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3D dynamic numerical programming and calculation of vertical buried tube heat exchanger performance of ground-source heat pumps under coupled heat transfer inside and outside of tube

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ABSTRACT

Targeting the underground vertical buried tube heat exchangers (BTHEs) of ground-source heat pumps, a physicomathematical model of heat and mass transfer that couples the turbulent flow field in the tube with the groundwater seepage in the surrounding soil was established in this study. FORTRAN language was used to design a 3D dynamic numerical calculation program for this model, and the geotechnical thermal response test data was used to verify the reliability of this program. It also used the program to comparatively analyze the error influence of the assumption of uniform velocity flow field in the tube on heat transfer performance analysis. Considering the turbulent flow field in the tube, the influence of groundwater seepage and inlet flow velocity in buried tube on the heat transfer performance of BTHEs was further explored. The results show that the assumption of uniform velocity flow field in the tube caused a relatively significant error with the heat transfer performance analysis on buried tube, and both the soil seepage velocity and flow velocity in the tube influenced the heat transfer performance of buried tube. This study aimed to provide a programming method for the in-depth study of buried tube heat transfer performance.

1. Introduction

As a high-efficiency and energy-efficient renewable energy technology, the ground-source heat pump technology has attracted much attention and widely applied in the recent years. Moreover, the buried tube heat exchanger (BTHE) constitutes a core part of the technology, and the magnitude of its heat transfer capacity directly affects the efficiency of the overall unit. Therefore, it is particularly important to probe into the heat transfer performance of BTHEs.

The heat transfer performance of the BTHEs of ground-source heat pumps (GSHPs)is usually studied by three methods, i.e., analytical method, numerical method, and experimental method. Among them, the results of numerical method are more approximate to the actual results than the analytical method and more cost-saving and time-saving than the experimental method. Therefore, the numerical method has been commonly used in this field. The numerical method can be further classified into two types: commercial numerical simulation software and self-compiled programs. Commercial software is easy to use and simple to operate, but for some special issues, its internal conditions cannot be freely modified. For the studies on ground-source heat pump systems, considering that the actual soil mass is a porous medium and the existing commercial software has numerous limitations in the heat and mass transfer calculation of porous media, it is necessary to develop self-compiled programs to study some of the issues related to the thermal seepage coupling of vertical buried tube geothermal heat exchangers.

Currently, the commercial numerical simulation softwares that can be used for this purpose mainly include FLUENT, ANSYS, and ADINA. Decoupling calculations for inside and outside tubes have been reported [1–6]. The heat transfer performance of buried tubes was studied by the 2D-FDTD method based on the line heat source model [1,2]. A model of 2D numerical heat transfer with a constant heat flux inside the tube was established using the finite volume method [3–5]. A 3D constant-heat flux heat transfer model of a vertical buried tube was established [6]. The coupling calculations for the inside and outside tubes have been reported [7–14], but the geotechnical side was studied using pure heat conduction calculation. The effects of groundwater seepage on BTHEs have been reported [15–22];all the models were established assuming geotechnical homogeneity and uniform and advective groundwater seepage, i.e., based on a simplification of the saturated zone

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including Andrew D. et al.'s model, 2D finite element model [15], C.K. Lee and H.N. Lam's 3D finite difference model [16], M. Nabi's 3D finite volume model [16], and some other thermal seepage coupling models for the heat transfer of buried tubes [18–22].

Compared to commercial softwares, self-compiled programs are rarely used in the numerical models of BTHEs. Considering the tube fluid as a uniform velocity flow field (the buried tube cross-sectional velocity is a constant at each point) and under the condition that the geotechnical seepage only considered a horizontal uniform seepage, a related 3D numerical calculation program for energy equation was compiled, the temperature distribution was obtained, and the influence of underground seepage on the heat transfer performance of BTHEs was analyzed [23]. Similarly, a 3D numerical calculation program of energy equation of the buried tube heat exchanger (BTHE) was complied, and the heat transfer of multiple drills in soil layers was simulated [17,24]. The numerical calculation program of a "quasi-3D model" was established for decoupling inside and outside a tube [25], where the 3D transient heat transfer was decomposed into 1D heat conduction along the depth direction and 2D heat conduction in the horizontal plane. By making a U tube equivalent of an equivalent-diameter single tube and providing the heat transfer per unit well depth in a drill, the numerical calculation program of quasi-3D heat conduction for decoupling inside and outside a tube was compiled [26]. A numerical calculation program of 3D heat conduction for decoupling inside and outside a tube was developed, and the effect of burial depth and uniform flow velocity of the tube on thermal short circuit was analyzed [27]. A 3D dynamic numerical calculation program is compiled for the dynamic calculation and analysis of the thermal environment of the room[28].

