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Experimental investigation of a solar driven direct-expansion heat pump system employing the novel PV/micro-channels-evaporator modules

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HIGHLIGHTS

- A novel PV/micro-channels-evaporator heat pump was experimentally investigated.
- The new module achieved higher thermal and electrical efficiency over the existing one.
- This is a highly efficient and practically feasible solar heat pump system.
- The testing thermal, electrical and overall efficiencies are 56.6%, 15.4% and 69.7%.
- The system had the average COP of 4.7 under the testing days.

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ABSTRACT

This paper aims to investigate a solar driven direct-expansion heat pump system employing the novel PV/micro-channels-evaporator modules, in terms of its solar thermal, electrical and overall efficiency, as well as coefficient of performance (COP), at the real-time operational condition. This work was undertaken through a dedicated system design, construction, field-testing and performance analysis. It was found that the novel PV/micro-channel-evaporator modules could achieve an average thermal, electrical and overall efficiency of 56.6%, 15.4% and 69.7% respectively at the specified operational condition, while average COP of the system reached 4.7. The innovative feature of the system lied in the structure of the evaporator that was made of the parallel-laid micro-channels. Such a structure created the reduced interior cross-sectional area and thus increased vapor flow velocity within the channels, while the high vapor velocity generated a higher shear stress exerted upon the liquid-vapor interface, leading to the reduced liquid film thickness, increased refrigerant evaporation rate, and increased electrical and heat outputs. The research has provided the fundamental data and experience for developing a highly efficient and practically feasible solar heat pump system applicable to the cold climatic conditions, thus contributing to significant fossil fuel saving and carbon reduction in the global extent.

1. Introduction

A heat pump has been proven to be an energy efficient heating technology that, compared to traditional gas-fired heating systems, can save around 50% of fossil fuel energy and consequently, the same percentage of CO_2 emission [1]. However, owing to a few inherent difficulties remaining with this technology, the use of the heat pumps for building space heating is still limited. At the present, there are 11 GW and 12.85 GW installed heat pump capacities in the UK and China, representing 38.2% and 5% of the nations' building heating market [2,3] respectively. The most outstanding challenges lie in the high demand for electrical power, and insufficient heat transfer between the heat source and the refrigerant within the heat pump. Development of a solar PV powered direct-evaporation heat pump has a potential to tackle these challenges.

A solar-assisted heat pump (SAHP) combines the heat pump with the solar collector, thus enabling the use of solar energy to provide space heating and hot water for buildings. Two types of SAHP, i.e., direct and indirect ones, are in existence [4]. The direct

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Nomenclature

A	area, m^2
C_p	specific heat of water, J/(g K)
G	solar radiation, W/m^2
P	power generation (PV); power consumption (pump and compressor), W
h	enthalpy of a refrigerant, J/g
T	storage water temperature, °C
M	mass flow rate, g/s
W	the weight of water in the storage tank, kg
COP	coefficient of performance
η_e	electrical efficiency of the PV/micro-channels-evaporator (PV/T) module
η_t	thermal efficiency of the PV/micro-channels-evaporator (PV/T) module
$\eta_{overall}$	overall energy efficiency of the PV/micro-channel-evaporator (PV/T) module
τ	interval time of the data collection, s
ε	PV cells spreading factor in the PV/micro-channels-evaporator (PV/T) module

Subscripts

PV	PV cells
PVT	PV/T module
R	refrigerant used in the system
comp	compressor
w	circulating water
wt	water in the heat storage tank
$^{o}_{wt}$	initial temperature of the water within the heat storage tank
$^{f}_{wt}$	final temperature of the water within the heat storage tank
i	inlet
o	outlet
j	quantity of the PV/T modules
pump	pump

type, termed as the 'direct-expansion', makes use of the solar collector as the heat pump evaporator, thus enabling the direct evaporation of the refrigerant within the solar collector by receiving the striking solar radiation [5]. In a direct SAHP, if a photovoltaic (PV) module is fitted to the upper surface of the evaporator module, a PV/evaporator module is thus generated [6]. This module could convert part of the absorbed solar energy into electricity that could be used to power the compressor, and meanwhile, convert other part of the absorbed solar energy into heat that could be used to evaporate the refrigerant within the channels. Given sufficient PV cells in the module and an adequately sized battery, the PV integrated direct expansion heat pump could be entirely powered by solar energy, thus yielding a near-to-zero carbon heating operation when the sunlight is available. Furthermore, as the evaporation temperature of the refrigerant is usually in the range 10–15 °C, the evaporator will cool the PV cells from its initial temperature of 50–60 °C [7] to eventually 15–20 °C. As the PV's electrical efficiency is adversely proportional to its temperature, the reduced PV temperature will lead to the enhanced solar electrical efficiency and reduced PV area and cost, compared to that at the normal temperature condition.

