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A new analytical solution for horizontal geothermal heat exchangers with vertical spiral coils

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ABSTRACT

Horizontal geothermal heat exchangers (HGHEs) with vertical spiral coils have been increasingly used in ground source heat pump (GSHP) systems. Research studies have been conducted using field tests and simulations trying to reveal the heat transfer mechanism of HGHEs with vertical spiral coils and to provide a good heat transfer performance. However, there is no analytical solution has been established for HGHEs with vertical spiral coils. Of particular interest is the temperature variation at the soil surface. The study presented in this paper proposes the development of a mathematical vertical ring-coil model used to describe the heat transfer process of HGHEs with vertical spiral coils. In this new model, the spiral heat exchanger is simplified as a series of ring coils that inject/extract heat in/from a semi-infinite medium. A single ring model in an infinite medium is first introduced. Using images and superposition, a multiple ring-coils analytical solution is then given. The significant influence on the heat transfer performance of HGHEs temperature variation of the ground surface is then considered. A periodically changed boundary condition is being taken into consideration in the modeling process. The validity of the model was examined by a field test and a 3-D simulation model. The analytical solutions may provide a desirable and better tool for the simulation/design HGHEs with vertical spiral coils.

1. Introduction

Currently the ground-coupled heat pump (GCHP) system is widely used in commercial or residential buildings for cooling, heating and hot water application. Compared with the air source systems, the GCHP has advantages as regards electricity consumption, maintenance cost and environmental protection [1]. A GCHP system typically includes a geothermal heat exchanger (GHEs) system, a heat pump unit and a heat distribution terminal system. GHE is the key connecting device between the heat pump unit and ground sources and as such is regarded as the most important component of a GCHP system in both the design or construction stages. In general, the typical geothermal heat exchangers could be divided into two groups: the vertical ground heat exchangers (VGHEs) and the horizontal ground heat exchangers (HGHEs) [2]. VGHEs are usually used in urban area, but its high installation cost makes this types of heat exchangers hardly be widely used on the market. HGHEs, with the advantage of low installation cost, provide an alternative GHE solution in suburbs with sufficient land area such as golf courses, farms and rural cottages. The HGHE system is usually buried in a shallow trench with a configuration of single/multiple linear pipe or spiral-types pipes as shown in Fig. 1.

To improve GCHP reliability and optimize their operation, much research has been conducted to investigate the GHE heat transfer process and many advanced analytical models have been developed for VGHEs, in addition to both experimental and numerical studies [3–5]. Of particular note is the pile geothermal heat exchanger [6,7]. However, few studies based on HGHEs have been reported and of these most were focused on experiment analysis or numerical simulation. Demir et al. [8] established a 2-D numerical model to estimate the temperature response of straight linear HGHEs. A heat flux boundary condition was applied on the ground surface to simulate the influence of temperature change [8]. A simplified 3-D numerical model was developed by Congedo et al. with the aim of investigating the heat transfer efficiency of HGHEs, using different configurations. It was found that the vertical spiral HGHEs enabled a stronger heat transfer performance than that of the linear and slinky HGHEs [9]. This finding was further confirmed by field tests [10]. The first HGHE analytical model was developed by Ingersoll and Plass in 1948 [11]. In this model, the straight linear HGHE was regarded as an infinite line heat source

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Nomenclature

x, y, z	cartesian coordinate (m)
X, Y, Z	dimensionless Cartesian coordinate
v_c	buried depth of coils (m)
b	coils pitch
r	radial coordinate (m)
r_0	coil radius (m)
R	dimensionless radial coordinate
k	thermal conductivity (W m^{-1} K^{-1})
α	thermal diffusivity (m^2 s^{-1})
ρ	density (kg m^{-3})
c	specific heat (J kg^{-1} K^{-1})
q_r	heat extraction/injection per ring source
t	time (s)
A	temperature amplitude
Fo	Fourier number
N	numbers of ring-coils

Greek symbols

Θ	dimensionless excess temperature
θ	excess temperature (°C)
σ	angle coordinate (rad)
τ	time (s)
ω	periodic coefficient
β, μ	integral parameter
ε	initial phase angle (rad)

Superscript

$'$	integration parameter
+	original heat source
–	image heat source

injecting/extracting heat into/from an infinite medium. Ground surface temperature fluctuation was neglected in the modeling process. Mei et al. [12] then, proposed a modified infinite line model in a semi-infinite medium. This model was still only used for straight linear HGHEs and likewise neglected the surface temperature variation [12]. A ring source model is possibly the latest development. The slinky-loops was separated into a series of separated ring coils [13], and shows a good daily performance [14]. However, as with the semi-infinite model, this ring source model also assumed the ground surface temperature boundary to be constant temperature boundary.

