 7.7 to 27.1 m (Stajniak 1978), which is shown on the map in Fig. 2.

The neutral surface temperature T_0 is an important indicator for assessing the quality of thermograms. This parameter is used as a basic condition to assess the quality of the performed temperature profiling in broadly understood boreholes, which also include borehole heat exchangers. Plewa (2000) claims that the temperature T_0 in Poland at depth h_0 should be within the range of 6 to 9°C, which is the basic criterion for assessing the quality of the temperature profiling performed. Borehole temperature logs in urban areas often exhibit deviations from the regional geothermal gradient and the deviation increases towards the ground surface in the top 100 m approximately (Bayer et al. 2016, Sliwa et al. 2019).

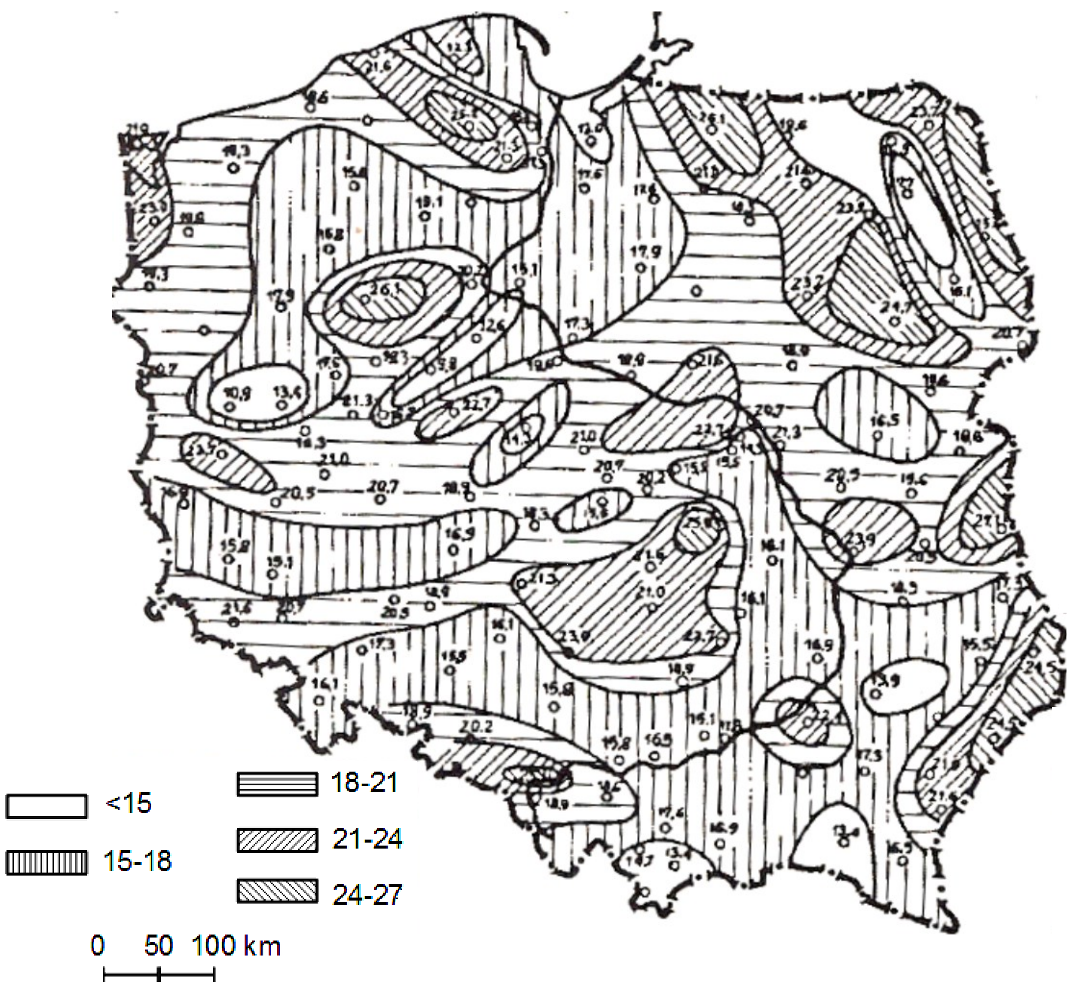

Figure 2: Map of the depth of range of annual changes of air temperature in the rock mass (Plewa 1994).

TRT performed on the same borehole at different times of the year will give different results, because above the neutral surface the temperature of the rock mass varies with time. This is especially true of shallow borehole heat exchangers, e.g. 30 m deep.

Analyzing the individual factors influencing the violation of the equilibrium of the rock mass temperature field, the following have the greatest impact (Plewa 1994, 2001):
a) circulation of drilling fluid through the hole during drilling,
b) drilling fluid temperature,
c) drilling progress,
d) drilling time.

It is not possible to evaluate the impact of each of the individual factors as these effects overlap. The e circulation (Plewa 2000), i.e. its flow velocity, type and temperature, has the greatest influence on the degree of thermal equilibrium disturbance in the borehole. The circulation of drilling fluid, the temperature of which is usually very different from that of the rock mass, disturbs the natural thermal field in close proximity to the bore hole (BHE). In engineering practice, temperature profiling to determine the geothermal degree is reduced to measuring the temperature of the fluid in the pipes of the hole heat exchanger. Therefore, this test should be performed after an appropriate time, when the temperature of the liquid filling the exchanger is equal to the temperature of the surrounding rock layers. It is considered that borehole heat exchanger is in heat equilibrium when the circulating fluid temperature change, does not exceed the accuracy of the measuring device over a certain period of time. The standard accuracy of the measuring devices is 0,1°C. For boreholes up to 3000 m deep, stabilization time should not be less than 10 days (Plewa 2000).

