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A novel PV/T-air dual source heat pump water heater system: Dynamic simulation and performance characterization

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ABSTRACT

To enable the heat pump water heater maintain efficient operation under diverse circumstances, a novel PV/T-air dual source heat pump water heater (PV/T-AHPWH) has been proposed in this study. In the PV/T-AHPWH system, a PV/T evaporator and an air source evaporator connect in parallel and operate simultaneously to recover energy from both solar energy and environment. A dynamic model is presented to simulate the behavior of the PV/T-AHPWH system. On this basis, the influences of solar irradiation, ambient temperature and packing factor have been discussed, and the contributions of air source evaporator and PV/T evaporator are evaluated. The results reveal that the system can obtain efficient operation with the average COP above 2.0 under the ambient temperature of 10 °C and solar irradiation of 100 W/m^2. The PV/T evaporator can compensate for the performance degradation of the air source evaporator caused by the increasing condensing temperature. As the evaporating capacity in PV/T evaporator remains at relatively low level under low irradiation, the air source evaporator can play the main role of recovering heat. Comparing the performance of dual source heat pump system employing PV/T collector with that utilizing normal solar thermal collector, the system utilizing PV/T evaporator is more efficient in energy saving and performance improvement.

1. Introduction

The photovoltaic (PV) technology is recognized as an important approach to realize sustainable development and carbon emission reduction. To facilitate the development of PV technology, raising the electrical efficiency and cutting down the manufacturing cost are essential for technological innovation. As the conversion efficiency of PV cell descends with the rising operation temperature, so removing the excess heat from PV cell is the key for the performance improvement [1]. By combining normal solar thermal collector with PV cell, photovoltaic/thermal (PV/T) technology could harvest improved electrical efficiency and thermal energy with compact structure [2]. Kern et al. first proposed the concept of PV/T in 1978 [3]. Subsequently, the PV/T collectors with various structures utilizing different coolants have been investigated by researchers [4–6]. Bhattarai et al. compared PV/T system with PV panel and conventional collector, and the PV/T system was proven to be the most economical [7]. Guo et al. developed tri-functional photovoltaic/thermal collector, which could generate heated water/air and electricity simultaneously [8].

By integrating PV/T technology with direct-expansion solar assisted heat pump system, the refrigerant based PV/T heat pump was developed to attain better cooling effect for PV cell. Ji et al. analyzed the behavior of a solar assisted heat pump (SAHP) experimentally and theoretically, and the novel direct-expansion PV evaporator in the system could achieve satisfactory thermal and electrical performance [9,10]. Tsai developed a novel model for the PV/T heat pump system based on MATLAB, and the interaction between PV characteristic and environmental conditions was taken into consideration [11]. Zhou et al. investigated the behavior of a novel SAHP system employing the PV/micro-channels-evaporator with enhanced heat transfer capacity, and the average COP of 4.7 can be achieved in the field test [12]. Gunasekara et al. predicted the behavior of a PV/T evaporator in SAHP system by artificial neural network model, and the environment temperature and solar irradiation were identified as the most influential elements [13]. Bellos et al. evaluated a range of SAHP systems with different configuration forms, and the PV/T coupled heat pump is the most environmental friendly and economical solution for space heating [14].

As the solar irradiation and other outdoor climatic conditions randomly change with the ground latitude, seasonal conversion, circadian replacement and various complex meteorological factors, the working condition of solar assisted heat pump system is unpre-

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Nomenclature

u	velocity, m/s
t	time
P	power consumption, W
T	temperature, °C
p	pressure, Pa
c	specific heat, J/(kg·K)
$\dot{m}$	mass flow rate, kg/s
E	electricity output, W
Q	heat exchange capacity, W
h	specific enthalpy, J/kg
I	solar irradiation, W/m^2
x	vapor quality
U	overall heat transfer coefficient, W/(m^2·K)
R	thermal resistance, K/W
V	volume, m^3
M	mass, kg
v	specific volume, m^3/kg
L	length, m
S	pitch, m
N	the number of tube rows
g	gravitational acceleration, m/s^2
k	thermal conductivity, W/(m·K)
D	diameter, m
A	area, m^2
n	rotation speed, rad/s
Ra	Rayleigh number
Pr	Prandtl number
Re	Reynolds number
Nu	Nusselt number

Greek

α	heat transfer coefficient, W/(m^2·K)
β	absorptivity
γ	mass flow distribution ratio
ρ	density, kg/m^3
δ	thickness, m
σ	Stefane-Boltzman constant, W/(m^2·K^4)
η	efficiency
ε	emissivity
τ	transmittance
ζ	packing factor
γ	mass flow distribution ratio
θ	tilt angle, degree
κ	volume expansion coefficient
μ	dynamic viscosity, kg/(m·s)
χ	polytropic index

Subscripts

a	ambient/air
air	air source evaporator
ad	adhesive material
b	base panel
cap	capillary
con	condenser
com	compressor
dis	discharge
dt	domestic water tank
eva	evaporator
et	electrical
g	glass cover
i	inner
in	inlet
l	liquid
o	outer
out	outlet
pv	PV module
PV/T	PV/T evaporator
p	refrigerant pipe
r	reference
ref	refrigerant
s	insulation layer
sys	PV/T-AHPWH system
sky	sky
suc	suction
th	thermal
v	vapor
w	water

dictable, which causes the unstable operation of the system. Hawlader et al. indicated that the performance of direct expansion solar assisted heat pump is significantly influenced by solar irradiation [15]. For PV/T-assisted heat pump water, Tsai reported that the random variation of the outdoor environment has negative influence on the operation performance. Calise et al. proposed a novel SAHP system driven by PV/T collectors. In the study, the decrease of system performance was observed under the weather conditions with scarce solar irradiation [16,17].

Therefore, the concept of dual source heat pump was presented to continuously utilize solar energy and improve the system efficiency. Zhao et al. presents a dual source heat pump by introducing buffer storage to deposit the heat generated by air source heat pump and the collected solar energy [18]. Chargui et al. introduced control function for a dual source heat pump applied in residential building during winter. In the study, the heat load, consumed energy and temperature distribution were investigated based on TRNSYS software [19]. Wang et al. proposed a dual source heat pump system by designing a novel evaporator which combined the hot water channel with heat transfer fins. In the evaporator, the hot water channel transferred energy from PV/T collector to refrigerant, and the heat transfer fins could absorb energy from the ambient [20]. To explore the application of dual source heat pump in cold climate zone, Shan et al. integrated an active solar heating system with air source heat pump and conducted field test in a full-scale house [21]. Cai et al. applied dual source in the multi-functional heat pump with air source and solar energy working for the system alternately [22]. However, most previous dual source heat pumps combined with solar energy in indirect ways, which brought about complex structure and high initial investment. There was rarely report about the dual source heat pump with double evaporators, which involves both the air source evaporator and PV/T collector into the refrigerant cycle simultaneously. And the performance of PV/T collector in dual source heat pump system has been rarely evaluated.

To improve the performance of heat pump water heater under a wide range of operating conditions, a novel PV/T-air dual source heat pump water heater (PV/T-AHPWH) has been proposed. In the PV/T-AHPWH system, the air source evaporator and PV/T evaporator in parallel combination operate simultaneously to absorb energy from solar energy and environment. The two evaporators can compensate for the inefficiency under adverse operating conditions to enable the PV/T-AHPWH system to obtain relatively high COP. A dynamic model is presented to simulate the behavior of the PV/T-AHPWH system. In particular, a two-dimensional model for PV/T evaporator is embedded into main program. The influences