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Numerical and lab experiment study of a novel concentrating PV with uniform flux distribution

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ABSTRACT

The uniform illumination profile that falls on the PV cell is good for PV output and lifespan, however the flux distribution of the concentrating PV appears to be non-uniform in most cases which is harmful for the overall performance of the concentrating photovoltaic. In order to overcome this disadvantage, a novel asymmetric compound parabolic concentrator concentrating PV with uniform flux distribution is proposed in this paper. A two-dimensional finite element model is built for electrical performance simulation of the concentrating photovoltaic module. The prototype of the concentrating photovoltaic module is manufactured and assembled to conduct the indoor lab experiment under Standard Test Condition to verify the feasibility and reliability of the model. The outdoor experiments are conducted to show the electrical performance of the concentrating photovoltaic module under the real weather condition. Then the model is used to analyze the electrical performance of the PV cell under the flux distribution created by the proposed concentrator. The results show that the electrical performance of the proposed concentrating photovoltaic module is close to that under the uniform flux distribution with the same total radiation level, which confirms that the proposed concentrator is beneficial for the PV output under concentrating illumination due to uniform flux distribution.

1. Introduction

Solar concentrating system can attain a larger solar irradiation than that without solar concentrator. For PV application, solar concentrating system can get a higher flux intensity which can save lots of PV cells and reduce the cost significantly in theory. There are many CPV (concentrating photovoltaic) systems were designed and studied by researchers. Du et al. designed a mirror lens CPV with the active water cooling [1]. Renzi et al. analyzed the performance of two 3.5kWp CPV systems under real operating conditions [2]. Li et al. simulated and tested a low concentrating solar concentrators integrated with building for CPV [3,4]. Mallick et al. designed an asymmetric concentrator in the specular reflection or total internal reflection forms for building integrated CPV application [5–7].

However, many solar concentrators can only provide non-uniform flux distribution, which usually have significant impact on the PV output. What's more, the presence of non-uniformity increases the temperature across some portions of the cells and causes hotspots which will finally intensify material aging and thus tend to deteriorate the cell performance. As the concentration ratio increases, it will become more difficult to maintain uniformity of the flux on the solar cells. In Coventry's study, an experiment comparison was conducted on a single solar cell in both uniform and non-uniform flux distribution. The results showed that there is a reduction in open circuit voltage of 6.5 mV and an obvious deviation of *I-V* curves is observed under the uniform and non-uniform illumination conditions, and the author pointed out an efficiency drop from 20.6% with uniform illumination to 19.4% with non-uniform illumination [8,9]. Katz et al. [10] produced a localized illumination for a 100 mm^2 triple-junction GaInP2 /GaAs/Ge cell with the uniform front metallization with the total power varies from 0.1 W to 8 W. The experiment results indicated that the open voltage, fill factor and PV cell efficiency all got a decline affected by the local illumination compared with the uniform illumination. Manor et al. [11] conducted the experiment for the large photoactive area organic cell with poly (3-hexylthiophene) (P3HT)/PCBM BHJ under the uniform and localized illumination and the results showed that a decline of the open voltage was observed between the localized and uniform illumination.

On the contrary, there are many precedents of improving the performance of the concentrators by flatten the flux illumination profile that falls on the receiver of the concentrator where the PV cell is attached. Li et al. [12] concluded that the lens-walled CPC (compound

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Nomenclature

C	Geometric concentration ratio
Eg(eV)	Material band-gap energy (1.124 eV for silicon)
FF(%)	Fill factor
G(W/m2)	Illumination profile
Isc(A)	Short-circuit current
J^e(A/m2)	Current density
Kb(J/K)	Boltzmann constant
n	Diode ideal factor
Pmax (mW)	Maximum power
Qj (A/m3)	Generated current density
q_e(C)	Electron charge
Rsh(Ω)	Sheet resistance
T(K)	PV cell working temperature
te (m)	the depth of the emitter
V(V)	Solar cell/module voltage
Vj(V)	Junction voltage
Voc(V)	Open-circuit voltage

Greek symbols

Λ(°)	A certain degree
θ' (°)	The incidence angle for the optimization concentrator
θ(°)	The incidence angle for the original concentrator
σ(S/m)	Conductivity of the material
λ(°)	Rotation angle

parabolic concentrator) whose flux distribution is more uniform than the normal mirror CPC shows higher fill factor values and the experiment certified their conclusions. Wang et al. [13] proposed that for the tube receiver with parabolic trough collector system, decreasing the heat flux gradient and peak magnitude on the receiver can reduce the thermal stress and avert receiver failure. Hatwaambo et al. [14] demonstrated that the fill factor of the low concentrating CPCs can be improved by a semi-diffuse aluminum sheet reflector with rolling grooves oriented parallel to the plane of the solar cell module due to more uniform flux distribution across the solar cell.

