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A novel hybrid approach for in-situ determining the thermal properties of subsurface layers around borehole heat exchanger

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ABSTRACT

Performance of shallow geothermal systems such as borehole thermal energy storage (BTES) and ground source heat pump (GSHP) mainly depends on the thermal properties of the subsurface and proper design of borehole heat exchangers (BHE). This paper introduces a novel hybrid approach for measuring the effectiveness of BHEs and surrounding subsurface thermal properties, which combines traditional thermal response test (TRT) with the borehole temperature relaxation method (BTR), based on two dimensional radial conductive heat transfer. The new method allows for: (1) evaluation of how convective heat loss at groundwater layers influence estimation of subsurface thermal properties; (2) examination of non-uniform heat transfer through a BHE to stratified subsurface layers; and, (3) calculation of depth-dependency of thermal properties of unsaturated subsurface layers. The hybrid approach was tested using a 50 m U-type BHE, the results of which indicated that convective heat transfer at the groundwater level altered the real value of effective thermal conductivity from 0.45 to 1.56 W/m K. The non-uniformity of heat transfer along the BHE was confirmed by calculations that showed subsurface thermal conductivities were depth dependent, varying between 0.34 and 0.61 W/m K.

1. Introduction

The use of shallow geothermal energy by means of ground source heat pump systems (GSHP) and the utilization of a subsurface as a medium for seasonal thermal energy storage systems are becoming significantly attractive especially for the energy intensive appliances of the buildings such as space heating and hot water supply [1,2]. These systems can replace conventional coal or petroleum powered heating technologies and help to reduce carbon dioxide emissions to the atmosphere [3,4].

The extraction of the geothermal energy or storing the excess energy in subsurface layers are carried out primarily by means of vertical heat exchangers installed into boreholes and backfilled with grouting materials. The borehole heat exchangers (BHE) are usually integrated to a heat pump or to a storage system. The efficiencies of these systems generally depend on both the thermal properties of the subsurface and the energy performance of the BHEs, which needs to be determined in advance [5–7].

The thermal response test (TRT) is considered one of the most commonly applied tools in order to design borehole thermal energy storages (BTES) and GSHP. Based on the previous studies involving the application of the TRT, the effective thermal properties of the subsurface and the borehole are calculated, which are necessary to construct BHE properly and assess its efficiency. Moreover, the results from TRT provide an approximation on how efficient any area will be as a thermal energy storage medium (e.g. BTES) and complement pre-design of the GSHP within the appropriate engineering parameters [8].

The operating principle of the conventional TRT installation is quite simple. While passing through the installation, the temperature of the working fluid is gradually increased with nearly constant heat input rate supplied by an electric heater. The heated fluid, in turn, circulates through a BHE thus warming up the borehole and the subsurface layers around it. During the heat injection phase (i.e. TRT), the temperature of the working fluid is constantly measured at the inflow and outflow sections of the BHE. The test is

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Nomenclature

$c_{p,1}$	specific heat capacity of the borehole material (kJ/kg K)
$c_{p,2}$	specific heat capacity of the subsurface layer at a particular depth (kJ/kg K)
$c_{p,av}$	average specific heat capacity of the subsurface (kJ/kg K)
Ei	exponential integral (–)
k_{eff}	effective thermal conductivity of the subsurface (W/m K)
k_1	thermal conductivity of the borehole material (W/m K)
k_2	thermal conductivity of the subsurface at a particular depth (W/m K)
L	length of the borehole (m)
m	slope of the regression line (–)
Q	heat transfer rate (W)
R	correlation coefficient of the regression line (–)
R_b	borehole thermal resistance (m K/W)
r	radius (mm)
r_b	borehole radius (mm)
t	time (s)
t_0	initial time of the relaxation phase (s)
T_1	borehole temperature (°C)
T_2	subsurface temperature at a particular depth (°C)
T_{sub}	effective subsurface temperature (°C)
T_g	undisturbed subsurface temperature at a particular depth (°C)
$T_{g,av}$	depth-averaged undisturbed subsurface temperature (°C)
T_f	fluid temperature (°C)
T_{in}	inlet temperature (°C)
T_{out}	outlet temperature(°C)
T_b	borehole wall temperature (°C)
u	integral variable (–)
Y_i, J_i	Bessel functions (–)

