Energy and Buildings 93 (2015) 99–109

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Applications of building-integrated coil-type ground-coupled heat exchangers—Comparison of performances of vertical and horizontal installations

Jin-Uk Lee, Taeyeon Kim*, Seung-Bok Leigh

Department of Architectural Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu 120-749, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form 21 January 2015
Accepted 8 February 2015
Available online 16 February 2015

Keywords:
Renewable energy
Building energy
Geothermal
GCHE
PHC pile
Coil type

ABSTRACT

The building-integrated coil-type ground-coupled heat exchanger (GCHE) was used to overcome the high installation cost of the heat exchanger. A field test and simulations were conducted to analyze the performance of GCHE when installed vertically or horizontally. The vertical GCHE refers to the coil-type GCHE installed at the center of a PHC (pre-stressed high-strength concrete) pile used for the building foundation. The horizontal GCHE refers to the coil-type GCHE laid horizontally on the bottom of the building.

The amount of electric power consumed by the horizontal GCHE system was higher than that consumed by the vertical GCHE system. The coefficient of performance (COP) through a cooling experiment was identified as 3.9–4.3 for the vertical type and 3.3–3.7 for the horizontal type.

The simulation model was used to examine the annual performance evaluation for the vertical and horizontal GCHEs. The comparison of the year-round energy consumption values showed that the vertical GCHE has about 15% higher heating/cooling efficiency than the horizontal GCHE. The return period was six years in both the horizontal and vertical GCHEs for the short term, but the cost saving in the vertical GCHE was about 28% higher in the long term.

1. Introduction

Since recently, renewable energy has been increasingly used to mitigate climate change and to reduce energy consumption. Various types of energy consumption in buildings can be supplemented by renewable-energy systems. Of the many renewable-energy systems available, the ground-coupled heat exchanger (GCHE) has become one of the most popular systems for reducing energy consumption in buildings due to its performance and the fact that it can be used year-round, without the influence of the outdoor air [1,2].

Many studies have been conducted to evaluate the thermal performance of GCHE. Yang et al. introduced the theoretical background of the vertical GCHE and how to evaluate its thermal performance [3]. This study showed that the use of GCHE can contribute to energy saving in hot or cold regions. Michopoulos et al. observed that the vertical GCHE has high energy efficiency in both summer and winter and is also capable of achieving a 22.7% CO_2 reduction compared to the existing heating/cooling systems [4].

Other studies have been conducted on the horizontal and vertical GCHEs. Esen et al. tested a horizontal GCHE in Turkey and found that the horizontal GCHE is more efficient than the general heating systems in terms of coefficient of performance (COP) and in the economic aspect [5,6]. Tarnawski et al. applied the horizontal GCHE to residential buildings and concluded that it is more efficient than electricity or gas [7]. Petit et al. conducted a comparative study of the existing air conditioners and GCHE and proved that both the horizontal and vertical GCHEs were more efficient than other heating systems in the economic aspect [8,9]. Zhai et al. investigated the performance of GCHE for over two years and found that its use reduced the operating cost by 55.8% compared to the use of the air source heat pump [10].

Despite the aforementioned advantages of GCHE, it is difficult to use due to its high installation cost. Indeed, the digging process for the installation of GCHE is very costly and requires much energy. Healy et al. suggested that GCHE has an economic possibility compared to the existing systems, but that the GCHE installation cost accounts for 38% of the total cost [11]. Genchi et al. reported that about 87% of the total CO_2 generated during the installation of GCHE is generated during the digging process [12]. In addition, Congedo et al. and Sanaye et al. pointed out the high initial investment cost of GCHE [13–16].

* Corresponding author. Tel.: +82 2 2123 5783.
E-mail address: tkim@yonsei.ac.kr (T. Kim).

http://dx.doi.org/10.1016/j.enbuild.2015.02.020
0378-7788/

To reduce the initial investment cost of GCHE, the horizontal GCHE can be used instead of the vertical GCHE. As the horizontal GCHE is generally not installed deeper than the vertical GCHE, it can lower the digging cost [17–19]. It does not provide good general thermal performance, however, compared to the vertical GCHE.

Another approach that utilizes GCHE with building structures has been proposed for construction cost savings. Suryatriyastuti et al. reported that GCHE using a building foundation has a high heat capacity and a sufficient performance. It can achieve initial cost savings [20]. Hamada et al., Gao et al., Bozis et al., Jalaluddin et al., and Park et al. also used building structures for construction cost savings [21–25]. The use of the structure, however, limits the GCHE installation length, and it is difficult to exchange heat sufficiently with the underground. Therefore, it does not provide a sufficient thermal performance.