Franklin and Coventry [9] indicated that the parabolic trough concentrator has the Gaussian flux profile on the cell. Li et al. presented that the lens concentrator has also a non-uniform distribution [15]. Some methods can also be considered to improve the flux distribution, such as the use of active or passive cooling mechanisms [16–18], use of high-grade silicon solar cells, and/or the use of semi-diffuse reflectors [14] on the already existing concentrator geometries have been tried. Huang et al. indicated that when the receiver plane is placed somewhat upwards or downwards from the focus, the Fresnel solar concentrator can improve the uniformity of flux distribution [19]. Secondary optical elements can also be used to weaken negative effects of the non-uniformity [20,21]. Perez-Enciso et al. [22] proposed a method to achieve a uniform flux distribution with a multi-faceted point focus concentrator, however for most of solar concentrators, the uniformity of flux distribution is still an inevitable problem.

Compound parabolic concentrators are the typical solar concentrator with Gaussian flux profile which is a promising concept for it can works with a fixed installation. The high solar irradiation can make solar cells produce larger amounts of currents, but the non-uniform illumination lowers the efficiency due to the losses caused by the increase in series resistance. Mammo et al. [23] revealed that efficiency deviation is mainly due to the non-uniform illumination distribution.

In order to overcome this disadvantage, and the need of achieving homogenous flux distribution on photovoltaic, thermal or other kind of receivers in solar concentrating devices is a common issue. Thus, this paper displayed a novel concentrating PV with uniform flux distribution. It is found through the ray tracing simulation that the flux distribution of the proposed novel concentrating PV is very uniform with the variance value of 0.327 which is much more uniform than that of the normal symmetric mirror CPC whose variance value is 4.764 with the same geometric concentration ratio. Through the simulation and experiment, the modeled *I-V* curves for the PV cell under the uniform flux distribution and that under the flux distribution created by the proposed concentrator show a good agreement, which indicates that the electrical performance of the concentrating PV module is close to that under the uniform flux distribution with the same total radiation level. The study proves the benefits of the proposed concentrator for the output improvement of the solar cells under concentrating illumination. As for the cost of the proposed CPV module, It was demonstrated by Mallick et al. that for the low-concentration dielectric compound concentrator PV technology, a reduction of the overall system cost of up to 53% could be expected in volume production instead of the small number of systems currently manufactured though the cost of the dielectric concentrator may outweigh the PV material cost savings, especially when the price of PVs has fallen significantly [6]. And the material quality of the concentrator proposed in the paper is only 1/4–1/5 of that of the dielectric concentrator, so it can further reduce the cost as well as the weight.

2. The CPV module

2.1. The geometry

The geometry of the proposed concentrator is designed in the asymmetric structure as shown in Fig. 1, which is composed of the asymmetric compound parabolic curves in the form of the lens structure and mirrors. An air gap is set between the lens and mirrors, thus the sun rays can be collected either by the total internal reflection or by the specular reflection, which will increase the optical performance of the concentrator. For the further structure optimization, the concentrator is designed by rotating the original concentrator around the up end point of the absorber M by a certain degree λ which means that the incidence angle for the original concentrator θ will be θ' for the optimization concentrator: $\theta' = \theta - \lambda$. The optimization structure of the concentrator integration with PV is detailed studied in the paper. The angle between the normal of the absorber and the incident ray is defined as the incidence angle for the proposed concentrator. The geometric concentration ratio (C) is 2.4 ×, which is defined as: Aperture width/Absorber width.

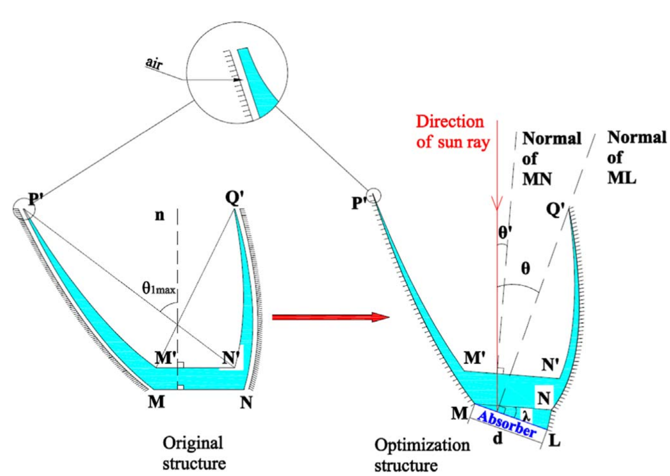

Fig. 1. The geometry of the proposed concentrator and its optimization structure.