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## Radiance/Pmap simulation of a novel lens-walled compound parabolic concentrator (lens-walled CPC)

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### Abstract

This study presents a Radiance/Pmap ray-tracing analysis of a lens-walled compound parabolic concentrator (lens-walled CPC), which has a thin CPC-shape lens attached to a common mirror CPC or being mirror-coated outside. The lens-walled CPC may have a larger acceptance angle than a mirror CPC and could be an alternative to a solid dielectric CPC which may be heavy and costly. The lens-walled CPC may be a promising design for building-integrated photovoltaics applications. The well-known ray-tracing software Radiance with its supplementary Pmap is used to verify the principle of the presented lens-walled CPC and examine its optical performance against the mirror and solid CPCs. A comparison of simulation results between Radiance/Pmap and a commercial software Photopia is also given.

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**Keywords:** Lens-walled, CPC, Radiance/Pmap simulation, acceptance angle, optical efficiency

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### 1. Introduction

A compound parabolic concentrator (CPC) comprises of two parabolic curves with their axes of symmetry tilted to form an acceptance angle to enable collection of both direct and diffuse solar radiation. The compound parabolic concentrator (CPC) is the well-known low concentration solar concentrator. The

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CPC was proposed by Roland Winston and further developed by Walter Welford mainly in the 70's [1, 2]. The CPC-based concentrating PV systems have the feature of non-tracking and high liability, and can be potentially cheaper than the common flat PV systems, so they have received great interest for building-integrated applications [3, 4, 5]. A stationary east-west orientated trough CPC usually has a tilt angle about equal to the local latitude to maximize the solar collection. The annual percentage of collectable solar irradiation for the trough CPC is primarily dependent on its acceptance angle. The incidence angle of solar radiation changes within  $\pm 90^\circ$  to the ground surface normal. However, a study [6] shows that the solar radiation predominantly falls within  $\pm 35^\circ$  of the north-south projected incidence angle to the CPC aperture normal and even smaller for locations of higher latitude. A stationary mirror CPC with a half acceptance of  $35^\circ$  can collect about 85% of the annual solar irradiation. For locations of higher latitude, a stationary mirror CPC with a half acceptance of  $23.5^\circ$  can collect about 75% of the annual solar irradiation. The corresponding geometrical concentration ratio is about 1.75 for  $35^\circ$  and 2.5 for  $23.5^\circ$ . A higher geometrical concentration ratio would be desired for concentrating PV application in order to considerably reduce PV size, but this will result in a smaller acceptance angle. Use of a solid dielectric (e.g., acrylic) CPC can give a larger acceptance angle, but it has a larger weight.

The lens-walled CPC as shown in Figure 1 may be a measure to overcome these disadvantages. The lens-walled CPC has a thin CPC-shape lens attached to the inside of a mirror CPC or has the outside surface of the lens to be mirror-coated. The shape of lens may be formed by rotating the parabolic curves of a CPC by a small degree inwardly around their top end points. The angle of rotation may be called the lens forming angle. The refraction of lens and the mirror reflection may direct the light coming at a larger incidence angle to reach the base of the lens-walled CPC, so it would have a larger acceptance angle than the corresponding mirror CPC. Moreover, the weight of the lens-walled CPC will be much lighter compared with a solid dielectric CPC. Radiance/Pmap ray-tracing simulation will be used in this study to analyse the characteristics of the lens-walled CPC in terms of its acceptance angle and optical efficiency.

