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Evaluation of thermal efficiency in different types of horizontal ground heat exchangers

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ABSTRACT

The utilization of geothermal energy is constantly increasing for economic and environmental advantages that this brings. Use of horizontal ground-heat exchangers (GHEs) can reduce installation cost and compromise between efficiency and cost. Among many kinds of horizontal GHEs, slinky and spiral-coil-type GHEs show higher thermal efficiency. This paper presents the results of experiments on the heat exchange rates of horizontal slinky, spiral-coil and U-type GHEs installed in a steel box (5 m × 1 m × 1 m). A commercial dry sand was used to fill the steel box, and thermal response tests (TRTs) were conducted for 30 h to evaluate heat-exchange rates according to various GHE-types. The U-type GHE showed the highest heat exchange rate per pipe length, about two and two and half times higher thermal efficiency than that for the horizontal slinky and spiral-coil-type GHEs, respectively. Furthermore, the heat exchange rates per pipe length with a relatively long pitch interval (pitch/diameter = 1) were 100–150% higher than those with a relatively short pitch interval (pitch/diameter = 0.2), in both spiral-coil and horizontal slinky-type GHEs. A cost-efficiency analysis was also performed, and it revealed that the U-type GHE was most economical under conditions of providing equivalent thermal performance.

1. Introduction

Among various renewable energy resources, geothermal energy has been regarded as the most efficient for space heating and cooling [1–5]. Geothermal energy has great potential as a directly usable type of energy, especially in connection with ground-source heat pump (GSHP) systems. Hence, GSHP systems combined with various types of ground-heat exchangers (GHEs) have been widely used since the early 20th century [6–8].

The main elements of a GSHP system are the geothermal heat pump and a GHE. The GHE extracts heat from, or injects it into a circulation fluid (e.g., water or anti-freeze solution) flowing through a heat exchanger installed in the ground. Since the ground provides a relatively uniform temperature year-round, the circulation fluid is able to release heat to the ground in summer and absorb heat from it in winter. The GHE is an important element that determines the performance and initial installation cost for the entire system. The most widely used types involve 150–200 m-deep vertical, closed loops. Considering their high initial cost of construction, there have been many studies [9–12] aimed at obtaining higher thermal efficiency and lower construction cost of closed-loop, vertical, ground-heat exchangers. Recently, a closed-loop vertical-type GSHP system with an energy-pile foundation was used, in which the GHEs were embedded in cast-in-place grout piles [13–16].

Although there has been substantial research covering closed-loop vertical-type GHEs, there has been little about closed-loop horizontal-type GHEs (Fig. 1). Furthermore, there is only one commercial design program which is called GLD (ground loop design) for the horizontal-type GHEs in contrast with many design program for the vertical-type GHEs [17,18]. Even so, the use of horizontal GHEs can reduce installation cost and minimize the compromise between increase in efficiency and cost [19–21]. Horizontal GHEs are usually installed in a trench approximately 1.5–3 m deep, and their thermal efficiency is affected by pipe configuration, type of pipe, trench depth and ground thermal properties [22–25]. Among them, Congedo et al. [23] analyzed the thermal efficiency of different types of horizontal GHEs using numerical analysis method. Their calculation suggested the thermal superiority of spiral-coil-type GHE in comparison with line and slinky type GHEs. Li et al. [26] considered thermal performance of spiral-coil-type GHE under the existence of the groundwater flow effect. However, there are a few researches for thermal efficiency evaluation among different kinds of horizontal GHEs with experimental results, and a few researches for relation between cost analysis and thermal efficiency results.

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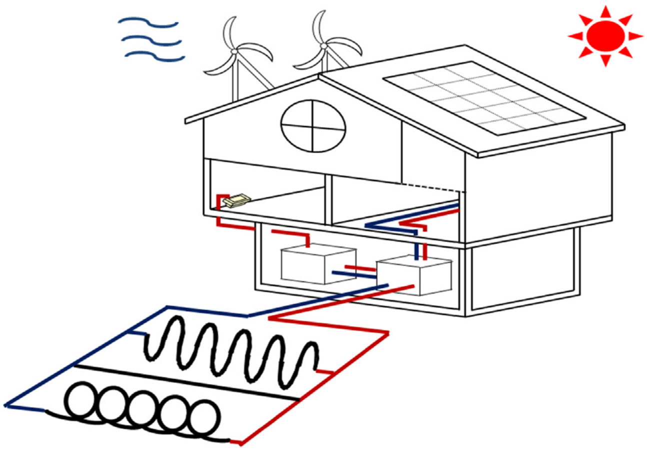

Fig. 1. Schematic diagram of horizontal GHEs.

Therefore, this paper presents the results from an experimental study by comparing the heat exchange rates of horizontal slinky, spiral-coil and U-type GHEs installed in a steel box. In situ TRTs (thermal response tests) were conducted for these three kinds of horizontal GHEs so as to evaluate heat exchange rate. In addition to the experimental approach to calculate the heat exchange rate, a cost-efficiency analysis considering actual whole construction procedure using horizontal ground heat exchangers was conducted in order to evaluate optimal thermal efficiency of each type GHEs and suggested optimal horizontal GHE type.

