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Research Paper

Study the performance of borehole heat exchanger considering layered subsurface based on field investigations

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HIGHLIGHTS

- A well-designed boreholes test was conducted in layered subsurface.
- The test outlet temperature was compared with the homogeneous FLS model.
- Temperature rise of different radial distance at different depths were discussed.
- Axial temperature profiles under different heating time are presented.

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ABSTRACT

In bedrock geology districts, the stratum in the ground heat exchanger (GHE) borehole varies along the vertical direction. In this paper, the layered subsurface is investigated and the ground temperature variations are studied based on the test systems. Under 60 days' heat injection and 65 days' self-regeneration test in the borehole-#2, the outlet temperature of the analytical homogeneous finite line source (FLS) model is 2.2 °C and 1.2 °C higher than the tested outlet temperature on at 30th and the 90th day, respectively. The temperature rises at radial distance of 3 m, 6 m and 9 m to the heat injection borehole at depth of 12 m, 25 m and 80 m are recorded and discussed. After 60 days' heating, the temperature rises at radial distance of 3 m at depth of 12 m, 25 m and 80 m are 0.82 °C, 5.86 °C and 3.85 °C respectively. A numerical model considering five strata is developed according to the field investigations, and the axial temperature profiles of different layers at different distance under different heating time are presented and explored. It indicates that the layered subsurface and groundwater flow play the non-negligible role on evaluation performance of BHEs.

1. Introduction

In China, the vertical ground source heat pump (GSHP) system is widely used because of its environmental conservation and low running cost. The borehole heat exchangers (BHEs), which are the most important part of the GSHP system are always 80–150 m deep. The subsurface thermal properties greatly influence on the temperature distribution around borehole.

In order to estimate the performance of the vertical BHE, many analytical and numerical models have been developed: the infinite line source model (ILS) [1] and cylindrical heat source model [2] were widely used for the thermal analysis of BHEs because of their simplicity and high speed in computation. Based on the cylindrical source model, Bernier et al. [3] suggested a multiple load aggregation algorithm to calculate the performance of a single borehole under variable load. Fossa et al. [4] developed the cylindrical heat source model by using multiple load aggregation algorithms to simulate hourly energy variations. Eskilson [5] proposed the finite line source (FLS) model using the numerical finite-difference method. Zeng et al. [6] improved the FLS model by imposing a constant temperature at the ground surface. Some other studies [7,8] developed the FLS model to estimate heat transfer of BHE. Li et al. [9,10] proposed the analytical composite-medium line-source model for BHE. Yang et al. [11], Hu et al. [12] and Fei Lei et al. [13] developed the composite line source model. Recently, some scholars have conducted research on the spiral coil ground heat exchanger [14], which has the advantage of more heat transfer area and the thermal "short-circuit" between supply and return pipes [15]. In recent years, with the development of computers and numerical methods, numerical simulation studies are widely used.

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Nomenclature

a	thermal diffusivity (m^2/s)
λ	thermal conductivity (W/m K)
ρc	vol. heat capacity (J/m^3 K)
H	borehole depth (m)
c	specific heat (J/kg K)
q_L	average heat flux per unit length (W/m)
λ_{TRT}	effective subsurface thermal conductivity from TRT (W/m K)
λ_{wmtc}	the weighted average thermal conductivities by the steady flat plate method (W/m K)
T_{fi}	inlet temperature of BHE (°C)
T_{fo}	outlet temperature of BHE (°C)
T_g	undisturbed ground temperature (°C)
R_{bh}	borehole thermal resistance (m K/W)
COP	coefficient of performance
GSHP	ground source heat pump
BHE	borehole heat exchanger
TRT	thermal response test

Subscripts

g	grout
s	subsurface
por	porous media
i	inlet
o	outlet

Finite difference methods [16], finite volume methods [17], and finite element methods [18] have been extensively used for describing the heat transfer mechanisms and thermal response in the subsurface for BHEs. By simplifying the thermal resistance and capacity model, Bauer et al. [19] presented a 3-D numerical model to simulate a thermal response test (TRT) over short and long time scales, and hence, to analyze the fluid temperature variations in the downward and upward tube. Wb. Yang et al. [20] put forward the borehole heat exchange effectiveness (BHEE), by which the inlet and outlet fluid temperature of BHE can be calculated directly.

