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Determination and analysis of parameters for an in-situ thermal response test

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ABSTRACT

An in-situ thermal response test (TRT) is important for ground source heat pump (GSHP) systems. To obtain precise ground thermal properties, determining and controlling the TRT parameters are important. In this study, the determine principle of heating power was discussed for an in-situ TRT. The influence of test time and flow velocity on the test results was analysed. The results showed that the heating power has large influence on the heat transfer capacity and time to reach a quasi-stable state and little influence on the soil thermal conductivity. The suitable heating power is to ensure that when the water temperature is stable, the inlet temperature of the buried pipe meets the outlet temperature of the heat pump unit, usually 35 °C. When the heating power was increased by 15.70% and decreased by 16.18%, the heat transfer capacity increased by 17.10% and decreased by 14.64%, the time to reach a quasi-stable state increased by 29.16% and decreased by 8.33%, and the soil thermal conductivity had relative errors of 4.17% and 2.98%, respectively. If a heating power is selected accurately, the quasi-stable state can be reached within a test time of 24 h; extending the test time had no significant effect on the test accuracy. A flow velocity of 0.4–0.6 m/s in pipe is recommended for in-situ TRT.

1. Introduction

Ground source heat pump systems have become widely used in recent years because they reduce energy consumption and protect the environment. The underground soil thermal properties are important parameters for the design of a borehole heat exchanger (BHE). If the relative error of the soil thermal conductivity is 10%, the deviation in the BHE design length can reach up to 4.5–5.8% [1]. If the design length of the BHE exceeds the required length by 10–33%, the GSHP loses its economic advantage [2]. Therefore, precise measurement of the soil thermal properties is important.

The thermal response test (TRT) is widely recognized as the most effective method for measuring soil thermal conductivity [3,4]. This approach was first proposed by Morgenson in 1983 and then widely introduced in countries developing geothermal energy. During a TRT, water is constantly heated by an electrical heater or heat pump. A circulating pump is needed to drive the water to circulate in the BHE and release heat to the ambient grout and soil. The inlet and outlet water temperatures and the flow rate are measured. Based on the measured results, the soil thermal conductivity can be calculated through parameter identification methods [5].

In the TRT process, the electrical heater power affects the accuracy of the test results. Many researchers have studied the influence of the heating power on TRT results through experiments [6–10]. Their results showed that the heating power exerts a large effect on the heat transfer capacity, but a small effect on the soil thermal conductivity. Zhou [9] found that increasing the input fluid temperature of the BHE from 37 °C to 43 °C increased the heat transfer capacity by 36.8%. Yu discovered that increasing the heating power by 1.3 times increased the soil thermal conductivity by only 2.5%[10]. Especially under geological conditions with groundwater seepage, the effect on the heat transfer capacity is more significant.

These results indicate that the heating power affects the test results. Therefore, the heating power should be injected accurately during an in-situ TRT. However, the different geological conditions, buried depth of the pipe, and forms of buried pipe mean that the heating power and determination principle should be considered for each specific thermal response test project.

The flow velocity of the fluid inside the pipe is also an important parameter. It is related to the heat transfer coefficient inside the pipe, the flow resistance and the number of buried pipes. Many scholars have studied the influence of the flow velocity on the soil thermal properties [11–14]. Zhou [9] showed that the flow velocity

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Nomenclature

T_0	initial temperature of the soil [K]
T_f	average fluid temperature of the circulation fluid [K]
T_{in}	inlet temperature in pipe [K]
T_{out}	outlet temperature in pipe [K]
Q	heating power [W]
q	heat transfer capacity per unit borehole depth [W/m]
L	borehole depth [m]
k	slope of fitting line
R_b	borehole resistance [K/(W/m)]
h	mass-transfer coefficient [W/m^2 K]
Nu_f	Nusselt number
Re	Reynolds number
Pr	Prandtl number
λ_s	thermal conductivity of soil [W/(m K)]
λ_f	thermal conductivity of fluid [W/(m K)]
γ	Euler constant 0.5772
r_b	diameter of the borehole [m]
c_f	specific heat of fluid [kJ/kg K]
m	mass flux of the fluid [kg/s]
α	thermal diffusion [m^2/s]
d_i	interior diameter of pipe [m]
u	velocity of fluid [m/s]
ν_f	kinematic viscosity of fluid [m^2/s]
ρ_f	density of fluid [kg/m^3]
τ	time [s]

has a little effect on the soil thermal conductivity when the fluid is in turbulent flow. Fu [11] found that the velocity has a greater effect on the fluid temperature than on the thermal conductivity. Wang [14] simulated a heat exchange with the TRNSYS simulation program and found that the heat transfer capacity is significantly enhanced when the velocity is greater than 0.6 m/s.

