Comparison of coefficient of performance (COP) between an underground water source heat pump system and an air source heat pump system for greenhouse heating in cold and snowy areas in Japan

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Abstract

With the increasing cost of fossil fuels, the use of air source heat pumps (ASHPs) for greenhouse heating has become widespread in Japan. In general, the coefficient of performance (COP) of an ASHP depends on the outside air conditions, while the same is not expected for an underground water source heat pump (UWS-HP) system. Few studies have examined these comparisons in colder regions. In the present study, a UWS-HP system is developed, and the COPs of a UWS-HP (COPuws) and an ASHP (COPair) for use in greenhouse heating are investigated. The key results of the study can be summarized as follows:

1) COPuws ranged from 4.0 to 5.7 and had an average value of 4.9. COPuws was generally higher than COPair regardless of the outside temperature.
2) COPair ranged from 2.2 to 4.5 and had an average value of 3.4. Using the average hourly heat transfer coefficient obtained from the analysis of the UWS-HP, COPair was found to decrease with decreasing outside temperature.
3) COPair decreased with increasing frequency of the reverse cycle defrosting.
4) COPuws was not affected by the outside temperature, and inlet and outlet water temperature was approximately 1°C and 11.5°C, respectively.

Key words: Coefficient of performance (COP), Cold and snowy areas, Heating load, Renewable energy, Underground water.

1. Introduction

Greenhouses equipped with fossil fuel fired heating systems are widely used in cold and snowy areas of Japan such as Hokkaido or the Tohoku region. Although the unit price of crude oil declined in 2009, it began to rise again in 2010. A number of commercial growers installed air source heat pumps (ASHPs) to reduce the cost of heating in recent years. The coefficient of performance (COP) of a heat pump (HP) is an indicator of its efficiency, and COP ratings are provided by the device manufacturer. These values are evaluated at both inside and outside temperatures, as mandated by the Japanese Industrial Standard (JIS) (Japanese Industrial Standards Committee, 2005). However, under these standards, manufacturers privately determine the COP rating of their heat pumps, so the COP rating often does not accurately reflect the actual COP under realistic field conditions. In general, the COP of a ASHP decreases as the outside temperature decreases; consequently, the actual COP in cold and snowy areas is expected to be lower than the COP rating. Although several studies have examined the effects of outside field conditions on the COP of ASHPs, most have been conducted in the Kanto region, which has a warmer climate than that of Hokkaido and Tohoku. For example, Tong et al. (2010) and Sasaki (1989) investigated the COP of ASHPs in Chiba and Kanagawa Prefecture, respectively. Few studies have been carried out to investigate the performance of ASHPs in colder and snowy areas.

In contrast, geothermal HP systems for the heating of houses are in widespread use throughout North America, Europe, and other many areas (Lund et al., 2004). The major thermal sources of these systems are underground water or geologic strata, which are stable year-round, regardless of the outside conditions. Therefore, such systems are also expected to be a good thermal source for HP systems in cold and snowy areas.

In the present study, we developed an underground water source heat pump (UWS-HP) system and compared its performance to that of a ASHP for the heating of two identical greenhouses located in cold and snowy areas.

2. Materials and Methods

2.1 Greenhouses and heat pump systems

The experiments were conducted at two north-south-oriented experimental greenhouses in Sakata, Yamagata Prefecture, Japan (Fig. 1) from November 17, 2010 to January 13, 2011. Both greenhouses were 11 m long, 7.2 m wide, and 2.7 m high. An UWS-HP (RWEYP224A, Daikin Co., Osaka, Japan; power rating: 25.0 kW) was installed in one greenhouse (Guws) and a ASHP (LFFYP224A, Daikin Co., Osaka, Japan; power rating: 21.2 kW, COP rating: 3.60) was installed in the other (Gair)
The UWS-HP had a compressor capacity of 6.0 kW. The compressor was equipped with an inverter control system. The underground water (ca. 14°C) used as the thermal source was pumped from a nearby production well of 15 m depth. An automatic flow rate controller was equipped with a motor-operated valve to control the flow of the underground water. The heat energy of the underground water was transferred to coolant circulating through the HP system via a plate-type heat exchanger (SS-BHE T050, MDI Co., Mie, Japan). The motor-operated valve opened when the underground water temperature at the outlet of the heat exchanger was less than 12°C. A condenser fan-coil unit was installed at the southern end of Guws.

