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Analysis of the first thermal response test in Algeria

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Abstract Ground source heat pumps (GSHPs) mean attractive heating and cooling systems. Optimum design of a borehole heat exchanger (BHE), as the outer part of a GSHP heating system, requires knowledge of the thermal properties of the soil. Those data, the effective thermal conductivity of the soil λ_{eff} and the average temperature of the soil T_0 enable us to determine the necessary number and depth of boreholes. The determination of thermal conductivity of the soil in laboratory experiments does not usually coincidence with the data under in situ conditions. Therefore, an in situ method of experimental determination of these parameters, thermal response testing (TRT) is used primarily for in situ determination of design data for BHEs. In this study, which was the first TRT in Algeria (Tlemcen site), the purpose was to determine the effective ground thermal conductivity. Measured data were evaluated by the line source model. Used method and performed evaluation are presented for a borehole drilled in clay, silt, and sand. The resulting effective ground thermal conductivity was 1.364 W/m K and the borehole thermal resistance was 0.18 K/(W/m).

Keywords Thermal response test · Thermal conductivity of soil · Ground source heat pump

State of the art

Ground source heat pump (GSHP) systems are fast becoming state-of-the-art technology to meet the heating and cooling requirements of the buildings. These systems have high energy efficiency potential which results in environmental and economical advantages. The energy efficiency of the GSHP systems can be further enhanced by optimized design of the borehole system. The data from thermal response tests (TRT) is used to evaluate undisturbed ground temperature, ground thermal conductivity, and borehole thermal resistance values for all boreholes.

Mogensen [1] first presented the TRT as a method to determine the in situ values of ground thermal conductivity and thermal resistance in borehole heat exchanger (BHE) systems. Mogensen's method was used to evaluate existing BHE systems at several occasions. The first mobile measurement devices for TRT were independently constructed in Sweden and USA in 1995. This technology has been utilized in a number of countries.

Mainly eight countries (Sweden, Canada, Germany, Netherlands, Norway, Turkey, United Kingdom, and USA) have developed the technique. Recently, France and Switzerland also have taken up using the method. The Swedish response test device, TED, was constructed at Luleå University of Technology in 1995–1996 [2]. In late 2000, Çukurova University, Turkey, took over one of the two Swedish test rigs. The Swedish TED design has been used also in Norway [3] and Canada [4] and has been the inspiration of the three rigs that are in used in Germany [5].

In Africa, just theoretical studies of TRT have undertaken so far were Eswaisi et al. [6] and these same studies have been realized, in collaboration with the originator of the method: the Swedish.

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Introduction

The heat transfer between the secondary working fluid and the surrounding rock in GSHP installations depends on the arrangement of and the heat transfer in the BHE flow channels, possible convection in the borehole, the thermal properties of the BHEs as well as of the borehole filling material. The thermal resistances associated with these different parts are normally added together and called borehole thermal resistance, defined as R_b by Hellström [7].

A common method for evaluating the heat transfer performance of BHEs and ground properties is a TRT, dating from 1983, when Mogensen [8], together with two students from The Royal Institute of Technology (KTH), Sweden, suggested and built the first borehole thermal response tester arrangement. A 2.7 kW constant cooling power was applied to the working fluid in a BHE, while logging the fluid temperature as well as the cooling power. Mogensen [8] found that it was possible to calculate R_b in addition to the ground thermal conductivity. Later, at the end of the 90s, TRT methods were studied further and several articles were published by Gehlin and others (e.g., Gehlin) [9]. Nowadays, the most common TRT equipment consists of a mobile rig containing an electric heater, a pump, and temperature and flow sensors. Usually, the heat injection is kept constant. Numerous response testers have been built around the world and they are being used as a standard procedure for measuring the ground thermal conductivity in energy wells and for testing BHE performance. The result of conventional TRTs is very useful and allows a more accurate sizing of BHE installations. However, it presents merely an average thermal conductivity of the surrounding ground and an average borehole thermal resistance.

