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Improving angular response of crossed compound parabolic concentrators using rectangular entry aperture

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ABSTRACT

A novel design of crossed compound parabolic concentrator (CCPC) that has a rectangular entry aperture is presented, which has the advantage of considerably improved angular response compared to a conventional CCPC that has a square entry aperture. It is found that the half acceptance angle of this novel design is 40° for a 4.0x rectangular concentrator when operating in the "east-west" direction, which is approximately 10° larger than that of a conventional square concentrator of the same concentration ratio. This is a substantial increase and completely unexpected because the design theory for this type of concentrators predicted a much smaller half acceptance angle of 26.6°. Experimental and simulation work reported in this paper confirms this discovery. The results reveals that the observed improvement is attributed to multiple light reflection inside the concentrator, which was not considered in the commonly employed design theory. An important implication of this work is that the multiple light reflection plays an important role in the angular response of the CCPC and its effect cannot be neglected in the design.

1. Introduction

One of the key challenges that face the world today is to reduce global warming and environmental impact due to the use of fossil fuels while meet the increasing demands for energy supply. Solar energy is a promising solution because it is freely available, abundant and inexhaustible [1,2]. Concentrated Photovoltaic (CPV) is a technology that use the solar concentrators to focus the solar radiation from a relatively large area to a small PV cell area. It has potential to reduce the cost of the PV systems if the cost of the concentrators is much lower than the cost of the solar cells [3]. Although CPV is no longer a viable route for the silicon-based PV systems due to the recent dramatic decrease in the price of silicon solar cells, it is still beneficial to applications where relatively more expensive solar cells such as GaAs and InP are employed.

Solar concentrators are generally categorized by reflective and refractive concentrators. Reflective concentrators use specular mirrors whereas the refractive concentrators use lenses, and both types of concentrators aim to concentrate the sunlight to a focal area where the solar cell is placed [4]. Both reflective and refractive concentrators are further classified into three categories based on the geometrical concentration ratio (C_g): low concentrating system (2-10x), medium concentrating system (10-100x) and high concentrating system (>100x) [5–7].

The compound parabolic concentrator (CPC) is a type of reflective and non-imaging concentrators used frequently in low concentrating systems [8]. Winston was one of the first to recognize the potential of CPC for applications in solar energy concentration and proposed a configuration of two-dimensional (2D) CPC, together with the principle for concentrator design [9], which laid the foundation of CPC development for solar energy concentration. In his initial design, a trough is formed by two reflective parabolic surfaces with a large aperture on the top and smaller aperture at the bottom. All light entering into the top aperture will be concentrated to the bottom aperture, making it a very efficient light concentrator. Later, the effect of receiver misalignment and the mirror errors of the 2D CPC was discussed by Rabl in 1979 [10]. The 3D CPC is an improved design of the 2D CPC, where the geometrical concentration ratio is increased [11–13]. The CPC has the ability to harvest all solar radiation within an acceptance angle [14,15]. A modification was made to conventional symmetrical CPC, resulting in asymmetrical CPC that has two different parabolic reflector profiles with different acceptance angles [16]. Mallick et al. studied the 2D asymmetric CPC and found the maximum power output can be increased by 62% compared to the non-concentrating PV panel [17].

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The power output of PV systems varies with the angle of incidence to the PV cell surface [18]. The light incident angle relative to the solar cell surface has significant influence on the power output of PV systems [19]. Compared to flat panel PV systems, the angular response of the CPV systems is relatively poor because their ability to receive the sunlight is limited by the half acceptance angle of the concentrators. In general, the half acceptance angle of a concentrator decreases with increasing its concentration ratio. For a given concentration ratio, the half acceptance angle can also be affected by different design. Sellami et al. investigated the angular response of a 3.6x CCPC (crossed compound parabolic concentrator), which shows a half acceptance angle of approximately 30° [11]. While Baig et al. studied a similar CCPC that has the same geometry but fabricated using clear polyurethane material [20]. They found that the half acceptance angle of this concentrator increased to about 40° due to the light is firstly refracted at entry aperture surface before it is reflected by the parabolic mirrors. The angular response of other types of CPCs have also been investigated [21–24]. Saitoh et al. reported a 3.2x hexagonal CPC that has a half acceptance angle of 32° [13]. To date, the research effort in this aspect focuses only on determination of the half acceptance angle once a concentrator is designed and contracted. The effort aimed at improving the angular response of the concentrator appears to be missing. The purpose of this work is to demonstrate the possibility of improving the angular response of the compound parabolic concentrators through geometrical modification of the concentrators.

2. Design and construction of concentrator

Two crossed compound parabolic concentrators (CCPC) were designed for this investigation. Both have the same geometrical concentration ratio of 4.0x, but one has a square aperture and the other has a rectangular aperture as shown in Fig. 1. The concentrator with the square aperture represents a conventional CCPC configuration, which is used as the benchmark for comparative study (hereafter refers to as sCCPC). The concentrator with the rectangular aperture is a modified configuration (hereafter refers to as rCCPC), whose angular response is to be investigated. The CAD files for 3D printing of the concentrators were produced using Solidworks software with the parabolic profiles created using the method reported by Rincon et al. [25]. The three key parameters of CCPC design are the geometrical concentration ratio (C_g), the half acceptance angle (θ_c) and the height of the concentrator (H), which are given by [26]

$$C_g = \frac{Entry\ Aperture\ Area}{Exit\ Aperture\ Area} \tag{1}$$

$$\theta_c = \sin^{-1}\frac{1}{\sqrt{C_g}} \tag{2}$$

$$H = \frac{a\,(1 + \sin\theta_c\,)}{2\,\tan\theta_c} \tag{3}$$

where, a is the entry aperture area of the concentrator in cm divided by two as the given equation is for 2D-CPC with two parabolas.

