Comparison of Calculated and Measured Ground Thermal Properties

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Abstract: - This paper presents a way of calculating the in-situ borehole ground thermal properties. For this procedure a U-tube ground heat exchanger embedded in a borehole is utilized, allowing hot water to circulate in the tube. The water is heated with constant power and its temperature is recorded in constant time intervals. Then the results are analyzed using the line source method. The formulas are solved using a simple excel program to derive the values of the thermal properties with a fitting technique. These results are compared with measured values of samples taken from the same area where the borehole is located. The comparison shows that only the experimental results analyzed with the theoretical model can give reliable values because the data concern the actual stage of compaction and moisture content of the soil.

Key-Words: - ground heat exchangers, ground thermal properties, line source method.

1 Introduction

For heating and cooling, Ground Coupled Heat Pumps (GCHPs) perform better than Air Coupled Heat Pumps because the ground has a lower temperature than the atmosphere in the summer and vice-versa in winter. To exploit effectively the heat capacity of the ground, Ground Heat Exchangers (GHEs) are used. Therefore, information on the temperature and other thermal properties of the ground are essential for the sizing of GHEs and GCHPs.

The temperature of the ground at the deeper layers is mostly affected by the structure and physical properties of the soil with the thermal conductivity being the most important.

For the above reasons the ground thermal properties at a specific location will be estimated by an in-situ experimental method and measured directly on soil samples, with the results to be compared.

Many researchers have investigated the ground thermal properties in the past and evaluated models for the estimation of the GHE performance.

Yun and Santamarina [1] investigated the effect of thermal conduction in dry soils. According to their study, the contact quality and number of contacts per unit volume in granular materials in relation to the presence or not of liquids or cementing agents in the pores are the main factors affecting their thermal conductivity. Although the thermal conductivity of minerals is higher than 3 W m^{-1} K^{-1} the thermal conductivity of dry soils made of minerals is less than 0.5 W m^{-1} K^{-1}. This is due to the presence of air in the dry soils and its low thermal conductivity of 0.026 W m^{-1} K^{-1}. The improvement of the interparticle contacts of dry soils and the reduction of their porosity enhance their thermal conductivity.

Schiavi [2] analyzed simulated Thermal Response Test data in order to evaluate the effect of a three-dimensional model in determining the actual value of the soil thermal conductivity and borehole thermal resistance. These values are necessary for the design of geothermal energy storage systems. For the 3D system simulation the finite element method, implemented within the Comsol Multiphysics environment, was adopted. The analysis confirmed that the Line Source Model applied to the Thermal Response Test represents a sufficiently accurate approach for the U-tube configuration.

Kim *et al.* [3] developed a numerical model for the simulation of temperature changes in a borehole heat exchanger (BHE). The model calculated the thermal power transferred from heat pumps to BHEs, while considering the nonlinear relationship between the temperature of the circulating fluid and the thermal power. To simulate the vertical closed-loop ground heat pump (GHP) system, three modules were added to the 3D numerical simulator TOUGHREACT. The modules calculated the heat transfer between the U-tube and the circulating fluid, the circulation of the fluid in the BHE and the rate of energy transfer from a heat pump to a BHE. The developed model was validated by comparison with two experimental datasets and was used for the

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BHE design of an actual system that was numerically evaluated with respect to the temperatures of the circulating fluid at the BHE inlet and outlet, the heat pump efficiency, the heating power and electric power of the heat pumps.

Eslami-nejad and Bernier [4], presented an analytical model to predict steady-state heat transfer in double U-tube boreholes with two independent circuits operating with unequal mass flow rates and inlet temperatures. For the modeling it was assumed that the heat capacities of the grout and pipe inside the borehole were negligible, the ground and the grout were homogeneous and their thermal properties were constant, the borehole wall temperature was uniform over the borehole depth, heat conduction in the axial direction was negligible and the combined fluid convective resistance and pipe wall thickness conduction resistances were assumed to be equal in both circuits. This two-region model was validated experimentally and was in very good agreement with experimental data in the steady-state regime. The proposed model was then used to study a double U-tube borehole configuration with one circuit linked to a ground-source heat pump operating in the heating mode and the other to thermal solar collectors.

