EMPIRICAL ASSESSMENT OF SOLAR-ASSISTED MULTI-SOURCE HYBRID HEAT PUMP SYSTEM WITH THERMAL ENERGY STORAGE

Summary

This study was conducted to develop a regenerative hybrid heat pump system for winter greenhouse heating to utilize surplus heat over the optimal production temperature of garden crops,. The proposed system is a 3RT (10.5kW) capacity combined heat pump system that can provide stable heating by integrating greenhouse surplus heat, an outdoor air source, and a solar collector. The system is designed and controlled to maintain an internal temperature of 15℃ for blueberry cultivation through various operational modes based on outdoor temperature and insolation conditions. As results, the developed hybrid heating system showed high efficiency during empirical tests, achieving an average heating COP of 7.5 in the outdoor heat source mode and 6.8 in the thermal storage heating mode at an average outside temperature of 11.4℃.

Keywords: greenhouse heating, multi-source heat pump, thermal energy storage, surplus heat recovery, solar thermal, mode switching control.

1. Introduction

Reducing fossil fuel dependence and winter heating costs remains a critical challenge in protected horticulture (Kim and Choi, 2002; Park, 1996). While greenhouses are highly sensitive to external climates, they naturally accumulate solar thermal energy, frequently generating unutilized surplus heat at the upper level during sunny days (Choi et al., 1999; Morrison et al., 2004). To efficiently harness such thermal energy and reduce carbon emissions, recent studies have highlighted hybrid heat pump systems integrating multiple heat sources and thermal storage, which significantly improve system efficiency and achieve energy savings of up to 50–60% compared to single-source systems (Lim, 2012; Nam and Gao, 2014; Song et al., 1997). Addressing this potential, this study proposes a combined heat source heat pump system designed to actively store daytime greenhouse surplus heat for nighttime heating. This paper details the development of the proposed hybrid system and evaluates its empirical operational performance in an actual winter greenhouse environment.

2. Experimental methods

As shown in the schematic (Fig. 1) and the actual installation picture (Fig. 2), the proposed hybrid heat pump system has a capacity of 3RT (10.5 kW heating capacity) and utilizes eco-friendly R-410A refrigerant. The system consists of a scroll compressor, a thermal expansion valve (TXV), a plate heat exchanger for the thermal storage tank, and fan coil units equipped with turbo fans for heat exchange with both the greenhouse interior and outdoor air. A 4-way valve is employed to seamlessly switch between various operation modes within a single integrated system. Additionally, a solar collector is installed independently at the top of the system to directly collect solar energy and store it in the storage tank.

In the operation of the system, a developed controller automatically dictates the operational modes based on real-time thermal conditions. When the internal temperature of the greenhouse exceeds 15 ℃—the optimal growth temperature for blueberries—the system activates the heat pump thermal storage mode, capturing daytime surplus heat concentrated at the upper part of the greenhouse due to buoyancy. Conversely, when the internal temperature drops below 15 ℃, the system switches to heating modes. If the water temperature in the storage tank is above 30 ℃, a direct water heating mode is operated. If it is below 30 ℃, the system operates the heat pump using either the outdoor air or the storage tank water as the heat source, depending on the outdoor temperature. The solar collector storage mode operates independently whenever the temperature difference between the collector outlet and the storage tank exceeds 20 °C.

The experimental method was conducted in an actual blueberry greenhouse with a floor area of 110 ㎡ located in Jeju, South Korea. To systematically evaluate the system's performance and calculate the Coefficient of Performance (COP), various parameters were monitored. The power consumption of the compressor and fans, solar radiation, refrigerant pressure, water flow rates, and temperatures (using T-type thermocouples) were continuously measured and recorded in real-time through a data logger network. The experiment was carried out by dynamically changing the operational modes to maintain the target greenhouse temperature while maximizing the utilization of stored surplus heat.

