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New quasi-3D model for heat transfer in U-shaped GHEs (ground heat exchangers): Effective overall thermal resistance

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ABSTRACT

U-shaped GHEs (ground heat exchangers) are critical components in ground-coupled heat pumps and seasonal ground heat storage. This article reports a new quasi-3D heat transfer model for the circulating fluid in U-shaped GHEs to tackle the variation of the fluid temperature along the U-shaped channels. The model is derived from a full-scale temperature response function (G-function). The fluid temperatures in the descending and ascending legs are derived as functions of time and borehole depth. The quasi-3D model, together with the full-scale G-function, yields several effective overall thermal resistances of analytical forms. We also revise and improve the design formula proposed in the ASHRAE handbook by applying the effective thermal resistances. The improved design rule requires fewer input parameters but can address more influencing factors than the original ASHRAE's design formula.

1. Introduction

The subject of heat transfer through borehole GHEs (ground heat exchangers) consists of a set of problems that are central to the design of GCHPs (ground-coupled heat pumps) and seasonal ground heat storage [1–3]. A borehole GHE comprises one or more U-shaped pipes inserted in a vertical borehole (Fig. 1). A heat-carrying fluid is circulated through the U-shaped channels to absorb (or discharge) heat from (or to) the ground. The calculation of heat transfer in the ground involves complicated media and geometry, various geologic conditions, and diverse time and time scales [4,5], thus leading to a huge challenge to geothermal engineers.

Research into heat transfer via GHEs aims to develop a relation between borehole length and the thermal resistances of the heat transfer in the ground [1]. Such a relation requires solving the thermal problem in the ground in a reliable and efficient manner. In terms of efficiency, analytical solutions with some appropriate assumptions are attractive for predicting the mid- and long-term thermal processes of GHEs [2,6–10]. As a seminal work, Ingersoll et al. proposed an infinite line-source solution and an infinite cylindrical-source solution for heat transfer through buried pipes [2]. Deerman and Kavanaugh used the infinite cylindrical source solution, in conjunction with an equivalent-diameter assumption, to predict the thermal response of U-shaped GHEs [7]; however, these solutions are applicable only for mid-term heat transfer.. To address the long-term thermal response, the infinite line-source model was improved by using the method of images to obtain finite line-source models [8–10]. To tackle the short-term thermal process, Yavuzturk and Spitler developed a short-term response factor using a 2D finite volume model [11]. Subsequently, various numerical methods, including the finite element method [12–14], finite difference method [15,16], finite volume method [17–19], and thermal-network method [20–22], have been used for this purpose. In contrast, a large number of analytical short-term solutions have also been derived by using the equivalent-diameter approximation for U-shaped pipes [23–27], which treats the U-shaped pipe as a straight pipe of an equivalent-diameter co-axial with the borehole. Recently, we have developed a set of composite-medium line-source solutions for the short-term responses of GHEs [6,28]. These analytical solutions enable the removal of the empirical equivalent-diameter assumption and resolve the difficulties associated with the composite medium and the U-shaped geometry. Furthermore, we have combined infinite and finite line-source solutions, as well as the composite-medium line-source solution to form a composite model [4]. This combined model can analytically

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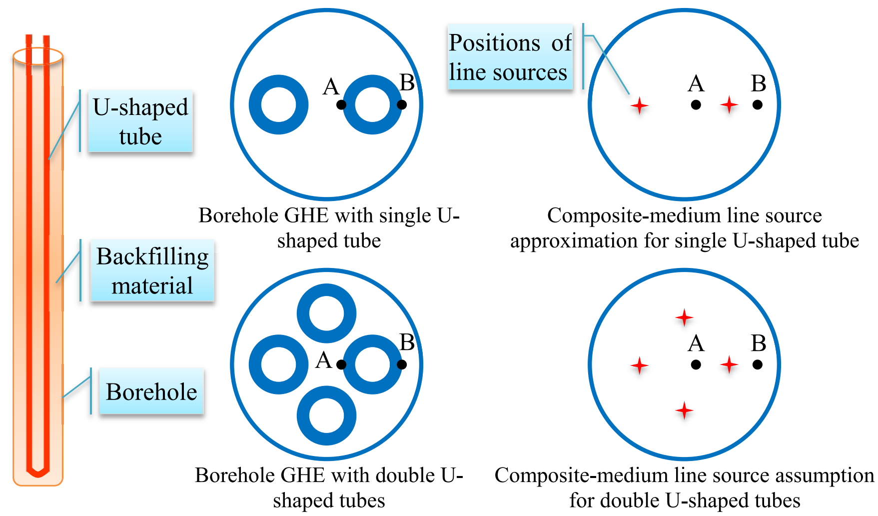

Fig. 1. Schematic diagram of borehole ground heat exchangers and composite-medium line source assumption for U-shaped pipes.

calculate the thermal response of GHEs from several minutes to decades, thus named full-scale G-functions [4].