The geometrical concentration ratio is the ratio of the entry aperture area to the exit aperture area. The half acceptance angle represents the maximum angle that the concentrator can collect the incoming solar radiation and the height of concentrator is the distance between the top and bottom apertures. In design of the concentrators for this study, the geometrical concentration ratio is fixed at 4.0x, which is a typical ratio for CCPCs. The exit aperture area of the concentrators was designed to be 10 mm × 10 mm, so that it matches the area of the solar cells used for this study. Using equations (1)–(3), the entry aperture of the CCPC is determined to be 20 mm × 20 mm and the height is 26 mm, which has a half acceptance angle of 30°. In order to design a rCCPC that has the same geometrical concentration ratio of 4.0x, the exit aperture area of 10 mm × 10 mm and the height of 26 mm, we can select the entry aperture area as 16 mm × 25 mm and consequently, the half acceptance angles are 33.97° and 26.59°, respectively. The thickness of the walls is 2 mm for both concentrators. The geometrical parameters of the design

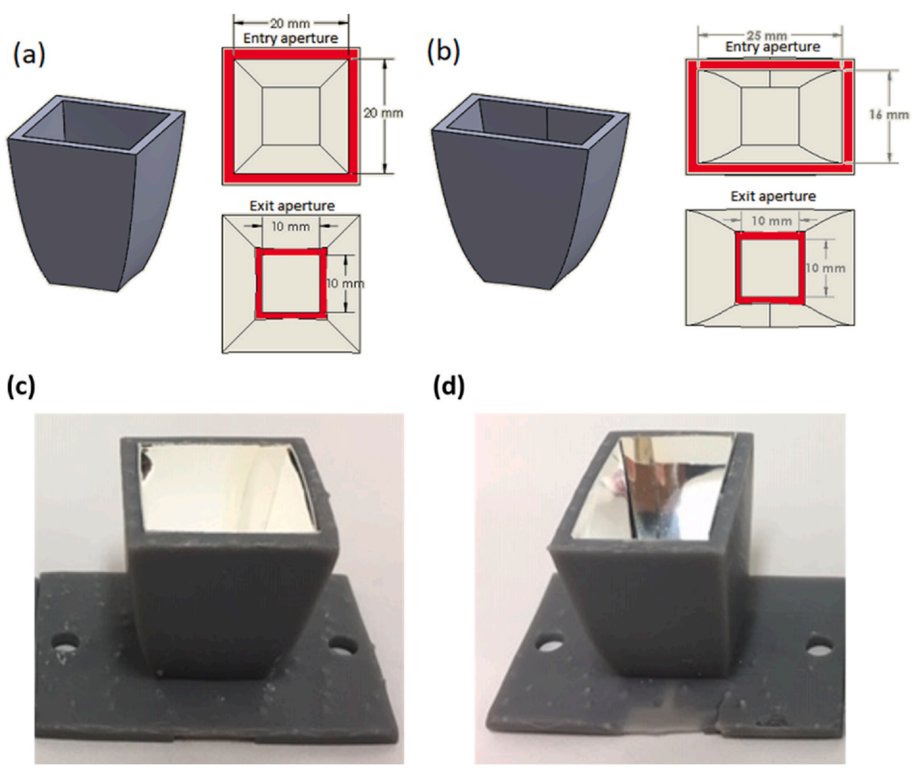

Fig. 1. The CAD files of the 4.0x concentrators created using the Solidworks for (a) sCCPC and (b) rCCPC, and the photographs of fabricated concentrators for (c) sCCPC and (d) rCCPC.

for both sCCPC and rCCPC are summerised in Table 1.

The frame of the designed concentrators was fabricated using Form 1+ 3D printer, which offers high resolution (<25 micro-meter) and smooth surface finish. The material used for 3D printing is Formlabs resins, which is a proprietary liquid photopolymer that can be solidified into acrylic plastic by laser. The reflective surfaces were formed by covering the inner surfaces of the concentrators with the aluminum foil of a spectral reflectivity of 95% and 0.2 mm thick obtained from *Alanod GmbH* [27]. A supporting base was designed at the bottom of the concentrator to hold the concentrator in place during testing. Fig. 1(c) and (d) shows a photograph of the two constructed concentrators.

3. Simulation

The angular response of the designed concentrators was initially investigated using ray tracing analysis. TracePro solfware was employed for this analysis because it has widely been used for study of the solar concentrators, showing good agreement between simulations and experiments [28–30]. The simulation model developed in the TracePro for this study was validated using a standard square 4.0x concentrator and the expected concentration ratio was obtained (see Appendix), confirming the validity of the model. Then, the angular response of the 4.0x sCCPC was determined as the reference for comparative study. The incident irradiance employed for this investigation is 1000 W/m^2 and the light intensity received at the exit aperture area was measured as a function of the angle of incidence (AOI). Fig. 2 illustrates the resultant irradiance maps from 4 selected angles of the 4.0x sCCPC. The number of rays used for all simulations in this study is 1,000,000 and the irradiance maps show the actual results of the simulations using 1,000,000 rays. However, the ray-trace plots shown in the figures are the corresponding simulations using 100 rays so that the paths of the rays can be seen clearly.

