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A new performance evaluation algorithm for horizontal GCHPs (ground coupled heat pump systems) that considers rainfall infiltration

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ABSTRACT

This study presents a novel performance evaluation algorithm for horizontal GCHPs (ground coupled heat pump systems) that considers rainfall infiltration. The influence of rainfall infiltration on the thermal characteristics of shallow trenches is examined using infiltration analyses, and then a numerical analysis study is conducted in order to investigate how rainfall infiltration affects the performance of HGHEs (horizontal ground heat exchangers). According to the thermal performance test results in unsaturated ground with a varying thermal conductivity profile, the rainfall infiltration results in a widening fluid temperature gap between the inlet and outlet, and it increases the thermal efficiency compared with that without rainfall. Furthermore, in fully saturated ground, groundwater advection has a positive influence on the performance of the heat exchanger, and the advection effect varies with the local ground conditions such as hydraulic conductivity and void ratios. In the cooling mode, the free convection phenomenon occurs in shallow trenches, and this fluid circulation attenuates the ground temperature increases due to the heat source, which leads to a significantly faster heat steady state. However, noticeable free convection only occurs if the ground has a high permeability coefficient.

1. Introduction

GCHP (ground coupled heat pump) systems have attracted significant attention in recent years due to the trends to increase energy savings and reduce greenhouse gases that offer important environmental and economic benefits. These systems utilize the relatively constant ground temperature as a heat reservoir: a heat source in winter and a heat sink in summer [1–3]. As a result of the tremendous amount of complimentary stored energy in the ground, GCHPs have become one of the most profitable technologies that guarantees high heat efficiency compared with traditional heat pump systems. In general, GCHPs can be classified into open and closed loop systems; the most common type is the closed loop system that uses vertical borehole GHEs (ground heat exchangers) because it requires a smaller area and guarantees much higher energy efficiency [4–6]. However, the high initial installation costs of the drilling operation that is required for these systems are an inevitable drawback of vertical borehole GHEs. Thus, HGHEs (horizontal ground heat exchangers) offer a viable alternative solution that obtains a good compromise between high efficiency and low costs [7–9], as long as a large area of land is available. In horizontal GCHPs, high-density synthetic plastic GHEs are horizontally buried in shallow trenches in order to circulate the fluid that absorbs heat from the ground or emits heat into the ground. HGHEs should be installed in the ground where the soil conditions are favorable for excavation as well as for heat transfer. In agricultural farms and rural areas, there are sufficient areas for HGHEs; therefore, it can be assumed that their implementation would be preferred in these areas [10].

The primary heat transfer mechanisms of HGHEs involve multiple processes: heat convection between the circulating fluid and the pipe, and heat conduction inside the ground. Furthermore, if the ground is fully saturated, the effects of advection and free convection might also be considered in the heat transfer mechanism. Thus, there have been extensive investigations on the heat transfer mechanism that consider various ground conditions. For example, Mei [11] developed a model that predicts the thermal behavior of coil-type HGHEs considering the soil freezing effect and thermal interference, and Therrien et al. [12] developed a unique

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tool, named HydroGeoSphere, that combines fully integrated hydrologic/water quality/subsurface flows. Gan et al. [13] conducted experimental and computational investigations into a GSHP system that utilizes rainwater as the heat source/sink using a GHE integrated into a water storage tank and the surrounding soil. Furthermore, Fujii et al. [14] conducted numerical simulations of a field test in order to evaluate the performance of slinky HGHEs considering the energy balance at the ground surface. Chong et al. [15] developed a three-dimensional numerical analysis model and investigated the thermal performance of slinky HGHEs with various GHE configurations. Furthermore, Li et al. [16] examined the groundwater effect on the performance of coil-type HGHEs, which enabled the establishment of a moving ring source model, and they analytically solved the temperature response of coil-type HGHEs using groundwater flows. In numerical analyses, Wu et al. [17] conducted 3D numerical analyses for slinky HGHEs, and their performances were compared with that of a straight GHE. Moreover, Congedo et al. [7] conducted simulations on HGHEs using the CFD (computational fluid dynamics) code Fluent, and they evaluated the system performance through considering different GHE configurations. Another numerical study [18] investigated the effect of changing the soil and load parameters, and pipe HSD (horizontal separation distances) on the HGHE performance using Abaqus/CAE and Matlab codes. More recently, the simulations undertaken by Simms et al. [19] presented the annual performance of HGHEs in soils with heterogeneous thermal conductivities.

