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Short-term fluid temperature variations in either a coaxial or U-tube borehole heat exchanger

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This paper uses composite cylindrical heat-source (CCS) models and typical thermal response test procedures to investigate two full-scale borehole heat exchangers (BHE); where one is a U-tube BHE, and the other, a pipe-in-pipe (coaxial) BHE. A previously developed CCS model is compared to a simplified infinite line-source (ILS) model. A time-varying heat-flux term is verified for the U-tube case, noting the error found when using the CCS model. A model is developed using a similar approach accounting for a coaxial configuration showing a root mean square error (RMSE) of less than 0.1 °C over the duration of the test.

1. Introduction

Short-term analysis of borehole heat exchangers (BHE) is important when considering systems that often undergo transient ground-loop operation; this will occur when the ground-loop is re-engaged after allowing the fluid temperatures to recover during cyclic operation (Luo et al., 2015). Short-term fluid temperature responses are needed for such a system since the coefficient of performance for a geothermal heat pump is largely based on its entering fluid temperature (Xu, 2007). In order to more accurately size ground-coupled heat pump (GCHP) systems, in the case of bore field design, a thermal response test (TRT) can be performed on-site to estimate the ground's thermal properties and an effective borehole thermal resistance (Gehlin, 2002). The borehole resistance is typically found for quasi steady-state conditions and is effectively the thermal resistance between the working fluid of a BHE and the surrounding ground. For transient conditions where short-term operation is experienced, it is desirable to size a bore field based not only on a steady-state borehole resistance, but also on the thermal capacity of the heat exchanger material. Analytical models for radial heat conduction are often used to interpret the time-varying temperature response in the working-fluid during a TRT. TRTs are typically performed using an above ground heater which delivers a constant rate of heat input to a working fluid being circulated through a fully operational BHE. The configuration of these heat exchangers in North America is often of a single U-bend pipe travelling the length of a backfilled borehole (considered here as a U-tube BHE) (Sarbu and Sebarchievici, 2014). However, many different configurations have been investigated worldwide (including concentric pipe-in-pipe heat exchangers considered here as a coaxial BHE) with the aim of lowering the effective borehole thermal resistance, and hence, the cost associated with a reduced required length of heat exchanger.

TRTs reportedly have a typical minimum duration of 10–52 h and can include an initial pumping phase, a heating phase, and a recovery phase (Liu and Beier, 2009). Prior to the test, it is required to allow the borehole to settle and approach an undisturbed temperature which usually takes 3–7 days. By monitoring the inlet and outlet temperatures experienced by the working fluid during a TRT, a mean fluid temperature can be deduced. The mean fluid temperature (often taken as the arithmetic mean of the inlet and outlet temperatures) from a TRT is often fit with an analytical model in order to estimate the required thermal properties of the ground

Abbreviations: BHE, borehole heat exchanger; TRT, thermal response test; GCHP, ground coupled heat pump; ILS, infinite line source; ICS, infinite cylindrical source; CCS, composite cylindrical source; RMSE, root mean square error.

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and borehole (Beier and Ewbank, 2012). A major downfall of previous analytical models is the assumption of a constant heat flux to the surroundings experienced uniformly along the depth of the borehole, where this is not the case during short-term transient operation of a ground-loop.

Traditionally, analytical models have been based off of Lord Kelvin's line source theory (leading to the *infinite line source* or ILS model) or Carslaw and Jaeger's cylindrical-source solutions (leading to the *infinite cylindrical source* or ICS model). The ICS model contains a response function that is commonly expressed in a Fourier-Bessel form and can be thought of as simply multiple line-sources placed around the periphery of a cylinder (Carslaw and Jaeger, 1959). For each analytical model, the solutions have been developed to estimate the temperature response in the ground or, for the case of composite models, in the surrounding composite media. These response functions – referred to in the application of ground heat exchangers as *g-functions* (g) (Ingersoll et al., 1954) – are related to the Fourier number (Fo). The Fourier number is a dimensionless time variable that characterizes transient heat conduction by the ratio of conductive heat transport to the quantity storage rate ($\alpha\tau/L^2$) where; α is the thermal diffusivity of the material, τ is the characteristic time, and L is the length through which heat conduction occurs.

Conventional models for borehole wall temperature variations are often one-dimensional considering only radial heat conduction from a constant heat source in the ground, which is assumed to be a homogenous medium (Philippe et al., 2009). The borehole is typically limited to a small enough diameter to be able to ignore the heat capacities of the material within it; however, in order to effectively interpret short-term temperature responses for a TRT it is necessary to accurately represent the properties of the bore materials (grout, pipes, and working fluid) (Li and Lai, 2013). To do this, g-functions often incorporate two dimensions; this is especially important for conventional U-tube heat exchangers where the heat source does not produce a response that is symmetric in the radial direction (Li and Lai, 2012).