The ASHP had a compressor capacity of 5.9 kW. The compressor was equipped with an inverter control system too. The unit used as the thermal source was located outside the south wall of Gair. A condenser fan-coil unit (same type as that used in the UWS-HP) was installed at the southern end of Gair.

The roofs and sidewalls of Guws and Gair were covered with polyolefin film (Diastar, MKV-Dream Co., Tokyo, Japan; thickness: 0.15 mm). Both greenhouses were heated to 15°C by their respective HP systems, and Oriental Hybrid Lily (Lilium, Oriental Group cv. ‘Siberia’) plants were grown inside during the experimental period.

2.2 Measurements

Measurements of the quantities described below were taken every minute by data loggers (GL-800, Graphitec Co., Kanagawa, Japan), after which the hourly average values were calculated. A daily average was then calculated using hourly averaged data collected during HP operation.

The inside air temperatures of Gair and Gair, \( T_{\text{air, Gair}} \) and \( T_{\text{air, Guws}} \), respectively, as well as the outside air temperature \( T_{\text{air}} \) were measured (in °C) by ventilated platinum resistance thermometers placed 1.5 m above the ground.

The underground water temperature at the inlet and outlet of the plate-type heat exchanger (\( U_{\text{inlet}} \) and \( U_{\text{outlet}} \) in °C) of the UWS-HP were measured using copper-constantan thermocouples, and the underground water flow rate (1 s\(^{-1}\)) was measured using a vortex flow meter (VF-2225, TOKYO KEISO CO., Tokyo, Japan).

Likewise, the coolant temperatures at the inlet and outlet of the condenser \( (C_{\text{inlet, Gair}}) \) and \( C_{\text{outlet, Gair}} \), and the coolant flow rate \( (V_{\text{coop}} \, 1 \, \text{s}^{-1}) \) were measured using the same devices as mentioned above.

The ambient temperature of the outside unit of the ASHP was measured using a platinum resistance thermometer (°C), and we counted the daily number of reverse cycle defrostings.

The total electric power consumption per floor area of each heat pump system \( (W_{\text{uws}} \) and \( W_{\text{air}} \) in W m\(^2\)) was measured using a power sensor (KM20-A11, Omron Co., Kyoto, Japan). To determine these values, we measured electric power consumption (all in W m\(^2\)) of the compressor \( (W_{\text{uws, comp}}) \), condenser fan-coil \( (W_{\text{air, comp}}) \), and coolant circulation pump \( (W_{\text{pump}}) \) for the UWS-HP, and of the compressor \( (W_{\text{air, comp}}) \) and condenser fan-coil \( (W_{\text{air, f}}) \) for the ASHP.

2.3 Calculation of heating load and system COP

The daily heating load of \( G_{\text{uws}} \) \( (Q_{\text{uws}}, \text{W m}^{-2}) \) was calculated as follows:

\[
Q_{\text{uws}} = (C_{\text{inlet}} - C_{\text{outlet}}) \cdot V_{\text{coop}} \cdot C_{\text{p, co}} \cdot A_{\text{uws}}^{-1} + W_{\text{uws, comp}} \quad (1)
\]

where \( C_{\text{p, co}} \) is the specific heat of the coolant (J kg\(^{-1}\) °C\(^{-1}\)) and \( A_{\text{uws}} \) is the floor area of \( G_{\text{uws}} \) (79.2 m\(^2\)).

