Thermal Performance of a Borehole Heat Exchanger Under a High Geothermal Gradient and Strong Groundwater Flow

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ABSTRACT

This paper was performed to test the thermal performance of a borehole heat exchanger (BHE) under a high geothermal gradient and strong groundwater flow. Test results showed that after measuring the natural ground temperature profile, the geothermal gradient was calculated as a high value of 0.08°C/m. Despite this, there did not appear an expected enhancement on the heat extraction performance of the BHE. Due to the cooling effect by strong groundwater flow with a low temperature, the ground temperature around the BHE was reduced greatly, which was favorable for heat injection in summer and unfavorable for heat extraction in winter. The present results can provide useful guides for design of BHEs in ground source heat pump applications under similar hydro-geological conditions.

1. Introduction

In recent years, GSHPs have been used very quickly around the world, because they are among the most energy efficient air-conditioning systems for residential and commercial buildings [1]. In China, the total area of buildings applying GSHPs exceeded over 140 million square meters in 2012, and is increasing at an amazing annual rate of 20% or higher. The performance of GSHPs depends strongly on the heat transfer between the soil and the BHEs. Generally, for a soil with low hydraulic conductivity, the heat transfer process is dominated by heat conduction based on Fourier’s law. In fact, it is easily found that many construction sites have a number of groundwater aquifers. It has been recognized that groundwater flow affects the thermal performance of BHEs in aquifers [2]. Considering the complexity of flow and heat transfer of BHEs in aquiferous porous soils that are also related to specific hydrogeological conditions, this issue is attracting more and more attention, which can be seen in previous analytical, numerical, and experimental efforts [3-5].

Up to now, however, only a few field test studies are reported partially due to high comprehensive drilling costs, complex hydrogeological parameters and other uncertain in-situ factors. Witte et al. [6] discussed the effect of groundwater flow in the vicinity of a BHE during the thermal response test (TRT). By means of laboratory experiments with a thermal probe, Katsura et al. [7] verified that the effective thermal conductivity with groundwater flow is influenced by the period of elapsed time. Lim et al. [8] performed a field test on the thermal performance of BHEs in Korea. They found that due to the effect of groundwater flow and natural convection in boreholes, the effective ground thermal conductivity was enlarged greatly. In our previous tests in Baoding [9], it is found that groundwater flow could change the natural ground temperature profile, and then analyzed the enhancement effect on the thermal performance of BHEs. In field tests in Shouguang [10], it is further observed that the thermal performance of BHEs is extremely enhanced in those regions with multiple aquifers, and even the thermal response test results can be enlarged to a great extent by groundwater flow. But these tests seldom involve higher geothermal gradients than the normal value (e.g.20-30°C/km in Northern China). The purpose of this work was to perform the in-situ tests to obtain the thermal performance of a BHE under a high geothermal gradient and strong groundwater flow. This work is expected to provide further understanding on the groundwater flow affecting the thermal performance of BHEs.

2. Test Investigation

Figure 1 shows an in-situ view of the experimental setup measuring the thermal performance of a BHE. The setup mainly consisted of a heat or cold source system, a measuring system, and a BHE. The heat/cold source system was able to keep a relatively constant temperature inside a 40 liter insulated water tank, thus guaranteeing a stable inlet fluid temperature to the BHE. The water tank was made of stainless steel plates with the thickness of 2mm, and the polyurethane insulation layer surrounding the tank was 30mm thick. The heating was provided by an adjustable electric water heater, while the cooling was obtained by means of a R22
A refrigeration cycle consisting of a rotor compressor, a fin condenser, an expansion valve, and a coil evaporator. The condenser was cooled by an axial air-cooling fan. The maximum heating and cooling output was 12kW and 9kW, respectively. In addition, an advanced PID temperature controller was mounted on the operation panel. The operational temperature for the water tank ranged from 5 to 40°C. A 90W circulating pump was used to maintain the flow circuit. Its maximum flow rate and the hydraulic head were 2.5m³/h and 6m, respectively. The measuring system included two Pt1000-type temperature sensors with ±0.1°C accuracy, a GPR-II type electromagnetic flow meter with ±0.001m³/h accuracy, and other auxiliary instrumentation for control and display. In addition, for measuring the natural ground temperature distribution, ten calibrated Pt1000-type temperature sensors were embedded at the different depths of the borehole. Before the installation, all temperature sensors were calibrated by a constant-temperature bath with ±0.01°C accuracy.

In the present test, a 100m deep borehole was drilled in Changli (latitude 39.70°N, longitude 119.17°E), China. The diameter of boreholes was about 250mm. A double U-shaped high-density polyethylene (HDPE) pipe was used for the BHE, and the nominal pipe diameter was 32 mm. After installing the BHE, the mixture of clay soil and fine-medium sand was used to the backfills. All exposed pipes were insulated effectively in order to reduce the undesired loss of heat or cold. The test period extended from December 2012 to January 2013. According to the geological survey data provided by Tianjin Institute of Geology and Mineral Resources (TIGMR), the Quaternary stratum covered the range of 100m, and the deeper layer was covered with the Tertiary stratum. Figure 2 shows some soil samples from the test borehole. It can be seen that at the depth of about 12m and 90m, there were relatively thick medium-coarse sand layers with strong groundwater flow, which can explain why core drilling samples were locally incomplete. At other depths, the ground layer of clay, silt clay and silt sand was dominated and the hydraulic conductivity was much lower.

