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Temperature distribution and performance of ground-coupled multi-heat pump systems for a greenhouse

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A B S T R A C T

The primary objective of a greenhouse is to produce good plant-growth conditions such as temperature and humidity. One of the hot issues for the greenhouse is to provide an appropriate heating system which can achieve favorable temperature condition and save energy. In this study, the performance of a ground-coupled multi-heat pump system for the greenhouse heating was investigated. The ground-coupled multi-heat pump system was composed of GLHX (ground loop heat exchanger) and multi-heat pump unit which had one outdoor unit and two or more indoor units. The temperature distribution within the greenhouse using the ground-coupled multi-heat pump system was represented relatively uniform comparing to when the conventional heating system and GCHP system were adopted, because the capacity of each indoor unit could be changed linearly according to the variation of load. The temperature difference between the maximum and minimum temperatures and the standard deviation of inside temperature for the greenhouse were 2.1 °C and 1.2 °C, respectively. It is necessary to develop the multi-heat pump unit which can be operated with high performance at relatively low temperature setting conditions. The system COP of the ground-coupled multi-heat pump unit decreased greatly at part load condition due to relatively high power consumption of the ground circulation pump. Therefore, it is suggested that a control algorithm of the ground circulation flow rate has to be developed to maximize energy saving by applying the ground-coupled multi-heat pump system to the greenhouse.

1. Introduction

From an economic point of view, the main objective of horticultural greenhouses is to advance the normal season production or to obtain a completely out-of season production, which corresponds with higher crop prices [1]. The most important parameters to be controlled inside a greenhouse are temperature, humidity and light [2]. Especially, optimization of air temperature in greenhouses is of particular importance in relation to plant-growth and development [3]. The conventional solution for this problem is the burning of some fossil fuel inside the greenhouse during dangerous freezing night. Since fuel prices are high, this option is very expensive, but it is necessary, considering the possibility of the complete destruction of plants. As an alternative, a ground-coupled heat pump (GCHP hereafter) system has been spotlighted as an efficient heating system, because it has great potentials for energy reduction in air conditioning and reducing CO_2 emissions [4–8].

Fujii [9] evaluated the increase in heat exchange rates resulting from the presence of flowing groundwater, using a 2D finite-difference numerical simulation model. Cui et al. [10] focused on the study of the transient heat transfer behavior of the ground loop heat exchanger (GLHX hereafter) in alternative modes in short-time scale. The FEM is used to analyze the temperature distribution in the borehole field. Esen et al. [11] developed a numerical model of heat transfer in the ground for determining the temperature distribution in the vicinity of the horizontal GLHX. They derived an analytical solution of the transient temperature response. Esen et al. [12] conducted an experimental study to assess the techno-economic performance of a GCHP system and air source heat pump system in hot and arid climate. The economic analysis clearly showed that GCHP systems were economically preferable to the air source heat pump system. Esen et al. [13] investigate the energetic and exergetic efficiencies of GCHP system with horizontal GLHXs as a function of depth trenches for heating season. The results showed that the energetic and exergetic

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Nomenclature

COP_{hp}	heat pump unit COP (coefficient of performance)
COP_{sys}	GCHP system COP (coefficient of performance)
C_p	specific heat [kJ/kg K]
$\dot{m}$	mass flow rate [kg/s]
Q_{ID}	heating capacity [kW]
Q_{OD}	heating absorption rate from the ground [kW]
T_i	inlet temperature [°C]
T_o	outlet temperature [°C]
W_{hp}	heat pump unit power consumption [kW]
W_{pump}	circulation pump power consumption [kW]

efficiencies of the system increased when increasing the ground temperature. Hamada et al. [14] clarified the effects of applying the energy pile system by using the friction piles of buildings as GLHXs and studied the field performance of an energy pile system for space heating. Li et al. [15] developed an experimental system with different types of U-vertical GLHXs in situ and carried out a study on the thermal performance of U-pipes with sandstone or cement backfills. The SCW (standing column well) system was found to have very important applications in commercial and industrial designs, since it requires shorter boreholes and gives more stable temperature, especially in regions of higher heating load [16]. The performance of the GCHP system can be influenced by many parameters such as the depth, length and type of the ground heat exchanger [17,18]. Many studies have been executed about the performance of GCHP systems according to the ground conditions [5,17,19].

Most previous studies were focused on the application of GCHP system with constant speed water-to-water heat pump unit for buildings. Studies have rarely been executed on the GCHP system employed in the greenhouse considering temperature distribution within the inside space of the greenhouse. In this paper, the performance of a GCHP system adopting water-to-air multi-type heat pump unit for the greenhouse was analyzed.