It should be remembered that the temperature of the drilling fluid or the heat carrier in the borehole is measured, assuming that it is equal to the temperature of the rocks. In the case of a filling fluid with thixotropic properties, which is a Bingham liquid, this assumption seems to be correct. On the other hand, in the case of a heat carrier which is a Newtonian liquid, the problem of natural convection arises, which starts when there is a temperature difference in this liquid. And this is exactly the situation in hole heat exchangers.

A similar study of temperature profiles was carried out in Pałecznica on one of the 5 research borehole heat exchangers with a single U-tube 30 m deep (Sliwa et al. 2016a). The aim of the research was to determine the effective thermal conductivity of the installation depending on the parameters of the TRT test. Before TRT was performed, the temperature of the undisturbed rock mass was profiled. The TRT test consisted of 6 hours heat transfer fluid circulation in the installation to determine the average initial temperature and 48 h of heating for a total of 54 hours duration test. Temperature measurements were taken to observe how the temperature in the exchanger returned to its original value upon heating. They were also performed with the NIMO-T logger. The measurement results are presented in the diagram in Fig. 3, which shows the dependence of the temperature in the borehole on the depth for individual time intervals. After the end of TRT, 16 measurements were taken: initially every 1 h, then every 6 h. The last measurement, 54 h after switching off the device, was performed before starting the next test. It can be seen in the graph that the temperature has not fully returned to its previous value, however, it is very close to the initial, undisturbed temperature of the rock mass.

The purpose of the tests described in this article is to determine the time of thermal stabilization of the hole heat exchanger after drilling. If it is planned to perform a thermal response test after the borehole heat exchanger is being completed, it is highly recommended to wait until the temperature distribution stabilizes after drilling and bonding of the sealing grout. The literature does not yet provide the results of such research. The time for full stabilization is completely different if deep oil holes are made and drilling time is counted in months. Different if a hole is drilled in one day for a BHE. The presented test results indicate the time for full stabilization of the temperature in the hole after drilling and making the BHE sealed, which was made within two days. The time determined on the basis of the tests research indicates when the Thermal Response Test of the Borehole Heat Exchanger can be performed after its completion. The AGH Geoenergetics Laboratory carries out TRT after no less than 14 days from the end of all works at BHE.

2. DISORDERS OF ROCK MASS TEMPERATURE PROFILING

The purpose of geothermal research of a given geological profile is to determine the value of the temperature gradient in the borehole. When performing the above-mentioned temperature profiling, it is assumed that the temperature of rock layers at particular depths corresponds to the temperature of the liquid remaining in the borehole. It is assumed that the temperature of the fluid inside the heat exchanger tube at a certain level is equal to the ground temperature. This assumption is more accurate if the tube diameter is smaller and tube wall, as well as cement thickness, are small. Smaller diameter decrease time required for the fluid to obtain steady-state with the surrounding area. Due to low-temperature gradient and low inner tube diameter (low Rayleigh number below critical), it is assumed that inside the tube natural convection is negligible for the temperature profile stabilization. It can therefore be concluded that the correctness of post-drilling temperature profiling depends mainly on:

a) degree of thermal imbalance during drilling,
b) the time of establishing thermal balance after completion of drilling,
c) method of sealing the hole and setting time of the cement (sealing) slurry.

These processes mainly depend on:
a) drilling progress,
b) time of drilling operations performed,
c) borehole diameter,
d) temperature of the drilled rock mass intervals,
e) atmospheric air temperature during drilling,
f) physico-chemical properties of the liquid filling the hole during drilling (drilling mud),

g) sealing grout consistances,
h) correctness of filling the borehole with sealing grout,
i) the type of sealing slurry (binding heat),
j) the type of fluid in the borehole when standing up (possible natural convection).

