

## The effect of non-uniform irradiation on PV cell performance in a lens-walled CPC

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This study first describes the principle of a lens-walled CPC (compound parabolic concentrator) which compromises the advantages of common mirror CPC and solid dielectric CPC, by applying a lens shape on the surface of a common CPC. Due to the structural feature of a CPC, the irradiation on the base of a CPC is non-uniform, where a PV cell is installed for a CPC-PV application. A lens-walled CPC has a potential of producing more uniform irradiation. The profiles of irradiation are obtained with an optical simulation software Photopia for three types of CPC, i.e., mirror, solid and the proposed lens-walled CPCs. The profiles are then applied as a boundary condition in a finite element model of PV cell to evaluate the effect of non-uniform irradiation on the PV cell. The finite element model of a PV cell is validated against its specification data. The obtained IV curves and the corresponding maximum power points are compared between these three types of CPCs to check the advantage of a lens-walled CPC, for several incidence angles.

**Keywords:** lens-walled CPC, non-uniform irradiation, PV cell, finite element modelling (FEM)

### INTRODUCTION

Solar concentrators can be used to reduce the size of photovoltaics (PV) for a given area of installation. By using an inexpensive reflective sheet instead of PV cell, a low concentration PV system is promising to be about 40% cheaper than a common flat PV system [1], and fitted well with building integrated application [2]. Among the low concentration solar concentrators, the compound parabolic concentrator (CPC) is the most adopted due to its feature of stationary operation and wider acceptance angle. A lot of research efforts have been made to increase the acceptance angle of a CPC of given geometric concentration ratio, because a larger acceptance angle leads to a larger collection of solar radiation. For example, in comparison with a conventional mirror CPC, a solid dielectric CPC have larger acceptance angle for same geometric concentration ratio, but it is heavy in weight. In our previous studies [3, 4, 5], we have therefore proposed the design of a lens-walled CPC as an interesting compromise between the mirror and solid CPCs, with the aim to offer a larger acceptance angle with a lighter weight.

The incident light can be re-directed onto the base of a solar concentrator by reflection in a mirror CPC and/or refraction in a solid or lens-walled CPC. The concentrated radiation increases the energy input to a PV cell, but it can also cause certain amount of power loss due to the increased resistive loss [6]. The resistive loss is directly

proportional to the non-uniformity level of light distribution profile. The non-uniform distributed light can cause a region of higher intensity and thus a higher current source farther away from the bus bar of a PV cell [7]. Vishnoi et al [8] contributed a research to investigate the combination effect of non-uniform light regarding the surface resistance of PV cell. The predication was made from theoretical and experiment evaluation shows that the non-illuminated or less illuminated regions in the PV cell are act as a load, which results a decrease in conversion efficiency and open circuit voltage. In this study, we present a numerical analysis on the optical and electrical performance of a lens-walled CPC PV cell. The non-uniformity of light distribution by a lens-walled CPC and its effect on the PV performance will be also compared with those in a mirror or solid CPCs. The light distribution will be obtained from an optical simulation, while the PV performance will be predicted using 2D numerical analysis of current continuity equation.

### NUMERICAL MODELLING OF A LENS-WALLED CPC PV CELL

#### *System description*

The details about the lens-walled CPC have been presented by Su et al [3]. The shape of lens is formed by internally rotating the parabolic curves of a CPC with certain degree. The refraction of lens allows it to concentrate light from wider incident angle, as shown in Fig.1.

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The incoming light is refracted by the front surface of the lens and then reflected by its coated back surface. Due to this featuring structure, it makes a larger actual half acceptance angle  $\theta_{\max, ac}$  than its nominal half acceptance angle  $\theta_{\max}$ . The relationship between the geometrical concentration ratio (CR) and the nominal half-acceptance angle  $\theta_{\max}$  is given by

$$CR = \frac{S_1}{S_2} = \left( \frac{1}{\sin \theta_{\max}} \right)^{1 \text{ or } 2} \quad (1)$$

where  $S_1$  is the area of the CPC aperture and  $S_2$  is the area of the CPC base.

