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Thermal response test and numerical analysis based on two models for ground-source heat pump system

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ABSTRACT

Thermal response test (TRT) is becoming increasingly popular in obtaining the ground thermal properties as well as evaluating the performance of the ground heat exchanger (GHE) that determines the properties of ground source heat pump (GSHP) system. This study investigated a practical engineering project, which is located in Shijiazhuang, Hebei Province, as an example to test the ground thermal properties. A popular constant heating-flux method (CHFX) was used with the heat load of 3.6 kW and 8.4 kW, respectively. This investigation compared and analyzed the ground thermal properties by the line source model (LSM) and the cylinder source model (CSM). This study also conducted the sensitivity analysis on different data intervals by fixing starting time or ending time. Moreover, a new method (Bland–Altman analysis) was proposed to analyze and determine the agreement between simulated and experimental data. The results showed that the new method performed well in evaluating the agreement and could help to properly choose the test duration and data interval for thermal response test.

1. Introduction

Compared with conventional air-conditioning system, GSHP system has higher energy efficiency and lower environmental impact. Therefore, it is gaining increasing popularity for space heating and cooling in residential and commercial buildings [1,2]. The system mainly consists of a conventional heat pump coupled with a GHE, which is designed for the extraction or injection of thermal energy from/into the ground [3]. The storage capacity also depends on the energy balance. The peak capacity (highest specific extraction/injection rate) and coupled driving temperature difference (affecting performance of the system) is affected by borehole thermal resistance and thermal conductivity. Borehole thermal resistance is affected by the arrangement of flow channels and thermal properties of materials involved. The undisturbed ground temperature is necessary for a correct design of GSHP system [4]. Because the capacity of heat/cool exchange strongly depends on the thermal properties of the ground (thermal conductivity, borehole thermal resistance, heat capacity, undisturbed ground temperature and so on), it is very important to have knowledge of these properties when designing and optimizing GSHP air-conditioning system [5]. In situ thermal response test provides a very effective method to determine the ground thermal characteristics and to evaluate the performance of the GHE, which is the key of system optimization and further development of GSHP technology. Therefore, how to obtain accurate ground thermal characteristics is critical to study and explore.

Evaluation and analysis of the data gathered from in situ TRT is based on a conceptual model for the heat transfer processes occurring in the borehole and surrounding soil [4,6]. Many models like line source model [7], cylinder source model [8], Eskilson's model [9] and the later numerical model [10–12], can be used as the analysis methods. Several comparison studies of different evaluation models in analyzing the temperature response data have been done. Gehlin and Hellstrom [13] compared four different models (two models based on the line source theory, one model based on the cylinder source theory and a one-dimensional finite difference numerical model) for TRT evaluation. Signorelli et al. [14] studied the TRT using a 3D finite-element numerical model and compared its results with those of a simple analytical line source solution. Sass and Lehr [15] showed a quantitative approach to analyze TRT data with a non-steady state solution following the cylinder source approach. In addition, some researchers focused on performance prediction for GSHP system by applying numerous

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Nomenclature

c	volumetric heat capacity (J m^{-3} K^{-1})
$\bar{d}$	mean difference
d	standard error
E_i	exponential integral
F_0	Fourier number
G	G-function
H	effective borehole depth (m)
k	slope of the regression line
m	intercept of the regression line
n	sample size
p	dimensionless radius
q	heat transfer per unit length (W m^{-1})
Q	heat load (kW)
r	radial coordinate
R	thermal resistance (K W^{-1} m)
S	variance sum
S_d	standard deviation
t	time (s)
T	temperature (°C)
ΔT	temperature difference (°C)
T_0	undisturbed initial ground temperature (°C)
u	integral variable

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
γ	Euler's constant (0.5772)
λ	thermal conductivity (W m^{-1} K^{-1})

Subscripts

b	borehole
cal	the calculated value
exp	the experimental value
f	fluid
j	the time j
s	soil or ground
∞	infinite point

prediction models. Esen et al. [16–18] predicted GSHP system performance with the minimum data set using a fuzzy weighted pre-processing-based adaptive neuro-fuzzy inference system, a support vector machine method and neural networks with statistical data weighting pre-processing, respectively. But, an error analysis (Bland–Altman analysis) on a TRT under different test durations has rarely been found before.

