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Dynamic performance of a novel solar photovoltaic/loop-heat-pipe heat pump system

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HIGHLIGHTS

- A transient model was developed to predict dynamic performance of new PV/LHP system.
- The model accuracy was validated by experiment giving less than 9% in error.
- The new system had basic and advanced performance coefficients of 5.51 and 8.71.
- The new system had a COP 1.5–4 times that for conventional heat pump systems.
- The new system had higher exergetic efficiency than PV and solar collector systems.

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ABSTRACT

Objective of the paper is to present an investigation into the dynamic performance of a novel solar photovoltaic/loop-heat-pipe (PV/LHP) heat pump system for potential use in space heating or hot water generation. The methods used include theoretical computer simulation, experimental verification, analysis and comparison. The fundamental equations governing the transient processes of solar transmission, heat transfer, fluid flow and photovoltaic (PV) power generation were appropriately integrated to address the energy balances occurring in different parts of the system, e.g., glazing cover, PV cells, fin sheet, loop heat pipe, heat pump cycle and water tank. A dedicated computer model was developed to resolve the above grouping equations and consequently predict the system's dynamic performance. An experimental rig was constructed and operated under the real weather conditions for over one week in Shanghai to evaluate the system living performance, which was undertaken by measurement of various operational parameters, e.g., solar radiation, photovoltaic power generation, temperatures and heat pump compressor consumption. On the basis of the first- (energetic) and second- (exergetic) thermodynamic laws, an overall evaluation approach was proposed and applied to conduct both quantitative and qualitative analysis of the PV/LHP module's efficiency, which involved use of the basic thermal performance coefficient (COP_{th}) and the advanced performance coefficient ($COP_{PV/T}$) of such a system. Moreover, a simple comparison between the PV/LHP heat-pump system and conventional solar/air energy systems was conducted. The research results indicated that under the testing outdoor conditions, the mean daily electrical, thermal and overall energetic and exergetic efficiencies of the PV/LHP module were 9.13%, 39.25%, 48.37% and 15.02% respectively, and the average values of COP_{th} and $COP_{PV/T}$ were 5.51 and 8.71. The PV/LHP module was found to achieve 3–5% higher solar exergetic efficiency than standard PV systems and about 7% higher overall solar energetic efficiency than the independent solar collector. Compared to the conventional solar/air heat pump systems, the PV/LHP heat pump system could achieve a COP figure that is around 1.5–4 times that for the conventional systems. It is concluded that the computer model is able to achieve a reasonable accuracy in predicting the system's dynamic performance. The PV/LHP heat pump system is able to harvest significant amount of solar heat and electricity, thus enabling achieving enhanced solar thermal and electrical efficiencies. All these indicate a positive implication that the proposed system has potential to be developed into a high performance PV/T technology that can contribute to significant fossil fuel energy saving and carbon emission.

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Nomenclature

A	area (m^2)
c	specific heat capacity (J/kg K)
D	diameter (m)
Ex	exergy rate (W)
g	gravity acceleration (m/s^2)
h	heat transfer coefficient (W/m K)
h_c	convective heat transfer coefficient (W/m K)
h_m	hour angle (rad)
h_R	radiative heat transfer coefficient (W/m K)
H	thermal enthalpies (kJ/kg)
H_{hx}	height of heat exchanger plate (m)
I	solar radiation intensity (W/m^2)
k	thermal conductivity (W/m^2 K)
K	extinction coefficient of glass cover
L	length (m)
L_m	local latitude
m	mass flow rate (kg/s)
M	mass (kg)
n	mesh number; iteration number
n_g	ratio of refraction index
N	number
Nu	Nusselt number
q	energy rate per unit area (W/m^2)
Q	energy rate (W)
Pr	Prandtl number
R	thermal resistance (K/W)
Ra	Rayleigh number
Re	Reynolds number
t	time
T	temperature (K)
T_{sun}	the solar radiation temperature at 6000 K
V	velocity (m/s)
W	width (m)
x	width parameter
x_r	refrigerant saturation rate

Greek

α	absorption ratio
β_p	PV packing factor
β_{PV}	cell efficiency temperature coefficient
$r_{\parallel}$	parallel components of unpolarized radiation for smooth surfaces
$r_{\perp}$	perpendicular components of unpolarized radiation for smooth surfaces
δ	thickness (m)
δ_m	declination angle (rad)
ε	emissivity; porosity
ξ	exergy efficiency
η	energy efficiency
θ	collector slop (degree)
θ_1	incidence angle (rad)
θ_2	refraction angle of direct solar beam (rad)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant
τ_c	cover transmittance
$\tau_{c,a}$	transmittance due to absorption

Subscripts

a	air
b	backplane
c	cover
e	electricity
ei	electrical insulation
e, n	net electricity
EVA	ethylene–vinyl-acetate
f	fin sheet
fc	centre of fin sheet
fe	edge of fin sheet
fs	insulation around fin sheet
hp	heat pipe
hp, in	heat pipe inner wall
hp, o	heat pipe outer wall
hp, w	heat pipe wall
hx	heat exchanger
hx, in	heat exchanger inner space
hx, o	heat exchanger outer space
hx, r	refrigerant in heat exchanger
i	differential length node 'i'
k	differential time node 'k'
l	liquid
lf	liquid film
m	mean, module
p	PV
r	refrigerant
r, e	refrigerant evaporator
r, l	liquid refrigerant
rc	reference temperature
r, m	mean refrigerant
s	solid; sky
th	thermal
o	overall
v, e	vapour core in evaporator
w	water
wi	wick
ws	insulation of water tank
ws, in	inner tank insulation
ws, o	outer tank insulation

1. Introduction

Solar energy technology is one of the most important renewable technologies for heating and/or power generation, which, by 2030, expects to provide nearly 50% of the low and medium temperature heat in the EU [1] and 5% of global electricity demand [2]. The PV is currently the most popular solar power device that has the temperature-dependant solar electrical output. It is understood that increasing temperature of PV cells by 1 °C would lead to 0.5% reduction in the solar electrical efficiency for the crystalline silicon cells and around 0.25% for the amorphous silicon cells [3,4]. To control the cell temperature, several measures were applied to remove the accumulated heat from the back surface of PV modules and further to make advanced utilisation of the removed heat. This approach, known as the PV/Thermal (PV/T) technology, enables the dual solar collecting functions in one module for output of both electricity and heat. Such synergetic integration of PV and thermal collector not only results in improved PV efficiency, but also generates more energy per unit area whilst compared with conventional solar collecting devices. Additional characteristics of the PV/T technology lie in potential saving in material use, reduction in installation cost and homogeneous facade appearance. It is now becoming a significant solution to yield more electricity and offset heating load freely in contemporary energy environment.