It can be seen from Fig. 2 (a) that all the rays are concentrated to the exit aperture area when the concentrator is at normal incidence irradiance. The optical efficiency at this position was found to be 93.2% and the flux distribution exhibits typical symmetrical feature of the sCCPC with high peaks near the four corners. When the angle of incidence (AOI) changes to 15°, all the incident rays on the entry aperture area of the concentrator can still be concentrated to the exit aperture area but the light distribution becomes highly non-uniform with a high intensity band appeared in the middle as shown in Fig. 2 (b). The optical efficiency at this angle is found to be 86.5%. However, with further increasing the AOI, the optical efficiency of the concentrator is reduced considerably. This is because some of the incident lights in this case can no longer reach the exit aperture area but are reflected out of the concentrator as shown in Fig. 2 (c). When the AOI is greater than the acceptance angle of the concentrator, all incident lights are reflected out of the concentrator and no light can reach the exit aperture area of the concentrator as shown in Fig. 2 (d). It can be seen that the angle that causes the complete reflection is very close to the half acceptance angle predicted by the theory.

In the case of rCCPC, it is anticipated that the acceptance angle along the N-S direction will differ from the E-W direction as illustrated in Fig. 3, which shows the CAD design of a 4.0x rCCPC with a theoretical half acceptance angle of 33.97° along the N-S direction and 26.59° along the E-W direction. To confirm the theoretical prediction, a model for a 4.0x rCCPC was developed using the TracePro and its angular response was investigated.

The angular response of the 4.0x rCCPC was simulated along both N-S and E-W directions and the results of simulation are shown in Figs. 4 and 5, respectively. It can be seen that the 4.0x rCCPC has an optical efficiency of 93.5% for both N-S and E-W directions at normal incidence, which is similar to the corresponding sCCPC. Although the total light power received by the exit aperture for both sCCPC and rCCPC are similar, the symmetrical feature of light distribution at AOI = 0° is different, which shows a 2-fold symmetry in the rCCPC while it is 4-fold in the sCCPC. Furthermore, the angular response of the rCCPC along the E-W direction differs significantly from that along the N-S directions. When rotating along the N-S direction, the angular response of the rCCPC is similar to the sCCPC except for the half acceptance angle is slightly larger. However, when rotating along the E-W direction with the half acceptance angle beyond AOI = 15°, the light power received by the exit aperture of the rCCPC is much higher than that of the sCCPC, indicating a slow decrease in the light intensity with the angle of incidence for the rCCPC. It can be seen that the light power received by the exit aperture of the rCCPC at AOI = 30° is 36 times of that in the sCCPC. This result is completely unexpected because the half acceptance angle predicted by theory is only 26.59° as shown in Fig. 3. A careful inspection of the light reflection of Fig. 5 (c) reveals that a significant portion of incident light is able to reach the exit aperture after second reflection at this AOI. Since the half acceptance angle was calculated based on the theory that does not consider the multiple light reflection, it leads to a significant difference between theory and simulation. This surprising result indicates that the angular response of the CCPC can be improved by simple geometrical modification.

4. Experimental

To confirm the simulation results, the angular response of the fabricated sCCPC and rCCPC were investigated using an experiment setup shown in Fig. 6. An Orial solar simulator (LCS-100, Class ABB) was used as a light source, which is in a Faraday-cage used to shield the influence of external electromagnetic field and light. The concentrator was placed under the illumination area of the solar simulator. A monocrystalline silicon solar cell, which has an active cell area of 10 mm × 10 mm and was soldered on a direct copper bonded board (DCB), was placed at the exit aperture of the concentrator. The solar cell and concentrator were mounted on a water-cooled rotary stage, which enables controlling the temperature of the solar cell and changing the angle of incidence relative to the light beam from the solar simulator (Fig. 7). The I-V curves were obtained using an Autolab potentiostat (Metrohm) controlled by a computer. The temperatures of the solar cell, rotary stage and the ambient inside the Faraday-cage were monitored using K-type thermocouples and Pico Data Logger.

The testing was carried out at standard test conditions of 1000 W/m^2, AM 1.5G and 25 °C. The distance between the solar simulator lamp and the one-sun plane was determined using a reference solar cell (Solar Survey, SEAWARD) [31]. Care has been taken to ensure that the entry aperture of the concentrator is in alignment with the one-sun plane. The measurements were first carried out at AOI = 0° to check if the quality of the fabricated concentrators is satisfactory before used for angular response study. Fig. 8 shows the I-V and P-V curves obtained from the fabricated sCCPC and rCCPC at AOI = 0°, with the bare cell as the reference. The key electrical parameters determined from the I-V and P-V curves are listed in Table 2. The actual concentration ratio of a concentrator was determined from the ratio of the measured short-circuit current of the solar cell with a concentrator to that without the concentrator (i.e., bare cell only). Using the experimental data in Table 2, the actual concentration ratio of the fabricated sCCPC and rCCPC are 3.30 and 3.26, respectively. Since the geometric

Table 1
Geometrical parameters of the concentrators used for this study (sCCPC is a conventional CCPC with a square entry aperture. rCCPC is a new design with a rectangular entry aperture).

	sCCPC	rCCPC
Entry aperture (mm)	20 × 20	25 × 16
Exit aperture (mm)	10 × 10	10 × 10
Height (mm)	26	26
Concentration ration	4x	4x
Half acceptance angle	30.0°	33.97° (N-S), 26.59°(E-W)
Thickness of concentrator wall (mm)	2	2

