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Numerical study of a photovoltaic/thermal hybrid system with nanofluid based spectral beam filters

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ABSTRACT

This study presents a 3-dimensional numerical simulation of a flat-plate photovoltaic/thermal (PV/T) hybrid system using a nanofluid as the solar spectrum filter. A series of parametric studies have been carried out to investigate the module performance by employing different base fluid (water, therminol VP-1 and propylene glycol) - nanoparticle (Ag, Fe_3O_4 and SiO_2) combinations. The present work explores the effects of different nanoparticle concentrations, volume flow rates of applied nanofluids, as well as the solar spectrum intensities on the energetic and exergetic performances of the proposed module. Merit functions for various basefluid or nanofluid based hybrid PV/T systems are also assessed in order to determine their economic feasibility. The results show that the suspension of nanoparticles into basefluids has a considerable influence on the radiative heat fluxes that are absorbed by each component of such system. The selection of basefluid-nanoparticle combination is dramatically affected by the desired energy form, based on the system energetic and exergetic performances. Besides, both the system energy and exergy efficiencies are improved with the increment of solar irradiance, whereas they have a counter tendency by increasing the volume flow rate of working fluid. The employment of liquid absorptive filters in such systems can realize a higher energy output which is 179%–240% of that of a stand-alone PV system.

1. Introduction

Solar energy is considered as one of the promising energy resources, since it is green, free and sustainable. As one hour of solar radiation received by the Earth can cover the entire global energy consumption for one year [1], solar energy is frequently utilized for power generation by the following means: (1) solar photovoltaic (PV) systems in which solar spectrum is instantly converted to electric power, and (2) solar thermal systems in which solar energy is collected and directly used as a heat source for power cycles [2]. Despite the rapid proliferation of solar PV, the efficiency of PV cells still needs to be further improved. As a result, most of incident solar irradiance turns into heat, and the caused rise in the operating temperature of PV cells has a central role in the deterioration of the electric efficiency. Therefore, Jackson in 1955 [3] suggested for the first time the concept of spectral beam splitting hybrid PV/thermal (SBS-PV/T) system, which intercepts the wavelengths of light that are not converted to electricity before they land on the cell surface, and utilizes the intercepted wavelengths for thermal applications. Such approaches allow the exploitation of the available solar radiation in forms of heat and electricity concurrently, which could utilize nearly 80% of the incoming solar energy [4].

Various types of optical filters can be used for hybridization of SBS-PV/T, and were classified based on the configuration of the optical filter [2]: PV/T systems with interference filters, liquid absorptive filters, holographic and other filters including luminescent filters, diffractive filters, solid filters, and their combinations. The use of liquid absorptive filters has gained considerable attention lately, because absorptive liquids or heat transfer fluids (HTFs) are economical and versatile, and they can absorb unwanted solar spectrums of PV cells into heat and cool PV modules especially in concentrated solar applications. These filters are distinguished from other filters as having the ability to adjust and control the optical and thermal characteristics of HTFs by combining base fluid (BF) and solid nanoparticles (known as the nanofluid (NF)-based spectral splitting PV/T (NSS-PV/T) system). NF filters can exploit the whole solar spectrum efficiently, and the suspension of nanoparticles into BFs aims at good absorption in the solar spectrum below or over the band-gap wavelength of used PV cell. The rest of the spectrum corresponding to the PV spectral response transmits to PV cells for power generation. Actually, finding an ideal NF filter that has a high optical compatibility with hybrid systems and strong absorption

