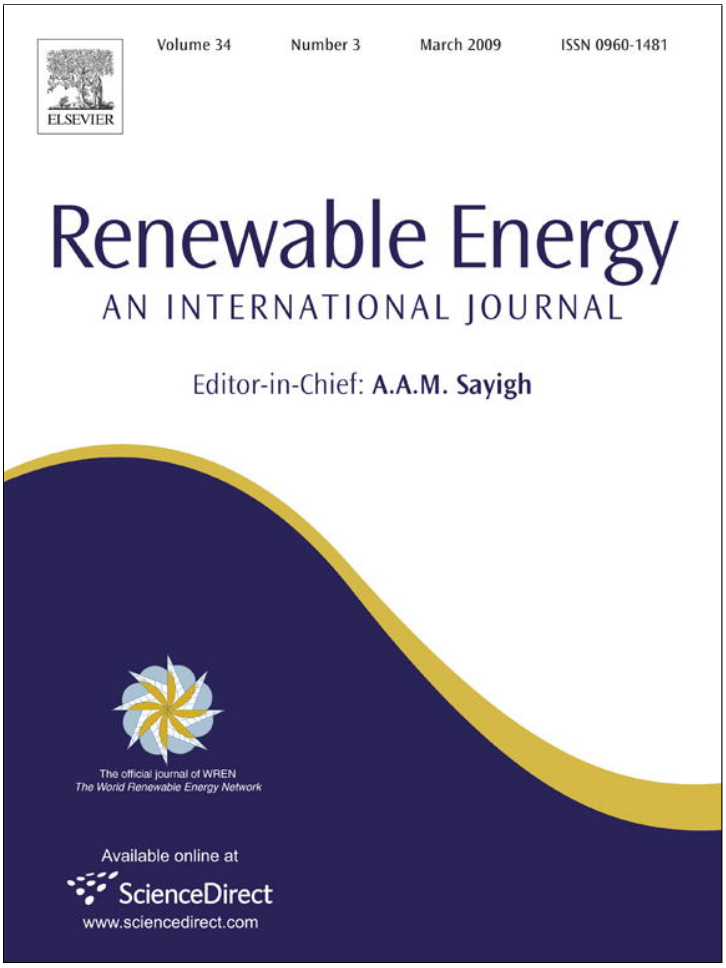
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Cooling performance of a vertical ground-coupled heat pump system installed in a school building

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ABSTRACT

This paper presents the cooling performance of a water-to-refrigerant type ground heat source heat pump system (GSHP) installed in a school building in Korea. The evaluation of the cooling performance has been conducted under the actual operation of GSHP system in the summer of year 2007. Ten heat pump units with the capacity of 10 HP each were installed in the building. Also, a closed vertical typed-ground heat exchanger with 24 boreholes of 175 m in depth was constructed for the GSHP system. To analyze the cooling performance of the GSHP system, we monitored various operating conditions, including the outdoor temperature, the ground temperature, and the water temperature of inlet and outlet of the ground heat exchanger. Simultaneously, the cooling capacity and the input power were evaluated to determine the cooling performance of the GSHP system. The average cooling coefficient of performance (COP) and overall COP of the GSHP system were found to be ~8.3 and ~5.9 at 65% partial load condition, respectively. While the air source heat pump (ASHP) system, which has the same capacity with the GSHP system, was found to have the average COP of ~3.9 and overall COP of ~3.4, implying that the GSHP system is more efficient than the ASHP system due to its lower temperature of condenser.

1. Introduction

As the problem of the fossil fuel depletion has been arisen, the needs for the renewable energy have significantly increased. Among the various renewable energy systems, ground heat source heat pump (GSHP) systems have been spotlighted as an efficient building energy system because it occupies less space compared to any conventional building HVAC systems so that the equipment rooms related to HVAC system can be greatly scaled down. While the conventional vapor compression heat pump system uses outdoor air as the heat source, GSHP system employs the ground heat source, which has the advantage of more stable temperature ranges. Also the ground temperature is generally higher than atmosphere in winter season, and it is lower than atmosphere in summer season so that GSHP system takes advantage of using the energy source generated from the ground heat, which can provide higher energy efficiency than the conventional vapor compression system. Therefore, GSHP system has great potentials for energy reduction in building air conditioning and reducing CO_2 emissions as the Kyoto Protocol adopted in 1997 [1–3].

