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Determination of vertical borehole and geological formation properties using the Crossed Contour Method

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ABSTRACT

This paper presents a new method called the Crossed Contour Method for determining the effective properties (borehole radius and ground thermal conductivity) of a vertical ground-coupled heat exchanger. The borehole radius is used as a proxy for the overall borehole thermal resistance. The method has been applied to both simulated and experimental borehole Thermal Response Test (TRT) data using the Duct Storage vertical ground heat exchanger model implemented in the TRansient SYstems Simulation software (TRNSYS). The Crossed Contour Method generates a parametric grid of simulated TRT data for different combinations of borehole radius and ground thermal conductivity in a series of time windows. The error between the average of the simulated and experimental bore field inlet and outlet temperatures is calculated for each set of borehole properties within each time window. Using these data, contours of the minimum error are constructed in the parameter space of borehole radius and ground thermal conductivity. When all of the minimum error contours for each time window are superimposed, the point where the contours cross (intersect) identifies the effective borehole properties for the model that most closely represents the experimental data in every time window and thus over the entire length of the experimental data set. The computed borehole properties are compared with results from existing model inversion methods including the Ground Property Measurement (GPM) software developed by Oak Ridge National Laboratory, and the Line Source Model.

1. Introduction

The National Institute of Standards and Technology (NIST) designed and constructed the Net-Zero Energy Residential Test Facility (NZERTF) (Davis et al., 2014; Fanney et al., 2015) to capture detailed performance of a net-zero energy residence that has the function and aesthetics of a typical modern home. As part of this effort, a vertical ground loop heat exchanger (GLHX) was installed at the site. A model of this GLHX was implemented in the TRaNsient SYstems Simulation (TRNSYS, 2012) program to simulate the thermal response.

This paper focuses on a series of studies conducted to determine the ground formation and borehole parameters associated with the vertical GLHX. A model of the bore field was utilized to infer the bore field characteristics. Initially, the modeled ground thermal properties, conductivity and heat capacity, were varied in an effort to match the experimental measurements. However, it was found that both the ground and borehole geometric parameters should be adjusted in order to achieve a good fit to experimental data. In this work, the average borehole radius (r_b) was varied as well as the ground formation thermal conductivity (k_g); these parameters were selected because the temperature profiles produced by the TRNSYS DST model had the greatest sensitivity to these parameters. The effective ground volumetric heat capacity (C_g) may also be an important parameter for GLHX system, but the accurate determination of thermal capacity from test data was not considered in this analysis because the temperature profiles were not very sensitive to it. The average borehole radius, as defined by half of the hole diameter, is used as a proxy for the borehole thermal resistance (R_{bt}). The borehole thermal resistance is related to a number of uncertain borehole parameters that include the U-tube spacing, the presence of air gaps between the U-tubes and the fill material thermal conductivity. All of these parameters affect the borehole resistance to heat transfer. The impact on thermal performance of changing any of these parameters can be captured by adjusting the average borehole resistance. Radius was chosen as borehole resistance proxy due to the high sensitivity of the borehole resistance approximation to changes in radius. The TRNSYS

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Nomenclature

C_g Ground formation effective volumetric heat capacity (kJ m^{-3}K^{-1})
k_g Ground formation effective thermal conductivity (W m^{-1}K^{-1})
k_{fill} Borehole backfill effective thermal conductivity (W m^{-1}K^{-1})
DeltaSlope Error measure calculated by taking the difference between the linear slopes (generated by linear regression) of two data sets (K s^{-1})
MBE Error measure calculated by taking the mean bias error difference (°C)
$\dot{Q}$ Total borehole heat transfer rate (kW)
r_b Average borehole radius (cm)
r_p Average outer radius of the U-tube pipe (cm)
R_{bt} Total borehole thermal resistance (K kW^{-1})
RMS Error measure calculated by taking the rms difference (°C)
t_0 Initial time of a data sample (h)
t_f Final time of a data sample (h)
T_0 Undisturbed ground formation temperature (°C)
T_b Mean borehole surface temperature (°C)
T_f Average fluid temperature in the borehole (°C)
$T_{f,in}$ Fluid temperature entering the borehole (°C)
$T_{f,out}$ Fluid temperature exiting the borehole (°C)
$T_{f,modeled}$ The average fluid temperatures at each time step for the modeled data set (°C)
$T_{f,measured}$ The average fluid temperatures at each time step for the measured data set (°C)
x_c Half the center-to-center distance between U-tube pipes (cm)

