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# Experimental study on the performance of solar-assisted multi-functional heat pump based on enthalpy difference lab with solar simulator

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ABSTRACT

In the enthalpy difference lab with a solar simulator, the performance of the indirect expansion solar-assisted multi-functional heat pump (IX-SAMHP) can be tested in stable external environment quantificationally. In this paper, the performances of the IX-SAMHP working in the solar water heating mode and solar space heating mode were compared under different conditions. The experimental results indicate that the evaporating heat exchange rate and condensing heat exchange rate were synthetically effected by the evaporating and condensing temperature in the solar water heating mode. Moreover, compared with the situation without irradiation, when the irradiation was 500 W/m$^2$, the evaporating heat exchange rate and condensing heat exchange rate increased by 37.4% and 32.3%, respectively. In the solar space heating mode, when the irradiation increased from 0 W/m$^2$ to 500 W/m$^2$, the heating capacity increased by 20.4%. In the second-law analysis, the calculating results demonstrate that the exergy efficiency of the IX-SAMHP would be enhanced by inputting solar energy to the evaporator.



## 1. Introduction

Solar energy is clean and sustainable energy resource. Due to the rising cost of conventional energy and growing concern about global warming, many studies have focused on the application of solar energy in daily life. In particular, by combining heat pump and solar energy, solar-assisted heat pump has become an effective energy-saving equipment [1–4]. According to the connecting mode of solar collector and evaporator, solar-assisted heat pump can be classified as: the indirect expansion solar-assisted heat pump and the direct expansion solar-assisted heat pump [5].

With the improvement of living standard, space conditioning and domestic water heating have become necessities in daily life. Thus the solar-assisted heat pump which can operate with these functions at different seasons becomes more and more attractive. On this basis, Ji et al. [6] proposed a solar-assisted multi-functional heat pump (SAMHP) with functions of domestic water heating, space cooling and space heating. And the feasibility of SAMHP has been verified in later studies [7–12]. Due to the complexity of the structure and diversity of the operation modes of the SAMHP, the operation performance of the system is effected by many factors. Wang et al. [7] and Liu et al. [8,9] studied the influence of outdoor temperature on the performance of the multi-functional heat pump. It was proved that as the evaporating pressure changed with the outdoor temperature in the air source heat pump system, the system performance and the optimal heat source combination would depend on the outdoor temperature. Jung et al. [10] and Jiang et al. [11] investigated the impact of the electronic expansion valve opening on the system performance. It was shown that the evaporating temperature in the high-stage cycle increased with the increase of the electronic expansion valve opening in a cascade multi-functional heat pump system. Cho et al. [12] proposed that the system could maintain optimal performance by adjusting the superheating temperature of the refrigerant in space/water heating mode.

In previous studies, Jiang et al. [11] and Cho et al. [12] simulated the indoor environment temperature by constant temperature water bath, and measured the inlet and outlet temperature of the water cooled heat exchanger to calculate the heating capacity in the space heating mode. However, the heat transfer performance in the water cooled heat exchanger is different from that in the air cooled heat exchanger. Because the measurement of the heating capacity in the space heating mode is difficult to obtain, most previous studies have focused on the water heating mode [13–15].

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**Nomenclature**

| | |
|---|---|
| $Q$ | heat exchange rate, W |
| $Q_c$ | condensing heat exchange rate, W |
| $Q_e$ | evaporating heat exchange rate, W |
| $\dot{m}$ | water mass flow rate, kg/s |
| $\dot{m}_a$ | air flow rate, $m^3$/h |
| $h_a$ | air enthalpy, J/kg |
| $V_n$ | specific volume of the air at the nozzle, $m^3$/kg |
| $D_n$ | humidity ratio of the air at the nozzle |
| $W_{sys}$ | energy consumption, W |
| $c$ | specific heat capacity of water, J/(kg K) |
| $m$ | mass of water in domestic water tank, kg |
| $T_W$ | average temperature of water tank, K |
| $T_{in}$ | water temperature entering the plate-type heat exchanger, K |
| $T_{out}$ | water temperature leaving the plate-type heat exchanger, K |
| COP | coefficient of performance |
| $W_{sys}$ | energy consumption, W |
| PR | pressure ratio of compressor |
| $P$ | pressure, kPa |
| $P_e$ | evaporating pressure, kPa |
| $t$ | time, min |
| $P_c$ | condensing pressure, kPa |
| $\eta_{ex}$ | exergy efficiency |
| $E_x$ | exergy rate, W |
| $\dot{I}_{rr}$ | exergy loss rate, W |
| $T_a$ | environment temperature, K |
| $T_H$ | temperature of high temperature heat source, K |
| $T_L$ | temperature of low temperature heat source, K |
| $I$ | irradiation, W/$m^2$ |

