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Thermal performance analysis of a ground-coupled heat pump integrated with building foundation in summer

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ABSTRACT

Geothermal energy has been provided to improve the energy performance of buildings with great support from the government in Korea. However, despite the many advantages of using a ground-coupled heat pump (GCHP) with geothermal energy, the high construction cost of the ground-coupled heat exchanger (GCHE) is the primary obstacle to prevent the supply and spread of GCHPs.

In this study, in order to overcome the problems of the conventional GCHP, a GCHP integrated with a PHC (prestressed high-strength concrete) pile, which is used in the foundation of buildings, was introduced and its thermal performance was analyzed through experiments conducted in summer. To increase the thermal performance, a coil-type pipe was used. The PHC-pile-integrated GCHP was installed at a depth of 15 m. However, because it was installed in the beneath of the building, it was not largely affected by the outdoor temperature. The measured effective thermal conductivity was 3.69 W/m °C, which is similar to that of a conventional vertical GCHP. Also, the COP was determined to be 3.9–4.3, which is slightly lower than the conventional vertical GCHP. However, considering the fact that the expensive drilling cost could be mitigated by 83.7%, the thermal performances were satisfactory.

1. Introduction

Recently in Korea, the energy consumption of buildings has rapidly increased. Technologies and policies for energy conservation to enhance the energy performance of buildings are being enacted with the great support of government. A representative policy promoted by the government is a building code, which has been enforced since 2004, which stipulates that 5% or more of new public building construction cost must be invested in renewable energy facilities.

Due to this building code, the renewable energy market in Korea has increased. Along with this, many Korean engineers have tried to find and develop effective applications for renewable energy. The ground-coupled heat pump (GCHP), which uses geothermal energy, has especially attracted much attention. Geothermal energy is an environmentally friendly energy source. Because most energy used in Korea is imported from overseas, it is considered to be a strong alternative that can reduce energy consumption in the building sector [1,2].

Geothermal research is being conducted in other countries, as well as in Korea. Yang et al. introduced the theoretical background for a vertical GCHP and methods to evaluate its thermal performance. They stated that energy can be saved even in cold or hot areas using such a GCHP [3]. Esen et al. installed a horizontal GCHE in Turkey in an experiment and reported that it was more efficient than general heating systems in terms of coefficient of performance (COP) [4,5]. Petit and Meyer compared the thermal performances of a GCHP with an air source air conditioner, finding that a horizontal or vertical GCHP was more favorable in terms of economic feasibility [6,7].

However, GCHPs are still expensive when compared to other systems, and the majority of the energy and cost is consumed in the installing process of the ground-coupled heat exchanger (GCHE). Healy and Ugursal indicated that a GCHP was economically efficient compared to conventional systems. However the cost to install the GCHE is still high about 38% of the total cost [8]. Also, Genchi et al. reported that 87% of the amount of CO_2 produced by installing the GCHE was generated during the drilling process [9]. There are many other researchers who also agree that the initial cost for a GCHP is high [10–13].

To mitigate high construction cost of a GCHP, this study introduces a PHC-pile-integrated GCHP that can reduce the costs generated during the drilling process and increases the efficiency of a GCHE. To analyze the thermal performance of the proposed GCHP, the effective thermal conductivity was analyzed through a thermal response test (TRT). Also, the COP of the GCHP was analyzed

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through an experiment within a house in summer. The analyzed results were compared with the findings of existing research for an evaluation.

2. PHC-pile-integrated ground-coupled heat pump

2.1. PHC-pile-integrated GCHE

The ground-coupled heat pump (GCHP) consists of a ground-coupled heat exchanger, a heat pump, and other equipment. The ground-coupled heat exchanger, which exchanges heat with the underground, has the greatest effect on the thermal performance of the GCHP. It offers various results according to the installation depth, shape, and other closely related variables.

Fig. 1 illustrates the ground-coupled heat exchanger (GCHE), as integrated with the PHC (prestressed high-strength concrete) pile in this study. The PHC pile is installed at the foundation of the building in order to support the building structure, and it is one of the most widely used pile types in Korea. As can be observed in the figure, the PHC pile is borehole-shaped. In the central empty space, a polybutylene (PB) pipe is installed in order to exchange heat with the underground. Therefore, the PHC-pile-integrated GCHE requires no separate drilling process for the GCHE, which directly and significantly reduces the costs when it is applied to a building.

