



A general distributed parameter model for ground heat exchangers with arbitrary shape and type of heat sources

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ARTICLE INFO

Keywords:

Ground-coupled heat pump
Ground heat exchanger
Distributed parameter model
Response factor
Simulation

ABSTRACT

The heat and mass transfer simulation model of a ground heat exchanger (GHE) directly affects the design and operation performance of a ground-coupled heat pump system. The GHE models based on the response function (like the Green function and g-function) can achieve a fast calculation speed. However, the heat sources in these models are limited to points or whole boreholes, leading to low calculation accuracy in heat transfer during a short time period and limitation to a certain GHE. A general distributed parameter model for a ground heat exchanger (RF model) is proposed based on the principle of response factors in this paper. A sandbox experimental platform is then built to test the temperatures of typical points in the double-layered soil and to validate the RF model. After that, the calculation of the RF model is simplified by determining suitable positions for the soil boundaries and the numbers of sub pipes and sub soil boundaries. Finally, the RF model is applied in different scenarios to demonstrate its characteristics. The results show that: (1) the RF model is suitable for different kinds of GHEs with arbitrary shape and type of heat sources releasing heat in arbitrary time steps; (2) the RF model has only 0.01 °C and 0.23 °C temperature response errors compared to those from numerical solutions and experiments, respectively; (3) the general RF model has similar accuracy to the numerical solution in calculating the distributed temperatures of the borehole and pipes, heat transfer in the short term, and heat transfer of borehole groups and the energy pile.

1. Introduction

The ground-coupled heat pump (GCHP) is becoming more and more popular around the world [1,2] because it is a clean and efficient technology for heating and cooling [3–5]. They are applied not only in the commercial and residential buildings [6,7], but also in the historical buildings [8] and agricultural facilities [9]. The ground heat exchanger (GHE) is an important component of the GCHP, of which the heat exchanging performance has greatly influenced the system design and operation [10,11].

There are currently a number of GHE models considering the effect of groundwater, which is beneficial to the heat transfer [12–21]. For example, Hecht-Mendez et al. [15,16] evaluated different numerical tools and studied the optimized energy extraction for borehole groups considering groundwater. Angelotti et al. [17] adopted MT3DMS coupled to MODFLOW to simulate U pipe in a saturated porous medium. Molina-Giraldo et al. [18] evaluated the effect of thermal dispersion on temperature plumes around a borehole using analytical solutions. Diao et al. [19] proposed an analytical moving line source model to calculate

heat transfer with groundwater. Hu [20] and Erol and François [21] improved the analytical model considering both multilayer and groundwater. However, there are also many studies [22–24] aiming to predict the heat transfer characteristics of GHE with dry soils, through various analytical and numerical models. On these occasions, the influence of groundwater can be ignored and the heat transfer around the GHE is purely unsteady heat conduction, thus the calculation models can be simplified. This study focuses on the improvement of the calculation accuracy and speed of the existing GHE models with relatively dry soil or negligible groundwater. In addition, some other important factors should also be considered in the soil field, such as different types and geometries of heat sources, different soil layers and different properties of soil and grout [25–28]. In the existing research, there are three main GHE models: numerical solutions, g-function models and the analytical solutions, which are specifically introduced in the following parts.

Numerical solutions, like the finite difference method [29], finite element method [30–32] and finite volume method [23–24,33–36], can consider the complex geometries of GHE to calculate the soil

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<https://doi.org/10.1016/j.enconman.2018.03.059>

Received 1 January 2018; Received in revised form 20 March 2018; Accepted 20 March 2018
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Nomenclature			
A, B, C	index	ε	temperature error, °C
c	specific heat capacity, J/(kg °C)	<i>Subscript</i>	
CON	the current temperature of a point in the soil field influenced by all the previous heat fluxes of heat sources	A	absolute error
F	area, m ²	k	kth layered soil
h	heat convection coefficient, W/(m ² °C)	n	nth heat source
L	length of U pipe, m	p	soil point P
m	mass flow rate, kg/s	r	relative error
Q	heat flux, W	s	heat source of heat exchange pipe
S	area, m ²	w	heat source of soil boundary
V	volume, m ³	$s_s n_s$	n_s th sub heat source of the s 'th pipe
Y	response factor	$w_w m_w$	m_w th sub heat source of the w 'th pipe
τ	time, s	f	fluid
ρ	density, kg/m ³	pw	pipe wall
λ	heat conductivity, W/(m °C)	in	pipe inlet
θ	excess temperature, °C	out	pipe outlet

temperature distribution accurately. However, since these solutions need to calculate heat and mass transfer of all the meshes in the soil field, they have a heavy workload and are very time-consuming. Especially for cases with different operation strategies, they should repeat similar numerical work in the whole calculation field.

