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A dynamic simulation method of ground coupled heat pump system based on borehole heat exchange effectiveness

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ABSTRACT

An updated method for the dynamic simulation of ground coupled heap pump (GCHP) system was proposed. The method developed an analytical heat transfer model for the borehole heat exchanger (BHE) with considering the variation of fluid temperature along borehole length and thermal interference between two adjacent legs of U-tube. Based on the BHE model, the borehole heat exchange effectiveness (BHEE) was put forward and defined, and then the influences of borehole thermal resistance, fluid thermal capacity and borehole depth on the BHEE were investigated. By quoting the BHEE in the system simulation, the inlet and outlet fluid temperature of BHE can be calculated directly by the BHEE rather than by the calculation of average fluid temperature of BHE, this can overcome the disadvantage of former model that the average fluid temperature must be calculated previously to determine the inlet and outlet temperature of BHE. Validation of the model was undertaken by comparison with the variable heat flux cylindrical source model validated experimentally and theoretically. The experimental validation was also conducted by a model experimental facility, and the results show that the model developed in this paper has a good predicted precision, and the predicted relative error is less than 3%.

1. Introduction

The new trends in energy savings and greenhouse gas reductions have led to explore alternative technologies to convert energy in a more efficient and clean way [1–3]. In recent decades, ground coupled heat pump (GCHP) has been recognized as being among the cleanest, most energy efficient and cost effective system for residential and commercial space heating and cooling applications. The main advantages of using the ground as the heat source or sink of the system is that the ground temperature at tens to hundreds of meters in depth is relatively constant and is generally lower in summer and higher in winter than that of ambient air temperature. This results in an overall improvement of the system performance and thus reduces operation costs. Therefore, GCHP systems have become increasingly popular in commercial and institutional buildings. A typical GCHP system consists of a conventional heat pump coupled with a borehole heat exchanger (BHE). In common configurations, the BHE consists of a loop installed in a horizontal or vertical style. Currently, a vertical U-bend ground heat exchanger (GHE) shown in Fig. 1 is usually preferred over horizontal style because it requires less ground area and offers better performance than the horizontal style due to smaller seasonal swing in the ground mean temperature. The dynamic simulation of the operation performance of GCHP system is crucial for its optimal design and operation. This requires a precise heat transfer model for modeling the heat transfer process between the BHE and surrounding soil. In order to estimate the heat transfer at the vertical BHE, different numerical [3–17] and analytical methods [18–32] as well as combination of the numerical and analytical solution [33,34] have been proposed. However, the numerical models are relatively complex and will consume a large number of computation time for a long-term (such as 20 years) simulation due to an iteration arithmetic. In contrast, analytical solutions are widely used for GCHP system simulation because of the simplicity and speed in computation.

The existing simplest analytical solutions are the Ingersoll's line source model [18] and the cylindrical source model from Carslaw and Jaeger [19]. Both models assume infinite length for borehole, and no steady state occurs. Kavanaugh [20] determined the temperature distribution or heat transfer rate around a BHE by using the cylinder source solution as the exact. Hart et al. [21] proposed an analytical equation for the ground temperature around a line source based on line source theory, and defined a far field distance. IGSHPA [22] adopted the line source model but updated formulate to approximate the exponential integral appearing in the line source solution. Zeng et al. [23] analyzed the transient heat conduction around borehole of a geothermal heat exchanger.

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Nomenclature

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

Greek letters

λ	thermal conductivity (W/m K)
θ	excess temperature (°C)
ε	borehole heat exchange effectiveness

Subscripts

b	borehole
c	convection
f	fluid
g	ground/grout
i,j	index to denote the end of a time step
i	inside
in	inlet
o	outside
out	outlet
p	pipe
s	soil

An analytical solution of the transient temperature response was derived with a line source of finite length. Bernier et al. [24] 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. [25] derived simplified forms for cylindrical source at borehole surface depending on the Fourier number. Lamarche and Beauchamp [26] 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. [27] 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. Bandos et al. [28] proposed a solution to the three-dimensional finite line source model for BHE. The model considers the prevailing geothermal gradient and allows arbitrary ground temperature changes. Molina-Giraldo et al. [29] proposed a new analytical approach for the BHE which considers both groundwater flow and axial effects by using moving finite line source model. Claesson et al. [30] developed a new analytical solution to model the short-term response of the BHE. The new solution studied the heat transfer and the related boundary conditions in the Laplace domain. Beier et al. [31,32] developed an analytical model of actual vertical temperature profile in the borehole heat exchanger for the late-time period of the in situ test. With this model one can estimate the soil thermal conductivity and borehole thermal resistance without the mean temperature approximation.

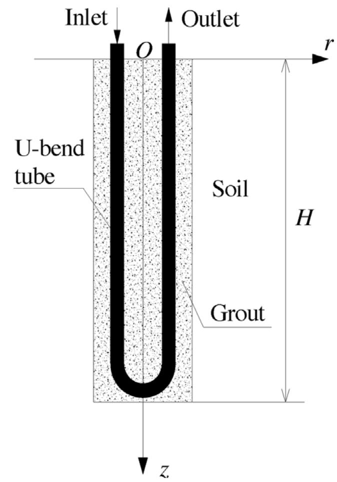

Fig. 1. Sketch map of vertical borehole heat exchanger.

However, due to the complicity of BHE's construction, most analytical solutions existed above rarely consider strictly the thermal interference between two adjacent legs of U-tube, and the variation of fluid temperature along the borehole depth is often neglected. Particularly, in the previous work, the average fluid temperature in the BHE must be firstly calculated through the BHE heat flux after the determination of borehole thermal resistance and far-field soil temperature, and then the inlet and outlet temperatures can be obtained through energy conservation analysis. This method practically neglects the temperature variations of fluid along borehole depth and thermal interference of two-legs of U-tube. In our previous work [35], we developed a two-region analytical solution model for the BHE by dividing the heat transfer regions of BHE into two parts at the boundary of borehole wall. The model takes fluid temperature variation along the borehole depth and the heat interference between two adjacent legs of U-tube into account. However, the borehole heat exchange effectiveness is not introduced in the system simulation. Moreover, the experimental validations on the fluid temperature variation along depth are also not carried out due to the restriction of experiments conditions.

In this paper, based on the developed BHE model with considering the variation of fluid temperature along borehole length and thermal interference between two adjacent legs of U-tube, the