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Improving parameter estimates obtained from thermal response tests: Effect of ambient air temperature variations

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ABSTRACT

This paper presents a method of subtracting the effect of atmospheric conditions from thermal response test (TRT) estimates by using data on the ambient air temperature. The method assesses effective ground thermal conductivity within 10% of the mean value from the test, depending on the time interval chosen for the analysis, whereas the estimated value can vary by a third if energy losses outside the borehole are neglected. Evaluating the same test data using the finite line-source (FLS) model gives lower values for the ground thermal conductivity than for the infinite line-source (ILS) model, whether or not heat dissipation to ambient air is assumed.

1. Introduction

Nowadays, ground-source heat pumps (GHPs) are a solid alternative as choice of system for heating and cooling in buildings (Omer, 2008; Sanner et al., 2005; Urchueguía et al., 2008). By comparison with standard technologies, they offer competitive levels of comfort, reduced noise levels, savings of greenhouse gas emissions, and reasonable environmental safety. Furthermore, their electrical consumption and maintenance requirements are lower than those required by conventional systems and, consequently, the annual cost is lower (Lund, 2000). Ground-source systems are recognized by the Environmental Protection Agency as being among the most efficient and comfortable heating and cooling systems available today.

A thermal response test (TRT) is a method of determining the effective on-site ground thermal conductivity in order to design ground coupled heat pump systems. These in situ tests are based on the ILS theory of heat transfer by thermal conduction (Ingersoll et al., 1954; Reuβ et al., 2009). Due to its two-dimensional nature, the ILS theory cannot describe axial temperature variations around geothermal borehole heat exchanger.

Fig. 1 represents a typical TRT test to measure the temperature response of the borehole heat exchanger (BHE) to a constant heat injection or extraction. A U-tube loop, through which a heat carrier fluid circulates, is inserted inside the borehole to approximately the same depth as the BHE planned for the site. To provide a constant heat flux to the ground, the fluid flow rate in the borehole loop and the temperature difference between inlet and outlet are kept constant during the testing. The outputs of the TRT are the inlet (T_{in}) and outlet (T_{out}) temperatures of the heat carrier fluid as a function of time (see Fig. 1). The difference between the temperatures T_{in} and T_{out}, measured at the end points of the U-tube, is used to determine the rate at which heat is transferred by thermal conduction into the ground.

The BHE, which consists of two tubes separated by filling material, can be modeled as a heat source in the form of a line or cylinder. The effective thermal resistance of the borehole (Mogensen, 1983) defines the temperature drop between the BHE surface and an average temperature of the fluid. The temperature of heat carrier fluid circulating through the loop varies with depth, as do the ground thermal properties. A weighted average of T_{in} and T_{out} measured at the end points of the U-tube is assumed to be the mean temperature of the heat carrier fluid over the loop length (Marcotte and Pasquier, 2008). Typically, their arithmetic average is compared with a reference temperature of the borehole surface from the ILS model, around which the TRT is designed. From these experimental data and with an appropriate model for average temperature around the BHE, the effective thermal conductivity of the surroundings is inferred.

Different analytical and numerical methods have been developed for determining ground thermal properties from the TRT output data. The cylinder heat source (Ingersoll et al., 1954) and line heat source (Carslaw and Jaeger, 1959) model for BHE with parameter-estimating techniques are commonly applied in Europe

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Nomenclature

$C(C_f)$ volumetric heat capacity of ground (fluid) ($\text{J}\,\text{m}^{-3}\,\text{K}^{-1}$)
D length along the piping between the temperature probe location and the borehole inlet or outlet (see Fig. 1) (m)
Ei exponential integral
$g(t) = \frac{2\pi\lambda}{q_Z}(T - T_O)$ thermal response function
G fluid volume flow rate ($\text{m}^3\,\text{s}^{-1}$)
H depth of the borehole heat exchanger (BHE) (m)
r radial coordinate (m)
$p = \langle Q_{air}\rangle / Q_t$ part of the total heat rate transmitted to the ambient air
r_b radius of the BHE (m)
R_a thermal resistance between fluid and ambient air ($\text{K}\,\text{m}\,\text{W}^{-1}$)
R_b borehole thermal resistance ($\text{K}\,\text{m}\,\text{W}^{-1}$)
$q_z = \frac{GC_f}{H}(T_{in} - T_{out})$ heat flow per unit length ($\text{W}\,\text{m}^{-1}$)
Q_{air} heat dissipation rate to the ambient air (W)
$Q_t = GC_f(T^*_{in} - T^*_{out})$ total produced heat rate (W)
s coordinate along the pipe in the range from 0 to D (m)
$t_0(t_1)$ start (end) point of the time interval (s)
$t_r = r_b^2/\alpha$ short time scale for the BHE (s)
$t_s = H^2/(9\alpha)$ Eskilson (1987) steady-state time scale (s)
$t_z = H^2/\alpha$ large time scale for the BHE (s)
T temperature of ground (K or °C)
T_a ambient air temperature (K or °C)
T_f temperature of heat carrier fluid (K or °C)
T_0 undisturbed ground temperature (K or °C)
T_{in} inlet temperature of BHE (K or °C)
T_{out} outlet temperature of BHE (K or °C)
T^*_{in} measured inlet temperature of BHE (K or °C)
T^*_{out} measured outlet temperature of BHE (K or °C)
z vertical axial coordinate (m)

