First in situ determination of the thermal performance of a U-tube borehole heat exchanger, in Cyprus

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ABSTRACT

A borehole heat exchanger can be used for the injection or extraction of thermal energy into/from the ground. One of the methods that can be used to determine the characteristics of a borehole U-tube heat exchanger is the line source method which is simple and does not need expensive equipment. This method is explained and a test is performed in order to determine a borehole's characteristics in layers consisting of clay, silt and sand at various analogies. For the borehole under test the ground thermal conductivity (λ) was found to be 2.7 W/(m K) and the effective borehole thermal resistance (R_b) to be 0.10 K/(W/m). The results of the test are very sensitive to the amount of initial data that are discarded. The test is also sensitive to the daily flux penetration through the ground which gradually increases the temperature of the top layers in summer and to the variation of the heating coil injection rate which affect the temperature of the fluid of the heat exchanger at some later time.

Keywords: Borehole, earth heat exchanger, thermal performance

1. INTRODUCTION

Borehole heat exchangers are used to exploit effectively the heat capacity of the soil and commonly they are coupled to heat pumps for increasing their efficiency. In a vertical U-tube borehole heat exchanger a water pump circulates fluid through pipes inserted into a borehole in the ground. The borehole, after the insertion of the U-tube is usually backfilled with grout in order to ensure good thermal contact with the ground. The grout is often a bentonite clay mixture, with the possibility of having thermally enhanced additives in order to present a thermal conductivity significantly lower than the surrounding ground. The circulating fluid is usually water or a water-antifreeze mixture.

A borehole heat exchanger is usually drilled to a depth between 20 to 300 m with a diameter of 10 to15 cm. A borehole system can be composed of a large number of individual boreholes. For a typical residential house in Switzerland, a borehole heat exchanger of 100 to 200 m is used, depending on the energy demand and the ground conditions. For typical ground conditions and a single borehole heat exchanger, the borehole length is sized for a heat extraction rate per meter borehole of about 50 W/m [1]. For sizing the borehole heat exchanger its thermal properties should be estimated.

Several models for calculating the thermal properties of a borehole heat exchanger are available. These models are based on Fourier's law of heat conduction and include the analytical line source model [2], the cylindrical source model [3] and several numerical models [4, 5].

2. LINE SOURCE MODEL

In this paper, the line source model, which is the most widely used method at this time is employed. The data analysis is based on the theory describing the response of an infinite line source model [6, 7]. Although this model is a simplification of the actual experiment, accurate data for the design of borehole heat exchangers can be obtained on site [8].

The change in ground temperature at a distance *(r)* from the line source after a time duration *(t)* of constant heat injection rate per active length of borehole(q_c , (W/m)) may be used as an approximation of the heat injection from the borehole heat exchanger [6]:

$$T_{(r,t)} - T_{(t=0)} = \frac{q_c}{4\pi\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du = \frac{q_c}{4\pi\lambda}E_1\left(\frac{r^2}{4\alpha t}\right) \quad (1)$$

Where u is an independent variable and E_1 is the so-called exponential integral. For large values of the parameter at/r^2, E_1 can be approximated with the following relation:

$$E_1\left(\frac{r^2}{4\alpha t}\right) = \ln\left[\frac{4\alpha t}{r^2}\right] - \gamma \quad (2)$$

For the above expression the maximum error is 2.5% when $\alpha t/r^2 \geq 20$ and 10% when $at/r^2 \geq 5$.

The above condition indicates that the accuracy increases as the thermal front reaches further beyond the borehole wall and the velocity of the thermal front is dependent on the ratio between thermal conductivity and heat capacity of the ground i.e. the ground thermal diffusivity [9].