GSHP system uses the ground temperature as a heat source in a heating mode and a heat sink in a cooling mode, respectively. In the cooling mode, GSHP system absorbs heat from the conditioned space (i.e. building) and discharges it to the ground through a ground heat exchanger while air source heat pump (ASHP) system discharges heat to outdoor air. Therefore, the COP of ASHP system is generally confined to the limited value strongly dependent to the outdoor temperature. However, the water circulated through the ground heat exchanger is used as the heat sink of the condenser, in which the temperature is lower than outdoor air by 10 °C approximately so that it can be possible for GHSP system to have higher COP than ASHP system.

Many researchers reported the comparison of calculated performance between ASHP and GSHP system [4–6]. These studies showed that GSHP is better energy-efficient system than ASHP since the temperature of the ground is more effective condition to operate the outdoor unit in both the cooling and heating modes of the heat pump system. The performance of the GSHP system can be influenced by many parameters such as the depth, length, and type of the ground heat exchanger, and also the flow rate of circulating water through the ground heat exchanger [7–11]. Hearly et al. [12] reported the optimal performance conditions of GSHP system based on computer simulation technique. However, all of those

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previous researches evaluated the performance of GSHP system based on laboratory scale or residential house scale tests. In these small scale tests or applications, they set the components of GSHP system such as compressors, heat exchangers, and pumps. Therefore, the COP of GSHP system was lower than the conventional heat pump system, and then they suggested that the several important design practices must be taken into account to achieve the higher performance. Doherty et al. [9] compared the heating and cooling performances of GSHP system which had the three different types of the ground heat exchanger such as the vertical ground loop, the horizontal slinky loop, and the tank coil loop.

In this work, the vertical type ground-coupled heat pump system was installed in a university building. To obtain more efficient GSHP system in view of total energy consumption, the compressor was controlled by an inverter to meet the need of cooling load under actual GSHP operating conditions. To obtain the stable temperature of circulating water in the ground heat exchanger, the boreholes were drilled down to 175 m under the ground. The parameters such as the relative subterranean temperatures to outdoor air temperatures, thermal diffusion characteristics of the ground heat exchanger, and the temperatures of circulating water were monitored. To evaluate the cooling performance, the COP of the GSHP system was determined by measuring the input power and cooling capacity.

2. Experimental setup and test method

To evaluate the performance of the GSHP system in this study, it was installed in the school building, located in Busan City in Korea (see Fig. 1). The building had total six floors, and the GSHP system provided the heating and cooling conditions in the first and second two floors, which has the total area of 1193 m^2.

Fig. 2 describes the system diagram of the GSHP system and the specifications of components are summarized in Table 1. Briefly, the GSHP system consisted of the water-to-refrigerant type outdoor units, the ground heat exchanger, and the indoor units. In this study, total 10 outdoor units (LRW-2900D, LG Electronics, Korea) were installed and each outdoor unit was composed of the water-to-refrigerant type heat exchanger, two compressors, an expansion device, and a four-way valve. One of the compressors was controlled by the inverter system in order to adjust power input for the compressor corresponding to the actual cooling load. It made the GSHP system more efficient by reducing power input at the partial cooling load conditions. Plate heat exchanger was used as a condenser which exchanged the heat between water circulating through the ground heat exchanger and refrigerant in the heat pump system. One can operate this GSHP system either in the heating mode or in the cooling mode by controlling the refrigerant flow direction with the four-way valve. Here, in our approach, we fixed our GSHP system in the cooling mode. One outdoor unit had the cooling capacity of 27 kW and covered three or four indoor units (LRD-N725T, LG Electronics, Korea) which had the cooling capacity of 7.2 kW.

Fig. 1. The schematic of university building, where the GSHP system was installed (number of floors: 6, total area: 1193 m^2).

High density polyethylene pipes were prepared as the ground heat exchanger. Water was circulated through the polyethylene pipes by pumps (ILP 100–250, Hyosung-Ebara Co., Korea) to extract the geothermal energy as a heat source or a heat sink. In the cooling mode, the heat obtained from the conditioned space (i.e. building) was dissipated to the ground through the ground heat exchanger. The ground heat exchanger was the closed vertical type (U-shaped) and had 24 boreholes of 175 m in depth. The distance between the boreholes was ~5 m.

