

In Situ Measurement of Ground Thermal Properties

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Abstract

Ground thermal properties are an important part of the design of underground thermal energy storage (UTES) systems and ground source heat pump (GSHP) systems. The design and economic feasibility of these systems critically depend upon the estimate of the ground thermal conductivity, yet, there have been no completely satisfactory methods for obtaining the thermal conductivity ground of the ground surrounding a borehole.

This paper describes an experimental apparatus capable of imposing a heat flux on a test borehole and measuring its temperature response. The thermal conductivity of the ground is then estimated using parameter estimation techniques in conjunction with a two-dimensional finite volume model. The technique has been validated for a cored borehole, comparing the estimate with measurements of the thermal conductivity of the core samples; and against a large laboratory simulation of a borehole surrounded by a homogeneous “soil” with an independent measurement of the thermal conductivity. An uncertainty analysis of the conductivity prediction is presented.

In order to obtain reasonably accurate results, a 50 hour test duration is recommended. However, it would be highly desirable to be able to perform the test in a shorter time period. Modification of the experimental procedure and analysis procedure that may allow significantly shorter test times are also examined.

Introduction

For design and simulation of ground loop heat exchangers used in ground source heat pump systems and underground thermal energy storage systems, the ground thermal properties are important input parameters. Both ground loop heat exchanger design tools and the simulation models rely on some estimate of the ground thermal conductivity and volumetric specific heat. This estimate is critical to the design, yet it is very difficult to make. The required borehole depth or length is highly dependent on the thermal properties of the ground.

The traditional approach to estimating the ground thermal properties has been to first ascertain the type (or types) of soil or rock that surrounds the borehole. Once the type of soil or rock is determined, its thermal conductivity can be estimated from tabulated data, such as that contained in the Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems Field Manual (EPRI, 1989). Since thermal conductivity values for ground formation types are reported in the literature within a rather broad range of values, a method for more accurately estimating the ground thermal conductivity is highly desirable. A method for experimentally measuring the effective ground thermal conductivity using a test borehole is briefly presented here; it is presented in more depth by AUSTIN, et al. (2000).

The ground thermal conductivity can not be directly measured – its value must be inferred from temperature and heat flux measurements. MOGENSEN (1983) described the concept of using such a measurement to estimate the ground thermal conductivity. Subsequently, development of an experimental apparatus began in 1995 at Oklahoma State University and was described by AUSTIN (1998). Simultaneously and independently, a similar apparatus was developed by EKLOF and GEHLIN (1996). GEHLIN and NORDELL (1998) report on results from in-situ thermal response tests conducted using the mobile testing facility at various locations in Sweden to predict ground thermal conductivities.

In order to determine the ground thermal conductivity from the temperature and heat flux measurements, some model of the heat transfer in the ground such as the line source approach (INGERSOLL and PLASS, 1948; MOGENSEN, 1983) or the cylinder source approach (CARSLAW and JAEGER, 1947) must be utilized. They are of interest here for possible inverse use—estimating the ground thermal properties from the performance rather than the performance from the ground thermal properties. Specifically, we are interested in imposing a heat pulse of “short” duration (1-7 days) and determining the ground thermal properties by analysis of the temperature response of the ground. Although the line source and the cylinder source approaches may be used inversely to estimate the ground’s thermal conductivity, they require several simplifying assumptions, the effects of which cannot easily be quantified. A detailed numerical model of the borehole reduces the uncertainties associated with these simplifying assumptions by providing a detailed representation of the borehole geometry and thermal properties of the fluid, pipe, grout, and ground. It may therefore be expected to provide a more accurate estimate of the ground thermal conductivity. Furthermore, use of the line-source procedure is highly sensitive to small fluctuations in input power, as demonstrated by AUSTIN (1998).

Parameter Estimation Methodology

The method presented here uses the NELDER and MEAD simplex algorithm (1965) as part of a parameter estimation algorithm to estimate the ground thermal conductivity. An alternative parameter estimation based approach has been described by SHONDER and BECK (1999). The parameter estimation model utilizes a transient, two-dimensional numerical finite volume model of the vertical borehole (YAVUZTURK et al. 1999) to estimate the temperature response of the ground to a known time-varying heat flux input. The numerical model is two-dimensional in the radial and angular dimensions; it uses a “pie-sector” approximation of the U-tube. The differences between the experimentally measured temperature response and the estimated temperature response are minimized by adjusting the thermal conductivities of the ground and the grout. Specifically, the sum of the squares of the errors (SSE) is minimized:

$$SSE = \sum_{n=1}^N (T_{exp} - T_{num})^2 \quad (1)$$

Where, N = The total number of data points over the duration of the experiment,

T_{exp} = Average of the calibrated input and output temperature at the nth data point,

T_{num} = Average fluid temperature at nth data point as predicted by the numerical model.

One, two, or more parameters might be estimated simultaneously. Although a number of approaches have been investigated, including estimating up to five parameters (soil conductivity, grout conductivity, soil volumetric specific heat, grout volumetric specific heat, and shank spacing) simultaneously, the most satisfactory approach only estimated the soil conductivity and grout conductivity. The grout conductivity acts as a surrogate for both the grout conductivity and the shank spacing.