The GSHP draws heat from the soil via sensors that are buried pipes.

Figure 1 shows the underground temperature (of Tlemcen: $D_f = 0.6939 \times 10^{-6}$ m^2 s^{-1}, because the land is rich in limestone [10, 11]) as function of the depth at different time during a year, which can be expressed [12–14] as:

$$T(t,z) = T_a + A_a \cdot e^{-\frac{z}{d_0}} \cdot \cos\left(2\pi \cdot \frac{t}{t_0} - \frac{z}{d_0}\right), \qquad (1)$$

where

$$d_0 = \sqrt{\frac{\lambda \cdot t_0}{C \cdot \pi}}$$

where $T(t,z)$ is ground temperature at depth h m below ground surface (°C), T_a is average ambient air temperature (°C), A_a is air temperature amplitude (°C), T is time over a year (s), t_0 is temperature variation period (s), d_0 is penetration depth (m), z is depth (m), λ is thermal conductivity (W/m K), and C is the volumetric heat capacity (J/m^3 k).

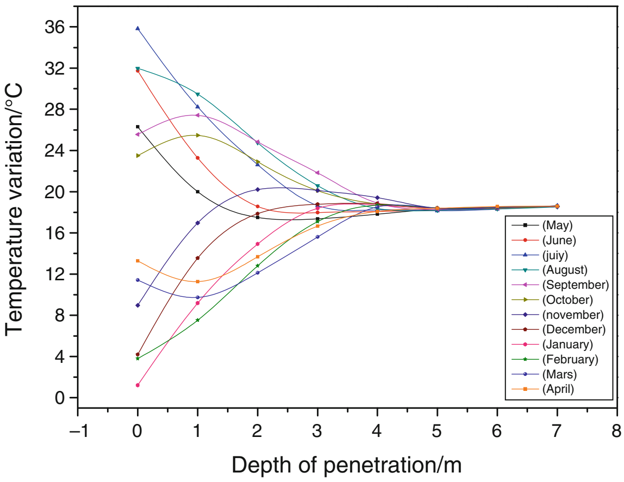


Fig. 1 Temperature field through Ground of Tlemcen (Limestone ground)

Study objective

In this study, the experimental setup will be erected to test the soil of the site as a heat exchanger with a heat pump for the air conditioning buildings. The objective of this test is to evaluate the following properties:

- The ground thermal conductivity of the soil k
- The thermal resistance R_b between the heat carrier fluid and the borehole wall.

Theory

The most exact way to determine the thermal properties, i.e., the effective ground conductivity and borehole thermal resistance, is carried out in in-situ TRT. This method was first presented by Mogensen [8], who suggested a simple arrangement with a circulation pump, a chiller or heater with constant power rate, and continuous logging of the inlet and outlet temperatures of the borehole.

There are two analytical techniques used to analyze the experiment's results. Both are based on Fourier's law of heat conduction:

1. Based on Kelvin's line source theory (LSM)
2. Based on cylinder source model (CSM).

The LSM methodology, which was used in this study, is a development of Kelvin's line source theory (Ingersoll et al.) [15]. In this method, the following assumptions are used:

- The line heat source (or sink) is assumed infinitely long i.e., pure radial heat conduction
- A constant heat capacity over the length of the line switched on at time = 0
- The medium is assumed to be initially at an uniform temperature.

Theoretical bases

Analytical solutions for heat conduction in a homogeneous infinite isotropic medium with a line heat source can be obtained starting from a particular solution of the general heat conduction equation**:**

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{a}\frac{\partial T}{\partial t}, \tag{2}$$

in the case that in the point (x', y', z') there is the instantaneous point heat source [16].

