ADVANCES IN THE DETERMINATION OF THE THERMAL GROUND PROPERTIES FOR THE DESIGN OF BOREHOLE HEAT EXCHANGERS USING THERMAL RESPONSE TESTS

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Abstract: *In order to correctly design a Borehole Heat Exchanger (BHE), it is necessary to have a precise determination of the thermal properties of the ground. Reliable values of the effective thermal conductivity of the soil, the BHE thermal resistance, and the temperature of the undisturbed soil allow to properly size the length, geometry and distribution of the BHEs field. In-situ Thermal Response Tests (TRTs) were developed with this objective. With time, computerized tools have been developed to allow rapid estimation of the properties based on a set of data acquired in short-term tests. This contribution illustrates the use of one tool, implemented in TRNSYS and based on the B2G model, for estimating the ground properties in a BHE located at the Polytechnic University of Valencia. Additionally, the impact of groundwater flow on the results obtained with the conventional analysis methodology of a TRT in the same BHE is analysed.*

Keywords: Borehole Heat Exchanger (BHE), Thermal response test (TRT), Effective thermal conductivity of the ground, BHE Thermal resistance, B2G Model.

1. INTRODUCTION

The thermal response test (TRT) is the most used method to obtain the necessary data for ground source heat exchangers (GSHE) proper design in medium or large installations. This test is a procedure technically and economically accepted by designers and promoters of shallow geothermal facilities, being used for more than twenty years. Ground thermal characteristics obtained by following the indications described in regulations and standards are assumed with no discussion among GSHE designers, regardless the limitation of the application of the model and the measurements conditions in the work site. However, the measurement and analysis of the thermal ground parameters: ground thermal conductivity, borehole thermal resistance and undisturbed ground temperature can be conditioned for different reasons. Thermal conductivity measured in a thermal response test is called effective thermal conductivity because, due to the effects of an inhomogeneous ground and the possible presence of groundwater flow, the heat transfer process is not pure conductive.

A thermal response test is carried out connecting mobile equipment formed by a heating or cooling system, a hydraulic pump, flow and temperature sensors, and a control system to a geothermal probe installed in a borehole to inject or extract a constant thermal power. Therefore, the first aspect to consider in a TRT is the equipment control system, which must guarantee to perform the test under constant power conditions. For example, using a PID control system allows a more accurate analysis by reducing the error associated with the measurements. Secondly, considering that the main outputs of the TRT are the inlet and outlet temperature of the heat carrier fluid as a function of time, minimizing the length of the connection pipes between the TRT equipment and the borehole should be a priority although sometimes it is not possible due to the worksite conditions.

For data analysis and thermal parameters characterization, different models are used, the most widely applied method is the infinite line source (ILS) but other approaches such as the finite line source model or cylindrical source model are also well known. These analytical models are used because of their simplicity and good accuracy of the results, mainly the ILS model, but a limitation to this methodology is the amount of groundwater flow. As the effective ground thermal conductivity determined in TRT includes convection effects, in these cases its value is strongly conditioned. Advective phenomena, that is how groundwater flow transports the heat injected, depending on groundwater velocity and the hydrogeological characteristics of the different ground layers, are not being considered in the heat transfer models mentioned.

This contribution presents two improvements in the estimation of ground and heat exchanger thermal parameters from thermal response tests. The first one [1] is a TRNSYS tool to obtain the grout and ground thermal properties by means of a parameter estimation technique in conjunction with a two-dimensional dynamic numerical model, the B2G model [3] upgraded version described in [1], which can provide accurate results with a much shorter testing time and without the necessity of a constant heat injection. The second one [2] is a simple analysis methodology for the thermal response tests performed under groundwater flow conditions intended for engineering application based on finite line analysis model. The objective of this second advance is that GSHE designers can know how the underground flow masks the result of the effective thermal conductivity and assess, based on this knowledge, what is the value that they will use for dimensioning.

Both advances in the methodology to analyse TRT data are used to evaluate ground thermal parameters of a site at Universitat Politècnica de València, where a monitored single U borehole heat exchanger was used as a test bench for these new techniques. Three tests were performed in this facility, and analysed using both advances, giving excellent results for both, in the first case (TRNSYS tool based in the B2G model), estimating with high accuracy ground thermal properties for very early data of TRT and, in the second case, estimating the bias produced in the value of the effective ground thermal conductivity by the underground water flow.

