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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 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 simulated and experimental bore field outlet temperature 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.

Key Words: Thermal Response Test, Ground Property Measurement, Parameter Estimation, Ground Thermal Conductivity, Ground Loop Heat Exchangers, TRNSYS Optimization, Geothermal

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Nomenclature and Abbreviations

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

Abbreviations	Definition
DST	Duct Storage Model
GLHX	Ground Loop Heat Exchanger
GPM	Ground Property Measurement tool, developed by Oak Ridge National Laboratory
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

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., 2014) 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 must 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. Ground thermal 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 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 have the potential to greatly reduce energy consumption and carbon dioxide output while saving consumers money over the lifetime of the heat pump equipment (Liu, 2010). One of the main barriers to greater adoption of this technology is the high initial cost of the system relative to conventional heating and cooling systems. A large portion of the initial cost is related to the installation of the ground loop heat exchanger (Yang, Cui, & Fang, 2010). It is common for ground loops 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.

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. 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).

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. Estimates based on neighboring drill logs or onsite drill cuttings are less expensive and less accurate than the alternatives. These methods are often selected for residential systems because the cost to perform a more accurate test often exceeds the cost of oversizing the system using a safety factor. 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 ground loop heat exchanger (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. The current standard is to estimate average properties for the ground volume affected by a 36 hour to 48 hour constant heat pulse of 49 W to 82 W per meter of bore (ASHRAE, 2011) Under ideal conditions, this test duration also reduces, but does not eliminate, the effect of the borehole thermal resistance on the results. Analytical techniques have been developed to extract some borehole properties from TRT data (Gehlin, 2002).

TRT tests do not directly measure ground or borehole properties. Instead they measure the heat transfer rate to the borehole and the temperature of the working fluid. The desired properties are then inferred using model inversion, i.e. adjusting the ground properties in a model until the results predicted by the model match the measured quantities. For the most common model, the Line Source Model (LSM), this process uses an equation that relates the slope of a linear fit of the average temperature data plotted against time on a log scale to the ground conductivity (Austin, 1995). For more complex models, multiple model runs and more sophisticated optimization methods must be used.

The potential error associated with using the LSM model to analyze TRT data was examined by Witte (2013). The analysis assumes typical measurement precision and accurate measurements and does not include any spatial and temporal variation of the ground properties or deviation of the TRT test from ideal conditions. A borehole resistance term, which is not included when estimating the formation thermal conductivity using the LSM, was estimated with a modified form of the model. The analysis showed the errors are on the order of 5 % for the ground thermal conductivity and 10 % to 15 % for the borehole resistance. A similar examination of the LSM was done by Signorelli et al. (2007), who looked at the sensitivity of the LSM to the test duration, heterogeneous sub-surface conditions, ground water movement, and variations in the data quality. The analysis was done with data sets generated using a numerical model created by the FRACTure geological modeling system. The numerical model was later validated with experimental test data and it was found that the expected error of the measured formation conductivity was about 10 %.

Borehole Heat Exchanger Models

Three GLHX models were used in this study to determine properties using experimental data generated from three TRT tests conducted by NIST. These models are the Line Source Model, the numerical model used in the Ground Property Measurement (GPM) tool developed by Oak Ridge National Laboratory (ORNL), and the TRNSYS implementation of the Duct Storage Model (DST).

The LSM is the industry standard for TRT analysis. It is based on the solution to an infinite line heat transfer problem with constant heat flux in an infinite medium (Ruan and Horton, 2010). The model greatly simplifies the geological formation and the borehole, but for long test durations with a constant heat input the LSM can provide reasonably accurate estimates of the ground properties. The analytical cylinder source model (Ingersoll and Zobel, 1954) has similar limits to the LSM in that it uses simple approximations of the geological formation and borehole.

ORNL developed a numerical infinite cylinder borehole model and used it to create the GPM tool (Shonder and Beck, 1997). The GPM tool is able to handle short time scale transients and unsteady heat inputs, providing higher accuracy and flexibility than the afore-mentioned analytical models. The Nelder-Mead optimization function is used to search for a set of formation conductivity (k_g) and borehole resistance (R_{bt}) that best matches the model predictions to a TRT data set. The in-situ determination of effective borehole resistance is an additional benefit of using the GPM tool, because this resistance is not determined using the analytic models.