2. Design and description of the system

GCHP systems with vertical-type GLHXs were installed in a greenhouse located in the southern part of Korea. The total area of the greenhouse was 715 m^2. Fig. 1 shows the photograph of the greenhouse. The climate data for the calculation of heating load were obtained from the Meteorological Administration. The greenhouse load was calculated for the climate date from November to March. The maximum designed heating load was 87.5 kW calculated by the procedure of the reference [21].

The GCHP system was composed of heat pump units and GLHXs. In this study, closed-loop vertical-type GLHX was selected. The GLHX was designed by using GLD software [22]. This software is a commercial program having a high reliability for the design of GCHP systems. From the design results, HDPE (high density poly ethylene, SDR 11, 0.04 m) pipes with length of 150 m were installed. The system had 8 boreholes of diameter 150 mm, and the distance between boreholes was designed to be 6 m. Ethanol (concentration of 20%) was used to fill the HDPE pipes.

Two heat pump units using R410A as a refrigerant were installed in the site to cover the greenhouse load. The heat pump units adopted were water-to-air multi-heat pump units. Multi-heat pump unit means the system has one outdoor unit and two or more indoor units [23]. The outdoor unit and indoor unit of the heat pump were equipped with plate type heat exchangers for evaporator and fin-tube heat exchanger for condenser. Each outdoor unit

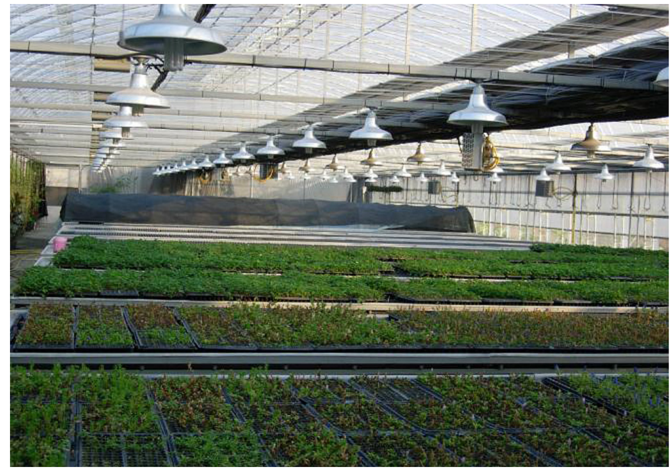

Fig. 1. Photograph of the greenhouse [20].

had a rated heating capacity of 53.5 kW. One outdoor unit of the heat pump in this study was connected to 7 indoor units together. The other outdoor unit was combined with 6 indoor units. All indoor units were the floor installed type and had the same rated capacity of 6 kW. The heat pump unit capacity could be changed by the variation of compressor speed according to the load variation. The outdoor units were installed at the mechanical room, and the indoor units were located inside the greenhouse. The detailed description for the GCHP system is shown in Table 1 and Fig. 2.

The heating operation performance of the GCHP system was measured. To investigate the characteristics of the GLHXs, RTD sensors (PT 100 Ω) with an accuracy of ±0.1 °C were installed on the surface of the HDPE pipe. To calculate the heating performance, temperatures were monitored at the selected locations using the RTD sensors, and the secondary fluid flow rate was also measured. A volumetric flow meter was installed to measure flow rate through the GLHE flow loop. The volumetric flow meter had an accuracy of ±0.2% of reading. Power consumption of the system was measured by using power meter with an accuracy of ±0.01% of reading. The uncertainty analysis of the system performance parameters such as the heating capacity and the COP was performed. The uncertainties of the heating capacity and the COP were calculated by using the Pythagorean summation discrete uncertainties. The overall uncertainty of the individual measurement is classified by systematic error and random error. The former is associated with the accuracy of the individual instrument, the latter is determined in accordance with a 95% confidence interval to satisfy ASHRAE Guideline 2 [24]. The uncertainties of heating capacity and COP were 3.1% and 3.2%, respectively.

Table 1
Specification of the ground-coupled multi-heat pump system.

Heat pump unit	No.	Unit 1	Unit 2
	Type	Water-to-air multi-heat pump	Water-to-air multi-heat pump
	OD unit capacity	53.5 kW	53.5 kW
	ID unit	6 kW × 7 floor installed type	6 kW × 6 floor installed type
	Refrigerant	R410A	R410A
GLHX	Type	Closed-loop vertical single U-tube	
	Dia. of borehole	150 mm	
	Depth of borehole	150 m	
	Distance between boreholes	6 m	
	No. of boreholes	5	
	Tube diameter	32 mm	