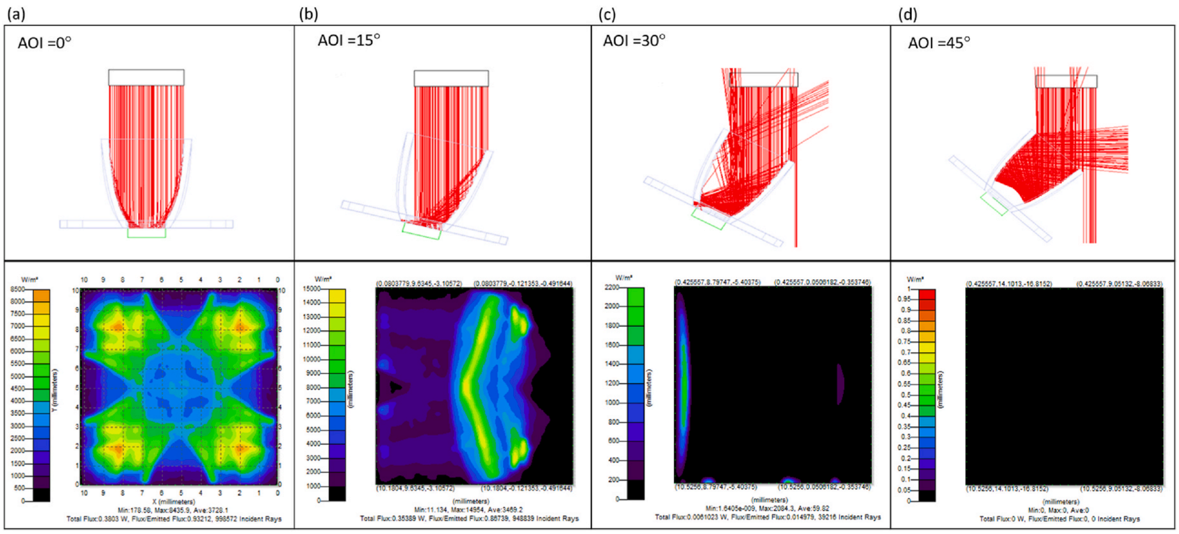

Fig. 2. Irradiance map showing the light distribution for the 4.0x sCCPC at four incidence angles: (a) AOI = 0°, (b) AOI = 15°, (c) AOI = 30° and (d) AOI = 45°. The number of the rays used in this simulation is 1,000,000.

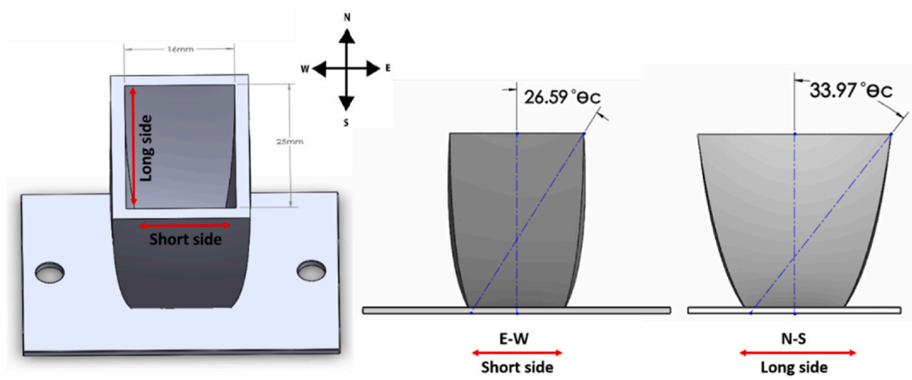

Fig. 3. CAD design of the 4.0x rCCPC showing the theoretical acceptance angles for (E-W) direction and the (N-S) direction.

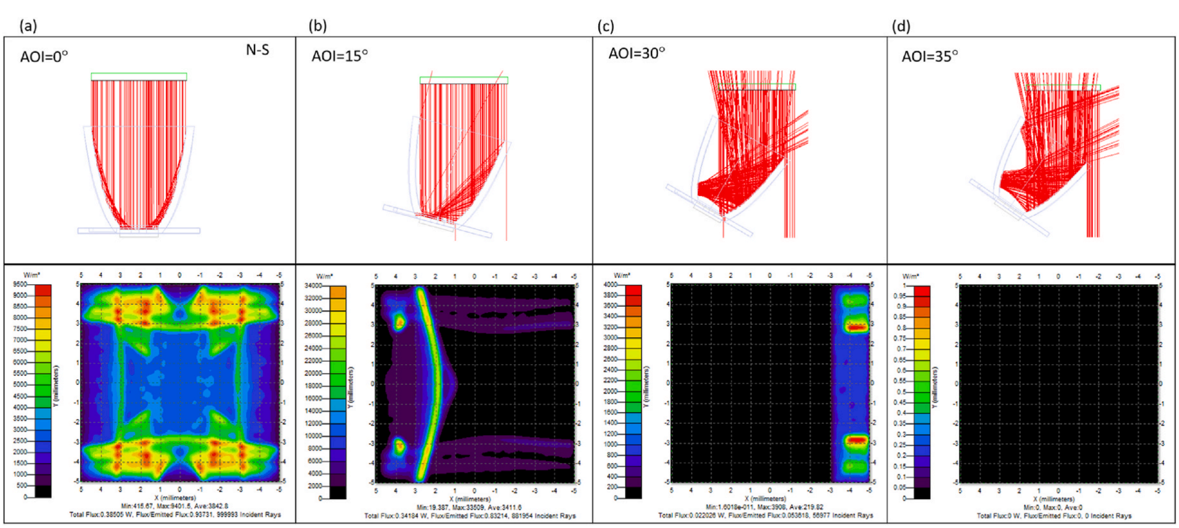

Fig. 4. Irradiance map showing the light distribution for the 4.0x rCCPC along N-S direction at four selected angles: (a) AOI = 0°, (b) AOI = 15°, (c) AOI = 30° and (d) AOI = 35°. The number of the rays used in this simulation is 1,000,000.

concentration ratio for both concentrators is 4.0, this corresponds to the optical efficiency of 82.4% and 81.5% for the fabricated sCCPC and rCCPC, respectively. These values are among the highest values reported for this type of concentrators, demonstrating the high quality of the fabricated concentrator. It is to be noted that the effect of the sun half angle is not considered in this study.