The research of this paper was motivated by a desire to investigate the sensitivity of ground thermal properties on different data intervals by applying different analysis methods. Moreover, the potential of Bland–Altman analysis on a TRT was also explored. With this purpose, an in situ TRT was carried out in Shijiazhuang, China. CHFX was used with the heat loads of 3.6 kW and 8.4 kW respectively. The inlet and outlet fluid temperatures were recorded with time. A comparison of the line source and cylinder source models to analyze the in situ TRT and their sensitivity with respect to the duration tests were presented by applying the same temperature response data. The final estimated results showed that the selection of starting time was the key to evaluate the cylinder source model and the values of thermal conductivity estimated with the line source model were slightly lower than that of the cylinder source model. Bland–Altman analysis was developed to analyze the agreement between the experimental and simulated data based on the line source and cylinder source theories in different data intervals, and to determine and choose duration of test. According to the final results, Bland–Altman analysis did a good work on evaluating the agreement for TRT. In order to obtain a highly accurate TRT estimation, it can be used as a new method to properly select the test duration and data interval.

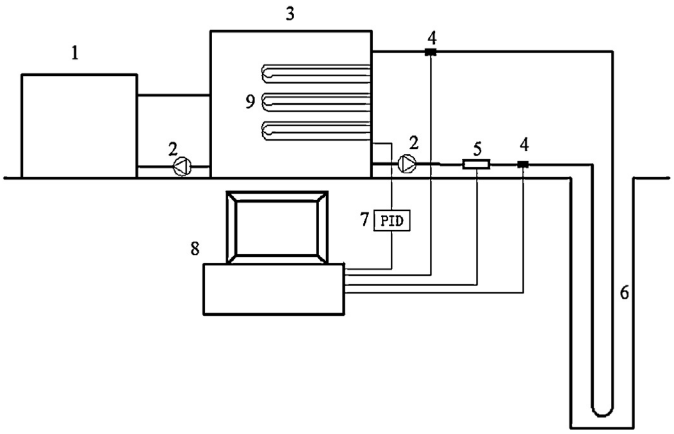

Fig. 1. Principle diagram of TRT equipment.

2. Experimental investigations

2.1. Experimental setup

2.1.1. Experimental apparatus

Principle diagram of TRT apparatus is shown in Fig. 1. The in situ equipment mainly consists of insulated water tank as well as inside coil heater, air-cooled refrigeration unit (with variable frequency), circulating pump, temperature sensors, data acquisition system, PID controller and GHE. There are six groups of electric resistance heaters in the insulated water tank. Three of them are stable with maximum heating power of 12 kW. The others are adjustable and are able to keep relatively constant water temperature combined with the PID controller on the operation panel. If lower water temperature is needed, air-cooled refrigeration unit using R-22 as refrigerant should be used. The insulated water tank can provide water at constant temperature between 4 °C and 45 °C. While in this case, we only adopted constant heating-flux method at 3.6 kW and 8.4 kW, without using the refrigeration unit. Two circulation pumps, one for the GHE loop and one for the refrigeration unit, are used. The water flow could be adjusted by a flow regulating valve. The inlet and outlet temperatures of the GHE were measured with Pt500-type temperature sensors. The measurement range and accuracy of the instruments are presented in Table 1. A data logger recorded the temperature and flow rate at interval of 1 min.

2.1.2. Measurement of the initial ground temperature

The initial ground temperature distribution is of great importance to the design of the GHE and evaluation of the TRT results. In the present work, the Pt100-type temperature sensors were embedded vertically in the ground along the GHE to measure

Table 1
The measurement range and accuracy of the instruments.

Instrument	Type	Range	Accuracy
Temperature sensors	Pt500-WZP type Pt100-WZP type	−50 to 260 °C −200 to 500 °C	$\pm(0.15+0.002\lvert t\rvert)$ °C $\pm(0.15+0.002\lvert t\rvert)$ °C
Flow meter	65-S type ultrasonic flow meter	0.03 to 6 m^3/h	2%