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# Constant-temperature thermal response test (TRT) with both heat injection and extraction for ground source heat pump systems: Methodology and a case study

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**Abstract**

An accurate estimate of site-specific underground thermal properties from thermal response tests (TRTs) is vital to the efficient and sustainable use of ground source heat pump (GSHP) systems. During a conventional TRT, the ground is perturbed by a heat injection and the response is measured in time. Despite the simplicity of the concept, conventional TRT fails to take into account the ground thermal response to heat extraction, which may affect the reliability of the thermal properties derived. To address the problem, an improved TRT based on both heat injection and extraction was proposed in this study. The improvements were demonstrated with an in-situ test carried out in Taiyuan, China. The measurement results showed that the ground thermal conductivity in Taiyuan was 1.56 W/(m K) and the borehole thermal resistance was 0.22 (m K)/W. The results also showed that, in the case of Taiyuan, ground thermal conductivities derived solely from heat injection test and heat extraction test were, respectively, 7.6% higher and 8.3% lower than that from the improved TRT. Thus, compared with the conventional TRT, the improved TRT consisting of both heat injection and extraction tests can provide test data more accurately reflect the annual performance of GSHP systems.



*Keywords:* analytical model; borehole heat exchanger; ground source heat pump system; ground thermal conductivity; in-situ test; thermal response test

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## 1. Introduction

Ground source heat pumps (GSHPs) take advantage of the moderate temperature of the earth to provide efficient heating and cooling for buildings [1]. In a GSHP system, thermal energy is transferred from/to the ground by circulating a heat transfer fluid in borehole heat exchangers (BHEs). A BHE typically consists of a high-density polyethylene U-tube buried vertically in a borehole of 20 to 300 m in depth that is backfilled with a grout mixture.

Site-specific ground thermal conductivity is among the key parameters that characterize the thermal performance of BHEs and thus is an essential basis for BHEs design and sizing. Several laboratory and in-situ methods are available to determine the ground property, among which in-situ thermal response test (TRT) is the most popular since it can take into account the actual borehole characteristics and provide estimates that are representative for the entire borehole length. Owing to the advantages, TRT has now become a routine practice in European, North American and Asian countries prior to the final design of a large installation.

Since the concept of TRT was first proposed in 1983, a large volume of research works have been published in order to improve its estimation accuracy. Previous works can be categorized as: determination of proper test duration; measures to lower test uncertainties; modelling of heat transfer phenomenon; and sensitivity analysis of derived estimates. Its popularity also leads to the publication of relevant guidelines that provide the recommended test procedures of a TRT.

Despite the research efforts, it is noted that the methodology of TRT has remained unchanged in the past decades. During a conventional TRT, a heat transfer fluid flowing in a BHE is heated with a constant rate (usually by using electrical resistance) to provide a positive heating pulse that perturbs the ground initially at equilibrium. The resulting ground thermal response is evaluated by way of monitoring the evolution of the mean temperature of the fluid at inlet and outlet of the BHE. Then, inverse method, based on an analytical or numerical solution to the heat conduction problem, is applied to the temperature data to find the ground thermal conductivity.

Though GSHPs operate in both heat injection (in the summer) and extraction (in the winter) modes, conventional TRTs consider only the ground thermal response to positive heating pulses. An assumption behind the methodology is that the heat transfer in the ground is governed by conduction only, in which case the conductivity estimates derived from heat injection and extraction tests should be identical. However, this may not be true in practice. Witte [2] carried out a series of TRTs in Wales, UK, and found that, for the same borehole, the conductivity estimates resulting from heat injection were 10% to 15% higher than those from heat extraction. It is because, during a TRT, heat injection creates a temperature gradient in and around the borehole. This leads to density differences in the underground moisture and thus a density-driven convective flow in induced. The flow enhances the underground heat transfer and results in higher conductivity estimates. In the context, the conventional TRTs can be improved by incorporating both heating and cooling pulses to the ground to ensure a better understanding of the BHE thermal performance. With this approach, it is also easier to see if a BHE is influenced by the convective flow.