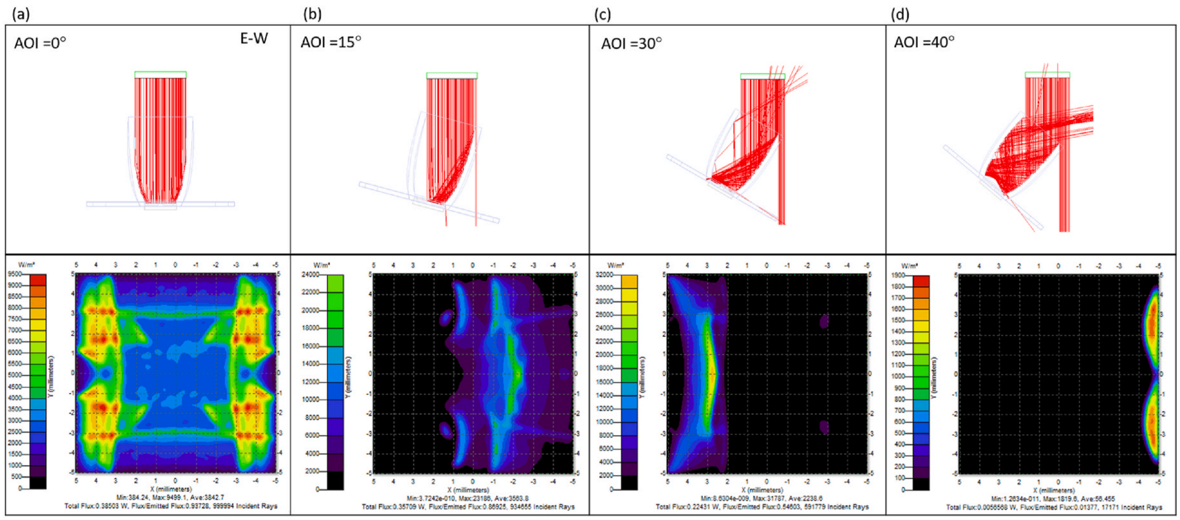

Fig. 5. Irradiance map showing the light distribution for the 4.0x rCCPC along E-W direction at four selected angles: (a) AOI = 0°, (b) AOI = 15°, (c) AOI = 30° and (d) AOI = 40°. The number of the rays used in this simulation is 1,000,000.

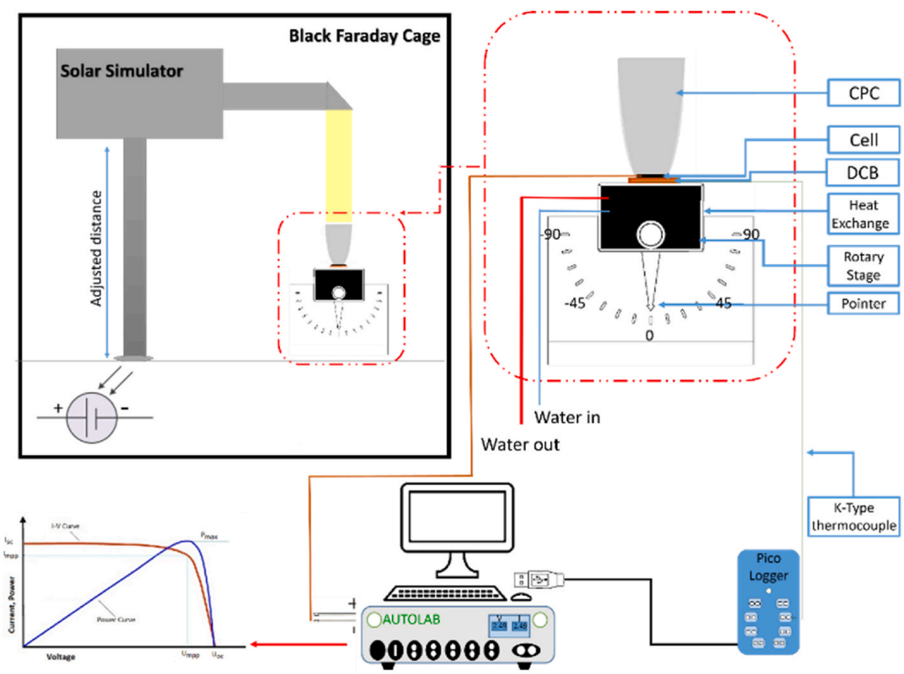

Fig. 6. Schematic diagram of the experimental setup for measuring angular response of the solar concentrators.

To investigate the angular response, the concentrators were rotated clockwise at an increment of every 5° up to + 45° and then repeated anticlockwise up to − 45°. I-V characteristics were recorded for each incremental angle. The power outputs of the concentrator systems as a function of the AOI were determined from the measured I-V curves (Appendix Figure A2). The results for three cases (i.e., sCCPC, rCCPC(E-W) and rCCPC(N-S)) are shown in Fig. 9. The tests were repeated 3 times for each case and the results presented in Fig. 9 is the average values from 3 measurements. It can be seen that the angular responses of the power outputs from all three cases show small differences within AOI <15°. However, when the AOI further increases, the angular response among 3 cases becomes increasingly different. For example, when the AOI reaches 25°, the light power received at the exit aperture of the sCCPC was approximately 15 mW, corresponding to a reduction by 61%. While it was approximately 30 mW for rCCPC(E-W), corresponding to a reduction of only 19%. Further increasing the AOI to 30°, the power output of sCCPC is reduced to merely 7% of the initial power output (at AOI = 0°), while the rCCPC(E-W) still generates about 46% of its initial power. It is to be noted that this improvement is achieved at no expense of reduction in concentration ratio and optical efficiency. This result demonstrates that the angular response of the CCPCs can be improved considerably by replacing a conventional sCCPC with a corresponding rCCPC that has a rectangular entry aperture and operates in the E-W direction.