Greek letters
$\alpha = \lambda/C$ ground thermal diffusivity (m^2/s)
γ Euler's constant
λ ground thermal conductivity ($\text{W}\,(\text{K}\,\text{m})^{-1}$)
$\eta[=D/(R_a C_f G)]$ dimensionless parameter

Superscripts
$\overline{\ldots}$ arithmetic mean
$\langle\ldots\rangle \left(= \int_0^H \ldots dz/H\right)$ integral mean
$\langle\ldots\rangle_t$ time average
$\ldots\uparrow(\ldots\downarrow)$ up (down) directions for heat carrier fluid circulation

Subscripts
a ambient air

(Claesson and Eskilson, 1988; Gehlin and Hellström, 2003; Sanner et al., 2005; Witte et al., 2002) and North America (Austin, 1998; Beier and Smith, 2002; Beier, 2008; Shonder and Beck, 2000). Kelvin's ILS model is among the most widely used models for evaluation of response test data at sufficiently large times because of the fact that the TRT was actually devised on the basis of ILS theory (Ingersoll et al., 1954; Mogensen, 1983).

The FLS model overcomes some limitations of the ILS model: its solution has been expressed as an integral (Eskilson, 1987), given zero temperature at the boundary of the semi-infinite medium.

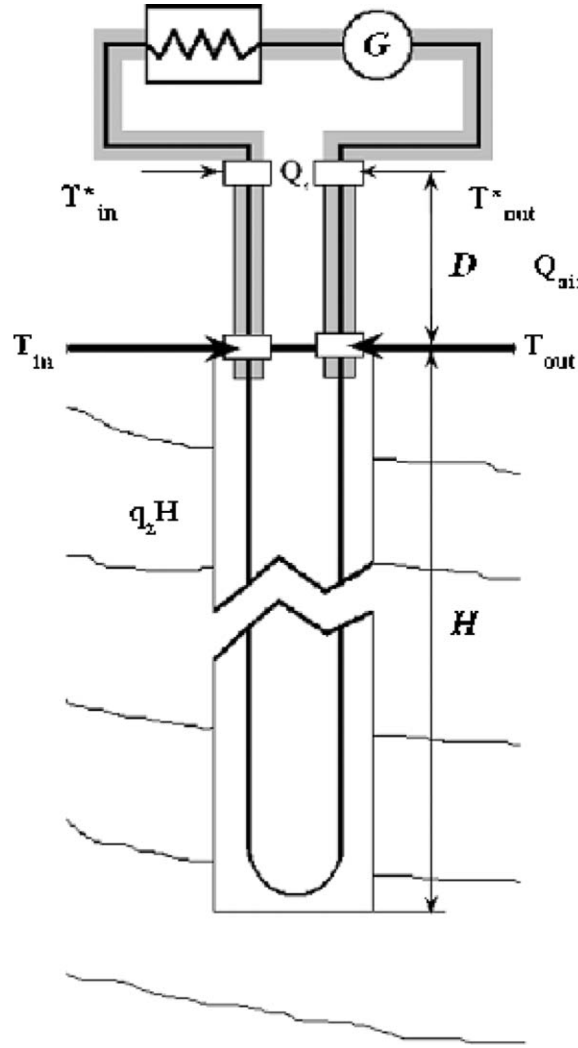

Fig. 1. Schematic of field test to measure ground properties.

The temperature response functions, so-called "g-functions" introduced by Eskilson (1987), are based on the solution of this model for the BHE temperature field at a constant heat load. The g-functions are computed for moderate times (Javed et al., 2009) and provide an asymptotic approach to the steady-state limit, which is not reached within the ILS model. The FLS solution for the ground temperature in the vicinity of the midpoint of the BHE depth was shown to be approximately the same as the classical result of the traditional ILS during the TRT (Bandos et al., 2009).

However, the best solution for applications is given by the mean integral temperature (Lamarche and Beauchamp, 2007; Zeng et al., 2002). This is because the average or effective thermal properties of the ground are used in the design. An exact solution for the temperature averaged over the borehole depth has been approximated, providing analytical formulae for a wide time range (Bandos et al., 2009) that account for the edge effects due to the vertical heat transfer along the borehole. These simple asymptotic expressions for the mean borehole temperature allow flexibility in parametric analysis of the test data. It is important to take account of the finite depth of the BHE because there is an incentive to install the minimum possible length and so decrease the cost of the ground source systems.

Evaluating TRT data based on the ILS model assumes that there is no heat transfer between the heat carrier fluid and the ambient air, and that there are no significant effects of boundary condi-