Experimental investigation on the influencing factors of the thermal response test using actively heated fiber optics

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Abstract. Shallow geothermal energy has received extensive attention as renewable energy for sustainable development in the last few decades. Thermal conductivity, usually estimated in-situ by thermal response test (TRT), is a key parameter for evaluating shallow geothermal energy resources and designing boreholes heat exchanges. However, it is still challenging to collect accurate data about strata thermal conductivity. With the application of copper mesh heated optical cable, actively heated fiber (CMCH), optics based thermal response test (ATRT) offers the possibility of fast and accurate in-situ estimation of thermal conductivity. However, the heat transfer process of ATRT is different from the traditional TRT and there is no standardized ATRT method yet. In this study, the influences of heating duration, heating power and recover time were studied using a physical model box. The results indicate that: (1) A more accurate calculated thermal conductivity requires a longer heating duration, considering the costs and errors, the heating duration is recommended to be in the range of 90~400 minutes. (2) The heating power has no significant effect on the calculated thermal conductivity but 15~40 W·m⁻¹ is recommended considering the measurement accuracy of DTS equipment. (3) If ATRT was interrupted, there should be a recover time longer than 24 hours before the following ATRT to avoid the interference of the previous test.

1. Introduction
Shallow geothermal energy has received more and more attention as renewable energy in the last few decades and it is mainly developed by ground source heat pump system (GSHP) [1-3]. The thermal conductivity of underground soil is one of the main parameters for evaluating shallow geothermal energy resources and designing GSHP[4-6]. If the relative error of the soil thermal conductivity is 10%, the deviation in the borehole heat exchanger (BHE) design length can reach up to 4.5~5.8%[7], which increases construction costs and deprives its economic advantage of GSHP. Therefore, it is important to accurately evaluate the thermal conductivity in the process of developing and utilizing shallow geothermal energy.

The thermal response test, proposed by Mogensen for the first time, is the most commonly used method to obtain the thermal conductivity of underground soil or rock[8]. In TRTs, a constant heating or cooling load is applied to the vertical BHE that is installed in a borehole, and the temperature at the inlet and outlet of BHE and flow rate of the working fluid are measured. Using the simplified infinite line source theory, soil thermal conductivity and borehole thermal resistance are simultaneously deduced [6, 9, 10], but they are average values ignoring any variation along the borehole. When applying conventional thermal response tests, the optimum design of the BHE is difficult to determine since the only average thermal conductivity of the underground soil is estimated[11]. In order to obtain the thermal conductivities of different strata along the borehole, temperature sensors are installed inside or on the outer wall of the BHE to measure temperature variation at different depths[12]. With the development of the distributed temperature sensing (DTS) technique using optical fibers, the temperature variation along a fiber can be measured during the TRT. Based on this so-called distributed thermal response test
(DTRT), the vertical trend of thermal conductivity in the borehole can be determined[11, 13]. Both TRT and DTRT are based on circulating a warmed heat carrier fluid in the pipes for a long time, although different researchers have different recommended values for the duration of the thermal response test, most are longer than 12 hours[14-17]. In addition, the researchers suggest a new method, in which the optical fibre cable is actively heated, and the warmed heat carrier fluid is replaced by heating wires[18, 19]. It should be noted that ATRT is sometimes categorized as enhanced thermal response test (ETRT) or enhanced geothermal response test (EGRT)[20, 21]. Recently, Zhang et al. [22] placed a specially designed copper mesh heated optical cables inside a U-pipe of the borehole for thermal response test, and evaluated a reliable thermal conductivity distribution along the borehole but with lower energy cost and a shorter test duration. ATRT has great potential in obtaining the thermal conductivity of the strata[19, 23], but there is no standardized method yet.

The key to the field implementation of TRT, DTRT or ATRT is to determine appropriate test parameters, such as heating duration and heating power. Several studies were made to evaluate the influence of different factors through numerical simulations, laboratory tests and field tests. Wagner et al. [24] studied the center distance between the inlet and the outlet tube, and the initial temperature distribution of the soil, with the help of finite element software FEFLOW, finding that both parameters could produce a 10% error in soil thermal conductivity. Richard et al. [4] constructed a large laboratory sandbox containing a borehole with a U-tube and implement TRT under more controlled conditions, which provided reference data sets for verifying borehole models and TRT analysis procedures. Zhou et al. [25] examined the determination principle of the heating power and the influence of heating power and test time on the test results through a TRT platform. Lee et al. [26] implemented a series of field thermal response experiments to analysis the effects of backfill material as well as heat exchanger tube arrangement. However, these conclusions cannot apply to ATRT due to the differences between ATRT and TRT. The diameter of copper mesh heated optical cables (CMHC) used in ATRT is 5 mm, which is about 1/10 of the conventional BHE[27]. Under such circumstance, the relationship between the line heat source, the grout, and the soil need to be reconsidered, and the influences of heating duration, heating power, the radius of borehole and grout need to be clarified, but there are still no clear conclusions.