The TRNSYS Type 557 borehole field component model is a full implementation of the Duct ground heat STorage (DST) model first presented by HellStrom (1989). The DST model is a hybrid analytical/numerical model that breaks the bore field heat transfer problem into three sub-problems: global, steady flow, and local. The sub-problems are then solved and superimposed in order to provide a solution. Similar to the GPM tool, the DST model captures the effective borehole resistance in addition to the ground thermal conductivity. In addition to the short-term predictions presented here, the TRNSYS ground heat exchanger model readily computes performance on a seasonal or yearly basis whereas the GPM tool does not. Therefore, using the TRNSYS ground heat exchanger model to tune the borehole parameters provides the added benefit of tuning the parameters using the same model (and related assumptions) and software platform that will be used to carry out the long-term simulations.

Many of the geometric and thermal parameters of the borehole have similar effects on performance. Due to the difficulty in teasing out which parameter is responsible for a change in the behavior of the borehole and the uncertain nature of a number of these parameters, they are typically lumped into a single equivalent borehole thermal resistance term, R_{bt}, defined as:

$$R_{bt} = (T_f - T_b)/\dot{Q} \quad , \tag{1}$$

where T_b is the mean borehole surface temperature, $\dot{Q}$ is the heat transfer rate, and T_f is the average fluid temperature, defined by:

$$T_f = \frac{T_{f,in} + T_{f,out}}{2} \quad , \tag{2}$$

where $T_{f,in}$ is the entering fluid temperature and $T_{f,out}$ is the exiting fluid temperature. The DST model uses a borehole resistance approximation given in Equation (3). In this study, the borehole resistance is modified by adjustment of the borehole radius, r_b.

$$R_{bt} = \frac{1}{4\pi k_{fill}}\left[\ln\left(\frac{r_b}{r_p}\right) + \ln\left(\frac{r_b}{2\,x_c}\right) + \frac{k_{fill} - k_g}{k_{fill} + k_g}\ln\left(\frac{(r_b/x_c)^4}{(r_b/x_c)^4 - 1}\right)\right] \quad , \tag{3}$$

where k_{fill} is the borehole backfill thermal conductivity (a.k.a., the grout conductivity), r_p is the outer radius of the ground loop pipes, and x_c is one half of the center to center spacing between the U-tube pipes.

3. Description of the Site and Data Sets Used

The NIST NZERTF has a 45.1 m (148 ft) deep vertical U-tube (borehole) GLHX, which contains three boreholes connected by buried piping. Additionally, before construction of the NZERTF, a single 91.4 m (300 ft) deep test borehole was drilled at the site of one of the vertical boreholes. Thermal response data were collected for both the GLHX and the test borehole and were used to estimate soil property data.

Three thermal response tests were conducted on the vertical GLHX using a TRT rig constructed inside the test facility. These data sets are referred to as Thermal Response Tests 1 (“TRT-1”), 2 (“TRT-2”) and 3 (“TRT-3”), carried out Jan. 25, 2013, Apr. 1 2013, and Sept. 9, 2014, respectively. The GLHX was not coupled with a heat pump before or in-between any of the tests. While the TRT test maintained a constant heat input to the bore field, each individual borehole did not receive a constant heat input; therefore, the properties estimated by the LSM model have significant uncertainty because the LSM model assumes a constant heat input. The boreholes do not receive constant or equal heat input because they have somewhat different lengths of supply and return tubing (and therefore the fluid has more time to exchange heat with the ground before entering the top of the borehole), and the flow rates are not exactly constant and equal throughout the test.

For the test borehole, the geological formation was recorded during drilling, and a TRT was performed using a mobile TRT rig operated by a contractor. The instrumentation used by the contractor had larger uncertainty compared instruments installed on the NZERTF TRT rig, however, mobile TRT data are still useful for comparison and are referred to as the conductivity or “K-test” data. The data from the test were provided by the test contractor (Schnabel Engineering, 2010).

