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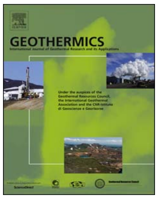

Use of a fiber optic distributed temperature sensing system for thermal response testing of ground-coupled heat exchangers

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ABSTRACT

A thermal response test (TRT) is commonly conducted at a site proposed for the installation of a ground-coupled heat pump system. The purpose of the TRT is to gather local data to infer thermal properties of the soil. Accurately estimating soil thermal properties enables designers to size the geofield appropriately and supports improved simulations of ground heat exchanger (GHX) systems to better estimate the system performance over both shorter-term and longer-term intervals.

This paper reports on the use of a fiber optic distributed temperature sensing system to spatially resolve the temperatures along the entire length of a U-tube within a vertical bore geothermal well. The fiber optic probe inside the U-tube provides spatial temperature data at a 2-m resolution throughout the duration of a TRT. The spatial temperature data within the U-tubes provided by a fiber optic probe offers the potential to determine other characteristics of a test bore, such as ground properties as a function of depth, which will enable much more accurate ground heat exchanger models in the future. An added outcome of this technique is a direct means to observe stratification of fluid temperatures which is another indicator of differences in ground properties that may occur along the depth of a vertical bore.

1. Introduction

A Ground Coupled Heat Pump (GCHP) is a heating and cooling system that uses the earth as a heat source or sink, respectively. GCHP systems leverage the relatively stable temperature of the ground that exists below a few meters in order to achieve improved capacity and efficiency compared to the ambient environment as a heat source or sink. The GCHP system, in its most basic configuration, consists of a heat pump with its condenser (cooling mode) or evaporator (heating mode) thermally linked to the ground heat exchanger using a secondary fluid. Increasingly common are GCHP systems comprised of a "geofield" having multiplicity of ground heat exchangers in a vertical bore configuration with single U-tubes grouted into a 6-inch hole drilled 100–500 ft in depth. Although GCHP systems are now relatively widespread and well-established, research on optimization and design of these systems continues. In fact, the more widespread these systems are, the more there is to gain from a proper characterization of the heat transfer to the ground (Gehlin, 2002).

The number of bores in a geofield will vary depending on the necessary heat exchange area for the size of a given heat pump system. A small GCHP system might consist of two discrete bores while a large system may consist of a field with hundreds of bores (Siliski et al., 2016). The geofield layout can take on different configurations based on the geology; it can be made up of many shallow bores or fewer but deeper bores, in a linear arrangement or staggered pattern. There are general guidelines for geofield layouts/designs (ASHRAE, 2011) but there is much to gain if the design could be optimized for the specific site. For example, it is generally recommended to have 20 feet of spacing between individual bores but spacing as large as 60 feet has been incorporated into some installations (Liuzzo-Scorpo et al., 2015). The spacing between bores is selected to prevent thermal interaction between adjacent bores. However, it has been shown that if there is even a small amount of subsurface water flow, the distance between bores can be greatly reduced; thereby, reducing the footprint of the geofield.

To adequately size the ground heat exchanger, it is necessary to accurately determine the ground thermal properties. The most common approach to infer ground properties is by using a Thermal Response Test or "TRT." During a TRT, a circulating fluid (usually water) is heated and then injected into the U-tube within an exemplar bore (i.e., the "test bore"). In its most common configuration, the TRT test rig contains the following elements: a circulating pump, flow meter, heating element, and temperature sensors to measure the U-tube inlet and

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outlet fluid temperatures. This setup provides data on the fluid flow rate and the measured temperatures of the fluid as a function of time (usually over a minimum period of 48-h). Data collected during a TRT are input to either an analytical model such as the line-source model (Mogensen, 1983) or a numerical model, such as those developed by Hellström (1982) and Shonder and Beck (1999). The result of analyzing TRT data is an "effective ground thermal conductivity" that represents an average thermal conductivity of the ground along the entire length of vertical bore. A potentially significant limitation of this technique is that it cannot provide any information regarding spatial variations in the ground conductivity along the bore length due to local geology. To address this limitation, this paper reports on the use of a fiber optic temperature sensing system incorporated into the supply and return side of a U-tube. This experimental technique allows the determination of anisotropic ground conductivity that can be caused by distinct underground layers and provides better estimates of ground properties which enables improved models for GCHP design to be realized.

The use of the TRT method discussed here that allows the measurement of the spatial variation of temperature with depth is particularly important in a region with a high water-table, such as Madison, WI which sits on an isthmus between two lakes. The geology of Madison is dominated by a relatively shallow water table composed of porous sandstone (the Upper Bedrock Aquifer) separated from a deep aquifer by a layer of shale (the Eau Claire Aquitard) that prevents water from penetrating, as shown in Fig. 1. The deep aquifer is an important source of water for the city of Madison and therefore large quantities of water are pumped from it causing significant groundwater flow rates below a depth of 70 m. The TRT conducted in this experiment makes use of a fiber optic Distributed Temperature Sensing (DTS) technology that can measure temperature along the length of the fiber optic cable during the TRT and after during the subsequent equilibration process. While a TRT using fiber optic DTS has been performed before, see (Acuña et al., 2009), these previous studies were in a region with relatively homogenous geology and consistent ground thermal properties. Neither of these are the case in Madison, WI where the present project is based.