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Nomenclature

A_c	absorption area, m
C_p	specific heat at constant pressure, $J\,kg^{-1}\,K^{-1}$
d_p	nanoparticle diameter, nm
E	energy, W
FF	fill factor of PV cell
H	height in z direction, mm
h	convection heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
I	radiation intensity, $W\,m^{-2}$
I_λ	spectral radiation intensity, $W\,m^{-2}\,\mu m^{-1}$
J	electric current of PV cell, A
k	imaginary component refractive index
k_b	Boltzmann's constant, $1.38066e^{-23}\,J\,K^{-1}$
m	relative refractive index of nanofluid
n	real refractive index
p	pressure, Pa
Pr	Prandtl number of nanofluid
Q	volume flow rate, $m^3\,s^{-1}$
Q_{abs}	absorption efficiency
q_{rad}	rate of radiative heat transfer per unit volume, $(W\,m^{-2})\,m^{-3}$
Re	Reynolds number of nanoparticle (Brownian-motion)
$\vec{r}$	direction vector
S_h	volumetric heat source, $W\,m^{-3}$
s	path length, mm
$\vec{s}$	position vector
$\vec{s}'$	scattering direction vector
T	temperature, K
u	flow velocity in x direction, $m\,s^{-1}$
$\vec{u}$	velocity vector in x direction
V	voltage, V
$\vec{V}$	velocity vector
v_∞	wind velocity, $m\,s^{-1}$
W	worth factor, 3

Greek symbols

σ	extinction coefficient, m^{-1}
κ	absorption coefficient, m^{-1}
λ	wavelength
η	energy efficiency
ηx	exergy efficiency
Ω'	solid angle
ϕ_v	nanoparticles volume fraction
∇	operator
α	particle size parameter
μ	dynamic viscosity, Pa s
ρ	density, $kg\,m^{-3}$
β	scattering coefficient, m^{-1}
γ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
τ	transmittance
φ	scattering phase function
∂	absorptivity
δ	temperature coefficient of PV cell, 0.43%

Subscripts

λ	certain wavelength
a	ambient
b	black body
bf	base fluid
$cell$	PV cell
el	electric
fr	freezing point
g	glass substrate
in	flow inlet
nf	nanofluid
oc	open circuit
out	flow outlet
p	nanoparticles
ref	reference
s	solid
s-a	stand alone
sc	short circuit
si	silicon
sun	solar irradiance
t	total
t	top
th	thermal
w	wall

Abbreviations

BF	Base Fluid
EVA	Ethylene Vinyl Acetate
MF	Merit Function
NF	Nanofluid
PV/T	Photovoltaic/Thermal

for the undesired wavelengths is quite challenging.

After reviewing the literature, the researches focusing on NSS-PV/T systems can be divided into three categories: (1) the experimental investigations, (2) the investigations combining experimental and theoretical approaches, and (3) the theoretical investigations. A summary of literature survey on NSS-PV/T systems is presented in Table 1. It is observed that the theoretical investigations that used the CFD codes to simulate the NSS-PV/T systems are quite limited. This is possibly due to the facts that the model of the whole system is very complex, and the system operation involves multiple physical processes including optics, electricity, heat and mass transfer. Jing et al. [5,6] have demonstrated the application of numerical simulations for such hybrid PV/T systems for two times. At the first investigation, a 2-dimensional (2D) NSS-PV/T system was inspected by using the silica/water NF with various particle sizes, of which the transmittance was tested experimentally [5]. The effects of light concentration and NF flow rate on the exergy and the photoelectric conversion efficiencies of the system were analyzed by using the gray DO model. Recently, Li and Jing [6] sought to improve their previous work by establishing a 3-dimensional (3D) model. In that work, they improved the previous model by employing the non-gray DO model with three wave bands (e.g., ultraviolet, visible, and near infrared), such that the absorption process in NFs can be simulated more precisely.

However, from the above literature reviews, the investigations on the NSS-PV/T systems using numerical simulations still need to be improved to realize the following two important points. First, the variations in the optical characteristics of NFs and other materials over the whole solar spectrum should be precisely captured for better prediction of the system performance. Second, the model should be validated by experimental results of hybrid systems containing spectral beam splitting techniques. In the present work, we present a 3D-CFD simulation of a flat-plate NSS-PV/T system, which is validated firstly by comparing it with the experimental results from two studies: Sardarabadi et al. [22] and Cui and Zhu [7]. This work also distinguishes itself by precisely considering the variations in the optical characteristics of NFs and other materials over the solar spectrum, providing a comprehensive

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