The solution for such thermal line source, proposed by Ingersoll, gives the temperature as a function of time (t) at any distance (r) from the line as follow:

$$T(t,r)=T_{\mathrm{g}}+\frac{q}{2\pi\cdot\lambda}\int_{\frac{r}{2\sqrt{\alpha . t}}}^{\infty}\frac{e^{-\beta^2}}{\beta}\mathrm{d}\beta. \tag{3}$$

Some references [9] write the last equation in different form, but mathematically they are the same, as follow:

$$T(t,r)=T_{\mathrm{g}}+\frac{q}{4\pi\cdot\lambda}\int_{\frac{r^2}{4\alpha\cdot t}}^{\infty}\frac{e^{-\beta^2}}{\beta}\mathrm{d}\beta$$

where T_{g} is undisturbed ground temperature (°C), q is heat capacity per meter over the line source (W/m), λ is ground thermal conductivity (W/m K), and α is ground thermal diffusivity (m^2/s)

Ingersoll [15] states that Eq. 3 is an exact solution only for a true line source, but that it can also be applied in most borehole systems with negligible error, after a few hours of operation i.e., $t > 20r^2/\alpha$, for small diameter pipes $\leq$50 mm. Results from LSM and numerical model, which consider heat flows in both vertical and radial directions for a borehole of finite length, show that the results from the numerical analysis result in 5% lower thermal conductivity value [17].

Many researchers have approximated the exact integration of Eq. 3 using simpler algebraic expressions. Ingersoll [15] presented the approximations in tabulated form, while Hart and Couvillion, approximated the integration by assuming that only a certain radius of the surrounding ground would absorb the heat rejected by the line source [18]. According to Yavuzturk [19] relied on Ingersoll et al. [15], after time $t > 25r^2/4$, Eq. 17 can be approximated as following:

$$T(t,r)=T_{\mathrm{g}}+\frac{q}{2\pi\cdot\lambda}\cdot I(X)$$

$$T(X)=2.303\cdot\log\left(\frac{1}{X}\right)+\frac{X^2}{2}-\frac{X^4}{8}-0.2886 \tag{4}$$

$$X=\frac{r}{2\sqrt{\alpha\cdot t}},$$

While according to Mogensen [8], after time $t > 4r^2/\alpha$, Eq. 3 can be approximated as following:

$$T(t,r)=T_{\mathrm{g}}+\frac{q}{4\pi\cdot\lambda}\cdot\left[\ln\left(\frac{4\cdot a\cdot t}{r^2}\right)-\gamma\right]+T_{\mathrm{g}}, \tag{5}$$

where γ is Euler's constant ($\gamma = 0.5772$). Equations 4, 5 give the same results, but since Eq. 5 is easier to use, it was used here. Substituting a distance that is equal to the borehole radius, Eq. 5 represents the temperature of the borehole wall:

$$T_{\mathrm{b}}(t)=T_{\mathrm{g}}+\frac{q}{4\pi\cdot\lambda}\cdot\left[\ln\left(\frac{4\cdot a\cdot t}{r_{\mathrm{b}}^2}\right)-\gamma\right]+T_{\mathrm{g}}. \tag{6}$$

By assuming a thermal resistance R_{b} between the heat carrier inside the pipe and the borehole wall, we can write:

$$T_{\mathrm{f}}(t)-T_{\mathrm{b}}(t)=R_{\mathrm{b}}\cdot q. \tag{7}$$

Equations 6, 7 give:

$$T_{\mathrm{f}}(t)=\frac{q}{4\pi\cdot\lambda}.\left[\ln\left(\frac{4\cdot a\cdot t}{r_{\mathrm{b}}^2}\right)-\gamma\right]+T_{\mathrm{g}}+R_{\mathrm{b}}\cdot q. \tag{8}$$