The test facility therefore has data for a total of four boreholes, including three for the GLHX, and one for the test borehole. The four tests (TRT-1, TRT-2, TRT-3, and K-test) effectively yielded ten TRTs; three each from the TRT-1, TRT-2 and TRT-3, and one from the K-test. Each TRT measures the response of three boreholes in the vertical U-tube GLHX. Each of the ten TRT data sets was run through parametric simulations and estimates of the ground formation thermal parameters were made using several methods. The test borehole (K-test) and borehole #3 from the TRT-1 and -2 data sets are at proximate locations and therefore the ground thermal properties are expected to be similar but not exactly the same because the boreholes have substantially different depths (K-test corresponds to a 91.4 m bore and TRT-1 and 2 have 45.1 m bores) and therefore different geologic formation. Additionally, the boreholes were drilled by different companies with different equipment and are unlikely to have identical effective radii or tube spacing. As this paper shows, the geometry of the boreholes can have a major impact on the predicted ground thermal properties.

4. TRNSYS Model

A simulation model of the TRT was created using TRNSYS 17 (Thermal Energy System Specialists LLC, 2012) with the DST model (Type 557). The simulation uses measured heating rate and mass flow rate as inputs to the model from one of the tests, and then outputs predicted values of the fluid inlet and outlet temperature as a function of time. The predicted temperature profiles were then written to a text file and processed using MATLAB software (MATLAB 2014). Additional data and a listing of the programs used are provided by Leyde (2014).

The physical borehole system has a time lag between the input temperature and the outlet temperature as a result of the time required for the working fluid to flow through the piping. The DST model in TRNSYS does not account for this effect. The estimated plug flow time of the actual system is on the order of the time step (5 minutes) used in the simulation. In order to capture this time lag, a time delay was added to the TRNSYS simulation. The plug flow time for the U-tube was estimated based on the tube length, internal tube radius, and volumetric flow rate. For the single borehole during the K-test the plug flow time constant was 4.7 min, whereas the plug flow time for an individual borehole during the TRT-1 and TRT-2 tests was 3.9 minutes. A time lag of 1 TRNSYS time step (i.e., 5 minutes) was introduced to the modeled borehole outlet temperature in all of the simulations.

The borehole radius and formation thermal conductivity were estimated by minimizing the error between the simulated and the measured temperature profiles. The error minimization used in this work was accomplished by finding the intersection of contours of zero error for different time windows of data, as described in Section 5. Several other parameter estimation methods were also used to provide a basis of comparison; these are based on the LSM, the Oak Ridge GPM tool, and a MATLAB controlled optimization of TRNSYS simulation where temperature error was minimized using a single time window that includes the entire time series of data.

MATLAB programs were created to process the TRNSYS output files in order to calculate the mean bias error (MBE) and root mean square (RMS) error as well as the deviation in the time rate of change of the simulated and recorded temperature profiles (*DeltaSlope*), using equations 4-6.

$$MBE = \frac{1}{N}\sum_{t_0}^{t_f}(T_{f,\ modeled,t} - T_{f,\ meassured,t}) \tag{4}$$

$$RMS = \sqrt{\frac{1}{N}\sum_{t_{0f}}^{t_f}(T_{f,\ modeled,t} - MBE - \ T_{f,\ meassured,t})^2} \tag{5}$$

$$DeltaSlope = \frac{dT_{f,\ modeled,t}}{dt} - \frac{dT_{f,\ measured,t}}{dt} \tag{6}$$

In Equations (4) and (5), t_0 and t_f are the initial and final times of the sample and N is the total number of data points in the sample. $T_{f,modeled,t}$ and $T_{f,measured,t}$ are the averages of the inlet/outlet fluid temperatures at each time step for the modeled and measured data sets. These temperatures are determined using equation (2). In Equation (6), the modeled and measured slopes are the slopes associated with linear regressions of the modeled and measured average borehole temperatures with respect to time.

5. Development and Description of the Crossed Contour Method

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 simulated and experimental bore field outlet temperature 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.