According to previous studies, no reliable analytical model, to describe the heat transfer behavior of HGHEs with vertical spiral coils, is available. Compared with straight linear and slinky-loop HGHEs, HGHEs with vertical spiral pipes have a short application history. However, due to the higher heat transfer efficiency and less land area requirements, the vertical spiral heat exchanger have been attracting a recent increased interest [9]. But due to the complex configuration of the vertical spiral pipes, the previous analytical models of HGHE failed to describe its heat transfer process.

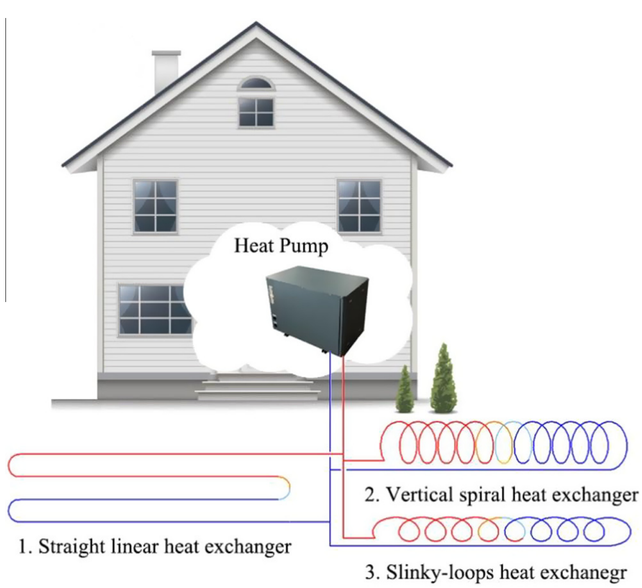

Fig. 1. Schematics of different geothermal heat exchangers.

Hence, a need for a new analytical model has been recognized for the design/simulation of vertical spiral HGHEs. Additionally, it is well noted that the temperature of the soil surrounding the HGHEs is sensitively affected by the temperature of the ground surface, and also has the ability to quickly retrieve its original temperature once cooling or heating operations have ceased [15]. Thus, it is important to take the temperature fluctuations of the ground surface into consideration during the heat transfer modeling process [16]. Accordingly, the boundary solution for vertical spiral HGHEs should be also derived.

Therefore, the aim of the study presented in this paper is to provide a methodology to enable a theoretical analysis of the heat transfer process of vertical spiral HGHEs. To achieve this, a vertical ring-coil model has been developed based on Green's function theory. In this new model, the spiral heat exchanger is simplified to form a series of ring coils that inject/extract heat in/from a semi-infinite medium. A single ring model in an infinite medium is first introduced. Based on the method of images and superposition, the multiple ring-coils analytical solution is then, given. As the temperature variation of the ground surface has a significant influence on the heat transfer performance of HGHEs, a sinusoidal temperature boundary condition is taken into consideration in the modeling process. To validate this new model, the on-site experiment and the proposed analytical model are compared. In addition, a numerical simulation model, based on the finite element method, has also been used to verify the long-term operation of the model. Two validation processes were conducted and a good agreement was shown. Finally, the temperature responses of different surface conditions were calculated by means of a valid analytical model and further discussed.

2. Ring-coil heat source solution

Taking the geometrical features of vertical spiral HGHEs and the impact of surface temperature into account, a new model, i.e. the vertical ring coils source model, is established. The vertical spiral HGHE was represented by a series of separated rings with a radius $\boldsymbol{r}_0$ and pitch $\boldsymbol{b}$ being coincident with the y-axis. In line with the assumptions in previous analytical models of geothermal heat exchangers [13,17], the ground is assumed to be a homogeneous medium with thermal properties remaining constant in the face of temperature change. The initial temperature of the ground soil is assumed to be uniform and constant. Based on the transient heat conduction equation and with the given assumptions and initial