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Analytical approach to groundwater-influenced thermal response tests of grouted borehole heat exchangers

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ABSTRACT

For ground-source heat pump (GSHP) systems, the thermal response test (TRT) is commonly used to determine the heat transport parameters of the subsurface. The main limitation of this approach is the assumption of pure conductive heat transport, which might result in significant deviations. Based on the moving line source theory, a parameter estimation approach is introduced, which is sensitive to conduction and advection. This approach is calibrated and successfully tested against three different test cases. The presented analytical approach therefore expands the field of application of the TRT to advection-influenced conditions beyond a Darcy velocity of 0.1 m day^{-1}.

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1. Introduction

The heat stored in the shallow subsurface is of growing interest to geothermal energy use. In the upper hundreds of meters of the earth's crust, the temperature usually does not reach much more than 20 °C (e.g., Taniguchi and Uemura, 2005; Zhu et al., 2011). Thus, the energy is only useful for space heating and air conditioning systems and is ideally extracted from wells or boreholes (in general to a depth of around 150 m (e.g., Hecht-Méndez et al., 2010)) combined with heat pumps. Alternatively, the ground may be used as storage medium for waste heat or for cooling purposes (Sanner et al., 2003). The most common variants of geothermal systems are ground-source heat pumps (GSHPs), where vertical boreholes act as borehole heat exchangers (BHEs) (Rybach and Eugster, 2010). A heat carrier fluid is circulated in closed tubes installed in the boreholes. In the heating mode, the injection temperature is slightly lower than the temperature of the ground. Circulation in the subsurface warms up the fluid and by operating the heat pump, the collected energy is extracted above, thus cooling the ambient ground. Temperature anomalies develop, and the radial temperature gradient forces the heat flow toward the BHE.

Since the geological, geophysical, and hydrogeological conditions that control the heat transfer processes and extraction efficiency vary, field investigation campaigns are suggested for larger-scale systems to ensure appropriate planning of shallow geothermal installation. The thermal response test (TRT), which is conducted in BHEs before heat mining begins is an established technique (Morgensen, 1983; Gehlin, 2002; Sanner et al., 2005; Signorelli et al., 2007; Beier et al., 2011; Raymond et al., 2011a,c). By monitoring the effect of short-term heating (or cooling), the thermal properties of the ground and the heat transfer efficiency between ground and BHE are interpreted.

In standard experiments, a heated or cooled fluid is injected and the temperature development, i.e. the response of the ground, is monitored at the BHE outlet. The slower the temperatures of the heat carrier fluid increase, the more heat is lost in the ground and, thus, the higher is the interpreted in situ effective thermal conductivity. The temperature time series are commonly evaluated based on the Kelvin line source theory that assumes an infinite, homogeneous and isotropic medium with a constant heat source (Carslaw and Jaeger, 1959). This evaluation provides the effective thermal conductivity (λ_{eff}) as well as the thermal borehole resistance (R_b), which is a measure of the heat transfer performance in the borehole. Both parameters are used for a case-specific planning and efficient operation of the GSHP system.

Standard TRT interpretation exhibits several shortcomings. It assumes a homogenous subsurface, no axial heat transport, uniform initial temperature distribution, and it approximates the BHE shape as an infinite line. Bandos et al. (2009) presented an analytical solution to overcome the limitations caused by the assumption of an infinite line shape. Another significant shortcoming is that only conductive heat transport is considered (e.g., Signorelli et al., 2007). However, shallow geothermal systems are

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Nomenclature

C	correction factor
c_p	volumetric heat capacity (MJ m^{-3} K^{-1})
D	thermal dispersion coefficient (m^2 s^{-1})
d_s	shank spacing (m)
Ei	exponential integral
k	hydraulic conductivity (m s^{-1})
Pe	Péclet number
q	heat transfer rate per unit length (W m^{-1})
r	radius (m)
r_{pin}	inner pipe radius (m)
r_{pout}	outer pipe radius (m)
R_b	thermal borehole resistance (m K W^{-1})
T	temperature (°C)
t	time (s)
t_c	time criterion (s)
u	integration variable
v	Darcy velocity (m day^{-1})
v_{th}	heat transport velocity (m day^{-1})
x, y	Cartesian coordinates (m)

