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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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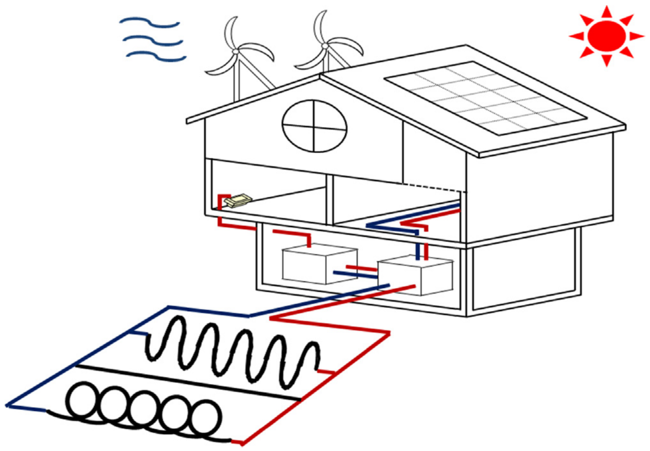


Fig. 1. Schematic diagram of horizontal GHEs.

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

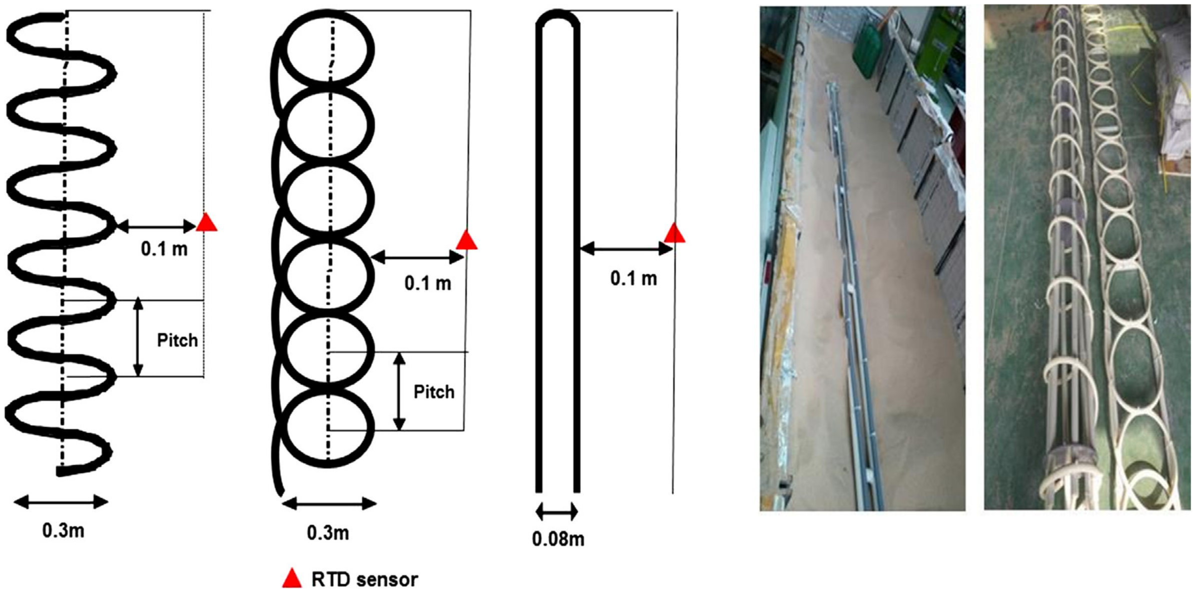
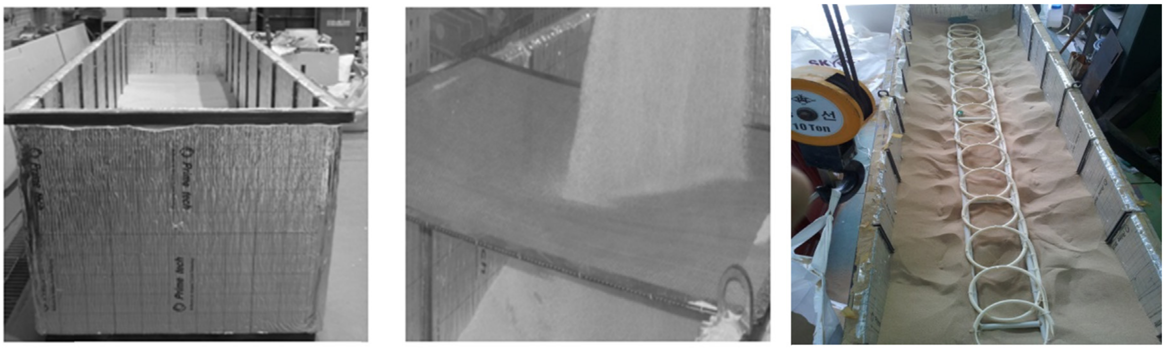