2 Problem Formulation

2.1 Line source method

For the determination of the thermal conductivity of solids in a laboratory environment, Stalhane and Pyk [5] devised the so-called single-probe method. The line source method is actually based on this method and since then this method became popular especially in Europe, where it is the most widely used method for calculating the thermal properties of the ground and for the design of BHEs. Initially, the thermal properties of the probe material were ignored in the calculations and the method was known as the line-source approximation. Ingersoll and Plass [6] applied the line source model to the design of GHEs. Blackwell [7] introduced the analytical method where the probe material and a possible contact resistance at the probe surface were taken into account. Blackwell also reported that the determination of the thermal conductivity and diffusivity at the same time using this method was not possible. The influence of the contact resistance on the thermal diffusivity was significant.

According to the theory of the simplified line source method, constant heat flow rate per active length of borehole should be supplied to the ground and the change in ground temperature at a defined distance from the line source after a time period should be recorded. Ingersoll and Plass [6] suggested the Eq. (1) below for the calculation of the temperature change in the ground

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

where:

$T_{(r,t)}$ – ground temperature at a distance (r) from the line source after a time period (t)

$T_{(t=0)}$ – initial temperature of the ground

q_c – constant heat injection rate per active length of borehole in W/m

λ – thermal conductivity of the ground

u – integration variable (unitless)

E_1 – exponential integral

The undisturbed ground temperature should be obtained before the beginning of the test. This can be achieved by circulating the fluid in the borehole heat exchanger and measuring its inlet and outlet temperature. At the beginning of the process the inlet and outlet temperature, as expected, differs. After a few hours, the temperature difference finally reaches its lowest value and stabilises. The time required for the temperature to become constant depends on the thermal properties of the borehole and the undisturbed ground.

The thermal front is defined as the distance that the heat injected from the line source can reach in the horizontal direction. The vertical effect of the heat dissipation from the line source is ignored. When the dimensionless time-to-pipe ratio parameter $\alpha t/r^2$ reaches large values, the exponential integral (E_1) can be approximated by Eq. (2) below. The larger the time that heat is injected in the ground, the bigger the radius of influence.

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

where:

γ – Euler's constant = 0.5772

When the parameter $\alpha t/r^2$ reaches values equal or greater than 20 Eq. (2) can give a maximum error of 2.5% while when it reaches values equal or greater than 5 the maximum error increases to 10%. Therefore, the above condition means that the accuracy increases as the thermal front reaches further beyond the borehole wall [8].

The thermal resistance between the fluid in the probes and the boundary of the borehole is known as the effective borehole thermal resistance, R_b and is defined by Eq. (3). The effective borehole thermal resistance takes into account both the geometrical parameters of the borehole heat exchanger (pipe diameter, length and spacing, number of pipes) and the physical parameters (thermal conductivity of the materials, flow rate in the borehole, fluid properties, etc.) [9].

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

where:

T_f – temperature of the fluid in the probe
T_b – temperature at the boundary of the borehole

Hence, the fluid temperature at the boundary of the borehole as a function of time is given by Eq. (4), arising by the substitution of Eq. (1) and (2) into Eq. (3).

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

In a U-tube GHE used in TRTs the fluid temperature ($T_{f(t)}$) is given by the arithmetic mean of the inlet (T_{fin}) and outlet fluid temperature (T_{fout}) flowing in the GHE ($T_{f(t)} = (T_{fin} + T_{fout})/2$).

Eq. (4) can be rearranged in a linear form as

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

If q_c is constant, the last two terms do not change with time and Eq. (5) becomes a simple linear relation:

$$T_{f(t)} = s \ln(t) + m \qquad (6)$$

where $s = q_c / 4\pi\lambda$ and m is a constant. Plotting $T_{f(t)}$ against $\ln(t)$ and estimating s and m, λ and a relation between R_b and α can be found.