In this paper, a physical model box for ATRT is prepared and a series of thermal response tests by controlling different test conditions were conducted. The influences of heating duration, heating power and recovery time were investigated to obtain recommended test parameters for ATRT.

2. Theory

2.1 ATRT model

ATRT system consists of a DTS demodulator, a power unit, grout, and a copper mesh heated optical cable (heating cable), as seen in Figure 1. The heating cable is installed in the center of borehole with a guide, and the borehole is filled with grout. The DTS demodulator connects to optical fiber of the heating cable and obtains temperature information. The power unit, usually a generator or electrified wire netting, connects to the copper mesh of heating power and provides energy for heating.

2.2 Linear heat source model

Kelvin’s line source theory is often used to evaluate a TRT, and also can be used in an ATRT. According to Kelvin’s line source theory, the BHE or heating cable is approximated as an infinite line source in a homogeneous, isotropic, initially at thermal equilibrium, and infinite medium, which injects or extracts a constant amount of energy (Q). The temperature response $\Delta T(\Delta T=T_0-T)$ is given by:

$$\Delta T = T(r,t) - T_0 = \frac{Q}{4\pi \lambda L} \int_{r^2/4\lambda t}^{\infty} \frac{e^{-s}}{S} dS = \frac{Q}{4\pi \lambda L} \left[ E_i \left( -\frac{r^2}{4\lambda t} \right) \right]$$

And $S$ a change of variable:

$$S = \frac{r^2}{4\lambda t}$$
Where $T(r, t)$ is the temperature at a time of $t$ and a radius of $r$. $T_0$ is the initial temperature of soil; $Q$ is heat exchange capacity; $\alpha$ is the thermal diffusivity of soil; $L$ is heat exchange length; $\lambda$ is the thermal conductivity of soils.

Equation (1) can be simplified by the Jacob approximation if $t$ is sufficiently large or $r$ is very small, i.e. if $r^2/4D_t t<<L$. There is a linear relationship between the temperature rise and the logarithm of time, and the slope is used to calculate the thermal conductivity of the soil. The relevant formula can be expressed as:

$$T - T_0 = k \cdot \ln t = \frac{Q}{4\pi\lambda L} \ln t$$

(3)

where: $k$ is the slope of curve $T$-$\ln t$, and can be graphically determined by curve fitting and minimizing the root mean squared error (RMSE). $q$ is heat exchange per unit length which equals heating power.

According to equation (3), thermal conductivity $\lambda$ can be obtained by:

$$\lambda = \frac{q}{4\pi k}$$

(4)

Using Kelvin’s line source theory, the thermal conductivity can be calculated by measuring the temperature rise of heating cable during ATRT, as shown in Figure 1(c).

![Figure 1. Schematic diagram of ATRT system. (a): DTS and Power unit, (b): Structure of CMHC, (c): Cross section and temperature rise of heating cable.](image)

### 3. Setup of physical model box

Physical model box experiments were conducted in a plexiglass cylinder (0.43 m in radius and 1.8 m in height) where ATRT can be well-controlled. Figure 2 shows the internal structure of the plexiglass cylinder, a 6-mm-diameter copper mesh heated optical cable is applied vertically in the center of the box, the soil is quartz sand with a diameter of 0.1-1 mm, the grout is a mixture of quartz sand and kaolin with a mass ratio of 1 to 3. The thermal conductivity and other physical properties of grout and soil were determined by the laboratory and shown in Table 1. In order to verify the DTS temperature test results, 12 PT100 temperature probes were placed in different positions inside the plexiglass cylinder.
Figure 2. Experimental setup showing the dimensions of the plexiglass cylinder and the deployment of the equipment.

