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Research Paper

Investigation on thermal performance of steel heat exchanger for ground source heat pump systems using full-scale experiments and numerical simulations

Shi-Jie Cao [a,*], Xiang-Ri Kong [a], Yelin Deng [a,b], Weirong Zhang [c], Lingyan Yang [d], Zi-Ping Ye [e]

[a] Department of Civil and Environmental Engineering, School of Urban Rail Transportation, Soochow University, Suzhou, China
[b] Department of Mechanical Engineering, University of Wisconsin-Milwaukee, United States
[c] Department of Architecture, Tokyo Polytechnic University, Japan
[d] China Academy of Building Research, Beijing, China
[e] The Sino-British College, USST, Shanghai, China

HIGHLIGHTS

- Study on the thermal performance of both vertical steel and PE U-tubes.
- Full-scale Experiments (U-tubes buried with a depth of 100 m) conducted.
- Study on the effects of inflow velocities, thermal resistance and surrounding soil.
- Cost analysis discussed for both PE and steel GSHP systems.

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ABSTRACT

In this manuscript, we investigated thermal performance for a new type of ground heat exchanger (GHE) with higher thermal conductivity materials of steel by using both methods of full-scale experimental tests (pipes buried underground with a depth of 100 m) and computational fluid dynamics (CFD) simulation. Thermal performance was based on the temperature differences between inlet and outlet of U-tubes and the heat transfer per unit borehole depth (Q_L). In addition, we also analyzed the entire thermal resistance of the borehole and the surrounding soil as well as the soil temperature distribution around the heat exchanger U-tubes. We found the further apart from the U-tubes, the smaller the soil temperature. Due to smaller heat resistance magnitude, the GHE performance of steel pipe was always better compared to conventional PE types, with Q_L increased up to 36%. Moreover, different inlet mass flow rates were also taken into consideration, and we found Q_L was always increasing with the increase of inlet velocities. The designed distance of GHE borehole was recommended to be larger than at least 1.4 m for steel pipe system and 1.2 m for PE one when the system is operated in continuous periods or intermittent operation of 8 h. Finally, cost analysis for both steel systems and the PE ones were discussed. This study will further facilitate for the future application of steel GHE for Ground Source Heat Pump systems.

1. Introduction

GSHP (Ground Source Heat Pump) is a system that uses the shallow earth energy as the heat sink or source to cool or heat buildings as well as domestic hot-water. As an energy-efficient and environmental-friendly way of cooling and heating buildings compared to conventional air conditioning systems, GSHP systems have been widely used in commercial and residential buildings. Moreover, the number of buildings with GSHP system has been continuously growing in recent years at an annual rate of 10–30% on a global basis [1,2].

Nevertheless, the limitation of GSHP is that the high initial investment cost due to wells digging, ground area occupation, etc., which imposes a great constraint to their market popularization. GHE (ground heat exchanger) is one of the most important parts influencing the thermal performance of GSHP system and typically configured in the shape of vertical U-tubes for the sake of higher efficiency and less occupied area [3–4]. Hence, to reduce the initial investment cost of GSHP system, it is of great importance to enhanc-

* Corresponding author.
E-mail address: shijie.cao@suda.edu.cn (S.-J. Cao).

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ing the thermal efficiency of GHE to reduce the meters of wells and save pipes of GHE. Many researchers have documented the influencing factors of heat exchange effects of GHE. These can be summarized by considerations of the material of GHE pipe [5–7], tube diameters/sizes, tube-connection configurations [5,8,9], buried depth of the vertical U-tube [10], inlet velocities of U-tube [5], thermal resistance of the borehole and ground [11], borehole backfill materials [12] as well as thermal performance of soil [13], etc.

Among these parameters, the material of U-tube GHE receives large attentions due to its considerable effect on thermal efficiency. Prior research has shown that GHEs made of superior thermal conductivity materials such as metals possess higher efficiencies compared with the most widely used PE materials (Polyethylene) [6–8]. Among some common metallic materials, copper pipes, which are available in different diameters and coil lengths have been investigated [14,15]. Though, some studies show that copper pipe can achieve 16% improvement in thermal performance of GHE compared to conventional PE pipe [6], and some drawbacks of the copper pipes make them hard to reach a large-scale implementation in real practice. Firstly, copper is a relatively expensive metal compared to steel and aluminium. On the other hand, copper pipe may undergo some corrosion in abnormally aggressive soils leading to a shortened service life [16].

Besides corrosion, many studies also highlighted the importance of the temperature distribution around GHE and thermal short-circuiting between two legs of the U-Tube influencing the thermal performance. Multiple studies have used numerical methods to determine a proper distance between two boreholes to present thermal short-circuiting. For example, Wang et al. [17] and Dai et al. [18] studied borehole resistance and thermal short-circuiting between two legs of the U-Tube by CFD simulation. Shang et al. [19] studied the geo-temperature recovery under the intermittent operation of GSHP system and reported that the soil properties have a far greater impact on the soil recovery than environment factors. Li et al. [20] established a 3-D model to simulate temperature variation and distribution around a U-tube GHE.