2.2 Cylindrical heat source method

Several researchers [10-12] have used this method in order to determine the thermal properties of the ground and especially the thermal conductivity and diffusivity. In this method, a single loop GHE is represented as a cylindrical source. The two pipes of the GHE are represented in the calculations as a single coaxial pipe with an equivalent diameter. The equivalent diameter is based on the diameter of the U-tube GHE and the center-to-center distance between the two tubes and is calculated by

$$D_{eq} = \sqrt{2D * L_s} \quad \text{for} \quad D \le L_s \le r_b \qquad (7)$$

where:

D_{eq} – equivalent diameter (m)
D – diameter of the U-tube (m)
L_s – center-to-center distance between the two tubes (m)
r_b – radius of the borehole (m)

Katsura *et al.* [13] proposed a method for calculating the temperature of the ground for heat extraction or heat injection purposes via multiple GHEs. In their study they treated soil as an infinite isotropic constant solid and a vertical ground heat exchanger (borehole) as a hollow cylinder in the infinite soil. Thus, assuming that the U-tube GHE is presented by a hollow cylinder, the effective borehole thermal resistance R_b can be calculated by modifying Eq. (3) above as:

$$R_b = \frac{\ln(r_2 / r_1)}{2\pi\lambda_b} \qquad (8)$$

where r_1 and r_2 are the internal and external radii of the hollow cylinder respectively and λ_b The thermal conductivity of the borehole which usually is known.

2.3 Thermal Response Test

For the determination of the thermal characteristics of the soil a borehole was drilled at Agios Georgios, Limassol with a depth of 127 m and a diameter of 0.155 m. In the borehole a U-tube GHE made of polyethylene pipe 40 mm in external diameter was installed at the full depth of the borehole and it was then filled with bentonitic clay (λ_b = 1.2 W m^{-1} K^{-1}). The tests were carried out by injecting constant heat energy into the borehole through the GHE with water acting as the heat carrier fluid. An in-line 2.9 kW electric heating coil was employed for the heat generation. The inlet and outlet temperatures of the water, its flow rate in the GHE and the input energy were recorded by data loggers every 15 minutes. Fig. 1 depicts the set-up of the equipment used in the experiment.

3 Problem Solution

3.1 Thermal Response Test Results

Fig. 2 shows the resulting figure of the water mean temperature plotted against time in seconds. If the above data are plotted against a natural logarithmic scale (Fig. 3) then the relation is a straight line from which s and m are estimated as s = 1.2442 and m = 15.625. From these data and using Eq.(5), λ = 1.46 W m^{-1} K^{-1}. A mathematical relation is then derived using m between R_b and α, but unfortunately from this relation the only useful information is that α cannot be greater than 0.0000015 m^2 s^{-1} since a larger figure will result in a negative $R_{b.}$

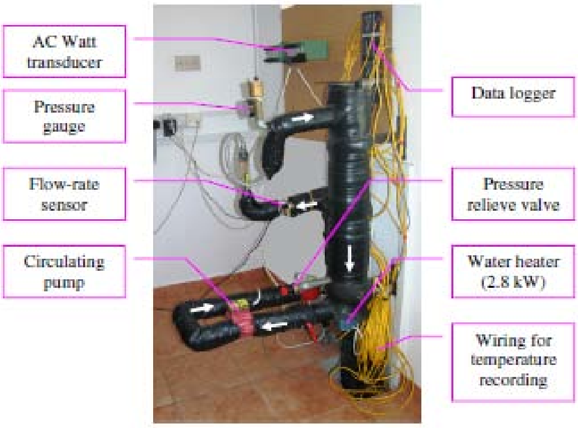

Fig. 1. Equipment used for the determination of the thermal conductivity of the borehole.

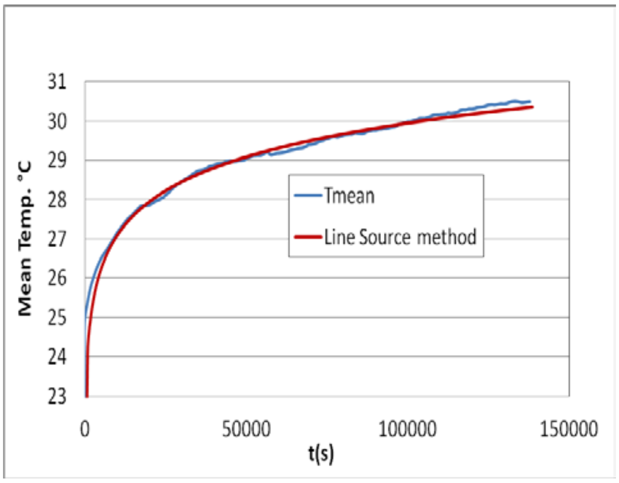

Fig. 2. Water mean temperature against time (s).

