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An applicable design method for horizontal spiral-coil-type ground heat exchangers

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ABSTRACT

The ground-source heat pump (GSHP) system using a horizontal ground heat exchanger (GHE) can be employed to reduce the installation cost and obtain a balance between efficiency and costs. Among the different types of horizontal GHEs, a spiral-coil-type GHE is one of the advantageous configurations in terms of thermal performance. However, there is no satisfactory guideline to design the horizontal spiral-coil GHEs, though design methods for other types of horizontal GHEs exist. Hence, in this study, a design method is proposed for the horizontal spiral-coil GHEs by modifying the boundary conditions of an existing equation. To verify the applicability of the proposed design equation, a laboratory thermal response test was conducted to validate the finite element model. Then, the validated numerical model was utilized for a computational fluid dynamics (CFD) simulation on an arbitrary building wherein a GSHP system with a horizontal spiral-coil GHE is operated. The entering water temperature (EWT) of 32.09 °C from the simulation result was lower than the design EWT criteria of 32.2 °C, implying that the thermal performance of the GHE for a month of operation is sufficient to cover the building load. The result provides the applicability of the proposed design method.

1. Introduction

Renewable energy has been widely used as a substitute for fossil fuels owing to its environmental advantages. Geothermal energy, which is one of the types of renewable-energy sources, does not affect the environment. Moreover, unlike other renewable-energy sources, geothermal energy is reliable regardless of the weather condition (Lamarche and Beauchamp, 2007) even if its efficiency is somewhat affected by the ambient condition (Congedo et al., 2012). In ground-source heat pump (GSHP) systems, a relatively constant ground temperature is employed to discharge heat in summer and obtain heat in winter for cooling and heating, respectively (Koohi-Fayegh and Rosen, 2014; Yang et al., 2013; Yoon et al., 2015a). Among the components of the GSHP system, the ground heat exchanger (GHE) plays an important role in transferring heat between the fluid circulating inside the pipe and the surrounding environment. Based on the contact method with the heat transfer medium, the GSHP systems can be classified into two types: an open system and a closed system (Sanaye and Niroomand, 2009). The open system obtains heating and cooling energy in direct contact with the heat transfer medium such as groundwater or surface water. A standing column well (SCW) is a representative open type system in which a deep vertical borehole is filled with groundwater up to the water table (Jeon et al., 2016b). The closed-type system, generally called ground-coupled heat pump system, directly employs the ground as a heat source with the circulating fluid inside of the GHE (Florides et al., 2013). The GCHP system can be divided into vertical and horizontal systems based on the installation orientation of the GHE (Yang et al., 2014). In the vertical system, the GHEs are installed vertically wherein the circulating fluid flows in the pipe buried in the ground to a depth in the range of 80–500 m; in the horizontal system, the GHEs are installed to a depth in the range of 1.5–3 m. The horizontal system has an advantage of the simple installation process in comparison to the vertical system, as it does not require drilling and grouting (Wu et al., 2010). Thus, a GSHP system with horizontal GHEs is economical in terms of cost because the cost associated with boring is avoided, which is more expensive than excavation costs in installing the horizontal GHE (Demir et al., 2009; Fujii et al., 2012; Fijii et al., 2013; Adamovsky et al., 2015). However, despite the economic benefits, the installation area required is considerable, which is a critical shortcoming, preventing the widespread use of horizontal systems. As an alternative to this problem, Bottarelli (2013) newly investigated the behavior of a novel type of a HGHE named ‘flat panel’, which is

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Nomenclature

A_s	Surface temperature annual swing above and below (K)
A_p	Cross section area of pipe (m^2)
c	Specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
C_p	Specific heat capacity at a constant pressure ($J\,kg^{-1}\,K^{-1}$)
D_o	Outer diameter of pipe (mm)
D_i	Inner diameter of pipe (mm)
d_h	Average hydraulic diameter (m)
F_{sc}	Short-circuit heat loss factor
f_D	Coefficient of friction
h_{ext}	Heat-transfer coefficient outside the tube ($W\,m^{-2}\,K^{-1}$)
h_{int}	Heat-transfer coefficient inside the tube ($W\,m^{-2}\,K^{-1}$)
hZ_{eff}	Effective convective heat-transfer coefficient
Q	Heat injection ($W\,m^{-3}$)
Q_{wall}	External heat exchange ($W\,m^{-3}$)
q_a	Annual average heat transfer (kW)
q_{lc}	Cooling peak load (kW)
q_{lh}	Heating peak load (kW)
q_l	Heat rate per length of borehole ($W\,m^{-1}$)
q_i	Internal heat generation (W)
R_b	Borehole thermal resistance ($m\,K\,W^{-1}$)
R_g	Ground-thermal resistance ($m\,K\,W^{-1}$)
R_{ga}	Ground-thermal resistance for annual pulse ($m\,K\,kW^{-1}$)
R_{gd}	Ground-thermal resistance for daily pulse ($m\,K\,kW^{-1}$)
R_{gm}	Ground-thermal resistance for monthly pulse ($m\,K\,kW^{-1}$)
R_p	Thermal resistance of pipe ($m\,K\,W^{-1}$)
T	Ground temperature (K)
T_f	Fluid temperature (K)
T_g	Undisturbed ground temperature (K)
T_H	Maximum ground temperature (K)
T_{in}	Inlet fluid temperature (K)
T_L	Minimum ground temperature (K)
T_M	Average ground temperature (K)
T_{out}	Outlet fluid temperature (K)
T_p	Temperature penalty (K)
T_{pi}	Temperature at pipe (K)
t	Time (d)
t_{0c}	Warmest day in cooling condition (d)
t_{0h}	Coldest day in heating condition (d)
u	Fluid velocity (ms^{-1})
V	Flow rate (lpm)
Z	Wall perimeter of pipe (m)
z	Soil depth (m)