As we can see from the Eq. 8 that fluid temperature is linear in relation to ln(t), therefore it can be rearranged in a linear form:

$$T_{\mathrm{f}}(t)=\frac{q}{4\pi\cdot\lambda}\cdot\ln(t)+q\cdot\left[\frac{1}{4\pi\cdot\lambda}\left(\ln\left(\frac{4\cdot a}{r_{\mathrm{b}}^2}\right)-\lambda\right)+R_{\mathrm{b}}\right]+T_{\mathrm{g}} \tag{9}$$

$$T_{\mathrm{f}}(t)=K\ln(t)+m \tag{10}$$

$$K=\frac{q}{4\pi\cdot\lambda}\quad m=q\cdot\left[\frac{1}{4\pi\cdot\lambda}\left(\ln\left(\frac{4\cdot a}{r_{\mathrm{b}}^2}\right)-\gamma\right)+R_{\mathrm{b}}\right]+T_{\mathrm{g}} \tag{11}$$

where a is thermal diffusivity of the ground (m^2/s), λ is thermal conductivity of the ground (W/m K), r_{b} is borehole radius (m), T_{g} is undisturbed initial temperature of the ground (K), t is time from start (s), q is heat injection rate per unit borehole length (W/m), R_{b} is thermal resistance (K m/W), γ is Euler's number (0.5772), and $T_{\mathrm{f}}(t)$ is arithmetic mean of the inlet fluid temperature ($T_{\mathrm{f_{in}}}$) and outlet fluid temperature ($T_{\mathrm{f_{out}}}$) of the borehole heat exchanger at time t

$$T_{\mathrm{f}}(t) = \frac{T_{\mathrm{f_{in}}} + T_{\mathrm{f_{out}}}}{2}. \tag{12}$$

By plotting the mean fluid temperature development against ln(t), the ground thermal conductivity and thermal resistance of the borehole can be calculated. First, we need to find out the characteristics of the line in Eq. 9, i.e., K and m, and then λ and R_{b} can be calculated as follows:

$$K = \frac{\Delta Y}{\Delta X} \quad \lambda = \frac{q}{4\pi \cdot K}. \tag{13}$$

This value of the effective thermal conductivity is used to calculate the thermal resistance:

$$R_{\mathrm{b}} = \frac{m - T_{\mathrm{g}}}{q} - \frac{1}{4\pi \cdot \lambda} \cdot \left[\ln\left(\frac{4 \cdot a \cdot t}{r_{\mathrm{b}}^2}\right) - \gamma \right]. \tag{14}$$

Consequently, thermal response data, i.e., temperature development in the borehole at a certain energy injection/extraction rate, allow the estimation of effective thermal conductivity of the ground and thermal resistance of the collector.

- First, we need to check out the validation of the line source model. Recall that the LSM is valid for one dimension heat transfer (radial heat flow); therefore, we need to find out the ground temperature profile. Great geothermal gradient means there will be vertical heat transfer, i.e., LSM is not valid.
- Second, the undisturbed ground temperature is required. This temperature is the mean temperature at half the active borehole depth. The easiest way to determine the undisturbed ground temperature is temperature loggings in the borehole or by circulating the heat carrier without heating for 10–30 min. The mean fluid temperature corresponds to the undisturbed ground temperature.

The last step is to turn on the heater and proceed the measurements 60–72 h. In the presence of groundwater, the ground thermal conductivity and borehole thermal resistance will increase with time [19, 20].

- Since it takes some time before a BHE behave as an ideal line source the first hours of data must be ruled out from the analysis [8]. Therefore, analysis starts after time = t:

$$t > \frac{20 \cdot r_{\mathrm{b}}^2}{\alpha}. \tag{15}$$

- The experiment should be carried out under conditions similar to real conditions i.e., type of BHE, borehole depth, borehole diameter, fluid flow rate, and mean power load of the GSHP. Change in fluid flow rate affects the Reynolds's number i.e., thermal resistance. Change in the mean power load affects the borehole thermal resistance [21] and effective ground thermal conductivity [20].
- If there is a failure during the experiment, we should wait until ground temperature recovery until 0.3 °C of its initial temperature. Let us assume that a failure occurred after time = t_1 from the start. The temperature change of the borehole wall is then:

$$\Delta T = \frac{q}{4\pi \cdot \lambda} \cdot \left[\ln\left(\frac{4 \cdot a \cdot t_1}{r_{\mathrm{b}}^2}\right) - \gamma \right]. \tag{16}$$