PV integrated evaporator is not a new concept and numerous researchers have worked on this for years. Ji et al. [8,9] developed a fin-tubing based PV/E module that was shown to yield electrical and thermal efficiencies of 12% and 50% respectively, and an average COP of 6.5. Chen et al. [10] investigated a fin-tubing based PV/E strip housed into a vacuum glazing tube, indicating that around 5% higher thermal and electrical efficiency can be achieved compared to Ji's configuration. Zhao et al. [11] investigated a finned-tubing based PV/E roof module, giving the predicted thermal and electrical efficiencies of 55% and 19%, and COP of 5.7. Zhang and Zhao et al. studied the performance of a novel solar photovoltaic/loop-heat-pipe heat pump system [11,12], indicating that the daily electrical, thermal and overall energetic efficiencies of the PV/LHP module were 9.13%, 39.25%, 48.37% respectively. Huang et al. [13] reported the performance of DX-SAHP under the frosting conditions, indicating that the solar irradiance of around 100 W/m^2 could prevent formation of the frosting when the ambient temperature is above −3 °C and the relative humidity is around 70%. Chow et al. [14] presented the theoretical study into a solar-assisted direct-expansion heat pump for water heating in a subtropical weather condition, indicating that the system can achieve an annual average coefficient of performance (COP) of 6.46, which is much better than that of the conventional heat pump systems. Mohanraj et al. [15] presented the feasibility of the artificial neural network (ANN) for use in predicting the performance of a direct expansion solar assisted heat pump, indicating that the Lavenberg-Marguardt (LM) with 10 neurons in the hidden layer is the most suitable algorithm with maximum correlation coefficients ($R2$) of 0.999, minimum root mean square (RMS) of 0.0075 and low coefficient of variance (COV) of 0.3363. Sun et al. [16] carried out the performance comparison between the conventional air source heat pump water heater (ASHPWH) and direct expansion solar-assisted heat pump water heater (DX-SAHPWH) under various operating conditions. Results show that, in clear day conditions, the COP of DX-SAHPWH was obviously higher than that of ASHPWH; while in overcast day conditions, COP of the both systems were almost the same. The average COP of the DX-SAHPWH system on annual base was remarkably higher than the conventional ASHPWH system, especially in winter season. Molinaroli et al. [17] provided a numerical analysis of a direct expansion solar assisted heat pump that uses R-407C as working fluid. The analysis was carried out through a steady state mathematical model, and the results indicated that the heat pump COP was strongly influenced by ambient temperature and solar radiation, whereas it is nearly independent on solar field surface. Moreno-Rodríguez et al. [5,18] carried out the theoretical model analysis and experimental validation of a direct-expansion solar assisted heat pump for domestic hot water applications. The results indicated that the theoretical COP could vary between 1.85 and 3.1, and the evaporation temperature varied between −8 °C and 18 °C. The maximum condensation temperature was 57 °C. The experimental COP was between 1.7 and 2.9, with an evaporation temperature of −20 °C and a condensing temperature of 30 °C and with an evaporation temperature of 20 °C and a condensing temperature of 60 °C, respectively. All the above case studies indicated that fin-tubing based structures have difficulty in achieving tight combination between the fins and the evaporating tubes, thus resulting in the increased contact thermal resistance and decreased heat transfer. The flat-plate structures were found to yield the enhanced electrical/thermal efficiencies and COP (5–10%) over the fin-tubing based ones owing to the good combination between the fins and rectangular tubes [19,20]. However, the use of the flat-plate tubes as the evaporator has high leakage and shape deformation risks that restricted its wide application in the heat pump projects.

Micro-channels are ideally suited for conducting heat transfer within small spaces, e.g. electronics, aerospace, and super-scale computing devices, where the large sized heat transfer elements