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Research Paper

Hybrid analytical model for composite heat transfer in a spiral pile ground heat exchanger

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HIGHLIGHTS

- The hybrid model considers coil sharpness and differing thermal properties of layers.
- 3D composite problem is decomposed to a 1D composite and a 3D homogeneous problems.
- 1D composite solution addresses the effect of differing thermal properties of layers.
- 3D homogeneous solution addresses the effect of the coil pitch.

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ABSTRACT

A spiral pile ground heat exchanger (PGHE) is a recently developed type of ground heat exchanger (GHE) used in ground-coupled heat pump system. Existing analytical models are not applicable to a spiral PGHE when the pile has thermal properties that are different from those of the soil. A novel hybrid analytical model to represent this situation was developed in the present study. The proposed model utilizes a decomposition algorithm to solve the problem of a coil line source embedded in a composite cylinder. The decomposition algorithm uses a composite cylindrical surface source solution to deal with the composite heat conduction along the radius and a coil line source solution to deal with the heat conduction between tube loops in depth direction. An assumption of homogeneity enables the solution of the hybrid model with only a slight error. The error of the hybrid model was investigated with respect to thermal properties and geometries of a spiral PGHE and compared with those of existing models. The error under normal cases was found to be acceptable for engineering applications. The proposed hybrid model is superior to existing analytical models, enabling simultaneous and reasonably accurate evaluations of the effects of the thermal properties of the pile and the coil pitch.

1. Introduction

Ground-coupled heat pump (GCHP) is an energy-efficient technology used for space heating and air conditioning. To limit the energy consumption of buildings and related environmental impacts, a large number of GCHP systems have been implemented in recent years. However, the initial cost of GCHP system is usually much higher than that of a conventional system due to a high installation cost of ground heat exchanger (GHE), a critical component of GCHP system. A new pile ground heat exchanger (PGHE) technology can now partly alleviate this problem. PGHE is a dual-purpose pile that combines a GHE with the pile of a building foundation using various tube arrangements. U-, W- or spiral tubes are installed vertically into the foundation pile with the gaps filled with grout. Heat is transferred between the fluid circulating in the tube and the surrounding soil through the pile. Tubes arranged as spiral coils can enlarge heat surfaces and therefore increase the amount of heat transferred between the tubes and surrounding soils relative to other installations such as U- or W-shaped systems [1,2]. There is growing interest in the research and applications of spiral PGHE [3–5].

Precisely evaluating the thermal performance of a GHE is essential for engineering utilization, e.g., in determining appropriate lengths of a GHE for design. Compared to conventional vertical U-shaped borehole GHE, a PGHE presents different heat transfer characteristics, i.e., complex tube arrangements, relatively larger diameter, difference in thermal properties of pile and soil, etc. These characteristics imply that the transient heat transfer occurring within the pile will significantly impact the heat exchange performance of a PGHE. Classical analytical models for a U-shaped GHE with small radius, such as the line source or hollow cylindrical source model [6] that typically disregards thermal dynamics occurring within borehole, are inadequacy for a PGHE,

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Nomenclature

k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
α	thermal diffusivity ($m^2\,s^{-1}$)
t	time (s)
T	temperature (°C)
θ	relative point temperature (°C), i.e., the difference between point temperature and mean surface temperature.
r	radial distance from pile center (m)
H	length (m)
φ	angle
q_l	heat rate per unit pile length ($W\,m^{-1}$)
R	thermal resistance ($m\,°CW^{-1}$)
b	coil pitch between tube loops (m)
$c\rho$	volumetric heat capacity ($J\,m^{-3}\,K^{-1}$)
κ	thermal conductivity ratio k_1/k_2
C	heat capacity ratio $c\rho_1/c\rho_2$

Acronyms

1-D/2-D/3-D	one-/two-/three-dimension
GCHP	ground-coupled heat pump
GHE	ground heat exchanger
PGHE	pile ground heat exchanger
FVM	finite volume method
TRT	thermal response test
CCSS	composite cylindrical surface source
ICSS/ FCSS	infinite/finite cylindrical surface source
ILS/ FLS	infinite/finite line source
IRCS	infinite ring coil source
ISCS	infinite spiral coil source
RCS	ring coil source
SCS	spiral coil source

especially in terms of a short-term process. In recent years, few studies on the heat transfer of PGHE have been conducted by means of numerical and analytical methods. The present study focuses on analytical methods for spiral PGHE.