Fig. 2. Horizontal GHEs for the thermal response tests: spiral (left), slinky (center), and U-type (right).

used to measure the heat exchange rate of the GHE under the condition that the inlet temperature is kept constant [33]. Then the heat exchange rate is calculated using Eq. (4).

$$Q = mc(T_{in} - T_{out}) \tag{4}$$

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 TPT should be conducted in order to evaluate the heat exchange rate using Eq. (4). However, 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 just the power of the circulating pump with no heat, and then the heat exchange rate was calculated using Eq. (4). Table 3 shows the specification of TRT equipment.



(a) Installation of steel box (b) Preparation of specimen (c) Installation of pipe

(d) Pipe connection (e) Completion of preparation

Fig. 3. Steps in preparation of the experimental set-up.

Table 3
TRT equipment.

Item	Specification	
Heater	Capacity 5 kW (within +3% error)	
Water Tank	20 L (SUS 304)	
Flow meter	2 < 20 lpm	
Pump	40 m head, 100 lpm	
Temperature Sensor	RTD (within ± 0.3 °C)	

3. Results and discussion

3.1. Experimental results

The TRTs were conducted for 30 h continuously to measure the heat exchange rates for the five different GHE cases. The temperature of the circulating water reached a near steady state after 20 h in the TRT. The initial temperature of the sand was 17–18 °C, and the average flow rate of the circulating water was 4–5.55 lpm. Figs. 4 and 5 show the heat-exchange rate per pipe length, and the average fluid-temperature distribution of short-pitch-interval (pitch/diameter = 0.2) horizontal slinky and spiral-coil-type GHEs. The total average heat-exchange rates for the slinky and spiral-coil GHEs were 290.61 W and 373.20 W, respectively. The average heat-exchange rates per pipe length for the slinky and spiral-coil GHEs were 4.40 W/m and 6.02 W/m, respectively. The average fluid temperature of the slinky GHE was higher than that of the spiral-coil GHE, and it is thought that heat was well transferred to the Joomunjin sand by the spiral-coil GHE because of the low fluid temperature. Figs. 6 and 7 show the heat-exchange rate per pipe length and average fluid-temperature distribution of long pitch interval (pitch/diameter = 1) slinky and spiral-coil GHEs, and of the U-type GHE. The total heat exchange rate of cases with long pitch interval was 10–40% lower than those with short pitch intervals (for slinky and spiral-coil GHEs). However, the heat-exchange rate per length of pipe, with long-pitch interval for slinky and spiral-coil GHEs, were 10.64 W/m (slinky) and 14.45 W/m (spiral coil). This was about twice as much heat exchange as accomplished by

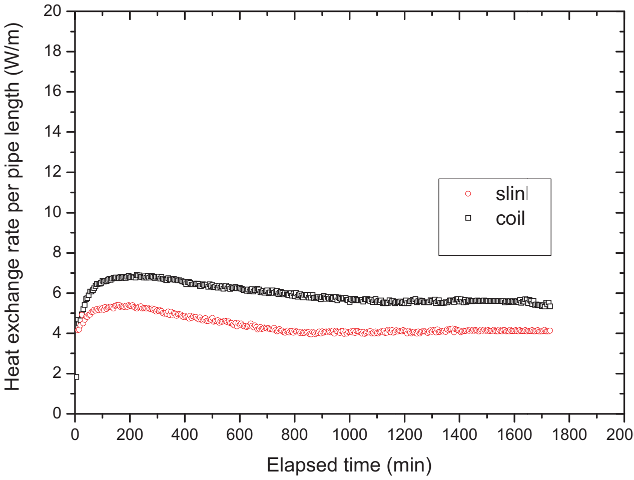


Fig. 4. Heat exchange rate per pipe length ($P = 6$ cm) for horizontal slinky and spiral-coil-type GHEs.