Although great progress in this field has been made, less attention has been paid to the development of an analytical model for tackling the variation of fluid temperatures along U-shaped tubes. Hellstrom [3] and Zeng et al. [29] derived several analytical expressions that can address the temperature variation along the U-channel. Such models, however, ignore the effect of the heat capacity of grouting material; thus, these models are unsuitable for predicting hourly temperature responses. Beier [30] proposed an analytical model for transient fluid temperature profiles along U-shaped tubes. But he used the empirical equivalent-diameter assumption. Three-dimensional numerical models can determine the fluid temperatures along the U-pipe but are time consuming for calculating long-term temperature evolution in the ground. Thus, a reliable analytical 3D model that is applicable to the whole time spectrum involved in borehole GHEs should be developed.

The purposes of this paper are twofold: to develop new analytical quasi-3D models for fluid temperatures along U-shaped tubes and to improve the design expression for borehole GHEs proposed in the ASHRAE handbook by applying the new quasi-3D models and the full-scale G-functions. The work conducted here yields effective overall thermal resistances for borehole GHEs with single and double U-shaped tubes. To the best of our knowledge, the effective overall thermal resistances should be the first analytical expressions that can address all the complications of the 3D effect, U-shaped geometry, composite media, and diverse time and space scales. These resistances favor the development of robust design methods for borehole GHEs.

2. Theory

Although heat transfer through GHEs and the surrounding ground is essentially a long-term transient process, decomposing the thermal process into a time-independent part and a time-dependent part is convenient for theoretical calculations [3]. In this study, we consider the heat transfer from the fluid to the U-shaped pipe (fluid-to-pipe) in a steady-flux state and that from the U-pipe wall to the ground (pipe-to-ground) in a transient state. The two processes are thermally coupled. The pipe-to-ground process can span a broad spectrum of time [5]. To solve this problem efficiently, we have developed a set of analytical temperature response functions (G-function) for borehole GHEs [4]. These G-functions provide a foundation for the new model developed here; thus, these G-functions are first summarized in the following section.

2.1. Full-scale temperature response functions (G-functions)

We first introduce the definition of temperature response function (G-function). If q_l is the given heat transfer rate per unit of borehole length (W/m), the following relation exists between q_l and the driving temperature difference for the pipe-to-ground thermal process:

$$T_p - T_0 = q_l G(t) \tag{1a}$$

or

$$q_l = \frac{T_p - T_0}{G(t)} \tag{1b}$$

where T_p is the average temperature on the U-pipe wall; T_0 is the initial temperature of the ground; The physical meanings of the G-function defined here are twofold: G is the temperature response on the U-pipe wall caused by a unit-step change in the heat flux (i.e., $q_l = 1$ in Eq. (1a)); G can be understood as a thermal resistance (Eq. (1b)).

The G-functions used in this paper are composite expressions consisting of a composite-medium line-source solution, a finite line-source solution, and an infinite line-source solution. The finite and infinite line-source solutions ignore the heat capacity of the material backfilled in a borehole and assume the borehole to be a line of finite or infinite length releasing (or absorbing) heat to (or from) the ground [2,8–10]; this assumption is only applicable to the prediction of mid- and long-term temperature responses. By contrast, the composite-medium line-source solution assumes the leg pipes of U-shaped tubes to be lines of heat placed in a composite medium [6,17,28]. This approach enables the heat capacity of the backfilling material to be addressed. Thus, this solutions is suitable for the calculation of short-term responses. The time domains of validity of the finite line-source solution and the composite-medium line-source solution overlap and can be matched to form a solution suitable for the whole time domain by the method of matched asymptotic expansions. The matched expressions of G-functions are applicable to periods of several minutes to decades and are named full-scale G-functions [4]:

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