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Numerical simulation and experimental validation of a high concentration photovoltaic/thermal module based on point-focus Fresnel lens

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HIGHLIGHTS

- A point-focus Fresnel lens photovoltaic/thermal module is proposed and studied.
- The electrical model is based on the Shockley diode equation.
- The thermal model is based on a two-dimensional steady-state heat transfer model.
- An electrical efficiency of 28% and a thermal efficiency of 60% can be obtained.
- Influence of independent parameters is investigated by validated models.

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ABSTRACT

Characteristics of a high concentration photovoltaic/thermal (HCPV/T) module equipped with point-focus Fresnel lens have been investigated in this paper. Both electrical and thermal models of the module are developed by numerical methods. The electrical model is based on the Shockley diode equation, and the thermal model is grounded on a two-dimensional steady-state heat transfer model. Influences of environmental parameters and coolant water are considered in the models. The inputs of the models consist of irradiance, ambient temperature, wind speed, water temperature and mass flow rate. The outputs mainly include electrical efficiency and thermal efficiency. The simulated results are compared with experimental results and a great agreement is obtained. By the virtue of the validated models, influences of different parameters on module performance are analyzed in detail. The results show that an electrical efficiency of 28% and a thermal efficiency of 60% can be obtained by the HCPV/T module. The electrical efficiency is mainly influenced by solar irradiation rather than cell temperature. The thermal efficiency increases with the increment of irradiance, ambient temperature and water mass flow rate. On the contrary, increasing water temperature and wind speed will lower the thermal efficiency. Also, the HCPV/T module can produce hot water as high as 70 °C without decreasing the electrical efficiency seriously.

1. Introduction

Concentrator photovoltaic (CPV) technology has been developed for over 30 years since the first modern PV concentrator was made at Sandia National Laboratories [1]. The general idea of concentrator photovoltaic is to use optics to focus sunlight onto a small receiving solar cell. In this way, the cell area in the focus of the concentrator can be reduced by the concentration ratio ($C > 300$ for high concentration photovoltaic systems). Consequently, this reduction allows the utilization of expensive but highly efficient multi-junction solar cells in an economical manner. As a matter of fact, the efficiency of multi-junction solar cells is reported to be higher than 40% [2–4]. On the CPV module level, photovoltaic efficiency above 35% have been reported [5–7].

Among high concentration photovoltaic (HCPV) modules/systems, Fresnel lens recently have been one of the best choices because of its advantages such as small volume, light-weight, mass production with low cost as well as effectively increasing the energy density. Xie et al. [8] gives a review on concentrated solar energy applications using Fresnel lenses in the last two decades, the highest photovoltaic conversion efficiency based on imaging Fresnel lens and non-imaging Fresnel lens is reported as over 30% and 31.5 ± 1.7%, respectively. Amongst the existed

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Nomenclature

Symbols

A	area, m^2
C	geometric concentration ratio
c_p	specific heat, J/(kg K)
D	tube diameter, m
DNI	direct normal irradiation, W/m^2
E_g	bandgap energy, eV
G	irradiance, W/m^2
h	heat transfer coefficient, $W/(m^2\,K)$
I	current, A
I_0	dark current, A
k	Boltzmann constant, 1.38×10^{-23} J/K, thermal conductivity, W/(m K)
K_0	temperature coefficient of short circuit current, A/K
$\dot{m}$	mass flow rate, kg/s
n	diode ideality factor
N	number of solar cells in a module, number of the finite-difference equations
Nu	Nusselt number
P	power, W
Pr	Prandtl number
q	electron charge, $1.6 \times 10^{-19}C$, heat energy, W
Q	energy, W
q''	heat flux, W/m^2
R_s	series resistance, Ω
R_{sh}	shunt resistance, Ω
Re	Reynolds number
T	temperature, °C
u	wind speed, m/s
v	viscosity, m^2/s
V	voltage, V
X	parameter

Subscripts

a	ambient
$conv$	convective
d	direct
e	electrical
exp	experimental
f	film
$Fresnel$	Fresnel lens
i	inlet
l	loss
m	module
max	maximum power point
o	outlet
oc	open circuit
opt	optical
ph	photocurrent
$prism$	optical prism
ref	reference
rad	radiative
sc	short circuit
sim	simulated
sky	sky
th	thermal
w	water

Greek symbols

ε	emissivity
η	efficiency
σ	Stefan–Boltzmann constant, 5.67×10^{-8} $W/m^2\,K^4$

point-focus Fresnel CPV systems, almost all the modules are passively cooled. One point of view [9] believes that passive cooling could work well for single-cell geometries with flux level as high as 1000× suns, because there is large area available for heat sinking. However, the fact is that a large part of the already collected solar energy is dissipated as heat to the environment. By contrast, an active thermal loop can easily enable heat transfer from the receiver to a thermal load. The heat can be further used as either cooling power or domestic water by solar cooling and air conditioning [10–12] or solar desalination [13–16] technologies. Therefore, a hybrid PV/T system with point-focus Fresnel lens can definitely improve the utilization of solar energy.

A kind of HCPV/T module equipped with point-focus Fresnel lens was proposed in our previous work [17]. The outdoor experimental results show that the module could obtain an instantaneous electrical efficiency of 28% and an instantaneous thermal efficiency of 55% simultaneously. Changes of electrical and thermal efficiencies of the module caused by solar irradiation and water temperature have been discussed based on experimental data, but more characteristics of the module are difficult to be obtained only by outdoor experiments. Hence, these issues, such as irradiation and temperature dependence on module performance, should be investigated on model level. Besides, a validated model is beneficial to either module optimization or performance prediction. Over the years, several researchers have studied the characteristics of non-concentrating hybrid PV/T collectors by mathematical methods [18–23]. Nevertheless, literatures on the performance modeling of CPV/T modules/systems are fragmented, especially in the cases of HCPV/T systems. Kribus et al. [24] presented an evaluation on a miniature dish CPV/T system whose concentration ratio is 500×. The heat transport system, the electrical and thermal performance, the manufacturing cost and the resulting cost of energy have been analyzed. Rosell et al. [25] set up a model to simulate the thermal behavior of a low concentrator PV/T system which is the coupling of a linear Fresnel concentrator (C = 30) with a channel photovoltaic/thermal collector. Reisl et al. [26] developed a theoretical model to describe the response of trough systems in terms of module temperature, power output and energy yield. However, models established in these studies are mostly either oversimplified or by empirical equations.

In this paper, both electrical and thermal models of the HCPV/T module (C = 1090) are developed by numerical methods. The module is firstly proposed by our team and it is an integration of CPV system with point-focus Fresnel lens and thermal collector. The electrical model is rooted on the Shockley diode equation which is widely used [27–29], and the thermal simulation is conducted by adopting a two-dimensional steady-state heat transfer model. The models are applied to evaluate, analyze as well as predict the module performance. The electrical model focuses on dependence of module's electrical performance on cell operating temperature and irradiance. The thermal model is employed to investigate the proportion of heat collected and dissipated. It also can be used to determine the thermal profile on the receiver, which is scarcely possible to be acquired by one-dimensional heat transfer analysis. The simulated results are compared with experimental results subsequently. Furthermore, influence of independent parameter including DNI, water temperature, mass flow rate, ambient temperature and wind speed on module performance are discussed by virtue of the validated models.