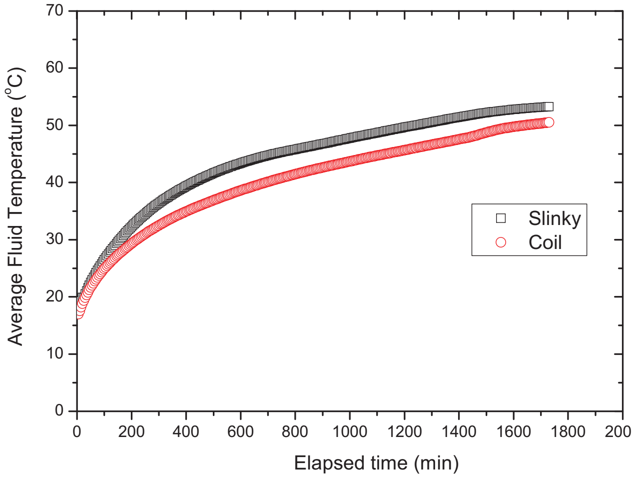


Fig. 5. Average fluid temperature distribution ($P = 6$ cm) for horizontal slinky and spiral-coil-type GHEs.

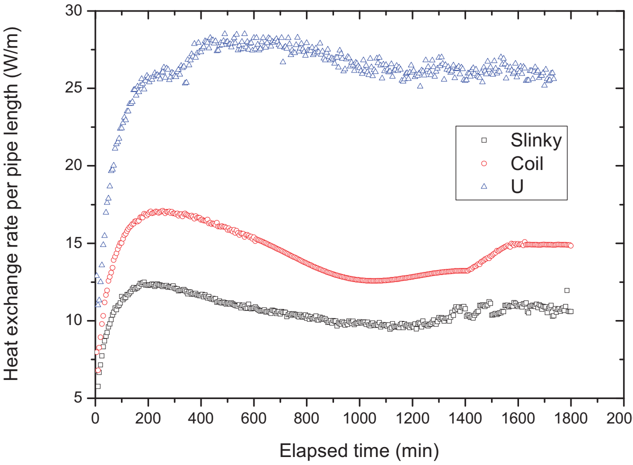


Fig. 6. Heat exchange rate per pipe length ($P = 30$ cm) for horizontal slinky and spiral-coil and U-type GHEs.

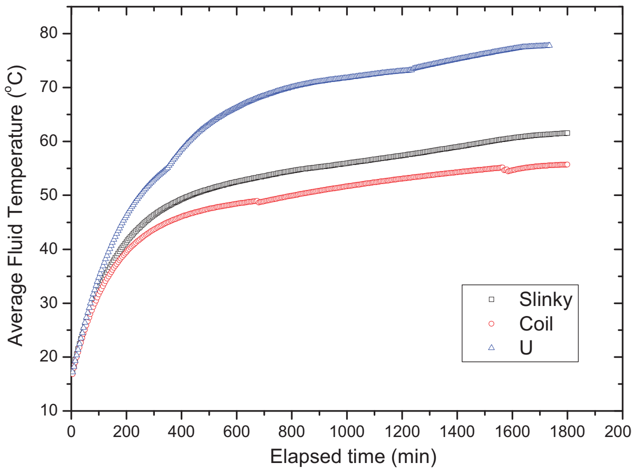


Fig. 7. Average fluid temperature distribution ($P = 30$ cm) for horizontal slinky, spiral-coil and U-type GHEs.