A TRNSYS DST model was used to demonstrate the concept of using intersecting minimum error contours to estimate borehole parameters. The temperature response was computed first for a GLHX with specified nominal borehole parameters of k_g = 3.3 W m^{-1}K^{-1} and r_b = 5.5 cm; the resulting temperature data are treated as a surrogate for experimental data. Next, the TRNSYS DST model was operated in an environment where the borehole parameters were not known *apriori*, and needed to be determined. The simulation was carried out with parametrically varied values of k_g and r_b, and the response was compared with the surrogate experimental data. Combinations of parameters that resulted in zero *DeltaSlope* error were used to construct contours in the parameter space of ground thermal conductivity (k_g, y-axis) versus borehole radius (r_b, x-axis) for different simulation time windows as shown in Figure 1. It is not possible to determine the k_g and r_b parameters from a single contour because there are multiple solutions that all satisfy the zero *DeltaSlope* error requirement. However, it has been observed that the contours for all of the time windows cross at a single point, which corresponds to the borehole radius and ground thermal conductivity parameters that make the simulation best match the experimental data for the entire test duration. This method of using the contour intersection point to determine borehole parameters is referred to as the Crossed Contour Method.

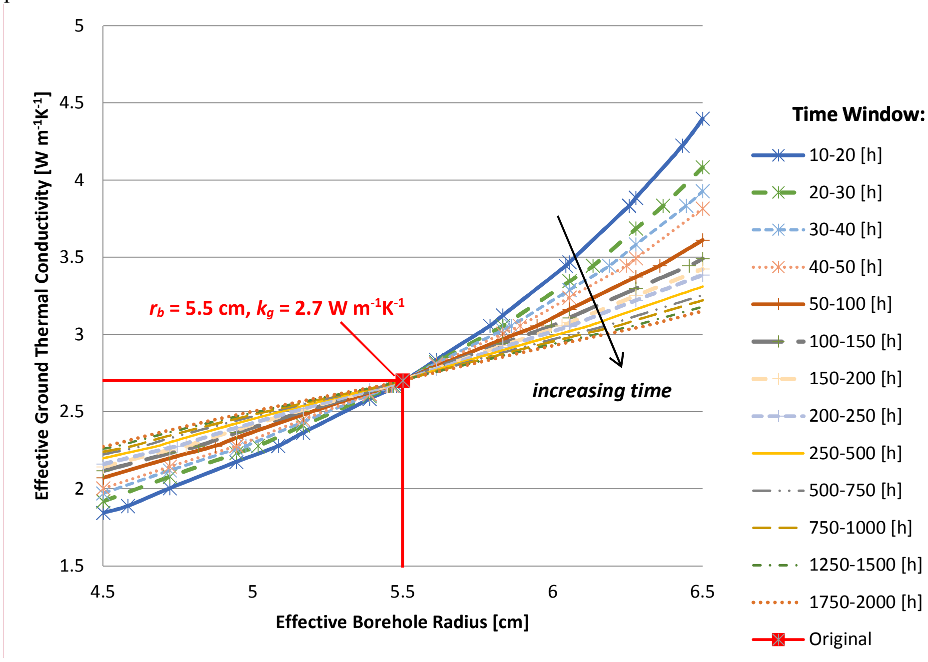

Figure 1: Contours of zero Delta Slope Error for simulated TRT test (representing Borehole 1) for 2000 hours.

The Crossed Contour Method is a parameter estimation method and thus other models, parameters, error measures, time windows, and independent variables (in place of time) could be used. This method is effective as the radius and thermal conductivity have different effects on the temperature profiles at different time scales and neither effect is really ever negligible, particularly during the duration of any TRT test. For the results shown in Figure 1, where modeling results are used as a surrogate for data, the method works perfectly and the intersection is a clearly defined, unique point.

It is interesting to note that the sensitivity of ground thermal conductivity to the selection of borehole radius does not completely disappear with increased TRT duration, even out to 2000 hours. This is contrary to the assumption used in the Line/Cylinder Source Models, which assumes that after an initial time period the thermal response (and subsequent calculation of ground conductivity) the is independent of the borehole resistance (which is effectively represented here by the borehole radius).

