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Evaluation of stainless steel pipe performance as a ground heat exchanger in ground-source heat-pump system

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ABSTRACT

This paper presents a numerical and experimental study of the evaluation of stainless steel (STS) pipe performance as a ground heat exchanger (GHE). U-type GHEs of circular polybutylene (PB) and annular STS were installed in a steel box (5 m × 1 m × 1 m), and indoor thermal response tests (TRTs) were conducted for 30 h to evaluate the heat-exchange rates. The U-type GHEs of PB, annular STS, and indoor TRT conditions were numerically modeled using a three-dimensional finite-element method. The average pipe diameter for the annular STS pipe was determined by the finite-element method. The exchange rate of the annular STS pipe was approximately 10% higher than that of the circular PB pipe, and the temperature distributions measured in the TRT and calculated by the numerical analysis exhibited reasonable agreement. In addition, the borehole thermal resistance and heat-exchange rate under the assumption that the annular STS pipe would be applied in an actual vertical heat exchanger system were calculated. It is expected that the borehole thermal resistance would be decreased by 25% and that the heat-exchange rate would be increased by 15% with annular STS pipe in comparison with PB pipe.

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1. Introduction

Among the various renewable energy resources currently available, the use of geothermal energy has increased rapidly in many parts of the world [1–8]. Geothermal energy is regarded as one of the most efficient forms of energy, and it has great potential as it is directly usable. A ground-source heat-pump (GSHP) system combined with GHEs (ground heat exchangers) absorbs and extracts geothermal energy for space heating and cooling [9–14]. A typical GSHP system is generally composed of a geothermal heat pump and a GHE. The GHE extracts or emits heat using a circulation fluid, such as flowing water or an anti-freeze solution. The GHE is an important element that determines the thermal efficiency and initial construction cost of the entire GSHP system, and generally, closed-loop vertical types involving depths of 150–200 m are most commonly used [15–17]. The closed-loop vertical-type GHE system is composed of a GHE pipe, the ground, and grout to fill the empty space between the pipes inside the borehole (Fig. 1).

Considering their high initial construction cost, there have been many studies of closed-loop vertical-type GHE systems in an effort to realize higher thermal performance [18–21]. Heat transfer through GHE pipe is closely related to the heat transfer between the fluid that circulates within the GHE pipe and the complex medium (grout/ground) [22,23]. Therefore, the ground thermal conductivity and borehole thermal resistance are among the most important parameters in the design of a GSHP system [16,24]. Because it is difficult to control the ground thermal condition artificially to increase the thermal performance of a GSHP system, researchers have conducted a variety of studies to decrease the borehole thermal resistance. It is well known that the borehole thermal resistance can be decreased by increasing the thermal conductivity of the grout and the GHE pipe and by optimizing the type of pipe used and the pipe configuration [25–28]. In terms of the pipe shape, several studies have examined the flow and heat-transfer efficiency of pipes of various shapes [29,30]. Pressure-drop and heat-transfer characteristics for pipes of various shapes have been studied (circular, elliptical, circumferential, wavy, and twisted), and twisted

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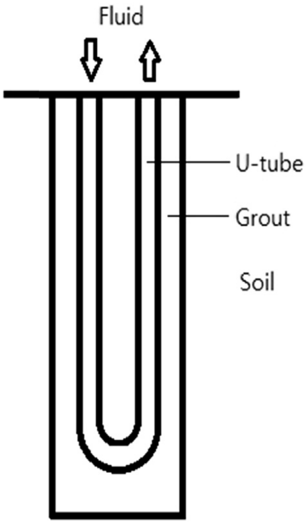

Fig. 1. Diagram of the closed-loop vertical-type GHE.

elliptic and stream-wise wavy circular types were found to be better than other types [31]. However, most GHE pipe is circular pipe consisting of high-density polyethylene (HDPE) and polybutylene (PB). These types are commonly used as GHEs owing to their convenience and low cost, although their thermal properties are not ideal for heat exchange. On the other hand, the thermal conductivity of stainless steel (STS) is more than 40 times higher than that of PB, and STS has strong corrosion resistance, while the thermal resistance of annular pipe is less than that of circular pipe, making this type better for transferring heat [24]. Furthermore, there have been few previous studies on the applicability of STS pipe as a GHE.

