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Analysis on the transient heat transfer process inside and outside the borehole for a vertical U-tube ground heat exchanger under short-term heat storage

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A B S T R A C T

A three-dimensional unsteady model is established to study the heat transfer performance for a vertical U-tube ground heat exchanger (GHE). The transient heat transfer process between the inside and outside of the borehole under short-term heat storage is analyzed. The results indicate that the soil temperature field in the depth direction at the center section is distributed in a "narrow belt shape". The thermal interference distance of the ground heat exchanger under short-term heat storage is within a radius of 1 m, while the main heat transfer field is within a radius of 0.4 m. The inside borehole temperature field is dominated by the inlet branch of the U-tube, and it gradually becomes uniform as the heat storage time increases. For the temperature difference between the inside and outside of the borehole, the longer the heat storage time is, the greater the temperature difference between the borehole wall and the surrounding soil is and the lower the temperature difference between the fluid in the U-tube and the borehole wall is. At the same time, the change in temperature difference between the surrounding soil and the more distant boundary soil is not obvious.

1. Introduction

A vertical U-tube ground heat exchanger (GHE) is one of the most important devices for the effective utilization of shallow geothermal energy [1,2]. The heat transfer process inside and outside the borehole has a direct effect on the heat storage performance of the GHE. The heat transfer between the inside and outside of the borehole involves many links, such as the fluid in the U-tube to the inner pipe wall, the inner wall to the outer wall of the U-tube, the outer wall of the U-tube to the borehole wall, the borehole wall to the surrounding soil, and the surrounding soil to the faraway boundary soil. It is important to analyze the transient heat transfer process inside and outside the borehole to use GHEs as short-term heat storage.

In the past decade, most researchers have focused on the heat transfer performance of the vertical U-tube GHE. A number of analytical and numerical models have been developed to simulate vertical U-tube ground heat exchangers [3–12]. Lee et al. [3] conducted a computer simulation of borehole ground heat exchangers using the three-dimensional implicit finite difference method with a rectangular coordinate system. They recommended that their method would give more precise results compared with the finite line source model in designing a large borefield. Li et al. [4] presented a three-dimensional unstructured finite volume model for a GHE and used the Delaunay triangulation method to mesh the cross-section domain of the borefield. According to the comparison of the model predictions and experimental data of the GHE exiting temperature, the prediction accuracy of their model had been verified. Michopoulos et al. [5] developed a model to predict the fluid temperature at the ground heat exchanger outlet. These researchers considered the heat transfer phenomenon in the soil and the temporal variation of the thermal load of the GHE. An updated two-region vertical U-tube GHE analytical model was proposed by Yang et al. [6]. These researchers applied this model in the dynamic simulation of a ground coupled heat pump system. Based on an electrical analogy, the CApacity Resistance Model was presented by De Carli et al. [7] and Maestre et al. [8]. Considering the combined effect of groundwater flow and axial influence, Molina–Giraldo et al. [9] developed a new analytical approach to study the heat transfer at the GHE. These researchers concluded

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that for Peclet numbers between 1.2 and 10, both effects have to be accounted for when evaluating the temperature response of a BHE at the borehole wall. A three-dimensional numerical model of the GHE was presented by Rees et al. [10], including explicit representations of the circulating fluid and other borehole components. These researchers verified the model using both short timescale data and long timescale data. With dynamic thermal boundary conditions, Wang et al. [11] established one numerical simulation model to predict the solid zone (pipe, grout and soil) temperature variation for a long-term heat storage and a large-scale application of the GHE. A one-dimensional element with multiple degrees of freedom was used in a numerical model for a single vertical BHE [12] to determine a more accurate temperature of the fluid.

Aside from the established models of a GHE, the thermal performance of a GHE has been investigated in the literature [13–17]. Taking into consideration the three GHE field geometries, three types of time periodic heat loads and two thermal conductivities of the ground, Lazzari et al. [13]reported the minimum annual value of the fluid temperature in a double U-tube GHE for a period of 50 years. Based on the simulation results of the fluid temperature under the conditions of four different distances between adjacent BHEs and two values of the maximum heat load per unit BHE length during winter, these researchers determined that the distance and heat load keep the fluid temperature above the limit of −5 °C for design purposes. The heat exchange rates of the three types of GHEs with different operation modes have been investigated numerically by Jalaluddin et al. [14]. The results showed that a discontinuous 2 h operation in cooling mode, an alternative operation mode of cooling process and heating process, and operating discontinuously for 6 and 12 h in a day were helpful for increasing the heat exchange rate. The turbulent phenomena inside a vertical U-tube was described by Bouhacina et al. [15]. These researchers studied the variation of the borehole wall temperature and the wall heat flux with the operation time and found the temperatures distribution in and around the borehole in the Y and X directions. Pu et al. [16] investigated the effect of the Reynolds number, tube diameter and tube connection configurations on the thermal and pressure performance of vertical U-tube GHEs numerically. Zhang et al. [17] developed an iterative algorithm for evaluating the thermal performance of a GHE by coupling the two formulas for calculating the heat transfer rate. These researchers studied how such factors as the inlet fluid temperature, fluid flow rate, and borehole depth influenced the thermal performance of the GHE.

