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Experimental studies of a variable capacity direct-expansion solar-assisted heat pump water heater in autumn and winter conditions

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ABSTRACT

A variable capacity direct-expansion solar-assisted heat pump (DX-SAHP) system was studied experimentally under the meteorological condition of Qingdao located in the East China area. It was mainly made up of a solar collector/evaporator, a variable-frequency rotary-type hermetic compressor, a micro-channel condenser, and an electronic expansion valve. A series of experiments were carried out, in order to evaluate the performance of the DX-SAHP system during the autumn and winter period, including the system coefficient of performance (COP), the electric power to the compressor, the evaporating and condensing pressures, and the discharge temperature of the compressor. Experimental results showed that for the base case considered in this study, under the sunny and overcast day conditions in the autumn, the average COP was higher than 4.0 and 3.0, respectively. Even in the extreme weather of the winter conditions, the average COP was also higher than 2.5. In general, with the increase of water temperature, the compressor speed increased gradually, and the corresponding electric power of the compressor increased sharply. The condensing pressure also increases, as does the discharge temperature of the compressor, while the evaporating pressure remains a relatively low level with smaller variations.

1. Introduction

In view of sharply increasing primary energy consumption and the world wide restrictions which have been adopted regarding their impact on global warming and environmental status, alternative energy sources are receiving considerable attention around the world, so predicament of energy shortages leads researchers to find new sources of energy. Solar energy, unlike conventional fossil fuels, is clean, readily available, non-contaminant and most inexhaustible of all known energy sources. Nowadays, building energy consumption accounts for 40% of the society energy consumption on a global scale (Sun et al., 2015). From a sustainability perspective, solar utilization has been proposed as a cheap and effective means of building energy conservation. Space heating and water heating account for a significant share of the energy consumed in domestic applications. Thus, it is imperative to search for new energy systems as related to energy efficiency and environmental improvement for space or water heating.

Various thermal applications including space heating and water heating could be achieved by the combination of solar energy and heat pump (Ozgener and Hepbasli 2007; Thirugnanasambandam et al., 2010). Malali et al. studied the thermal performance of a solar heat pump system for water heating. The experimental results showed that system COP ranging from 3.6 to 5.6 could be obtained for the month of January for locations such as New York City, Norfolk and Tampa (Malali et al., 2016). Paradeshi et al. proposed a numerical research of a solar heat pump for space heating. Results showed that the thermal performance of system was strongly influenced by solar collector/evaporator area, solar radiation intensity, ambient temperature and wind speed (Paradeshi et al., 2016). Heat pump technology allows for temperature upgrading and capacity expansion of solar thermal energy, which is so-called solar assisted heat pump (SAHP). The heat gain can then be supplied to domestic hot water. If the refrigerant evaporates after absorbing solar energy in a bare flat-plate collector, which means the collector and evaporator are combined into single unit (collector/evaporator), a direct-expansion solar-assisted heat pump (DX-SAHP) system is formed. In a DX-SAHP system, solar radiation is used directly as the heat source, which can provide a higher evaporating temperature than the indirect solar thermal systems (Hepbasli and Kalinci, 2009; Sun et al., 2014). It should be noted that one of the key factors that affect the coefficient of performance (COP) is the evaporating temperature for a heat pump system.

The idea of DX-SAHP systems was first put forward by Sporn and Ambrose (1955). In the years that followed, many different types of DX-SAHP systems had been studied theoretically and experimentally. The results indicated that the DX-SAHP system was influenced strongly by the solar radiation intensity and solar collector/evaporator area. The

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Nomenclature

C_p	specific heat (J kg^{-1} K^{-1})
COP	coefficient of performance (dimensionless)
I	solar radiation intensity (W m^{-2})
M	mass (kg)
M	mass flow rate (kg s^{-1})
n	compressor speed (rpm)
P	pressure (MPa)
T	temperature (K)
t	temperature (°C)
u	wind speed (m s^{-1})
W	power (W)
τ	heating time (s)
π	pressure ratio (dimensionless)

Subscripts

a	ambient
c	condensing
com	compressor
dis	discharge
e	evaporating
f	final
i	initial
j	j_{th} time step
k	total number of time steps
m	average
r	refrigerant
w	water

increase of the solar radiation intensity significantly benefited the performance of the system but decreased the system exergy efficiency, and the increase of the solar collector/evaporator area always contributed to the performance improvement, while it should be kept in a proper range to guarantee the excellent operating performance (Kuang et al., 2003; Jiang and Dai, 2016; Chen and Yu, 2017). DX-SAHP systems based on the combination of collector and evaporator could offer significant advantages in terms of thermal performance owing to its ability to control collector surface temperature, thus significantly increasing collector efficiency (Sushil et al., 1984; Taherian et al., 2011; Moreno-Rodríguez et al., 2012; Tagliafico et al., 2014). Compared to the traditional air-source heat pump systems, the DX-SAHP systems could obtain a higher evaporating temperature while expending less energy, which led to a significant improvement of system performance (Morrison et al., 2004; Lerch et al., 2015; Tzivanidis et al., 2016). Deng et al. studied a combined solar/air dual source heat pump water heater system operating with R134a. The simulation results showed that the presented system had a better performance compared to the conventional DX-SAHP systems, and it could produce a higher COP and heating capacity under the condition of a low solar radiation intensity (Deng and Yu, 2016).