3. Results and Discussion

Figure 3 shows the measured results of the natural ground temperature profile in the case of Changli. It can be seen that the constant ground temperature zone covered the depth of about 20-25m, with a temperature of 12.5°C, which is the same as the balanced ground temperature tested when the BHE was operating under the condition without heating or cooling, only driven by the circulating pump. This temperature is also called as “the initial ground temperature”[4]. At a deep zone below 25-75m, the temperature increased linearly with depth. The temperature gradient was 0.08°C/m, much higher than the normal value (e.g. usually 0.02-0.03°C/m in Northern China). Such a high geothermal gradient is related with a relatively thin thickness of the total...
Quaternary stratum above the rock bed and strong local geological actions. In addition, according to the drilling test data from adjacent geothermal production wells with the depth of 300m, the warm water temperature was about 38°C at the sandstone layer (Minghuazhen Group) from the upper Tertiary stratum. From this temperature, it was estimated that the geothermal gradient was 0.093°C/m, i.e., (38-12.5)/(300-25)=0.093°C/m, which was in agreement with the above measured geothermal gradient. It was also found that the ground temperature at those depths with strong groundwater flow deviated severely from the background trend (i.e. conductive-type ground temperature profile). For example, due to the cooling effect of groundwater flow, the ground temperature at 12m decreased to 12.0°C. Especially, the actual ground temperature at 100m was only 16.7°C (18.5°C if calculated by a linear increase in temperature), nearly approaching to the ground temperature level at 75m, which indicated that the ground temperature profile became more complex due to the existence of groundwater flow.

With respect to the climate conditions in Changli, the accumulated heating load of buildings is usually much higher than the accumulated cooling load. In such a case, when GSHP systems are applied, the ground temperature surrounding the BHE may potentially decrease over a number of years, resulting in a lowering of performance of the heat pump as the fluid temperature drops in winter. Theoretically, a high geothermal gradient is favorable for heat extraction of BHEs as a result of the supplement of deep geothermal energy. If there exists groundwater flow, however, the heat transfer of BHEs will be changed to a different extent, depending on the in-situ hydro-geological conditions.

Figures 4 and 5 show the heat transfer rates of the BHE as a function of the depth, where the average flow rate through the BHE was 1.7m³/h. Here, if the heat transfer rate is calculated as negative, it indicates that heat transfer occurs from the ground to the BHE, i.e. the heat injection mode for cooling. Otherwise, it indicates that heat transfer occurs from the BHE to the surrounding ground, i.e. the heat extraction mode for heating. It can be seen that except for the starting process, as the heating or cooling time increased, the heat transfer rate of the BHE dropped gradually and then reached a relatively steady state after 20-24 h. When the inlet/outlet temperature of the BHE was 7.2/8.5°C for the heat extraction mode and 24.4/21.6°C for the heat injection mode, the experimental heat transfer rate of the BHE was -23.2W/m and 58.7W/m, respectively.

Further, the average ground thermal conductivity was estimated as 2.85W/mK, 60% higher than the average test value (1.78W/mK) of drilling soil samples using thermal probe method (TPM) [11]. And this verified again that groundwater flow can enlarge the thermal response test results of BHEs. In this case, even though the geothermal gradient was high, groundwater flow seemed to be much favorable for heat injection of the BHE. It indicated that compared with a geothermal gradient, strong groundwater flow had a more important influence on the thermal performance of the BHE, or groundwater flow weakened greatly the effect of the geothermal gradient on the thermal performance of the BHE.

Figure 6 shows the variations of the heat transfer rate of the BHE with the average fluid temperature. Through the regression using the Least Square Method, there appeared a linear relation. From the line slope, the thermal performance of BHEs can be compared easily, i.e., a larger line slope indicates a better heat transfer rate of a BHE. When the heat transfer rate is zero, the
average fluid temperature equals to the balanced ground temperature, the initial ground temperature or the temperature of the constant-temperature ground layer. In the test of Shouguang (latitude 36.86° N, longitude 118.80° E) [12], the average ground thermal conductivity was 2.61 W/mK, with the slope of 5.3023. By contrast, the average ground thermal conductivity was 2.85 W/mK with the slope of 5.448. Even though two cases had a closing ground thermal conductivity enlarged by groundwater flow, the thermal performance of BHEs was much different. Under the same average fluid temperature through the BHE, the present heat transfer rate was lower than that in the case of Shouguang. The major difference of two cases is the temperature of the local constant-temperature ground layer, which depended mainly on the geological locations and climate conditions. In most cases, a high constant-ground temperature means a good heat extraction and a poor heat injection of BHEs, independent of groundwater flow.

4. Conclusions

This paper describes the results of a group of field tests to measure the thermal performance of BHEs under a high geothermal gradient and strong groundwater flow. From the experimental results above, the following conclusions can be obtained:

(i) After measuring the natural ground temperature profile, the present geothermal gradient was calculated as a high value of 0.08°C/m, over 3 times higher than the normal geothermal gradient in most other areas. Despite this, there did not appear an expected enhancement on the heat extraction performance of the BHE.

(ii) Under groundwater flow conditions, the heat transfer performance of BHEs is often changed to a different extent, depending on the in-situ hydro-geological conditions. Due to the cooling effect by strong groundwater flow with a low temperature, the ground temperature around the BHE was reduced greatly, which was favorable for heat injection in summer and unfavorable for heat extraction in winter.

References