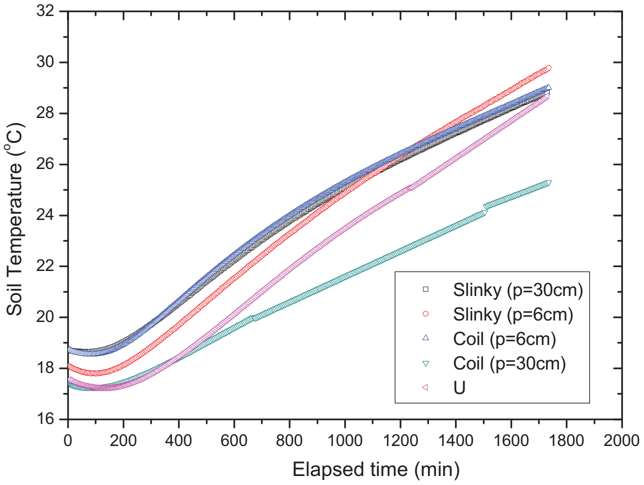


Fig. 8. Soil temperature distribution over time.

cases with short pitch interval. It can be inferred that use of small intervals between coils increases interference in heat transfer and leads to small heat exchange rates per pipe length [26]. For the U-type GHE, the total heat-exchange rate was the lowest among the three GHEs, but the heat exchange rate per pipe length was higher than for any other types. Fig. 8 shows the ground-temperature distribution for the five TRT cases. The ground temperature of the slinky GHE (pitch/diameter = 1) was the highest among the five cases, and it is thought that the high fluid temperature led to high ground temperature because of heat transfer between the pipe and ground. In spite of this, the ground temperature of the U-type GHE showed a little lower temperature than that of the slinky-type GHE (pitch/diameter = 1). It seemed that the temperature sensor on the ground was mislocated when using the U-type GHE. Table 4 summarizes the test results.

3.2. Cost-efficiency analysis

Based on the heat-exchange value of each heat-exchange type shown in Table 3, we next conducted a cost-efficiency analysis. Based on Korean standard estimates for civil construction [34], price information [35], and the hypothesis that the same amount of ground heat would be produced, the construction costs for the necessary site excavation, pipe installation and site-preparation process were calculated. Accepting that the heat-exchange rate per pipe length was higher for a pitch interval of 6 cm than for 30 cm, and using the values for a pitch interval of 30 cm as the basis, the cost-efficiency of horizontal spiral-coil, slinky, and U-type heat exchangers was analyzed.

The process for installing horizontal heat exchangers largely consists of excavation, pipe installation, refilling, and site clearing by compaction. Based on the results shown in Table 3 and Korean standard estimates for civil construction, the unit price for each process and the construction costs were calculated as shown in Table 4. From this analysis, pipe-installation was priced based on estimates. For the spiral-coil and slinky GHEs, PB pipe was used and HDPE (high-density polyethylene) pipe was used for the U-type GHE. The unit price of HDPE pipe per meter in Korea was about 560 Won and 3000 Won for PB pipe. This was because spiral-coil and slinky GHEs cannot be manufactured with HDPE pipe, which is about five times cheaper than PB pipe. For the excavator, it was assumed that it could operate 8 h a day and 40 m^3/h for the general sandy and gravel soils. Daily operation cost for the excavator was estimated about 780,000 Won, and unit price was based on the cubic meter. Similarly, daily operation cost for the site clearance equipment was about 520,000 Won, and unit price was based on the site area (square meter). The excavation depth was set at 2 m below the ground surface and the trench width was set at 1 m. As for the spiral-coil-type, because the heat-exchange rate per trench length was calculated to be 64 W/m, the necessary site area, the amount of excavation, the pipe lengths, and the compaction construction costs per heat-exchange type needed to produce a total of 6500 W were calculated (Table 5).

Table 4
Summary of test results.

GHE	Pitch (*P*)	Heat exchange rate (W)	Heat exchange rate per pipe length (W/m)
Spiral coil	*P* = 6 cm	373.20	6.02
	P = 30 cm	260.21	14.45
Horizontal slinky	*P* = 6 cm	290.61	4.42
	P = 30 cm	255.30	10.64
U-type		210.89	26.00

Table 5
Results of cost analysis1.

	Excavation & refilling	Total pipe length (m)	Site clearing area (m^2)	Total cost (Won)
Spiral coil	100 m × 1 m × 2 m	450	100	2,345,313
Horizontal slinky	102 m × 1 m × 2 m	611	102	2,848,219
U-type	123 m × 1 m × 2 m	250	123	1,364,234

1$ = 1100 Won (May 2015).