Any combination satisfying the relation between R_b and α results in the same plot of the estimated temperature shown in Fig. 2 (curve for Line Source method). For this reason Eqs.(7) and (8) are used. For a tube diameter of 0.043 m and a center-to-center distance between the two tubes of 0.095 m, the borehole thermal resistance is estimated as R_b = 0.074 m K W^{-1} and from the relation between R_b and α, $\alpha = 0.395\times10^{-6}$ m^2 s^{-1}.

3.1 In situ measurements

The different layers that were encountered during drilling of the borehole at Agios Georgios, Limassol are shown on Table 1. To compare the results with actual measurements, samples of marl from the same area where measured.

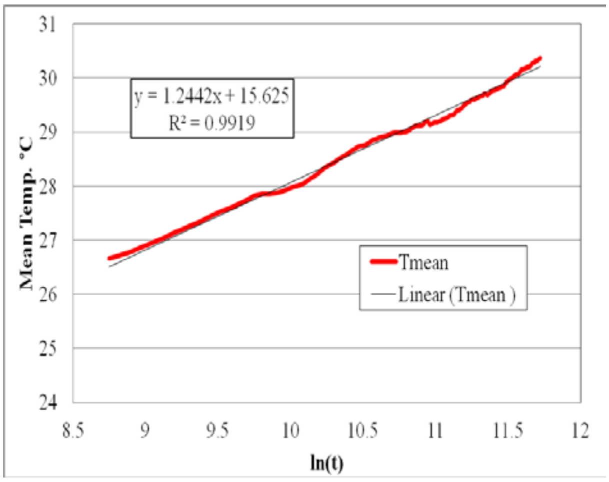

Fig. 3. By plotting the water temperature against the natural logarithm of time, s and m are estimated.

Table 1. Depth and geology of borehole

Agios Georgios, Limassol	
Type of material	Depth (m)
Red soil	0-4
Silty sand with some gravels	4-16
Yellow marl	16-38
Green marl	38-127

For the measurements, the Isomet 2104 portable heat transfer analyzer was used. The Isomet 2104 analyzer is a device that uses surface probes for direct measurement of thermophysical properties, thermal conductivity and volume heat capacity of a wide range of materials. The measurement principle is based on the temperature response of the sample to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater. The surface probe assures a direct thermal contact with the surface of the sample. The accuracy of the instrument when measuring thermal conductivity in the range 0.015 to 0.7 W m^{-1} K^{-1} is 5% of the reading +0.001 $W\ m^{-1}\ K^{-1}$, while in the range 0.7 to 6.0 W m^{-1} K^{-1} is 10% of the reading. The various samples of marl that were collected gave a thermal conductivity value of λ = 0.6–1.5 W $m^{-1}K^{-1}$, which depended greatly on the stage of the sample (dry or wet), a specific heat capacity of 750–1000 J kg^{-1} K^{-1} with a resulting diffusivity of 0.4–0.68 $\times 10^{-6}$ m^2 s^{-1}.

4 Conclusions

This paper presents a way of calculating the in-situ borehole ground thermal properties. For this procedure a U-tube GHE embedded in a borehole was utilized, allowing hot water to circulate in the tube. The water was heated with constant power. The results were analyzed using the line source method. The formulas were solved using an excel program to derive the values of the thermal properties with a fitting technique. The obtained results were λ = 1.46 W m^{-1} K^{-1}, R_b = 0.074 m K W^{-1} and α = 0.395×10^{-6} m^2 s^{-1}. These results were compared with measured values of samples taken from the same area, where the borehole was located. The comparison shows that only the experimental results analyzed with the theoretical model can give reliable values because the data concern the actual stage of compaction and moisture content of the soil. Since undisturbed soil cannot be sampled during drilling the only available source is any exposed soil in the nearby area, which will not have the correct amount of moisture in it and will give wrong readings if directly measured. In this case the direct values obtained were λ = 0.6–1.5 W m^{-1} K^{-1} and α = $0.4–0.68\times10^{-6}$ m^2 s^{-1}.

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