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Simulation analysis on dynamic performance of a combined solar/air dual source heat pump water heater

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ABSTRACT

This paper investigated a combined solar/air dual source heat pump water heater system for domestic water heating application. In the dual source system, an additional air source evaporator is introduced in parallel way based on a conventional direct expansion solar-assisted heat pump water heaters (DX-SHPWH) system, which can improve the performance of the DX-SHPWH system at a low solar radiation. In the present study, a dynamic mathematical model based on zoned lump parameter approach is developed to simulate the performance of the system (i.e. a modified DX-SHPWH (M-DX-SHPWH) system). Using the model, the performance of M-DX-SHPWH system is evaluated and then compared with that of the conventional DX-SHPWH system. The simulation results show the M-DX-SHPWH system has a better performance than that of the conventional DX-SHPWH system. At a low solar radiation of 100 W/m^2, the heating time of the M-DX-SHPWH decreases by 19.8% compared to the DX-SHPWH when water temperature reaches 55 °C. Meanwhile, the COP on average increases by 14.1%. In addition, the refrigerant mass flow rate distribution in the air source evaporator and the solar collector of the system, the allocation between the air source evaporator and the solar collector areas and effects of solar radiation and ambient air temperature on the system performance are discussed.

1. Introduction

As well known, heat pump has been an attractive technology as it is an efficient method to save energy and improve overall energy efficiency for various heating applications [1]. Heat pumps can extract heat from different heat sources, such as ground, air or water sources, and use it for space heating or water heating [2–4]. Among heat pumps, there has been interest in the development of solar-assisted heat pump water heaters (SHPWHs) as solar energy is a renewable and clean energy [5,6]. The SHPWH system is mainly classified as two types: the indirect expansion SHPWH (IDX-SHPWH) system where the solar collector is coupled with the heat pump via the water circulation system, and the direct expansion SHPWH (DX-SHPWH) system where the solar collector serves as an evaporator in the refrigerant cycle [7]. Over the past years, many studies concerning DX-SHPWH systems have been performed since the DX-SHPWH system offers several advantages over the IDX-SHPWH systems [8]. These studies include the thermodynamics analysis, optimization design, modeling and experiment of DX-SHPWH systems.

Helvaci et al. [9] simulated the multiphase flow in a flat plate solar energy collector. Higher heat transfer coefficient is observed in boiling flow region compared to the liquid and vapor flow regions. Chaturvedi et al. [10] simulated and developed a variable capacity DX-SHPWH for domestic hot water application. A high thermal performance of the DX-SAHPWH system can be achieved, which is affected significantly by the variation of solar radiation. Li et al. [11] carried out experimental performance analysis of a DX-SHPWH and provided some suggestions for the system optimization, i.e. the electronic expansion valve and variable frequency compressor should be utilized for improving the system performance. Cerit et al. [12] investigated the effect of rollbond evaporator design on the performance of a DX-SHPWH experimentally. The experiment results show that the evaporator with flat manifold can reach a high performance. Chow et al. [13] developed a mathematical model to predict the operating performance of a DX-SHPWH system. Based on this model, they evaluated the annual energy performance of the system and the system could achieve a year-long average COP of 6.46. Kong et al. [14] conducted thermal performance analysis of a DX-SHPWH based on lumped and distributed parameter approach, and analyzed the effect of various parameters on the thermal performance of the system. Gorozabel Chata et al. [15] theoretically analyzed a DX-SAHPWH system for several refrigerants. The refrigerant R-134A shows a highest COP

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Nomenclature

A	area (m^2)
C_b	bond conductance (W m^{-1}K^{-1})
C_p	specific heat (kJ kg^{-1}K^{-1})
D	external diameter of the tube (m)
d	diameter of the tube (m)
F	fin efficiency
F'	collector efficiency factor
f	friction coefficient
g	acceleration due to gravity (m s^{-2})
h	specific enthalpy (J kg^{-1})/heat transfer coefficient (W m^{-2}K^{-1})
I_T	solar radiation (W m^{-2})
j	heat transfer factor
m	mass flow rate (kg s^{-1})
n	compressor speed (rpm)
P	pressure (Pa)
Q	heat (W)
s	spacing (m)
T	temperature (K)
t	temperature (°C)
Δt	temperature difference (K)/superheating degree (°C)
U_L	overall heat loss coefficient (W m^{-2} K^{-1})
u	speed (m s^{-1})
V	volume (m^3)
v	specific volume (m^{3}kg^{-1})
W	pitch of the tube (m)/work (W)
x	vapor quality

