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Performance investigation on a novel spectral splitting concentrating photovoltaic/thermal system based on direct absorption collection

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ABSTRACT

The photovoltaic unit and the thermal unit are coupled in a concentrating photovoltaic/thermal (CPV/T) system and solar cells always operate at high temperature in order to obtain high quality thermal energy, which results in the overheating problem of solar cells. In the present study, a novel spectral splitting concentrating photovoltaic/thermal (SS-CPV/T) prototype based on direct absorption collection had been set up. The concentrator in the system is a truncated CPC by eliminating multiple reflections of solar radiation (called EMR), which was designed by our group. Water is used as both spectral splitting medium and heat transfer fluid in the spectral splitting subsystem. Distribution of the incidence angle of the irradiance illuminating on the filter at the outlet aperture of EMR was considered. The radiation transfer model was established to obtain the optical performance of the filter. And the electrical-thermal coupled model was proposed to predict the electrical and thermal performances of the SS-CPV/T system. When the total solar irradiance was about 1000 W/m^2 and the diffuse irradiance ratios were 15.0%, 17.8% and 24.0% respectively, the experimental electrical efficiencies of the SS-CPV/T system were 9.6%, 9.4% and 9.0% respectively and the thermal efficiencies were 52.0%, 50.7% and 48.5% respectively. The theoretical electrical efficiencies were 10.4%, 10.2% and 9.8% respectively and the theoretical thermal efficiencies were 52.8%, 51.5% and 49.4% respectively. Comparison experiments on the electrical and thermal performances of the CPV/T systems with and without spectral splitting were also conducted. Under the condition of the same outlet fluid temperature the maximum temperature of solar cells in the SS-CPV/T system was about 5.6 °C lower than the temperature of outlet fluid and about 12 °C lower than the maximum temperature of solar cells in the CPV/T system without spectral splitting. Finally, the theoretical model was expanded to higher concentration ratios to study the effects of the concentration ratio on the electrical and thermal performances of the CPV/T systems with and without spectral splitting. The results illustrate that compared to the CPV/T system without spectral splitting, the SS-CPV/T system has higher electrical efficiency when the concentration ratio is larger than 10 and higher exergy efficiency when the concentration ratio is larger than 14 for the outlet fluid temperature of 50 °C. And for 70 °C outlet fluid temperature, these two concentration ratios shift to 9 and 15 respectively. Thus, spectral splitting technology is more advantageous in the CPV/T systems with moderate and high outlet fluid temperature and concentration ratios.

1. Introduction

The concentrating photovoltaic/thermal (CPV/T) system has drawn much attention due to its low cost and high overall efficiency. Typically, a CPV/T system consists of a PV/T module, a concentrator (CPC, Fresnel lens or reflector and trough collector, etc.), a supporting frame and a tracking system. Rosell et al. (2005) set up a CPV/T prototype with a two-axis tracking linear Fresnel concentrator (11 × concentration ratio) and the measured thermal efficiency was above 60%. Their theoretical analysis confirmed that thermal conduction between the PV cells and the absorber plate is a critical parameter. Li et al. (2011) studied the performances of solar cell arrays based on a trough concentrating photovoltaic/thermal (TCPV/T) system and figured out that the optimum concentration ratio for the single crystalline silicon cells was 4.23. Kong et al. (2013) set up a low concentrating photovoltaic-thermal hybrid (PV/T) system to study the electrical and thermal outputs under different weather conditions. The concentrator in the system combined Fresnel lens and flat mirrors. The results revealed that the electrical efficiency was about 10% and the thermal efficiency was about 56% on a clear day.

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Nomenclature

A	area (m^2), spectral absorptivity
CR	concentration ratio
C_p	specific heat capacity of fluid ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)
d_e	equivalent diameter of flow channel (m)
FF	fill factor
F_λ	function of solar irradiance wavelength distribution
G	solar radiation intensity ($W{\cdot}m^{-2}$)
h	thickness (m), heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
I	circuit current (A)
k	absorption index of a medium
m	mass flow rate of water ($kg{\cdot}s^{-1}$)
n	refractive index of a medium, number of solar cell module
Nu	Nusselt number
P	electrical power (W)
Q	solar radiant flux (W)
R	spectral reflectivity
Ra	Rayleigh number
R_{DNI}	ratio of direct normal irradiance
R_s	series resistance (Ω)
R_{SDI}	ratio of solar diffuse irradiance
S	area of the collector (m^2)
SR_λ	relative spectral response of solar cells
t	temperature (K)
T	spectral transmittance
u_{wind}	wind velocity ($m{\cdot}s^{-1}$)
V	circuit voltage (V)