The ration between the required time t to reach the recovery point, ΔT after a signal pulse of length t_1 is given by [22]:

$$\frac{t}{t_1} = \frac{1}{e^{\left(\frac{\Delta T * \cdot 4\pi \cdot \lambda}{q}\right)} - 1}. \tag{17}$$

So, for a mean load of 30 $\mathrm{Wm^{-1}}$, and failure after 12 h, then the required time until the temperature change of the borehole wall is back to $T_{\mathrm{b}} - T_{\mathrm{g}} = 0.3$ °C is $\sim$43 h (assuming a ground thermal conductivity of 3.5 $\mathrm{Wm^{-1}\,K^{-1}}$), where capacity $C = 2.4.10^6\ \mathrm{Wm^{-1}}$, and thermal diffusivity of soil $D_f = 0.6939 \times 10^{-6}\ \mathrm{m^2\,s^{-1}}$ (in Tlemcen site), then $\lambda = C \cdot D_f = 1.66\ \mathrm{Wm^{-1}\,K^{-1}}$, and the rate of heat injection rate per unit borehole length $q = 60\ \mathrm{Wm^{-1}}$.

Figure 2 shows the theoretical mean fluid temperature as function of the time. Hence, thermal conductivity can be determined from the slope of the line "k" resulting by plotting the mean fluid temperature against ln(t), Fig. 3.

Experimental procedure and results

Unlike the previously derived theoretical equations, which represent the analytical solution for heat transfer in an

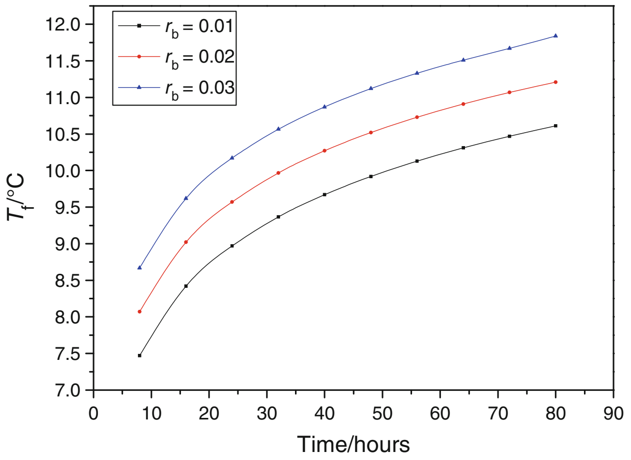


Fig. 2 Theoretical mean fluid temperature circulated through borehole, Eq. 9 with $\lambda = 3.5\ \mathrm{Wm^{-1}\,K^{-1}}$ and $q = 60\ \mathrm{Wm^{-1}}$

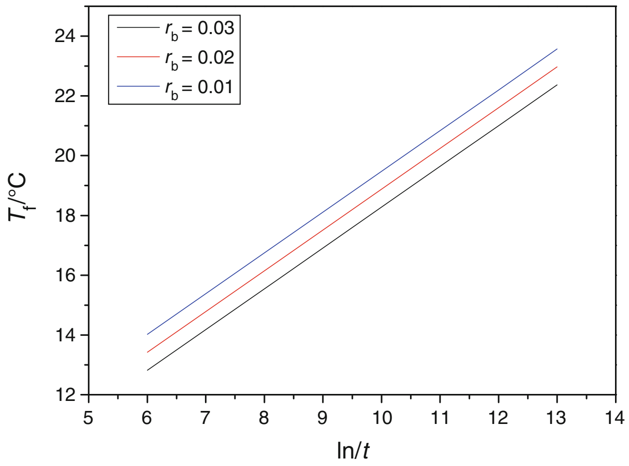


Fig. 3 Theoretical mean fluid temperature circulated through borehole, Eq. 10 with $\lambda = 3.5$ Wm^{-1} K^{-1} and $q = 60$ W^{-1} m^{-1}