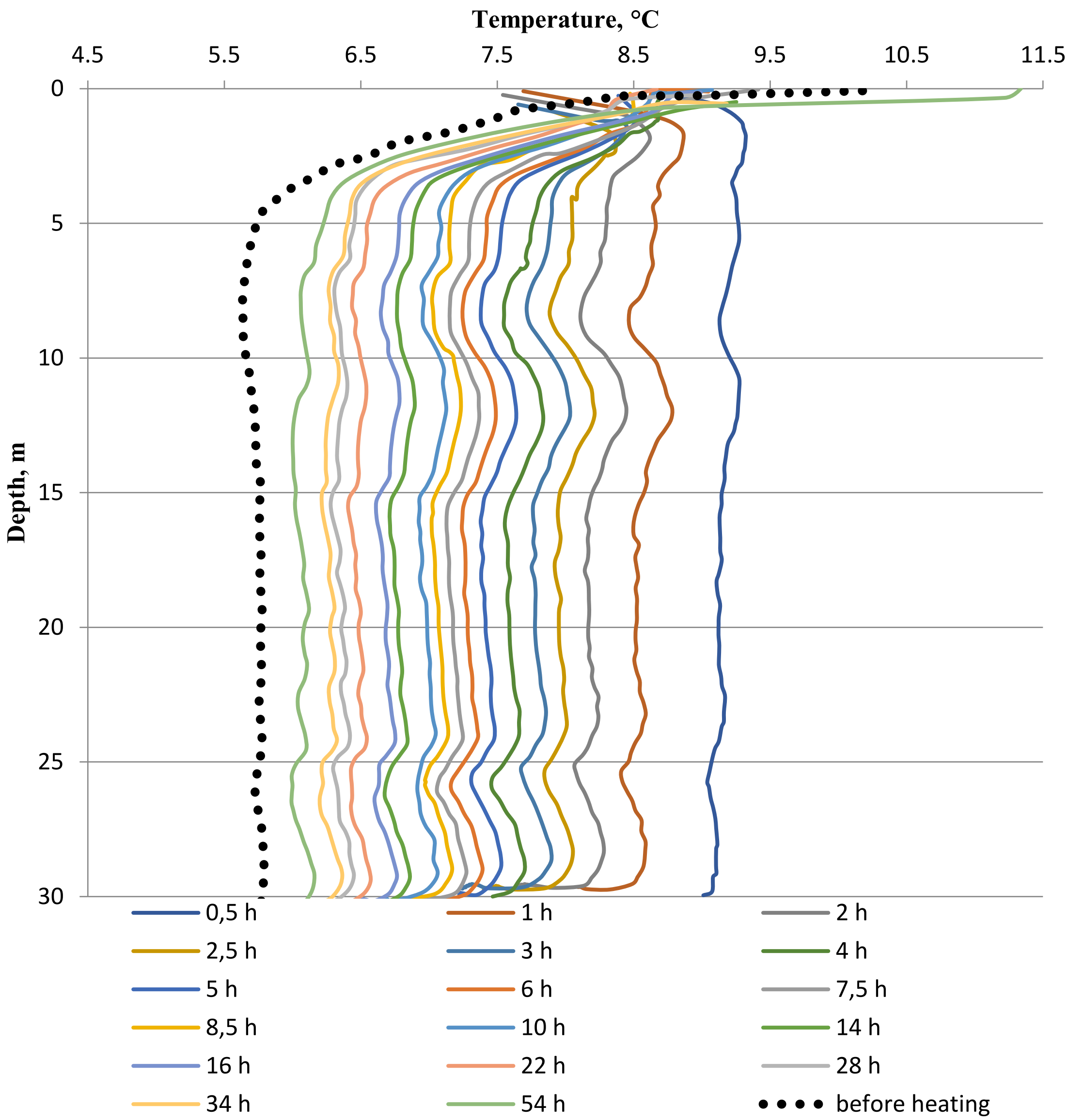

Figure 3: Diagram of the temperature dependance in the borehole heat exchanger per depth for measurements before and after the TRT test (Sliwa et al. 2016a).

3. RESEARCH METHODOLOGY

One of the borehole heat exchangers in between pavilions A4 and D2 at the AGH University of Science and Technology in Krakow was used for the research. After the drilling process, a 45 mm outer diameter U-tube was put into the hole and cemented, filled with water under a pressure of 4 bar. The increased pressure of the liquid allows to determine the tightness of the U-tube after the process of starting and cementing. The entire process of drilling works lasted about 2 days. The study of the temperature curves was carried out for 14 days with a constant measurement hour (3 pm). The first measurement was made immediately after the cementing process (approx. 30 minutes from the end of the sealing grout pressing). The TermorotaS mixture was used as the sealing slurry, which was injected with an injection pump through the drill string from the bottom of the hole to the top. TermorotaS is an industrial sealing mixture for filling hole heat exchangers, with a thermal conductivity of about 2 $W/m^{-1} \cdot K^{-1}$ after hardening. It is used as a suspension after mixing with water. It is recommended to prepare a mixture of 600 dm^3 of water and 1100 kg of powder. The physical properties of the powder are a density of 2600 $kg \cdot m^{-3}$ with a bulk density of 900 to 1000 $kg \cdot m^{-3}$ and a moisture content of up to 2% (TermorotaS Product Card).

3.1 Measurement technique

The NIMO-T (Non-wired Immersible Measuring Object for Temperature) device is used to measure pressure and temperature in borehole heat exchangers (Fig. 4). The device is submerged in an borehole heat exchanger tube with a minimum internal diameter of 26 mm filled with water (or other heat carrier). It descends freely at a constant speed, which can be adjusted from about 0.1 $m \cdot s^{-1}$ to 0.6 $m \cdot s^{-1}$ by the air volume inside the device (appropriate overlays). Measurement conditions with this device should not exceed the temperature of 40 ° C and the pressure of 40 bar (400 m depth of the hole when filled with water). The limitations are related to the applied seals and installed electronic systems. Additionally, after connecting the NIMO-T device to a computer with Geowatt AG software, you can set the time interval between successive data records. The frequency of measurement and data recording in the internal memory was 2.3 s during free fall. The average depth interval between the measurements was 12.99 cm with a standard deviation of 1.56 cm. After the logger reaches the deepest point of the bore exchanger, the operator activates the circulation pump previously installed at the other end of the U-tube, allowing the device to be raised to the surface (Fig. 5). The circulation of the heat carrier in the exchanger disturbs the temperature profile, therefore the authors of this article used a rope of appropriate strength to pull the device out of the exchanger pipe without starting the circulation. This method significantly reduces the impact of the measurement itself on the stabilization time of the temperature profile. The pressure measurement, taking into account the density of the liquid in the exchanger, allows to determine its depth. Table 1 presents the most important parameters of the NIMO-T device. The prototype of the device was already described in 2005 (Rohner et al. 2005).