Description of the Experimental Apparatus and Test Procedure

The experimental apparatus is housed in a trailer that can be towed to the site and contains every-thing needed to perform a test – the apparatus, two generators, and a purge tank (AUSTIN 1998). A simplified schematic of the test system is shown in Figure 1.

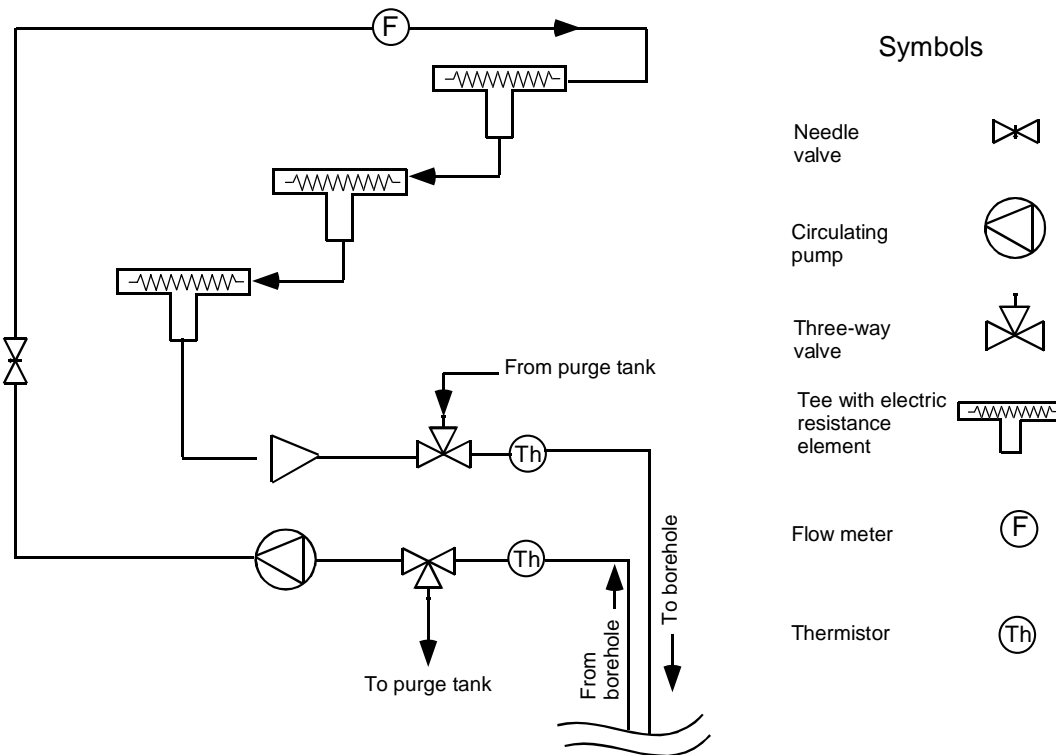


Figure 1: *In-situ thermal conductivity test system schematic*

Once connected to a U-tube that has been inserted into a borehole, and after the system has been purged, a heat flux is imposed on the borehole using the three in-line water heaters, and the temperature response (average of inlet and outlet fluid temperatures, which changes with time) of the borehole is measured. Experimental measurements are made every 2.5 minutes using a data logger, and the power input, the entering/exiting fluid temperatures of the loop and the volumetric flow rate are downloaded to an on-board computer.

A test length of 50 hours was found to be satisfactory for typical borehole installations. A shorter test length is highly desirable, and may be the subject of future research.

Model Validation

For validation of the parameter estimation model predictions, several tests have been conducted where the ground conductivity was established independently. One test was performed on a borehole that was drilled with a coring bit. The conductivity of 19 representative samples was then measured in a guarded hot plate apparatus (SMITH 1998; SMITH, et al. 1999a) to obtain an independent estimate for its thermal conductivity. Another test was performed using a medium-scale laboratory experiment (SMITH 1998; SMITH, et al. 1999b) where the geometry and thermal characteristics of a borehole are replicated under controlled conditions. The thermal conductivity of the soil material used in the experiment was determined independently with a calibrated soil conductivity probe.

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A comparison between predicted and independently determined thermal conductivity values for both the cored borehole and the medium-scale laboratory tests shows a very reasonable agreement. A maximum deviation of about 2.1% is observed (cored borehole) while the simulated borehole with dry sand and the simulated borehole with saturated sand display a deviation of only about 2.0% and 1.3% respectively. As expected, the errors associated with the predictions of the thermal conductivity of the grout are greater since the second independent parameter is used as a surrogate to account for uncertainties in the borehole.

Sensitivity Analyses

A series of sensitivity analyses have been performed to evaluate the influence of a number of input parameters that cannot be determined exactly, but estimated with some uncertainty. (The term “input parameters” refers here to parameters that are not estimated with the parameter estimation procedure, e.g. far-field temperature, volumetric specific heats, shank spacing, borehole radius) In addition, the duration of the test and experimental errors impact the results, so a sensitivity analysis is performed for both.

