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Research Paper

A new method for calculation of short time-step g-functions of vertical ground heat exchangers

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HIGHLIGHTS

- A method to simplify the CMILS model of vertical GHE was proposed.
- G-function was easily implemented and quickly calculated by proposed method.
- Experimental verification was made through a reported reference data.
- Comparison studies showed that the proposed method had a good performance.

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ABSTRACT

The composite medium infinite line source model (CMILS) was recently developed to describe the heat transfer of borehole ground heat exchanges. But this model is very complicated and time-consuming to calculate the solutions, which limit its practical applications. This paper presents a method to simplify the CMILS model and develops short time-step response g-functions using the simplified CMILS model. The advantage of the new short time-step response g-functions is that they are simple in calculation with comparable accuracy compared with CMILS model. Simulation studies show that g-functions calculated by simplified CMILS model match nicely with the experimental data. Detailed comparisons are also carried out between the simplified CMILS model and other numerical or analytical models through simulation.

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1. Introduction

Energy consumption in building HVAC sector, accounting for about 37 percent of total building energy use [1], has received increasing attention in the last decades due to the energy shortage and environmental concerns. Ground source heat pump (GSHP) system, which is one of the cleanest, most energy-efficient and operational cost-effective systems, has been considered as one of the effective ways to significantly reduce energy consumption for space air-conditioning of buildings [2]. However, the higher initial cost of ground heat exchangers (GHEs) impedes its wide acceptance. In order to efficiently reduce the length of GHEs and consequently the capital cost of the systems, it is crucial to develop a mathematical model that can accurately predict the heat transfer in and around boreholes to avoid costly oversizing of the GHEs. Among the several model variables, the short time response has significant influence on the GHE performance [3–5]. It is critical to 1) the heat flux build-up stages; 2) during the seasons when both heating and cooling are required; and 3) calculating hourly or sub-hourly thermal energy use.

Heat transfer process of GHEs depends on the soil temperature field. Most existing models were based on either analytical, numerical or combination of the two. There are three fundamental analytical models for outside borehole, i.e. infinite line source model (ILS) [6,7], cylindrical heat source model (CHS) [8] and finite line source model (FLS) [9,10]. These models are long time response models as the geometry of the borehole is assumed to be a line or a cylinder without considering the heat transfer features inside the borehole.

The concept of g-function which is introduced by Eskilson [11] is adopted in this study. The g-function model, which defines a relationship (Eq. 1) between the heat flux q extracted from or rejected to the ground at the borehole wall and the borehole wall temperature T_b, can be applied in all cases as it is the thermal response solution of a borehole at its wall. Because the g-function model based on numerical solution treats the borehole as a finite line source, it is only suited to the middle and long time response [3,12].

$$g\left(t/t_s, r_b/H, B/H, D/H\right) = -\frac{2\pi k_s}{q}(T_b - T_g) \tag{1}$$

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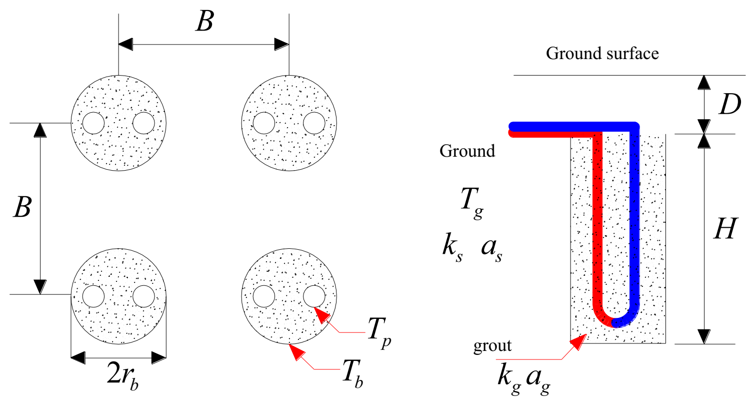

Fig. 1. Schematic layout of typical bore field geometry [12].

The typical bore field geometry and the parameters using in g-function definition [12] are described as Fig. 1. The g-function has four parameters: t/t_s, a non-dimensional time where t_s is a characteristic time ($t_s = H^2/9a_s$); r_b/H, the non-dimensional borehole radius where r_b is the borehole radius and H is the height of the borehole; B/H, the bore field aspect ratio where B is the distance between adjacent boreholes; and D/H, the fourth non-dimensional parameter where D is buried distance of the head of borehole U-tubes.