To simplify the calculation, current GHE models commonly use a response function, like the Green function or g-function. These response functions build a direct relation between the temperature and heat sources. Based on them, the heat transfer is no longer calculated in the whole soil field and therefore the calculation time is saved compared with numerical solutions.

The Green function defines a transient point as the heat source [37]. Integrating the Green function over the geometry and the heating time of the sources can achieve the soil temperature. Since the heat source of the Green function is the transient point, the workload is large if it is calculated by numerical simulations [38], and several assumptions should be made if it is calculated by analytical solutions. Analytical solutions [22,39–44] have a discount on accuracy because of the many assumptions. The commonly used infinite and finite line source models ignore the practical geometry of the borehole, the thermal capacity inside the borehole and the groundwater flow. So, they cause apparent errors in the transient heat transfer and cannot calculate accurately with the variable inlet fluid temperature. Li [43,44] modified the analytical solution for calculating the short-term heat transfer. However, it ignored the actual geometry of the U pipe and was not suitable for spiral pipes [43] and was unreasonable for the long-term calculation [44].

The g-function [45–50] defines a whole borehole with a constant heat flux as the heat source. The borehole here is cylindrical instead of a line source, however the heat transfer inside the borehole is steady in Eskilson model [45], which is reasonable only when the heat source releases heat for longer than 3–12 h. Thus, this solution still has a non-negligible error when calculating short-term heat transfer. To improve this model, Yavuzturk et al. [46] and Gallero et al. [47] proposed the short time-step g-function model. This model built a two-dimensional numerical model to describe the unsteady heat transfer inside the borehole, making it suitable for short-term heat transfer prediction. However, this model assumed a fixed heat flux ratio between the inlet and outlet pipe, ignoring the influence of the fluid velocity.

As a summary, the geometry and type of heat sources of the Green

function and g-function in the existing models are limited, leading to inaccurate calculation of the heat transfer of the soil around the GHE. In the research on ventilation, the response factor was used to reflect the relationship between the source and the field [51]. The heat source of the response factor can be an arbitrary shape and releases heat in an arbitrary time-step. This overcomes the limitation of the Green function and g-function, allowing accurate calculation of the heat transfer. In our previous research [52], the definition of the response factors used for soil heat conduction is introduced and the soil temperature distribution influenced by a borehole with a constant heat flux is calculated.

In this paper, based on the principle of the response factor in soil heat conduction, (1) the different types of heat sources in the soil around the GHE are summarized; (2) the calculation methods of the heat fluxes of different heat sources based on the different known parameters are deduced; (3) the general distributed parameter GHE model is proposed to calculate the soil and fluid temperature distribution accurately and fast. So, the unsteady heat transfer outside the pipe, the fluid temperature variation along the flow direction, heat transfer from soil boundaries, rapidly varied fluid temperature and the inner thermal influence between borehole groups can be considered. Then, a sandbox experiment is established to validate the accuracy of the proposed model, and the suitable position of the soil boundaries and the suitable number of sub heat sources are determined to reduce the calculation workload as well as to guarantee the calculation accuracy. Finally, several cases under different conditions are calculated to show the accuracy of the proposed model in practical projects.

2. The general distributed parameter model for GHE

In the soil, the GHE can be of different types, like boreholes, energy piles with U pipes or spiral pipes, energy walls or energy tunnels. The energy piles/walls/tunnels are geostructures incorporating the primary heat exchangers through the foundation elements (e.g., piles and basement walls) or into the tunnel linings [53]. But for different GHEs, for the pipes buried inside, the inlet temperature and fluid velocity are known, and the fluid temperature varies along the direction of flow. The soil surface has a known temperature which can be considered as similar to the outdoor or indoor air temperature. The surrounding and bottom soil boundaries have a constant initial soil temperature. As a summary, there are two kinds of heat sources in the soil, pipes and the

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