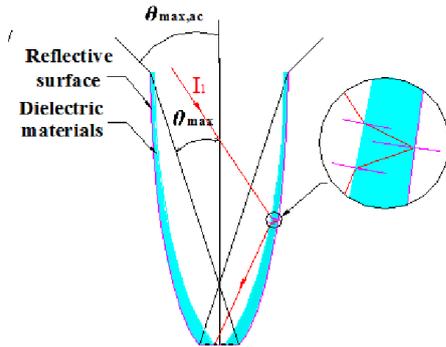


Fig.1. Working principle of the lens-walled CPC [4]



Fig.2. A lens-walled CPC affixed with a PV cell [10]

A sample lens-walled CPC with a geometry concentration ratio of 2.5X is shown in Fig.2. The lens-walled CPC body is made with clear acrylic material, which has a high transparency and is resistant to humidity and other solvents. A common fabrication process is using Computerized Numerical Control (CNC) machine to cut out a CPC straightaway from an acrylic block. This method can offer high accuracy in geometry sizing, but the high conducting temperature due to the cutting mechanism may decrease the material transparency. In addition, some extra machining steps increase the general costs of production. Another suggested fabrication technique is resin casting [9]. It is typically a cold forming process, which pours the acrylic resin into designed model and curing at the room temperature to form the required shape. The casting method is easier to

implement in comparison with CNC cutting and allow mass production of CPC modules with lower cost.

Referring to our previous work [9], the implemented PV cell strip is from a single junction mono-crystalline silicon PV cell. It has three bus-bars (1.5 mm \* 10 mm), seven fingers (0.1 mm \* 156 mm), as illustrated in Fig.3.

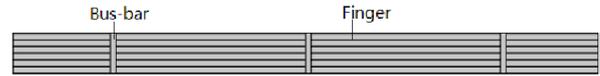


Fig.3. Front grid of a PV cell strip

### Modelling theory

In this numerical modelling study, the optical analysis of three different CPCs and electrical analysis of PV cell were conducted separately, but they were coupled by the boundary condition of irradiation on the PV cell.

#### 1. Optical analysis of the CPCs

In this study, the ray-trace simulation was implemented using a commercial software Photopia for all three kinds of CPCs. Reflection, refraction and optical absorption were taken into account in simulation [3] and the detailed discussions about optical flux distribution on the base of each CPC can be found in [10]. The simulated irradiation profile would be used as a boundary condition in the numerical modelling of a PV cell.

#### 2. Electrical analysis of the PV cell

In order to resolve the issue with non-uniform illuminations and determine the current density distribution, the PV cell needs to be simulated by solving the continuity equation, i.e.,

$$-\nabla \cdot (\sigma \nabla V) = Q_j \quad (2)$$

Where  $V$  is the electric potential,  $Q_j$  represents the current source and  $\sigma$  is the conductivity of material [9, 11]. The current source  $Q_j$  could be understood as the current density generated by a PV cell. This current density can be obtained by some parameter values independent of the cell dimensions, so it is possible to discuss results under different conditions for the same cell. The PV cell one diode model takes into account a photo-generated current, recombination, and shunts, so the current source in the illuminated emitter regions can be defined as:

$$Q_e = C_1 G + C_2 T^3 \exp\left(\frac{-E_g}{kT}\right) \left[ \exp\left(\frac{qV_j}{nkT}\right) - 1 \right] + C_3 V_j \quad (3)$$

In the finger and bus-bar regions, it can be defined as:

$$Q_d = C_2 T^3 \exp\left(\frac{-E_g}{kT}\right) \left[\exp\left(\frac{qV_j}{nkT}\right) - 1\right] + C_3 V \quad (4)$$

The terms  $C_1$ ,  $C_2$  and  $C_3$  are coefficients specific to a given cell,  $C_1$  is the photocurrent density per unit of incident power,  $C_3$  is the inverse of cell shunt resistance  $R_{sh}$ , and  $C_2$  is related to the saturation current density  $J_0$  at the standard temperature  $T_0$  and can be expressed as:

$$C_2 = \frac{J_0}{T_0^3 \exp\left(\frac{-E_g}{kT_0}\right)} \quad (5)$$

This continuity equation is suggested to be solved by the finite element method (FEM) [11, 12]. In this study the finite element method was applied to obtain the solution using COMSOL Multiphysics software [9].

