

Heating performance of a ground source heat pump system installed in a school building

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ABSTRACT: This paper presents the heating performance of a water-to-refrigerant type ground source heat pump system (GSHP) installed in a school building. The evaluation of the heating performance has been conducted under the actual operating conditions of GSHP system in the winter. Ten 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. For analyzing the heating 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 heating capacity and the input power were evaluated for determining the heating performance of the GSHP system. The average heating coefficient of performance (COP) of the heat pump was found to be 5.1 at partial load of 47%, while the overall system COP was found to be 4.2.

Keywords: Ground source heat pump(GSHP), Water-to-refrigerant, Heating performance, Coefficient of performance(COP), Air source heat pump(ASHP)

NOMENCLATURE

COP = coefficient of performance

$\dot{Q}$ = heat transfer rate (kW)

$\dot{W}$ = power consumption rate (kW)

Subscripts

c = compressor

f = fan

HP = heat pump

p = pump

1. INTRODUCTION

The growing awareness and popularity of the ground source heat pump (GSHP) system have had the most significant impact on renewable energy 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, the 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 the winter season, and it is lower than outdoor air in summer season so that the 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, the GSHP system has great potentials for energy reduction in building air conditioning and reducing CO₂ emissions as the Kyoto Protocol was adopted in 1997 [1-4].

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

It has been reported that the comparison of the calculated performance between the ASHP system and the GSHP system [5-7].

These studies show that the GSHP is better energy-efficient system than ASHP since the temperature of the ground is more effective condition to operating the outdoor unit in the cooling and heating mode of the heat pump system than outdoor air. 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 [8-12]. Hearly et al.(1997) reported the optimal performance conditions of the GSHP system using computer simulation technique. However, all of those previous researches evaluated the performance of the GSHP system based on laboratory scale or the residential house scale tests. In these small scale tests or applications, they set the components of the GSHP system such as compressors, the heat exchangers, and pumps. Therefore, COP of the system is lower than the conventional heat pump system and they suggested that the several important design practices must be taken into account to achieve the higher performance [13]. Doherty et al. (2004) compared the heating and cooling performances of the GSHP systems 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. Also this research showed that the CO₂ savings and the payback period of the GSHP system compared with the gas heating and the electrical heat in heating mode.

In this study, the vertical type ground-couple heat pump system is installed in a university building. For obtaining more efficient the GSHP system in view of total energy consumption, the compressor in the GSHP system was controlled by an inverter to meet the heating load under the actual conditions. To obtain 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 ground temperatures according

to outdoor air temperatures, thermal diffusion characteristics of the ground heat exchanger and the temperatures of circulating water were investigated. As a heating performance, the COP of the GSHP system was determined by measuring the input power and heating capacity.

2. EXPERIMENTAL SETUP AND TEST METHOD

To evaluate the performance of the GSHP system, it was installed in the school building, located in Busan City in Korea (see a photograph shown in Fig. 1).

The building had totally six stories, and the GSHP system provided the heating and cooling conditions in the first and second floors, which has total area of 1,193m².

Fig. 2 describes the system diagram of the GSHP system and the specifications of the components were summarized in Table I. Briefly, the GSHP system consisted of the water-to-refrigerant type outdoor units, the ground heat exchanger, and the indoor units. In this study, totally ten 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 4 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 heating load.



Fig 1: Building of the ground source heat pump system installed.

Table I: Specification of the components consisting of the GSHP system.

Main circuit	Component	Specification
Ground coupling circuit	Ground heat exchanger (1)	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: 7.5kW, 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: Matsushida 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, Heating capacity: 8.1 kW Air flow rate: 17 m ³ /min

It made the GSHP system more efficient by reducing power input at the partial load conditions. Plate heat exchanger was used as a evaporator 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 4 way valve. In this study, we fixed our the GSHP system in the heating mode. One outdoor unit had the heating capacity of 32.6 kW and covered four or three indoor

units (LRD-N725T, LG Electronics, Korea) which had the heating capacity of 8.1 kW.

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 heating mode, the heat removed from the conditioned space (i.e. building) was absorbed by 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 heating performance of GSHP system (see Fig. 2). Each indoor unit was installed in an office space which has the area of 43.2 m², respectively. To investigate the characteristics of the heat diffusion 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 ground temperatures which might be varied with the temperature of the ground heat exchanger.

