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Research Paper

Numerical study of an inclined photovoltaic system coupled with phase change material under various operating conditions

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HIGHLIGHTS

- A numerical study of PCM layer attached behind PV panel is performed.
- Phase change process of a PCM is studied under Tunisian climate.
- 9 g/m^2 of dust deposition reduces PV panel power output of about 3 W at midday.
- Wind direction increase from 30° to 60° rises PV panel temperature from 64 °C to 69 °C.

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ABSTRACT

Photovoltaic panels suffer from high temperatures. A large part of absorbed solar radiation is converted into heat, which causes heating of PV cells and therefore leads to decrease PV efficiency. The effect of integrating different PCMs with different thicknesses is studied. Coupling photovoltaic panel with the suitable macro-encapsulated phase change material layer is important for having better thermal regulation of PV panel. In the current thermodynamic investigation, melting and solidification processes of the selected PCM are carried out. To achieve a realistic simulation of heat and mass transfer of PV-PCM system, it is very important to analyze the effects of the following exterior operating conditions on PV panel performance: wind direction, wind speed and dust accumulation. Dust deposition density of 3 g/m^2, 6 g/m^2, and 9 g/m^2 reduces electrical power of about 1.2 W, 2.8 W and 3 W, respectively. Moreover, the increase of wind speed leads to increase the heat losses due to forced convection and therefore reduces PV panel temperature. Eventually, wind azimuth angle increase causes an increase in the operating temperature of the PV panel.

1. Introduction

One of the renewable energy technologies that are being promoted is solar energy; such energy is known to have the potential of generating electricity directly by using solar photovoltaic or by converting heat into electricity from solar thermal energy. Photovoltaic cells can absorb up to 80% of the incident solar radiation available in the solar spectrum. However, only a limited amount of the absorbed incident energy is converted into electricity depending on the conversion efficiency of the PV cell technology. The high temperature of PV modules reduces the efficiency of a PV system by 0.4–0.5% per K [1,2]. The operating temperature of the PV panel usually varies between 40 °C and 85 °C in hot climates [3] and could exceed the upper range in some real cases in summer as presented in [4]. Several studies have considered PV panel as a building element. Therefore, thermal regulation of a building integrated photovoltaic (BIPV) module is required to enhance its electrical efficiency and to increase its power output. So far, several methodologies have been used for thermal regulation of PV panel such as active cooling or passive cooling methods.

Active cooling methods require external devices, such as pumps to pump water or fans to force air, in order to maintain the temperature of the BIPV system at a level consistent with higher power output. For instance, pumping water for cooling in locations characterized by great potential of solar energy, like deserts, may be unsuitable because water is rare. Moreover, it causes an insupportable maintenance that leads to increase the operating costs.

To reduce the temperature rise of a BIPV system using active techniques, Yun et al. [5] have studied the effect of ventilated wall-integrated PV system with an opening behind the PV. The findings have led to a rise of about 2.5% in the electrical output of PV panel.

Lu et al. [6] studied the annual thermal performance of a BIPV system. In this paper, authors have discussed mainly the impact of the

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Nomenclature

A	upper surface of the PV panel (m^2)
A_{pv}	surface area of PV panel (m^2)
Ai	anisotropy index
B	liquid fraction of PCM
Cp	specific heat capacity (J/kg K)
D	Dirac delta function
F	the view factor
F_T	absorbed solar radiation with dust deposition (W/m^2)
FF	fill factor
f	correction coefficient
Gr	Grashof number
G_T	incident solar radiation (W/m^2)
g	acceleration due to gravity (m/s^2)
k	thermal conductivity (W/m K)
$K_{\tau\alpha}$	Incidence angle modifier
Lf	latent heat (J/kg)
L_c	characteristic length (m)
M	air mass modifier
M_{ref}	reference air mass modifier
P	pressure (Pa)
Pr	Prandtl number
Q	internal heat generation (W/m^3 K)
Re	Reynolds number
Ra	Rayleigh number
T	temperature (°C)
$T_{e,amb}$	exterior ambient temperature (°C)
T_{sky}	sky temperature (°C)
T_{PV}	PV panel temperature (°C)
T_{ref}	temperature at standard condition (°C)
T_f	fusion temperature (°C)
TES	thermal energy storage
T	time (s)
u	velocity of PCM in x direction (m/s)
v	velocity of PCM in y direction (m/s)
v_{air}	wind velocity (m/s)
$v_{pv,cell}$	volume of the PV cells (m^3)
ΔT	transition temperature (°C)

Greek symbols

α	angle of inclination with the horizontal (°)
α_p	thermal expansion factor of air (1/K)
α_p	absorptivity of the glass cover
β	thermal expansion coefficient of PCM (1/K)
β_{ref}	temperature coefficient (1/K)
$\Delta\tau$	transmittance reduction
ε_{glass}	surface emissivity of the glass
ε_{al}	aluminum emissivity
γ_{pv}	PV panel orientation (°)
γ_w	wind direction (°)
η_{pv}	electrical efficiency
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ρ_g	ground reflectance (albedo)
ρ_D	dust deposition density (g/m^2)
σ	Stefan–Boltzmann constant ($W/m^2 K^4$)
τ	transmittance of polluted panel
$(\tau\alpha)(\theta)$	transmission/absorptance product
θ	incidence angle of solar radiation (°)
θ_r	refraction angle (°)

Abbreviation

AM	air mass
BIPV	building integrated photovoltaic
HDKR	Hay, Davies, Klucher, Reindl
PCM	phase change material
PV	photovoltaic
PV-PCM	Photovoltaic phase change material
STC	standard test conditions

Subscripts

a	air
al	aluminum
b	beam radiation
b,n	beam radiation at normal incidence angle
c	characteristic
d	diffuse
e,amb	exterior ambient
g	ground
liq	liquid phase
n	normal incidence angle
r	refraction
solid	solid phase
T	titled

thickness of an air duct on the thermal performance of the system.

A global comprehensive review could be observed in the researches of Sargunanathan et al. [7].

Passive cooling methods are based on the application of absorbing materials of heat excess released by the photovoltaic panel. The integration of PCM on the back side of a PV panel is a preferable passive cooling method since it needs less operating and maintenance costs compared to active cooling techniques [8], it does not require any intervention of external devices and additional energy [9] thanks to its ability of storing and releasing heat [10].

PCMs undergo a reversible phase change process depending on their fusion temperature. They absorb/release heat during their fusion/solidification phase change. The selection of the ideal PCM for a better thermal regulation of PV panel is very important. Hence, an appropriate PCM for such application must bear several criteria: large latent heat of fusion, high thermal conductivity, chemically stable, non-corrosive, non-toxic and its melting temperature must be within the PV system's operating range [11].

PCMs are mainly classified as non-organic, organic and eutectics PCMs [12].

Non-organic PCM: Hydrated salts are the most frequently used PCM in this category. They have high latent heat storage capacity, non-flammable and they are available at low prices. However, their main disadvantage is that their super cooling problem during phase change process which leads to irreversible transition phase [13].

Organic PCMs: Paraffin, carbohydrate and fatty acids are the most used PCMs for thermal energy storage in this group. Being recyclable, having the ability of melting congruently, having high heat of fusion and freezing without much under-cooling compared to inorganic PCMs [14] are their most known advantages. However, they have low thermal conductivity in their solid state and can be available at high prices [11].

Eutectic: Eutectic is a mixture of pure compounds with a volumetric storage density slightly higher than organic substances. However, their thermo-physical properties data are limited because the use of such materials is new for energy storage applications.