Energy and Buildings 48 (2012) 199–205

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A method and case study of thermal response test with unstable heat rate

Pingfang Hu[a,*], Qingfeng Meng[a], Qiming Sun[a], Na Zhu[a], Changsheng Guan[b]

[a] School of Environmental Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
[b] School of Engineering and Architecture, Wuhan University of Technology, Wuhan 430074, PR China

ARTICLE INFO

Article history:
Received 23 September 2011
Received in revised form 19 January 2012
Accepted 28 January 2012

Keywords:
Variable-rate heat
Ground thermal properties
Unsteady state method

ABSTRACT

This paper proposed a new method based on modified composite model in the thermal response test (TRT) in the variable heat rate case study. The new method considered the unsteady-state heat transfer in the borehole instead of the line-source model assumption. A Matlab program was compiled which can perform inversion calculation to obtain the ground thermal properties. The superposition principle was used to process the variable-rate problem. This new method was applied to two thermal response tests. The simulation value based on the method shows a good agreement with the measurement data of water temperature. The proposed method would save the time and reduce the cost of TRT when power fluctuation or failure occurs.

1. Introduction

The current test method of ground thermal properties in Ground Source Heat Pump (GSHP) system is TRT. Generally, the slope determination method or two-variable parameter fitting method is used to obtain the thermal conductivity and borehole thermal resistance.

More than ten countries in the world are dealing with this test. And the studies or modified methods are under development.

Roth et al. used commercial software “Origin6” to calculate thermal conductivity and borehole thermal resistance [1]. They performed a comparison between conventional slope determination method and geothermal properties measurement data software which is based on numerical solutions and two variable-parameter fitting developed by Shonder and Beck [2,3].

Nagano et al. [4] and Lim et al. [5] carried out a TRT and provided effective data for the GSHP design. Esen and Inally conducted a TRT in project using the vehicle measuring device and obtained the ground thermal conductivity and borehole thermal resistance [6].

Pahud and Matthey used slope determination method based on line-source model in a TRT and analyzed the effect of backfill material and tube spacing on the heat transfer of the ground heat exchanger [7]. Florides and Kalogirou adopted the estimation value of ground volumetric heat capacity and calculated ground thermal conductivity and borehole thermal resistance [8]. Sharqawy et al. made first in situ determination of ground and borehole thermal properties in Saudi Arabia [9].

The average fluid temperature in the tube is needed in the calculation of ground thermal properties. At present, it is assumed that the fluid temperature in the tube changes linearly with path length, and the average fluid temperature in the tube is arithmetic average of the inlet and outlet temperatures. Marcotte and Pasquier presented “p-liner” average fluid temperature considering the non-linear variation of fluid temperature [10].

In the TRT, it is necessary to hold the input power at a constant rate. So power outages or high voltage fluctuations are not allowed. However, a constant supply of electricity is generally very difficult to achieve in the actual project. Although the regulator may be installed and the power stability will be improved, the effect was limited, especially when the power cut occurred.

Gustafsson and Westerlund conducted multi-injection rate TRT to detect the convective heat influence and to examine the effect of different heat injection rates. They found that an increase in heat injection rate results in a higher effective bedrock thermal conductivity [11].

Austin et al. used a two dimensional numerical model to determine the thermal conductivity of the ground. He also analyzed the sensitivity of ground thermal conductivity to uncertainties of power-input and other parameters [12]. Martin and Kavanaugh presented that a ten- to twelve-day delay is required before retesting a borehole if a 48-h test has been conducted in a rock formation. If the initial test was terminated before 48 h, the waiting period could be proportionally reduced to a minimum delay of 24 h [13].

Beier and Smith developed a deconvolution algorithm based on the composite line-source model which adapts the Laplace domain approach to remove variable heat-rate effects from in situ tests. The inputs to the algorithm were the transient heat rate and the ground-loop temperature curves, which were determined by the usual measurements of entering and discharging loop temperature and electric power [14]. In addition, Beier and Smith proposed a method to estimate testing time through an analytical solution for

* Corresponding author. Tel.: +86 27 87792165 415; fax: +86 27 87792101.
E-mail address: pingfanghu21@163.com (P. Hu).