A series of studies and applications have been put forward in the field of DX-SAHP water heaters from the theoretical and experimental point of view. Li et al. introduced and analyzed a DX-SAHP experimental set-up, which was tested under typical spring climate in Shanghai China. The experimental results showed that the system COP could reach 6.61 and 3.11 respectively under the sunny day condition and the rainy night condition (Li et al., 2007a, 2007b). Kong et al. established a simulation model to predict the thermal performance of a DX-SAHP system which could supply hot water for domestic use during the whole year. Results showed that simulation results agreed well with experimental data, and the higher thermal performance could be achieved (Kong et al., 2011). Cerit et al. carried out three DX-SAHP systems using R134a as the working fluid, which were identical except collector-evaporator design. Results indicated that maximum values of the COP were 3.3, 3.14, and 2.42, respectively under typical meteorological conditions during the November in Turkey (Cerit and Erbay, 2013). Kong et al. determined some optimal control strategies of DX-SAHP systems over a wide range of operating conditions, which proved that it could regulate the degree of superheat in range of 5–10 °C effectively (Kong et al., 2018).

Numerous papers have studied the influence of refrigerant on the thermal performance of the DX-SAHP system. Khorasaninejad et al. simulated and analyzed a DX-SAHP system performed for five different refrigerants including R245fa, R134a, R123, R407C and R22. It was indicated that R245fa produced the highest COP, followed by the R134a, R123, R22 and R407C, respectively (Khorasaninejad and Hajabdollahi, 2014). Kong et al. simulated the thermal performance of R410A, R22 and R290 in the DX-SAHP system. The results showed that the COP of the R290 system was higher than that of the R22 and R410A system (Kong et al., 2016). Li et al. studied the effects of R22, R134a and R744 on the performance of a DX-SAHP system. Results showed that the COP of the R134a system was higher than that of the R22 or R744 system when ambient temperature exceeded 13 °C (Li et al., 2015).

In order to reduce the exergy losses and maximize the COP further, the variable-frequency compressor and the electronic expansion valve should be utilized for the DX-SAHP system. Zhao et al. developed and studied a variable capacity geothermal heat pump system. The test results showed that the heat and cool capacity increased almost linearly by increasing frequency, while the COP presented different trends depending on water tank temperature (Zhao et al., 2003). Kuang et al. performed a multi-functional DX-SAHP system with a variable speed compressor for domestic use. The results indicated that the system could guarantee a long-term operation under very different weather conditions and relatively low running cost during the whole year (Kuang and Wang, 2006). Kong et al. conducted a simulation study of a DX-SAHP system, which was shown that with the increase of the compressor speed, the electric power to the compressor and the heating power increased, while the COP decreased (Kong et al., 2017). Li et al. proposed a closed loop feedback proportional integral (PI) control based on the superheat degree at the outlet of the solar collector in a DX-SAHP system. Results showed that more proper control algorithm should be improved and variable frequency compressor should be used in the DX-SAHP system to regulate the refrigerant flow cascaded with the electronic expansion valve (Li et al., 2007a, 2007b). Davide et al. presented a variable capacity heat pump with variable speed drives. The presented model could be used to develop a control strategy with double regulation and a proportional integral action to maximize the seasonal system performance (Davide et al., 2015).

Previous works investigated the thermal performance of variable capacity DX-SAHP systems from different aspects. Hawlader et al. presented a simulation study of the performances of DX-SAHP system using R134a with variable speed compressor. Results showed that the thermal performance of the system was affected significantly by the compressor speed. For a specific solar radiation intensity, a higher compressor speed led to a lower evaporating temperature in the solar collector/evaporator, which resulted in lower COP and higher collector efficiency (Hawlader et al., 2001). Chaturvedi et al. performed a DX-SAHP system with a variable speed compressor for domestic use. Results indicated that the system COP could be improved significantly by lowering the compressor speed when the ambient temperature raised, and the system COP was less sensitive to ambient temperature under the condition of higher compressor speed (Chaturvedi et al., 1998). However, there is a lack of experimental investigations into the effects of various parameters on the system performance using R134a as