The thermal characteristics of a borehole heat exchanger are determined by its effective borehole thermal resistance R_b, which defines the proportional relationship between the temperature difference of the fluid (T_f) and the borehole wall (T_b) and the heat rate exchanged by the borehole so:

$$R_b = (T_f - T_b)/q_c \quad (3)$$

As the temperatures and heat rate are time-dependent, this relation disregards the heat capacitive effects of the borehole itself. The effective borehole thermal resistance takes into account both the geometrical parameters of the borehole heat exchanger (pipe spacing, diameter, number of pipes, depth) and the physical parameters (thermal conductivity of the materials, flow rate in the borehole, fluid properties, etc.) [1].

The fluid temperature is evaluated by taking the line source temperature at the borehole radius ($r=r_b$) and adding the effect of the borehole thermal resistance (R_b) between the fluid and the borehole wall. Thus the quality of the borehole heat exchanger is higher with a lower borehole thermal resistance and the fluid temperature (T_f) as a function of time is:

$$T_{f(t)} = \frac{q_c}{4\pi\lambda} * \left[\ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right] + q_c R_b + T_{(t=0)} \quad (4)$$

where, $T_{f(t)}$ denotes the arithmetic mean of the inlet fluid temperature ($T_{f\text{-}in}$) and outlet fluid temperature ($T_{f\text{-}out}$) of the borehole heat exchanger at time t [$T_{f(t)}=\frac{1}{2}(T_{f\text{-}in}+T_{f\text{-}out})$].

Equation (4) can be rearranged in a linear form as:

$$T_{f(t)} = \frac{q_c}{4\pi\lambda}\ln(t) + q_c\left[R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma\right)\right] + T_{(t=0)} \quad (5)$$

Hence the thermal conductivity can be determined from the slope of the line resulting from the plotting of the fluid temperature against ln *(t)*.

Solving Eq. (3) in respect to R_b we get:

$$R_b = \frac{T_{f(t)} - T_{(t=0)}}{q_c} - \frac{1}{4\pi\lambda} * \left[\ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right] \quad (6)$$

Therefore, using the value of the thermal conductivity determined above, leads to a number of borehole thermal resistances, one for every pair of fluid temperature and time and consequently a mean value can be calculated. This procedure also requires knowledge of the ground volumetric heat capacity, which can normally be deduced with adequate precision from the geological data of the site.

The effective borehole thermal resistance may also be determined on the basis of Eq. (5) by using a software that can deduce the equation of $T_{f(t)}$ against ln*(t).* Such a program may fit a straight line, using the method of least squares, to the arrays known y's and x's and produce the appropriate formula.

The undisturbed ground temperature can be obtained before the beginning of the test by circulating the fluid in the borehole heat exchanger and measuring its temperature.

For the in situ test for estimating ground thermal conductivity a pulse of fixed energy flux is imposed on the borehole and the resulting temperature response is measured.

The response test for the u-tube in the borehole was carried out by heating the circulation medium in the tube with an electric heater supplying a constant heat output of 2.7 kW. Flow, temperature, and several other test parameters were recorded during the experiment at specific time intervals.

4. GEOLOGICAL DATA OF BOREHOLE

The lithology prevailing over the site of the borehole is the Nicosia-Athalassa formation and is represented by the calcareous sandstone and the in situ mari. Yellowish-creamy, fine to coarse-grained weak to moderately cemented, calcareous sandstone is present in the top 15 meters. Khaki, sandy marl (fine sand, clay and silt) follows for the next 15 meters and from 30 to 50 meters the soil consists of Grayish marl (fine sand 5-10%, clay 30-40%, silt 50-65%). The water table in the borehole is at about 15 meters. The layers above the water table contain about 30% of water and layers under it contain about 50% water. The discharge rate is estimated between 2 to 3 m^3/h. An analysis of the geological data gives a mean density ρ of the undisturbed soil of about 1900 kg/m^3 and a mean specific heat *(c_p)* of about 1400 J/(kg K). Consequently the ground volumetric specific heat capacity is $C = 2.66\text{x}10^6 \text{J}/(\text{m}^3\text{K})$.