### 3. Boundary conditions

Three main types of boundary conditions are considered in the simulation process. The relevant interface condition at interfaces between different media and interior boundaries represents continuity;

$$n \cdot (J_1 - J_2) = 0 \quad (6)$$

The electrical insulation is applied to ensure no electrical current flows into the boundary. At the interior boundaries, this means that no current can flow through the boundary and that the electrical potential is discontinuous across the boundary.

$$n \cdot J = 0 \quad (7)$$

The ends of the bus bars are connected to the external load and have an electrical potential equal to the cell operating voltage  $V_{cell}$  as an input parameter.

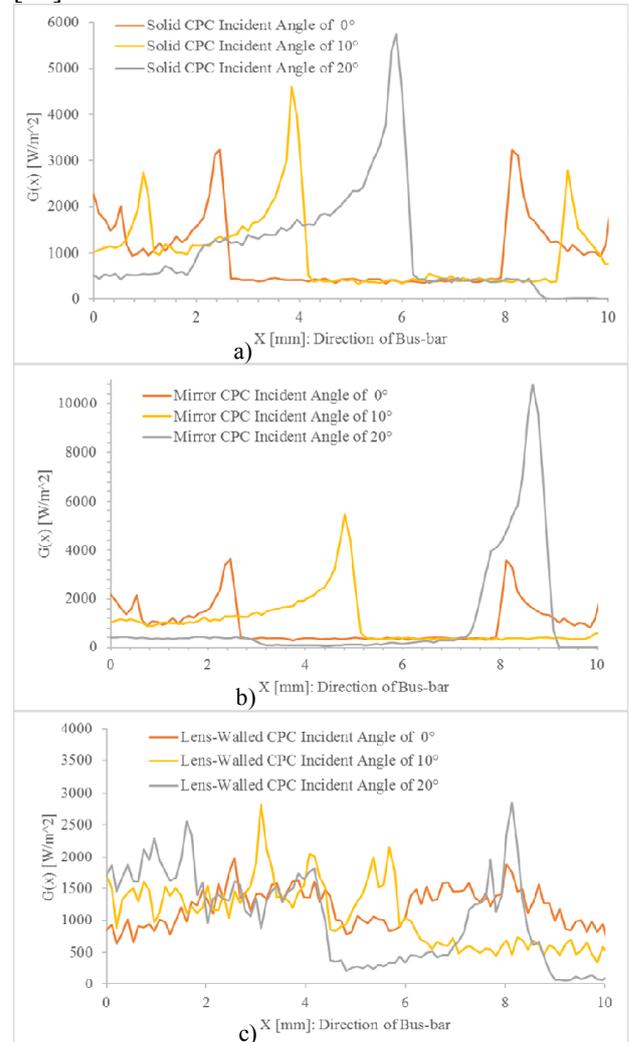
$$V = V_{cell} \quad (8)$$

## RESULTS

The optical analyses of three CPCs were carried out by using ray tracing technique. The light profile from each corresponding CPC was produced. Moreover, in the finite element method (FEM) analysis, a PV cell was divided into a number of small elements with relevant boundary conditions. The electrical analysis was based on the PV cell IV characteristics under different illumination distribution conditions. As the comparison was focused on the effect of illumination distribution, the average intensity values were fixed at  $1000\text{W/m}^2$  and the cell temperature was assumed at  $25^\circ\text{C}$ .