0378-7788/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2012.01.036

Nomenclature

c_s	ground heat capacity (J/(kg K))
c_g	grout heat capacity(J/(kg K))
d_i	inside diameter of the tube (m)
d_o	outside diameter of the tube (m)
D	distance between two legs of the U tube (m)
d_b	diameter of the borehole (m)
d_w	effective diameter of the single tube
K	coefficient of heat exchange between fluid and inside of the tube W/(m^2 K)
q	constant heat injection rate (W/m)
r	radius (m)
R_b	borehole thermal resistance (K m/W)
R_w	the thermal resistance between the fluid and the radius of undisturbed soil (K m/W)
t	time length (s)
T_f	mean fluid temperature in the borehole heat exchanger (°C)
T_0	undisturbed ground temperature (°C)
$T_{cal,i}$	calculated fluid temperature in the borehole heat exchanger (°C)
$T_{exp,i}$	measured fluid temperature in the borehole heat exchanger (°C)

Greek letters

γ	Euler's constant=0.5772
λ_b	thermal conductivity of the backfill material (W/(m K))
λ_p	thermal conductivity of the tube (W/(m K))
ν	viscosity of the fluid (m^2/s)
λ_s	soil thermal conductivity (W/(m K))
λ_g	grout thermal conductivity (W/(m K))
ρ_s	soil density (kg/ (m^3)
ρ_g	grout density (kg/ (m^3)
τ	time (s)
α	thermal diffusivity (m^2/s)

the TRT, taking into account the thermal storage of the circulating fluid, the borehole radius and the thermal properties of the grout and soil. The modified Bessel functions were used in the composite model for heat transfer through the ground-loop heat exchanger [15].

In order to analyze the electrical power interruption effect on the test, Beier and Smith presented a method to estimate the recovery time when one restarted the test after a power interruption [16]. Otherwise, Beier developed an equivalent-time method to remove the effects of the interruption and estimate soil thermal conductivity and the method was verified with test data from a large laboratory sandbox [17]. It was an analytical method which had been used in solving an analogous problem for tests on oil wells in petroleum engineering.

In the previous study, the heat transfer in the borehole is generally treated approximately by line-source model which ignores the thermal capacity of the circulating fluid, the grout and the differences in properties of the grout that depart from the soil properties. The approximation may result in some errors, because the thermal capacity of grout, tube and fluid in the tube has influence on the heat transfer in the borehole though it is relatively small.

In generally, the test and data processing in the situation with a large input power fluctuation or power cut need to be further studied. And the suitable and simple method is needed in the project.

This paper presents a new method based on modified composite model in which the unsteady state heat transfer was considered in the borehole (hereinafter referred to unsteady method). The method can be used to handle the measuring of the TRT in unsteady electric power supply condition, especially the power interruption situation. The general approach was to adopt the unsteady state heat transfer nature in the borehole in the composite model. Superposition principle was used to process the variable heat rate. The inversion calculation was conducted to obtain ground thermal conductivity and volumetric heat capacity based on the measuring data. Two test cases were studied with the method. The method was also compared to line-source model and the deconvolution algorithm based on composite line-source model presented by Beier and Smith, which has been validated with data from a large-scale laboratory sandbox [12] (hereinafter referred to Beier algorithm).

2. Measuring device and principle

The measuring device for the TRT is shown in Fig. 1. It was connected to the ground heat exchanger (GHE) to form a circulating system. By adding an electrical power and recording the electrical power, flow rate and fluid temperature at a constant interval, the thermal conductivity and volumetric heat capacity can be calculated by analytical or numerical models.

3. The unsteady state method

3.1. The composite line-source model

A simplified borehole model was developed by Bixel and van Poollen which was called composite line-source model, as shown in Fig. 2 [14,18]. The U tube with two legs was replaced by a single tube with an equal borehole resistance. The effective diameter of the single tube was d_w. The thermal resistance of the tube wall and the thermal resistance between the fluid and inside wall of the tube which were relatively small were merged with the borehole resistance corresponding to the effective diameter d_w. The treatment of double U tube was similar to that of single U tube.

The borehole resistance can be interpreted the comprehensive thermal resistance between inside wall of tube and borehole wall [3].

$$R_b = \frac{1}{2\pi\lambda_g}\ln\frac{d_b}{d_w} \quad (1)$$

On the basis of line source theory, the soil temperature is written as [14]:

$$T(r,\tau) - T_0 = \frac{q}{4\pi\lambda}\int_{r^2/4\alpha\tau}^{\infty}\frac{e^{-u}}{u}du = \frac{q}{4\pi\lambda}E_1\left[\frac{r^2}{4\alpha\tau}\right] \quad (2)$$

The mean fluid temperature of the circulating fluid in the tube can be written as:

$$T_f = T_0 + qR_b + \frac{q}{4\pi\lambda_s}\left[\ln\left(\frac{16\lambda_s\tau}{{d_b}^2\rho_s c_s}\right) - \gamma\right],\ \tau \ge 1.25\frac{d_b^2\rho_s c_s}{\lambda_s}c \quad (3)$$

3.2. The modified composite model

Here we developed a modified composite model based on the composite model introduced in Section 3.1.

The thermal resistance between the fluid and the borehole boundary is the thermal resistance between the fluid and infinity minus that between the borehole outside wall and infinity. The thermal resistance between the fluid and the radius of undisturbed