Thermal performance evaluation of stainless steel pipe as a ground heat exchanger

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ABSTRACT

In recent years, the utilization of geothermal energy for buildings has increased significantly. Especially in growing urban areas, there is a need for supplementary research to maximize the efficiency of heat exchange in geothermal energy systems on space-restricted sites. There is currently a little research about improving the heat exchange by choice of pipe materials. Circular pipes of high-density polyethylene (HDPE) and polybutylene (PB) are commonly used as ground heat exchangers (GHEs) for convenience and cost benefit, but PB pipes, in particular, have thermal properties that do not have a favor in the heat exchange. Therefore, this paper presents the results of an experimental study on the use of annular stainless steel (STS) pipe as a GHE. Thermal response tests (TRT) were conducted to measure heat exchange rates in circular PB pipe and annular STS pipe installed in a steel box with the dimension of 5 m × 1 m × 1 m. Dry Joomunjin standard sand was used to fill the box and TRTs were performed for 30 hours to reach a steady state. As a result, the annular STS pipe showed about 9% higher heat-exchange rate (per pipe length) than did the circular PB pipe. Compared to the length of heat exchanger required under the same conditions, the annular STS pipe needed was shorter than the circular PB pipe. It is concluded that the STS pipe could be used as an efficient GHE.

Keywords: ground heat exchanger, thermal response test, stainless steel pipe

1 INTRODUCTION

In recent years, renewable energy has grown rapidly around the world relative to fossil fuels for many good reasons (e.g., global warming, pollution, fossil fuel depletion, etc.). The utilization of geothermal energy, a type of renewable energy, has significantly increased with the demand. The GHE systems utilize shallow underground pipes to exchange ground heat. This source maintains a relatively constant temperature that allows emission and absorption of heat energy for heating and cooling. One kind of ground-source heat-pump systems, the closed loop system, has vertical and horizontal configurations. The horizontal system is installed at a shallow depth (1–3 m) parallel to the surface. The horizontal GHEs are cheaper to build but they need a larger area for construction. Therefore, reducing the length of a GHE is an important way to reduce the construction cost and to minimize the required site area. With the growing need for energy in urban areas, maximizing the efficiency of heat exchange is a key factor in the efficient utilization of geothermal energy in space-restricted sites.

Research has shown various ways of reducing the length of GHEs. Lee et al. (2014) studied the evaluation of thermal performance and initial cost of U, W and coil types of GHEs. Yoon et al. (2014a) compared the experimental results of heat exchange rates in spiral-coil and horizontal-slinky types of GHEs. There has been much research about various methods to increase the efficiency of GHEs (Pulat et al. 2009; Wu et al. 2010; Benazza et al. 2011; Chong et al. 2013). In the field of mechanical engineering, there have been studies on the flow and heat-transfer efficiency of pipes of various shapes (Nishimura et al. 2003; Mahmud et al. 2003). Park et al. (2013a) showed pressure-drop and heat-transfer characteristics for pipes of various shapes (circular, elliptical, circumferential wavy and twisted; a total of six types). The results indicated that the twisted elliptic, and stream-wise wavy circular, were better than other types.

However, in geotechnical engineering, most of the GHE pipe used is circular pipe of HDPE (high-density polyethylene) and PB (polybutylene). These have commonly been used as GHEs for convenience and low cost, even though their thermal properties do not have a favor in the heat exchange. Circular pipes are also known to reduce the heat-transfer coefficient.
The thermal conductivity of STS (stainless steel) is more than 40 times higher than that of PB and STS has strong corrosion resistance. Moreover, the thermal resistance of annular pipe is less than that of circular pipe, making them better for transferring heat. Therefore, this paper presents an experimental study of annular STS 304 pipe for use as a GHE. In this study, the heat exchanger lengths required was compared, under the same ground conditions, for annular STS and circular PB pipe buried in a dry sand.

2 EXPERIMENTAL PRINCIPLES AND METHODS

2.1 Heat Transfer Mechanism of GHEs

The heat transfer mechanism of the GHE is related to the process of absorbing heat from, and emitting heat to, a buried pipe and the surrounding ground as the heat transfer fluid flows through the pipe. Heat transfer between the GHE and the surrounding ground involves a complicated mechanism, and heat transfer to the ground is mostly through conduction (Brandl 2006). Heat conduction is a process in which energy is passed from one area of a medium to another by molecular or atomic irregular activities. According to Fourier's law, for heat flux through an arbitrary area, the heat-transfer-governing equation used for conduction in the ground is:

\[ q = -\lambda \frac{dT}{dx} \]  

(1)

where \( q \) is the heat flux, \( \lambda \) is the thermal conductivity, \( T \) is the temperature, and \( x \) is the local coordinate. The TRT can be used to measure the ground thermal conductivity, using a line source or cylindrical source model, by supplying a certain heat to the equipment. In contrast, the thermal performance test (TPT) is conducted to measure the heat exchange rate of the GHE at a constant inlet temperature. The heat exchange rate was calculated using Equation 2.

\[ Q = m'c(T_{\text{inlet}} - T_{\text{outlet}}) \]  

(2)

where \( T_{\text{inlet}} \) is the inlet temperature of the fluid, \( T_{\text{outlet}} \) is the outlet temperature of the fluid, \( m' \) is the flow rate of the fluid, and \( c \) is the specific heat capacity of the circulating fluid. The TPT could not be conducted using the steel-box mockup because the heat capacity of the sand was so low that the inlet temperature of the TPT could not be kept constant. The inlet temperature of the TPT exceeded the designated temperature during the test. Therefore, the TRTs were conducted without heat and just the power consumption of the circulating pump.