For experimental data sets this method still works, albeit not as cleanly. When comparing a model to experimental data, there will be differences between the model used in the parameter

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Commented [HMS2]: change "hr" to "h" estimation, in this case the TRNSYS DST model, and the actual experimental data. These differences occur as a result of errors in the measurements and the inability of the simplified model to represent the physical experiment. When these differences are not captured by the parameters being estimated, k_g and r_b (which is a proxy for R_{bt}), the modeled temperature profiles do not perfectly match the experimental profiles in all time windows. Consequently all of the error contours will not intersect at a single, unique set of parameters. The k_g and r_b parameters that are selected are those values that minimize the error summed for all the time windows that are to be considered. Note that the Crossed Contours method is not restricted to a particular set of parameters. The borehole radius and ground conductivity were selected in this analysis, but the method could be used to study other parameter sets such as the grout thermal conductivity and ground thermal capacitance. For the relatively short-term data presented here, the temperature profiles were not very sensitive to the ground thermal capacity so it was not selected as a tuning parameter.

Figure 2 shows the *DeltaSlope* error contour plot for a simulation of K-test, where the Crossed Contour Method is used to identify the values of r_b and k_g that capture the test borehole parameters. The contours of zero *DeltaSlope* error are plotted for different 5-hour time windows yielding ground thermal conductivity and borehole radius, 3.3 W m^{-1}-K^{-1} and 5.7 cm, respectively. The same results were found when the *MBE* was used in conjunction with the Cross Contour method. Figure 3 shows the *DeltaSlope* error contour plot for a simulation of TRT-1, Borehole 1 yielding ground thermal conductivity and borehole radius, 2.6 W $m^{-1}K^{-1}$ and 5.4 cm, respectively.

All of the parameters estimated using the Crossed Contour Method produce good fits between the modeled and experimental data. However, the inclusion of early data in the analysis results in lower estimates of thermal conductivity and larger estimates of borehole radius. This behavior is due to the DST model over-predicting the time rate of change of the average working fluid temperature during short time transient events due to the simplifications in estimating the borehole thermal capacitance. In the TRNSYS DST implementation only the heat capacity of the working fluid and of the ground formation are considered; the capacitance of the U-tube, borehole backfill/grout, and any casing that is present are all ignored.

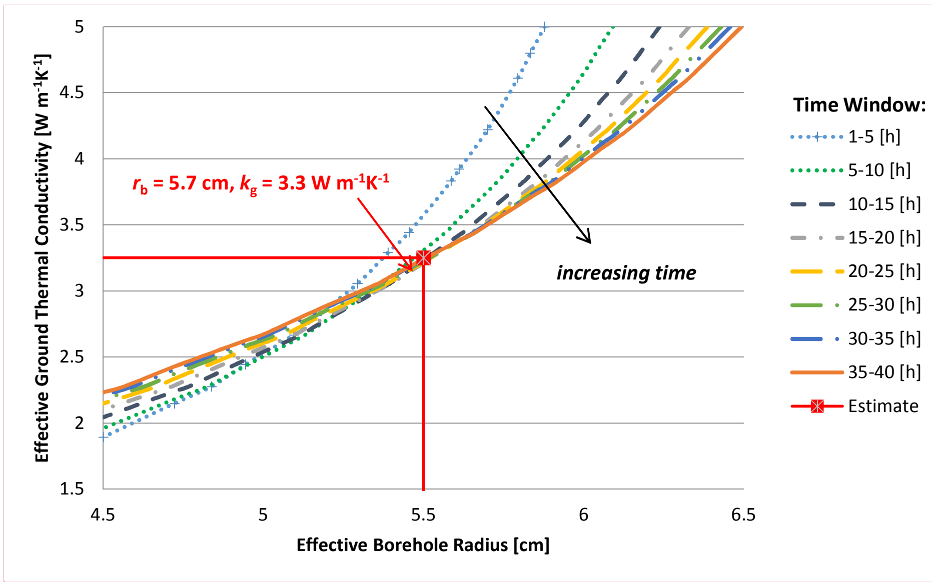

Figure 2: Contours of zero Delta Slope Error for data from the K-test (representing Borehole 1) for 40 hours.