This paper is organised as follows. Section two describes both methodologies, describing first standard TRT analysis. Section three presents the analysis and results discussion of the TRT data using both methodologies. And section four presents the conclusions.

2. METHODOLOGY

2.1. TRT

The purpose of a thermal response test is to find an accurate estimation of three parameters approximately describing the thermal behaviour of the ground under consideration and needed to design a ground coupled heat pump installation. These parameters are the undisturbed ground temperature, T_o, the effective ground thermal conductivity, λ, and the borehole thermal resistance, R_b.

Line source analysis assumes that the borehole heat exchanger behaves as a linear heat source emitting constant thermal power. This analysis also assumes the ground is a homogeneous infinite medium whose thermal behavior is characterized by its thermal conductivity, λ, and its thermal diffusivity, α. Considering the source with an infinite length, meaning that the borehole depth, L, is much bigger than the borehole radius, r_b, the solution of this thermal problem gives the temperature of the ground as a function of the radial coordinate, and the time, t:

$$T(r,t) = T_0 - \frac{Q_z}{4\pi\lambda} Ei\left(-\frac{r^2}{4\alpha t}\right) \tag{2.1}$$

Where T_0 in the undisturbed ground temperature and Q_z the constant heat power injected to the ground per length unit. Symbol Ei represents the Euler integral. For sufficiently large times this expression can be approximated by:

$$T(r,t) \approx T_0 + \frac{Q_z}{4\pi\lambda}\left\{ln\frac{4\alpha t}{r^2} - \gamma + \mathcal{O}\left(\frac{r^2}{4\alpha t}\right)\right\}, \qquad for \qquad \frac{4\alpha t}{r^2} \gg 1 \tag{2.2}$$

This expression is usually used to estimate the value of the temperature at the borehole radius, r_b, during a Thermal Response Test:

$$T(r_b,t) = T_b(t) = T_0 + \frac{Q_z}{4\pi\lambda}\left\{ln\left(\frac{t}{t_b}\right) - \gamma\right\}, \qquad for \qquad t \gg t_b = \frac{r_b^2}{4\alpha} \tag{2.3}$$

Then, borehole thermal resistance, R_b, is defined to model the inner problem of heat transfer inside the BHE, relating the average of the fluid temperature, $T_{ave}(t)$, with the temperature at the borehole surface, $T_b(t)$, through the expression:

$$T_{ave}(t) = T_b(t) + Q_z R_b \tag{2.4}$$

Thermal response tests measure inlet, T_{in}, and outlet temperature, T_{out}, to the borehole heat exchanger, as well as fluid mass flow, $\dot{m}$, allowing calculating average fluid temperature, T_{ave}, and thermal power injected to the ground, Q_z, through:

$$T_{ave} = \frac{T_{in}+T_{out}}{2} \qquad\qquad Q_z = \frac{\dot{m}\, C_p\,(T_{in}-T_{out})}{L} \tag{2.5}$$

If the assumptions of the ILS analysis are reasonable for the thermal response test under consideration, then average fluid temperature will follow the expression:

$$T_{ave}(t) = T_0 + Q_z R_b + \frac{Q_z}{4\pi\lambda}\left\{ln\left(\frac{t}{t_b}\right) - \gamma\right\} \tag{2.6}$$

Usual analysis plots data of average fluid temperature against logarithm of time. Then, a linear behaviour of these experimental data will confirm the assumptions of the ILS, extracting ground thermal properties and borehole resistance from the slope, *a*, and the intercept, *b*, of the linear fit:

$$a = \frac{Q_z}{4\pi\lambda} \qquad\qquad b = T_0 + Q_z\left(R_b - \frac{\ln(t_b)-\gamma}{4\pi\lambda}\right) \tag{2.7}$$

From the slope, *a*, effective thermal conductivity of the ground is estimated, $\lambda = Q_z/4\pi a$, and from the intercept, b, a relationship between the undisturbed ground temperature, T_0, the ground thermal diffusivity, α (included in the time constant $t_b = r_b^2/4\alpha$) and the borehole thermal resistance, R_b, is found. If a measurement of the undisturbed ground temperature is done and an estimation of ground thermal diffusivity is available, then borehole thermal resistance can be calculated from expression:

$$R_b = \frac{b-T_0}{Q_z} + \frac{\ln(t_b)-\gamma}{4\pi\lambda} \tag{2.8}$$

2.2. TRT analysis software

An innovative TRNSYS tool to estimate the ground thermal properties applied to a TRT, but without the necessity of a constant heat injection and much shorter heat injection periods (11-16 hours), in comparison with conventional methods (up to 50 hours), was developed. The methodology used consists of a parameter estimation technique in conjunction with a two-dimensional dynamic numerical (6C8R-*n;* six thermal capacitances, eight thermal resistances and *n* vertical divisions) model, the B2G model [1] and [3] implemented as a TRNSYS type. Finally, using the TRNOPT optimization algorithm, both the conductivity of the ground and the grout of a BHE are determined.