### Optical performance

The different light profiles were obtained by using optical analysis tool Photopia. A comparison is made between solid CPC, mirror CPC and lens-walled CPC with light profiles under three different incident angles, as presented in Fig.4. The non-uniformity of light distribution could be defined as the difference between peak and nadir points of the irradiance. For both solid and mirror CPCs, the non-uniformity of light distribution increased with larger incident angles while the peak irradiance point also has shifted. This is due to the principle and structure of a CPC, in which light is focused onto a narrower patch when the incident angle is closer to the half acceptance angle. In the contrast, the light profile from lens-walled CPC distributes more smoothly with lower peak irradiance value. This is because the lens makes the refracted light more scattering, which is evident in ray-tracing [10].



**Fig.4.** Corresponding light profiles for three different incident angles: a) Solid CPC b) Mirror CPC c) Lens-walled CPC

Electrical performance

The high illuminated regions produce larger resistive losses which result in the decrease in PV cell open circuit voltage [12]. Fig.5 presents the IV curve of PV cell corresponding to the light profiles of each CPC. The PV cell performances have taken varying degree of influences due to the non-uniformity of light distribution. For the cases of solid and mirror CPCs, an obvious dropping in PV cell open circuit voltage can be observed at incident angle of 20°. Table 1 lists the maximum power points (MPP) for each case of CPCs. From the results, there are no obvious variations for the case of lens-walled CPC. In terms of the performance of the PV cell, the property of the light profiles makes the lens-walled CPC have less influence on the PV cell.

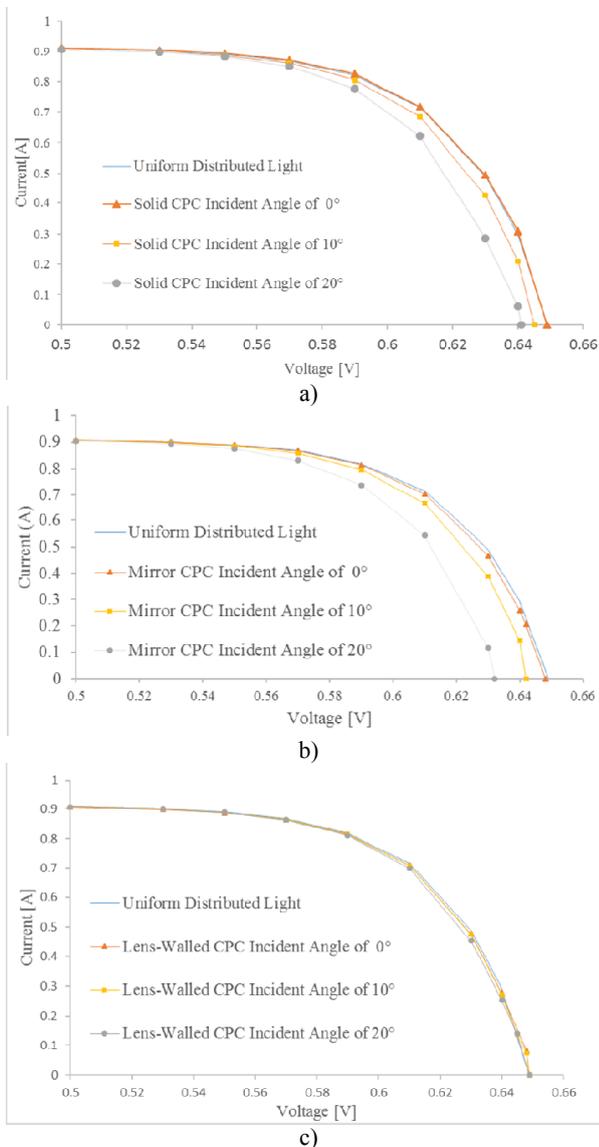


Fig.5. Predicted IV curves of PV cell for three kinds of CPCs (A zoom in): a) Solid CPC b) Mirror CPC c) Lens-walled CPC

Table 1. Maximum power points (MPP) of PV cell for three types of CPCs

CPC	0° incident angle	10° incident angle	20° incident angle
Solid	0.493W	0.490W	0.485W
Mirror	0.493W	0.488W	0.480W
Lens-walled	0.493W	0.493W	0.492W

According to the light distribution profiles, the resistive losses distributions for each case of CPCs are different for one to another. In Fig.6, the resistive losses distributions for all three CPCs at the 20° incident angle are illustrated. It can be observed that the lens-walled CPC has the lowest resistive loss value. It can also be seen that there are huge resistive losses for the mirror CPC, which is almost ten times greater than the lens-walled CPC.