infinite medium with a line heat source with the constant rate of heat generation, located in the axis of an infinite cylinder with a relatively small radius, the experimental procedure simulates heat transfer in a semi-infinite medium also with a line heat source with the constant rate of heat generation, which is also located in the axis of an infinite cylinder with a relatively small radius. In addition, this procedure does not take into account either the temperature change by depth of the ground or daily temperature changes of surface layers of the ground. However, since that line source is very long and temperature changes by depth of the ground are relatively small, and daily temperature fluctuations affect very shallow depth of the ground, it can be considered that they do not have an important influence on the accuracy of the obtained results.

Description of the experimental installation

The experimental installation which was used to perform the controlled heating of the earth, and monitor its thermal "response" to determine the effective thermal conductivity of the soil, is shown in Fig. 4. A vertical heat exchanger, 60 m long, buried in a vertical, 16.5-cm diameter borehole, subsequently filled was located in the courtyard of the Abou Bekr Belkaid University of Tlemcen (Algeria).

Measuring procedure

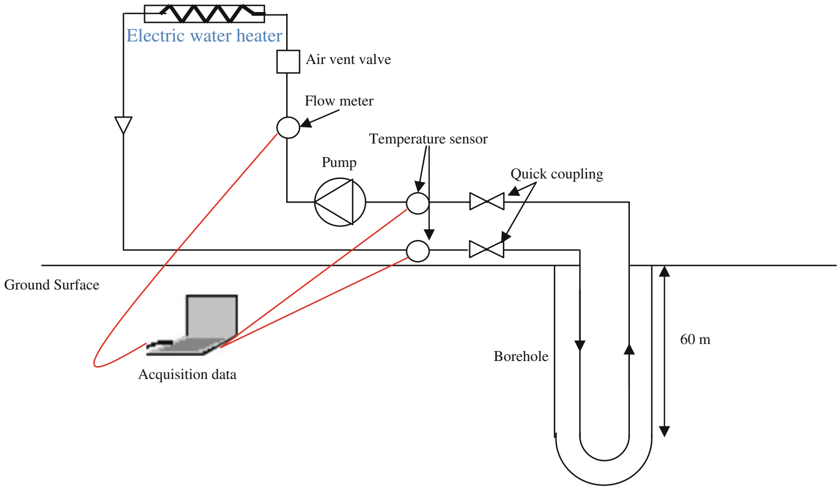
As already mentioned, to determine the effective thermal conductivity of the soil by TRT, it is necessary to know the undisturbed ground temperature T_0, the rate of heat generation of the heat source q, and, finally, to monitor the temperature changes of the heat source $T_{\mathrm{f}}(t)$.

The undisturbed ground temperature is determined in the previous phase. In this phase, the water pump was the only one that was working and only the changes of the water temperature at the entrance to the VBHE and exit from it were measured. Although this phase lasted longer than 12 h, it was noticed, after only 20 min, that the value of temperature in both water flows already became equal and stabilized at $T_0 = 17.55$ °C. Based on this, it was concluded that the average undisturbed ground temperature has precisely that value.

The rate of heat generation of the heat source q was determined in the phase of heating the soil. This phase started with the electric boiler being turned on and followed right after the previous phase. The heating phase lasted for 5 days. In fact, out of the total of six electric heaters, only three were turned on, providing about $3 \times 1.16 = 3.48$ Kw of thermal power. At the same time, the actual value of the realized heat flow to the soil—the rate of heat generation of the heat source q—which was measured and recorded using the ultrasonic flow heat meter, had a somewhat lower average value which amounted to 3.489 Kw (Figs. 5, 6, 7, 8).