When the permeability is sufficiently high, there may be moving water in subsurface, advective transport has to be considered, some field tests done by Gehlin and Hellstrom [21] indicated that groundwater flow influenced on performance of BHE, even in fracture zones, the smaller groundwater flow rates might cause significantly enhanced heat transfer. Diao et al. [22] presented an analytical solution accounting for groundwater flow of an infinite line source (ILS) and Molina-Giraldo et al. [23] extended the moving infinite line source model to the case of a finite source. Luigi Schibuola et al. [24] showed the high humidity of the soil had a close relationship with the performance of GSHPs, and the humidity of the soil varied in different layers. Alberto Liuzzo-Scorpo et al. [25]found a way to use the thermal response test as a means to determine the groundwater flow influence in order to reduce the borehole spacing perpendicular to groundwater flow direction. Yang et al. [26] found that the increasing water content can alleviate the underground thermal imbalance of GSHP. Various studies have investigated the heat flow of BHEs by considering the flow of groundwater around the BHEs [27-29].

In the above papers, scholars usually simplified the underground as homogeneous soil. In real, the subsurface may contains different layers, and a homogeneous medium might not adequately represent the layered system. Sutton et al. [30] subdivide stratified geology into multiple horizontal layers and obtained the temperature distribution of each layer using the infinite length cylindrical source solution. Raymond [31] developed a 3-D numerical model for a single BHE accounting for non-ideal conditions with complex geological systems and the heterogeneous distribution of subsurface properties, but the simplification of the heat transfer inside borehole might lead to some deviations. A 3-D Finite Element Model (FEM) for BHE considering the thermal characteristics of surrounding geological layers were given by Aranzabal et al. [32], and a detailed depth-depending thermal conductivity profile along vertical BHE subsoil surrounding is presented. Luo et al. [33] examined thermal performance of BHE by investigating the thermal and hydraulic properties of rock-soil around the BHE. Based on the experimental data and FEFLOW software, a numerical model was developed, but the BHE was only simulated as vertical 1-D discrete element. Luo et al. [34] proposed that analysis of thermal conductivity in layered subsurface should take into account groundwater flow. The effect of groundwater flow on thermal performance of the BHE is further examined by using the FEFLOW software. Lee [35] and Zhou et al. [36] gave the numerical model for BHE in multilayer ground geology, however, the groundwater flow was ignored. Through the experimental results, ZalmanOlfman et al. [37] found that the specific heat exchange rate per unit-depth of borehole and the temperature response varied with depth. Fujii et al. [38] developed an improved thermal response test method by using optical fiber sensors positioned in the U-tubes, the results showed that the local geology and aquifer had a great relationship with heat transfer of BHE. Wagner [39] and Lee [40] developed the thermal response tests focused on the effect of the subsurface heterogeneities, groundwater flow and temperature gradient.

From the above survey, there are quite a few studies have been done on the ground temperature field considering the layered subsurface. Some studies [41-43] took the layered subsurface into account; however, their works were basically based on the short-term operation of GSHP system or a thermal response test processes. Some research works taking into account the stratum profile, but only through simulation software without the GSHP system running data [40,44]. There are very limited cases reported on experimental analysis for temperature response at different depth considering the layered subsurface.

In this paper, the BHEs drilled in the layered subsurface in Zhu Shan, Nanjing, China was examined. Firstly, the investigating works and thermal response test (TRT) are implemented and the subsurface thermal properties at different depths are measured in laboratory. Secondly, to probe how the complex geological formation and groundwater flow influence on ground temperature. The heating water circulated through borehole-#2 from 26th June to 25th August 2011, and then followed the 65 days self-regeneration period. The tested outlet temperature is compared with the analytical FLS models, and the temperature rises at radial distance of 3 m, 6 m and 9 m to the borehole-#2 at depths of 12 m, 25 m and 80 m are discussed. According to the analysis of the temperature data and thermal properties distribution in the borehole, a numerical model considering five strata is developed to explore the axial temperature profiles of different layers.

2. Experimental investigations

The BHEs system including 5 boreholes was installed in Zhushan, Nanjing, China. The schematic diagram of the constructed experimental system is illustrated in Fig. 1. According to the