We selected an outdoor unit and its corresponding four indoor units to investigate the cooling performance of GSHP system (see Fig. 2). Each indoor unit was installed in an office space which has the area of 43.2 m^2, respectively. To investigate the characteristics of the heat transfer from the ground heat exchanger to the ground, T-type thermocouples were installed on the pipe of the ground heat exchanger, 1.5 m and 2.5 m away from the surface of the pipes under the ground in order to measure the subterranean temperatures which might be varied with the temperature of the ground heat exchanger. Indoor/outdoor temperature and relative humidity were also monitored to determine the cooling capacity of the indoor units. The cooling capacity of indoor unit is the difference of the enthalpies between the inlet and outlet of the indoor unit. The power consumption rate of heat pump system was measured with a wattmeter (WT1600, Yokogawa, Japan). We also installed another wattmeter (MWT-340S, Micronics, Korea) to measure the total power consumption of the GSHP system, including energy consumed by the heat pump and water circulating pumps. All the information regarding temperature, relative humidity, and power consumption rate were periodically recorded with a data acquisition system (34970A, Agilent).

3. Results and discussion

3.1. Subterranean temperature profile

Fig. 3 shows the daily averaged subterranean temperature at the depth of 2.5–30 m and outdoor temperature measured during March 21–September 30, 2007. At the depth of 2.5 m and 5 m, the temperature was greatly influenced by the outdoor temperature. However, the subterranean temperature below 10 m in depth was observed to keep constant around ~16 ± 2 °C regardless of the abrupt change in the outdoor temperature.

Fig. 4 shows the average temperature of circulating water, the surface temperature of the ground heat exchanger, and the subterranean temperatures at 1.5 m and 2.5 m away from the ground heat exchanger at the depth of 10 m. The temperature of circulating water was increased up to ~22 °C as the outdoor temperature increased so that the cooling load increased. The temperature of circulating water strongly affected the surface temperature of the ground heat exchanger, while the underground temperatures 1.5 m and 2.5 m apart from the ground heat exchanger appeared to be constant regardless of the circulating water temperature. It implies that a U-tube of the ground heat exchanger was not affected by the heat transfer from another U-tube of the ground heat exchanger since the distance between the U-tubes was sufficiently separated with the distance of ~5 m.

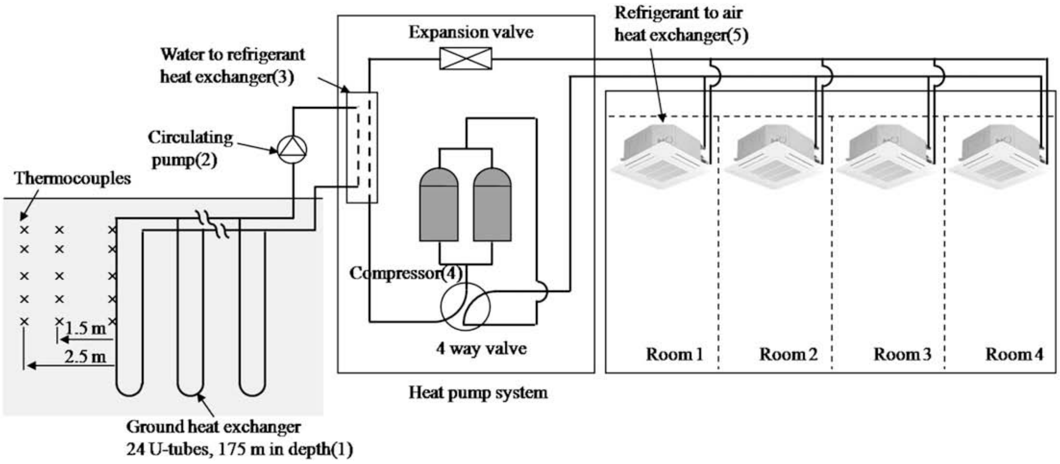

Fig. 2. Schematic diagram of ground source heat pump system with a vertical closed type heat exchanger.

3.2. Cooling performance of the GSHP system

We selected the day, August 16, which showed the highest outdoor temperature and cooling load, to estimate the daily cooling performance of the GSHP system. Fig. 5 first shows the variation of circulating water temperature at the inlet and outlet of the outdoor unit of the GSHP system. At that time, the average outdoor temperature was ~32.7 °C and the inlet temperature of circulating water was maintained almost constant at ~21.5 °C while the outlet temperature of circulating water was increased with increasing the cooling load. The circulating water temperature came from the ground heat exchanger was much lower than the temperature of outdoor air, which acted as the heat sink of the air source heat pump system generally in the summer season.