The measured temperature values are shown in Fig. 7. The same figure also shows the water temperature

Fig. 4 Schematic of the experimental installation



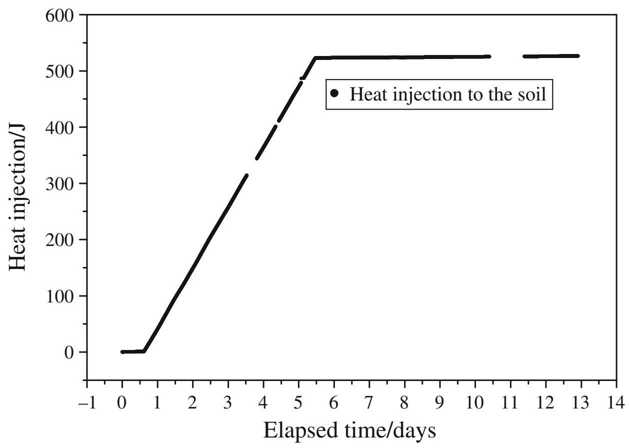


Fig. 5 Heat energy delivered to the ground

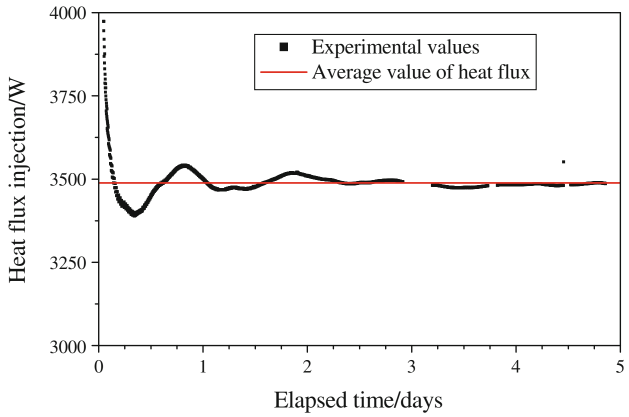


Fig. 6 Change of heat flow to the ground and its average value during the "heating" phase

measured after the heating phase—after the boiler was turned off, in the recovery phase—phase of recovering to the initial state.

Processing of experimental data

In order for the collected experimental data to be assigned to the described theory and thus serve to determine the effective thermal conductivity of the soil, first, only the data on water temperature at the entrance to the VBHE and the exit from it which were collected during the heating phase were extracted. Then, change in the mean temperature of the water circulating through the buried exchanger (T_f) was determined as the mean arithmetic value of the previously selected temperature data (T_{in} and T_{out}, Fig. 7).

Then, those data were transferred in a semi logarithmic coordinate system $\ln t - T$ (Fig. 9). The commercial program OriginPro 8.0 was used to determine the equation of the straight line $T = k \ln t + C_1$, which most appropriately