The B2G TRNSYS type developed is used to simulate a TRT during a defined injection time. The geometrical characteristics and the thermal properties of the BHE and surrounding ground are set as parameters and the measured inlet temperature (T_{in}) and mass flow rate ($\dot{m}$) are introduced as inputs in the model. Therefore, the result of the TRNSYS simulation is the outlet temperature (T_{out}), which is compared with the experimental values. The Root Mean Square Error (RMSE) between the simulated (T_{B2G}) and experimental outlet temperature ($T_{experimental}$) at the end of the simulation is calculated according to equation (2.9):

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}\left(T_{B2G,t} - T_{experimental,t}\right)^2}{n}} \tag{2.9}$$

The estimation of the thermal properties of the ground and grout (being their initial guess values and the volumetric heat capacity of grout and ground fixed estimated based on the data provided from the TRT or tabulated data) can be done carrying out several simulations, varying these properties and trying to minimize the RMSE at the end of the simulation.

The geometry of the BHE is introduced as a parameter and the experimental data (inlet temperature and mass flow rate) are introduced as inputs. The time of heat injection for which the estimation of conductivities is carried out is introduced as an additional parameter, so that the conductivities will be estimated for that specific injection time (also called *test duration*). It should be noted that the input TRT experimental data needed in the model stands for an amount of heat injection, which not necessarily must be constant during the test.

The methodology is schematized in Figure 1, where the results obtained for a given test duration (t) are: Grout conductivity (k_b), Ground conductivity (k_g) and RMSE obtained with the calculated values of k_b and k_g.

This methodology could be applied in-situ during the TRT duration, calculating the thermal conductivities and RMSE in intervals of one hour. In this context, a stop criterion for the TRT duration must be defined. For this purpose, the relative variations of the ground conductivity (Δk_g) and RMSE ($\Delta RMSE$) with respect to the previous hour values are calculated and the TRT would be stopped when these variations are below a certain tolerance (in this work a 2 % of variation per hour was used). This time will be referred in the following as *stop time*. Therefore, when both the variations of ground conductivity and RMSE for a certain injection time are below this percentage with respect to the previous hour calculated value, it is considered that the TRT can be stopped, and the last values of conductivities are considered the estimated representative values.

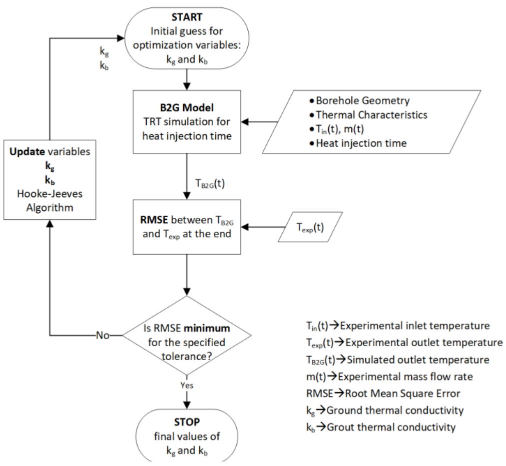

Figure 1. Optimization methodology flow diagram to estimate the thermal conductivities for a specific TRT duration