The cooling performance is represented by the coefficient of performance (COP) which is generally defined as follows,

$$\mathrm{COP}_{\mathrm{HP}} = \frac{\dot{Q}_{\mathrm{sl}}}{\dot{W}_{\mathrm{C}}} \tag{1}$$

where $\dot{Q}_{\mathrm{sl}}$ is the heat removal rate from indoor units and $\dot{W}_{\mathrm{C}}$ is the power consumption rate spent by the compressor. However, in this work, we defined a new COP to evaluate the cooling performance of overall system, including heat pump, water circulating pumps, and fans in both the outdoor and indoor unit,

$$\mathrm{COP}_{\mathrm{overall}} = \frac{\dot{Q}_{\mathrm{sl}}}{\dot{W}_{\mathrm{C}} + \dot{W}_{\mathrm{P}} + \dot{W}_{\mathrm{F}}} \tag{2}$$

where $\dot{W}_{\mathrm{P}}$ and $\dot{W}_{\mathrm{F}}$ are the rate of power consumed by water circulating pumps and fans, respectively. The heat transfer rate, $\dot{Q}_{\mathrm{sl}}$, was calculated by the mass flow rate and enthalpy difference of the air between inlet and outlet of indoor units, which had the evaporators. To determine the mass flow rate and enthalpy of air, the volumetric flow rate, temperatures, and relative humidity were measured.

Fig. 6 represents the daily cooling capacity, power consumption rate, and COP of heat pump system on August 16, 2007. It was observed that the cooling load varied with time and

Table 1
Specification of the components consisting of the GSHP system

Main circuit	Component	Specification
Ground coupling circuit	Ground heat exchanger	Vertical closed U-bend type Borehole diameter: 150 mm Internal diameter of U-bends: 42 mm Borehole depth: 175 m, material: polyethylene
	Circulating pump	Manufacturer: Hyosung-Ebara. Co. Model: ILP 100–250 Volumetric flow rate: 45–130 m^3/h Power: 7.5 kW, speed: 1750 rpm
Heat pump circuit (Manufacturer: LG Electronics; model: LRW-N2900D)	Heat exchanger	Manufacturer: SWEP capacity: 32.6 kW Type: plate heat exchanger
	Compressors	Manufacturer: Matsushita type; Rotary Refrigerant: R-410A: 1. Inverter type: 4.2 HP (3.1 kW) 2. Fixed type: 4.2 HP (3.1 kW)
	Indoor unit	Manufacturer: LG Electronics Model: LRD-N725T, cooling capacity: 7.2 kW Air flow rate: 17 m^3/min

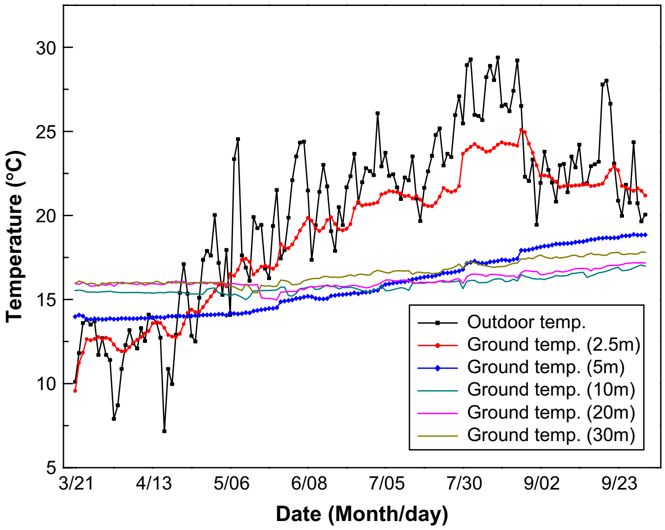

Fig. 3. The evolution of daily average subterranean temperature and outdoor air temperature from March 21 to September 30, 2007.