Therefore, to overcome the disadvantages of the copper pipe, in this study we designed a steel GHE pipe with high resistance to corrosion, low cost, and high thermal performance. We investigated the thermal performance of the newly designed steel pipe for GSHP system by using full-scale experiment tests (buried at the depth of 100 m underground) and numerical simulations. Thermal performance of the steel pipe is benchmarked with the conventional PE pipe. The coupled heat transfer between circulating fluid and the surrounding soil was systematically analyzed. Additionally, the change and recovery of geo-temperature of soil surrounding the GHE for both PE and steel pipes were also investigated. The feasible distance between two boreholes of steel GSHP system was recommended as well.

2. Methods

The general methodology of this study is depicted in Fig. 1. Firstly, a new type of GHE U-tube with steel material was designed. Next, the two types of U-tubes was buried with the same depth and backfilled with same materials (original soil). Then the thermal performance of two types of U-tubes was compared using experiment measurement based on temperature differences between inlet and outlet of U-tubes as well as the heat transfer per unit borehole depth. Finally, the feasibility of our new scheme was carried out.

2.1. Laboratory overview and test system

Fig. 2 demonstrates the whole laboratory test system of GSHP located at Yangcheng Lake Campus of Soochow University. The real-time monitoring campaign was conducted from Aug. 22th to Sep. 25th, when outdoor maximum average temperature is 29 °C. The system adopted 10 vertical U-tubes with an initial depth of 100 m in various shapes, diameters as well as materials. In this work, thermal performance of smooth PE U-tube and steel ones with dimensions of 26 mm was considered. The space between each borehole was around 5 m and each borehole was backfilled with the original soil.

The vertical U-tube of the ground heat exchanger (GHE) is a vital part of the Ground Source Heat Pump system. A schematic diagram of the ground heat exchanger of the vertical borehole with a single U-tube is illustrated in Fig. 3. The soil temperature field was monitored by 4 temperature sensors (Instrument: ds18b20), which were placed at different depths (10 m, 20 m, 30 m, 50 m) along the U-tube below the ground, remarked as A, B, C, and D shown in Fig. 3.

Fig. 4 shows a physical image and the cross–section of PE pipe and steel one. These two types of pipes share the same cross-sectional area of 530.66 mm^2 and the same inner radius of 26 mm, while the PE pipe is 2 mm thicker than the steel pipe (with thickness of 1 mm). It should be mentioned that a piece of thin PE layer was covered out of the steel pipe surface, with the thickness of 0.2 mm. The steel U-tube used in GSHP consists of 40 short steel pipes with a length of 5 m each. The hydraulic oil pump was applied to press connections between each two pipes avoiding water to be seeped out (shown in Fig. 5(a)). The distance between two legs of the U-Tube was 0.11 m. Finally, backfilled soil was inserted into a borehole of 0.18 m in diameter at surrounding areas after finishing laying GHE under the ground (shown in Fig. 5(b)).

An industrial platinum resistance thermometer (Instrument: Pt100) with a measurement range of 0.01–419.527 °C was used to measure the inlet and outlet water temperature of each exchanger (a minimum scale of 0.01 °C and a sampling error of "±0.02") as illustrated in Fig. 6(a). As shown in Fig. 6(b), the inlet flow rates of U-tube were measured by flow meters (Instrument: HRW-DN10P1F1F3) and the measurement range was 0.2–1.2 m^3/h with a sensitivity of 0.5%. The monitoring data was collected by automated data acquisition system every 1 min.

2.2. Numerical mechanism

In our study, CFD simulations, including the PE U-tubes and steel U-tubes shown in Fig. 4, also investigated comparative thermal analysis of two types of pipes for vertical ground heat exchangers. In order to obtain the thermal performance of two types of U-tubes and the soil temperature field around the underground U-tube, ANSYS FLUENT 16.0 was employed for CFD simulation. To reduce the amount of total mesh and optimize grid quality, the calculating domain was then partitioned into several sub-domains, with unstructured (Fig. 7(3)) and structured grids adopted separately in different sub-domains of U-tubes. The bottom of U-tube has an irregular shape, and the unstructured mesh is employed in this region. In addition, a local mesh encryption method was applied. Grid mesh near-wall was densified using size function while the mesh far away from the backfilled soil and U-tube was reduced.

The first grid-point is located at a distance of 7×10^{-4} m from the wall of U-tube. The computational geometry and mesh are depicted in Fig. 7. The mesh applied was sufficiently resolved when compared to refined mesh. In our study, the distributions of flow and temperature field were solved by SIMPLE arithmetic and k - ε RNG model [10,21–23], which has been proved to a reliable turbulence model to predict heat and flow distributions for GHE pipes.

In the process of the numerical simulation, we first obtained the steady flow field with certain inlet flow velocities. Then the temperature field of the coupled heat transfer process between the