2.2 Experimental Overview

TRTs were performed in the laboratory of the Korea Electric Power Research Institute. A mimetic diagram of the TRT is presented in Fig. 1. The setup includes a steel box, TRT equipment and temperature sensors. Two temperature sensors were installed at the entrance and exit of the GHE pipe. A RTD (Resistance Temperature Detector) was used to measure the temperature, and a data logger was used to collect and store the data.
Temperature Detector) sensor was set up 0.1 m from the center and 1.8 m from the end of the pipe. The TRT equipment (Table 1) consists of a heater, a pump, a flow meter, and a water tank (Park et al. 2013b). The steel box size was 5 m × 1 m × 1 m (L × W × H). It was filled with a standard Korean sand (called Joomoonjin sand) that was completely dried. Table 2 presents the physical and thermal properties of the sand (Yoon et al. 2011).

Table 1. Thermal response test equipment (Yoon et al. 2014b)

| Item       | Specification |
|------------|---------------|
| Heater     | Capacity 5 kW |
| Water Tank | 20 L (SUS 304) |
| Flow meter | 2 ~ 20 lpm |
| Pump       | 40 m head, 100 lpm |
| Sensor     | RTD |

Table 2. Properties of Joomunjin sand

| Properties           | Value |
|----------------------|-------|
| Uniformity Coefficient, \(c_u\) | 2.06  |
| Curvature Coefficient, \(c_c\)   | 1.05  |
| Specific Gravity, \(\rho_s\)      | 2.65  |
| Maximum Dry Density, \(\rho_{dmax}\) (kN/m³) | 16.17 |
| Minimum Dry Density, \(\rho_{dmin}\) (kN/m³) | 13.49 |
| Water Content, \(w\) (%)           | 0     |

Two U-shaped pipes (pipe diameters: PB 20 mm, STS 15 mm) with length of 4 m were installed horizontally in the sand. The specifications of the GHEs are presented in Table 3. The STS annular pipe is a streamlined shape, and hence it has a variety of internal diameters. The thermal conductivity of the STS pipe is much higher than that of the PB pipe.

Table 3. Specifications of GHEs

|          | PB (20A) | STS (15A) |
|----------|----------|-----------|
| External diameter (mm) | 20       | 18.1 (maximum) |
| Internal diameter (mm) | 16       | 14.1 (minimum) |
| Thickness (mm)         | 2        | 0.25~0.3    |
| Thermal conductivity (W/m·K) | 0.38    | 14.9       |

3 TEST RESULTS

Tests were conducted for 30 h continuously for two types of GHE for predicting the heat-exchange rates. As shown in Fig. 2, the temperature differences between the inlet and outlet reached almost a steady state within 1000 min after the start of the test. The initial temperature of the sand was 24~26 °C and the water pump was operated at an average of 5.3~6 lpm (liter per minute) to circulate the water through the GHEs. Fig. 3 and Fig. 4 present the average fluid-temperature
distribution, and heat-exchange rate per pipe length, of the two U-type GHEs (PB, STS) in relation to elapsed time. The average heat-exchange rates of PB (circular) and STS (annular) were 210.9 W and 229.2 W, and those per pipe length were 26.0 W/m and 28.3 W/m, respectively. The STS was better in view of the heat exchange than PB, which can be explained by the fact that the average fluid temperature of PB was higher than that of STS, and thus the fluid temperature rose slowly. Table 4 summarizes the test results.

| GHE Material   | Heat exchange rate (W) | Heat exchange rate per pipe length (W/m) |
|----------------|------------------------|------------------------------------------|
| PB (Circular)  | 210.9                  | 26.0                                     |
| STS (Annular)  | 229.2                  | 28.3                                     |

The heat-exchange rate per pipe length of the STS GHE was 9% higher than that of PB according to the test results. As there is currently no method to design a system with STS pipes, it will be necessary to develop equations and design techniques for this purpose in the future.

4 CONCLUSIONS

In this study, to compare the heat exchange rates of GHE by material, TRTs were conducted to measure heat exchange rates for circular PB pipe and for annular STS pipe installed in a steel box filled with a dry sand. The following conclusions were drawn from the research results.

The average heat-exchange rates of PB (circular) and STS (annular) pipe were 210.9W and 229.2W; and the heat exchange rates per pipe length were 26.0W/m and 28.3W/m, respectively. The STS pipe was better at heat exchange than the PB pipe.

The thermal conductivity of the STS is higher than that of PB and also the heat exchange area of the STS is greater than that of PB due to its annular shape. As a result, the heat exchange rate per pipe length of the STS GHE was about 9% higher in the test.

Metal pipes are known to have a higher thermal conductivity than polymer pipes. However, there are a few studies about the corrosion resistance and price benefit of metal pipes. Thus, it is necessary to analyze the life cost cycle of metal GHEs. There is currently no program for designing a system with annular pipes. In the future it will be necessary to develop equations and design techniques to find out which shape of metal pipe is more effective.

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