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Research Paper

Experimental and numerical study on the thermal performance of ground source heat pump with a set of designed buried pipes

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HIGHLIGHTS

- Study on the thermal performance of designed vertical U-tubes with petals.
- Experiments (U-tubes buried with a depth of 100 m) conducted.
- Study on the effects of turbulent diffusion, flow resistance and advection.
- Future design of guidelines provided.

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ABSTRACT

The configuration of pipes is one of the most important factors for the thermal behavior of the Ground Source Heat Pump system (GSHPs). However, few studies have considered the influences of pipe shape in the perspective of turbulent diffusion and pressure loss effects. This paper investigates thermal performance of ground heat exchanger (GHE) with a set of designed U-tubes (i.e., either smooth or with different petals) by using experimental measurements and computational fluid dynamics (CFD) simulation. Thermal performance is based on temperature difference between inlet and outlet of U-tubes as well as the impact on the surrounding soil. First, an experiment (U-tubes buried with a depth of 100 m) was conducted to validate the CFD k-ε RNG model for a smooth U-tube, which agrees well with experiments with suitable boundary conditions and appropriate parameters. Next, CFD simulation tool was mainly employed for other evaluations. Different inlet velocities of U-tubes were considered, and we found the heat transfer per unit borehole depth QL increases with the increase of inlet velocities, e.g., the QL of smooth U-tube was 35 W/m at inlet velocity of 0.2 m/s, and increased by 43% when the velocity was increased to 1.2 m/s. Although U-tubes with different petals would increase the turbulent heat diffusion effects, the flow resistance is also increased due to the increase of pressure loss coefficient, further leading to the declined advection effects on heat exchange. It is shown that the thermal performance of smooth U-tube at different velocities is always better than the petals type. Finally future design of guidelines is given in discussion.

1. Introduction

According to the latest statistics in 2015, China maintains the world's largest energy consumer, and coal remains the dominant fuel accounting for 64% of China's total energy consumption [1]. Larger dependence of coal will triggers environmental issues, e.g. air pollutions. Therefore, it is a trend to develop and apply renewable and clean energy sources to lower China's reliance on the use of fossil fuels, and further, improve the environmental quality [2]. Besides, among various energy consuming sectors, the building sector accounts for nearly one-quarter of the total energy consumption, 70% of which is due to space cooling or heating [3]. Hence, it is of great importance to exploit renewable energy resources for building air-conditioning systems. As an energy-efficient and environmental-friendly system, Ground Source Heat Pump system (GSHPs) has been growing continuously on a global basis with the range from 10% to 30% annually in the past few decades [4]. As for China, GSHPs were used for space heating and cooling around 100 million square meters in 2009, while the figure had tripled to 300 million square meters by the end of 2014 [5].

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GSHPs is a system that converts the geothermal energy transferred from the soil to heat or cool buildings. The performance of GSHPs mainly depends on its borehole heat exchangers made of polyethylene (PE), typically in the shape of U-tube. The heat exchanger of GSHPs could be configured either horizontally or vertically while the latter configuration is much more commonly applied thanks to its higher efficiency and less area occupation [6,7]. In a city with high concentration of residents, vertical ground heat pump systems are becoming increasingly popular for heating and cooling in commercial and residential buildings in China [8]. Nevertheless, the disadvantage of GSHPS is high initial investment cost due to wells digging, ground area occupation etc., which imposes a great constraint to their market penetration. Also, other considerations, e.g. land use and borehole digging, could also limit the usage of GSHPs for building development [9]. Hence, it is of great importance to improve borehole heat exchanger's thermal performance of GSHPs in order to reduce the initial cost.

From previous studies, the heat transfer effect of heat exchangers could be enhanced by considerations of the tube diameter/size, buried depth of the vertical U-tube, tube-connection configurations and inlet velocity of U-tube or conductivity of backfill soil etc., which have been studied by many investigators using numerical simulations [7–10], experiment measurements [11–20] and artificial neural networks (ANN) [21–23]. For instance, Congedo et al. [7] studied three different configurations of horizontal ground heat exchangers using CFD simulations. Experiments were conducted for Thermal Response Test (TRT) to evaluate the thermal performance of borehole heat exchangers and determinate the ground thermal conductivity of GSHPs [14]. Jalaluddin et al. [15] studied heat exchanger rate of several types of ground heat exchangers (including U-tube, double U-tube, and multi-tubes) installed in a steel pile foundation. Experiments and numerical simulation on the heat exchanger of GSHPs were investigated by Pu et al. to study the thermal response of helical heat exchanger and the thermal conductivity of soil [18]. Compared to experimental study, the numerical simulation would be an efficient way to predict thermal response of GSHPs as well as other detailed temperature and flow information [19]. Besides, the geo-temperature recovery under the intermittent operation of GSHPs with the porous theory was studied [20]. The results showed that the soil properties could have a great influence on the temperature of soil recovery while the environmental factors have negligible effects.

