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A two-region simulation model of vertical U-tube ground heat exchanger and its experimental verification

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ABSTRACT

Heat transfer around vertical ground heat exchanger (GHE) is a common problem for the design and simulation of ground coupled heat pump (GCHP). In this paper, an updated two-region vertical U-tube GHE analytical model, which is fit for system dynamic simulation of GCHP, is proposed and developed. It divides the heat transfer region of GHE into two parts at the boundary of borehole wall, and the two regions are coupled by the temperature of borehole wall. Both steady and transient heat transfer method are used to analyze the heat transfer process inside and outside borehole, respectively. The transient borehole wall temperature is calculated for the soil region outside borehole by use of a variable heat flux cylindrical source model. As for the region inside borehole, considering the variation of fluid temperature along the borehole length and the heat interference between two adjacent legs of U-tube, a quasi-three dimensional steady-state heat transfer analytical model for the borehole is developed based on the element energy conservation. The implement process of the model used in the dynamic simulation of GCHPs is illuminated in detail and the application calculation example for it is also presented. The experimental validation on the model is performed in a solar-geothermal multifunctional heat pump experiment system with two vertical boreholes and each with a 30 m vertical 1 1/4 in nominal diameter HDPE single U-tube GHE, the results indicate that the calculated fluid outlet temperatures of GHE by the model are agreed well with the corresponding test data and the guess relative error is less than 6%.

1. Introduction

Ground coupled heat pump (GCHP) has been showed to be a very efficient method of providing heating and cooling for residential and commercial buildings compared with traditional HVAC equipment and is widely accepted as one of the best renewable energy technology. A typical GCHP system consists of a conventional heat pump coupled with a ground heat exchanger (GHE). In common configurations, the GHE consists of loops installed in a horizontal or vertical style. Currently, for most buildings, a vertical U-tube GHE configuration is usually preferred over horizontal style because it requires less ground area and offers better performance than the horizontal due to smaller seasonal swing in the ground mean temperature.

Recent research in the GCHP field has contributed to reducing the life cycle and to broadening the application of this technology. One important research area is modelling, which allows system dynamic simulations to be performed. For GCHP system, simulation is an important tool for system optimization design purpose as well as for investigating long-term system performance. For this a reliable and feasible heat transfer analysis model of GHE is required. Currently, there have been a number of models that can predict transient heat transfer in vertical U-tube GHE. The models are mostly based on either some analytical solutions like line source heat source theory proposed by Ingersoll and Plass [1] and cylindrical heat source theory first presented by Carslaw and Jaeger [2] and Ingersoll et al. [3] and later refined by Deerman and Kavanaugh [4] or numerical solutions like the one proposed by Eskilson's [5] and Hellstrom [6] that were used for designing vertical boreholes used in GCHP systems.

Stand-alone numerical models have been reported by Mei and Emerson [7], Kavanaugh [8], Lei [9], Muraya et al. [10], Rottmayer et al. [11], Thornton et al. [12], Yavuzturk et al. [13,14], Lee and Lam [15] and Li and Zheng [16]. Eskilson [5] calculated the ground temperature around a GHE using two-dimensional explicit finite-difference method. He proposed a dimensionless temperature response factor, called *g*-function, to describe the performance of borehole and developed *g*-function curves based on selected borefield configurations. Hellstrom [6] developed a model for vertical ground heat exchanger stores, and calculated the store performance based on the superposition of a local, steady flux and global solution. Kavanaugh [8] used a two-dimensional finite-difference method to study the performance of a borehole with concentric

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Nomenclature

a_s	soil thermal diffusivity ($m^2\ h^{-1}$)
a_1, a_2, a_3	curve-fit coefficients (–)
b_1, b_2, b_3	curve-fit coefficients (–)
C_1, C_2	constants (–)
c_p	constant pressure specific heat ($kJ\ kg^{-1}\ K^{-1}$)
D_U	spacing of U-tube shanks (m)
d	diameter (m)
Fo	Fourier number (–)
G	cylindrical source analytical solution (–)
H	borehole length (m)
h	convection coefficients ($W\ m^{-2}\ K^{-1}$)
K_1	equivalent heat conductivity between the fluid inside leg and borehole wall ($W\ m^{-1}\ K^{-1}$)
K_{12}	equivalent heat conductivity between two legs ($W\ m^{-1}\ K^{-1}$)
M	thermal capacity of fluid ($W\ K^{-1}$)
$\dot{m}$	mass flow rate of fluid ($kg\ s^{-1}$)
N	power consumption (W)
p	ratio of the radius (–)
Q	heat transfer rate (W)
q	heat transfer rate per unit length pipe ($W\ m^{-1}$)
R_{11}, R_{22}	thermal resistance between the circulating fluid in a certain U-tube leg and the borehole wall ($m\ KW^{-1}$)
R_{12}	thermal resistance between two individual legs ($m\ KW^{-1}$)
$R_1^{\Delta}, R_2^{\Delta}$	equivalent thermal resistance between the fluid of two leg of U-tube and borehole wall ($m\ KW^{-1}$)
R_{12}^{Δ}	equivalent thermal resistance from the fluid of one leg to another ($m\ KW^{-1}$)
T	temperature (°C)
t	time (h)
z	depth (m)