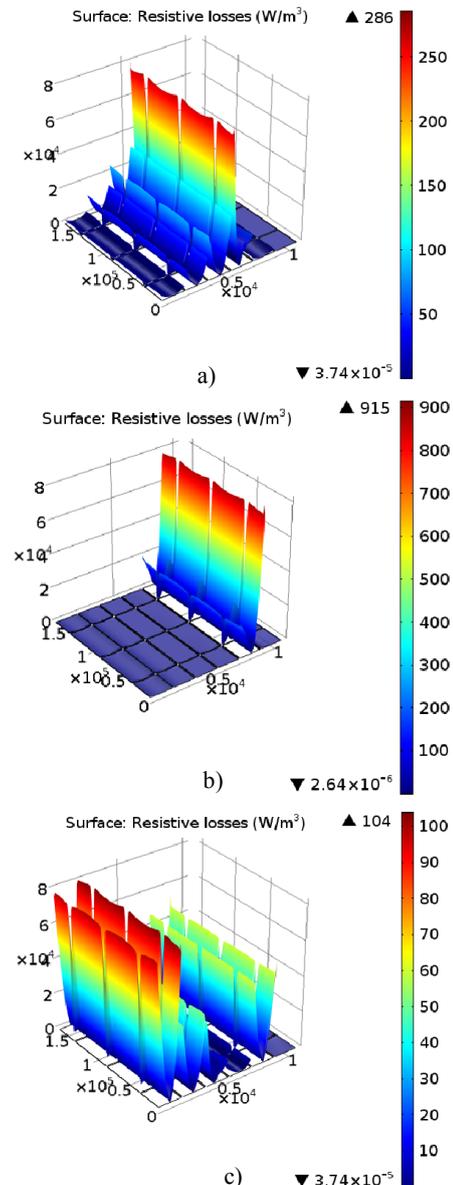


Fig.6. Resistive loss distribution at 20° incident angle (a) Solid CPC b) Mirror CPC c) Lens-walled CPC (not to scale ratio)

The open circuit voltage under the condition of uniform distributed light is 0.649V. Table 2 lists the percentage difference in PV cell open circuit voltages in comparison with the uniform condition for each CPC for three incident angles.

**Table 2.** Percentage difference in the open circuit voltages compared with the uniform distribution

CPC	0° incident angle	10° incident angle	20° incident angle
Solid	0%	0.62%	1.23%
Mirror	0.15%	1.08%	2.62%
Lens-walled	0%	0%	0%

The major effect of the non-uniform distributed light is the variation in the open circuit voltages. The high localised current density in the emitter region increases the resistive loss. Consequently, the response of the PV cell to the high resistive loss results in a reduction in the cell's open circuit voltage.

The combination effect of non-uniform light is not obvious at the 0° incident angle. The decrease in open circuit voltage is intensified as the incident angle increases. On comparison of the three CPCs, the mirror CPC has the lowest open circuit voltage at the 20° incident angle which is mainly due to the high non-uniformity of its light distribution. The light distribution profile for a lens-walled CPC is relatively uniform, which minimises the influence of resistive loss.

### CONCLUSIONS

This paper has described the optical and electrical analysis of a lens-walled CPC PV cell. The optical light distribution profiles have been obtained in order to carry out a coupled electrical analysis of PV cell in a CPC. A detailed study has been presented on the IV performance of PV cell under non-uniform distributed light. The following conclusions can be gained from this work:

a) Non-uniform light causes cell efficiency drop, reflected as the reduction of open circuit voltage. The contributor of this phenomenon is the high resistive loss under non-uniform illumination;

b) Non-uniformity of irradiation in a CPC increases with incident angle. The lens-walled CPC has smoother light distribution and bring less impact on PV cell performance among the three types of CPCs.

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