Indoor/outdoor temperature monitored to determine the heating capacity of the indoor units. Power consumption rate of the 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 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 Ground temperature profile

Fig. 3 shows the daily averaged the ground temperature at the depth of 2.5 ~ 20 m and outdoor temperature measured during October 1, 2007. ~ March 31, 2008. At the depth of 2.5 m and 5 m, the temperature was greatly influenced by the outdoor temperature. However the ground temperature below 20 m in depth was observed to keep constant around $\sim 16 \pm 2^\circ\text{C}$ regardless of abrupt change in the outdoor temperature.

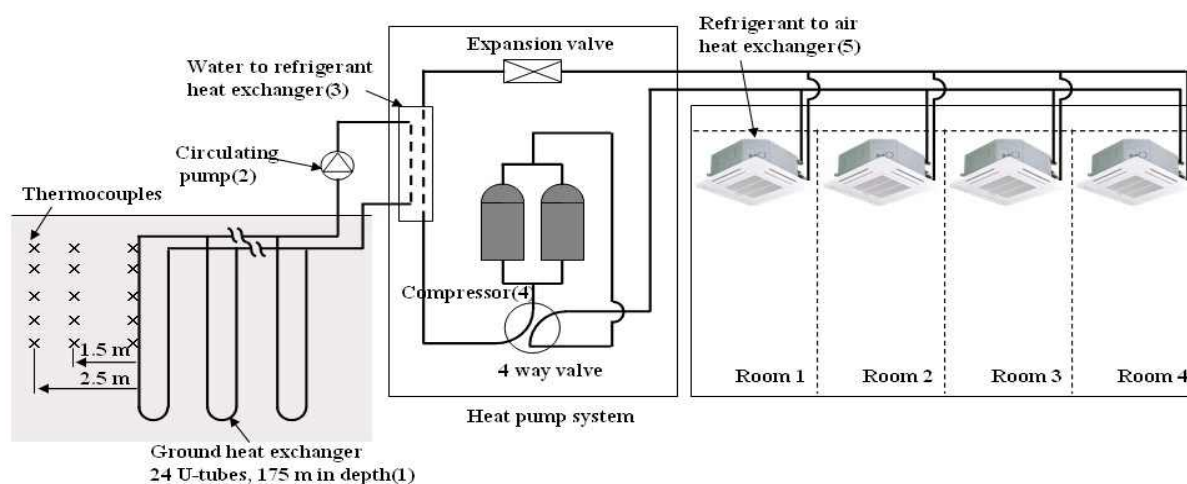


Fig 2: System diagram of the ground source heat pump.

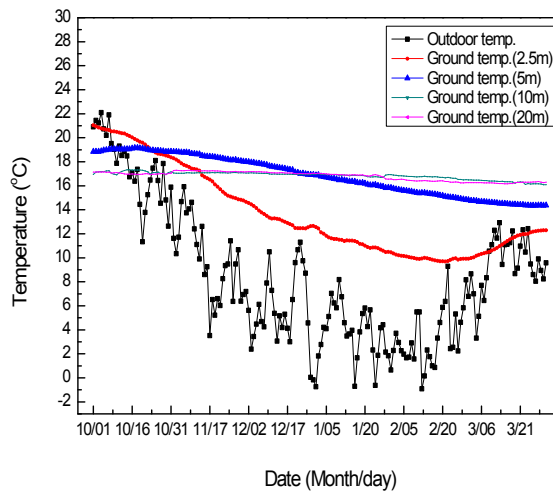


Fig 3: The daily average ground temperature and outdoor temperature variations from October 1 to March 31, 2008.

Fig. 4 shows the average temperature of circulating water, the surface temperature of the ground heat exchanger, and the ground temperatures at 1.5 m and 2.5 away from the ground heat exchanger at the depth of 10 m. The temperature of circulating water was decreased up to ~ 14.1 °C as the outdoor temperature decreased so that the heating load increased.

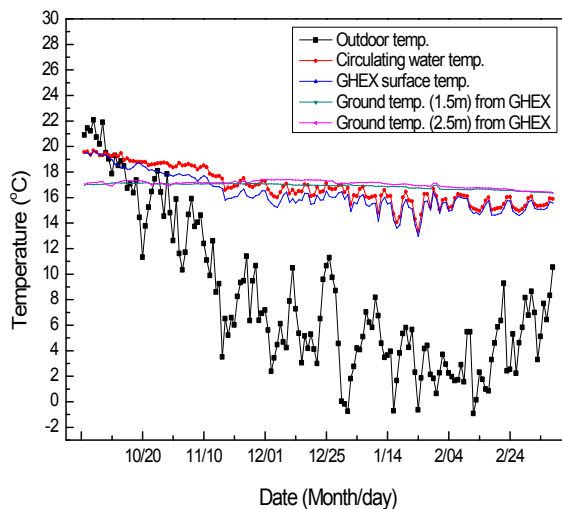


Fig 4: The daily average outdoor temperature, inlet water temperature and outlet water temperature of the ground heat exchanger (GHE) from October 1 to March 31, 2008.