Greek symbols

α_{eff}	effective thermal diffusivity (m^2/s)
α_1	thermal diffusivity of the borehole material (m^2/s)
α_2	thermal diffusivity of the subsurface at a particular depth (m^2/s)
γ	Euler's constant (≈0.57721)
ρ_1	density of the borehole material (kg/m^3)
ρ_2	density of the subsurface at a particular depth (kg/m^3)
ρ_{av}	average density of the subsurface (kg/m^3)

Acronyms

BHE	borehole heat exchanger
BTR	borehole thermal relaxation
LSM	line source model
MSE	mean squared error
SD	standard deviation
TRT	thermal response test

usually continued up to 48 h or more, according to the recommendations [9,10]. Applying the line source model (LSM) to the recorded temperature data, thermal properties of the subsurface and the borehole are then estimated [8,11–13]. Usually, TRT installation set up in an open air environment after being integrated to BHE by means of connecting pipes. Due to the weather conditions there are usually heat losses or gains through the connecting pipes and elements of the TRT installation. Moreover, the electric heater cannot supply constant heat flux to the circulating fluid because of the voltage fluctuations from the grid. Therefore, such heat exchanges of the TRT equipment with the ambient air and the non-uniform operation of the electric heater causes instabilities to the heat injection process throughout the test. Consequently, these instabilities are reflected in the resulting thermal properties of the subsurface evaluated by means of the LSM [14,15].

According to the geological structure of the earth, ground consists of different layers and thicknesses of said layers vary based on location. However, the LSM does not consider geological heterogeneity, but instead provides (i) effective thermal conductivity k_{eff}, which averages the thermal properties of all subsurface layers along the entire length of the BHE, including grouting materials; and, (ii) effective borehole thermal resistances R_b, which is the overall resistance of the borehole materials to heat flow inside the entire BHE. In fact, estimated values of k_{eff} and R_b are depth dependent [12]. Moreover, the presence of groundwater flow and type of aquifer have a significant influence in artificially enhancing the actual results of k_{eff} and R_b [16,17]. In case of single and double U-type BHE, spatial separation between inlet and outlet pipes, and type of grouting material may also slightly affect the results obtained by the LSM [18]. Nevertheless, the aforementioned disadvantages can be improved by controlling the external processes that affect the results of TRT as well as by combining TRT with other possible methods to obtain results that are more accurate in terms of evaluating subsurface thermal properties.

Thus, the aim of the current study was to develop a new hybrid approach that integrates TRT with the borehole temperature relaxation (BTR) method which would allow in-situ analysis not only of the effective thermal properties of a BHE but also: (i) depth-dependent thermal properties of the subsurface around a BHE; (ii) non-uniform heat transfer from the BHE to stratified subsurface layers; and, (iii) the influence of groundwater in the estimation of real subsurface thermal properties. The BTR method of the hybrid approach is based on the mathematical formulation by Carslaw and Jaeger [19,20] which considers two-dimensional radial conductive heat transfer in an infinite subsurface layer internally bounded by a borehole. This method permits estimation of the thermal properties of subsurface layers, relying on temperature measurements within a borehole during the thermal energy relaxation phase, which is initiated after heat injection phase of TRT. The authors tested the hybrid approach using a 50 m borehole equipped with a single U-type BHE located in The Technical University of Sofia, Plovdiv Branch (Plovdiv, Bulgaria) and the current paper deals with the results of these studies.

2. Experimental set-up and BHE installation

The schematic diagram of the installation designed to apply the hybrid approach based on TRT and BTR method to estimate subsurface thermal properties around BHE is illustrated in Fig. 1. The installation, which is established above in a trailer, consists of an electric heater (Gorenge), a circulation pump with variable flow control (Wilo, model: TOP-S), an 8-liter expansion tank, a flow meter (Model: Kobold, KSK), a monometer (Omega Engineering), an automatic air vent and connecting pipes wrapped with insulation material. The connecting pipes of the test installation were attached to the 50 m single U-type BHE, which is located in the Technical University of Sofia - Plovdiv Branch, Plovdiv, Bulgaria