Performance of a borehole heat exchanger under the influence of geothermal gradient, an exploration of BHE optimization alternatives

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Abstract

This paper will primiarly focus on the possible consequenses of considering geothermal gradient when attempting to optimize the geothermal borehole heat exchangers. Based on previous studies on the distributed thermal response test, an adaptation of an existing analytical solution of coaxial borehole heat exchanger (CBHE) is proposed. We believe it is crucial to estimate the added thermal benefit from geothermal gradient, especially when there are needs to achieve better thermal performance of the boreholes. Understanding the growing demand of geothermal energy for district systems, this paper examines the possibility of incorporating the geothermal gradient in estimating the performance of borehole heat exchangers, and subsequently the optimization of borehole heat exchanger configurations through the proposed analytical model. According to our results, the adapted analytical model was adequate to estimate the thermal responses from the test well, and can be used as a tool to estimate different coaxial borehole heat exchanger configurations. We estimate adding insulation and changing diameters of CBHEs could improve the heat extraction by up to 60%(What's the actual number?).

Keywords:

1. Introduction

Geothermal energy is gradually becoming a much more popular option amongst other renewable energy sources. Its abundance in near-earth surface and reliable nature during long-term operation has attracted researchers from geophysical, geotechnical and building engineering. A particular challenging task during the design of borehole heat exchangers is the estimation of desired borehole length, which is often achieved using single in-situ thermal response tests happening at or close to the site of the project. This is often achieved by averaging the thermal conductivity of the overall borehole during the entire thermal response test, which is further used in estimating the overall borehole thermal resistance, and thus ultimately the necessary length of boreholes. The most prevalent method currently used in this process was first proposed by Ingersoll in 1954. His method helped engineers to estimate the total required length of borehole heat exchanger under some common simplifications, and three hypothetical energy injection stages and assumed ground thermal resistance over time. A few fundamental assumptions of this method included homogeneous ground (temperature and geological conditions), constant heat injection rate and therefore limited emphasis on the vertical variation of heat exchange along borehole heat exchangers.

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To characterise the thermal potentials of boreholes, thermal response tests (TRTs) are often used when estimating the borehole resistances. Following the ASHARE guidelines, the inlet and outlet temperature at the borehole are recorded. The thermal conductivity of the borehole is the mean rate of temperature change over the natural logarithmic time of either the inlet or outlet temperature beyond the initial period of heat injection. The thermal conductivities are further used to estimate the borehole resistance and other parameters to evaluate potential borehole field designs. This method clearly does not provide enough information regarding the temperature evolution along the depth of borehole, i.e. the geothermal gradient situation of individual boreholes.

The state-of-the-art methods used in estimating the thermal properties during thermal response tests (TRTs) were first proposed by Ingersol in 1954, and further expanded into ASHRAE guidelines in ASHRAE Handbooks. This method attempt to estimate the borehole resistance through three hypothetical stages of heat injection. The total required length of borehole heat exchangers are therefore determined through the borehole thermal resistance determined through the in-situ TRT, which is based on the assumption of the ground being completely homogenous. For district-level systems with larger heating/cooling demands, this could mean up to 4,000 boreholes (Liu, Conference proceeding 2019). As geothermal energy sources become more popular, it might be beneficial for new geothermal installations to seek alternative solutions that requires fewer boreholes due to space constraints where fewer boreholes at larger depths should ideally yield similar heat extraction/removal results.

However, the homogeneity assumption completely disregards the geothermal gradient of the ground, particularly at a larger depth. This is a temperature increase along the depth of wells at the rate of an average 25 to 30 $°C$ per kilometer due to absorbed solar power. Under different circumstances, the geothermal gradient could vary between significantly: from as little as 1 $°C$ to as much as 5 $°C$. While the ground temperature of GSHP are often considered to be around 15 $°C$, the temperature at the bottom of borehole could be up to 25 $°C$ for a 500 m deep borehole heat exchanger(citation). However, as the existing thermal response tests only requires a single undisturbed ground temperature, this thermal potential may very much be overlooked since only the mean temperature of the ground is necessary for conventional TRT calculation.

Recent research have pointed out possibilities to use distributed TRTs that utilise fibre optic sensors that produces depth-specific temperature measurement along the borehole. This approach is currently understood as the Distributed Thermal Response Test (DTRT). This approach acknowledges the temperature variations along the depth of borehole heat exchanger through the measurement of fiber optic cables, where the optic signals are interpreted as temperature distribution along the cables. This approach has been helping researchers improving their models and evaluation methods of borehole resistances (Meyer 2013) and analytical solutions (Walker 2015). A few pioneering researchers even proposed distributed thermal response test, which is essentially adding a distributed temperature sensing (DTS) cable to the borehole heat exchanger during the investigation. However, while most of these investigations were successful, the driving force of the differences between heat fluxes at different depths remains to be further understood: the heterogeneity of the ground is still oversimplified within the existing DTRT methods, particularly with respect to the different underground water flow and thermal properties of different ground layers.

This paper aims at changing this status-quo by adapting an existing analytical solution of coaxial borehole heat exchanger under the influence of geothermal gradient. We will validate the adapted model through the experimental data collected during a recent test well drilled on campus at Princeton University, which provide further validation for the model's usage in predicting the thermal responses of borehole heat exchangers under the influence of geothermal gradient. We also aim at generating the potential changes in performance when alternative designs of coaxial borehole heat exchangers' (CBHEs) configurations and insulation levels are considreed. We hope this paper is the first of many to set the ground for future comparison with DTRT methods used and designed for coaxial borehole heat exchangers proposed by McDaniel.