Greek letters

α	Thermal diffusivity ($m^2\,s^{-1}$)
ρ	Density ($kg\,m^{-3}$)
ρ_f	Fluid density ($kg\,m^{-3}$)
λ	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
λ_p	Thermal conductivity of pipe ($W\,m^{-1}\,K^{-1}$)
λ_f	Thermal conductivity of fluid ($W\,m^{-1}\,K^{-1}$)
λ_n	Thermal conductivity of nth wall ($W\,m^{-1}\,K^{-1}$)
θ	Temperature response (K)

positioned horizontally and edgeways in a shallow trench. They found that the flat panel was able to involve a large soil volume, and this behavior in turn enables high-energy performance, at least in the cooling mode. Maritan (2013) suggested the compact radiator style HGHE to reduce the space needed for a horizontal installation, and presented the operation data of a residential 6 kW geothermal heat pump system. Boughanmi et al. (2015) presented a novel types of GHE called a conic basket heat exchanger, and conducted the experiment to greenhouse in Tunisia. Meanwhile, a horizontal spiral-coil GHE can be employed to minimize the installation area by densely arranging the GHE in the form of a ring-shape (Yoon et al., 2015b; Morrone et al., 2014).

Accordingly, studies have been conducted on the performance of horizontal spiral-coil GHEs through experimental and numerical analyses. Congedo et al. (2012) studied the main factors affecting the performance of a horizontal-type GHE using a numerical analysis. They found that the most important parameter to maximize the heat-transfer performance of the system is the thermal conductivity of the ground; the best performance was obtained when employing the horizontal spiral-coil-type GHE. In addition, the result presents at high ground thermal conductivity of $3\,W\,m^{-1}\,K$, which exhibits that the thermal performance of the GHE is nearly doubled compared to low ground thermal conductivity of $1\,W\,m^{-1}\,K$. Kim et al. (2016) obtained similar results through small-scale experimental and numerical analyses and revealed that the diameter of a horizontal GHE is not a critical factor to determine the thermal performance of GHE by performing a parametric study. They investigated the thermal performance of horizontal GHEs, and found that heat exchange rate of a horizontal spiral-coil GHE is 10–11% higher than the slinky one. Go et al. (2016) analyzed the design factors of a horizontal spiral-coil GHE by conducting a total 160 parametric studies using numerical simulation models validated with indoor experiment. They proposed an optimal design condition (coil pitch: 0.08 m, setting depth: 2.5 m, circulating fluid velocity: 0.7 m/s) from an economic standpoint. However, they noted that this condition also varies with the unit cost of operation and initial investment. Li et al. (2017) developed an operation model of GSHP systems with horizontal spiral-coil GHEs using a numerical program and conducted a sensitivity analysis. They investigated the effects of the design factors of the GSHP system and operation mode of the system. According to their analysis, the difference between average inlet fluid temperatures with and without considering heat pump in cooling and heating models could be 4.1% and 11.5%, respectively. The results show that the heat pump COP should be taken into consideration in analyzing the operation of GSHP system. Li et al. (2012) provides a theoretical method to analyze the heat performance of a horizontal spiral heat exchanger, developing a moving ring source model that can consider the groundwater flow effect. Moreover, the experiments were carried out to study the soil temperature variation during the operation of a spiral heater with different water velocities. Besides the abovementioned previous studies, studies regarding the heat transfer behavior of a spiral-coil GHE also have been conducted to the energy pile in which the spiral-coil GHE is vertically installed. Bezyan et al. (2015) presented the best configuration of the spiral-coil energy pile with the highest efficiency in a heat transfer rate, based on 3D fluid-solid coupled numerical simulation. They found that the spiral-coil GHE with 0.4 m pitch showed the highest efficiency in a heat exchange rate. Yang et al. (2016) investigated the influences of inlet temperature, intermittent operation mode, spiral pitch and pile material on the thermal performance and soil temperature distribution regarding the spiral-coil energy pile. They revealed that high inlet temperature, intermittent operation control, and reducing spiral pitch can increase the heat release rate through a model experiment. Dehghan (2017) studied the thermal performance of a vertical spiral GHE, experimentally and computationally. Thermal interactions and working fluid temperature variation were investigated, evaluating the performance for nine spiral GHEs configuration employing the validated numerical models. For improved GSHP system performance design, this study suggests that distance between spiral GHEs should be at least 6 m, and embed depth of spiral GHEs 2 m from the ground surface.

The appropriate estimation of the trench length of the horizontal