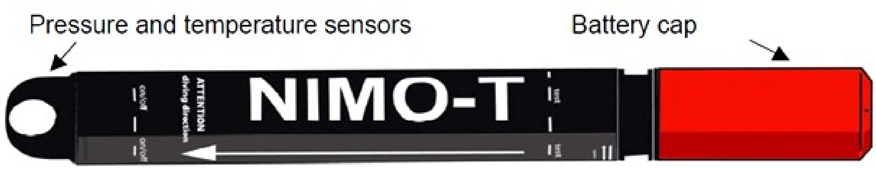

Figure 4: NIMO-T device measuring the temperature in a borehole heat exchanger (Instruction manual 2009).

Table 1: The most important parameters of the NIMO-T device (Schaerli et al. 2007, Instruction manual 2009).

Diameter	23	mm
Lenght	187/224	mm
Weight (with battery)	80/85	g
Max. depth	400	m
Accuracy of temperature measurement	+/-0.0015 +/-0.1	°C – relative temperature °C – absolute temperature
Accuracy of the pressure measurement	+/-0.02 +/-0.1	bar – relative pressure bar – absolute pressure
Temperature and pressure sampling / recording rates	2.3, 4.6, 6.9 or 9.2	s

3.2 Geology and exercise borehole heat exchanger

In the area of the research carried out, the subsurface layer consists of Quaternary river sand formation with various fractions. The thickness of the Quaternary is approx. 15 meters. Below there are tertiary (Miocene) loams, claystones, mudstones, several dozen meters thick. It is estimated that in the area of the conducted research, the depth of Miocene sediments is approx. 85 m below sea level. Below there are Upper Jurassic formations, formed as fractured gray limestones with silicate stone crumbs (Sator 2017). The lithological profile is presented in Table 2. Based on the analysis of geological materials and information on archival boreholes, it was established that the water-bearing table in the area of the works being conducted is at the level of 3 meters above sea level. In order to make the exchanger, rotary drilling was used with the right (normal) mud circulation. A cutter bit with a diameter of 190.5 mm (7½ in) was used to drill the first 6 meters of the hole. Then the excavation was covered with a preliminary column of pipes with a diameter of 168 mm. Then, drilling was performed with a cutter bit with a diameter of 143 mm (55/8 in) to a final depth of 84.5 m. After the drill string was pulled out, a U-tube PE 100 SDR 13.6, with an outer diameter of 45 mm from Muovitech, was put in place. Placement was supported by a drill string. Then, through this conduit, the opening was sealed with cement grout from the bottom to the ground surface.

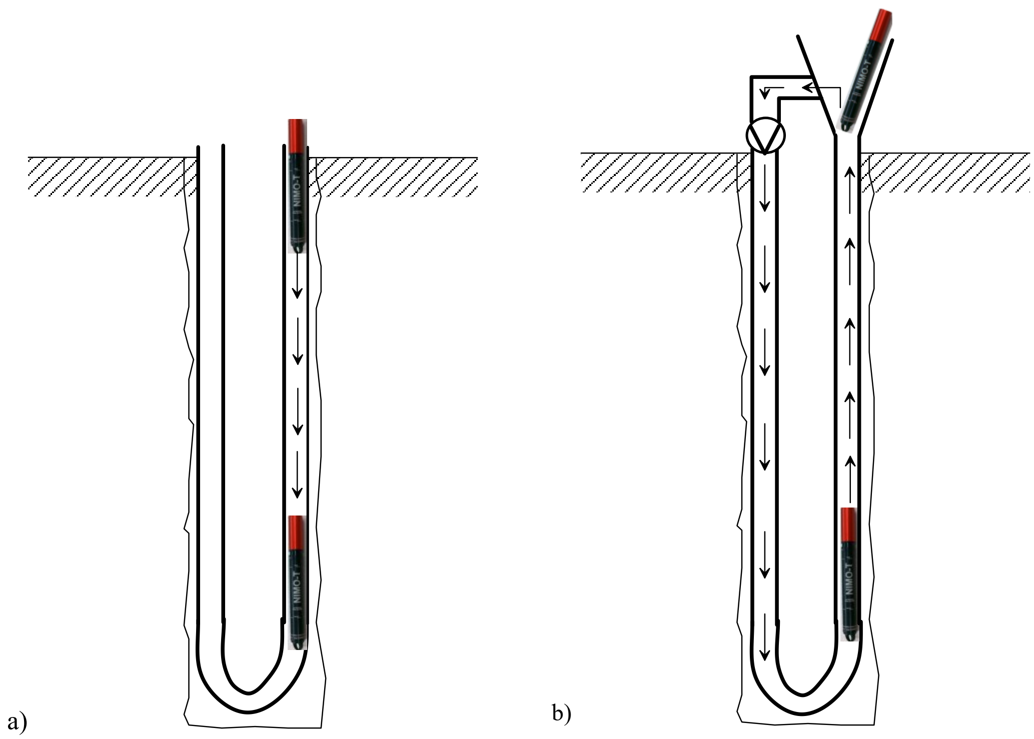

Figure 5: Movement of NIMO-T in a U-tube: a) free fall of the device in the heat carrier, b) retrieval of the device by pumping.

Table 2: Lithological and stratigraphic structure of the studied rock mass (Sliwa et al. 2017).