5. U-TUBE BOREHOLE HEAT EXCHANGER CHARACTERISTICS AND EQUIPMENT SPECIFICATION

In Cyprus, there are no studies undertaken so far related to the efficiency and cost estimation of borehole heat exchanger systems and it is of interest to examine such systems in this environment. For this purpose, we have installed a 50 m deep U-tube heat exchanger, made from polyethylene pipe with 32mm external and 25mm internal diameter. We have also installed 20 thermocouples at various depths, for recording the ground temperature and exploit the possibilities of using this type of systems. In order to carry out the test an electrical heater was installed in line with the pipes. A circulation pump, expansion valve, an air separator, a feeding line and well-insulated pipes were also fitted. The circuit was also provided with sensors and a data acquisition system for electronically recording the flow and the power provided to the heating coil. Temperatures at the inlet and outlet of the heat exchanger and at various depths of the borehole as well as the flow rate and power input to the heating coil were recorded at 15 minutes intervals with a data logger type Omega OMB-DAQ-55/56 USB data acquisition module.

6. EXPERIMENTAL RESULTS

Before the beginning of the test, the borehole heat exchanger fluid was circulated and in this way the undisturbed ground temperature was recorded. Figure 1 indicates the recorded temperatures of the fluid. Therefore, the mean temperature was measured to be 23.85 °C.

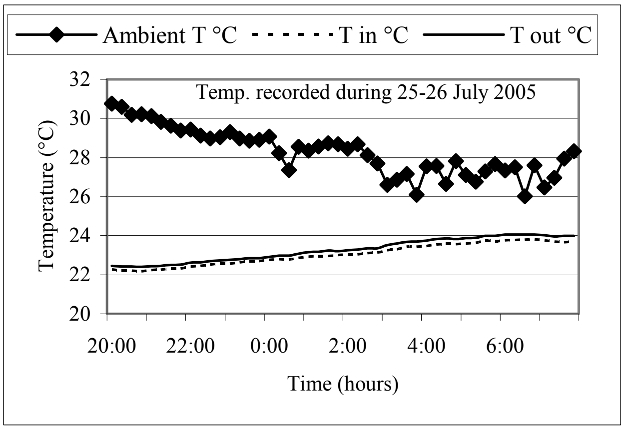

Fig. 1 Recorded inlet and outlet temperatures of the circulated fluid during 25 and 26 July 2005, before test.

After the establishment of the fluid mean temperature the heater was switched on and the test was carried out for 240 hours (ten days). During the test, the flow of the pump remained nearly constant at about 6.2 l/min. The recorded mean fluid temperature, ambient temperature and power input to the system are indicated in Fig. 2. As it is seen, the mean fluid temperature increased continuously for the first 120 hours (5 days) and then a steady state was reached.

The steady state can better be seen in Fig. 3 where the mean fluid temperature is plotted for various days against the hours of the day (for 8:00 in the morning to 8:00 in the morning of the next day). As can be seen from this figure the mean fluid temperature profile follows the same path for the last 120 hours of the test which indicates that a steady state is reached. Therefore the test data of the first 120 hours are taken into consideration for deriving the geothermal properties by using the line source model which specifically requires the absence of steady state. The experimental values recorded in this period are indicated in Fig. 4.

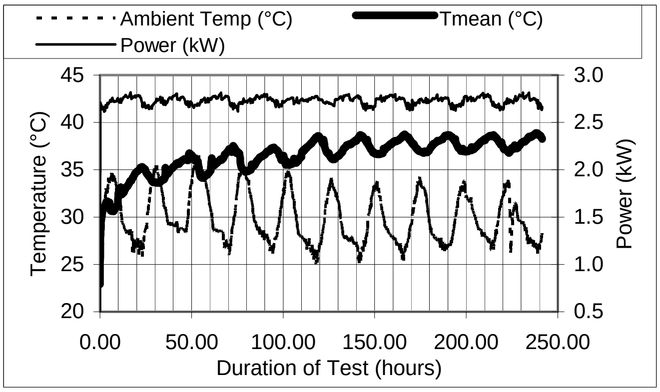

Fig. 2 Mean fluid temperature, ambient temperature and power input to the system during the test.

