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Performance study of heat-pipe solar photovoltaic/thermal heat pump system

Hongbing Chen [a], Lei Zhang [a], Pengfei Jie [b,*], Yaxuan Xiong [a], Peng Xu [a], Huixing Zhai [a]

[a] Beijing University of Civil Engineering and Architecture, Beijing 100044, PR China
[b] School of Mechanical Engineering, Beijing Institute of Petrochemical Technology, Beijing 102617, PR China

HIGHLIGHTS

- The testing device of HPS PV/T heat pump system was established by a finished product of PV panel.
- A detailed mathematical model of heat pump was established to investigate the performance of each component.
- The dynamic and static method was combined to solve the mathematical model of HPS PV/T heat pump system.
- The HPS PV/T heat pump system was optimized by the mathematical model.
- The influence of six factors on the performance of HPS PV/T heat pump system was analyzed.

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ABSTRACT

A heat-pipe solar (HPS) photovoltaic/thermal (PV/T) heat pump system, combining HPS PV/T collector with heat pump, is proposed in this paper. The HPS PV/T collector integrates heat pipes with PV panel, which can simultaneously generate electricity and thermal energy. The extracted heat from HPS PV/T collector can be used by heat pump, and then the photoelectric conversion efficiency is substantially improved because of the low temperature of PV cells. A mathematical model of the system is established in this paper. The model consists of a dynamic distributed parameter model of the HPS PV/T collection system and a quasi-steady state distributed parameter model of the heat pump. The mathematical model is validated by testing data, and the dynamic performance of the HPS PV/T heat pump system is discussed based on the validated model. Using the mathematical model, a reasonable accuracy in predicting the system's dynamic performance with a relative error within ±15.0% can be obtained. The capacity of heat pump and the number of HPS collectors are optimized to improve the system performance based on the mathematical model. Six working modes are proposed and discussed to investigate the effect of solar radiation, ambient temperature, supply water temperature in condenser, PV packing factor, heat pipe pitch and PV backboard absorptivity on system performance by the validated model. It is found that the increase of solar radiation, ambient temperature and PV backboard absorptivity leads to the increase of the coefficient of performance based on thermal (COP_{th}) of HPS PV/T heat pump system, while the increase of supply water temperature in condenser, PV packing factor and heat pipe pitch leads to the decrease of COP_{th}. Furthermore, the increase of solar radiation and packing factor leads to the increase of the advanced coefficient of performance based on both thermal and electrical performances ($COP_{PV/T}$), while the $COP_{PV/T}$ decreases as the ambient temperature, supply water temperature in condenser and heat pipe pitch increase. The PV backboard absorptivity has little influence on the $COP_{PV/T}$ of HPS PV/T heat pump system.

1. Introduction

Shortwave radiation can be converted to electricity using photovoltaic (PV) technology. However, the photoelectric conversion efficiency is only 5–20% [1]. It is found that the photoelectric conversion efficiency is dependant on the temperature of PV cells [2–4]. When the PV cells' temperature is higher than 25 °C, the temperature increase of every 1 °C results in the reduction of power generation efficiency by 0.5% [5,6]. It is also observed that the extracted heat from PV panel could be employed for use by photovoltaic/thermal (PV/T) technology [7]. Moreover, the

* Corresponding author.
E-mail address: jpfteam@163.com (P. Jie).

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Nomenclature

Parameters

A	area, m^2
Bo	boiling coefficient
c	specific heat capacity, J/(kg·K)
D	diameter, m
De	equivalent diameter, m
h	enthalpy, J/kg
H	height, m
G	solar radiation intensity, W/m^2
k	thermal conductivity, W/m^2
L	length, m
m	mass flow, kg/s
M	mass, kg
N	power, W
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Q	heat exchange, W
q	heat flow, W/m^2
r	latent heat of vaporization, kJ/kg
R	thermal resistance, (m^2·K)/W
re	reflectivity
Re	Reynolds number
T	temperature, °C
t	time, s
u	flow velocity, m/s
v	mass flow per unit area, kg/(m^2·s)

Greek letters

α	absorptivity; heat transfer coefficient, W/(m^2·K)
γ	PV packing factor
δ	thickness, m
ε	emissivity
η	efficiency
θ	installation angle
μ	coefficient of kinetic viscosity, N·s/m^2
ξ	porosity of the wick
ρ	density, kg/m^3
σ	Stefan-Boltzman constant, W/(m^2·K^4)
t	transmissivity
χ	dryness

Subscripts

a	air
Al	aluminum sheet
b	backboard; boil
c	condenser, condensation
co	collector
cr	refrigerant in condenser
cri	critical
cw	water in condenser
cap	capillary
com	compressor
e	evaporator, evaporation
ex	exergy efficiency
exp	experimental value
ele	electrical
eq	equivalent
ei	heat conduction silica gel
ew	water in evaporator
$hpeva$	evaporation section of heat pipe
$hpcon$	condensation section of heat pipe
in	thermal insulation material
i	in; inlet
g	glass cover
l	liquid
o	out; outlet
ov	overall efficiency
pv	PV panel
pv/t	photovoltaic/thermal
r	refrigerant
R	reference
sat	saturation
sh	superheated
sim	simulation value
sp	sing phase
th	thermal
tp	two phase; traditional thermal power generation
tw	tube wall
v	vapor
w	water
wm	water in manifold
wt	water in storage tank
$wick$	liquid wick of heat pipe

photoelectric conversion efficiency could be improved due to the reduction of PV cells temperature. But it's difficult to make full use of the extracted heat because of the intermittency of solar energy and low collector efficiency of PV panel. Therefore, various PV/T panels have been put forward in previous studies, including air-cooled PV/T panel [8–16], water-cooled PV/T panel [17–26], direct-expansion PV/T panel [27–32], heat-pipe solar (HPS) PV/T panel [33–38] and HPS PV/T heat pump system [39–43].

The simplest method to cool down PV cells is air-cooled PV/T panel by natural or mechanical ventilation [8–16]. However, the natural ventilation method is restricted by weather conditions, and the mechanical ventilation method has a high cost. In addition, the increase of photoelectric conversion efficiency for this structure is poor due to the limited cooling effect. Alternatively, a circulating water channel could also be used to extract heat from PV panel [17]. The cooling effect of this method is better than that of air-cooled panel, but the inner structure of PV cells could be destroyed in cold weather conditions due to the freeze of water pipe on the backboard of PV panel. A more advanced PV/T structure is direct-expansion PV/T panel. Evaporation coils are placed beneath PV panel so that the refrigerant can pass through it [27]. The PV cells in this structure can be cooled down to a very low temperature, leading to higher photoelectric conversion efficiency and better utilization of the extracted heat. But this structure has some inherent problems, such as a mass use of copper coils and gas tightness.

As for the heat-pipe solar (HPS) PV/T structure, heat pipes are integrated with PV panel so that PV cells can be cooled down to a relatively low temperature. In addition, the freeze of water pipes can be avoided by using heat pipes. Pei et al. [34] designed a novel HPS PV/T system and developed a dynamic model to predict the performance of this system. The results indicated that the thermal efficiency was 41.9% and the electrical efficiency was 9.4%. Zhang et al. [35] established a simulation model of the HPS PV/T system using TRNSYS. The tank volume of the HPS PV/T system was optimized, the electric power generation was also calculated and the