To enhance the thermal performance of GCHE, the approach using a coil-type pipe has been proposed. Zhang et al. proposed that the energy pile technology is needed to reduce the installation cost of GCHE. They also pointed out that the energy pile applying spiral coils has a large heat transfer area compared to the existing U-shaped GCHE, and that it is thermally efficient [26]. Cui et al. reported that the application of the spiral coil to the pre-stressed high-strength concrete (PHC) pile increases the heat transfer efficiency [27]. Man et al. also performed numerical analysis and demonstrated that the coil-type GCHE has higher heat transfer efficiency than the U-shaped GCHE [28]. Most GCHEs using spiral coils, however, are installed vertically. Few studies that compared and evaluated the performances of GCHEs when installed horizontally under the same conditions have been reported.

In the previous study by the authors, the building-integrated coil-type GCHE, which was installed vertically on the building foundation, was introduced [29]. The field measurement was conducted to analyze the thermal performance in summer. The performances were found to be satisfactory considering the installation cost. Further studies were needed, however, for the various installation methods of the GCHE. Also, the thermal performance should be analyzed based on the annual weather condition.

In this study, an experiment and computer simulations were performed, and the thermal performance of the coil-type GCHE when applied to the foundation (vertical installation) and bottom (horizontal installation) of the same building was analyzed. The effective thermal conductivity of GCHE was measured to analyze its basic thermal performance. The electric power consumptions of the vertical and horizontal GCHE systems for cooling were also analyzed through a field experiment, using an experimental house in summer. Based on the measurement results, computer simulation was validated under the same weather conditions.

After the validation, computer simulation was conducted to analyze the annual heating/cooling performance under the annual weather conditions, and the return-on-investment (ROI) was calculated. Quantitative analysis was performed with regard to the thermal performance and economics of the two kinds of coil-type GCHE applied to building structures.

The building-integrated coil-type GCHE can be used when it is difficult to prepare an additional land for the GCHE in urban buildings. In addition, it can be installed under building parking lots. Both of these cases are advantageous for construction cost savings because GCHE is installed during building construction.

2. Outline of the coil-type GCHE

2.1. Coil-type GCHE

The ground-coupled heat pump (GCHP) generally consists of a GCHE, a heat pump, and peripheral equipment. The GCHE, which exchanges heat with the underground, has a very large impact on the performance of the GCHP. Although there are several installation methods of the coil-type GCHE, this study focused on the GCHE that has been used at the foundation or bottom of a building.

Table 1
Specifications of the vertical and horizontal GCHEs.

Type	Vertical GCHE	Horizontal GCHE
Fluid flow rate (l/min)	22	23.5
Length (m)	15	15
Maximum depth (m)	15	1.5
Pipe length (m)	196	
Pipe material	Polybutylene	
Pipe diameter (mm)	25	
Grouting material	Coarse sand	

2.2. Installation methods

To evaluate the various thermal properties and performances of the coil-type GCHE installation methods in this study, two cases were selected: (1) when the coil-type GCHE is installed vertically in the PHC pile (Fig. 1(a); hereinafter, “vertical GCHE”); and (2) when the coil-type GCHE is installed horizontally at the bottom of the building (Fig. 1(b); hereinafter, “horizontal GCHE”). The GCHEs were installed at the experimental building (Fig. 2(a)).

The PHC pile for the vertical GCHE is installed at the building foundation and plays a role in supporting the building. It is one of the most commonly used piles for the building foundation. The PHC pile presented in this study was 15 m long and had a 0.34 m inside diameter and a 0.5 m outside diameter. As shown in the figure, the PHC pile was a hollow-type pipe. A PB (polybutylene) pipe was installed in the hollow portion in the coil form for exchanging heat with the underground. The total length of the PB pipe was 196 m. Coarse sand was used as a grouting material. As the PHC-pile-integrated GCHE has no separate digging process, it can reduce the construction cost when applied to a building.

In the case of the horizontal GCHE, which is generally installed 1.5 m deep at the bottom of the concrete foundation, a PB pipe with the same size as the vertical GCHE (15 m long and with a 0.34 m inside diameter) was installed horizontally in the coil form. It was placed in the trench at the bottom of the building and was covered with coarse sand.

To avoid frozen pipes, 20% ethylene glycol solution was used as a circulating fluid of GCHE. The specifications of the vertical/horizontal GCHEs are listed in Table 1. The vertical and horizontal GCHEs in the study were designed to have the same fluid flow rates. In the experiment, however, the flow rates of the GCHEs were slightly changed as listed in Table 1. The difference of the fluid flow rate was only 6.4%, which was ignorable for the initial performance analysis.

2.3. Total GCHE system

The schematic diagram of the entire GCHE system is shown in Fig. 2. The GCHE was installed in the experimental building located in Songdo (latitude: 3722.80N; longitude: 12,640.25E), Incheon, South Korea. The system consisted of the GCHE, header, heat pump, buffer tank, and other equipment. The collected heat was used through the radiant cooling/heating system. The vertical and horizontal GCHEs were connected with one header and could be turned on/off through the valve. Thus, the vertical and horizontal GCHEs could not be operated simultaneously. This is because the GCHE was designed for experimental purposes and for measuring the thermal performance.