On the other hand, the angular response of the rCCPC operating in N-S direction become poorer than that of sCCPC. Both the degradation in rCCPC(N-S) and the improvement in rCCPC(E-W) are predicted by the TracePro simulation. Fig. 10 shows the experimental data of the angular responses for all three cases compared to the corresponding simulated results, which show a good agreement between the experiment and simulation for all three cases. Careful inspection of the simulated light reflection paths in Fig. 5(c) and (d) reveals that the improvement of

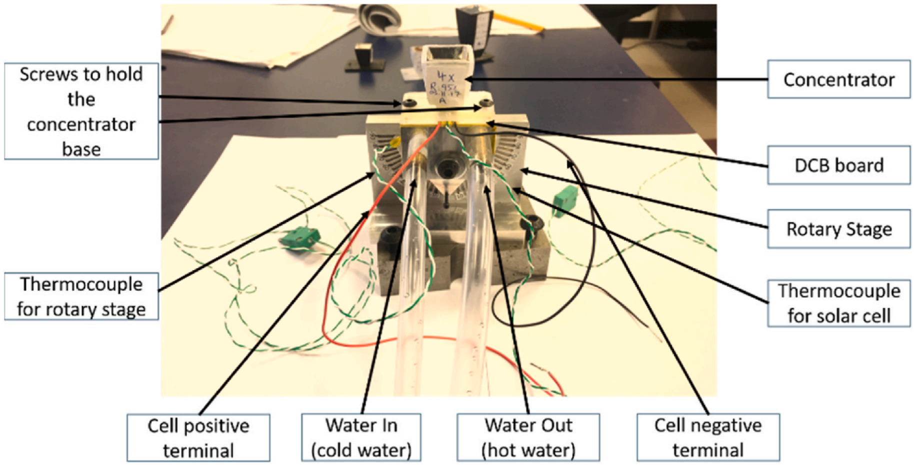

Fig. 7. A photograph of the concentrator on a rotary stage for angular response measurements.

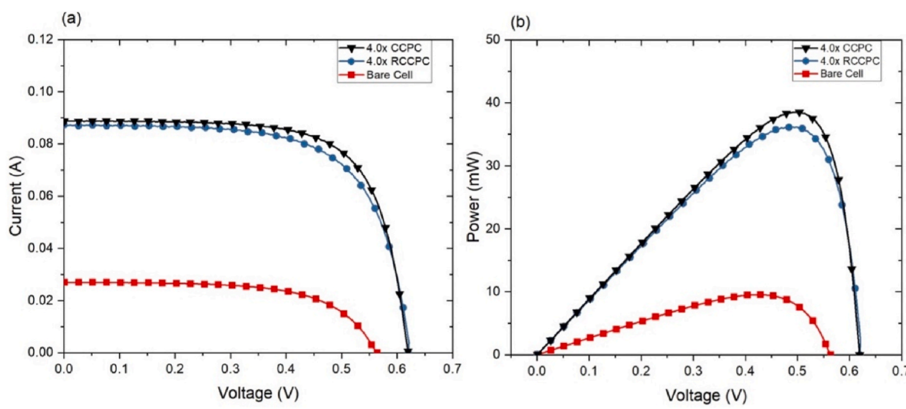

Fig. 8. The measured I-V (a) and P-V (b) characteristics of the 4.0x sCCPC, 4.0x rCCPC and the bare cell.

Table 2
Electrical parameters of the bare cell, 4.0x sCCPC and 4.0x rCCPC (η_s is the efficiency of the solar cell and η_c is the optical efficiency of concentrator; the bare cell is the solar cell tested under one sun irradiance without concentration.).

	I_{sc} (A)	V_{oc} (V)	P_{max} (mW)	(FF) (%)	η_s (%)	η_c (%)
Bare cell	0.027 ± 0.002	0.565 ± 0.002	9.88 ± 0.01	65.0	9.88	–
sCCPC	0.089 ± 0.002	0.620 ± 0.002	38.50 ± 0.01	70.0	11.70	82.4
rCCPC	0.088 ± 0.002	0.618 ± 0.002	37.00 ± 0.01	68.0	11.25	81.5

angular response in rCCPC(E-W) is due to the fact that significant amount of lights can reach to the exit aperture after second reflection inside the concentrator. This explains the reason for a considerably large difference between the theoretical half acceptance angle (26.59°) and the actual experimental result (40°) because the multiple light refection had been neglected by the current design theory. Clearly, the multiple light reflection inside a concentrator can play an important role in angular response and the design of the CCPCs must consider the contribution of multiple light reflections. The results of this investigation also indicate that although the current design theory can provide reliable description of conventional square CCPCs it should be used with care when dealing with other type of CCPCs.

5. Conclusions

This work reports a new design of crossed compound parabolic concentrator (CCPC) that has a rectangular entry aperture (instead of conventional square aperture), which led to an increase in the half acceptance angle. A comparative study was carried out experimentally using a 3D printed 4.0x rectangular CCPC and a 4.0x square CCPC. The results show that the half acceptance angles are 40° and 30° for the rectangular CCPC and the square CCPC, respectively. As a result, when the angle of irradiance is approaching 30°, the power output from the square CCPC becomes negligible, while the rectangular CCPC can still generate more than 50% of its nominal power (i.e., the power produced at AOI = 0°). The technological and economic benefits of this improvement is evident because it can produce more power in a stationary CPV system or reduce the complicity and operation of tracking in a non-stationary CPV system.

