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Experimental performance analysis and optimization of a direct expansion solar-assisted heat pump water heater

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Abstract

In this study, a direct expansion solar-assisted heat pump water heater (DX-SAHPWH) with rated input power 750 W was tested and analyzed. Through experimental research in spring and thermodynamics analysis about the system performance, some suggestions for the system optimization are proposed. Then, a small-type DX-SAHPWH with rated input power 400 W was built, tested and analyzed. Through exergy analysis for each component of DX-SAHPWH (A) and (B), it can be seen that the highest exergy loss occurs in the compressor and collector/evaporator, followed by the condenser and expansion valve, respectively. Furthermore, some methods are suggested to improve the performance of each component, especially the collector/evaporator. A methodology for the design optimization of the collector/evaporator was introduced and applied. In order to maintain a proper matching between the heat pumping capacity of the compressor and the evaporative capacity of the collector/evaporator under widely varying ambient conditions, the electronic expansion valve and variable frequency compressor are suggested to be utilized for the DX-SAHPWH.

Keywords: Heat pump; Water heater; Coefficient of performance; Solar collector efficiency; Exergy

1. Introduction

Solar energy is renewable and "free", which can be a heat source of heat pump like the air source. In order to improve the heat pump COP, the idea of combining the heat pump with solar energy application system has been proposed and developed by many researchers around the world. In a so-called direct expansion solar-assisted heat pump (DX-SAHP), the collector and evaporator are combined into one unit (collector/evaporator), where the refrigerant circulating in heat pump system gets evaporated by absorbing the incident solar energy (and/or ambient air energy). The DX-SAHP offers several advantages over the conventional SAHP, such as superior thermodynamic performance, lower system cost and longer life time of collector/evaporator.

It is estimated that, in China, solar water heater have been marketed for about 10 billion RMB Yuan each year. It is also reported that China has 5 million solar water heaters installed in families in 2000, and it is still being developed more and more rapidly. In virtue of its advantages over conventional solar water heaters, the DX-SAHPWH is expected to have a giant potential market in China.

The DX-SAHP concept was first considered by Sporn and Ambrose in West Virginia [1]. Following their work, many theoretical and experimental studies have been reported in the past 27 years [2–26]. A review paper in this field has indicated that the COP values of the DX-SAHP systems range from 2 to 9 and the collector/evaporator efficiencies vary between 40% and 75% under different climatic conditions, experimentally [25]. With different matching between the system components, especially the collector/evaporator and the compressor, the COP and η_{coll} values are very different each other. So the proper matching between each component has an important impact on the performance of the DX-SAHPWH.

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Nomenclature

A_c	solar collector/evaporator area, m^2
COP	coefficient of performance
C_{Pw}	specific heat at constant pressure of water, kJ/kg K
D	outside diameter of the tube, m
$\dot{E}_{Q_w}$	exergy rate of hot water, kW
$\dot{E}_{rad}$	exergy rate of solar radiation, kW
e	specific exergy, kJ/kg
F	fin efficiency
F'	collector efficiency factor
$\dot{H}$	enthalpy rate, kJ
h	specific enthalpy, kJ/kg
h_w	wind heat transfer coefficient, W/m^2 K
$\dot{I}_{rr}$	exergy loss rate, kW
I_T	total solar radiation intensity, W/m^2
$\dot{m}_r$	mass flow rate of refrigerant, kg/s
M_w	mass of water in domestic water tank, kg
N	compressor motor speed, rpm
P	pressure, Pa
$\dot{Q}_{cond}$	condensing heat rate of refrigerant, kW
$\dot{Q}_{eva}$	evaporating heat rate of refrigerant, kW
$\dot{S}$	entropy rate, kJ/K
s	specific entropy, kJ/kg K
T	absolute temperature, K
U_{Lc}	collector heat loss coefficient, $U_{Lc} = h_w + 4\varepsilon\sigma T_0^3$, W/m^2 K
U_{Lcond}	condenser heat loss coefficient, W/m^2 K
V_d	displacement volume, cm^3/rev
V_w	wind velocity at ambient environment, m/s
W	pitch of the tubes in collector/evaporator, *m*
$\dot{W}_i$	indicated power of compressor, kW
$\dot{W}_{comp}$	total input electric power to compressor, kW

Greek symbols

α	absorptivity of collector/evaporator
χ	exergy loss coefficient
ε	emissivity of collector/evaporator plate
η	efficiency
η_V	volumetric efficiency
v_1	specific volume of suction refrigerant vapor, m^3/kg
σ	Stefan–Bolzmann constant, W/m^2 K^4
τ	time, or one data acquisition interval, *s*

Subscripts

0	ambient air
comp	compressor
coll	collector/evaporator
cond	condensation or condenser
eva	evaporation or collector/evaporator
ex	exergy
f	refrigerant fluid
p	collector/evaporator plate
rad	solar radiation
r	refrigerant
sa	sol–air
v	expansion valve
w	hot water in tank
i	inlet, or *i*th sequence of each component of the DX-SAHPWH system
j	*j*th segment of data acquisition interval
o	outlet
1, 2, 3, 4	state

Except for the collector/evaporator, the rest of the DX-SAHPWH system employs ordinary materials and components currently available in the refrigerating and air conditioning industry. The study of the performance enhancement for collector/evaporator is significant for the development of the DX-SAHPWH.

In this study, the focus aims at developing a DX-SAHPWH with higher performance suitable for Chinese potential market. At present, two prototypes (DX-SAHPWH (A) and (B)) were built in sequence in Engineering Research Center of Solar Power & Refrigeration, MOE, China (in Shanghai Jiao Tong University, latitude 31.22 'N, longitude 121.48 'E). Seasonal experiments, the first-law-oriented energy analysis and the second-law-oriented exergy analysis for the DX-SAHPWH (A) and (B) systems were conducted, respectively. A methodology for the design optimization of the collector/evaporator was also introduced and applied.

It should be noted that refrigerant R-22 was used in this study, even though it would be phase out by the year 2040 in developing countries, such as China, where R-22 is still widely used on heat pump systems. It is significant to deal with improving the heat pump systems' thermal performance using R-22 as refrigerant in order to enhancing the energy saving in the developing countries. On the other hand, the analysis in this way can be applied in the same way to heat pump systems using other kinds of refrigerant.

2. System description and experimental setup

2.1. Thermodynamic cycle of the DX-SAHPWH system

Fig. 1 shows the schematic diagram of the DX-SAHPWH (A) in the present study. An unglazed solar collector as evaporator, an R-22 rotary-type hermetic compressor, a hot water tank with an immersed copper tube coil heat exchanger as condenser, a thermostatic expansion valve (TEV), some accessories and connective copper pipes compose the DX-SAHPWH system.