Thickness, m	Lithology	Stratigraphy
0.0 – 1.8	Anthropological lands (uncontrolled embankment)	Quaternary
1.8 – 2.5	Silt	
2.5 - 15.0	Medium sand	
15.0 – 30.0	Clays	Tertiary - Miocene
30.0 – 85.0	Gray shale	

3.3 Meteorological conditions

For the correct interpretation of the obtained test results, it was necessary to obtain meteorological data from the period of the research. For this purpose, the authors asked for the data to be provided to the Institute of Meteorology and Water Management of the National Research Institute in Krakow. The meteorological data include 2 days of drilling work, 15 days of temperature measurements in a bore heat exchanger and calibration measurement 22 days after the last stabilization measurement (Dane meteorologiczne 2017). The graphs show: the average daily air temperature (Fig. 6) and the daily sum of precipitation (Fig. 7). These factors mainly affect the thermal conditions of the rock mass to the depth of the neutral surface temperature h_0.

3.4 Result of the measurements

As a result of the measurements, a stabilization chart of temperature profiles was obtained in one of the newly drilled well-bore heat exchangers at the AGH University of Science and Technology in Kraków (Field B). The first measurement was made about 1 hour from the end of pressing the sealing grout. The temperature curve studies were carried out for 15 days with a constant measurement time (3 pm). The values of the measured temperatures are presented in Fig. 8. In order to check the full stabilization of the obtained temperature profiles, measurements were made 22 days after the last measurement (on October 6, 2017). On the basis of the obtained results and the comparison with the lithological profile, it can be concluded that the depth of the neutral surface cannot be determined. In the clays layer, at a depth of 70 m below sea level. there is the lowest temperature in the profile. It is higher than the range indicated by Plewa (2000) as the temperature value (from 6 to 9 ° C) at the depth of periodic heat penetration for Poland. Only from a depth of about 70 m, a constant increase in the temperature of the heat carrier in the hole heat exchanger can be observed. This is due to the location of the borehole in a highly urbanized area (Sliwa et al. 2019).

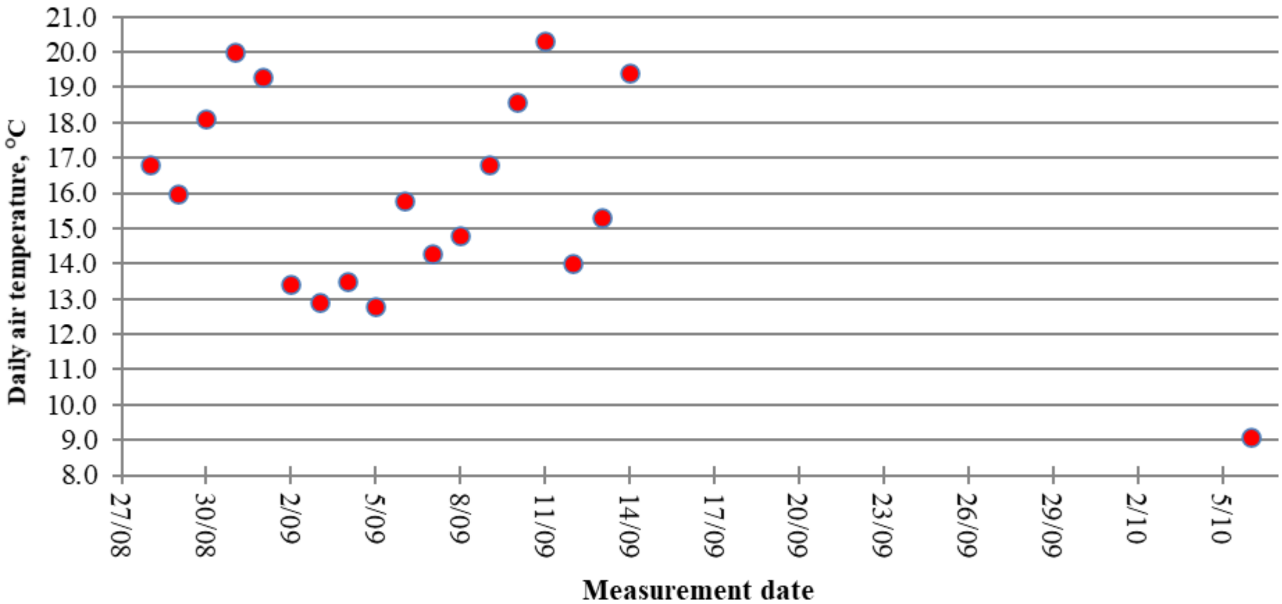

Figure 6: Average daily air temperature for the 1st row synoptic station: Kraków-Balice (station height 237 m above sea level, barometer height 241.53 m above sea level).

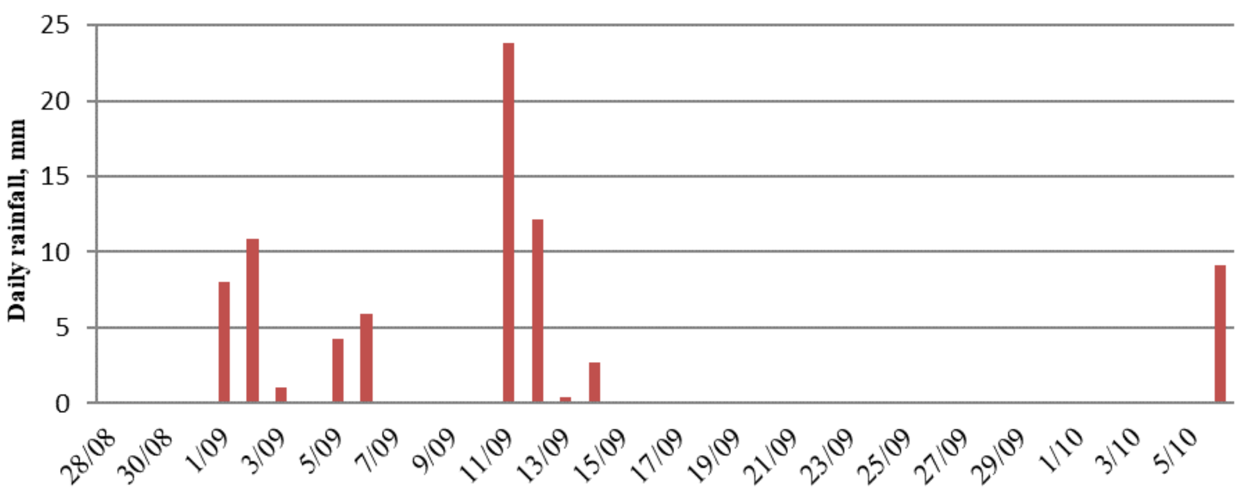

Figure 7: Daily amount of precipitation for the synoptic station of the first row: Kraków-Balice (station height 237 m above sea level, barometer height 241.53 m above sea level).

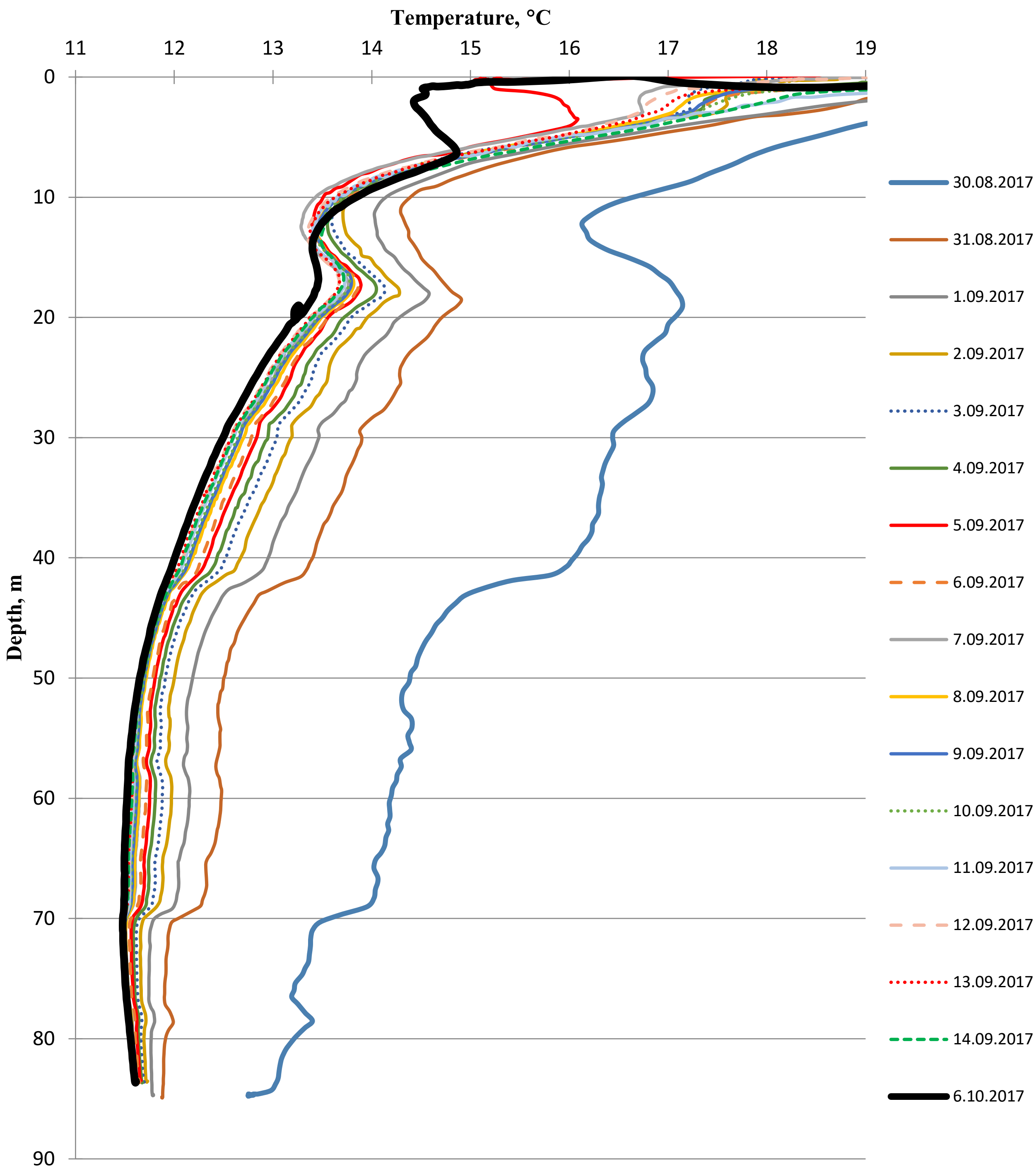

Figure 8: Chart of temperature profiles for the borehole heat exchanger between buildings A4 and D2 (BHEs Field B of Laboratory of Geoenergetics).