2. Experimental setup

2.1. Mockup of steel box

Equipment was installed in order to measure the heat exchange rate of each GHE. The setup included a heater, pump, flow meter, water tank and mockup steel box. The set-up was multi-functional; it was able to measure heat exchange and ground thermal conductivity because it was equipped with controllers for both temperature and heater. Soils were compacted to a certain density within the steel box (5 m × 1 m × 1 m) and the GHEs were installed. The steel box was insulated with double layers of 10 mm polyethylene. Over that, a tent (3 m × 6 m) was covered in which a far-infrared radiation heater was operated during the TRT to maintain constant indoor temperature. Temperature sensors were also installed at GHE inlet and outlet pipes to monitor temperature variation in programmed time steps.

Joomunjin (a standardized coarse-grained Korean sand) was used in the test. By applying the sand-raining method [27,28], a nearly homogeneous layer of sand filled the steel box. The thermal properties of the sand were measured using the transient hot-wire method [29,30], adjusted for the unit density and void ratio present in the steel box. The properties of the sand are listed in Table 1. The center of the GHEs was located at a depth of 50 cm in the steel box, and 4-m pipes were installed horizontally in the soil. After sieving (sieve size 3.35 mm), dry sand was used to fill the steel box to a unit weight of 13.97 kN m^{-3} (with void ratio of 0.9). Horizontal slinky, spiral-coil and U-type GHEs were installed and connected to the equipment during the test. Polybutylene pipes (inner/outer diameter 16 mm/20 mm) were used as GHEs. The diameter of the slinky and spiral-coil GHEs was 30 cm, and the distance between the U-type pipes was 0.08 m (Fig. 2). A temperature sensor was also installed in the steel box to measure soil temperature during the test. The total length (L) of the spiral-coil-type GHE was calculated using Eq. (1) [31].

Table 1
Physical and thermal properties of Joomunjin sand.

Parameter	Value
Uniformity coefficient, C_u	2.06
Curvature coefficient, C_c	1.05
Specific gravity, G_s	2.65
Maximum dry density, $\gamma_{d\max}$ [kN m^{-3}]	16.17
Minimum dry density, $\gamma_{d\min}$ [kN m^{-3}]	13.49
Water content, w [%]	0
Thermal conductivity, λ [W/m K]	0.26
Specific heat capacity, c [J kg^{-1} K^{-1}]	785
Thermal diffusivity, α [m^2 s^{-1}]	2.57×10^{-7}

Table 2
Specifications of the experimental GHEs.

GHE	Pitch (P)	Number of loop (N)	Total length (L)
Spiral coil	P = 6 cm P = 30 cm	N = 63 N = 15	L = 62 m L = 18 m
Horizontal slinky	P = 6 cm P = 30 cm	N = 63 N = 15	L = 66 m L = 24 m
U-type			L = 8 m

$$L = \int_0^h \sqrt{\omega^2 r_o{}^2 + 1} \quad dz = h\sqrt{\omega^2 r_o{}^2 + 1} \tag{1}$$

where $\omega = 2N\pi/h$ indicates the wave number, r_o is the coil radius, h is the vertical depth of coil and N is the number of coil turns. The total length of the horizontal slinky-type GHE was calculated using Eq. (2) [32].

$$L = NL_l + 2PN + \frac{\pi d}{2} + d \tag{2}$$

where N represents the number of slinky turns, and L_l is the length per slinky loop. Here, P is the pitch interval of the slinky and d its radius. TRTs were conducted for five different combinations including GHE type, as well as pipe pitch (loose or dense), with emphasis on the slinky and spiral-coil-type GHEs. Table 2 shows GHE specifications for the five cases. An effort was made to keep identical every condition except pipe-type, in order to evaluate the heat-exchange rate according to pipe-type, but the total length could not be identical because of differences in the shapes of the pipes. Fig. 3 shows the TRT process.

2.2. Theory of TRT analysis

The heat transfer mechanism of the GHE is related to the process of absorbing and releasing heat to and from the borehole and the surrounding ground as the heat transfer fluid flows through the pipe within the borehole. Heat transfer between the GHE and the surrounding ground involves a complex mechanism, but heat transfer to the ground is mostly through conduction [6,11]. The heat-transfer-governing equation used for conduction in the ground is shown below.

$$-\frac{d}{di}\left(\lambda \frac{dT}{di}\right) + \rho c \frac{dT}{dt} + q_i = 0 \quad (i = x, y, z) \tag{3}$$

where T is the temperature, λ is the thermal conductivity, ρ is the density, c is the specific heat capacity, q_i is the internal heat generation. Analytical models, including line source and cylindrical source, and numerical analysis models, are used to determine the thermal conductivity of the ground. The TRT can be used to determine the ground thermal conductivity, using a line source or cylindrical source model, by applying constant heat to the equipment. On the other hand, the thermal performance test (TPT) is