The presence of the convective flow leads to another concern that the conductivity estimates may vary depending on the heat injection rate adopted in conventional TRTs. It is expected that a higher injection rate may result in larger heat convection and thus a higher effective ground thermal conductivity. A TRT performed with a certain injection rate therefore captures only the heat transport characteristics for that circumstance. This brings us to the question of how to determine the injection rate for a specific GSHP application. In this regard, it is reasonable to take it as the expected peak load on the BHE for an actual system, but the information is often missing prior to a detailed planning of the borehole field. Accordingly, the injection rate is often chosen arbitrarily within the range of 30 to 80 W/m of borehole as a rule-of-thumb in practice since there is no prescribed guideline for the heating rate. This obviously brings uncertainty to the TRT estimates. In the context, a constant-temperature TRT that performs heat injection or extraction at fixed inlet temperature to the BHE (e.g. 35 $^{o}$C and 6 $^{o}$C) to represent the heat transfer conditions prevailing when a GSHP is in operation may be preferable.

To overcome the limitations, this study proposes a constant-temperature TRT with both heat injection and extraction to determine the ground thermal conductivity and to examine the influence of the natural convection on the BHE heat transport. To this end, a new TRT test rig featured by its ability to maintain a fixed inlet temperature to the BHE and enable conducting heat injection and extraction tests simultaneously is proposed. The current research also presents a data analysis method compatible with the new TRT concept. Finally, an in-situ test carried out in Taiyuan, China, is outlined to demonstrate the effectiveness of the proposed TRT.

## 2. Test and analysis methodologies

### *2.1. Test rig*

To allow testing with both heat injection and extraction, a heat pump is used instead of electrical resistance to provide heating and cooling pulses to the ground. The schematic of the proposed test rig is shown in Fig. 1. It mainly consists of a water-to-water heat pump, two circulating pumps, two gate valves, two buffer tanks, and two tank-immersed electrical resistances. The heat pump comprises a variable speed scroll-type compressor, an electronic expansion valve, and two heat exchanger coils. The TRT is performed by connecting a BHE to each of the tanks, in which the fluid (i.e. water) is heated or cooled by the heat pump. The electrical resistances are employed to maintain a constant temperature in each tank. This is realized with a computerized monitoring program that is capable of reading real-time water temperatures from the sensors located in the tanks and, on this basis, providing on-line adjustments to the outputs of the electrical resistances.

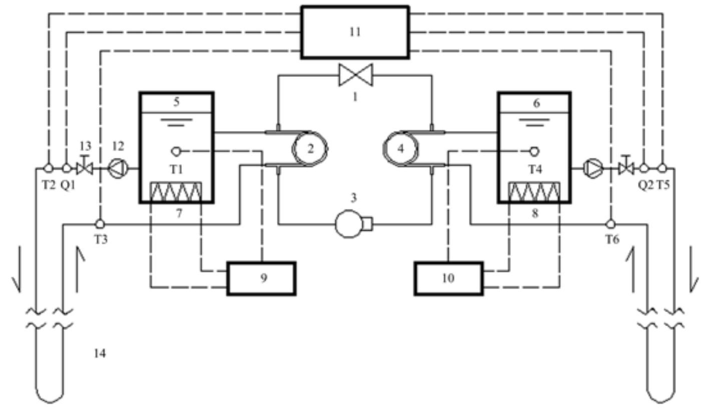


Fig. 1. Schematic of the proposed test rig (1: expansion valve; 2: evaporator; 3: compressor; 4: condenser; 5-6: water tank; 7-8: electrical resistance; 9-10: PID controller; 11: data logger; 12: circulating pump; 13: gate valve; 14: BHE; T1-T6: thermocouple; Q1-Q2: flow meter)

In the context of this study, thermocouples (Type K) were used to measure the water temperatures inlet to and outlet from the BHEs. To guarantee the reliability of the measurements, the thermocouples used were pre-calibrated in a constant temperature bath to have an accuracy of ±0.1 $^{o}$C. Two turbine flow meters with an accuracy of ±0.01 $m^3$/h were used to measure the water flow rates through the BHEs.