It is interesting to note that the improvement of the half acceptance angle observed in the rectangular CCPC was not anticipated by the current design theory. The reason for the improvement was identified through simulation, which reveals that the improvement in angular response of the rectangular CCPC is attributed to multiple light reflection inside the concentrator that has been neglected in the current design theory of the CCPCs. Clearly, this work demonstrates that the multiple light reflection inside a concentrator plays a significant role in the angular response which cannot be neglected in the design. Although

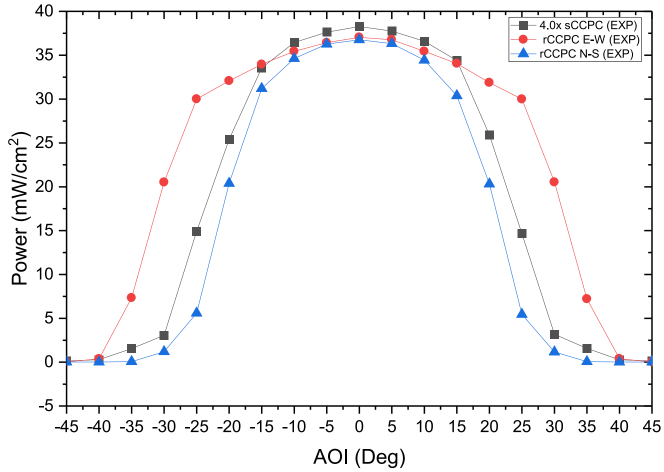

Fig. 9. Experimental results of the power outputs of the 4.0x sCCPC and 4.0x rCCPC concentrator as a function of the angle of incidence (AOI). The angular response of the rCCPC systems were measured along both the E-W and N-S directions.

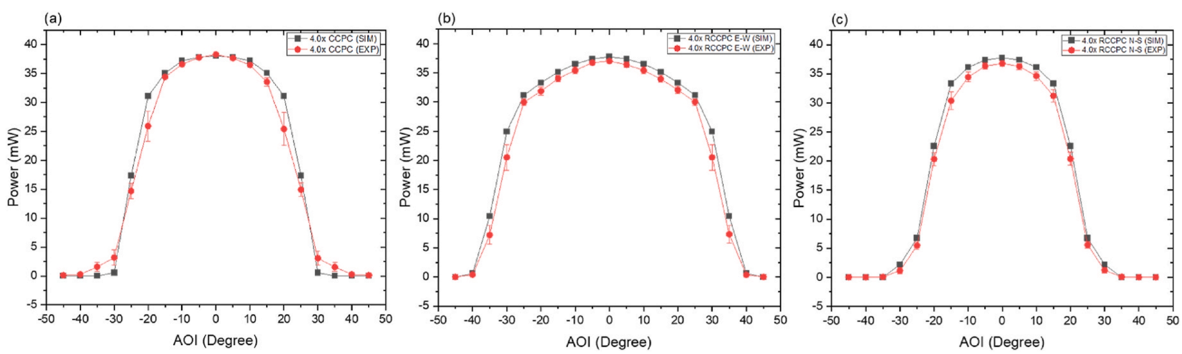

Fig. 10. Experimental and simulated power output as a function of the angle of incidence (AOI) for (a) a 4.0x conventional square CCPC, (b) a 4.0x rectangular CCPC rotating along the E-W direction, and (c) a 4.0x rectangular CCPC rotating along the N-S direction. The experiments were performed under the standard testing conditions of 1000 W/m^2, AM 1.5, and 25 °C. The data presented were the average values of three measurements. The simulation was carried out using a TracePro model with 1,000,000 rays.

the current design theory of the CCPCs provide satisfactory prediction for the concentration ratio at normal incident, a reliable design of the angular response of the CCPCs requires ray-tracing simulation that takes into account the multiple light reflection inside a concentrator.

Data availability

Information on the data underpinning the results presented here, including how to access them, can be found in the Cardiff University data catalogue at [10.17035/d.2023.0236715125].

CRediT authorship contribution statement

Mazin Al-Shidhani: Conceptualization, Methodology, Software, Validation, Data curation, Writing – original draft, Visualization, Investigation, Formal analysis. **Min Gao:** Conceptualization, Supervision, Writing – review & editing, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX. Initial validation of TracePro model