The temperature of circulating water strongly affected on the surface temperature of the ground heat exchanger, while the ground temperatures 1.5 m and 2.5 m apart from the ground heat exchanger appeared constant regardless of the circulating water temperature. It implies that an U-tube of the ground heat exchanger was not affected by the thermal diffusion of the another U-tube of the ground heat exchanger.

3.2 Heating performance of the GSHP system

We select the day, January 8, 2008, which showed low outdoor temperature and heating load, to estimate the daily heating 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 ~ 6.3 °C and the inlet temperature of circulating water was maintained almost constant at ~ 15.3 °C while outlet temperature of circulating water was increased with decreasing heating load.

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

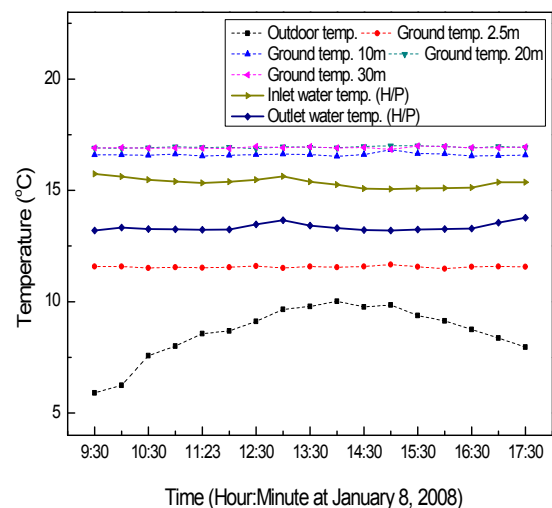


Fig 5: The variation of the water temperature at the condenser inlet and outlet of the ground source heat pump.

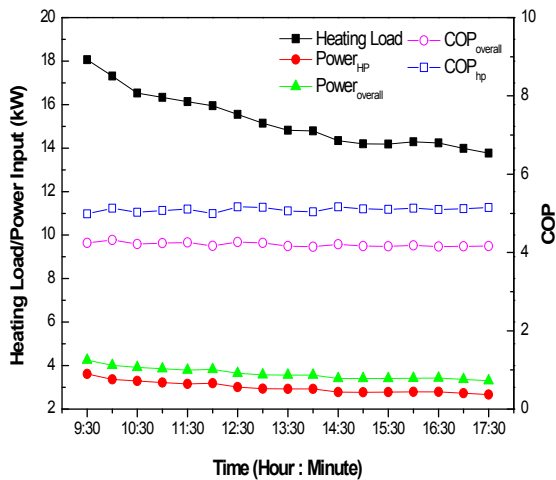


Fig 6: Heating capacity, power consumption rate and COP of the GSHP system at January 8, 2008.

$$COP_{HP} = \frac{\dot{Q}}{\dot{W}_C} \quad (1)$$

where $\dot{Q}$ is the heat obtained from indoor units and $\dot{W}_C$ is the power consumption rate spent by the compressor. However, in this work, we defined a new COP to evaluate the heating performance of overall system including water circulating pumps and fans in the indoor unit .

$$COP_{overall} = \frac{\dot{Q}}{\dot{W}_C + \dot{W}_P + \dot{W}_F} \quad (2)$$

where $\dot{W}_P$ and $\dot{W}_F$ are the power consumed by water circulating pumps and fans, respectively.

Heat transfer rate $\dot{Q}$ was calculated by the air flow rate and enthalpy difference of air between inlet and outlet of indoor units which had the condensers. To determine the air flow rate and enthalpy of air.

Fig. 6 represents the daily heating capacity, power consumption rate, and COP of heat pump system on January 8, 2008. Heating load varies with time and the average value of heating load was observed to be 15.3 kW which was only the 47% of the full heating capacity (32.6 kW) of the GSHP system. Conclusively, the COP of the

heat pump system was calculated to be ~5.1 at the partial heating load condition. However, the overall COP of the heat pump system was calculated to be ~4.2.