According to the results of the analysis, the net construction costs were lowest for the U-type heat exchanger. This heat exchanger had an economic efficiency about 20% (or more) better than the spiral-coil and slinky GHEs. In the case of the U-type, however, because the necessary area was 20% or more greater than for the spiral-coil and the slinky GHEs, when the purchase of a site is required to construct a horizontal heat exchanger, the additional site-purchase costs must be taken into consideration. Since there is a considerable disparity in the publicly announced prices of sites based on the usage and area of the site, an appropriate type of heat exchanger must be selected in consideration of the actual conditions. Comparing the spiral-coil and slinky GHEs, because the area needed is nearly identical, the spiral-coil-type is more cost-efficient than the horizontal slinky-type, when considering GLD.

4. Conclusion

In this paper, in order to measure the heat-exchange rate of horizontal GHEs per type, several (i.e., spiral-coil, horizontal slinky, and U) types of GHE were installed inside a steel-box mockup (5 m × 1 m × 1 m). TRTs were conducted for 30 h continuously, and the heat-exchange rates were calculated. Based on these heat-exchange rates, a cost-efficiency analysis was conducted. In consideration of the GHE type and the pitch interval, heat-exchange rates were measured for five combinations, and the following conclusions can be reached.

First, in this study, the heater inside the water tank was not supplied with electric power and electric power was only provided for the circulation pump. The TRTs were continuously conducted for 30 h to measure the heat-exchange rate achieved by the ground inside the steel-box mockup. When the pitch interval was 6 cm and the pitch/diameter was 0.2, the overall average heat-exchange rates amounted to 373.20 W and 290.61 W for the spiral-coil and slinky types, respectively. When calculated in terms of the heat exchange rate per pipe length, the values were 6.02 W/m and 4.40 W/m, respectively. In addition, when the pitch interval was 30 cm and the pitch/diameter was 1, the overall average heat-exchange rate amounted to 260.21 and 255.30 W for the spiral-coil and slinky GHEs. While the overall amount of heat decreased in comparison with cases where the pitch interval was 6 cm, the heat-exchange rates per pipe length were 14.45 W/m (spiral-coil) and 10.64 W/m (slinky). Thus, the spiral-coil and slinky GHEs exhibited values approximately 100% and 150% greater, respectively, when the pitch interval was 30 cm. It is thought that small intervals between coils increases heat-transfer interference and leads to lower heat-exchange rates per pipe length, in comparison with larger intervals. Overall, the spiral-coil GHE showed a 30–40% greater heat-exchange rate per pipe length than did the slinky GHE. Furthermore, when the U-type GHE was used, the overall average heat-exchange rate amounted to 210.89 W. However, the heat-exchange rate per pipe length was 26 W/m. Therefore, this GHE showed values approximately twice as large as those for the spiral-coil and the slinky types, meaning that the U-type GHE showed the best thermal performance among the other types, based on its heat-exchange rate per pipe length.

Second, based on the heat exchange rate per GHE type, a cost-efficiency analysis was conducted using Korean standard estimates for civil construction and relevant price information. The assumption was made that the same amount of heat would be produced from the ground in each case, and the construction costs for the required sites were calculated. Since the heat-exchange rate per pipe length was higher for a pitch interval of 6 cm than for 30 cm, the cost analysis was conducted based on the 30-cm pitch interval for the spiral-coil, horizontal slinky GHEs, and U-type GHEs. According to the cost-efficiency analysis, the net construction costs were lowest for the U-type GHE, and it had economic efficiency approximately 20% better than the spiral-coil-type and the horizontal slinky-type. However, the site area required for installation of the U-type GHE was about 20% larger than for the other GHEs. Therefore, it is necessary to consider the potential for higher site-purchase costs. This means that the appropriate GHE type for each site must be selected considering the publicly announced prices of sites based on the usage and area of the site. Furthermore, when compared with the horizontal slinky GHE, the spiral-coil showed superior cost-efficiency in consideration of GLD, because the size of the site-areas needed was nearly the same.

Consequently, it is necessary to conduct a parametric analysis of, and design model development for, the spiral-coil-type heat exchanger, in which GLD has not been taken into consideration. It is also necessary to apply the optimal heat exchanger in comparison with the U-type through the cost analysis, including the purchase of the site, based on conditions in the field.

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