The site for the present work is a relatively new, high tech laboratory built in downtown Madison, WI – the Wisconsin Institutes for Discovery (WID). The WID's GCHP has a rated capacity of 385 tons and its geofield is comprised of 82 bores, each 300 feet deep arranged around the perimeter of the facility (Knudson, 2013). This system, predominantly, runs in cooling mode operation where heat is rejected from the heat pump system though the bore field into the ground. The behavior of the WID's geofield is of particular interest due to a higher than expected effective ground thermal conductivity of 2.33 BTU/ft-hr-°F predicted by on a conventional TRT that was performed prior to construction (GRTI, Inc., 2008). The GCHP system experienced performance issues following start-up. Specifically, the GCHP system had been plagued by persistently high geofield temperatures and unexpectedly long geofield thermal decay during extended periods of time with none or minimal heat input to the geofield. For example over the course of one and half years without appreciable thermal energy input into the ground, the observed ground temperatures were still significantly higher than the expected undisturbed ground temperature of 52 °F as shown in Fig. 2. This paper describes the use of a relatively new technique of distributed temperature sennsing during a TRT to understand factors that may be contributing to the underperformance of the site's geofield. The transient temperature profiles along the depth of the bore obtained during tests reflect the geological formations unique to Madison that influence the behavior of the WID geofield.

2. Experimental setup

The experimental portion of this work involved conducting a TRT on an existing bore within the WID's geofield. During the fall of 2015, two of the WID's geofield bores were excavated in order to expose their wellheads. This excavation allowed the researchers to conduct other diagnostic tests on the bores and to install custom, permanent access infrastructure in anticipation of the TRT detailed in this paper. An in-situ TRT was conducted during the summer of 2016 using a custom thermal response test rig, shown in Fig. 3. This test rig not only incorporates the usual TRT sensing elements, e.g., inlet/outlet temperature sensors, but it also includes a unique fiber optic temperature measurement system that enabled real-time monitoring of the transient temperatures within the supply and return U-tubes at discrete locations along the bore as the thermal response test progressed.

The TRT rig contains the heating elements (8400 W in total), circulating pump, flow meter, thermostats, data logger, and SPRT's (thermistors) as shown in Fig. 3. The circulating pump provided an average of 6 gpm during the test. Temperature measurements at the inlet and outlet of the TRT rig are made using two Hart Scientific standard platinum resistance thermometers (PRTs). A four-wire configuration is used to accurately measure the resistance of the sensor by eliminating the voltage drop contributed by the leads of the current source. Self-heating of the PRTs is minimized by using a small (10 μA) drive current. Temperature readings are taken every second and 1-min time-averaged values are stored. A Campbell Scientific CR3000 data logger is used for the data collection and storage as well as providing the PRT current source and resistance measurement (Table 1).

The distributed fiber optic temperature sensing system requires three calibration baths to ensure accurate temperature data. For this

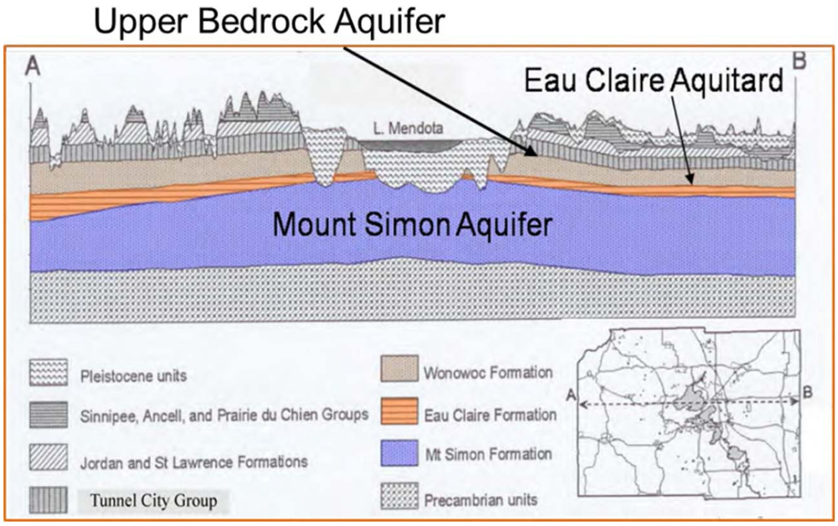

Fig. 1. The Geology below Madison, WI. (Gotkowitz et al., 2002).