Greek letters

λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
θ	excess temperature (°C)

Subscripts

abs	absorbed by heat pump
b	borehole
c	convection
f	fluid
g	ground
h	heat load
hp	heat pump
i, j	index to denote the end of a time step
i	inside
in	inlet
o	outside
out	outlet
p	pipe
s	soil

tube. Lei [9] used a finite-difference method to establish a vertical U-tube ground heat exchanger model. He introduced a double two-dimensional cylindrical coordinate system for converting three-dimensional to two-dimensional problem. Muraya et al. [10] used a transient two-dimensional finite element method to investigate the thermal interference between the U-tube legs. Rottmayer et al. [11] developed a numerical U-tube heat exchanger model based on an explicit finite-difference technique. Thornton et al. [12] used the vertical ground heat stores model developed by Hellstrom [6] to perform a complete system simulation of a family housing unit by TRNSYS. Yavuzturk et al. [13,14] expanded the long-time step response factor conception of Eskilson [5] to small time steps. Lee and Lam [15] developed a numerical model of borehole ground heat exchanger using a three-dimensional implicit finite-difference method with rectangular coordinate system. Li and Zheng [16] presented a three-dimensional unstructured finite volume model for vertical U-tube ground heat exchanger using Delauany triangulation method to mesh the borefield. However, the elaborate numerical models cited above are relatively complex and do not permit an easy understanding of the physical process involved. At the same time, the numerical models will also consume a large number of computation times in the long-term (such as 20 years) simulation due to iteration arithmetic, and thus are not very fit for engineering design and long-term system dynamic simulation. In contrast, the analytical models are relatively easy to comprehend, and the resulting analytical solution can easily be programmed, thus are used widely for system simulation of GCHP.

The existing simplest analytical solutions are the line source model from Ingersoll and Plass [1] and the cylindrical source model from Carslaw and Jaeger [2]. Both models assume infinite length for borehole, and no steady-state occurs. Kavanaugh [8] determined the temperature distribution or heat transfer rate around a GHE by using the cylinder source solution as the exact. Hart and Couvillion [17] proposed an analytical equation for the ground temperature around a line source based on line source theory, and defined a far field distance. IGSHPA [18] adopted the line source model but developed formulate to approximate the exponential integral appearing in the line source solution. Deerman and Kavanaugh [4] described the application of cylindrical heat source model by comparing simulation results with experimental data from test sites. Zeng et al. [19] analyzed the transient heat conduction around borehole of a geothermal heat exchanger. An analytical solution of the transient temperature response has been derived with a line source of finite length. Bernier et al. [20] suggested a multiple load aggregation algorithm to calculate the performance of a single borehole at variable load based on cylindrical source model. Hikari et al. [21] derived simplified forms for cylindrical source at borehole surface depending on the Fourier number. Lamarche et al. [22] presented a new analytical approach to treat the thermal response of vertical heat exchanger. It solves the exact solution for concentric cylinders and is a good approximation for the U-tube configuration. Bandyopadhyay et al. [23] obtained the Laplace domain solutions for the equivalent single core of the U-tube in grouted borehole. Both the average fluid temperature and borehole boundary temperature have been obtained using Gaver–Stehfest numerical inversion algorithm from these solutions.

Due to the complicity of borehole construction, however, most analytical solutions existed above rarely consider strictly the heat interference between two adjacent legs of U-tube, and the variation of fluid temperature along the borehole depth is often neglected by the models. The borehole can be visualized as a complicated heat exchanger with grout materials and U-tube filled with the heat carrier. The key point for the heat transfer analysis lies in that how to consider the influences of the U-tube configuration and grout material on heat transfer. Currently there are several methods to do it, the most common way is to use the equivalent diameter of U-tube [24]. However, the method does not strictly consider the heat interference between two adjacent