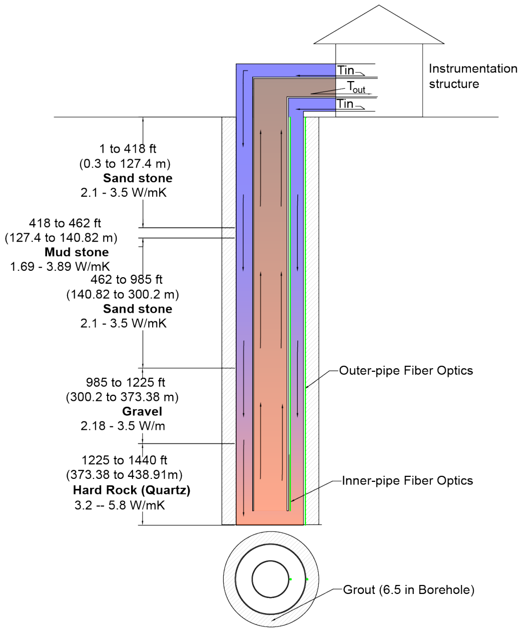

Figure 1: Hydro-geological condition estimated through USGS survey immediately taken after the drilling of the well estimated at 1440 ft(438.9 m).

2. Method

2.1. Experiment

2.1.1. Site and Borehole Heat Exchanger

Need for geothermal district heating/cooling demand for potentially the entire campus. It is crucial to assess the possibilities of using deeper geothermal heat exchangers.

The drilling of the well took place beginning August 8th, 2019. To characterize the formation layering at the drill site, a geological survey was performed immediately after the drilling. On top of the geological conditions shown in Figure 1, the tremmie

The hydro-geological makeup of the well is

2.1.2. Experimental Setup

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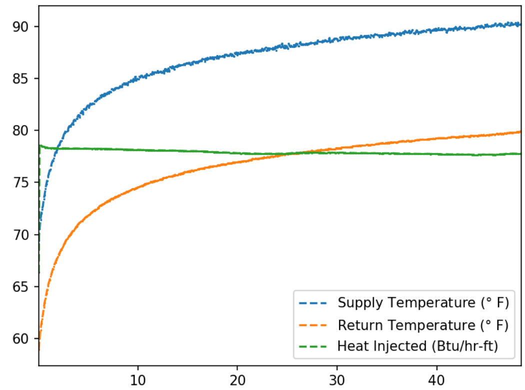

Figure 2: Temperature measured at the inlet and outlet of the well site.

books. This method attempt to estimate the borehole resistance through three hypothetical stages of heat injection.

To estimate the thermal conductivity of the formation, a thermal response test was performed on the drill site on September 10th, 2019. The test follows the guidelines recommended by the Americal Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) in its HVAC Applications Handbook, Geothermal Energy Chapter. The borehole was uniformed grouted from the bottom to the top via premie pipe, and had a delay of more than five days between loop installation and test startup. The undisturbed formation temperature was estimated through the recorded temperature from the fiber optic cable installed along and around the borehole heat exchanger. The duration of the test was 48.5 hours, where the data (inlet, outlet temperature and heat injection rates) was collected every five minutes. The heat injected was estimated to be 51 to 85 Btu/hr (or 15 to 25 W) per foot of the borehole, which averaged to be approximately 30.5 kW total heat input throughout the test.

For the purpose of the conventional TRT the project procured, the data collected by the company performing the test first undergone the procedures of a conventional TRT calculation. The relatively steady slope shown in Figure 2 of both the inlet and outlet temperatures since the 10th hour of the operation can be used to determine the overall thermal conductivity of the borehole. This can be achieved by taking the natural log time rate of change of the temperature of either the inlet and the outlet, and can be further expanded into the thermal diffusivity of the formation through an estimated heat capacity of the borehole. The estimated heat capacity of the bore can be estimated through the geological conditions previously confirmed through drilling (as shown in Figure 1.

The overall borehole resistance R_b may therefore be estimated through Equation 1[1].

$$R_b = \frac{H}{Q}\{T(t) - T_g - \frac{Q}{4\pi\lambda_g H}[E_i(\frac{r_b}{4\alpha_g t})]\} \tag{1}$$

However, there are some inherent limitations of this method. First and foremost is the homogeneity assumption of the ground. The conventional method clearly assumes the ground to be at a homogeneous temperature along the depth of the heat exchanger, where the thermal conductivity, thermal diffusivity are also constants. However, as can be observed from Figure 1 produced from the USGS measurement, it was clearly not the case. In particular, the hard rock or quartz at the bottom of the borehole will likely lead to a much larger thermal conductivity of the borehole, allowing the working fluid to extract more heat at the same flow rate. Within the scope of this paper, we will continue to use a single thermal conductivity calculated from the thermal response test (and the time log temperature gradient thereof) at the top of the heat exchanger to continue our analysis. However, for future research, it is desirable to expand this into a more detailed DTRT study.

2.2. Analytical Model

We will be adapting the analytical model from Beier et al., which was developed to predict the thermal response from a CBHE with known geological parameters. This model was developed to adopt undisturbed ground temperature measurement from fiber optic temperature sensors (also referred to as distributed temperature sensor, or DTS).

2.3. Analytical Solution

For each time step, a new analytical solution can be solved along different t, r and ???(What was this other parameter?)

3. Results

3.1. Measured results from TRT

4. Discussion and Further Optimization

5. Optimization

As we have

Importance - and shortcomings of having the

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