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Technical Note

Improved method and case study of thermal response test for borehole heat exchangers of ground source heat pump system

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ABSTRACT

Thermal response test (TRT) is crucial for the determination of the ground thermal conductivity and the evaluation of the thermal performance of borehole heat exchangers (BHEs) of ground source heat pump (GSHP) system. This paper presented a novel constant heating-temperature method (CHTM) for TRT. Further, a type of improved TRT equipment was developed and the mathematical model to deal with test data was presented. Based on the measurement of the natural ground temperature distribution, an in situ TRT case was carried out. The experimental results showed that, compared with the conventional TRT with constant heating-flux method (CHFM), CHTM has an obvious advantage of reducing the time period reaching a steady heat-transfer state between the BHE and its surrounding soils. This improved TRT equipment can effectively operate under both heat-injection and heat-extraction modes, and its test data can accurately reflect the thermal properties of the soils as well as the thermal performance of the BHE under different operation conditions. Finally, the advantages and disadvantages between CHTM and CHFM were compared, which can provide a useful reference for the design of GSHP system.

1. Introduction

In recent years, ground source heat pumps (GSHPs) have been used increasingly around the world, because they are among the cleanest and most energy efficient air-conditioning systems for commercial and residential buildings. A typical GSHP system mainly consists of a conventional heat pump unit coupled with a group of borehole heat exchangers (BHEs). BHEs are devised for the extraction or injection of thermal energy from or into the ground. However, the thermal performance of BHEs is site-specific, due to the differences of the underground thermal properties, sizes and configuration of BHEs, and backfill materials of boreholes. For this purpose, an in situ thermal response test (TRT) is required to obtain the actual heat-transfer performance between the ground and a BHE, as well as the ground thermal properties including the thermal conductivity, which is helpful for the design and optimization of GSHP system. Since from the 1990s, both the academic and commercial TRT cases have been increasing rapidly in European, American and Asian countries [1,2]. In China, TRT was recommended by the national standard of Technical Code for Ground Source Heat Pump System (GB50366-2005).

At present, most conventional TRT equipment operates only under the heating mode driven by a group of fixed electric resistance heaters. This is the so-called constant heating-flux method (CHFM). Such typical cases were reported in the previous studies by Austin [3], Shonder and Beck [4], Witte et al. [5], and Sanner et al. [6]. More recently, using the above TRT method, Pahud [7] compared the thermal performance of a BHE with the backfill materials of quartz sand and bentonite. Florides [8] also determined the thermal performance of a U-pipe BHE in Cyprus, using a 2.82 kW electric heater to provide a steady heat injection into the ground. These experimental results showed that, for a good CHFM-based TRT, it is crucial to set up the system correctly and to minimize the possible external influences including the radiative and convective heat loss of BHEs with the ambient.

In spite of this, there are still some problems that merit our attention. For instance, the voltage instability in the grid may directly result in the fluctuation of the thermal power injected into the ground. Thus, the stability of TRT results will be greatly affected. On the other hand, from the point of view of engineering applications, the design for a typical hybrid GSHP system using an assisted cooling tower is often based on the heat-extraction performance of the BHE in winter. However, this required heat-extraction rate is not obtained directly from the conventional CHFM-based TRT. Even if it can be calculated indirectly by means of the estimated ground thermal properties and other mathematical or numerical models, there may be a certain uncertainty of the results.

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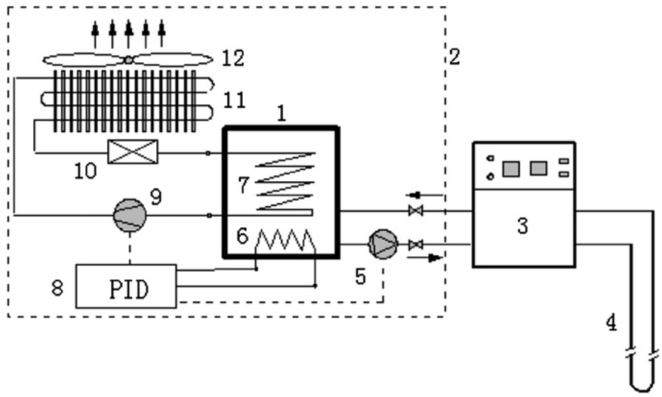

Fig. 1. Principle diagram of the improved TRT equipment. (1: insulated water tank; 2: heat/cold source system; 3: measuring system; 4: borehole heat exchanger; 5: circulating pump; 6: water heater; 7: evaporator; 8: PID controller; 9: compressor; 10: expansion valve; 11: condenser 12: axial cooling fan.).