A summary of the sources of uncertainties and their effect on the ground thermal conductivity estimation is given in Table 1. The uncertainty in the input parameters has a corresponding uncertainty in the estimated ground thermal conductivity. Since the uncertainties described in Table 1 pertain to parameters that are all independent or nearly independent from each other they may be added in quadrature. Thus, the total estimated uncertainty of the ground thermal conductivity estimations falls within a range of about 9.6% - 11.2% depending on the level of the estimated thermal conductivity, since very low conductivity sands appear to be more sensitive to the estimate of the volumetric specific heat.

Table 1: Summary of primary sources of uncertainties in the estimation of thermal conductivity of the ground

| Source/Input uncertainty | Estimated uncertainty in predicted k_{ground} |
|---|---|
| Length of Test – approx. 50 hours | $\pm 6.5\%$ |
| Power Measurement. ($\pm 1.5\%$ uncertainty.) | $\pm 1.5\%$ |
| Estimate of the volumetric specific heat of the ground. ($\pm 335 \text{ kJ/m}^3\text{-K}$) | $\pm 2.6\%$ (average soils) or $\pm 6.3\%$ (extremely dry soils) |
| Estimate of the borehole radius. ($\pm 12.7 \text{ mm}$) | $\pm 3.6\%$ |
| Estimate of the shank spacing. ($\pm 40\%$) | $\pm 1.6\%$ |
| The numerical model. | $\pm 1.2\%$ |
| Estimate of the far-field temperature. ($\pm 0.6 \text{ }^\circ\text{C}$) | $\pm 4.9\%$ |
| Total Estimated Uncertainty | $\pm 9.6\% - 11.2\%$ |

Efforts to Shorten Test Length

In the U.S., there has been significant interest in using shorter *in situ* test lengths. Although the authors have recommended 50 hour test lengths, it would be highly desirable to have shorter test lengths. One contractor (WELLS 1999) who performs *in situ* tests in the Ohio area, estimates the cost to the customer for a 12 hour test at \$4500; and \$6800 for a 48 hour test. About \$2000 represents the cost of drilling the borehole, installing the U-tube, and grouting the borehole. Labor costs for this contractor are about \$42/hour. Furthermore, according to the contractor, since many of the *in situ* tests are done as part of utility-funded feasibility studies, the additional cost for a 50 hour test is hard to justify.

Accordingly, a limited amount of research has been done to try and reduce the required test time. The main reason that the current estimation procedure requires such a long test is that it takes time to resolve the differences between the effects of the ground thermal conductivity and the effects of the borehole resistance, or grout thermal conductivity. If a single parameter estimation could be used, it should converge much more quickly. Single parameter estimation may be used if the thermal characteristics of grout and pipe well known; the convective resistance in the U-tube is accurately determined; the borehole diameter and U-tube placement are precisely controlled; and the borehole geometry may be represented in the numerical model with high fidelity.

The first two items can reasonably be achieved. It is not at all clear whether it is feasible to control the borehole diameter and U-tube placement precisely in the field. An improved numerical model has now been developed that uses a ‘boundary-fitted’ grid system that is much more flexible and can more accurately represent the U-tube pipe geometry than the “pie-sector” approximation. This makes the calculation of the heat fluxes and temperatures inside the borehole much more accurate. This is important for prediction of the borehole response near the beginning of the *in situ* test and should lead to better parameter estimations. This has been demonstrated (SPITLER, et al. 1999) in the “medium-scale” laboratory experiment (SMITH 1998; SMITH, et al. 1999b), where an accurate, converged estimate of the ground thermal conductivity has been obtained in about 12 hours. However, it is not yet clear that this will work properly in the field. A test recently performed at Oklahoma State University (SMITH 2000) utilized spring-loaded spacers placed every 1.5 m in an effort to force the U-tube to rest against the borehole wall. Analysis after the installation suggested that between the spacers, the U-tube was not in contact with the borehole wall, and no significant improvement in the ability to quickly estimate the ground thermal conductivity resulted. The spacers did, however, create a very low borehole resistance.

Conclusions and Recommendations

An experimental apparatus has been developed that is capable of imposing a heat pulse on a test borehole, and measuring its temperature response. The ground thermal conductivity is estimated using a parameter estimation technique in conjunction with a two-dimensional numerical model. For three tests where the ground thermal conductivity was independently measured, the thermal conductivities estimated with the apparatus and analysis procedure described here were within 2.1% of the independently measured values. A sensitivity analysis suggests that the total uncertainty for field tests is on the order of $\pm 10\%$.

A test length of 50 hours is currently recommended. However, it would be highly desirable to develop a test and analysis procedure that would allow an acceptable estimate of the thermal conductivity to be obtained with a much shorter test, say 12 hours. In order to achieve this, methods for controlling the U-tube position and borehole diameter that are practical to use under field conditions are needed. Then, further testing and research would be warranted. Also, since the duration of the test depends on the desired accuracy, any improvement in accuracy of the method may allow for a shorter test. Accordingly, methods for reducing the uncertainty of the input parameters should be investigated. In particular, methods for more accurately estimating the far-field temperature, the average borehole radius, and the ground volumetric specific heat should be pursued.

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