Using the calculated value of \( Q_{\text{uws}} \) the daily value of \( \text{COP}_{\text{uws}} \) was calculated using the following equation:

\[
\text{COP}_{\text{uws}} = \frac{Q_{\text{uws}}}{W_{\text{uws, comp}} + W_{\text{pump}} + W_{\text{uws, f}} } \quad (2)
\]

In general, it is very difficult to accurately measure the COP of a ASHP system in the field. However, the two experimental greenhouses of the present study were of identical dimensions and were set up in the same area. Therefore, the average hourly heat transfer coefficients of \( G_{\text{uws}} \) and \( G_{\text{air}} \) \( (H_{\text{uws}} \) and \( H_{\text{air}} \)) were assumed to be equal and were calculated as follows:

\[
H_{\text{uws}} = H_{\text{air}} = \frac{Q_{\text{uws}}}{(T_{\text{uws}} - T_{\text{out}}) A_{\text{uws}}} \quad (3)
\]

The daily heating load and the daily \( \text{COP} \) of \( G_{\text{air}} \) \( (Q_{\text{air}} \) and \( \text{COP}-
The measured value of $P_{wa}$ was 0.109.

$Q_{air} = H_{air} (T_{air} - T_{out}) A_{air}$

$COP_{air} = \frac{Q_{air}}{W_{air, comp} + W_{air, cf}}$

where $A_{air}$ is the floor area of $G_{air}$ (79.2 m$^2$).

3. Results and Discussion

3.1 Operating characteristics of the ASHP

Figure 2 shows the effect of the outside temperature $(T_{out})$ and heating load $(Q_{air}, Q_{uw})$ on $COP_{air}$ and $COP_{uw}$. During the experimental period, $T_{out}$ ranged from -1.4 to 12°C. Over this temperature range, $COP_{air}$ ranged from 2.2 to 4.5, had an average value of 3.4, and decreased with decreasing $T_{out}$. Additionally, $Q_{air}$ ranged from 38.5 to 162.1 W m$^{-2}$ and had an average value of 107.4 W m$^{-2}$.

The Japanese Industrial Standard (Japanese Industrial Standards Committee, 2005) defines the inside and outside temperatures used to determine the COP rating of ASHPs used for air conditioning. The dry and wet bulb temperatures for outside are 7°C and 6°C, respectively, whereas those for inside are 20°C and 15°C, respectively. From the regression line shown in Fig. 2 (left side), $COP_{air}$ was determined to be 3.65 when the outside dry bulb temperature was 7°C, which is slightly higher than the rated COP of this system. This discrepancy may be attributed to the difference between $T_{air}$ during the present measurement and that when the rating was determined. Specifically, the set temperature to initiate heating in this experiment was 14°C, whereas the COP rating was determined at a much higher inside temperature of 20°C. If the set temperature was increased to 20°C, we expect that the measured value of $COP_{air}$ would approach the COP rating.

Figure 3 shows the relationship between the daily number of reverse cycle defrosting and $COP_{air}$. The daily number of reverse cycle defrostings ranged from 0 to 44, and $COP_{air}$ decreased as the daily number of reverse cycle defrostings increased, which is consistent with previous reports (Tong et al., 2010; Sasaki, 1989). Tong et al. (2010) indicated that COP values were affected by $T_{out}$ and relative humidity, as well as the frequency and duration of reverse cycle defrosting. Although the frequency and duration of reverse cycle defrosting are not described in this paper, values were reported by Furuno et al. (2012) for the same ASHP as that used here. They reported that reverse cycle defrosting occurred once every 30 or 60 minutes when the outside temperature was approximately below 0°C, which is similar to our previous report.

During the course of this study, the daily average value of $T_{out}$ ranged from -1.4 to 12°C. Thus, the measured $COP_{air}$ was generally lower than the COP rating. In general, the daily average value of $T_{out}$ in cold and snowy areas of Japan such as Hokkaido and Tohoku is lower than those measured during the course of this study. The average COP of the ASHP is therefore likely to be even lower than that indicated by the experimental results. Thus, reducing heating costs will be difficult even if commercial growers in cold and snowy areas of Japan install an ASHP.
3.2 Operating characteristics of the UWS-HP

As shown in the left-hand side of Fig. 2, $COP_{uws}$ ranged from 4.0 to 5.7, had an average value of 4.9, and $COP_{uws}$ decreased with increasing $T_{out}$ (Fig. 2). $COP_{uws}$ was slightly higher than $COP_{air}$ over the entire range of $T_{out}$. Additionally, $Q_{uws}$ ranged from 45.7 to 137.9 W m$^{-2}$, had an average value of 103.8 W m$^{-2}$, and $COP_{uws}$ increased with increasing $Q_{uws}$. In contrast, the relationship between $COP_{air}$ and $Q_{air}$ was not so clear.