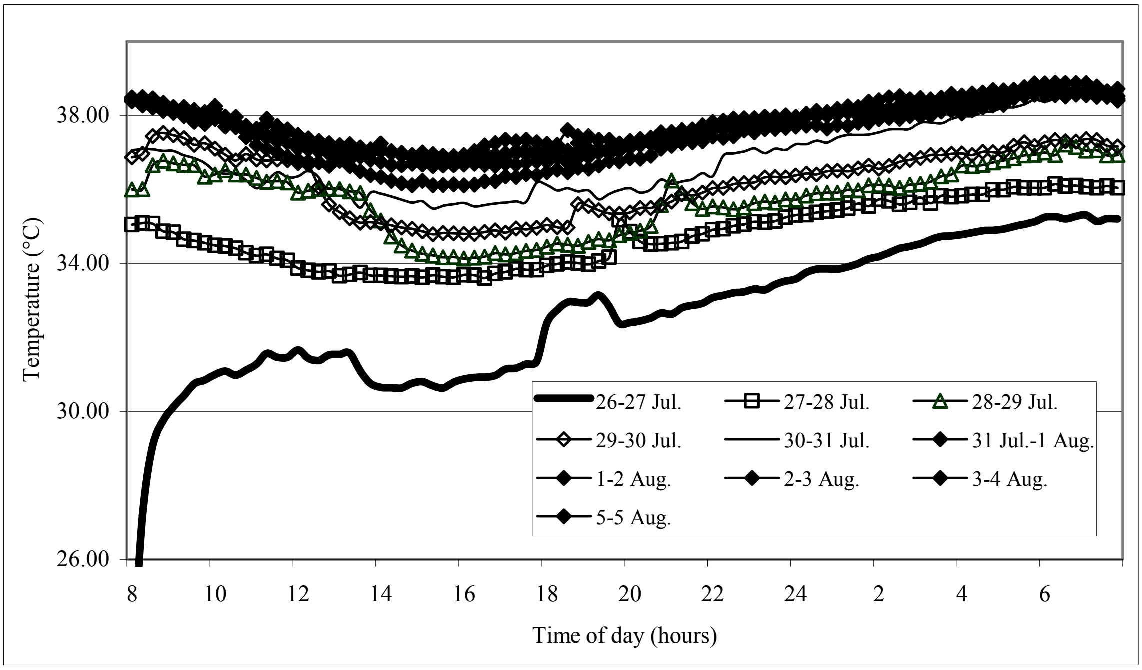

Fig. 3 Mean fluid temperature against time of day (for 8:00 in the morning to 8:00 in the morning of the next day)