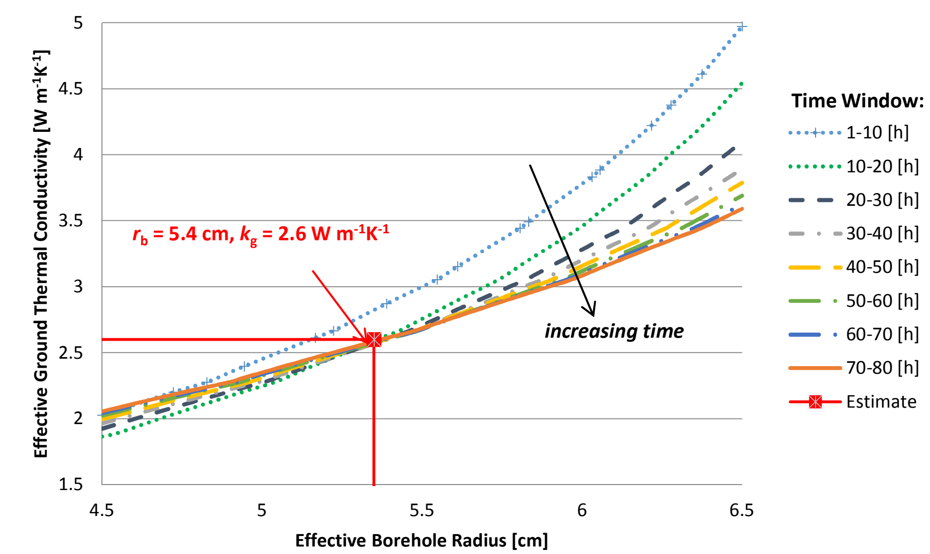

Figure 3: Contours of zero Delta Slope Error for data from the TRT-1 borehole 1 test for 80 hours.

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The Crossed Contour Method offers several benefits including easy visualization of the results, computational efficiency, and flexibility. These are discussed more completely below.

Visualization of results: The borehole parameters are quickly and clearly identified as the approximate intersection point of the contours on the borehole parameter parametric chart as seen in Figures 2-3. This chart could be used to check an automated version of a Crossed Contour analysis. Furthermore, the Crossed Contour chart clearly shows outlier data that should be eliminated for the property estimation. For example, the 1 h to 10 h time window error contour in Figures 2 and 3 does not intersect with the approximate intersection of the other error contours because the DST model cannot match the experimental data both in early and later time periods. The inability of the DST model to predict very short term behavior is caused by the known inaccuracy related to the borehole heat capacity. If this inaccuracy had not been previously known, the Crossed Contour chart would have directed attention to it and guided the decision to not include the 1-10 hour data. Finally, the error contour plots also provide a useful visualization of how sensitive the estimation of one parameter (e.g., the thermal conductivity) is to the other parameter (e.g., the effective borehole radius). Figure 3 shows that near the contour intersection point, a difference in borehole radius of 0.5 cm changes the conductivity prediction by 0.8 W $m^{-1}K^{-1}$ (about 25 %).

Computational efficiency: Running a large number of simulations ahead of time using different combinations of the parameters (k_g and r_b) allows the resulting simulated temperature profiles to be used in a manner similar to a look-up table that can be accessed quickly in order to prepare the crossed contour plots and visualize the results. The computation time required for multiple TRNSYS simulations of a TRT with differing radius and conductivity parameters is small. The use of multiple time windows and contour plotting allows continuous trends in the error measurement to be extrapolated from a finite number of simulation runs and allows for a best estimate of the borehole parameters to be predicted, even though a simulation with those specific values has not been run.