Man et al. [7] first proposed a homogeneous solid cylindrical surface source model for various types of PGHE, including U- shaped and spiral PGHE. The tubes of a PGHE that releases heat to the surrounding soil were modeled using a cylindrical surface heat source embedded in a homogeneous solid, without considering the difference between the properties of the pile and the surrounding soil. Compared to the classical line source or hollow cylindrical source models in which the pile is assumed to be a steady-state process, the 'solid' model had made a clear progress in addressing the effects of the heat capacities of the pile. An infinite source solution for the short-term response and a finite source solution for the long-term response were derived from a well-known line and ring source solutions [8]. Based on Man's finite source solution, Bandos et al. [9] developed an exact integral solution for determining the mean temperature over the depth of a PGHE and gave a set of asymptotic formulas of the exact solution for various time scales to facilitate its applications. Li and C.K. Lai [2] took the innovation step further in implementing the solid cylindrical surface source method. A composite solution was derived based on Jaeger's line source solution in composite medium [10]. Differences between the properties of the pile and the surrounding soil were considered in the composite model. Li's work shows that the thermal conductivity and heat capacity of the pile are important factors that shape the temperature responses of a PGHE.

To be precise, as a one-dimension (1-D) model, cylindrical surface source models can only evaluate the mean temperature of a vertical cylindrical surface through a tube, rather than the point temperature at the tube wall. The tube wall temperature is critical to determining the fluid temperature in GHE applications. Theoretically, for a vertical spiral-shaped arrangement of the tube, the vertical temperature distribution exhibits greater fluctuation on the cylindrical surface closer to the coiled tube, i.e., the difference between the point temperature and the mean cylindrical surface temperature is greater. Further a larger coil pitch between tube loops corresponds to a greater temperature fluctuation. Two detailed models have been developed to resolve the heat conduction problem related to coil shape to obtain accurate point temperature for a spiral PGHE. The two detailed models employed a two-dimension (2-D) and a three-dimension (3-D) coil line sources in place of the 1-D cylindrical surface source embedded in the homogeneous solid. Cui et al. [11] was the first to propose a ring coil source model in which the spiral coil tube was simplified to multiple separated ring coil sources. Then, Man et al. [4] developed a more accurate spiral coil source model, using a spiral line expression that completely describes the 3-D path of a spiral-shaped tube line. Man's spiral coil source is a continuous 3-D source while Cui's ring coil sources are discontinuous 2-D sources. The axial heat transfer of spiral coil tube is exactly represented by Man's model.

Park et al. [12–14] performed experimental validations of existing thermal models for spiral PGHE. In their works, a 3-D finite element numerical model and several homogeneous analytical models, including the solid cylindrical surface source model, ring coil source model, spiral coil source model, and line source model, were compared with experimental data drawn from a lab test and from field Thermal Response Test (TRT) of spiral PGHE. The numerical model was found to be in good agreement with the measured data from the lab test at various observations points. The spiral coil source model exhibited better agreement with the lab test results than the other analytical models. It should to be noted that Park's lab test were subjected to a homogeneous medium case. They studies show these homogeneous analytical models to be inapplicable to a real spiral PGHE used in pile and soil with differing thermal properties [13].

A composite heat conduction problem arises in a PGHE with a large radius, with the need to model the internal dynamics of the pile by considering the different properties of pile and surrounding soil. For a composite problem of a U-shaped borehole GHE, the U-tubes were typically simplified as a single equivalent tube at the center of borehole. Thus, the original composite problem can be reduced to a simpler 1-D multi-layered radial heat conduction problem. Some studies had provided various analytical solutions for the 1-D multi-layer composite heat conduction of a U-shaped borehole GHE, e.g., 'Buried Electrical Cable Model' [15] in consideration of two-layered heat capacities of grout and soil, and Javed's thermal network model [16] in consideration of three-layer capacities of fluid, grout and soil. Our group has also made efforts to address the 1-D composite problems. Hu et al. [17] have proposed a composite cylindrical model for TRT analysis of a PGHE for estimating the thermal property parameters of the soil. The present authors [18] have presented a frequency solution for a two-layered composite cylinder and have suggested a corresponding frequency decomposition algorithm for calculating the responses to a time-varying load. However, the 1-D simplification method of using an equivalent tube instead of U-shaped tubes is not appropriate for spiral tubes, which represent a 3-D heat conduction problem. In addition to the composite medium problem of the differing thermal properties of the pile and the soil layers in the horizontal direction, the thermal interference between tube loops in the vertical direction also directly impacts the heat conduction of the coil tube. Through field tests conducted on two cast-in-place spiral PGHEs with coil pitches of 200 and 500 mm and finite element analyses, Park et al. [5,19] investigated the effects of coil pitches and thermal interference on the thermal performance of a spiral