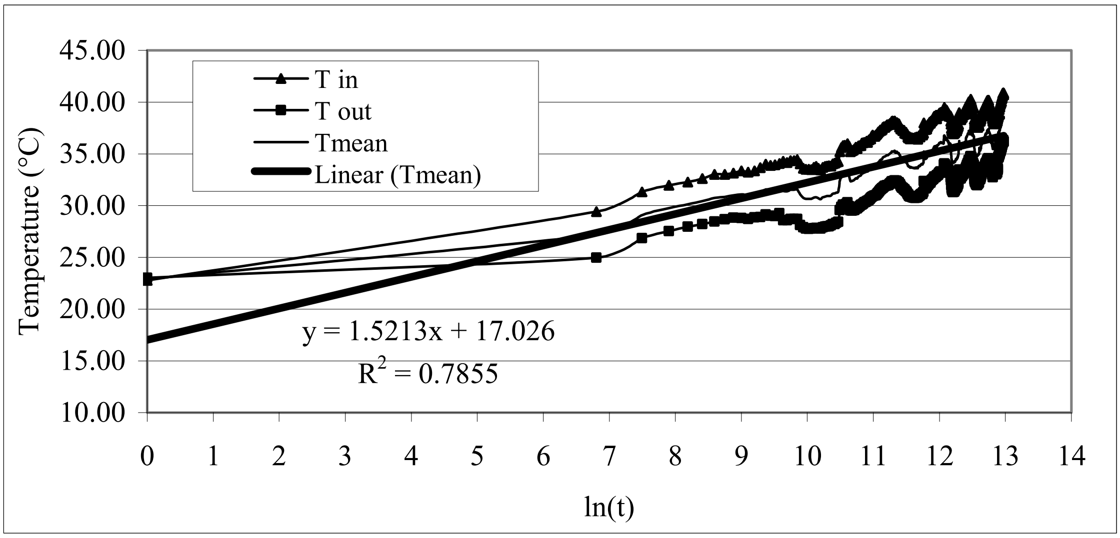

Fig. 4 Mean fluid temperature for the first 120 hours plotted against the time logarithm, ln(t), with time in seconds.

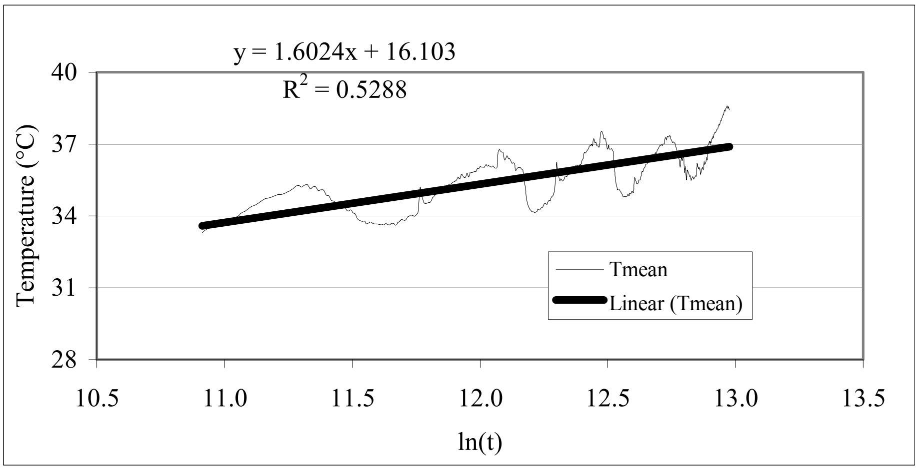

Fig. 5 Data satisfying the criterion $\alpha t/r^2 \geq 5$

The analysis of the theory presented in section 2, requires that a certain amount of data at the beginning of the test be discarded so that the approximate solution used in deriving the method, approaches the exact solution. For the characteristics of the borehole under study discarding the first 15 h of data is necessary so that the requirement $\alpha t/r^2 \geq 5$ is fulfilled. Figure 5 presents the mean fluid temperature and the trend line as well as the equation of the trend line for the actual data eventually used.

The trend line equation makes possible the calculation of the ground thermal conductivity (λ) and the effective borehole thermal resistance (R_b) as indicated in Table 1. As it is observed, ignoring more initial data makes the trend line fitting factor increasingly (R^2) worse. This is due to the fact that the collected data were affected by mainly two factors.

The first factor is the daily flux penetration through the ground which gradually increases the temperature of the top layers and therefore the temperature of the fluid of the heat exchanger at some later time. The second factor is a variation of the heating coil injection rate per active length of borehole of about 3 W/m (about 5%) as seen in Fig. 2. This combined effect has a time shift of about 8 hours from the maximum ambient temperature and about 2-3 hours from the maximum heat injection causing a gradual rise in the mean fluid temperature of about 2°C.

Table 1. Ground thermal conductivity (λ) and the effective borehole thermal resistance (R_b) as calculated when ignoring a certain amount of initial data (hours off).