The g-function approach is considered as state-of-the-art and has been implemented in many building energy simulation software including EED, Trnsys, Energy Plus, and so on.

Eskilson's g-functions are applicable for times greater than ($5r_b^2/a$) as estimated by Eskilson, which implies times of 3–6 hours for typical boreholes [13]. However, typically applicable times of short time g-functions are in the time scale of minutes. Yavuzturk [13] extended Eskilson's concept of non-dimensional temperature response function and developed a numerical model for short time-step response which approximated the geometry of U-pipes as pie sector shape as shown in Fig. 2. A total steady state borehole resistance was subtracted from the obtained pipe wall temperature to adhere to Eskilson's g-function definition (Eq. 1). For a constant heat transfer rate, the temperature difference between U-pipe wall and far-field ground was calculated by the numerical model. This total resistance includes a convective resistance between fluid and U-pipes, a pipe resistance of U-tubes and the grout resistance. The method that subtracted out the resistance from the g-function resulted in a negative borehole wall temperature for times approaching zero [12,14]. The short time-step model was validated using actual operating field data from an elementary school building.

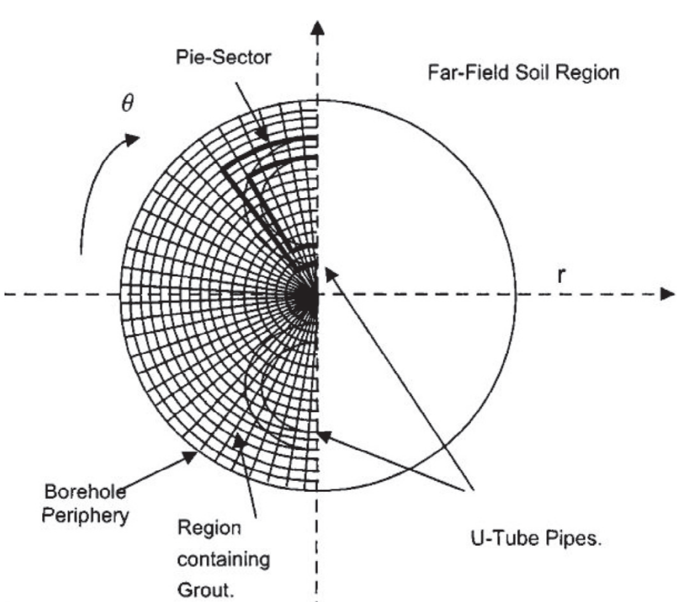

Fig. 2. Yavuzturk's numerical model using simplified pie-sector representation for single U-tube pipes [13].

Other numerical methods using commercial software packages are also widely used to determine the value of g-functions [14–20].

However, most numerical approaches have the disadvantages of time-consuming and lack of flexibility for different geometry configuration in practical applications. G-functions of GHEs with different geometry configurations should be pre-calculated and stored in the programs as a database. Users are limited to these configurations and need an interpolation in using the database which may lead to computing errors.

Due to above reasons, analytical solutions [12,21–26] to calculate the short and long time-step response of boreholes have generated a lot of interest from researchers. Sheriff [22] used the FLS model to redraw the g-functions where a different boundary condition was used. Cimmino et al. [12] compared the differences between the g-functions provided by Eskilson and those obtained using analytical solutions, ILS, CHS and FLS as shown in Fig. 3. Young [24] employed the borehole fluid thermal mass (BFTM) model by modifying the classical buried electrical cable (BEC) method and drawing an analogy between buried electric cable and vertical borehole. Beier et al. [27] developed a semi-analytical model, which first solved the borehole heat transfer problem in the Laplace domain and then used a numerical inversion to obtain the time domain solution. Javed and Claesson [4,28,29] also developed an analytical solution using the equivalent diameter method to determine the short-term response of borehole heat exchangers.

Lamarche et al. [25,26] used an equivalent diameter approach (Fig. 4) and developed an analytical solution for the short term response of vertical boreholes that took into account the different thermal properties of grout and soil. A closed analytical form (Eq. 12) of thermal response in the form of g-function can be obtained. This model gave a good agreement with COMSOL software [30] in which an actual U-tube configuration model of COMSOL was made.

Li et al. [31–34] developed a new composite media line source (CMILS) model based on Jaeger's infinite instantaneous line source solution in composite cylindrical media. This model was appropriate for the short time response as it took the grout into consideration. However, the CMILS model is fairly sophisticated, and its computation is time-consuming even with advanced numerical integration methods.

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