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Characterizing lithological effects on large scale borehole heat exchangers during cyclic heating of the subsurface

David C. Smith*, A.C. Elmore

Geological Engineering Department, Missouri University of Science and Technology, McNutt Hall, Rolla, MO, 65409, United States

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ABSTRACT

This paper presents the results of a study where subsurface temperatures were monitored adjacent to the u-tube of a central borehole of a large scale 144 borehole heat exchanger (BHE) at multiple depths. This was an effort to develop a method to characterize the variability of thermal properties of the various lithological units surrounding the BHEs of large scale ground coupled heat pump systems during the operation of the system. Saturation of the units and lithology was shown to affect the performance of the BHE resulting variable temperature fluctuations and heat flux at different depths within the borehole. Median heat flux tended to increase with decreasing temperature ranges measured by the sensors. The lowest median heat flux was in the location nearest to the surface in the least saturated zone. In the more saturated zone, the highest median heat flux were at locations where the lithological units were composed of 75 percent or greater dolomite while the lowest median heat flux where in lithological units composed of 30 percent or greater chert.

1. Introduction

The use of ground coupled heat pump (GCHP) systems is increasing rapidly throughout the United States. Boyd et al. (2015) estimated 8 percent annual growth with 80,000 units installed per year with most of the growth taking place in the midwest and eastern regions of the country. This growth has been fueled by rising energy costs coupled with consumer tax credits for installing the systems (Boyd et al., 2015). GCHP system feasibility studies have been recently carried out throughout the world due to increased interest (Lu et al., 2017; Li et al., 2018; Yousefi et al., 2018).

The effectiveness of these systems is due to their ability to remove heat energy from buildings during the warm summer months and store that energy in subsurface which remains a relatively constant temperature year-round. Likewise, they are able to extract energy from the subsurface during the cold winter months to heat buildings. GCHP systems are efficient at transporting heat energy between buildings and the subsurface through the use of heat exchangers ground heat exchangers. There are many types of ground heat exchangers but they are generally classified as open- or closed-looped (Florides and Kalogirou, 2007). Open-loop ground heat exchangers are open systems that circulate groundwater through the system and then reject that heated or cooled water back into the ground. Closed-loop ground heat exchangers are closed systems and circulate water through the system with no mass exchange with the present groundwater. These systems can come in many different configurations from shallow to deep; and can be placed vertically or horizontally (Florides and Kalogirou, 2007). Large industrial systems generally have deep closed loop borehole heat exchangers (BHE) that extend tens of meters into the soil or bedrock and are made up of multiple boreholes.

The body of GCHP research has continued to grow. Acuña and Palm (2010, 2013) demonstrated the effectiveness of an annular coaxial pipe BHE which is a uses a central pipe that carries water from the surface to the bottom of the borehole while an outer energy capsule carries the water to the surface. The energy capsule maintains contact with the borehole wall in theory. This is an advantage to the u-tube design in which the u-tube is encased in grout. The coaxial BHE expands to the diameter of the borehole. The coaxial pipe BHE has been shown to decrease the total required borehole length when compared to the single or double u-tube design (Raymond et al., 2015).

The industrial use of GCHP systems on institutional scales have also increased sharply in recent times as colleges and business have brought GCHP systems online for heating and cooling. In 1994, Robert Stockton College in New Jersey was one of the earliest institutions to bring a large scale GCHP system online. The system consists of 400 bore holes drilled to depths of 130 m (m) and was drilled into the local aquifer (Taylor et al., 1997). Ball State University (BSU) completed a large scale GCHP system in 2012. This system was the largest of its kind at the time

* Corresponding author.
E-mail address: dcsqm9@mst.edu (D.C. Smith).

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of construction. The system consists of 3600 boreholes drilled to depths of 122–152 m (Ball State University (BSU, 2016). These BHE's can commonly extend through the unsaturated zone and into the saturated zone (Choi et al., 2011).

Despite the increase in the construction of large-scale GCHP systems only a small fraction of the construction cost is used to characterize the geohydrology of the site or monitor the long term effects that these large systems have on the aquifer (Florea et al., 2017). The industry generally relies on a single thermal response test (TRT) which is used to characterize the effective thermal conductivity of the subsurface (Sanner et al., 2014; Raymond et al., 2011). The TRT measures the response of the rock and soil as heated water is pumped through a single u-tube grouted into a borehole. This can also be accomplished by using heated cables and a series of thermistors as shown by Raymond et al. (2010). However, a single TRT does account for long term changes in the groundwater saturation and flow (Smith et al., 2018). There is a growing body of research showing the important role that groundwater has on large GCHP systems but more specifically, the BHE. The presence of groundwater increases the overall thermal conductivity of the rock or soil (Clauser and Huenges, 1995; Robertson, 1988; Albert et al., 2017). Mohamed et al. (2015) constructed a bench-scale GCHP system model which showed that heat flux between the heat exchanger and the model's sandy soil was enhanced when the water level was higher. Smith et al. (2018) studied the operation of a large scale GCHP system in a major karstic aquifer. Data was collected during nearly a year of operation of the system which saw periods of high and low saturation in the aquifer. The study showed that the effectiveness of the GCHP system's BHE during periods of high saturation was nearly 90 percent and was as low as 38 percent during periods of the lowest saturation. Smith et al. (2018) reported that water levels recorded in a nearby groundwater observation well has shown a declining trend in the saturation of the aquifer since 1968. The study showed the importance of characterizing the long term and seasonal changes in the saturation of the aquifer (Smith et al., 2018).

