Performance analysis on a large scale borehole ground source heat pump in Tianjin cultural centre

Baoquan Yin\(^1\) and Xiaoting Wu

Tianjin Architecture Design Institute, Tianjin Engineering Center of Green Building Mechanical & Electrical Technology, Tianjin 300074, China.

\(^1\)yinyou1984@163.com

Abstract. In this paper, the temperature distribution of the geothermal field for the vertical borehole ground-coupled heat pump was tested and analysed. Besides the borehole ground-coupled heat pump, the system composed of the ice storage, heat supply network and cooling tower. According to the operation data for nearly three years, the temperature constant zone is in the ground depth of 40m -120m with a temperature gradient of about 3.0°C/100m. The temperature of the soil dropped significantly in the heating season, increased significantly in the cooling season, and reinstated in the transitional season. With the energy balance design of the heating and cooling and the existence of the soil thermal inertia, the soil temperature stayed in a relative stable range and the ground source heat pump system was operated with a relative high efficiency. The geothermal source heat pump was shown to be applicable for large scale utilization.

1. Introduction

In China, the ground source heat pump (GSHP) system has entered the stage of rapid development. By the end of 2012, shallow geothermal applications area has achieved 300 million square meters.

Liu et al. \cite{1} analyzed the feasibility and performance of GSHP in three cities in cold climate zone of China, utilizing the energy simulation software TRNSYS. Lu et al. \cite{2} presented an analysis of the performance of several GSHP systems and compared the cost of them against other conventional heating/cooling methods using several economic indicators, which offered a reference to GSHP design. Babak \cite{3} investigated the thermal performance of vertical spiral ground heat exchangers (GHEs) experimentally and computationally. Different numbers of spiral GHEs were considered, and nine spiral GHEs were shown to be the most reasonable configuration. Zhai et al. \cite{4} introduced a minitype GSHP system for satisfying the thermal environment of a meeting room with the covered area of 180 m\(^2\) in Shanghai, China. Their experimental results were instructive to the design and operation of GSHP systems in Shang\(\mathrm{h}^{\mathrm{a}}\) and other cities with similar climatic feature. Kurevija et al. \cite{5} analysed one real retrofit project including 16 borehole heat exchangers with thermal enhanced grout completion, utilizing steady-state thermal response step testing. Ikeda \cite{6} presented an optimization method to determine the optimal operations of a hybrid GSHP system that was used to handle the cooling load and hot water demand, which was beneficial for the actual operation. Luo et al. \cite{7} conducted a techno-economic analysis for operation management of borehole heat exchangers of a large-scale hybrid GSHP system.

The performance of the GSHP system was influenced by the temperature field of the ground. In order to ensure the system function normally in a long-term operation, the heating and cooling load...
balance should be considered in the system design, and the temperature field variation of the ground should be monitored and controlled during the system operation. In this paper, the geothermal field of the vertical borehole ground source heat pump based on a complex three-stage heating and cooling system of Tianjin Cultural Centre was analyzed. The distributed temperature acquisition and transmission system was built through a total of twelve observation wells, including six exchanger wells with the depth of 120m, and the others were set around the heat transfer wells to monitor the temperature distribution of the ground.

2. System scheme and monitoring

2.1. System scheme

The regional energy system of Tianjin Cultural Centre, composed of 3789 soil borehole heat exchangers, was set under the Central Lake. In-situ thermal conductivity tests showed that the heat extraction and removal rate were 70W/m and 40W/m respectively. The average initial soil temperature was about 15°C within the range of 120m, and soil thermal conductivity was 1.3W/(m·K). Using the vertical double U-type heat exchanger, the design depth was 120m, drilling diameter was 200mm, and their interval was 4.8 m. The reversed return pipe road system was connected to the South and North Energy Station, shown in Figure 1.

![Figure 1](image)

**Figure 1.** The function and scenery of Tianjin Cultural Centre.

Through a series of analysis, the capacities of soil heat exchangers were lower than the system load demand, which were 5.4% and 13.2% respectively. To ensure the seasonal thermal equilibrium, the auxiliary heat source and heat removal equipment should be deployed. In addition, the heat supply network was available to this area. Through the comparative analysis of technical and economic features, the ice storage, heating network and cooling towers were used for the peak shaving. The GSHP system with three-stage coolers was shown in Figure 2.

2.2. Dynamic monitoring

Taking into account the temperature distribution of the geothermal field, and the flow of groundwater, the monitor holes in the buried tube area were set in a rectangular zone, given by Figure 3. (a) is the distribution of the testing hole, (b) are the temperature sensors at the different depth, (c) is the temperature distribution measure point around the exchanging hole. The No.6 test spot was set outside the well region in order to monitor the background temperatures of the geothermal field. The monitoring holes No.6 and exchanging holes No.1 to No.5 were both buried underground at the depth of 120m, and the temperature measuring point was set at the interval of 10m along the depth in order to monitor the vertical temperature distribution, see figure 3(b). These two measures were taken to monitor the temperature distribution of the whole buried tubes zone and analyze the influence of the underground water runoff on the temperature distribution.