To sum up, most of the researchers concluded that the configuration of the pipes is one of the most important factors for the thermal behavior of the ground source heat exchangers. However, there are few studies regarding the influence of the shape of U-tubes on the thermal performance of heat exchangers in the perspective of diffusion and advection effects of both heat and flow motions. Additionally, changing the shape of the U-tube should also result in a change of the pressure loss, i.e., inner flow resistance loss, which further affects the heat exchange effects between U-tube and ground soil. Therefore, in the current work, we will systematically study and analyze the thermal performance of a set of designed buried vertical U-tubes with different petals for GSHPs. Both numerical simulations and experiments were applied to investigate the coupled heat transfer between circulating fluid and the surrounding soil. Different influential factors of thermal response will be investigated, including turbulent heat diffusion effects, pressure loss coefficient as well as inlet flow velocities.

2. Methods

The general methodology of this study is depicted in Fig. 1. Firstly, a series of U-tubes were designed in the perspectives of the surface structure either smooth or with different petals. Next,

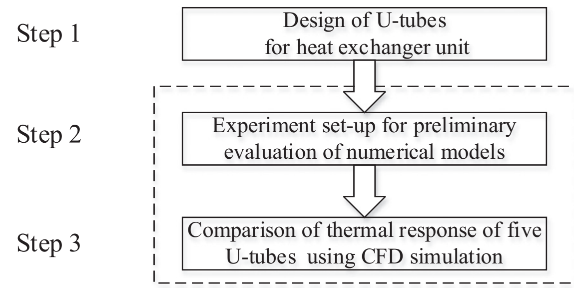

Fig. 1. The GSHPs experimental test and CFD simulation procedure.

experiments were conducted to test thermal response for validating numerical simulations. Then the thermal performance of five different U-tubes was compared using CFD simulations to analyze the influencing factors of thermal response of U-tubes including turbulent heat diffusion effects, pressure loss coefficient as well as inlet flow velocities of U-tubes.

2.1. Laboratory overview and test system

Fig. 2 demonstrates the whole system of GSHPs used for our experiments located at Yangcheng Lake Campus of Soochow University. The system adopted 8 vertical U-tubes with an initial depth of 100 m in various shape and diameters. In this work, thermal performance was studied for smooth pipe and pipe with 8 petals (both pipes have the same cross-sectional area of 530.66 mm^2). The space between each borehole was more than 5 m, and each borehole was backfilled with original soil. The soil temperature field was monitored by two temperature sensors (Instrument: ds18b20), which were placed at depths of 50 m along the tube below the ground. 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"). The inlet flow rates of U-tube were measured by flow meters. The data was collected automatically by data collection software every 1 min. The climatic data used in the simulation were tested from Jan 16th to Feb 10th 2016 by the lab of GSHPs located in Suzhou (China) at the coordinates: East Longitude 120.69 and North Latitude 31.40.

In the heating mode, the change of soil temperature at the depths of 50 m during the heat operation period was investigated. From Fig. 3, when GSHPs was running for 7 h, the extracting heat from the water in the ground produced a reduction in soil temperature. The ground temperature was recovered when the heat pump was switched off and become steady after 20 h at a depth of 50 m.

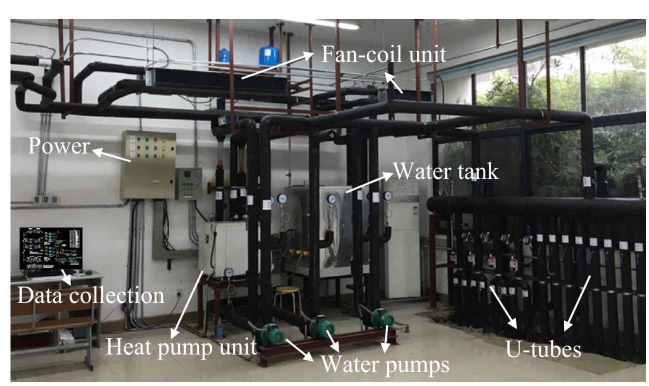

Fig. 2. Laboratory test system of ground source heat pump.