### *2.2. Test data analysis*

#### *2.2.1. Line source model*

Many analytical models are available for deriving the ground thermal conductivity from test data. Among these models, the infinite line source model is the most widely used because of its simple form and convenience for application. However, as the model relies on the assumption that the borehole is of infinite depth, which is obviously not the case in practice, finite line source model is used in this study to evaluate the ground thermal response. According to Zeng et al. [3], the temperature distribution around a finite depth borehole can be written as:

$$T\left(r,z,t\right)=T_0+\frac{q}{4\pi k_s}\int_0^H\left[\frac{\operatorname{erfc}\left(r^+/\sqrt{4\alpha t}\right)}{r^+}-\frac{\operatorname{erfc}\left(r^-/\sqrt{4\alpha t}\right)}{r^-}\right]ds \tag{1}$$

$$r^+=\sqrt{r^2+\left(z-s\right)^2},r^-=\sqrt{r^2+\left(z+s\right)^2} \tag{2}$$

where $r$ is the radial coordinate (m); $z$ is the axial coordinate (m); $t$ is the time (s); $T_0$ is the undisturbed ground temperature ($^oC$); $q$ is the heat transfer rate per unit depth of borehole (W/m); $k_s$ is the ground thermal conductivity (W/(m K)); $H$ is the borehole depth (m); $\alpha$ is the thermal diffusivity ($m^2/s$).

On the basis of Equation (1), the characteristic temperature of the borehole wall, $T_b(t)$, can be determined by taking the radial coordinate, $r$, as the borehole radius. Then by reference to the "$g$-function" proposed by Eskilson [4], the expression for $T_b(t)$ can be simplified as:

$$T_b\left(t\right) = T_0 + \frac{q}{2\pi k_s} g\left(t^*, \beta\right) \tag{3}$$

where $t^*=t/t_s$, $t_s=H^2/9\alpha$, $\beta=r_b/H$; $r_b$ is the borehole radius (m).

As indicated in Equation (3), the $g$-function is essentially a dimensionless temperature response factor, which can be determined analytically by:

$$g\left(t^*, \beta\right) = \int_{\beta}^{\sqrt{\beta^2+1}} \frac{\operatorname{erfc}\left(\gamma z\right)}{\sqrt{z^2-\beta^2}} dz - \int_{\sqrt{\beta^2+1}}^{\sqrt{\beta^2+4}} \frac{\operatorname{erfc}\left(\gamma z\right)}{\sqrt{z^2-\beta^2}} dz - D_A - D_B \tag{4}$$

where $D_A$ and $D_B$ are integrals of the complementary error function defined by Lamarche and Beauchamp [5].

### *2.2.2. Borehole thermal resistance*

Thermal resistance within the borehole (i.e. borehole thermal resistance) is another parameter that should be evaluated prior to the determination of the ground thermal conductivity. The resistance applies between the fluid in the U-tube and the borehole wall. Therefore, it depends on both the thermal properties of the borehole components, including U-tube and grout mixture, as well as on the physical arrangement of the U-tube in the borehole. A range of methods have been proposed to evaluate the resistance. Among them, the multipole method is a state-of-the-art method to compute borehole thermal resistance. It is derived from a two-dimensional analysis of the quasi-steady-state heat transfer within a borehole using a combination of line sources and multipoles. Javed and Spitler recently compared a number of methods for computing the borehole thermal resistance and found that the multipole method yields the most accurate results under all investigated scenarios. The method is also used in this study. Expressions for this method are rather long. To avoid duplications, they are not repeated here. Readers can refer to previous works.

### *2.2.3. Ground thermal conductivity*

On the basis of above analysis, and by reference to Equation (3), the heat transfer rate per unit depth of borehole, $q$, can be expressed as:

$$q = \frac{2\pi k_s}{g + 2\pi k_s R_b} \Delta T_p \tag{5}$$

where $R_b$ is the borehole thermal resistance ((m K)/W); $g$ is the analytical $g$-function; $\Delta T_p$ is the "$p$-linear average" temperature of circulating fluid with respect to the disturbed ground temperature ($^oC$).

As shown in Equation (5), theoretically, the relationship between $\Delta T_p$ and $q$ should be linear. On this basis, a series of tests can be carried out with different $\Delta T_p$ and $q$ (positive and negative) to constitute a complete TRT. For $\Delta T_p$, it can be determined from the measurements of inlet and outlet fluid temperatures. Once the slope of the line, $S$, obtained by linear fitting of $\Delta T_p$ and $q$, is determined, the ground thermal conductivity can also be evaluated by using Equation (5).

## 3. In-situ test

Based on the improved TRT, an in-situ test was carried out in Taiyuan, China. Two boreholes of 200 mm diameter and 100 m depth were drilled. The boreholes were separated by 2 m to avoid thermal interference between them during test.

The test began five days after the backfilling was done. Before switching on the heat pump and the electrical resistances, the undisturbed ground temperature was first measured by circulating the fluid in the two BHEs and recording the inlet and outlet temperatures at 10 s intervals. This process lasted for 30 min. It was found that the inlet and outlet temperatures tend to be stable at 16.1 °C after about 25 min. Therefore, in this case, the undisturbed ground temperature was measured to be 16.1 °C.

Once the undisturbed ground temperature was determined, the heat pump and the electrical resistances were switched on. Note that the test rig has the ability to maintain a constant inlet fluid temperature to the borehole and enable conducting heat injection and extraction tests simultaneously. The TRT described could therefore be divided into two stages. The measurement methods were similar for both stages. The only difference was that, in the first stage, the inlet fluid temperatures were set as 35 °C for the heat injection test and 6 °C for the heat extraction test, while in the second stage, inlet fluid temperatures were set as 30 °C and 8 °C, respectively. As for the flow rate of the circulating fluid, it was maintained nearly constant at 0.215 kg/s for both stages.

The recorded inlet and outlet temperatures ($T_{in}$ and $T_{out}$) and the obtained $q$ of the two BHEs are shown in Fig. 2. As can be seen, $T_{out}$ and $q$ tend to be stable after about 20 h. This is due to the heat transfer entered a steady state regime where the temperature difference between inlet and outlet fluid was kept constant and all of the heating (or cooling) load provided by the test rig was dispersed in the surrounding ground.