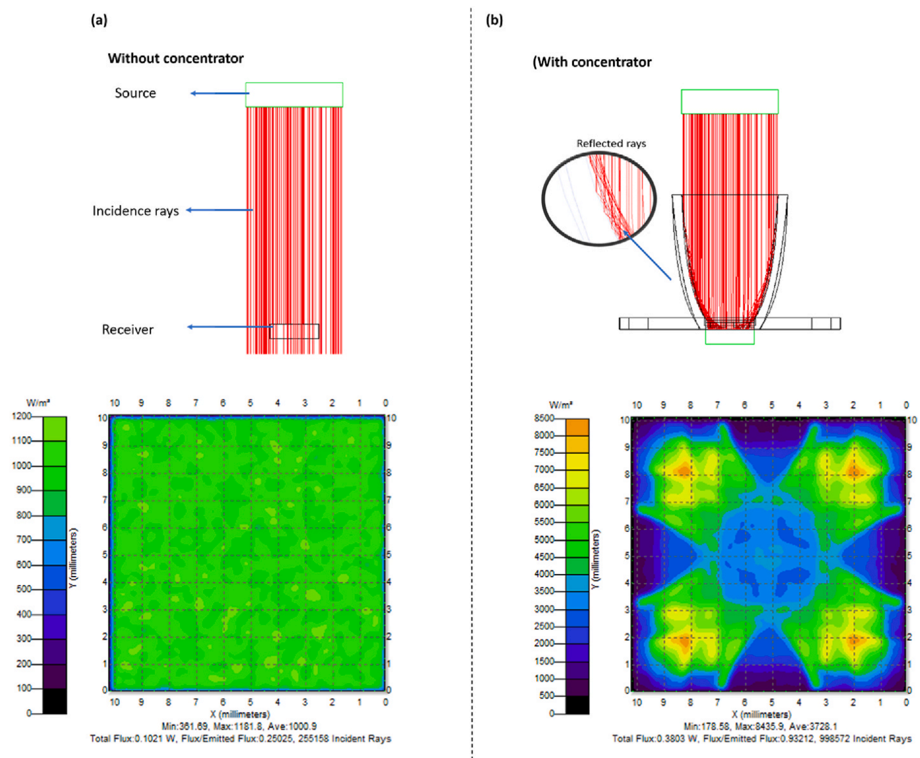

Fig. A1. Validation of the TracePro model of a 4.0x sCCPC. (a) The irradiance map under 1000 W/m^2 irradiance without concentrator and (b) The irradiance map at the exit aperture of a 4.0x CCPC which receives an irradiance of 1000 W/m^2 at its entry aperture. The optical efficiency of approximately 95% obtained from the above simulated results confirms the validity of the model because small losses are expected. The number of rays used for this simulation is 1,000,000.

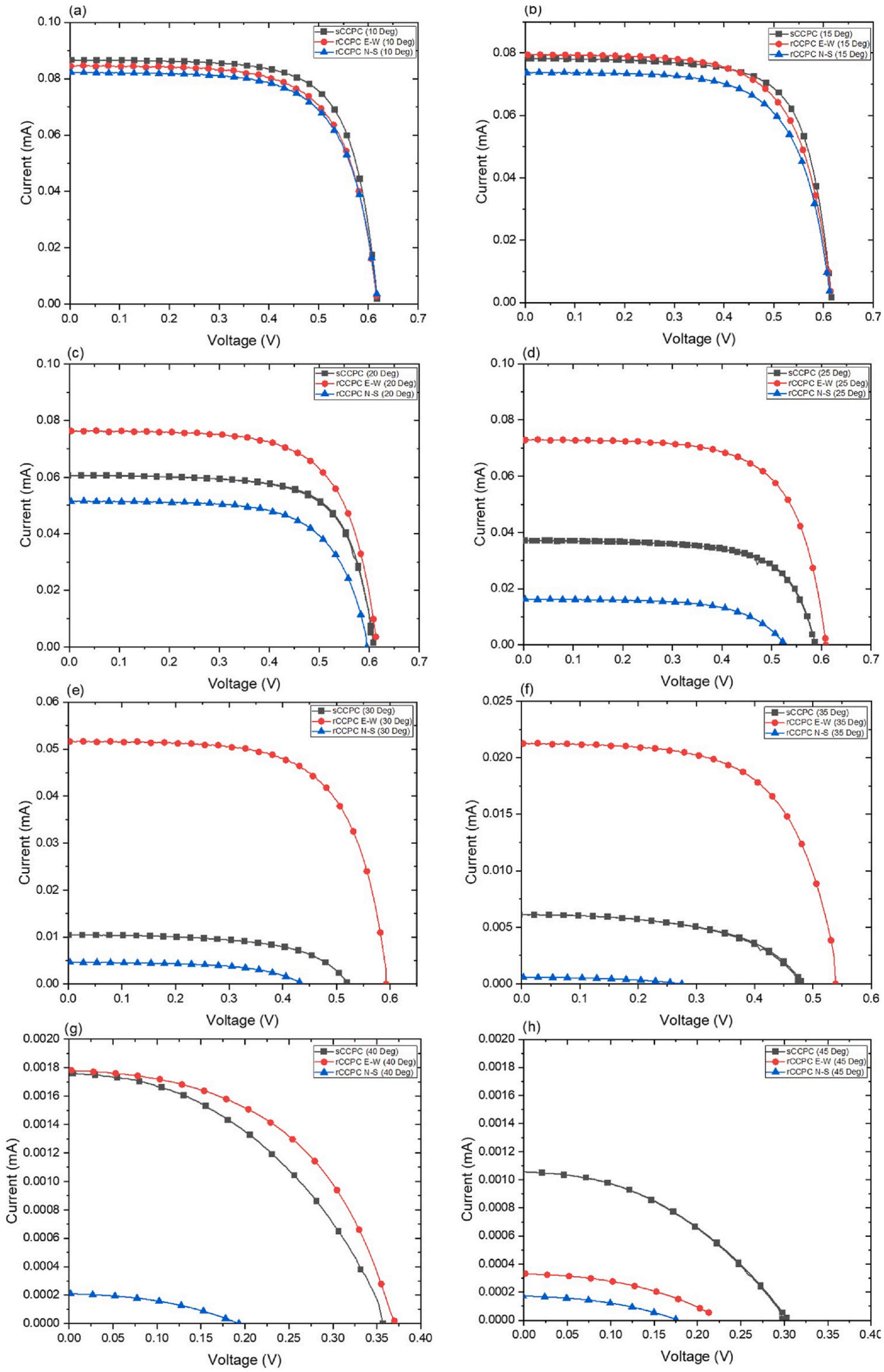

Fig. A2. I-V curves at different AOI for the sCCPC, rCCPC(E-W) and rCCPC(N-S) (a) I-V curve AOI = 10°, (b) I-V curve AOI = 15°, (c) I-V curve AOI = 20°, (d) I-V curve AOI = 25°, (e) I-V curve AOI = 30° and (f) I-V curve AOI = 35°.(g) I-V curve AOI = 40° and (h) I-V curve AOI = 45°.

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