Therefore, this paper presents a numerical and experimental study of stainless steel (STS) pipe to determine its applicability as a ground heat exchanger (GHE). U-type GHEs of circular PB and annular STS were installed in a steel box, and indoor TRTs were conducted to evaluate the heat-exchange rates. The TRT conditions were numerically modeled using the finite-element method coupled with a computational fluid dynamics (CFD) analysis. Furthermore, the borehole thermal resistance levels and heat-exchange rates were predicted with annular STS pipe under the assumption that they would be installed in an actual vertical-type GHE system.

2. Experimental setup

2.1. Setup of the GHE

The TRT experimental setups were prepared in the laboratory of the Korea Electric Power Research Institute. A diagram of the TRT is presented in Fig. 2. The TRT equipment included the setup of a heater, pump, flow meter, water tank, and mockup of a steel box. Two resistance temperature detector (RTD) sensors were attached at the entrance and exit of the GHE pipe, and another RTD sensor was installed 0.1 m from the center and 1.8 m from the end of the pipe to measure the sand temperature during the test. Sand was filled in each case to a specific density of 13.97 kNm^{-3} within the steel box (5 m × 1 m × 1 m), and GHEs of PB and SUS were installed. Joomunjin sand (standardized coarse-grained Korean sand) was used in the TRT. A nearly homogeneous layer of sand was filled into the steel box through a sand-raining method [32]. The thermal properties of the sand were measured using the transient hot-wire method [33,34]. Typically, the transient hot-wire method is used to determine thermal conductivity. This measurement system consists of a needle probe with a heater and temperature sensor. A current passes through the heater, and the system monitors the temperature of the sensor over time. In this research, a KD2 Pro thermal properties analyzer (Decagon Devices, Inc.) was used to measure the thermal properties of sand. The range of thermal conductivity was 0.02–2.00 W m^{-1} K^{-1}, and accuracy was ±10% from 0.2 to 2 W m^{-1} K^{-1}, ±0.01 from 0.02 to 0.2 W m^{-1} K^{-1}. Table 1 shows the properties of the Joomunjin sand used in this study [35]. The center of the GHE was located at a depth of 50 cm in the steel box, and two U-shaped pipes (pipe diameters: PB 20 mm, STS 15 mm) with a length of 4 m were installed horizontally in the sand. The specifications of the GHEs are presented in Table 2 [31]. STS annular pipe has a streamlined shape; thus, it has a variety of internal diameters. Fig. 3 shows the TRT process, and Table 3 shows the specifications of the TRT equipment.

2.2. Analysis of TRT results

The heat transfer mechanism of the GHE involves the absorbing and releasing of heat to and from the grout material and the surrounding ground as the heat transfer fluid flows through the pipe within the borehole. In contrast, the heat transfer behavior between the ground heat exchanger and the surrounding ground involves a complex mechanism, and the heat transfer to the ground takes place mainly through conduction [36]. The governing equation for heat transfer from conduction in the ground can be represented by

$$-\frac{d}{di}\left(\lambda\frac{dT}{di}\right)+\rho c\frac{dT}{dt}+q_i=0 \quad (i=x,y,z), \tag{1}$$

where T is the temperature, λ is the thermal conductivity, ρ is the density, c is the specific heat capacity, and q_i is the internal heat generation. Analytical models including the line source and cylindrical source, along with numerical analysis models are used to determine the ground thermal conductivity. The TRT can be used to determine the ground thermal conductivity using a line source or cylindrical source model by applying a constant heat capacity to the TRT equipment. On the other hand, a thermal performance test (TPT) can be used to measure the heat-exchange rate from the GHE under the condition that the inlet temperature is kept constant [19,35]. The heat-exchange rate per borehole length (Q/L) can then be obtained by

$$\frac{Q}{L}=\frac{mc(T_{in}-T_{out})}{L}, \tag{2}$$

where T_{in} is the inlet temperature of the fluid, T_{out} is the outlet temperature of the fluid, and m is the flow rate of the fluid. Fundamentally, the inlet temperature should be kept constant to conduct a TPT. However, it was impossible in this case to conduct a TPT in the steel box because the heat capacity of the sand was so low that the inlet temperature of the TPT could not be held constant. The inlet temperature of the TPT increased despite the fact that there was no heat input into the TPT equipment. Therefore, the TRTs were conducted with only the power of the circulating pump and with no heat supply, and the heat-exchange rate was then calculated with Eq. (2).

3. Numerical analysis

A finite-element analysis program coupled with a CFD module in COMSOL Multiphysics [37] was used to simulate the TRTs

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