Greek symbols

α	current temperature coefficient (K^{-1}), absorptivity, thermal diffusion coefficient of air ($m^2{\cdot}s^{-1}$)
β	coefficient of volumetric expansion of air (K^{-1})
γ	power temperature coefficient (K^{-1})
δ	thickness (m), distance (m)
ε	emissivity
η	energy efficiency
θ	angle of light(°)
λ	wavelength of light (nm), thermal conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
ν	kinematic viscosity of air ($m^2{\cdot}s^{-1}$)
ξ	exergy efficiency
ρ	reflectivity of concentrator
σ	Stefan-Boltzmann constant
τ	transmittance

Subscripts

A	absorption
air	air
Al	aluminium plate
amb	ambient
b	bottom
c	glass cover of PV/T module
dif	solar diffuse irradiance
DNI0	direct normal irradiance without reflection of concentrator
DNIR	direct normal irradiance with reflection of concentrator
el	electrical
f	fluid
g	glass
i	i-th parameter
I	circuit current
in	inlet
j	j-th parameter
k	k-th parameter
m	maximum
mid	outlet of PV/T module
oc	open circuit
out	outlet of filter
P	power
pv	pv
R	reflectivity
ref	reference condition
sc	short circuit
ss	spectral splitting
t	total, top
T	transmission
th	thermal
w	wind
λ	spectral

In CPV/T systems, the photovoltaic unit and the thermal unit are coupled to save space by sharing the concentrator and the supporting frame. In order to obtain high quality thermal energy, solar cells always operate at high temperature, which results in the overheating problem of solar cells and limits the temperature of outlet fluid in CPV/T systems. A way of solving these two problems is to introduce spectral splitting technology. In spectral splitting concentrating photovoltaic/thermal (SS-CPV/T) systems, the photovoltaic unit and the thermal unit are decoupled by splitting the solar irradiance into two parts: the energy over band gap of solar cells is directed to the photovoltaic unit to produce electricity while the energy blow band gap is conducted to the thermal unit to harvest heat. Among a variety of spectral splitting methods, thin-film filters and absorptive liquid filters are the preferred spectral splitting approaches in the developed SS-CPV/T systems owing to their high optical efficiency, well matching with the concentrator and low cost (Ju et al., 2017). Research on the SS-CPV/T systems mainly focuses on four aspects: (1) Selection of the filters and analysis of their optical performances; (2) Establishing theoretical model to predict the electrical and thermal performances of the SS-CPV/T systems; (3) Testing the performances of the SS-CPV/T prototype; (4) Study on the effects of the concentration ratio and the heat transfer coefficient of the cooling system on the performances of the SS-CPV/T systems. Crisostomo et al. (2014) fabricated SiN_x/SiO_2 multilayer thin film filters by using plasma-enhanced chemical vapor deposition. Testing results showed that the filters have high reflectance (≥95%) for light between 713 and 1067 nm and high transmittance (≥90%) for sunlight outside that reflection window. Shou et al. (2012) manufactured a broadband TiO_2/SiO_2 multilayer thin-film filter for a hybrid PV–TEG system through an electron beam evaporation plant and concluded that hybrid PV–TEG system with the filter has higher efficiency than the CPV system when the solar irradiance becomes appropriately high. An et al. (2016) carried out experimental study on the SS-CPV/T system with a Cu_9S_5 nanofluid filter. The maximum overall efficiency of the system was 34.2% and the temperature of outlet fluid could be above 100 °C. Jing et al. (2015) prepared SiO_2/water nanofluid with different particle sizes as both the filter and heat transfer fluid in the SS-CPV/T system. Optimum parameters for the highest exergy efficiency of the system were obtained by the CFD method.

Among the present studies on the SS-CPV/T systems, the electrical and thermal efficiencies are not so high. One reason is that the optical performance of filters can't match the spectral response of solar cells perfectly. The other reason is that complex optical structure contributes to much more optical loss and low optical efficiency. Some theoretical works have been carried out on the SS-CPV/T system with a CPC