No.1 test spot was set in the centre of the buried tubes zone and No.3 test spot was set at the edge. In order to analyze the mutual effect of the tube group, around the exchanger holes 1 and 3, the 3
monitor hole of 40m depth ground temperature influence radius was arranged with the distance of 1m, 2m and 2.4m respectively.

![Diagram of System Process](image)

**Figure 2.** System process of the flow diagram.

3. **Results analysis**

According to the monitoring results, the original ground temperature in the depth of 40m and 120m were 14.9°C and 17.3°C respectively, indicating a temperature rise of 0.2-0.4°C with every 10m depth increase. It could be concluded that the soil had a good thermal gradient. While the background temperature fluctuated acutely in the depth of 5m, with a minimum value of 14.6°C in June and a maximum value of 16.5°C in January.

In the heating season, soil temperature dropped significantly. It dropped to 7.4°C in 2012.2.18, and 7.2°C in 2013.1.5.

In cooling season, soil temperature increased significantly. It reached to 21.8°C in 2012.8.28, and 23.3°C in 2013.8.18.

In the transitional season, the ground heat exchanger was not operation, the temperature of soil reinstated. Within 120m-60m depth, the temperature at different depths distributed regularly. In the depth range of 50m-10m, the temperature distributions at different depths were not significantly different. However, the temperature change was quite different within 10m depth.

After the soil temperature reaching to the lowest value in the coldest month of the year, it usually rebounded in February. Until summer the temperature of the buried tubes could drop to 12.8°C in the underground depth of 10m, while in 120m it would increase to 15.2°C with an average temperature rise of 5.4°C to 7.8°C. From the end of the cooling period to the next heating period, the soil temperature dropped significantly with a minimum value of about 15°C, and then rebounded to the normal value (as shown in Figure.4), which had an average descending temperature of 8.4°C.
Figure 3. The temperature monitoring point arrangement of geothermal filed.
Figure 4. The soil primitive and ground heat exchanger temperature of different depths.

The heat exchanger hole acted as a ground source heat pump heat exchanger, thus it had a great effect on the soil geothermal field. Figure 5 presented the continuous monitoring results for about three years. The peak and valley value firstly appeared in the soil near to the exchanging holes with a relatively much higher and lower temperature respectively. When the units were in the refrigeration state, the heat is released into the ground by the exchanging holes and the temperature at the distance of 1m to the exchanging holes was higher than that of 2.4m, and 2m followed by (i.e. $T_{1m} > T_{2.4m} > T_{2m}$), while in the heating state it was $T_{1m} < T_{2m} < T_{2.4m}$.

There were several differences of the temperature fluctuations between the exchanging holes and its surrounding soil. Maybe it was because: 1) the volatility of the surrounding soil had a large delay of three month before reaching to the peak and valley. 2) the soil had an apparent thermal inertia, and its temperature amplitude was small. The temperature volatility of the exchanging holes was $16.2^\circ C$, and the maximum amplitude of its surrounding soil was $3.7^\circ C$.

Figure 5. Temperature distribution at different distances to the underground exchanger.
4. Discussions and conclusions
For this project, the underground tubes were located under the landscape lake which was also integrated with the ice storage system. The buried tubes as the heat exchanger were the heat sink for the main chiller at daytime and for the refrigerator during the night. During the continuous operation for three years, the change of the ground temperature was relatively stable. Totally, the ground was taken as a huge energy storage with a low input and output amplitude.

Based on the three years’ data analysis, it was shown that with the energy balance of the heating and cooling, the geothermal source heat pump could be used for a large scale. The underground heat exchanger temperature change zone is in a depth of 0m-40m, and the temperature constant zone is around 40m-120m (14.9°C in 40m and 17.3°C in 120m). The temperature gradient was about 3.0°C/100m. Therefore the heat exchangers were located in the high temperature gradient zone of the ground.

The temperature amplitude of for the heat exchanger well at the depth of 40m was 7.2°C to 23.4°C for the heating and cooling season respectively, while the soil temperature is 13°C to 16.7°C. With three months delayed, the impact radius was more than 2.4m. The ground temperature decreased by about 0.3°C from October 2012 to October 2013. Therefore, the system operation need to be adjusted in future.

The ground temperature amplitude at a distance of 2.4m to the exchanging holes between the winter and summer was 2-3°C. The geothermal influence radius was much larger than 2.4m, thus there existed a heat bridge among the exchanging holes. As discussed above, the soil thermal inertia was about three month delay of the heat input and output from the heat exchanger. As well as considering the mutual balance between the quantity of heat and cool of the building, the soil thermal inertia could avoid the soil temperature to be too high or too low to a large degree, which as a result could ensure the great efficiency of the ground source heat pump system. Nevertheless, it was far from satisfaction to reflect the trend of a large scale of well groups in long operation with 2 to 3 years experimental results. Therefore, the ground temperature should be monitored and documented continually in order to support the subsequent engineering design and guide the operation as a reasonable reference.

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