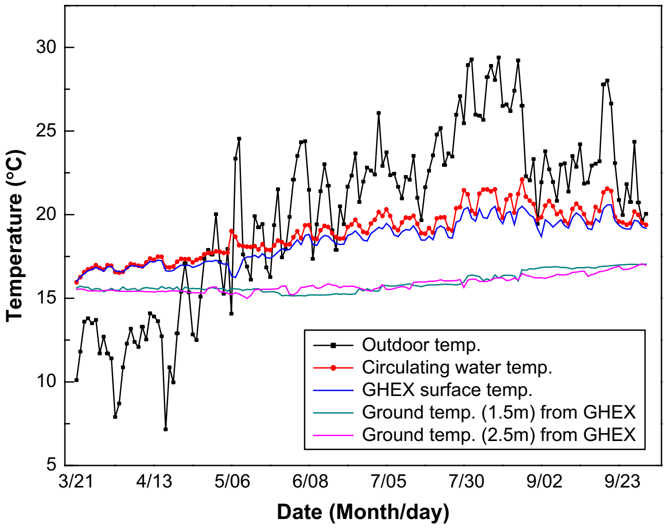

Fig. 4. The evolution of daily average temperatures of outdoor air, circulating water, surface of ground heat exchanger, and subterranean temperatures apart from ground heat exchanger.

the average value of cooling load was observed to be ∼19.1 kW which was only the 65% of the full cooling capacity (27 kW) of the GSHP system. Conclusively, the COP of the heat pump system was calculated to be ∼8.3 at the 65% partial cooling load condition. However, the overall COP of the heat pump system was calculated to be ∼5.9 at the 65% partial cooling load condition.

3.3. Comparison of cooling performance of GSHP and ASHP systems

In the cooling mode of the general heat pump system, the heat obtained from the indoor unit is dissipated into outdoor air at the condenser. Therefore, the COP of ASHP system is strongly dependent to the outdoor temperature. Unlike ASHP system, however, GHSP system possibly has higher COP than ASHP system because the water circulated through the ground heat exchanger is used as the heat sink of the condenser, in which the temperature is lower than outdoor air by 10 °C approximately.

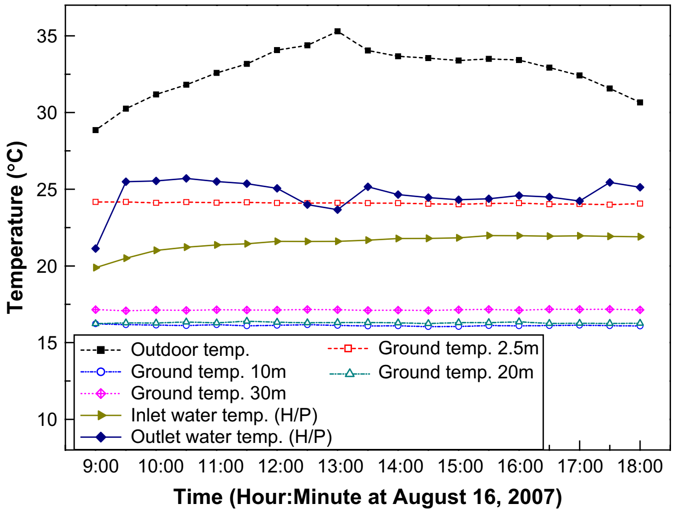

Fig. 5. Inlet and outlet temperature of water circulated through ground heat exchanger.

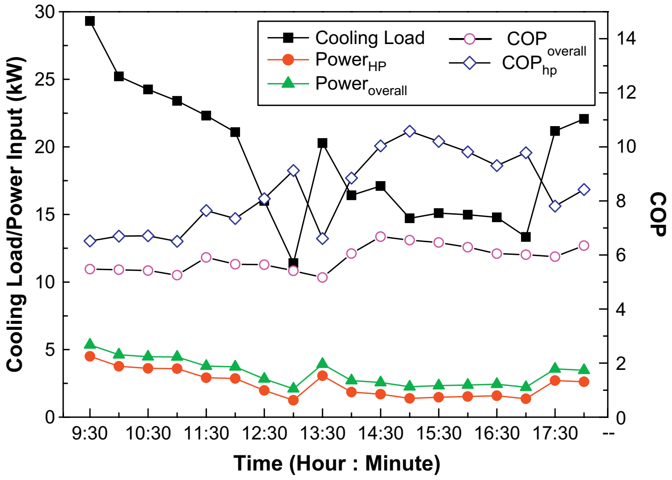

Fig. 6. The cooling capacity, power consumption rate, and COP of GSHP system at August 16, 2007.