Flexibility: The Crossed Contour Method is a flexible parameter estimation technique that can be applied using modeling tools other than TRNSYS, other independent parameter sets, and other measures of the error. Also, the method can be applied to software with no built-in optimization capabilities (which can be used to find the best property estimates); the utility of this characteristic is demonstrated here with use of the TRNSYS DST model because it was desirable to use the same model for parameter tuning (with short-term measurements and simulations) and for longer-term system simulations (not presented here) in order to avoid inconsistencies related to differences in model assumptions.

6. Results of the Parameter Estimates

The Crossed Contour Method was compared to three other methods. The LSM analysis does not model the borehole itself and therefore a borehole radius must be assumed in order to obtain thermal conductivity and capacity. Likewise, the GPM tool takes in the nominal borehole parameters and calculates a borehole thermal resistance in order to optimize the ground thermal conductivity and heat capacity. Both the LSM and GPM methods used a nominal borehole radius of 5.7 cm. The third method, the direct TRNSYS optimization, integrates the same TRNSYS DST model that was used in the Crossed Contour simulations with the MATLAB "fminsearch" function, which is an implementation of a Nelder-Mead optimization routine. This method is a direct, two dimensional minimization problem in which the borehole radius and thermal conductivity are varied in order to minimize the discrepancy, as measured with RMS error, between the predicted result and measured data over the *entire* test period, excluding some amount of initial data. The parameters presented here as the "TRNSYS optimization" are the averages of the results produced by excluding 4 different lengths of initial data: (10 , 20, 30, and 40) h. Unlike the GPM method, the direct TRNSYS optimization and the Crossed Contour Methods vary borehole thermal resistance and ground thermal conductivity while assuming a nominal ground heat capacity.

The optimum parameter estimates generated from each data set by every analysis method are summarized in Table 1. For the ten tests presented here, the estimates of r_b and k_g range from 4.7 cm to 5.7 cm and 1.8 W m^{-1}K^{-1} to 3.7 W m^{-1}K^{-1}, respectively. The range of computed conductivity is remarkable considering: (1) the estimation methods use the same data sets to select the parameters, (2) the close proximity of the boreholes to each other, and (3) tests TRT-1, 2, and 3 were carried out for the same set of boreholes. Some of this variation appears to represent variation in the data itself. Analysis of the K-test test data yields a higher value of k_g regardless of the analysis method that is employed. Other variations appear to be related to differences between the analysis methods; the direct TRNSYS optimization generally yields the highest k_g and the lowest r_b values.

There is also variation in predicted performance from the three different tests, but this variation may not be as significant as it appears at first glance. For example, in the Crossed Contour estimates for borehole 1, k_g and r_b were 2.6 W m^{-1}K^{-1}, 2.7 W m^{-1}K^{-1} , and 3.5 W m^{-1}K^{-1} (TRT-1, 2, and 3), and 5.4, 5.5, and 5.3 cm (TRT-1, 2, and 3), respectively. However, as shown in Figure 3, all of these values are very close to the intersection point of the minimum error contours and they all lie along the general slope of the contours. The estimates from TRT-1, 2, and 3 will therefore yield very similar prediction of borehole thermal behavior.

Table 1: Summary of Estimated Ground Properties

	LSM		**GPM**		**Crossed Contour**		**TRNSYS Optimization**	
	r_b	k_g	r_b	k_g	r_b	k_g	r_b	k_g
	cm	**W m^{-1}K^{-1}**	**cm**	**W m^{-1}K^{-1}**	**cm**	**W m^{-1}K^{-1}**	**cm**	**W m^{-1}K^{-1}**
Test Data Set	*Test borehole, 91.4 m (300 ft) deep*							
K-testK-test	5.7	3.4	5.7	2.6	5.5	3.3	5.6	3.4
Test Data Set	*GLHX boreholes, 41.5 m (148 ft) deep*							
TRT-1 Borehole 1	5.7	2.3	5.7	2.1	5.4	2.6	5.5	2.7
TRT-1 Borehole 2	5.7	2.3	5.7	2.2	5.1	2.7	5.1	2.7
TRT-1 Borehole 3	5.7	2.8	5.7	2.6	4.9	3.3	4.7	3.0
TRT-2 Borehole 1	5.7	1.9	5.7	1.8	5.5	2.7	4.7	2.3
TRT-2 Borehole 2	5.7	1.9	5.7	1.9	5.0	2.7	4.7	2.4
TRT-2 Borehole 3	5.7	2.3	5.7	2.2	4.7	3.0	4.7	2.9
TRT-3 Borehole 1	5.7	2.8	5.7	2.7	5.3	3.5	5.2	3.3
TRT-3 Borehole 2	5.7	2.7	5.7	2.7	5.1	3.3	5.1	3.3
TRT-3 Borehole 3	5.7	3.1	5.7	2.9	4.9	3.7	4.8	3.6