The impact of the drilling process and the heat of cement slurry hydration disrupting the temperature profile of the hole heat exchanger is best illustrated by the curves of the tests carried out on August 30 - September 2, 2017. The heat of hydration is best visualized during the first measurement with the NIMO-T device, 1 hour after the end of the U-tube cementation process. Fluctuations in the temperature curve of the borehole exchanger in layers of clays and gray shales may indicate occurrence layerings with rocks masses with various thermal conductivity values λ. For clays and gray shales, the conductivity value is in the range: 1.6 - 2.2 $W \cdot m^{-1} \cdot K^{-1}$ (Gonet et al. 2011).

Testing with the NIMO-T device included the following stages:

- launching the logger (target temperature measurement at a given depth every 2.3 s),
- bottom temperature measurement lasting about 1 minute,
- pulling out the logger.

In order to correctly interpret the obtained curves, the change of the bottom temperature during the research, the authors of this article presented in tab. 3 and in fig. 10.

Analyzing the obtained results, the time of thermal stabilization of the 85-meter hole heat exchanger was about 315 hours (over 13 days) after the drilling and cementing process.

After 3-4 days, the difference between the individual measurements is less than the absolute accuracy of the device, which for NIMO-T is 0.1°C. By analyzing the layout of curves in the temperature profile, it is possible to find a significant stabilization of the profile after 5-6 days from the completion of drilling works. The stabilization time for borehole heat exchangers differs from that of the oil wells. The longer time is primarily influenced by the difference in depth (for borehole heat exchangers usually up to 200 m, in the case of the exploration borehole more than 1100 m (Fig. 9), the geometry of the boreholes, the cement stone used to seal the annular spaces (Sapińska-Śliwa et al. 2017). It is worth noting that the accuracy of the measuring instruments in both cases was similar and amounted to 0.1°C.

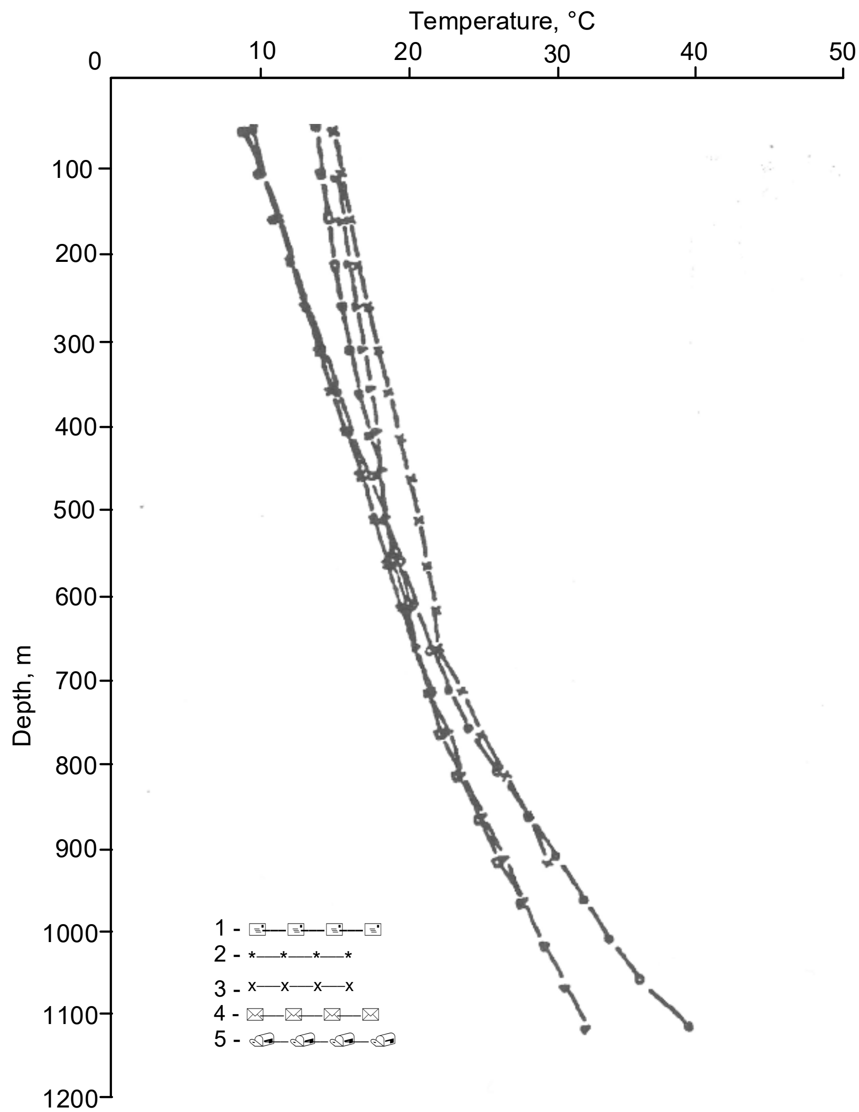

Figure 9: List of exemplary temperature profiles in boreholes, 1 and 2 under steady equilibrium conditions (Lublin 57 and Lublin 58 boreholes), 3, 4 and 5 under unsteady thermal equilibrium conditions (Plewa 2000).

Table 3: Temperature change in the bottom of the borehole heat exchanger with time.

