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Theoretical investigation of the energy performance of a novel MPCM (Microencapsulated Phase Change Material) slurry based PV/T module

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ABSTRACT

Aim of the paper is to present a theoretical investigation into the energy performance of a novel PV/T module that employs the MPCM (Micro-encapsulated Phase Change Material) slurry as the working fluid. This involved (1) development of a dedicated mathematical model and computer program; (2) validation of the model by using the published data; (3) prediction of the energy performance of the MPCM (Microencapsulated Phase Change Material) slurry based PV/T module; and (4) investigation of the impacts of the slurry flow state, concentration ratio, Reynolds number and slurry serpentine size onto the energy performance of the PV/T module. It was found that the established model, based on the Hottel–Whillier assumption, is able to predict the energy performance of the MPCM slurry based PV/T system at a very good accuracy, with 0.3–0.4% difference compared to a validated model. Analyses of the simulation results indicated that laminar flow is not a favorite flow state in terms of the energy efficiency of the PV/T module. Instead, turbulent flow is a desired flow state that has potential to enhance the energy performance of PV/T module. Under the turbulent flow condition, increasing the slurry concentration ratio led to the reduced PV cells' temperature and increased thermal, electrical and overall efficiency of the PV/T module, as well as increased flow resistance. As a result, the net efficiency of the PV/T module reached the peak level at the concentration ratio of 5% at a specified Reynolds number of 3,350. Remaining all other parameters fixed, increasing the diameter of the serpentine piping led to the increased slurry mass flow rate, decreased PV cells' temperature and consequently, increased thermal, electrical, overall and net efficiencies of the PV/T module. In overall, the MPCM slurry based PV/T module is a new, highly efficient solar thermal and power configuration, which has potential to help reduce fossil fuel consumption and carbon emission to the environment.

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 low and medium temperature heat [1] and 5% of total electricity demand [2] within the EU. The PV is currently the most popular solar power device that has the temperature-dependent electrical output. It is understood that increasing temperature of the PV cells by 1 °C would lead to 0.5% reduction in solar electrical efficiency for the crystalline silicon cells and around 0.25% for the amorphous silicon cells [3,4]. To control the temperature of the cells, several measures were applied to remove the accumulated heat from the rear of the PV modules and further to make good utilization of the removed heat. This approach, known as the PV/Thermal (PV/T) technology, has been proven to be effective in increasing the system's solar conversion ratio and making economic use of solar energy.

The commonly used fluids for cooling the PV cells in a PV/T module are air, water and refrigerant. The air based PV/T system has relatively poor heat removal effectiveness owing to air's lower density, specific heat capacity and thermal conductivity, resulting in around 8% and 41% of peak electrical and thermal efficiencies

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Nomenclature

A	effective module area (m^2)
A_φ	factor
$A_{c,f}$	cross area of fluid flow (m^2)
$A_{hx,r}$	cross area of the refrigerant in heat exchanger (m^2)
C_p	specific heat capacity
$C_{p,lr}$	specific heat capacity of the liquid refrigerant (J/kg K)
D	diameter (m)
F	standard fin efficiency
F_R	heat removal factor
F'	thermal efficiency factor
f_{pv}	PV cell packing factor
g	gravity acceleration (m/s^2)
h_c	convection heat transfer coefficient (W/m K)
h_R	radiation heat transfer coefficient (W/m K)
I	solar radiation intensity (W/m^2)
K	thermal conductivity (W/m^2 K)
L	length (m)
L_1	preheating region length (m)
L_2	phase change region length (m)
m	fin variable
$\dot{m}$	mass flow rate (kg/s)
m_r	mass flow rate of the refrigerant (kg/s m^2)
m_w	mass flow rate of water (kg/s)
N_p	U-turn number plus 1
Nu	Nusselt number
p	pressure (pa)
q	energy rate per unit area (W/m^2)
Q	energy rate (W)
Pr	Prandtl number
R	thermal resistance (K/W)
R_0	universal gas constant (kJ/kmol K)
r	thermal resistance per square meter (m^2 K/W)
R_a	Rayleigh number
S	heat absorbed per unit area by module (W/m^2)
Ste	Stefan number
T	thermodynamic temperature (K)
t	temperature (Co)
U	overall heat coefficient (W/m K)
v	velocity (m/s)
W	width (m)
w	mass fraction

Subscripts

a	air
abs	absorption
b	bond
bp	backplane
fin	fin
c	cover, convection
c_{in}	internal glass cover
c_{ex}	external glass cover
$core$	core of the MPCM particle
$shell$	shell of the MPCM particle
$particle$	MPCM capsule (particle)
$slurry$	MPCM slurry
water	carrying fluid (water)
e	electricity
ei	electrical insulation
e,n	net electricity
EVA	ethylene–vinyl-acetate
f	fluid, i.e., water or slurry
g,pv	glass layer of PV limitation
i	inner
L	loss
m	mean
n	mesh number
o	outer, overall
p	absorb pipe (tube)
$p,_w$	absorb pipe wall
pv	PV cell
$pv-fin$	PV lamination to fin sheet
R	radiation
rt	reference temperature
s	solid; isentropic
th	thermal
u	useful

Greek

α	absorption ratio
β_p	PV cell area factor
β_{pv}	PV cell efficiency temperature coefficient (1/°C)
δ	thickness (m)
ε	emissivity
η	efficiency
θ	collector slop angle (deg)
λ	fluid flow friction factor
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant
φ	volumetric concentration ratio
μ	dynamic viscosity (kg/m s)
τ	visual transmittance

respectively [5]. The water-based PV/T system is a different development that supposed to overcome the disadvantages of the air-based system. This type of system can obtain solar electrical and thermal efficiencies of 9.1% and 41.9% respectively [6], slightly better than the air-based system owing to the limitation of continuous growth of the water temperature over the operational period. To maintain a steadily lower PV temperature, the refrigerant-based PV/T system is proposed to install the evaporation coils underneath the PV module that allows a low temperature refrigerant to flow through. This could lead to a significant increase in the electrical and thermal efficiencies of PV/T module, reaching around 12% and 50% respectively [7]. Despite of these advantages, the refrigerant-based PV/T technology faces several practical challenges, i.e., high risk of refrigerant leakage and uneven refrigerant flow/distribution across the multiple coils in a large area [8].

PCMs (Phase Change Materials) are chemical substances that change phase from solid to liquid when absorbing heat from an energy source or from liquid to solid when releasing heat to an energy sink, whilst the temperature of the materials remain constant. The PCMs normally have higher thermal capacity owing to the latent heat contained in the heat transfer process and are therefore, suitable for use in PVs' heat collection. PCMs are broadly classified as organic materials (e.g., paraffin and non-paraffin) and inorganic materials (e.g., salt hydrates, eutectics pentaerythiol and pentaglycerine); both classes contain materials with phase change temperatures in the range 15–30 °C, which is the desired