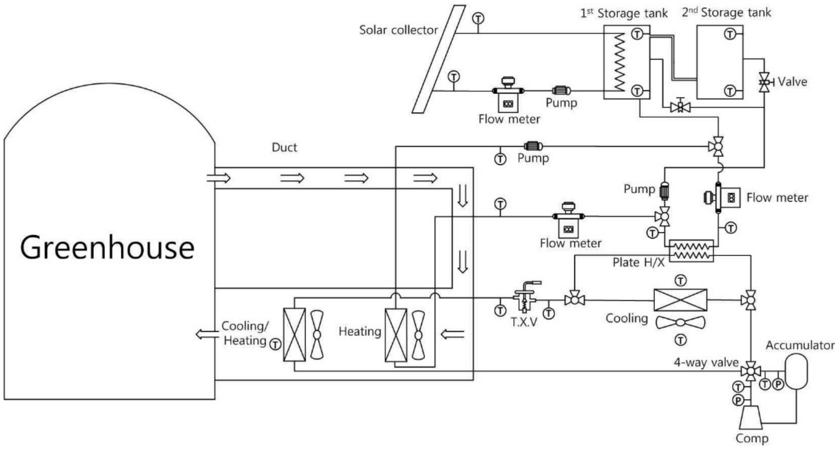


Fig. 1 : Schematic of a hybrid heat pump system

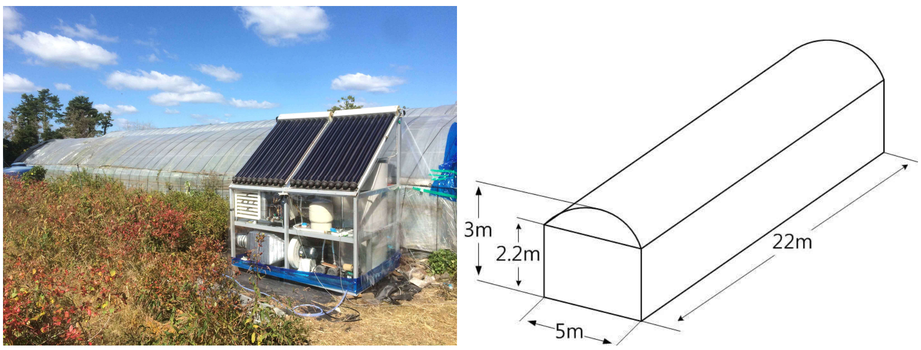
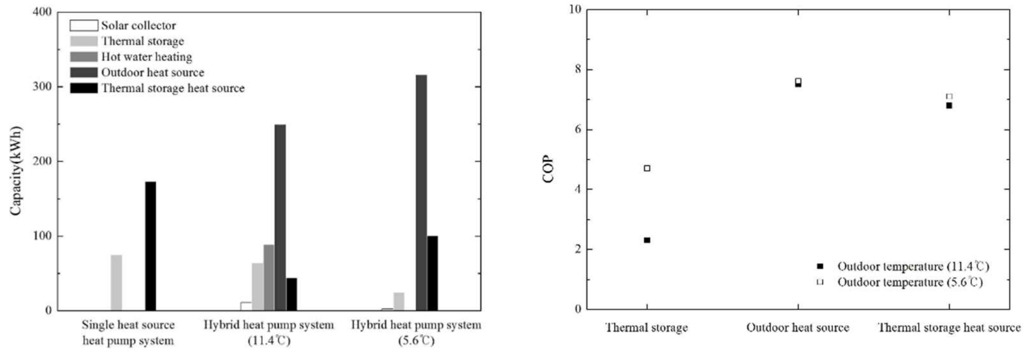


Fig.2 : Picture of developed hybrid heat pump system in the empirical site and Dimension of greenhouse

3. Results and discussion

Fig. 3(a) illustrates the daily heating energy production of the hybrid heat pump system, highlighting its operational adaptability under mild (11.4°C) and cold (5.6°C) outdoor conditions. Under the mild condition with abundant solar and surplus greenhouse heat, the system produced a total of 382.6 kWh of heating energy, actively utilizing direct hot water heating (88.8 kWh) alongside air-source (249.6 kWh) and storage-source (44.2 kWh) heat pump operations. Conversely, under the cold condition, where direct heating was unviable due to insufficient storage temperatures, the system autonomously compensated by extending the air-source (316.2 kWh) and storage-source (100.5 kWh) heat pump operations. Through this flexible mode-switching, it generated a total of 416.7 kWh to successfully meet the increased heating load.

The operational stability and high efficiency of this multi-source approach are clearly demonstrated in Fig. 3(b), which compares the coefficients of performance across varying outdoor conditions. Despite the colder weather and the absence of direct heating, the hybrid system consistently maintained high heating efficiencies. The air-source mode achieved an average heating coefficient of performance (COP_h) of 7.6 at 5.6°C (compared to 7.5 at 11.4°C), and the storage-source mode achieved a COP_h of 7.1 at 5.6°C (compared to 6.8 at 11.4°C). These findings confirm that the developed hybrid system provides superior operational flexibility and overall efficiency, effectively overcoming the capacity limitations of conventional single-source systems in cold environments.



(a) Total capacity by each operation mode (b) COP

Fig. 3: System performance of the experiment

4. Conclusions

This study aimed to develop a hybrid thermal storage heat pump system capable of providing a stable heat supply for agricultural greenhouses by actively utilizing surplus indoor heat, ambient air, and solar radiation. As results, the proposed hybrid system generated total heating energies of 382.6 kWh at an average outdoor temperature of 11.4°C, and 416.7 kWh at a colder condition of 5.6°C, by flexibly switching among direct water, air-source, and storage-source heating modes. It was also observed that the developed multi-source system achieved more than twice the heating capacity of a conventional single-source system (173.6 kWh), confirming its superior operational stability, high efficiency, and robustness against fluctuating weather conditions.

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