No.	Measurement date	Temperature °C	Temperature difference °C	No.	Measurement date	Temperature °C	Temperature difference °C
1	30-08-2017	12.777	-	10	08-09-2017	11.620	0.008
2	31-08-2017	11.877	0.900	11	09-09-2017	11.614	0.007
3	01-09-2017	11.784	0.093	12	10-09-2017	11.612	0.001
4	02-09-2017	11.721	0.063	13	11-09-2017	11.611	0.002
5	03-09-2017	11.693	0.028	14	12-09-2017	11.605	0.006
6	04-09-2017	11.673	0.020	15	13-09-2017	11.602	0.003
7	05-09-2017	11.659	0.014	16	14-09-2017	11.603	-0.001
8	06-09-2017	11.646	0.013	17	6-10-2017	11.607	-0.004
9	07-09-2017	11.628	0.018				

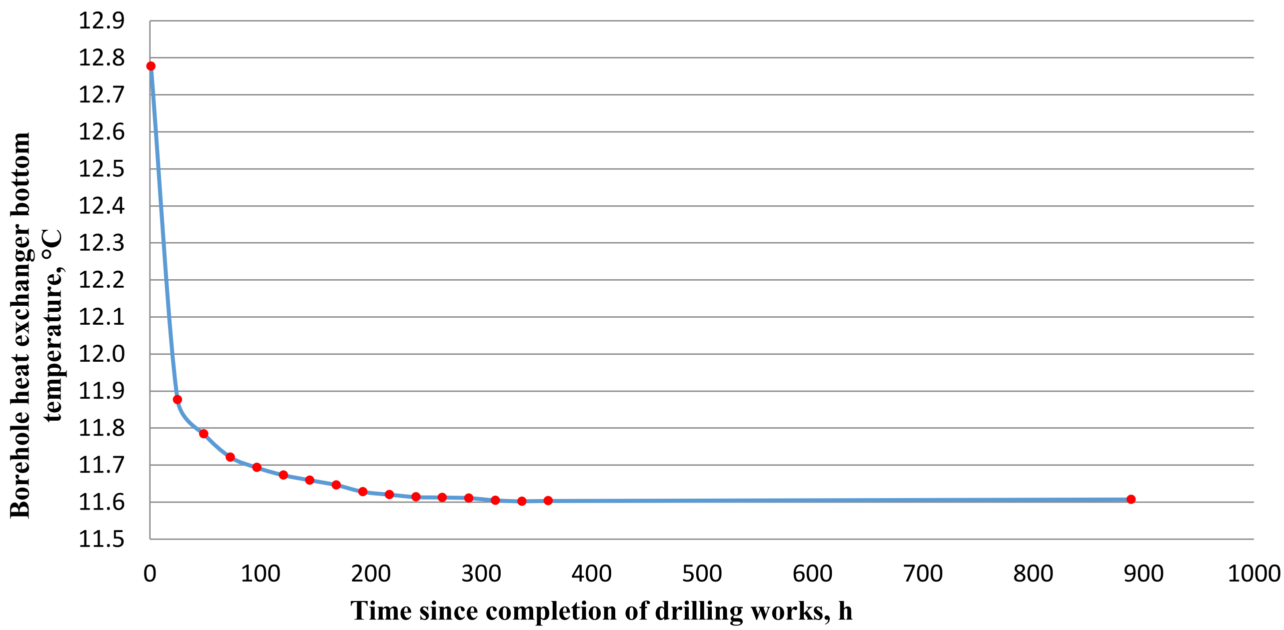

Figure 10: The diagram of the bottom temperature stabilization of the borehole heat exchanger.

For further observations, it is suggested to perform similar tests with different sealing slurries (Sliwa et al. 2017). First, however, the setting times of such slurries and the temperature behavior during setting and cooling of the slurry samples should be determined.

4. CONCLUSIONS

1. The geothermal survey of the geological profile determines the temperature gradient of the rock layers in the borehole. The temperature of rock layers at particular depths corresponds to the temperature of the liquid remaining in the borehole heat exchanger. No natural convection in the U-tube is assumed due to the ratio of the horizontal to vertical dimension, i.e. 0.04:85, i.e. approximately 1: 2100.
2. The degree and time of thermal imbalance during drilling operations depend mainly on: drilling progress, drilling time, hole diameter and hole depth, temperature of drilled rocks, air temperature during drilling, physical and chemical properties of the liquid filling the borehole (drilling mud), the recipe of the sealing grout used and the quality of filling in the borehole with the sealing grout.
3. The neutral temperature surface is the boundary layer between the rock mass with daily and seasonal temperature fluctuations, and the layers where no such temperature changes are observed over time. In the area of conducted works, this limit cannot be determined using the conducted research. They should be carried out throughout the year, due to the impact of municipal infrastructure (heated buildings, water supply, sewage, heat supply, etc.).
4. Analyzing the obtained data, the time of thermal stabilization of the 85-meter borehole heat exchanger, after which the TRT test can be performed, was approximately 3 - 4 days after the drilling process. After this time, the difference between successive measurements is lower than the absolute accuracy of the measuring instrument (for NIMO-T it is 0,1°C). After arranging the curves in the temperature profile, it is possible to find a significant stabilization of the profile after 5-6 days from the completion of drilling works.
5. Taking into account the relative accuracy of the device, the stabilization was achieved after 313 hours (over 13 days).

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