Table 2 represents the performance of the GSHP system and the ASHP system. Here, the total cooling capacity of the ASHP system (LRP-V2905B, LG Electronics, Korea) was same with that of GSHP system installed in the building tested. The ASHP system operated at the cooling load of 60% is shown in Table 2. One can see that the COP_{HP} of the GSHP (i.e. $COP_{HP} = \sim 8.3$) is ∼210% larger than that of ASHP (i.e. $COP_{HP} = \sim 3.9$). The higher COP of GSHP system than ASHP system is attributed that the reservoir temperature at the condenser is much lower in the GSHP than in the ASHP system. It makes the heat pump cycle to operate in lower discharge pressure and temperature of the compressor. The GSHP and ASHP system have the discharge pressure of 1620 kPa and 2731 kPa, respectively, while they have the same suction pressure in compressor (see Table 2). Therefore, the power input in the compressor of the GSHP system was significantly reduced compared with the compressor of the ASHP system. Here it is noted that the overall COP of the GSHP system (i.e. overall $COP_{HP} = \sim 5.9$) is higher than that of the ASHP system (i.e. overall $COP_{HP} = \sim 3.4$) by only 74%. It is because the GSHP system used the additional power for pumps to circulate water through the ground heat exchanger.

Generally, the cycle efficiency of the heat pump system is strongly affected by the condensing temperature in a cooling mode. In other words, the heat pump system is more efficient as the condensing temperature is decreased. It is because the heat pump system consumes less power by employing the condensing temperature decreased. Fig. 7 describes the simplified pressure–enthalpy diagram of the cycles for the comparison of both the GSHP and ASHP systems. As one can see in Fig. 7, the smaller amount of power is spent in the compressor of the GSHP system compared with ASHP system because the temperature of the condenser is shown to be much lower, indicating that the GSHP system conduct much better performance than ASHP system.

Table 2
Comparison between GSHP and ASHP system at the same cooling load conditions

		GSHP	ASHP
Condenser	Average circulating water temperature (°C)	21.5	–
	Outdoor air temperature (°C)	32.7	35
Compressor	Discharge pressure (kPa)	1620	2731
	Suction pressure (kPa)	956	956
Cooling performance	COP_{HP}	8.3	3.91
	$COP_{overall}$	5.9	3.37

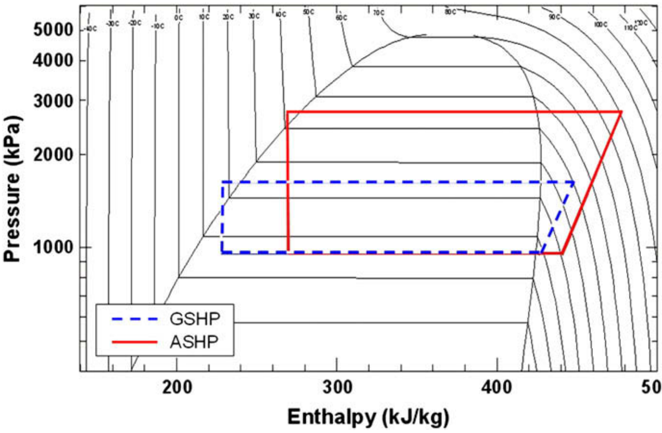

Fig. 7. Simplified pressure–enthalpy diagram of GSHP and ASHP cycle.

4. Conclusions

In this work, the GSHP system with the ground heat exchanger of the vertical closed type was designed and constructed for a university building air conditioning. The COP_{HP} and $COP_{overall}$ of the GSHP system were determined to estimate the daily performance of the cooling system operated. It was observed that the COP_{HP} and $COP_{overall}$ of GSHP system were ~8.3 and ~5.9, respectively. The $COP_{overall}$ of GSHP system was found to be lower than COP_{HP} because $COP_{overall}$ included the energy consumed by GSHP system with additional water circulating pumps and fans. Also, these COP values were compared with the COP of ASHP system, which had the same cooling capacity with our GSHP system. We observed that the $COP_{overall}$ of the GSHP system was higher than that of ASHP system by 74%. It is presumably because the condensing temperature of heat pump cycle was dropped by almost 10 °C in the GSHP system and it made the compressor to spend less power. This implies that the GSHP system has the potential advantages over the conventional building cooling systems in view of energy efficiency and overall operating cost. In this GSHP system, the subterranean temperature was observed to be almost constant throughout the year, presumably indicating that it is also able to be efficiently operated as a heating system for the building in a winter season.

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