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An improved analytical model for vertical borehole ground heat exchanger with multiple-layer substrates and groundwater flow

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HIGHLIGHTS

- An improved analytical model for vertical borehole ground heat exchanger is provided.
- The improved analytical model cater the groundwater flow in multiple-layer geologies.
- The soil temperature around the BHE can be forecasted very well.
- Long-term performance of BHE can be evaluated accurately.
- Groundwater flow can effectively alleviate the heat (cold) accumulation of soil.

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ABSTRACT

An improved analytical model for vertical borehole ground heat exchanger (BHE) which takes into account effect of groundwater flow in multiple-layer geologies is applied to simulate and analyze the long-term temperature response of soil around BHE with the unbalanced seasonal dynamic load. The present model was validated by experiment for a single borehole with good agreement, and it can find that the average of temperature integral along the borehole wall depth is taken as the representative temperature of the borehole wall will be more reasonable. Moreover, the influence of groundwater flow velocity on soil temperature around the borehole was investigated, the results show that the deformation of plane temperature field caused by groundwater advection, as equivalent velocity reach a certain order of magnitude, groundwater flow can effectively alleviate the heat (cold) accumulation. Finally, the temperature change of soil around borehole at different operation time was simulated, results indicate that the higher the groundwater velocity is, the faster time make temperature field to achieve stability. This analytical model provides better flexibility and versatility to research further the effect of groundwater flow in layered geologies.

1. Introduction

The application of renewable energy will be more and more popular with increasing of the global energy consumption. Among various kinds of renewable energy resources, geothermal energy has a great potential especially in connection with ground source heat pump systems (GSHPS) has been regarded as energy efficient way of space heating in winter and air conditioning in summer [1–7]. GSHPS are one of the major technologies for shallow geothermal energy production in many countries [4,8,9], especially it is widely used in residential and commercial buildings [10].

GSHPS absorbs geothermal energy rely on buried tube heat exchanger (BHE), so BHE is the main components of the GSHPS, and is a connector for heat transfer between circulating fluid and soil. There are two arrangement ways of BHE, horizontal and vertical arrangements, are used in real GSHPS according to the operating condition and the surrounding soil property. The vertical system requires less land area, and the system capacity can be enhanced simply by using longer boreholes. Indeed, the vertical borehole arrangements are the most popular kinds of BHE ever installed. Vertical borehole configurations are often favored to horizontal collectors because of their smaller space requirements and because they are less influenced by seasonal temperature fluctuations from the surface. In GSHPS, one or more vertical pipes are installed down to depths of around 50–150 m [11], depending on the prevailing geological conditions and the specific energy. Moreover, the high installation cost for the BHE is a major restriction to the adoption of the GSHPS, therefore, a proper system design and

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Nomenclature

x, y, z	Cartesian coordinate (m)
α	thermal diffusivity ($m^2 \cdot s^{-1}$)
k	effective thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
c	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
ε	porosity
t	temperature (°C))
u	groundwater advection ($m \cdot s^{-1}$)
G	green function
U	equivalent velocity of groundwater advection ($m \cdot s^{-1}$)
H	borehole length (m)
r	radius (m)
M	mass rate of fluid ($kg \cdot s^{-1}$)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
$2D$	spacing between two legs of U-tube (m)
h	convective heat transfer coefficient of fluid in u-tube ($W \cdot m^{-2} \cdot K^{-1}$)
R_{11}	thermal resistance between the inlet pipe and borehole wall ($m \cdot K \cdot W^{-1}$)
R_{22}	thermal resistance between the return pipe and borehole wall ($m \cdot K \cdot W^{-1}$)
R_{12}	thermal resistance between the two legs of U-tube ($m \cdot K \cdot W^{-1}$)
τ	time (s)
q	heating rate per length of source ($W \cdot m^{-1}$)
θ	excess temperature (°C)
μ	dynamic viscosity coefficient of fluid (Pa·s)
Pe	Peclet number
I	hydraulic gradient ($m \cdot m^{-1}$)
K	Hydraulic conductivity ($m \cdot s^{-1}$)
L	borehole spacing (m)

Superscript

$'$	integration parameter

Subscript

w	water
s	soil
i	layer number
in	inner
o	outer
g	grout material
p	U-tube material
f	fluid
b	borehole

assess the performance of BHE accurately can effectively improve energy utilization efficiency of GSHPS.

Thermal performance of BHE can be accurate estimate is important to maximize the economic benefit, researchers are announcing numerous studies on BHE in order to gain higher efficiencies, in recent years, there have been many studies related to the heat transfer in and around boreholes based on analytical, numerical and hybrid models. The related numerical models are based on finite volume methods (see for example [12–16]), finite element methods (see for example [17,18]) and finite difference methods (see for example [19]). However, numerical models give accurate solutions and are conducive to theoretical analysis but have limited flexibility and need extensive computational time. Analytical models, although less precise than numerical models are preferred in most practical applications because of their superior computational time and flexibility for parameterized design. Therefore, analytical model is particularly important for calculating borehole heat exchange and system configuration optimization.

Analytical solutions for vertical BHE have been improved and developed (see for example [25–30]) based on traditional classic analytical models [20–24] include the line source model and the cylindrical source model. Lamarche et al. [25] developed an analytical model for heat transfer of borehole based on finite line source (FLS) model, which has faster computation time than Eskilson [24] model. Yi et al. [26] developed a solid cylindrical model which was compared with the classical line source and "hollow" cylindrical source models of the BHE, and also validated by a numerical solution of the same model under the assumption that ground is homogeneous for boreholes and energy piles. Three analytical solutions are referred to as the infinite line source (ILS), the infinite cylindrical source (ICS) and the finite line source (FLS) models whose results are compared and validity domains are determined by Philippe et al. [27]. Bandos et al. [28] provided new approximate expressions for the average thermal response function that takes into account the prevailing geothermal gradient and allows arbitrary ground surface temperature changes is presented. Then the effective thermal conductivity and the effective borehole thermal resistance can be determined by fitting the thermal response test (TRT) data. Yang et al. [29,30] studied the heat transfer process of the vertical U-tube BHE for GSHP system by used a two-region simulation model and an experiment. This study concluded that the performance of the GCHP system is strongly affected by the ground initial temperature. However, most of the numerical model and the analytical model are in the premise of certain assumptions, such as the formation is homogeneous medium of gay or without the influence of groundwater flow, etc. In actual cases, the ground is usually composed of several layers with different thermal properties, the TRT analysis will become less accurate depending on the traditional models, in order to enhance the accuracy of estimation of thermal performance of vertical U-tube BHE is applied to the actual situation, many scholars have further explored, these include the following:

(a) Studies of BHE concern multiple ground layers

Wang et al. [31] determined the performance of a BHE in an inhomogeneous ground with multiple ground layers based on the numerical model of Eskilson [32]. Lee [33] investigated a TRT analysis count for multiple ground layers by a three-dimensional finite difference model and found an effective ground thermal conductivity and an effective ground volumetric heat capacity for a multilayer ground determined from a TRT analysis were adopted would have very little error in the simulated long term system performance under various ground compositions investigated. Yoon et al. [34] presented an experimental and numerical study on the evaluation of TRTs to measure the ground thermal conductivity and borehole thermal resistance using a precast high-strength concrete (PHC) energy pile and a closed vertical system with W-type BHEs installed in a multiple layered soil ground. They showed that the multipole method can be more precise in predicting the borehole thermal resistance. Georgios et al. [35] developed a new model applied to a multiple layer ground regime with different properties and the effect of the layer sequence on the outlet temperature is examined, where the model was also modified to