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Numerical simulation and experimental validation of indirect expansion solar-assisted multi-functional heat pump

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ABSTRACT

A novel indirect expansion solar-assisted multi-functional heat pump (IX-SAMHP) system which composes of the multi-functional heat pump system and solar thermal collecting system is proposed and studied in this paper. This system can fulfill space heating, space cooling and water heating with high energy efficiency by utilizing solar energy. For solar water heating mode and solar space heating mode, a dynamic model is presented and validated with the experimental results. The simulation results show good consistency with the experimental data, and the established model is able to predict the system performance at a reasonable accuracy (with the root mean square deviations less than 5%). On this basis, the performances of the IX-SAMHP system are investigated under different parametric conditions. For solar water heating mode, simultaneously operating the solar thermal collecting system and multi-functional heat pump system can be an energy efficiency method. With the solar irradiation rising from 0W/m^2 to 800W/m^2, the COP increases from 2.35 to 2.57. In solar space heating mode, the effect of the mass flow rate of water in evaporator is investigated. To balance the heating capacity and COP, the mass flow rate of water should be adjusted according to different temperature demands and heat load.

1. Introduction

The solar-assisted heat pump (SAHP) system which is an integration of heat pump and solar collector, can utilize solar energy as heat source to achieve high coefficient of performance (COP) [1]. 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 [2]. The concept of SAHP was first proposed by Sporn et al. [3]. Since then, numerous theoretical and experimental studies on the SAHP systems have been conducted by various investigators [4–9]. Huan-Liang Tsai proposed a novel model for a refrigerant-based photovoltaic/thermal assisted heat pump water heater (PVTA–HPWH) system [4]. The dynamic model featured the direct interaction of PV and thermal energy with environment and HPWH system. An indirect-style solar-assisted heat pump (i-SAHP) design was modeled using the TRNSYS software by S.J. Sterling, and it was compared to a traditional solar domestic hot water (SDHW) system and an electric domestic hot water (DHW) system [5]. In this study, the dual tank indirect solar-assisted heat pump system was proven to be the most energy efficient and had the lowest annual operating cost among the three models analyzed. A. Moreno-Rodríguez et al. investigated a direct-expansion solar-assisted heat pump for domestic hot water application [6], a mathematical model was developed to determine the operating characteristics of the system and validated with the experimental results from a prototype. Carsen J. Banister [7] studied a novel dual tank solar-assisted heat pump (SAHP) system configuration for domestic hot water heating, it was found that applying the system to a larger load can offer the potential for significant energy and cost savings, which would improve economic justifiability. Hikmet Esen et al. proposed experimental and model study of a solar-assisted ground source heat pump for heating mode, in which artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) were used to evaluate the performance of heating mode [10].

To further expand the application area and improve the efficiency of the heat pumps, numerous researchers have focused on the investigation of multi-functional heat pump system. Ji Jie et al. proposed a multi-functional heat pump with functions of domestic water heating, space cooling and space heating [11]. Xiaolin Sun et al. compared the exergy efficiency of the multi-

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Nomenclature

A	area, m^2
M	mass, kg
c	specific heat, kJ/(kg K)
P	energy consumption, kW
D	diameter, m
ρ	density, kg/m^3
k	heat conductivity coefficient, W/(m^2 K)
α	heat transfer coefficient, W/(m^2 K)
μ	dynamic viscosity, Pa s
$\dot{m}$	mass flow rate, kg/s
h	specific enthalpy, kJ/kg
T	temperature, °C
L	length, m
H	height, m
W	width, m
Q	heat exchange power, kW
V	volume, m^3
t	time, s
p	pressure, Pa
v	specific volume, m^3/kg
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
n	rotational speed, rad/s

Subscripts

com	compressor
a	air
dis	discharge
suc	suction
plate	plate-type heat exchanger
w	water
ref	refrigerant
eva	evaporator
con	condenser
st	solar water tank
dt	domestic water tank
in	inlet
out	outlet
coil	coil of domestic water tank
fin	finned pipe
i	inside
o	outside
cap	capillary
flow	flow channel
l	liquid

functional heat pump system and conventional air conditioning system [12]. Changyong Cho et al. studied the performance of a multi-function heat pump system working in different working modes [13]. Hae Won Jung et al. optimized the performance of the cascade multi-functional heat pump in each of the four operation modes by adjusting control parameters [14]. Some studies of the multi-functional heat pump system indicated that the optimal heat source combination was critical in optimizing the performance of the system [15–18]. On this basis, the solar-assisted multi-functional heat pump (SAMHP) which combines the advantages of the solar-assisted heat pump system and multi-functional heat pump system has been proposed [19,20]. The SAMHP system can provide better energy performance and higher equipment utilization throughout a year, and causes less thermal pollution than the heat pump water heater and the domestic air conditioner. Meanwhile, the system may result in colder fluid temperature entering the solar collector, which could improve the collector efficiency [5]. However, few theoretical study of the SAMHP has been conducted and the related experimental verifications are still insufficient.

In this study, a novel indirect expansion solar-assisted multi-functional heat pump (IX-SAMHP) system is presented. The system can operate in different modes and utilize solar energy to obtain high energy efficiency. A dynamic model is proposed to predict the performance of the IX-SAMHP system working in solar water heating mode and solar space heating mode. And the simulation is validated by the experimental results in our previous study which conducted in the enthalpy difference lab with a solar simulator [21]. With the validated model, the performances of the IX-SAMHP system are studied under the following conditions: different water temperatures in solar water tank and domestic water tank, different indoor environment temperatures, different mass flow rates of water in evaporator, and different solar irradiation. This research will help promote the development of such an innovative solar heating technology, and lead to reduction in fossil fuel consumption and carbon emission to the environment.

2. IX-SAMHP experimental system

The experimental system of IX-SAMHP is shown in Fig. 1. The IX-SAMHP system includes the solar thermal collecting system and multi-functional heat pump system. The solar thermal collecting system consists of two solar flat-plate collectors with an aperture area of 3.2 m^2, a solar water tank (300L), and a water pump. The multi-functional heat pump system is modified from a double-effect air conditioner. And it composes 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 (200L), a capillary, a one-way valve, a liquid accumulator and a water pump.

Compared with the traditional heat pump, the indoor and outdoor air heat exchangers of the IX-SAMHP system are connected in parallel with the domestic water tank and the plate-type heat exchanger respectively. Six working modes can be realized by different combinations of the evaporator and condenser. The flow diagram of the different working modes of the IX-SAMHP system is shown in our previous work [21].

In solar water heating mode, the solar water tank acts as the heat source and exchanges heat with the refrigerant via the plate-type heat exchanger. The domestic water tank working as the condenser absorbs heat from the refrigerant. In solar space heating mode, the indoor air heat exchanger serves as the condenser, and the plate-type heat exchanger works as the evaporator which is similar to the solar water heating mode.

The experiments have been conducted in the enthalpy difference lab with solar simulator. The indoor unit and outdoor unit are installed in the psychrometric chambers separately. In each psychrometric chamber, the environment temperature and humidity can be controlled, and the area of both chambers are 30 m^2. The solar simulator that generates stable solar irradiation is in parallel with the solar flat-plate collectors. The heterogeneity and instability of the solar simulator are under 5%, and the spectrum distribution satisfies the National Class B level standard. The