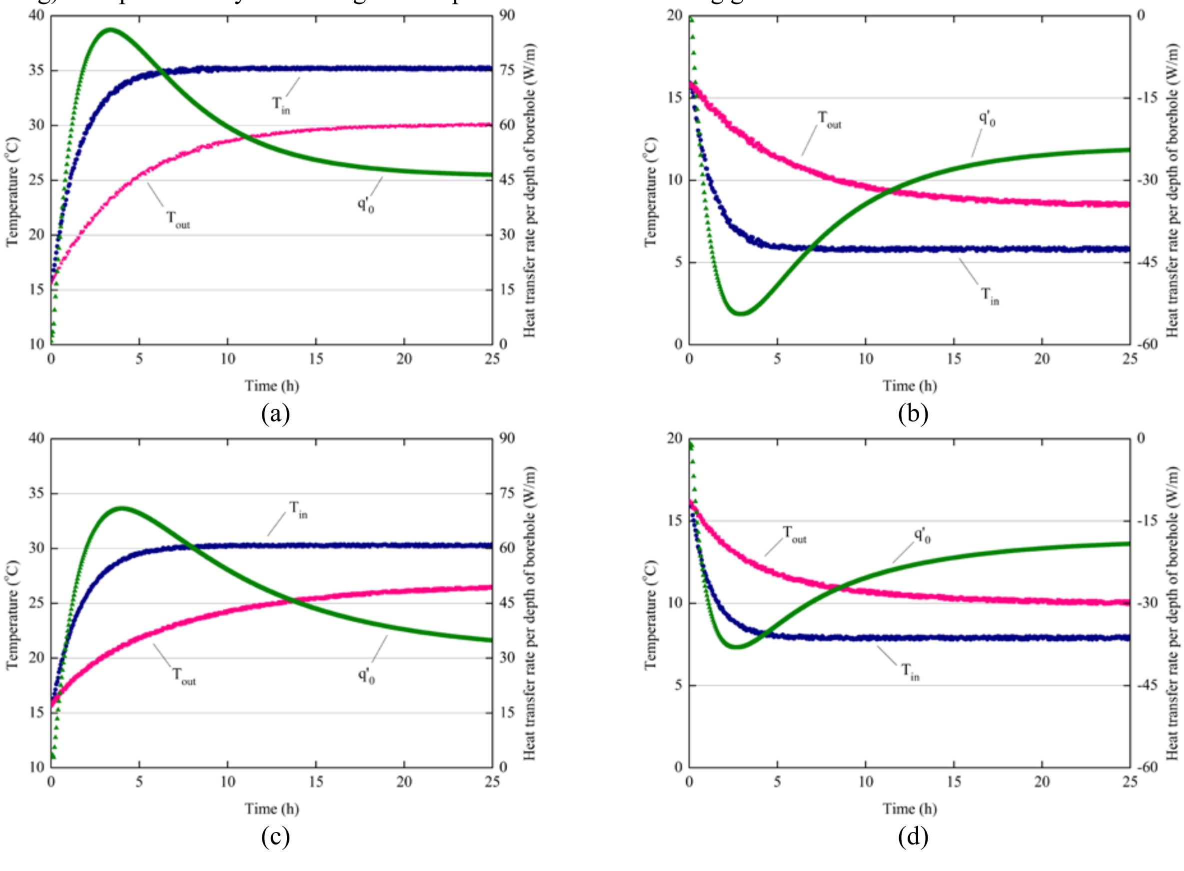


Fig. 2. Test results: (a) Heat injection test (inlet fluid temperature: 35.2 °C); (b) Heat extraction test (inlet fluid temperature: 5.7 °C); (c) Heat injection test (inlet fluid temperature: 30.3 °C); (d) Heat extraction test (inlet fluid temperature: 7.9 °C)

Fig. 3 shows the variation of $q$ with $T_p$. It can be seen that the relationship between these two parameters is approximately linear. This is consistent with the analysis in Section 2.2.4. By linear fitting using the Least Square Method (LSM), the slope of the line, $S$, was found to be 2.82. Therefore, the ground thermal conductivity could be obtained by using Equation (5). In the case of Taiyuan, the ground thermal conductivity determined from this TRT was 1.56 W/(m K), with the $g$-function and borehole thermal resistance being 1.32 and 0.22 (m K)/W, respectively.

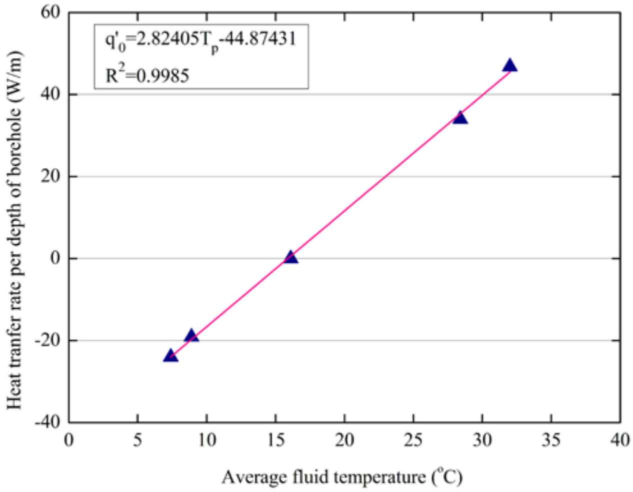


Fig. 3. Variation of the heat transfer rate with average fluid temperature

On the other hand, if only heat injection or extraction test was conducted, the slopes resulting from linear fitting were found to be 2.90 and 2.72, respectively. The derived ground thermal conductivities would thus be 1.68 W/(m K) and 1.43 W/(m K), respectively, which were 7.6% higher and 8.3% lower than that determined from the improved TRT. The analysis highlights the necessity of including both heat injection and extraction tests in a TRT to avoid mode-biased estimation and to provide test data more accurately reflect the annual performance of BHEs.

## 4. Conclusions

In this study, an improved TRT, together with a new test rig configuration and associated data analysis method, was proposed. The improved TRT was featured by its ability to maintain a constant inlet fluid temperature to the borehole and enable conducting heat injection and extraction tests simultaneously. On this basis, an in-situ test was carried out in Taiyuan, China. Significant difference was found between ground thermal conductivities obtained from heat injection and extraction tests. For the borehole under test, the value derived based on heat injection was 1.68 W/(m K), and that based on heat extraction was 1.43 W/(m K). Compared with the conventional TRT, the improved TRT can provide test data better reflect the annual performance of BHEs and, on this basis, enable a more accurate estimate of underground thermal properties, which is vital to the design of GSHP systems.

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