2.3. Groundwater flow impact in TRT

The purpose of this methodology is finding a phenomenological quantitative description of the effects observed in TRT data when underground water is present. In particular, the long-term effect driving to the unphysical result of a thermal conductivity depending on time and injected power. A phenomenological parametrization of this effect can be obtained with an expression for the effective thermal conductivity depending on the difference between the average fluid temperature, T_{ave}, and the undisturbed ground temperature, T_0, as the following one:

$$\lambda = \lambda_0 \left(1 + x\frac{T_{ave}-T_0}{T_0}\right) \tag{2.9}$$

Where the new parameter, *x*, quantifies the effect produced by underground water currents. Both observed dependencies, with time and with injected thermal power, can be described with this approach. With this parametrization, groundwater effects are phenomenologically integrated in the line source approach as a more complex definition of effective thermal conductivity. With this new definition for λ given in equation 2.9 and with the finite line source equations [2] relating average fluid temperature with time:

$$T_{ave} = T_0 + Q_z R_b + \frac{Q_z}{4\pi\lambda}\left\{ln\left(\frac{t}{t_b}\right) - \gamma - \left(\frac{3}{\sqrt{\pi}}\left(\sqrt{\frac{t}{t_L}} - \left(\frac{r_b}{L}\right)^2\sqrt{\frac{t_L}{t}}\right) - 3\frac{r_b}{L}\right)\right\} \tag{2.10}$$

where $t_L = \frac{L}{4\alpha}$, it can be written:

$$[f_0 - R_b]\left(1 + x\frac{T_{ave}-T_0}{T_0}\right) = \frac{\tau-\Delta\tau}{\lambda_0} \tag{2.11}$$

being:

$$f_0 = \frac{T_{ave}(t)-T_0}{Q_z} \quad ; \quad \tau = \frac{ln\left(\frac{t}{t_b}\right)-\gamma}{4\pi} \quad ; \Delta\tau = \frac{1}{4\pi}\left\{\frac{3}{\sqrt{\pi}}\left(\sqrt{\frac{t}{t_L}} - \left(\frac{r_b}{L}\right)^2\sqrt{\frac{t_L}{t}}\right) - 3\frac{r_b}{L}\right\} \tag{2.12}$$

Expression (2.11) represents the new prediction of this improved line source approach for the thermal response test data including underground water effects. The choice of f_0 variable is done to make data analysis independent of the injected power and then, allow to easily compare TRT data for different injected power. Defining de quantity $f_{GW}(x)$ as:

$$f_{GW}(x) = [f_0 - R_b]\left(1 + x\frac{T_{ave}-T_0}{T_0}\right) \tag{2.15}$$

final expression for this new prediction is:

$$f_{GW}(x) = \frac{\tau-\Delta\tau}{\lambda_0} \tag{2.16}$$

Representing $f_{GW}(x)$, calculated directly from experimental data, against $r - \Delta r$, calculated from the variable time, the observed slope will be the inverse of the effective thermal conductivity whitout the masking produced by underground water flow.

3. RESULTS AND DISCUSSION

3.1. TRT analysis software

The estimation of the ground and grout thermal conductivities (k_g and k_b respectively) using the TRNSYS tool described in section 2, was carried out for a TRT of 1 kW of heat injection carried out in a single U BHE located at Universitat Politècnica de València, Spain (see characteristics of the BHE in [1]). The grout and ground volumetric heat capacities were fixed according to the data provided by the reference or tabulated data and the estimation of thermal conductivities was carried out for different test durations, from 5 hours to 24 hours in steps of 1 hour. In addition, the estimation was carried out for durations of 30 hours and 45 hours. The time step used for the simulations was 30 seconds. Figure 2 shows the dynamic evolution of the estimated value of kg, kb and RMSE, as well as the relative variation of the kg and RMSE. Finally, Table 1 shows the results obtained.

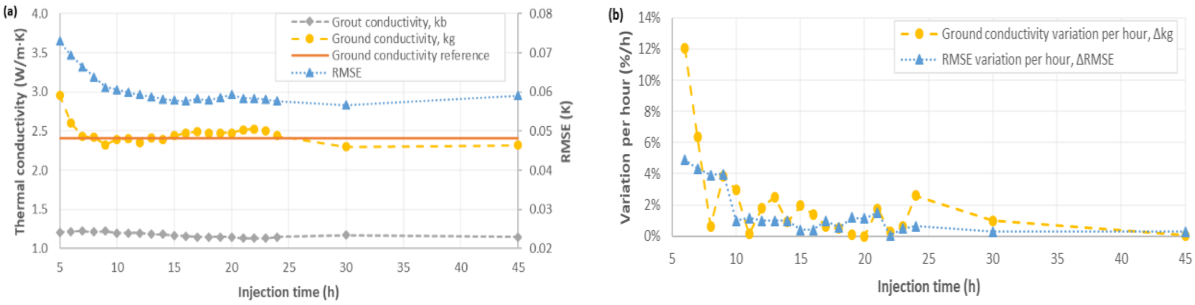

Figure 2. [1] Thermal conductivity estimation for the TRT for different test durations: (a) Results and error; (b) variation of the calculated ground conductivity and RMSE