Number of hours discarded	gradient	Intercept on temp. axis	R^2	λ *W/(m K)*	R_b *K/(W/m)*
0	1.5213	17.026	0.7855	2.845	0.1077
10	1.6747	15.201	0.6252	2.584	0.1001
15	**1.6024**	**16.103**	**0.5288**	**2.701**	**0.1047**
20	1.6753	15.190	0.4809	2.583	0.1005
30	1.9622	11.589	0.4490	2.206	0.0845

CONCLUSIONS

The line source model is an easy method of evaluating the characteristics of the borehole and does not need expensive equipment. It is observed though that it is very sensitive to the amount of initial results that are discarded. For the borehole under test the ground thermal conductivity (λ) is found to be about **2.7** W/(m K) and the effective borehole thermal resistance (R_b) to be about 0.10 (m K) /W. This is in accordance with values concerning similar types of ground layers [8]. The test is also sensitive to the daily flux penetration through the ground which gradually increases the temperature of the top layers in summer and to the variation of the heating coil injection rate which affect the temperature of the fluid of the heat exchanger at some later time.

NOMENCLATURE

t	time *(s)*
r	radius *(m)*
q_c	constant heat injection rate per active length of borehole $=Q/H$ *(W/m)*
γ	Euler's constant = 0.5772
λ	ground thermal conductivity *(W/(m K))*
α	ground thermal diffusivity (m^2/s), $\alpha = \lambda/C$
C	ground volumetric specific heat capacity $(J/(m^3K))$ $C = \rho * c_p$
P	ground density (kg/m^3)
c_p	specific heat of ground *(J/(kg K))*
u	independent variable
E_1	exponential integral
R_b	borehole thermal resistance *(K/(W/m))*
T_f	mean fluid temperature *(°C)*
$T_{(t=0)}$	undisturbed ground temperature before heat injection *(°C)*
$T_{f\,(t)}$	arithmetic mean of the inlet fluid temperature ($T_{f\text{-}in}$) and outlet fluid temperature ($T_{f\text{-}out}$) of the borehole heat exchanger at time t
H	active length of borehole *(m)*,
Q	total heat rate transferred by the borehole *(W)*
D_{eq}	Equivalent diameter (m)
r_b	radius of the borehole (m)
D	diameter of the U-tube (m)
L_s	center to center distance between the two legs (m)
n	number of U-tube legs in a borehole

REFERENCES

[1] D. Pahud, B. Matthey Comparison of the thermal performance of double U-pipe borehole heat exchangers measured in situ. Energy and Buildings 2001, Vol. 33 pp. 503-507.

[2] Ingersoll, L.R., O.J. Zobel, and A.C. Ingersoll. 1954. *Heat conduction with engineering, geological and other applications*. New York: McGraw-Hill.

[3] Carslaw H.S. and J.C. Jaeger, 1993. Conduction of heat in Solids, Second ed., Oxford: Clarendon Press.

[4] Shonder, J A., and J.V. Beck. 1999. Determining effective soil formation thermal properties from field data using a parameter estimation technique. *ASHRAE Transactions* 105(1): 458-466.

[5] Kavanaugh, S. P., and K. Rafferty 1997. Ground Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings, Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

[6] Ingersoll, R., and H. Plass, 1948. *Theory of the Ground Pipe Heat Source for the Heat Pump. Heating Piping and Air Conditioning*. July. pp. 119-122.

[7] Mogeson, P. 1983. Fluid to duct wall heat transfer in duct heat storages. In *Proceedings of the International Conference on Subsurface Heat Storage in Theory and Practice*. Swedish council for building research.

[8] In situ determination of underground thermal parameters. *Erich Mands, Burkhard Sanner*, IGD2001, 17.-22.09.2001. (International Summer School on Direct Application of Geothermal Energy. http://www.geothermie.de/ueb_seiten/ub_sanner.htm)

[9] Gehlin, S. 2002. Thermal response test, Method Development and Evaluation, Licentiate thesis.