Greek symbols

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

Subscripts and superscripts

f	heat carrier fluid
bw	borehole wall
sub	property of the subsurface
g	property of the grouting material
eff	obtained effective property value (without correction)
m	property of the porous medium
w	property of the groundwater
0	initial or undisturbed value
l	longitudinal
t	transversal
$*$	value corrected by C

frequently installed in water-saturated undergrounds. In aquifers, advective heat transfer due to groundwater flow can be significant (e.g., Witte, 2001). Accordingly, the effective thermal conductivity (λ_{eff}) obtained based on the Kelvin line source theory is an apparent parameter, which increases with Darcy velocity. Several studies have demonstrated the significant influence of groundwater flow (Witte and Gelder, 2006) and ambient air temperature variations (Bandos et al., 2011) on TRT results. Witte (2001) established an advection-dominated aquifer by performing a TRT, while groundwater was being extracted from a well 5 m away from the BHE. A comparison to the results of an undisturbed TRT showed an increase in the λ_{eff} value by a factor of 1.38. This relationship was also investigated by Bozdag et al. (2008), who performed four different TRTs in one BHE and correlated the obtained λ_{eff} and R_b values with the observed different hydraulic gradients. Their field measurements clearly indicated the influence of water table fluctuations, which govern groundwater flow velocities, on the TRT results. The influence of groundwater flow is also examined by several theoretical studies. For instance, Chiasson et al. (2000) numerically simulated TRTs to analyze the role of groundwater flow velocity and different evaluation periods with respect to the value of λ_{eff} that would be obtained by the line-source approach. They demonstrated that the resulting thermal conductivity value is an effective one and does not represent the thermal conductivity of the subsurface. Signorelli et al. (2007) comprehensively analyzed those effects and confirmed the findings by Witte (2001) that λ_{eff} increases continuously with evaluation time. In essence, the line source-based TRT evaluation of advection-dominated systems results in ambiguous λ_{eff} values. Signorelli et al. (2007) conclude that BHE dimensioning based on λ_{eff} in advection-dominated systems is rather problematic, because of the increasing instability of the resulting values.

A number of remedies have been suggested to reliably evaluate TRTs influenced by groundwater flow. One possibility to detect the influence of groundwater flow is a stepwise TRT evaluation based on the Kelvin line source theory (e.g., Sanner et al., 2005). Witte (2001) interpreted an increasing λ_{eff} value with increasing evaluation time step size as an indicator for groundwater flow. Another possibility is an enhanced TRT (Wagner and Rohner, 2008), where depth-depending temperature series during and/or after the heating period are evaluated (Fujii et al., 2009). Wagner and Rohner (2008) showed how specific layers with groundwater flow (enhanced λ_{eff} values) can be estimated. However, these concepts provide no information about the actual Darcy velocity. To overcome this, parameter estimation approaches based on numerical simulations (Raymond et al., 2011b) or alternative analytical equations (Katsura et al., 2006) were suggested. Raymond et al. (2011b) numerically quantified that the TRT examined at a field site was influenced by a groundwater flow velocity smaller than 10^{-5} m s^{-1}. Based on several simulation results with a groundwater flux between 10^{-6} and 10^{-8} m s^{-1} and λ_m values between 2.35 and 2.65 W m^{-1} K^{-1}, the measured temperature values could be reproduced (Raymond et al., 2011b). In a different context, Katsura et al. (2006) analyzed the heat response of a thermal probe in a sand-filled cylinder influenced by different water flow velocities. By calibration of the moving line source equation (Carslaw and Jaeger, 1959) to the measured thermal response it was possible to derive the groundwater velocity with a relative error of less than 20% (Katsura et al., 2006).

Previous studies have demonstrated the ambiguous character of the parameters determined by line source-based TRT evaluation, especially if groundwater flow influences the system. The objective of this study is therefore to develop an analytical approach to groundwater-influenced TRTs, which provides parameters more suitable for a detailed simulation of conductive and advective heat transport in the subsurface. For this purpose, an approach in line with the one by Katsura et al. (2006) is developed. Furthermore, we introduce a correction term to consider the effects caused by the lower hydraulic conductivity of a grouted BHE on the apparent (i.e., estimated) Darcy velocity in the vicinity of the BHE. This correction term is calibrated by artificially generated high-resolution TRT temperature time series and embedded in a parameter estimation framework. Finally, the applicability of this concept for the simultaneous determination of ground thermal conductivity, λ_m, and Darcy velocity, v, is discussed based on a set of scenarios adopted from related studies.

2. TRT models

2.1. Conductive line source

The most widely used procedure to evaluate a TRT is based on the Kelvin line source theory. This approach approximates the BHE as an infinite line source in a homogeneous, isotropic and infinite medium, which injects or extracts a constant amount of energy (q) by conductive heat transport only. The temporal and spatial temperature changes around the line source can be calculated as

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