Fig. 2. In situ test photo of the improved TRT equipment.

With the background above, a novel constant heating-temperature method (CHTM), instead of the conventional TRT method, was presented in this work. Further, a kind of improved TRT equipment was developed, in which both the heat-injection and heat-extraction operation were realized effectively. By far, several in situ TRTs have successfully performed in the Northern China areas, including Beijing, Tianjin, and Hebei province [9]. Related experimental results have verified several advantages of the improved TRT method and its test equipment. In addition, the differences between both TRT methods were compared. Another purpose of this work is to provide some useful guides for the design and optimization of GSHP system.

2. Experimental investigations

2.1. Experimental setup

Fig. 1 shows a principle diagram of the experimental system with the improved TRT equipment. It mainly consisted of a heat/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 L water tank, thus guaranteeing a stable inlet fluid temperature to the BHE. This was a major improvement based on the conventional TRT equipment. The water tank was made of SUS304-type stainless steel plates. The thickness of stainless steel plates and their polyurethane insulation layer was 2 mm and 30 mm, respectively. The heating function was provided by an adjustable electric water heater made of copper. The heater surface was coated with a thin layer of Teflon in order to avoid scaling. The cooling function was obtained by means of a typical R22 refrigeration cycle, which consisted of a compressor, a fin condenser, an expansion valve, and a coil evaporator. The condenser was cooled by an axial cooling fan. The maximum heating and cooling power were 12 kW and 9 kW, respectively. The heat/cold source system was also adjusted by an advanced PID integral controller mounted on the operation panel. In order to avoid the water shortage or overflow, two water level sensors were also installed at the bottom and top within the tank, respectively. In the present work, the operation temperature for the water tank ranged from 5 °C to 40 °C, with the accuracy of ±0.5 °C. A Wiley-RS25 type circulating pump with the input power of 90 W was used to keep the flow circuit. Its maximum flow rate and hydraulic head were 2.0 m^3/h and 6 m, respectively.

The measuring system mainly included two Pt1000-type temperature sensors with ±0.1 °C accuracy, a GPR-II type ultrasonic flow meter with ±0.001 m^3/h accuracy, a wattmeter, and other auxiliary instrument for control and display. The start flow rate of the flow meter was 0.0073 m^3/h. In order to guarantee the data validation of the inlet and outlet temperature of the BHE, all temperature sensors were calibrated before the installation by an XLR-1 type constant-temperature bath with ±0.01 °C accuracy. During the measurement, all temperature and flow rate signals were treated by an integral A/D converter, and then sent to an in situ computer through a standard RS485 transmission interface. All power consumptions were recorded by the wattmeter. In addition, for measuring the natural ground temperature distribution, additional calibrated Pt1000-type temperature sensors with ±0.1 °C accuracy were embedded at the different depths of the borehole. At the same time, an Aglient-34970A type data acquisition recorder was used.

Fig. 2 shows a general view of the improved TRT equipment during the in situ measurement in Hengshui (latitude 37.68°N, longitude 116.30°E), Hebei province. In the present TRT, the depth and diameter of the borehole were 100 m and 250 mm, respectively. The soil sampling analysis showed that the clay and silty clay were dominated within the range of the borehole depth. A double U-shaped DN32 type high-density polyethylene (HDPE) pipe was used as the BHE, and the medium-coarse sand was used for the backfill materials after drilling. In addition, all exposed pipes were isolated effectively using rubber-plastic materials with a thickness of 20 mm, in order to reduce the undesired loss of heat or cold.

The experimental period extended from August 16 to September 20, 2008. The whole test procedure under field conditions was as follows: Firstly, after the drilling and backfilling the borehole was kept at a natural recovery period, considering the disturbance effect of the drilling process on the natural ground temperature. Usually, it may take tens or hundreds of hours, depending on geological stratum conditions. Then the ground temperatures at different depths were recorded by the data acquisition recorder.

Secondly, the tank was filled with the filtering water in order to prevent the pump from blocking, and then the BHE was connected with the entrance and exit pipe of the heat/cold source system to form a closed circulation loop. Then the BHE was operating under the condition without heating or cooling, only driven by the circulating pump. After a long enough time, the inlet and outlet fluid temperature at a steady state were recorded.

Thirdly, the heat-extraction modes were operated. The inlet temperature of the BHE was set as a lower constant temperature ranging from 5 °C to 8 °C. Due to the heat extraction from the ground, the outlet temperature of the BHE tended to be increasing,