Abbreviations
DST Duct storage model
GLHX Ground loop heat exchanger
GPM Ground property measurement tool, developed by Oak Ridge National Laboratory
GSHP Ground source heat pump
LSM Line source method
MBE Mean bias error
NIST National Institute of Standards and Technology
NZERTF Net-Zero energy residential test facility
RMS Root mean square error
TRT Thermal response test

DST model does not account for the heat capacity of any of the components within the borehole. The work described here presents a new method for selecting the combination of ground properties and borehole parameters that provides the best match to experimental results. In this paper the thermal conductivity of the ground and the borehole radius are used for this purpose. This method is referred to as the Crossed Contour Method. This paper describes the development of the method and compares its results to alternative methods.

2. Background of borehole property measurement

When used in heating and cooling applications, ground source heat pumps (GSHPs) have the potential to reduce energy consumption and carbon dioxide output while saving consumers money over the lifetime of the heat pump equipment as noted in many studies, e.g., Nagano et al. (2006), Liu (2010), Garber et al. (2013), and Sarbu and Sebarchievici (2014). GSHPs operate with high efficiency because they are coupled with GLHXs that serve as a heat source/sink with a smaller temperature lift, compared to conventional air-source equipment. One of the main barriers to greater adoption of the GSHP technology is the high initial cost of the system relative to conventional heating and cooling systems in the U.S (California Energy Commission, 2014). A large portion of the initial cost is related to the installation of the GLHX (Yang et al., 2010; EPA, 2016). It is common for GLHXs to be made larger than necessary due to uncertainty in the ground properties and thus the actual heating/cooling capacity of the loop. Reducing this uncertainty can reduce the initial cost and thus improve the economic viability of these systems (Kavanaugh, 2000).

In geothermal applications, the geological formation properties of greatest interest are the undisturbed formation temperature (T_0), the ground thermal conductivity (k_g), and the volumetric heat capacity (C_g). These properties together are the primary factors that determine the potential capacity of a bore field of given length, and all of these properties are required in a ground-coupled heat exchanger model to provide an estimate of its short- and long-term performance. The geometric and thermal properties governing the behavior of the borehole itself, such as its radius and grout thermal conductivity, are also needed to prepare an accurate model (Javed and Spitler, 2016). These properties can be combined into an effective thermal resistance between the working fluid and the ground formation. The actual ground properties may change with the position in the formation, time and the presence of ground water flow as described by (Witte, 2013), (Fujii et al., 2009), and (Signorelli et al., 2007). However, some of this variation is captured in the effective properties determined in experimental short-term test of the GLHX thermal behavior.

The current methods of ground property assessment include: estimation based on drill logs from neighboring sites, estimation of properties using known ground/rock thermal properties of borehole cuttings, laboratory thermal tests performed on core samples, or performing a Thermal Response Test (TRT) on a test borehole to measure the formation's properties in situ (IGSHPA, 2009; Casasso and Sethi, 2014). Estimates based on neighboring drill logs or onsite drill cuttings are less expensive and less accurate than the alternatives. These methods are sometimes selected for residential systems because more accurate tests are often cost prohibitive. In larger commercial installations, oversizing the system is a significant expense so acquiring more accurate property data to properly size the system is cost effective. Taking core samples and running tests on them provides better localized ground/rock property data, but is relatively slow and expensive, only provides information on the material in the borehole itself, and requires drilling a borehole anyway. Due to these factors, in-situ TRTs are more commonly used (Austin 2000). TRT tests were performed at the NZERTF in order to provide more accurate ground property data for GLHX sizing and model development.

The Thermal Response Test involves drilling a borehole and setting up a GLHX, usually implemented as a single U-tube, within the borehole. The hole is then backfilled with grout and allowed to return to the undisturbed ground temperature. For the test itself, a constant flow of working fluid is sent through the GLHX and allowed to equilibrate with the surrounding ground temperature in order to measure T_0. Once equilibrium has been established, a constant heat input is applied to the fluid. The temperatures going into and coming out of the borehole are monitored in order to infer the average formation thermal properties. Alternatively, the downhole borehole temperature profile at rest (i.e. T_0) and during the TRT can be monitored with fiber-optic sensors (Fujii et al., 2009). The current standard is to estimate average properties for the ground volume affected by a 36 h to 48 h constant heat pulse of 49 W to 82 W per meter of bore (Kavanaugh, 2001) Under ideal conditions, this test duration also reduces, but does not eliminate, the effect