Typically a BHE is sized based off of quasi steady-state results where the thermal properties of the borehole material hold less of an effect; however, considering a transient response in the composite media of a BHE is beneficial when considering on/off performance (Pasquier and Marcotte, 2012). Performance during transient operation of a ground loop is important when considering peak loads and the variability of hourly building loads that often result in a transient thermal response. Composite models which consider the thermal capacity effects of bore materials can be used to more accurately simulate the short-term temperature response during a TRT (Yavuzturk and Spitler, 1999). Furthermore, when considering long-term temperature responses, it is necessary to consider the effects of axial heat conduction by considering a quasi-three-dimensional analytical model to account for fluid advection in the vertical direction (Rees and He, 2013; Pasquier and Marcotte, 2014). A *finite line source* (FLS) model, originally proposed by Eskilson (1987) and further developed by Zeng et al. (2002) and Lamarche and Beauchamp (2007), considers a finite length of heat exchanger to account for axial effects during long-term analysis (Bandos et al., 2009). The model by Lamarche and Beauchamp solves the pertaining double integrals in a unique manner which is computationally effective; even more recently, research has been conducted towards reducing the computation time of the FLS and similar analytical models (Pasquier, 2015). In the present paper, models which consider axial effects are outside of the scope of research where focus is kept on developing a simple, one-dimensional composite model for application to coaxial BHE's.

It has been previously shown using a 3D numerical model that the arithmetic mean of the surface inlet/outlet temperatures is not a true representation of the average working fluid temperature as it creates an overestimation in the borehole thermal resistance which can lead to over design (Marcotte and Pasquier, 2008). This overestimation creates an error that can be attributed largely to the fact that the fluid temperature response does not vary linearly with depth. It is also noted during short-term operation of a BHE that the heated working fluid does not immediately produce a constant heat flux to its surroundings uniformly along the depth of the borehole, but instead approaches this constant value based on the transient fluid residence time within the BHE. Taking the "p-linear" average has been suggested to improve the approximation of a mean fluid temperature deduced from surface temperature responses; this method makes the assumption that the fluid temperature response raised to the exponent, p, will vary linearly between the temperature response at the inlet and the outlet each at the same power, p. The value of p may vary with time and an algorithm has been previously proposed to estimate the values of p at each sampling interval and the required ground thermal properties during a TRT (Zhang et al., 2014). This $p(t)$*-linear* method requires either a valid theoretical or measured temperature profile along the flow path of the heat exchanger and cannot be used with a simple one-dimensional model without such data.

Another method of performing a TRT is to directly measure the vertical temperature profile of the working fluid rather than only measuring the entering and exiting temperatures. A distributed thermal response test (DTRT) uses fiber optic cables placed along the pipes of the BHE to measure the temperature variation of the working fluid along its flow path (Fujii et al., 2009; Acuña and Palm, 2010). These tests would typically require more computationally extensive and complicated numerical or analytical models for accurate interpretation; however, they may be applied to either a coaxial or U-tube BHE. From this, a need can be found for a simple analytical model for the interpretation of short-term fluid temperature variations during a typical TRT utilizing a coaxial BHE since many already exist for U-tube BHEs.

A composite cylindrical source (CCS) model presented by Hu et al. (2014) is investigated in Section 2.3 for the simulation of short-term fluid temperature variations during a TRT when considering a single, small-diameter U-tube BHE. Considering transient radial heat conduction within and around the borehole is important when designing systems for peak loads or cyclic operation of the ground-loop or heat pump. In order to model the transient response within a borehole the thermal storage rate of the individual materials should be considered. The model incorporates the thermal storage of the grouting material and has been previously validated for short-term simulation of ground heat exchangers having large diameters, referred to as energy piles, where the thermal interference between the pipes can be greatly reduced.

In the case of deep small-diameter U-tube BHE's, the ILS model can be used to accurately determine ground thermal properties; this may then be coupled with an analytical solution for steady-state heat transfer within the borehole. In Section 4 of this paper, the CCS model is compared to a simplified ILS model which is coupled with the *multipole method* and a time-varying heat-flux term using principles of temporal superposition. A time-varying heat-flux term is used as a simplification to represent the average distribution of the short-term heat-flux to the ground. A full-scale TRT is analyzed for a grouted (thermally enhanced grout or TE grout) U-tube BHE having known properties in order to test the CCS model for smaller diameter boreholes against the p-linear average, yielding a root mean square error (RMSE) of 0.37 °C; this is compared in contrast to a RMSE of 0.05 °C when using the simplified ILS model discussed.

A composite model is then developed for the case of a coaxial BHE using consistent logic as found in the previous CCS model. For the coaxial case, the simulation of surface fluid temperatures during a TRT may be performed while discarding the equivalent