Figure 4 shows the daily average values of the underground water temperature at the inlet and outlet to the plate-type heat exchanger ($U_{inlet}$, $U_{outlet}$) as well as those of $COP_{uws}$. $U_{inlet}$ remained at approximately 14°C over the entire course of experiment. $U_{outlet}$ was also stable regardless of $COP_{uws}$ and had an average value of 11.5°C.

Ground-source HPs come in two basic configurations: ground coupled (closed-loop) and groundwater (open-loop) systems (Lund et al., 2004). A number of studies have examined closed-loop HP systems for greenhouse heating. Ozgener and Hepbasli (2005) and Benli (2011) developed ground-source (closed loop) HP systems, the COPs of which were 1.7 to 2.6 and 2.0 to 3.5, respectively. Chai et al. (2012) and Iwasaki et al. (2013) reported groundwater-source (open-loop) HP systems, the COPs of which were 3.83 to 3.91 and 4.7, respectively. In the current study, the maximum and average values of $COP_{uws}$ were 5.7 and 4.9, respectively, which are higher than those reported in previous studies. $COP_{uws}$ was high because the temperature of the underground water was high and the amount of underground water was sufficient for heating. However, the temperature and amount of underground water depend on the production well, the performance of which depends on the geographical condition. In recent years, subsidence caused by the pumping of underground water has become a serious problem in Japan, so drawing out only the minimum required underground water is important.

Therefore, the systems considered herein were equipped with automatic flow rate controllers. Figure 5 shows the relationship between the heating load and the underground water flow rate for the UWS-HP. The underground water flow rate ranged from 2.9 to 11.8 ml m$^{-2}$ s$^{-1}$ and increased as $Q_{uws}$ increased.

These results suggest that the automatic flow rate controller performed well. This type of automatic flow rate controller is thought to be effective for use in not only experimental small-scale greenhouses, but also commercial large-scale greenhouses. In the present study, the flow controller opened the motor-operated valve when the underground water temperature at the outlet of the plate-type heat exchanger was less than 12°C. If the set temperature was lower than 12°C, the underground water flow rate would decrease below the experimental flow rate, resulting in a decrease in $COP_{uws}$.

The $COP$ of closed-loop HP systems is lower than that of open-loop HP systems. Although the former do not require underground water or a production well, they require bore holes for the thermal source, which increases the cost of the system. Therefore, commercial growers installing these systems must take these economic factors into consideration.

3.3 Comparison of $COP_{uws}$ and $COP_{air}$

$COP_{air}$ decreased with decreasing $T_{out}$ (Fig. 2). This trend is explained by the decrease in the outside temperature as a thermal source. On the other hand, $COP_{uws}$ did not decrease with $T_{out}$, and its average value was higher than that of $COP_{air}$. This suggests that UWS-HPs are more suitable for greenhouse heating than ASHP systems in cold and snowy areas.

In contrast, $COP_{uws}$ increased with decreasing $T_{out}$, and $COP_{uws}$ increased with increasing $Q_{uws}$ (Fig. 2). This trend could not be explained by the thermal source temperature. Therefore, the following should be noted. Although the power rating of the UWS-HP was 25 kW, the maximum heating load in this experiment was 137.9 W m$^{-2}$ and the floor area of the experimental greenhouse was 79.2 m$^2$, resulting in a required maximum output of 10.9 kW. This was less than half of the power rating of the UWS-HP, which indicates that the heating load was too low to obtain a $COP$ close to the rated $COP$. This suggests that it is important to select a HP system with an output power suitable for the floor area of the greenhouse.
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