Many organizations have put forward different requirements for the TRT time to obtain accurate test results. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [15], the test time should be at least 36–48 h. According to the International Energy Agency (IEA) [16–18], the test time should be more than 50 h. According to GB 50366-2009 specification in China [19], a test should be run for at least 48 h. Some researchers have studied the required test time to reach a quasi-steady state. Gao [20] found that it took 100 h for the TRT process to become stable. Zhao et al. [21] concluded that it only took 50 h. Zhuang [22] also postulated that it takes a long time for the TRT to reach stability. Lhendup [23] performed an in-situ TRT in Melbourne and found that the thermal conductivity was relatively constant after 70 h. Obviously, different test times have been recommended by different organizations and researchers. Therefore, determining how to control the test time to obtain accurate results is worthy of consideration in order to save labor and economic costs during the TRT process. The test time depends on the geological conditions, heat transfer performance, and heating power [24].

Thus the results of a TRT vary with the test parameters. This study examined the determination principle of the heating power and the influence of an uncertain heating power on the test results by using a TRT platform located in Donghua University. The test time and flow velocity were also analysed for the in-situ TRT.

2. Analysis of main factors

The TRT principle of vertical buried pipes is mainly based on the Kelvin line-source model developed by Ingersoll and Plass in 1948. This study also used the line-source method. According to the literature [25–29], the average temperature of the circulation fluid can be written as

$$T_f = \frac{Q}{4\pi\lambda_s L}\ln\tau\left\{\frac{Q}{L}\left[\frac{1}{4\pi\lambda_s}\left(\ln\left(\frac{4\alpha}{{r_b}^2}\right)-r\right)-R_b\right]+T_0\right\} \tag{1}$$

If the heat transfer capacity per borehole depth $q = Q/L$ is constant, Eq. (1) becomes a simple linear relation:

$$T_f = k\ln\tau + b \tag{2}$$

$$k = \frac{q}{4\pi\lambda_s} \tag{3}$$

where T_f is the average of the inlet and outlet temperatures in the borehole (i.e. $T_f = (T_{in} + T_{out})/2$), k is the slope of the fitting line of the mean temperature, and b is a constant.

Therefore, if q and the curve of the average temperature of the circulating fluid at the inlet and outlet varying with logarithmic time can be tested in a buried pipe, the slope of the curve k can be obtained. Based on Eq. (3), the soil thermal conductivity can be calculated as follows:

$$\lambda_s = \frac{q}{4\pi k} \tag{4}$$

Based on the heat transfer theory, the heat transfer by a BHE is as follows:

$$q = \frac{mc_f(T_{in} - T_{out})}{L} \tag{5}$$

and

$$q = hA\Delta T \tag{6}$$

where ΔT is the heat transfer temperature difference between the pipe and fluid, h is the heat transfer coefficient of the fluid (W/(m K)), and A is the heat transfer area (m^2).

The relation between λ_s and q is given by

$$-\lambda_s\frac{\partial T}{\partial r}|_{r=r_b} = q \tag{7}$$

The circulating fluid in the pipe is driven by a circulation pump. The heat transfer coefficient in a fully developed turbulent flow along smooth tubes is calculated as follows [30]:

$$Nu_f = 0.023Re^{0.8}Pr^{0.3} \tag{8}$$

$$Nu = \frac{hd_i}{\lambda_f} \quad Re = \frac{ud_i}{\nu} \quad Pr = \frac{\nu}{\alpha} = \frac{uc_f}{\lambda_f}$$

for

$$\begin{aligned} &10^4 \le Re \le 12\times10^4 \\ &0.7 \le Pr \le 120 \\ &L/d_i > 60 \end{aligned} \tag{9}$$

where Nu, Re and Pr are the convection Nusselt number, Reynolds number and Prandtl number, respectively, of the fluid in the tube; d_i is the interior diameter of the pipe (m); L/d_i is the ratio of the length to the diameter; λ_f is the thermal conductivity of the fluid; c_f is the specific heat of the fluid; ν_f is the kinematic viscosity of the fluid; ρ_f is the density of the fluid; and u is the velocity of the fluid in the pipe.

Based on the above formula, Eq. (6) can be written as

$$q = 0.023\pi u^{0.8}{d_i}^{0.8}{\nu_f}^{-0.5}(\rho_f c_f)^{0.3}{\lambda_f}^{0.7}\Delta T \tag{10}$$

Based on Eqs. (4) and (10), the factors influencing the soil thermal conductivity can be expressed as follows:

$$\lambda_s \sim f(u^{0.8}, {d_i}^{0.8}, {\nu_f}^{-0.5}, (\rho_f c_f)^{0.3}, {\lambda_f}^{0.7}, \Delta T, k^{-1}) \tag{11}$$