Table 1. Results of the estimation conductivities procedure

Results	Estimated
Ground conductivity (W/m·K)	2.40
Grout conductivity (W/m·K)	1.20
Borehole Resistance ((K·m)/W)	0.097
Stop time (h)	11
RMSE (K)	0.060

Comparing to the reference values, the estimated ground conductivity (2.4 W/(m·K)) was quite the same than the referenced value (2.41 W/(m·K)), with a difference lower than 0.5 %. The calculated borehole resistance was around 0.1 (K·m)/W and the referenced value was around 0.12 (K·m)/W, a difference of 0.02 (K·m)/W. It should also be noted that 11 hours TRT duration would be enough to accurately estimate the ground and grout thermal conductivities. Finally, regarding the total uncertainty in the calculation of the ground conductivity introduced by the estimation of different parameters, results obtained in the calculations were similar to other studies based on the ILS model or another BHE models (between ±10% and ±18%).

3.2. Groundwater flow impact in TRT

Data from three TRT performed in a monitored borehole at UPV [2] where analysed using standard finite line source analysis procedure and with the improved methodology that includes ground water effects. Figure 3 shows the quantity f_{0i} on the left image and f_{GWi} on the right image (subindex i represents the i test) as function of $\tau - \Delta\tau$, clearly sowhing that not including water effects drives to an effective conductivity increasing with time and power injected as can be seen on the left image (slope decreasing with time), and illustrrating that including ground water effects through x parameter (in this case the parameter x takes the value 3,4), TRT data fits very well for the three tests to the improved line source aproach, estimating a water unaffected effective thermal conductivity of 2,0±0,1 W/mK, in contrast with high uncertainty seen on the left image in which this parameter ranges from values at the beginning of the test around 2,0 W/mK and increasing up to values around 2,9 W/m·K at the end, increase whose origin is the convective effect produced by underground water flow.

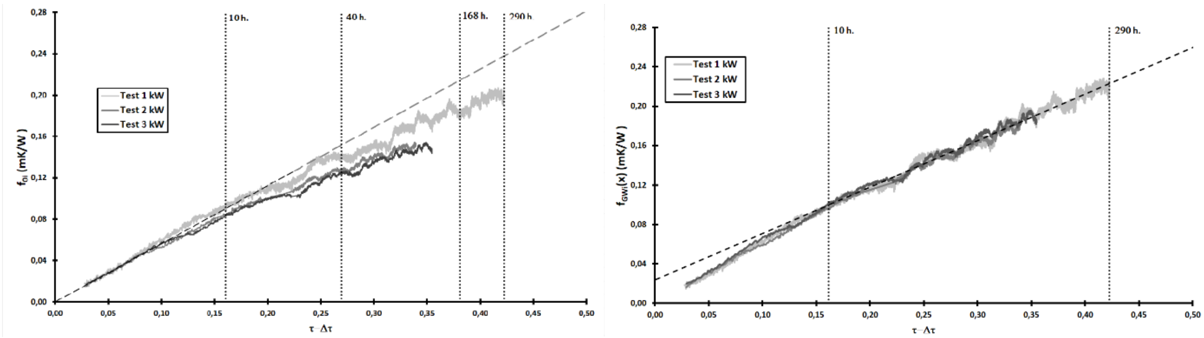

Figure 3. Values of the estimates f_{0i} (left) and f_{GWi} (right) for the three tests (i=1,2,3) as a function of $\tau - \Delta\tau$ (figures extracted from reference [2])

4. CONCLUSIONS

This paper presents a TRNSYS tool to obtain the grout and ground thermal properties thanks to the use of an accurate dynamic BHE model, like the B2G model, together with an optimization procedure in order to find the best combination of conductivities that fit the experimental results with the highest accuracy and in a much shorter testing time (up to 70 % lower compared to compared to other similar approaches existing in the reviewed literature) without the necessity of a constant heat injection. This short duration of the TRT needed, would allow the operator carrying out a TRT in only one day, with a consequent cost reduction and increasing its feasibility in small and medium installations. In addition, a methodology to include underground water effects in TRT data analysis is presented, illustrating its capability to estimate the effect on a real case.

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