Greek symbols

α	absorptivity
β	volume expansion coefficient
δ	thickness (m)
ε	emissivity/efficiency
φ	ratio
η	efficiency
λ	thermal conductivity (W m^{-1}K^{-1})
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
σ	Stefane Boltzmann constant (W m^{-2}K^{-4})

Subscripts

a	ambient air
c	collector/compressor/condenser
e	evaporator
f	fin/fluid/final
i	inner/inlet/initial
is	isentropic efficiency
l	liquid
m	mean
o	outer/outlet
p	collector plate
r	refrigerant
t	water tank
v	volumetric/vapor
w	water/wind
1 – 5	state points of refrigerant

among R-410A, R-407A and R-404C. Moreno-Rodríguez et al. [16] investigated the operating characteristics of a DX-SHPWH for domestic hot water applications. The results indicated that if conditions exceed the maximum value of the absorbed heat, the system would stop and start at short time intervals. Recently, DX-SHPWHs have further received considerable attention for domestic and industrial applications, and the performance and economics of different systems have been studied theoretically or experimentally in the literature [17–23]. Overall, these researches advanced more deep understanding of DX-SHPWH performance characteristics for practical applications.

Basically, the operation performance of a DX-SHPWH system can be mainly influenced by solar energy through a single integrated unit of collector/evaporator. The collector/evaporator used in such system can absorb both solar and ambient energy. However, the collector/evaporator cannot effectively absorb the heat from air source in contrast to conventional evaporators when solar radiation is not available sufficiently. In this case, the performance of the DX-SHPWH system could be degraded due to the inherent drawback in the heat transfer characteristics between the collector/evaporator and the ambient air. This leads to a disadvantage of the DX-SHPWH system compared to conventional air source heat pump water heater (ASHPWH) systems although the DX-SHPWH system has several known advantages [24]. In order to improve the existing DX-SHPWH system performance, it should be necessary to increase the utilization of ambient energy in the case of insufficient availability of solar energy. This may be achieved by the idea of a dual source heat pump system, i.e. combining a solar energy and air source [25,26]. A comprehensive usage of solar and ambient energy is obviously more efficient than a single heat source in a DX-SHPWH system, which can improve the quality of the energy available.

Following this idea, a combined solar/air dual source heat pump water heater system is investigated in this paper. In the dual source system, an additional air source evaporator is introduced in parallel way based on a conventional DX-SHPWH system. This modified DX-SHPWH (M-DX-SHPWH) system could operate in parallel to both the solar collector/evaporator and air source evaporator if the amount of solar energy supplied by the collector/evaporator is insufficient. This configuration can result in a higher energy performance of the M-DX-SHPWH under low radiation. In the present study, a dynamic mathematical model for the M-DX-SHPWH system is developed to evaluate the performance of the system. The effects of main parameter solar radiation and ambient air temperature on the performances are studied. The refrigerant mass flow distribution and the allocation of the areas of the two evaporators are also studied to make system a better performance. Moreover, a comparison is also performed between the conventional and modified cycles. The purpose of this study is to show the performance improvement potential of the M-DX-SHPWH system and provide basement for further experimental studies.

2. System description

Fig. 1 shows the schematic diagram of the M-DX-SHPWH system. It mainly consists of a flat-plate solar collector as an evaporator, a finned-tube evaporator, a hermetic compressor, a hot water tank with an immersed heat exchanger as a condenser, receiver and two electronic expansion valves (EEVs). The system works in two modes: (1) single solar collector mode (SM), which is operated when the solar radiation is high enough to heat the water efficiently; (2) combination mode (CM), which is operated when the