To sum up, in the existing literatures and studies, all the heat transfer models of self-compiled programs have significantly simplified the heat transfer of buried tubes, considered a buried tube wall as a constant heat flux boundary, or considered the flow in a tube as a uniform velocity flow field without calculating the flow field in the tube; no study was reported on any self-compiled program for the 3D numerical calculation of a convective heat transfer in a turbulent flow field for decoupling inside and outside a tube. In the actual problems, the fluid in a tube is generally in a turbulent state and undergoes convective heat transfer with tube wall, thus achieving heat transfer between the flow in the tube and the surrounding soils. The flow field in a tube significantly affects the heat transfer performance of buried tubes.

By targeting the BTHEs of GSHPs, a mathematical model of buried tube heat transfer was established in this study by considering both the heat convection in a tube turbulent field and the heat and mass transfer of a porous media in the surrounding soils. On such basis, FORTRAN language was used to compile a 3D dynamic numerical calculation program; this program was used to analyze the heat transfer characteristics of vertical buried tubes in thermal seepage coupling. The results obtained in this study will help GSHP programming in-depth study on the heat transfer performance of the BTHEs of GSHPs.

2. Physical model

The heat transfer of BTHEs is a complex and unsteady coupled heat transfer process involving heat convection with a turbulent flow between the tube wall and fluid in a tube, the heat conduction of tube walls and backfill materials, and the thermal seepage coupling of surrounding soil. To facilitate analysis and programming, some physical problems and geometric conditions were simplified where necessary.

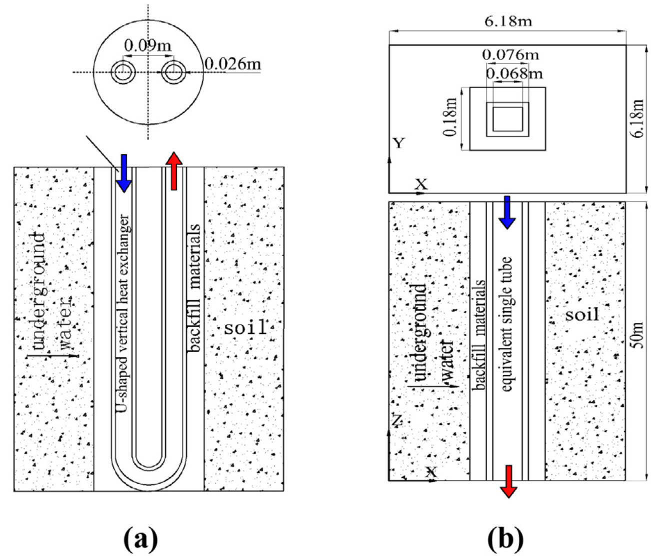

Fig. 1. Schematic diagram of the equivalent single tube:(a) Vertical section of U-tube. (b) Vertical section of the equivalent single tube.

2.1. Geometric model

The geometric prototype is a vertical single U-shaped buried tube with an inner diameter of 0.026 m and a tube wall thickness of 0.003 m; the U tube was spaced with 0.09 m central distance between the two branch tubes and a total tube depth of 50 m. The water flows into one side of the tube through the U tube and flows out from the other side as shown in Fig. 1(a). Here, the U tube was simplified into a vertical square cylinder single tube with a total burial depth of 50 m. In the same manner, water flows into the top side through the buried tube and flows out from the bottom side. First, the vertical U tube heat exchanger with two pins that influence each other in heat transfer is made equivalent to an equivalent-diameter single tube [29], where the algorithm of the equivalent diameter can be expressed as follows:

$$D_{eq} = 2r_{eq} = 2\sqrt{r_a L_S} = \sqrt{2DL_S}\ \mathrm{D} \le L_S \le r_b \tag{1}$$

where D_{eq} is the equivalent diameter, m;r_{eq} is the equivalent radius, m;r_a is the radius of the U-shaped tube, m;L_S is the central distance between the two branch tubes of the U tube, m; D is the diameter of the U tube, m; r_b is the radius of the tube well, m.

By substituting the values of inner and outer diameters into Formulation (1), the calculation results are obtained. The inner and outer diameters of the equivalent-diameter single tube were 0.068 m and 0.076 m, respectively. Then, the equivalent-diameter single tube was made equivalent to a vertical square cylinder, and to ensure the consistency between the thermal capacity of the tube wall and the mass flow in the tube, the inner and outer side lengths of the square cylinder buried tube should satisfy Formulas (2) and (3) [27]:

$$L_i = \sqrt{\pi} d_i / 2 \tag{2}$$

$$L_o = \sqrt{\pi \left(d_o{}^2 - d_i{}^2\right)/4 + L_i{}^2} \tag{3}$$

where L_i is the inner length of the equivalent square cylinder, m; L_o is the outer length of the square cylinder, *m; d_i* is the inner diameter of the equivalent-diameter single tube, m; d_o is the outer diameter of the equivalent-diameter single tube, m.

According to the calculation results, the vertical square cylinder single tube had an inner length of 0.060 m, an outer length of 0.067 m, and a burial depth of 50 m. The geometric model is shown