Table 1. Model parameters

|                        | Cable  | Grout  | Soil   |
|------------------------|--------|--------|--------|
| Radius(cm)             | 0.3    | 6      | 100    |
| Thermal conductivity (W·m⁻¹·K⁻¹) | 0.2 (Jacket) | 2.814 | 1.974 |
| Density(kg·m⁻³)        | /      | 2600   | 1560   |
| Heat capacity(kJ·kg⁻¹·K⁻¹) | /      | 1.031  | 0.842  |

4. Results and effects

4.1 Heating duration

In order to study the effect of heating duration, an experiment was conducted with a heating power of 40 W·m⁻¹ and a heating duration of 180 minutes. When the heating duration is 180 minutes, the thermal disturbance reaches the boundary of the plexiglass cylinder. The curves of temperature rise and calculated thermal conductivity using line heat source are given in Figure 3.
Figure 3. Temperature rise and calculated thermal conductivities with increasing of heating duration.

The red curve in Figure 3 shows the temperature rise of the heating cable. The irregular fluctuation of the temperature rise curve comes from the temperature measurement error of DTS. In the initial stage, the temperature of heating cable rises rapidly. After heating 150 s, the temperature of heating cable increases by 10.06 °C. Because, most of the heat generated by heating cable is absorbed by itself, resulting in a rapid increase in temperature. In 2000~10000 s, the temperature rises increased from 14.12 °C to 16.88 °C. With the increase of heating duration, most of the heat diffuses to grout and soil through thermal conduction, therefore the temperature of heating cable continues to increase but the growth rate gradually decreases.

The black curve in Figure 3 shows the calculated thermal conductivity using line source theory. In the initial stage, the calculated thermal conductivity increased rapidly and fluctuated with large amplitude. With the increase of heating duration, the calculated thermal conductivity gradually decreased and tended to be stable. When the heating duration is 10000 s, the calculated thermal conductivity is 1.99 W·m⁻¹·K⁻¹ with an error of 0.98%. The increase in calculated thermal conductivity in the initial stage of heating reflects the process of heat diffusion from heating cable to the grout and soil. Due to the existence of grout, the calculated thermal conductivity is greater than the thermal conductivity of the soil. Because the heating duration is shorter and the acquired temperature data is less, small temperature data changes will cause larger fluctuations in calculated thermal conductivity. The influence of the grout gradually decreases as enough heat is transferred to the surrounding soil. So, the thermal conductivity gradually decreases and approaches the thermal conductivity of soils.

If the heating duration is short, the grout and DTS measurement error have a greater impact on the calculated thermal conductivity. In order to improve the test accuracy, the heating duration should be no less than 90 minutes and be extended appropriately. So, the recommended range of heating duration is 90~400 minutes.

4.2 Heating power

A series of experiments were conducted with a heating duration of 180 minutes and heating power of 20, 25, 30, 35, 40 W·m⁻¹ respectively. Figure 4 shows the temperature rise under different heating powers. The calculated thermal conductivity and its distribution in 2000~10000 s are shown in Figure 5.

According to Figure 4, the temperature rise curves under different heating powers are similar, and the temperature rise at the same time increases with the increase of heating power. There is a maximum difference of 12% between calculated thermal conductivities under different heating power, and a maximum error of 7% with the laboratory measured value under different heating power. When heating
power is increased to 30–40 W·m⁻¹, the maximum difference between the calculated thermal conductivities is 4% and the maximum error with the laboratory measured value is 3%. There is no obvious linear or functional relationship between the calculated thermal conductivity under different heating power. In order to further analysis, the relationship between the heating power and the calculated thermal conductivity, the temperature rise caused by the same power (10 W·m⁻¹) under different heating powers are shown in Figure 6. According to Figure 6, the curves are coincident and have the same slope, which means that the same thermal conductivity can be obtained using the linear heat source model. So, the heating power has no significant effect on the calculated thermal conductivity.

![Figure 4](image1.png)

**Figure 4.** Temperature rises with increase of heating duration under different heating power.

![Figure 5](image2.png)

**Figure 5.** Calculated thermal conductivity with increasing of heating duration under different heating power.

It should be noted that measurement accuracy of DTS is not taken into consideration in above conclusions. According to line heat source theory and principle of error transfer, the maximum error caused by DTS equipment temperature measurement accuracy and thermal conductivity calculation can be calculated as follows:
According to Equation (5), when the temperature measurement error is constant, the thermal conductivity calculation error mainly depends on the temperature rise. Using the temperature rise data, the theoretical distribution range of the calculated thermal conductivity error under different heating power was calculated. Figure 7 shows the calculated thermal conductivity, the theoretical error distribution range and the actual measurement error distribution range under different heating power. The distribution range of actual measurement error is consistent with the distribution range of theoretical error, and the distribution range of the error shows a shrinking trend with the increase of heating power. Higher heating power induces higher temperature rise, which reduces the influence of DTS measurement errors. In such case, the error of the calculated thermal conductivity will decrease with the increase of power.