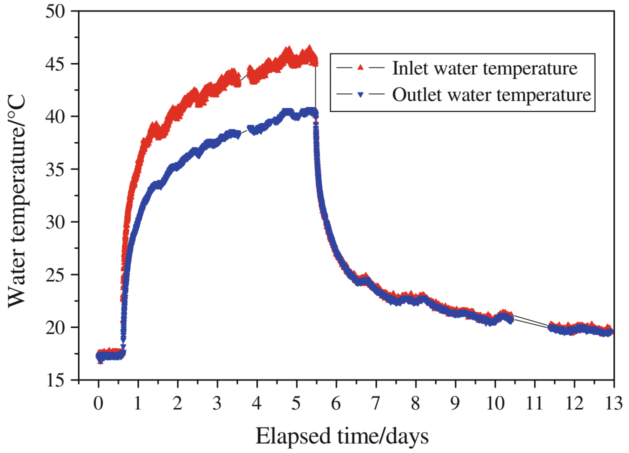


Fig. 7 Change of the water temperature

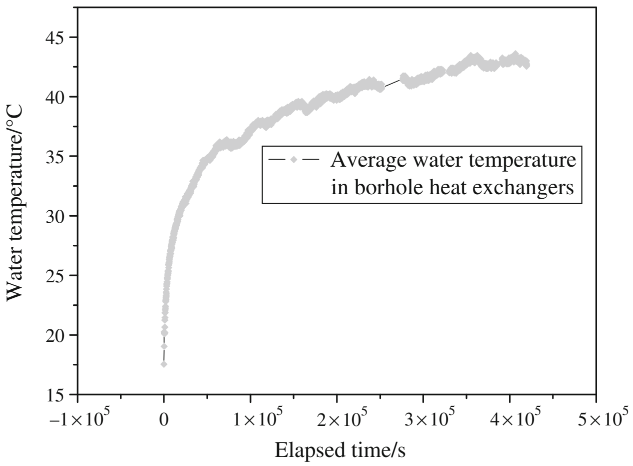


Fig. 8 Change of the average temperature of water in the buried heat exchanger during the heating phase

displays experimental data. With the correlation coefficient $rxy = 0.926$ and standard deviation $s = 0.358$, the value of thus determined direction of this line was $k = 3.32$ and the value of the segment of the ordinate was $C_1 = -9.16$

$$T = k \ln t + C_1$$

Under the assumption that the tubes of the buried exchanger, make a homogenous isotropic and infinite cylinder, with the radius r_b, in whose middle axis is the linear heat source, the previously determined constant k is, at the same time, the constant of the same name in the function described by the Eq. 5. Based on that, and by using the Eq. 3, the effective thermal conductivity of the soil around the examined well was determined:

$$\lambda_{eff} = \frac{q}{4\pi \cdot \lambda} = 1.364\ \mathrm{Wm^{-1}K^{-1}}.$$

In order to verify the accuracy of the obtained result and reliability of the method itself, TRT was repeated three

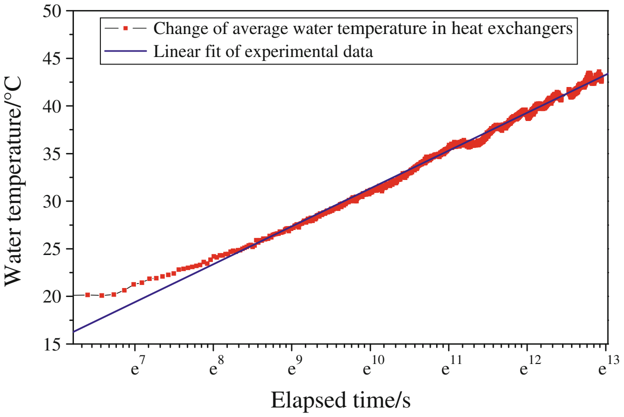


Fig. 9 Change of the average temperature of water in the buried exchanger during the heating phase by function: $T = k \ln t + C_1$

Table 1 Experimentally obtained value of the effective thermal conductivity of the soil in the same borehole in three different TRTs

No. of measurements	λ_{eff}	T_0
1	1.364	17.55
2	1.378	17.05
3	1.352	16.55

times in the same borehole at 60 day intervals. The obtained results are shown in Table 1.

Conclusions

For the borehole under test, the effective ground thermal conductivity (λ) was found to be 1.364 $\mathrm{Wm^{-1}\ K^{-1}}$ and the borehole thermal resistance (R_b) to be 0.18 $\mathrm{Km\ W^{-1}}$. This is in accordance with values for similar types of ground layers.

The experiment was carried out immediately after refilling the well, which means the soil density through the well was quite little comparing with the well wall, as well as, measured undisturbed ground temperature was higher that normal; this reason may be explain the low value of effective ground thermal conductivity.

We conclude that the TRT can easily be made, as it was done with this test.

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