It is clear from the above studies that the thermal characteristics of the trench have a significant influence on the performance of HGHEs. However, a significant factor that affects the thermal characteristics of shallow trenches is rainfall infiltration, which has rarely been investigated. As seen in Fig. 1, if it rains on the top of a trench, the wetting depth will be expanded from the subsurface to the deep soil where the ground water table exists; furthermore, the degree of saturation in the trench varies with differences in the rainfall infiltration. Moreover, it is known that soil saturation is strongly related to soil thermal conductivity [20–26], which is an input parameter in the design of HGHEs. Accordingly, the vertical thermal conductivity variation profile that results from rainfall infiltration must be considered when evaluating the performance of horizontal GCHPs. However, although various ground conditions have been examined in previous studies regarding the heat transfer mechanism of HGHEs, little attention has been given to the influence of rainfall infiltration on the thermal characteristics of shallow trenches. Furthermore, the effect of rainfall infiltration on the performance of HGHEs has not been investigated. Hence, this paper presents a novel performance evaluation module for horizontal GCHPs that considers rainfall infiltration.

The algorithm for this module is composed of two submodules: the first submodule is used for unsaturated ground and the second submodule is used for fully saturated ground (see Fig. 2). Then, the output results from each submodule are used as input boundary conditions for the numerical analysis model in order to evaluate the performance of HGHEs. Moreover, if there is a groundwater flow in the saturated ground, Darcy's law can be applied to the model in order to consider the groundwater advection effect. Furthermore, the Boussinesq approximation can successfully be combined with the Brinkman equation in the model in order to consider the free convection. Thus, this algorithm has enabled the performance evaluation of the horizontal GCHPs that considers rainfall infiltration, and this demonstrates its potential for use in the optimum operation of GCHPs.

2. Infiltration analysis

2.1. Properties of unsaturated soil

In general, the trench surrounding HGHEs is likely to have an unsaturated soil condition. Unsaturated soil, which is conceptualized as partially saturated soil, has a variety of different behavioral characteristics compared with saturated soil [27]. In order to understand the behavior of unsaturated soil, the SWCC (soil-water characteristic curve) is an essential soil parameter, and it defines the relationship between the volumetric water content and soil suction. As presented in Fig. 3, the SWCC can be classified into three zones depending on the magnitude of the matric suction: the capillary fringe zone for suction less than the air entry pressure, the continuous capillary zone for suction above the air entry pressure and water content below the residual value, and the residual zone for water content above the residual value [28,29]. In Fig. 3, the point ψ_b represents the matric suction at which air first begins to enter the largest soil pores, and the residual water content (θ_r) and saturated water content (θ_s) are defined as the minimum and maximum volumetric water content, respectively. Several models have been proposed for fitting the non-hysteretic SWCC function using experimental results; some representative models are listed in Table 1. Among these representative models, the Fredlund and

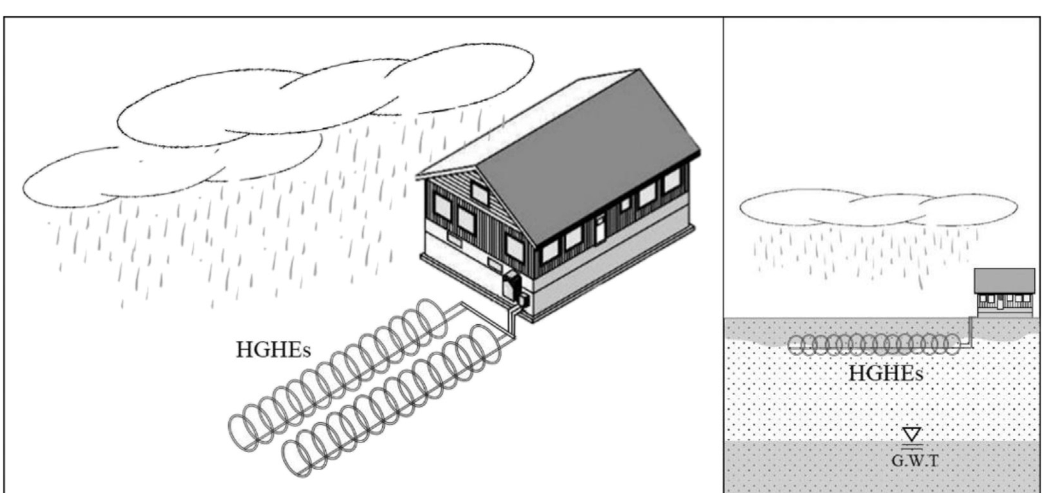

Fig. 1. Variation of soil saturation due to rainfall infiltration.