3.3 Comparison of heating performance of the GSHP with the ASHP

In the heating mode of the general heat pump system, the heat removed from the indoor unit was absorbed into outdoor air at the evaporator. Therefore, the COP of the ASHP system confines to the limited value strongly dependent to the outdoor temperature. However, the water circulated through the ground heat exchanger is used as the heat source of the evaporator, which temperature is higher than outdoor air by 9 °C approximately so that it can be possible for the GHSP system to have higher COP than the ASHP system.

Table II represents the performances of the GSHP system and the ASHP system according to the operating conditions. Here, the total heating capacity of the ASHP system (LRP-V2905B, LG Electronics, Korea) was same with that of the GSHP system installed in the building.

Table II: Comparison between the GSHP and the ASHP system at the same heating load conditions.

		GSHP	ASHP
Evaporator	Average circulating water temperature (°C)	15.34	-
	Outdoor air temperature (°C)	6.28	7
Compressor	Discharge pressure (kPa)	2850	2892
	Suction pressure (kPa)	1060	634
Heating performance	COP _{HP}	5.1	3.8
	COP _{overall}	4.2	3.2

The ASHP system operated at the heating load of 50% was shown Table 2. One can see that the COP_{HP} of the GSHP (i.e. $COP_{HP}=5.1$) is ~135% larger than that of ASHP (i.e. $COP_{HP}=3.8$). However, the overall COP of the GSHP system is higher than the ASHP system by only 31% because the GSHP system used the additional power for pumps to circulate water through the ground heat exchanger.

The reason why the GSHP system has higher COP than the ASHP is that the reservoir temperature at the evaporator is much higher in the GSHP than in the ASHP system. It makes the heat pump cycle to operate in higher suction pressure and temperature of the compressor.

The GSHP and the ASHP system have the suction pressure of 1060 kPa and 634 kPa, respectively, while they have same the discharge pressure in compressor (see Table II). Therefore, the power input in the compressor of the GSHP system was reduced compared with the compressor of the ASHP system.

Fig. 7 describes the simplified pressure-enthalpy diagram of the cycles for the comparison of both the GSHP and the ASHP systems. As one can see in Fig. 7, the smaller amount of power can be spent in the compressor of the GSHP system because the temperature of the evaporator can be increased.

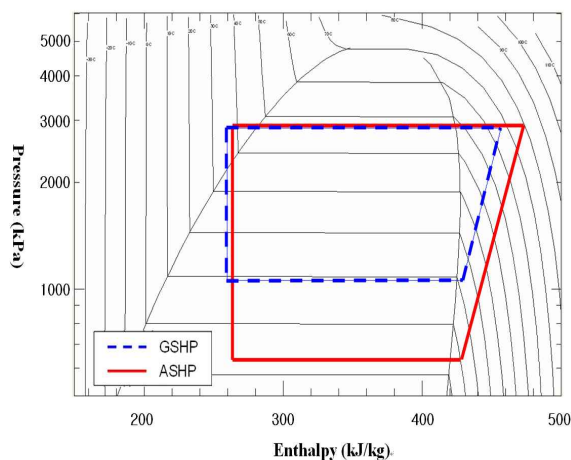


Fig 7: Simplified pressure-enthalpy diagram of GSHP and ASHP cycle.

4. CONCLUSION

In this work, the GSHP system with the ground heat exchanger of the vertical closed type is designed and constructed for the building air conditioning. For the preliminary study, the ground temperatures are measured. It is shown that the temperatures are maintained almost to be constant below 10 m in the ground within 1.5 °C. Also, heat diffusion characteristic is investigated and we conclude that a closed loop of the ground heat exchanger is not affected by the thermal diffusion from the adjacent closed loop of the ground heat exchanger.

COP_{HP} and $COP_{overall}$ of the GSHP system is determined to estimate the daily performance of the system operating in a selected day. This work represents that COP_{HP} is 5.1 and $COP_{overall}$ is 4.2. $COP_{overall}$ is lower than COP_{HP} because $COP_{overall}$ includes the energy consumed by water circulating pumps and fans. Also, these COP values are compared with COP of the ASHP system. $COP_{overall}$ of the GSHP system is higher than the ASHP system by 31% because the evaporating temperature of heat pump cycle can be dropped by almost 10 °C in this GSHP system and it makes compressor to spend less power. This conclusion represents that the GSHP system has some advantages over the conventional building heating systems, especially with regard to efficiency, energy cost, and overall operating cost.

To determine whether the GSHP system is effective or not, it is necessary to evaluate the life cycle cost (LCC) and to consider the payback time. This topic must be investigated in our future works.

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