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Optical and thermal modeling of a tilted photovoltaic module with sand particles settled on its front surface

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ABSTRACT

The lifted dust particles from the ground and the dust particles existing in the air all can deposit on the surface of a PV (photovoltaic) module. These particles create a dust cover on the module front surface and reduce incident solar energy to the module glass surface. This study aimed to analysis a tilted PV module with dust deposition on its front surface. The optical-thermal modeling of the PV module was carried out. The present research paid special attention to the dust layer settled on the PV module front surface. The dust layer was modeled from the thermal and optical point of views. A new optical model as well as a modified thermal model were developed and tested. The optical model was inspired by a few past studies. The optical-thermal model was verified with the measured data available in the literature. The results of the model showed reasonable quantitative and qualitative predictions in different conditions of the module surface. For instance, the results showed that the maximum power of a 30° tilted dusty PV module with 0.224 mg/cm^2 dust deposition density on its surface, is 13.53%lower than the clean tilted PV module. This study is highly useful in dusty regions and can help the PV designer to predict the power of the PV module with a good accuracy.

1. Introduction

The dust particle lifted from the ground due to a wind force or other activities and the dust particles transporting in the air, both can settle on the front surface of a PV (photovoltaic) module. These particles create a dust layer on the PV module surface and cause a reduction of incident solar energy on the module glass surface. The studies of dust deposition effects on a PV module performance have been done experimentally and theoretically. Most of these studies have been carried out experimentally and only a few studies have theoretical base. The experimental studies mainly focused on the optical characteristics of a PV module with dust deposition on its surface. For instance, Garg investigated the effect of dust deposition over a PV module surface on the incident solar energy reduction of a tilted PV module. He showed that the correction factor of incident solar radiation for a 45° tilted PV module with dust settlement is 0.92 [1]. Nahar and Gupta investigated solar radiation reduction of different materials used in a solar collector with dust deposition on its surface in the Tar desert. They showed that as the time interval of clean up processes increase, more solar radiation reduction is seen and this decreases at a higher tilt angle of PV module [2]. Said studied the performances of two solar collectors and a PV module in some dusty months of the year. He revealed that the output power of the PV module decreased 7% and the thermal performances of the two collectors reduced between 2.8% and 7% in each month due to the dust deposition [3]. Hassan and Sayigh placed a number of small pieces of glasses in a chamber and blew dust particles on them. They revealed that the transmittance curves of the glasses were qualitatively the same as the clean one, but the transmittance values were different. The difference enhances as the dust deposition increases on the glasses. They also found that the reflections of the glasses increase with increase of dust deposition in all the visible wavelengths [4]. El-Shobokshi and Hussein investigated different dust deposition densities on a PV module as well as different dust particle sizes and materials. They revealed that the smaller sizes decrease the transmittance more compared to the larger one. They also indicated that the PV module performance depends on the dust particle size distribution and its materials as well as dust mass fluxes. They showed that these three parameters are more important in the PV module power reduction compared to the

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Nomenclature

A	Absorption
$A^*_{c(\theta)}$	dimensionless dust covered area
C	Thermal capacity (kJ/kg °C)
d_p	dust particle diameter (μm)
E	energy (J)
f_w	working factor of the solar cell
F	radiation shape factor or view factor
G	irradiance (W m^{-2})
g	gravitational acceleration (ms^{-2})
Gr	Grash of number
h_B	convection heat transfer on back surface (W m^{-2} K^{-1})
h_F	convection heat transfer on front surface (W m^{-2} K^{-1})
J	Dust deposition density (kgm^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
L	length of PV module (m)
l_{ch}	characteristic length
M_i	equivalent transmission of single layer i
$\overline{M_i}$	inverse equivalent transmission of single layer i
n	Number of desired days
n_i	refractive index of layer i
N_i	equivalent reflection of single layer i
$\overline{N_i}$	inverse equivalent reflection of single layer i
Nu	Nusselt number
Pr	prandtel number
$\dot{Q}$	Heat transfer rate W
R_{h1}	heat resistance between Si layer and glass (m^2 K W^{-1})
R_{h2}	heat resistance between Si layer and tedlar (m^2 K W^{-1})
Ra	Rayleigh number
Re	Reynolds number
T_{amb}	ambient temperature (K)
T_1	Temperature of Si cell (K)
T_2	temperature of glass (K)
T_3	temperature of tedlar (K)
V_{wind}	local wind speed (m s^{-1})
W	width of solar cell panel (m)
α_i	absorption coefficient (m^{-1})
α	thermal diffusivity (m^2 s^{-1})
β_{el}	temperature coefficient of Si cell (K^{-1})
δ	Sun declination angle
δ_i	layer thickness (m)
φ	latitude (°)
ε	emittance
γ	azimuth angle (°)
B	tIlt angle ( )
ω	hourly angle (°)
η_{el}	efficiency of PV module
λ	wavelength (μm)
θ	angle (°)
ρ	reflection
$\overline{\rho}$	inverse reflection
σ	Stefan–Boltzmann constant
τ	transmission
$\overline{\tau}$	inverse transmission
ϑ	viscosity (m^2 s^{-1})

Subscripts

amb	ambient
B	back surface
cond	conduction
conv	convection
cr	critical
F	front surface
Gen	generation
in	incidence
out	outlet
rad	radiation
st	storage
d	dust
g	glass

exposed time of PV module to the dust deposition, [5]. Goossens and Kerschaever investigated the combined effects of wind velocity and particle concentration on the performance of a PV module inside a wind tunnel. They showed that lower wind velocities lead to lower particle depositions on the PV module and in this case the transmittance of incident solar energy due to creating a uniform dust cover gets better compared to the higher wind speeds [6]. However, they also showed that higher dust concentrations cause higher dust depositions and consequently higher reduction of PV module performance, [6]. Hegazy studied the effect of dust particle deposition on the transmittance reduction of several tilted glasses during one year in Minia-Egypt. He showed that the transmittance reductions of the glasses highly depend on the dust deposition density, which depends on the glass tilt angle and the exposed time of glass to the dust particle in the study region [7]. Elminir and et al. made some boxes in which several small glasses embedded on their surfaces. The glazes on the box surface were fixed at different tilt angles. Each box was set at an azimuth angle. They showed that the transmittance reduction depends on wind velocity, tilt angle, azimuth angle as well as dust deposition density on the glass, [8]. Casanova et al. showed that the loss of average daily solar energy during a year due to dust deposition on PV module is 4.4%. They also showed that this loss approaches 20% in case of no rain precipitation in the region, [9]. Adinoyi and Said investigated the effect of dust deposition on the surfaces of PV modules in the East of Saudi Arabia. They showed that the PV modules exposed to dust particles in a period of six months with no cleaning experience a 50% reduction of the PV module power in the study region. They also showed that using a sun tracker can decrease the losses of the PV module up to 50% [10].

Some studies computationally predicted a PV module power under different dust deposition densities on its surface. Al-Hassan investigated the effect of dust deposition on the performance a PV module mathematically. He developed a relation which took into account incident radiation, dust particle size, incident angle, and wavelength in the glass transmittance of PV module. He revealed that the wavelength of incident ray has a small effect on the transmittance in the visible range. His finding helps the photovoltaic designer to predict the PV module performance with dust deposition on its surface in a few conditions of PV module. This equation was based on the dust deposition density and dust particle size, [11]. Martin and Ruiz developed a mathematical model to take into account the losses due to dust deposition. This model was found based on a combination of the experimental and mathematical results [12]. Beatti et al. provided numerical and analytical models to study the effect of dust deposition on the surface of a PV module. These models were validated using the measured data.