Groundwater flow has also been shown to affect the performance of GCHP systems (Lee and Lam, 2007; Fan et al., 2007; Smith and Elmore, 2018; Chiasson et al., 2000). Lee and Lam (2007) demonstrated that borehole configuration was important when considering groundwater flow. Computer simulations of a GCHP system performance using different thermal loading profiles and different BHE configurations (width and length ratios of 1:1, 1:2, and 2:3) were conducted to compare the performance of different BHE configurations under groundwater flow. The square BHE configuration was less likely to be affected by groundwater flow direction (Lee and Lam, 2007). Conversely, by knowing the direction of groundwater flow, the configuration of the BHE could be optimized to increase the effective surface area of the BHE.

Fan et al. (2007) developed a dynamic mathematical model to account for groundwater advection and its influence on a BHE. Simulations of the model showed that the presence of groundwater significantly influenced the heat flux between the BHE and the surrounding soil. Changes in the velocity of the groundwater also had a noticeable effect on the heat flux between the soil and the BHE. Using groundwater velocities of zero, 15, 30, and 60 m per year (m/yr), Fan et al. (2007) reported that heat flux between the soil and the BHE increased with increasing groundwater velocity and suggested groundwater flow be considered in the design of GCHP systems.

Smith and Elmore (2018) observed the operation of the BHE of large scale GCHP system in fractured rock. The groundwater velocity was calculated based on a groundwater model of the area (Vandike, 1992) and pumping data from a large nearby municipal well. The study showed that an existing steep groundwater gradient of 4.0×10^{-2} was reversed in the opposite direction while also decreasing to 2.8×10^{-6} which greatly decreased the groundwater velocity from 15 to nearly zero m/yr. Smith and Elmore (2018) reported a significant decrease in the effectiveness of the GCHP system's BHE.

Chiasson et al. (2000) used the dimensionless Peclet number (Domenico and Schwartz, 1998) and a finite-element numerical groundwater flow and heat transport model to simulate the effects of groundwater flow on a single u-tube BHE in differing types of geologic material. Based on simulations and analysis of the Peclet number, Chiasson et al. (2000) reported that groundwater flow only has a significant effect on geologic materials with high hydraulic conductivities such as coarse-grained soils and fractured rock. Further simulation of TRT in different flow conditions showed that the resulting thermal conductivity values of the geologic material were artificially high with groundwater flow. Smith and Elmore (2018) monitored the performance of a large scale BHE for nearly a year which was in the vicinity of a nearby active municipal well. The groundwater flow was northward at 15 m per year but the periodic operation of the municipal well reversed the groundwater flow and significantly reduced velocity. The effectiveness of the BHE was found to be greater before and after the pumping of the municipal well.

Chiasson et al. (2000) used a finite-element numerical model to simulate the effects of groundwater flow on a single closed loop BHE. The study showed that groundwater significantly enhanced the heat flux when in materials with high hydraulic conductivity such as sands, gravels, and fractured rock (Chiasson et al., 2000).

A third and less explored factor that may affect the performance of BHEs is the lithology. Previous studies (Robertson, 1988; Siliski, 2014; Albert et al., 2017, 2015; Sass and Götz, 2012) have shown that thermal properties can vary with rock type. However, little attention is given to lithology as the industry standard TRT treats the underlying lithology as homogeneous (Florea et al., 2017). Research on the lithology surrounding BHEs of large scale GCHP systems at Stockton College (Taylor et al., 1997), BSU (Siliski, 2014), and the Missouri University of Science and Technology (S&T; Smith et al., 2018) show that the BHEs generally extend through multiple rock and soil units with different thermal and hydraulic properties.

This paper presents a new method for characterizing the performance of different rock or soil units based on heat flux during the operation of the system. A series of thermocouples were installed to monitor the temperatures at different locations along a central borehole of a 144 well BHE (Fig. 1). The effects of outside ambient air decrease with depth. Florides and Kalogirou (2007) have shown that subsurface temperatures below 5 m are generally stable throughout the year. The thermocouples in this study are at depths from 15.2 to 122 m below ground surface. The shallowest thermocouple was three times the depth at which the outside ambient air can affect the ground temperature.

2. Methods

2.1. Site description

The BHE is part of a much larger system on the Missouri University of Science and Technology (S&T) campus. The overall S&T GCHP system consists of 789 wells serving three primary plants and satellite system. The satellite system serves the Gale Bullman Multipurpose Building which uses the 144 well BHE for heat exchange to and from the subsurface and is drilled into the Ozark Aquifer. This aquifer is the most important source of water for most towns, water districts, and private wells in the region (Miller and Vandike, 1997). The aquifer is characterized by high production, large diameter wells producing upwards of 1100 to over 3800 liters per minute and private wells that can produce more than enough water for residential use (MDNR, 2017). The BHE in this study extends through 122 m (m) of soil and rock which is classified into 5 units based the wells' boring log and historical logs (MDNR, 2018a, 2018b, 2018c, 2018d) of nearby wells. Depth specific lithology data was determined from well log 009515 (MDNR, 2018b) which is the log for the city municipal well approximately 380 m from the site and the well logs from the production well and nearby temperature monitoring well