The thermal resistance is a crucial factor in designing or simulating a GHE. Sharqawy et al. [18] investigated the effective pipe-to-borehole thermal resistance of a vertical GHE and presented a best-fit correlation in dimensionless form. The thermal conductivity, thermal diffusivity and the steady-state equivalent thermal resistance of the underground soil were also determined by them [19]. Furthermore, the thermal interaction of multiple vertical GHEs, the heat dissipation effect on a GHE, the thermal capacity effects in a GHE, the groundwater flow and land surface effects on the thermal plumes of a GHE, the effect of the thermal interaction of GHEs on the ground heat pump efficiency, and the borehole thermal resistance in a GHE were investigated in the literature [20–25].

Because of the singleness of the heat source, more attention was paid to the long-term operating characteristics of a vertical U-tube GHE, whereas studies on the heat transfer performance and the transient heat transfer characteristics of a GHE in short-term heat storage are relatively scarce. Although Esen et al. [26] developed a finite element model to analyze the temperature distribution in the boreholes field in a short-term period, the depth direction temperature distribution of the GHE was not given. Beier [27] obtained the analytical solution of a transient model for a U-tube GHE. The transient vertical temperature in the circulating fluid was calculated, but the temperature differences between the inside and outside of the borehole were not discussed. The short-term GHE model has been validated against experimental data by Ruiz−Calvo et al. [28] and Pärisch et al. [29]. However, the thermal transfer performance of a GHE in the process of short-term heat storage has not been investigated.

This paper establishes a three-dimensional model for a ground heat exchanger and the surrounding soil by considering the thermal conduction and groundwater seepage. The accuracy of the model is validated by comparing it with experimental data. The temperature field of an underground vertical U-tube heat exchanger in the direction of depth and radial direction, together with the temperature difference between the inside and outside of the borehole, is obtained numerically. Finally, the thermal transfer of a vertical U-tube GHE with the temperature, time and space in the process of short-term heat storage is discussed.

2. Heat transfer model and numerical simulation

2.1. Physical model

The typical single U-tube heat exchanger consists of fluid in the U-tube, tube wall, backfill material and soil. The structure and detailed dimensions of the GHE are shown in Fig. 1. The fluid flows through the U-tube and recharges heat to the soil. The heat and mass transfer occurs in the surrounding soil in the heat storage process. As shown in Fig. 1, the inside and outside diameters of the U-tube are 25 mm and 32 mm, respectively. The distance between the tubes is 55 mm, and the diameter and depth of the borehole are 110 mm and 50 m, respectively. The diameter of the surrounding soil is 6 m.

2.2. Mathematical model

A three-dimensional unsteady model is established by considering the actual structure of the vertical U-tube heat exchanger, the thermal conduction and groundwater seepage in the surrounding

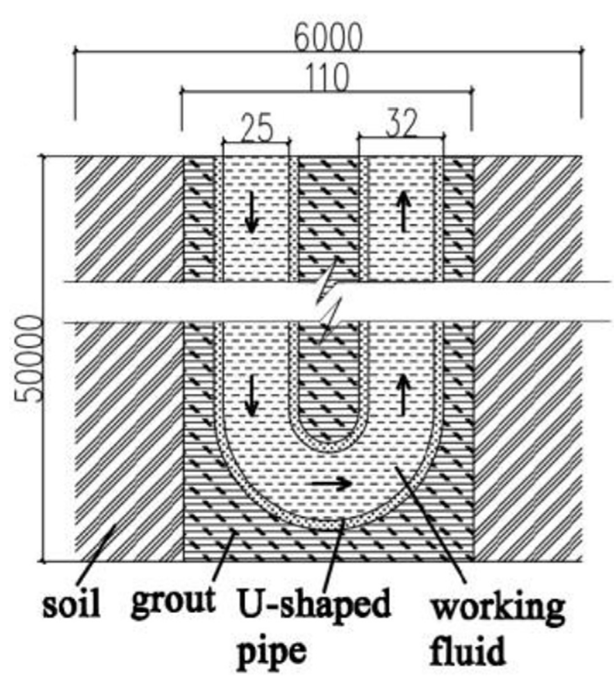

Fig. 1. Structure and dimension of the vertical U-tube GHE.