*Subscripts*

| | |
|---|---|
| $a$ | air |
| $w$ | water |
| $n$ | nozzle |
| $c$ | condensing |
| $e$ | evaporating |
| $h$ | space heating |
| wh | water heating |
| in | inlet |
| out | outlet |
| 0,1,2 | state |
| $L$ | low temperature |
| $H$ | high temperature |

In the studies of the combination of solar energy and multi-functional heat pump, Wang et al. [7] replaced solar collector with electricity heater to study the performance of the SAMHP under different solar irradiation. As stable solar irradiation is hard to maintain, most studies of the solar-assisted heat pump were implemented in the outdoor environment, and the solar thermal collecting processes were carried out in unsteady external environment [16,17].

In this study, the experiment was carried out in the enthalpy difference lab with a solar simulator, so the IX-SAMHP would operate in stable external environment. On this basis, the performances of the IX-SAMHP working in the solar water heating mode and solar space heating mode under different conditions were experimentally investigated. Moreover, the heating capacity of the IX-SAMHP in the solar space heating mode was measured by an air-enthalpy type calorimeter with high-degree of accuracy. Finally, the second-law analysis of the IX-SAMHP under different irradiation was discussed to estimate the influence of the irradiation on the exergy efficiency of the system.

## 2. Experimental setup and test apparatus

To study the performance of the IX-SAMHP, a prototype system has been setup in an enthalpy difference lab with a solar simulator. Fig. 1(a) shows the schematic diagram of the experimental system, which includes the solar thermal collecting system and multi-functional heat pump system. The solar thermal collecting system consists of two flat-plate collectors with an aperture area of 3.2 $m^2$, a solar water tank (200L), a water pump. Moreover, a solar simulator is used to simulate the solar irradiation incident on the surface of the flat-plate collector, as shown in Fig. 1(b). The multi-functional heat pump system is modified from a double-effect air conditioner. And it consists of a compressor, a reversing valve, an outdoor air heat exchanger, an indoor air heat exchanger, a plate-type heat exchanger, a domestic water tank (300L), a capillary tube, a one-way valve, a liquid accumulator and a water pump.

On the basis of normal double-effect air conditioner, the domestic water tank is in parallel with the indoor air heat exchanger, and the plate-type heat exchanger is in parallel with the outdoor air heat exchanger. Therefore, six working modes can be realized by different combinations of the evaporator and condenser. The flow diagram of the IX-SAMHP working in different modes is shown in Table 1.

In the enthalpy difference lab with solar simulator, the indoor unit and outdoor unit were installed in the psychrometric chambers separately, and the temperature and humidity can be controlled in each chamber. The solar simulator that generated stable solar irradiation was in parallel with the flat-plate collector. The heterogeneity and instability of the solar simulator are under 5%, and the spectrum distribution satisfies the National Class B level standard. The adjustable range of the irradiation is between 500 W/$m^2$ and 1200 W/$m^2$, with luminous area of 4 $m^2$.

The parameters needed to be measured include: temperature, pressure, irradiation, and heating capacity. The specifications of the measuring apparatus are shown in Table 2. In the solar space heating mode, the heating capacity of the indoor air heat exchanger is measured by an air-enthalpy type calorimeter and calculated by the air enthalpy method (ASHRAE Standard 116, 1993).

## 3. Thermodynamic analysis of the system

### 3.1. First-law analysis

The condensing heat exchange rate in the solar space heating mode is calculated by air flow rate enthalpy difference across the indoor air heat exchanger:

$$Q_{c\_h} = \dot{m}_a(h_{a\_i} - h_{a\_o})/[V_n(1 + D_n)] \tag{1}$$

where, $\dot{m}_a$ is the air flow rate, $h_{a\_i}$ is the enthalpy entering the indoor air heat exchanger, $h_{a\_o}$ is the enthalpy leaving the indoor air heat exchanger, $V_n$ is the specific volume of air at the nozzle, and $D_n$ is humidity of air at the nozzle.

The condensing heat exchange rate in the solar water heating mode is obtained by: