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Experimental investigation of a borehole field by enhanced geothermal response test and numerical analysis of performance of the borehole heat exchangers

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ABSTRACT

Thermal conductivity of the ground is generally measured in field by TRT (thermal response test) without considering non-uniformity and the groundwater flow. However, both factors can affect the performance of BHE (borehole heat exchangers) drastically. Hence, analysis of thermal conductivity in layered subsurface with taking into account groundwater flow and its effect on performance of BHE is necessary.

This paper analyzes thermal conductivity of a layered subsurface by both EGRT (enhanced geothermal response test) and laboratory measurement. Five different geological strata are investigated in a borehole field within depth of 80 m. In addition, flowmeter tests are implemented to examine the groundwater flow. Experimental results indicate: (1) EGRT fit very well with laboratory measurements in the strata without groundwater flow; (2) under groundwater flow, the EGRT leads to unreasonable outcomes due to convection effects.

The effect of groundwater flow on thermal performance of the BHE is further examined numerically. The modeling results show that heat transfer efficiency of the BHE increases by 55% within the aquifer. Therefore, the effects of groundwater on performance of BHE deserve to be considered in order to minimizing the total length of BHE in layered subsurface.

1. Introduction

A large number of GSHP (ground source heat pump) systems have been applied in residential and commercial buildings worldwide due to the attractive advantages of high energy and environmental performances [1,2]. It is reported that the utilization of GSHP systems increased by 10% annually in the past few decades [3]. In general, GSHP systems consist mainly of three parts: BHE (borehole heat exchangers), heat pump system and indoor units. GSHP systems are commonly coupled with the ground as heat source or sink for exchanging energy by circulation of heat carrier fluid in the tubes of BHEs [4,5]. Due to the ground remains constant temperature at certain depth (10–30 m) below the ground surface, GSHP systems can achieve higher energy efficiency as compared to the traditional air-conditioning systems [6].

Ground conditions including thermal conductivity, groundwater flow and initial temperature play vital role in performance of GSHP systems [7,8]. Accurate information of the ground is the prerequisite for optimizing GSHP systems [9]. Therefore, it is necessary to investigate the ground conditions very precisely. Thermal conductivity is significant to heat transfer of BHE in subsurface (e.g. heat diffusing and absorbing) [10,11]. In the past decades, many studies [12–15] have been performed concerning investigation of thermal conductivity of the ground. Thermal conductivity can be measured in laboratory by collected soil and rock samples. Abuel-Naga et al. [12] investigated thermal conductivity of soft Bangkok clay from laboratory and field measurements. The test results showed that thermal conductivity increased with increasing

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Nomenclature

T	temperature (°C or K)
R	thermal resistance (K*m/W)
Q	heat rate (W)
H	borehole length (m)
r	borehole radius (m)
q	thermal transfer rate (W/m)
c	specific thermal capacity (J/kg/K)
s	water head (m)
K	hydraulic conductivity (m/s)
t	time (s)
i	hydraulic gradient (−)
m	linear regression (−)
n	intercept of the slope line (−)
k	Boltzmann constant
h	Planck constant
$\Delta\nu R$	light frequency (Hz)
∇	laplace operator
v	flow velocity (m^3/s)

Greek symbols

ρ	density (g/cm^3)
λ	thermal conductivity (W/(m*K))
m	linear regression (−)
α	heat diffusivity (m^2/s)
γ	Euler constant (0.5772)

Subscripts

in	inlet flow
out	outlet flow
f	fluid
eff	effective
b	borehole
AS	anti-stokes
S	temperature-dependent stokes
G	ground
Line	linear source

soil density. Betermann et al. [15,16] measured thermal conductivity for unconsolidated ground from a depth of 10 m below the Earth's surface. The influence of parameters such as grain size, humidity, etc. on thermal conductivity was analyzed. The results showed unconstrained potential areas for exploitation where the thermal conductivity varies between 0.8 W/m*K and 1.2 W/m*K within the soil matrix. Based on the measurements, prediction of available potentials at a scale of 1:250,000 for vSGP (very shallow geothermal potential) was estimated for European countries [17].

On the other hand, thermal conductivity is more commonly measured in field by TRT (thermal response test). TRT has been proven to be a suitable method to investigate thermal conductivity of ground [18,19]. For a TRT, constant power input to the ground by circulating fluid in tubes and the temperature changes are recorded at both inlet and outlet of the ground. Two main parameters: effective thermal conductivity, λ_{eff}, and borehole thermal resistance, R_b, can often estimated by following linear source theory proposed by Hellström [20]. Sanner et al. [21] reported a study concerning current status and world-wide application of TRT. In this paper, the implementation and interpretation of TRT was introduced. Several case studies were also presented and discussed. Many factors such as climatic conditions, pipe insulation, constant power input etc., have been found can affect the measuring outputs of TRT. Moreover, a limitation of TRT is the groundwater advection effects. The measuring output can be substantially influenced by groundwater flow, leading to unacceptable deviation in estimation of the λ_{eff} [18].

Based the mentioned above, both TRT and laboratory measurements cannot reflect the groundwater effects. In order to overcome the drawbacks of the traditional TRTs and laboratory measurements, EGRT (enhanced geothermal response test) is developed [22]. EGRT is based on the DTS (distribution temperature sensing) system that is composed of optical fiber, measuring device and power input system. In DTS system, the temperature distribution can be measured with a small interval distance (e.g. 0.5 m). Hence, thermal conductivity of the ground can be examined along the depth. Compared to the traditional TRT, the EGRT can reflect more detailed information of the ground. Fuji et al. [23] did study on thermal conductivity measurements of the ground using EGRT and traditional TRT. Thermal conductivity obtained from EGRT fits very well with that of the traditional TRT. The EGRT further indicated that thermal conductivity increased obviously in the permeable zone in subsurface.

Furthermore, some other studies [24–26] mentioned that the effects of groundwater flow on the performance of BHE deserve to be considered, especially for long-term system operation. Zhang et al. [24] investigated numerically the heat transfer around buried coils of pile foundation heat exchangers for ground-coupled heat pump applications. Analysis of heat transfer in subsurface was implemented by taken into account groundwater flow. The results showed that the effect of groundwater should not be negligible. Wang et al. [26] did an experimental to study heat transfer of BHEs in ground. The findings indicated that thermal performance was enhanced under groundwater flow.

Natural ground is generally layered with different geological strata and the groundwater flow is often limited to the stratum with high hydraulic conductivity which is called aquifers [27]. Hence, thermal performance of BHEs can be drastically different with different strata. However, the former studies [10,15,28] examined the thermal conductivity without measuring of the groundwater flow. This means the effects of groundwater flow is neglected in thermal conductivity measurements. The effect of groundwater flow on performance of BHE is generally estimated numerically in most previous studies. Hence, a study deals with investigation of thermal conductivity with taking into account groundwater flow and its effect on performance of BHE is needed.

In this paper, thermal conductivity of a layered subsurface is investigated. The layered subsurface has five different geological strata within depth of 80 m. It is located in a borehole field of a GSHP system in Nuremberg city, Germany. Thermal conductivity is firstly examined along the depth by EGRT. On the other hand, thermal conductivity is also measured using the samples collected from these geological strata in laboratory. Both results obtained from EGRT and laboratory measurements are compared. Flowmeter tests is implemented in order to examine the groundwater flow in subsurface. The measuring results are used for analysis of the deviation of EGRT to laboratory measurements. Finally, the effect of groundwater flow on performance of BHE is examined numerically. Briefly, the main structure of this paper is organized as: Section 2 describes the study methodology including measurement of thermal conductivity by both EGRT and laboratory measurements, and investigation of groundwater flow; the measuring results are analyzed and the effects of groundwater flow on performance of BHE is further examined numerically in Section 3; finally, the conclusions of this paper are included in Section 4.