\[
\text{Error}_{\text{max}} = \left| \frac{\lambda_{\text{ref}} \pm \lambda}{\lambda} \right| = \left| \frac{q \cdot \text{ln}\frac{t}{\Delta T + T_{\text{error}}}}{4\pi \cdot \Delta T} \pm \frac{q \cdot \text{ln}\frac{t}{\Delta T}}{4\pi \cdot \Delta T} \right| = \left| \frac{T_{\text{error}}}{\Delta T + T_{\text{error}}} \right| \tag{5}
\]

Figure 6. Temperature rise per power with increasing of heating duration under different heating power.

Figure 7. Thermal conductivity error distribution under different heating power.
The heating power has no significant effect on the calculated thermal conductivity, but increasing heating power can reduce measurement errors. According to the theoretical distribution range of the thermal conductivity calculation error, when the acceptable error range is 10%, it is recommended that the heating power be 15~40 W·m⁻¹ during field testing.

4.3 Recovery time

In the field, electrical power outages or other unexpected events may interrupt the tests. If the test restarted immediately after an interruption, the uniform temperature assumption is often invalid at the time of restart. There should be a recovery time between two heating tests. Also, two adjacent tests should not have too long recovery time considering the costs. Therefore, it is necessary to determine the influence of the recovery time.

For conventional TRT, the ASHERA manual suggests that the recovery time should be about 10~12d until the temperature is restored to the initial temperature with a difference of less than 0.3 °C. In order to determine a reasonable recovery time of ATRT, an experiment with two heating stages was conducted in the plexiglass sand column. The first heating stage is performed normally with a heating duration of 180 minutes. The seconds heating stage was performed with a heating duration of 180 minutes again, when the temperature of the heating cable returns to about 0.3 °C greater than the initial temperature. Figure 8 shows the temperature under different stages.

According to Figure 8, the temperature of the heating cable decreases rapidly after the heating is stopped. With the extension of the recovery time, the temperature of the heating cable gradually decreases and is greater than the initial temperature by about 0.3 °C when the heating is stopped for 120 minutes. In the second heating stage, the curve of temperature rise is similar to the first heating stage, and the temperature rise of the second stage is 6.75 °C, which is lower than the temperature stage of 8.58 °C in the first test. The temperature rises and calculated thermal conductivity in 2000~10000 s is shown in Figure 9. The calculated thermal conductivity of the first stage is 1.85 W·m⁻¹·K⁻¹, which is a 6.28% error from the laboratory measurement value. But the calculated thermal conductivity of the second stage is 2.79 W·m⁻¹·K⁻¹, which is a 41.33% error from the laboratory measurement value. This shows that before the thermal disturbance caused by the first test is fully recovered, the calculated thermal conductivity obtained by the parallel test again is not accurate.

![Figure 8](image)

**Figure 8.** Temperature with increasing heating duration under different tests.

ATRT has a much shorter recovery time (i.e. 2h) than conventional TRTs (i.e. 10~12d). It is because the heating cable has a thinner diameter (larger contact surface area with the soil) and lower heat capacity. If the heating stopped, the heat stored in the cable can be transmitted to the soil more quickly, showing a rapid temperature decrease in Figure 8. In the contrast, the temperature of the soil may not have fully restored when the temperature of the heating cable is restored to the initial temperature. The axial heat conduction in the soil where the thermal disturbance has not been fully recovered violates the assumptions of the linear heat source theory, resulting in a larger calculated value of thermal conductivity.
Performing ATRT tests again after an inadequate recovery time leads to a higher thermal conductivity. It is recommended that the recovery time should longer than 24 hours before the following ATRT.

5. Conclusion
In this study, the influences of heating duration, heating power and recovery time were studied using an ATRT physical model box. The results indicate that:
(1) A more accurate calculated thermal conductivity requires a longer heating duration, considering the costs and errors, the heating duration is recommended to be in the range of 90–400 minutes.
(2) The heating power has no significant effect on the calculated thermal conductivity but 15–40 W·m$^{-1}$ is recommended considering the measurement accuracy of DTS equipment.
(3) If ATRT was interrupted, there should be a recover time longer than 24 hours before the following ATRT to avoid the interference of the previous test.

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