A study by Gao et al. showed that the GCHE could have sufficient thermal performance when it was installed 25 m deep below the ground level [14]. This study tests if the PHC-pile-integrated GCHE exhibits sufficient thermal performance even when it was installed 15 m deep although the PHC-pile-integrated GCHE is assumed to be installed much deeper and used for tall and large buildings with multiple basement floors or buildings with deep foundations. A single PHC pile unit is generally 15 m long, the PHC-pile-integrated GCHE is not installed 15 m deep below the ground level, but much deeper than 15 m because PHC piles are installed below the lowest basement floor as foundation piles. Moreover, multiple units of PHC piles that are vertically welded to each other are often used to create strong foundation. As the number of welded PHC piles increases, the installation depth of a GCHE becomes deeper. The most commonly used GCHE has a U-shaped pipe. When a U-shaped pipe is used in the PHC pile, the thermal surface area of the pipe is decreased. As a result, the efficiency of the GCHE declines.

In this study, a coil-type PB pipe (diameter, 25 mm) instead of a U-shaped pipe was used to mitigate the decline in efficiency. When a coil-type pipe is used, the surface of the pipe, which exchanges heat with the underground, increases. Therefore, it was expected that the overall efficiency of the GCHP would increase. The pitch of the coil-type pipe was designed to be loose in the upper area and dense in the lower area so that more heat exchange could occur in the lower underground, where the temperature is relatively stable. The overall length of the pipe was 196 m.

Before the GCHE was installed, the properties of the soil were surveyed. The underground included the silt layer, which contained little water and had relatively high thermal conductivity. It promotes heat exchange between the GCHE and the underground.

The circulating fluid in the GCHE was 20% ethylene glycol aqueous solution, which prevents freezing. Coarse sand was used as a grouting material inside the PHC pile, while a separate water supply pipe (diameter, 25 mm) was designed and installed to supply water regularly inside the PHC pile to enhance heat conductivity. The PHC pile used in this study was 15 m long with an inner diameter of 0.34 m and an outer diameter of 0.5 m.

2.2. Overall GCHP system

The distribution diagram of the entire GCHP system is shown in Fig. 2. The system consists of a GCHE, header, heat pump, buffer tank, and auxiliary parts. The collected heat is extracted through a radiant cooling/heating system. [15] The GCHP is installed in an experimental building (Fig. 2(a)). The experimental building is located in Songdo, an area in the city of Incheon, Korea.

The building consists of an office, five apartment units, and a mechanical room. The GCHP is responsible for the heating and cooling of two of the apartments. Heating and cooling is achieved through a radiant cooling/heating system (Fig. 2(b)) installed in the floor of the house. A total of five GCHEs were applied to the building's PHC piles. The subject building could not have a basement because of the shallow depth of the water table. Therefore the GCHE was installed around 15 m deep beneath of the building. The heat pump used in the GCHP and the specifications of the other equipment in the system are displayed in Tables 1 and 2.

Table 1
Specifications of the ground heat source heat pump.

Items	Specifications
Number of heat pump	1
Fluid flow rate of the GCHE (LPM)	27
Water flow rate for cooling/heating (LPM)	28
Heating capacity (kW)	11
Cooling capacity (kW)	10
Electricity power (kW)	2.06 for heating, 1.77 for cooling
Size ($L \times W \times H$, (m))	$5.4 \times 6.6 \times 7.0$
Weight (kg)	101

Table 2
Other equipment.

Items	Specifications	
Buffer tank	Capacity (l)	700
Expansion tank	Capacity (l)	60
Circulation pump	Electric power (W)	550, 370

2.3. Initial cost for installation

A comparison of initial installation costs between the conventional vertical GCHP and the PHC-file-integrated GCHP is shown in Table 3. The cost data was provided from the construction company, which built an experimental building including a GCHP system for the study. GCHP installation cost for each system reaches to 36.8% and 24.5% of the total cost, respectively. As shown in the table, to install the PHC-pile-integrated GCHP, the ground drilling cost was removed, and PE pipes were replaced to PB pipes. Therefore the cost was slightly increased. The installation cost is only 55.7% compared

Table 3
Initial costs for installation (unit: USD).

Items	Conventional vertical GCHP	PHC-pile-integrated GCHP
Installation of GCHP		
Ground drilling	58,900	–
Hole grouting	10,300	2000
PE pipe	9900	–
PB pipe	–	36,400
Pipe inserting	8600	7300
Ground trench	3600	–
Pipe installation	5900	8800
Etc.	1900	700
Sum.	99,100 (37%)	55,200 (24%)
Other system		
Equipment	102,300	102,300
Pipe installation	47,300	47,300
Control system	20,800	20,800
Sum.	170,400 (63%)	170,400 (76%)
Total	269,500 (100%)	225,600 (100%)

[*] The data are based on 80 RT