Given the relatively large range of borehole parameter estimates from the different techniques (LSM, GPM, Crossed Contour, TRNSYS Optimization,) two natural questions arise: which parameters should be used, and how much do they change the thermal behavior of the GLHX predicted by long-term, system simulations? Ideally, the parameters would be estimated using the same model that will be used to predict the long-term performance of the GLHX, so that modeling assumptions are applied in a consistent manner. In this case, the TRNSYS DST model was used to predict performance over the approximately 80 hour TRT tests. The different techniques are evaluated based on the ability of the TRNSYS DST model to predict measured TRT performance while using the ground conductivity and borehole radius parameters estimated from the various techniques. Table 2 shows the RMS error of fluid temperature leaving the heat exchanger compared to the TRT data for the different techniques. Note that this temperature is the industry standard Entering Water Temperature, where entering is relative to the HVAC system. The lowest RMS errors were generated by the TRNSYS optimization parameter estimates. The highest RMS errors were typically generated by the GPM parameter estimates, although the LSM parameter estimates for TRT-2 generated the highest observed errors. The average RMS errors for all the data set comparisons were: LSM 0.92 °C, GPM 0.99 °C, Crossed Contour 0.64 °C, and TRNSYS Optimization 0.54 °C.

Table 2: RMS Borehole Exit Temperature Error for Each Parameter Prediction Method

Test Data Set	LSM °C	GPM °C	Crossed Contour °C	TRNSYS Optimization °C
TRT-1 Borehole 1	0.67	1.08	0.67	0.63
TRT-1 Borehole 2	0.69	1.05	0.55	0.55
TRT-1 Borehole 3	0.73	1.27	0.52	0.45
TRT-2 Borehole 1	1.28	0.87	0.63	0.46
TRT-2 Borehole 2	1.37	0.89	0.53	0.45
TRT-2 Borehole 3	1.54	1.04	0.45	0.40
TRT-3 Borehole 1	0.67	0.81	0.89	0.72
TRT-3 Borehole 2	0.63	0.81	0.80	0.66
TRT-3 Borehole 3	0.65	1.08	0.68	0.51
Average	0.92	0.99	0.64	0.54

The average RMS errors from the LSM and GPM parameter sets are nearly double the errors from the Crossed Contour and TRNSYS Optimization parameter set. The difference is caused by inferior prediction of longer-term behavior from the LSM and GPM parameters. The LSM and GPM parameter sets result in closer matching of the initial data ($t < 10$ h) followed by moderate offsets for the later data ($t > 10$ h). The Crossed Contour and TRNSYS Optimization parameter sets result in overshooting of the initial data and near perfect matching of the later data.

7. Conclusion

The Crossed Contour Method generally results in lower and more consistent deviations relative to the LSM or GPM methods when predicting parameters for use in the TRNSYS DST model. The improvement of RMS temperature error presented here is relatively small (0.5 °C). This difference would not result in significantly different heat pump energy. However, the design of GLHXs is based directly on this temperature, and small differences in temperature do lead to real differences in size and first cost. Also, the evaluation presented here is only for 80 hours of operation; the cumulative effects over a multi-year simulation could be more substantial.

Future plans include coupling the GLHX with a heat pump for a much longer time-period and examining the temperature errors of TRNSYS DST model with borehole parameters from the various estimation techniques. It is also possible to use the Crossed Contour Method to examine other borehole parameters such as ground heat capacity, or with alternate models. The method could also be expanded to work with more than two parameters, albeit without the simple visual result of crossed contours in two dimensions.

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