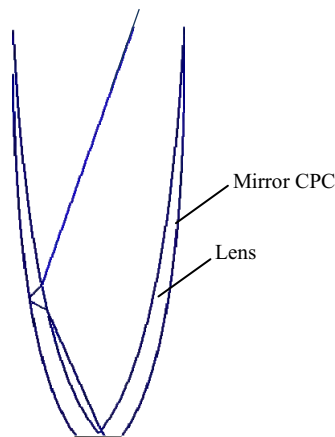
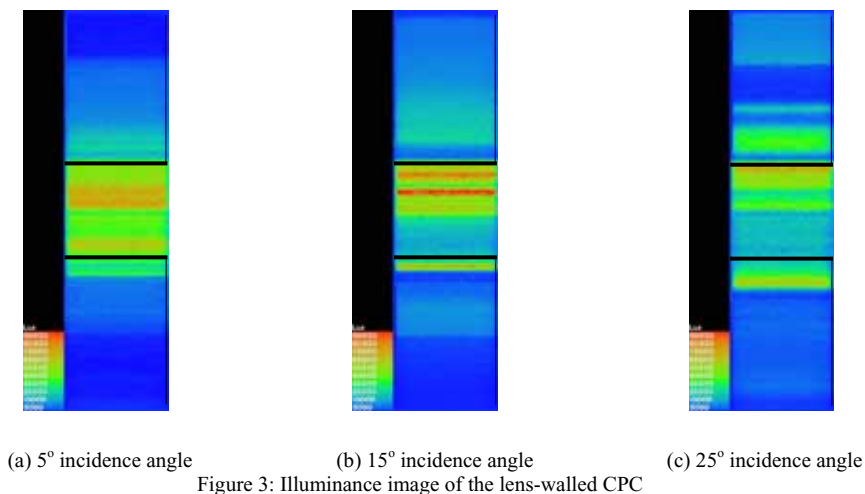
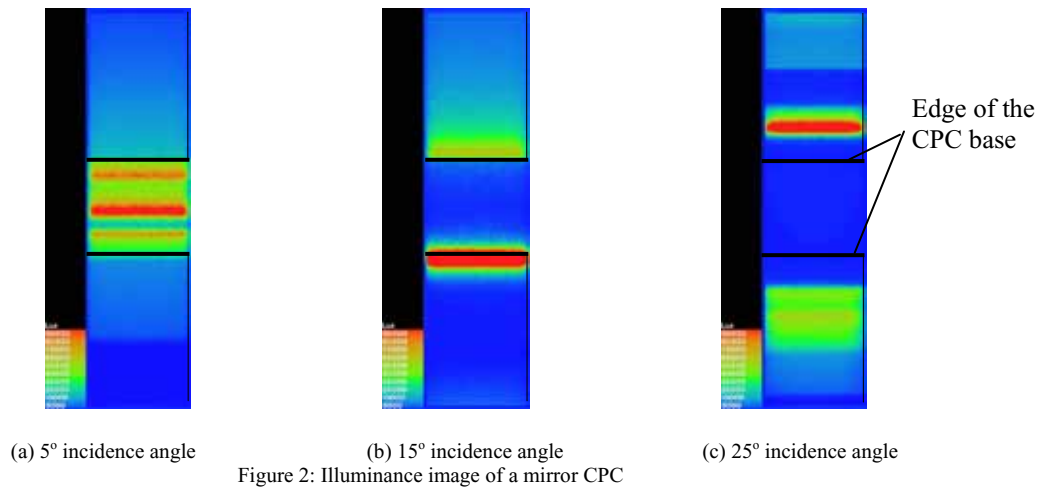


Figure 1: Principle of the lens-walled CPC

## 2. Radiance/Pmap simulation

The well-known highly accurate ray-tracing software Radiance with a supplementary Pmap was used to simulate the presented lens-walled CPC. Radiance was developed at the Lawrence Berkeley Laboratories and it employs backward ray-tracing algorithms, in which the light rays are traced back from

the point of measurement or view to the light source. The result is mathematically equivalent to forward ray-tracing, but the process is generally more efficient because most of the light leaving a source never reaches the point of interest [7]. However, developments in light redirecting designs (e.g., lightpipe and prismatic panel) have presented new challenges in classic Radiance simulation. It has been found that Radiance has a difficulty in simulation of refraction and specular reflection. This challenge has necessitated the development of the forward ray-tracing module Pmap (short for photon map) as a supplementary algorithm to the classic Radiance [8]. Roland Schregle has validated Radiance/Pmap simulation for several daylighting and shading designs and found that the simulation exhibits a deviation up to 10% compared to the measurements [9]. Radiance has a function called gensky which could be set by the users to generate different sky radiance distributions. In this study, the gensky function was set to generate the direct solar radiation solely for various incidence angles.



Ray tracing simulation was conducted to produce the illuminance images of a lens-walled CPC and a mirror CPC with the same geometrical concentration ratio of 4 to verify the principle of the lens-walled

CPC. Figure 2 shows the illuminance images of the inside surface of the mirror CPC for three incidence angles of  $5^\circ$ ,  $15^\circ$  and  $25^\circ$ . As expected, light at the incidence angle of  $5^\circ$  is concentrated on the base of the mirror CPC, but at the incidence angle of  $15^\circ$  which is slightly larger than the half acceptance angle of  $14.5^\circ$  light is concentrated around the edge of the mirror CPC's base. Light at the incidence angle of  $25^\circ$  can not reach on the base of CPC. Figure 3 shows the illuminance images of the inside surface of the lens-walled CPC which has a lens-forming angle  $3^\circ$  for three incidence angles of  $5^\circ$ ,  $15^\circ$  and  $25^\circ$ . It is evident that at the incidence angle of  $15^\circ$  most of light is concentrated on the base of the lens-walled CPC, and even at the incidence angle of  $25^\circ$  a large amount of light is still concentrated on the base of the lens-walled CPC. Comparison of Figures 2 and 3 indicates that the presented lens-walled CPC has a larger acceptance angle and more even irradiance distribution on its base, which is desired for concentrating PV applications.

### 3. Analysis

Radiance/Pmap ray tracing simulation was further used to determine the acceptance angle and optical efficiency of the lens-walled CPC and its counterpart mirror and solid CPCs as well. The simulated CPCs were trough-type with a geometrical concentration ratio of 4 and a base width of 10mm, and were represented by a number of small polygons in Radiance. The lens-walled CPC was considered to be formed by attaching a thin lens on the inside of the mirror CPC. The reflective surface was specified by modifying the optical parameters of the galvanized surface in Radiance, which uses a general reflectance model to calculate the reflectance distribution from the specularity and surface roughness [7, 8]. The equivalent specular reflectance was 0.9. For a fair comparison, a transmission coefficient of 0.9 was used for the dielectric lens material.

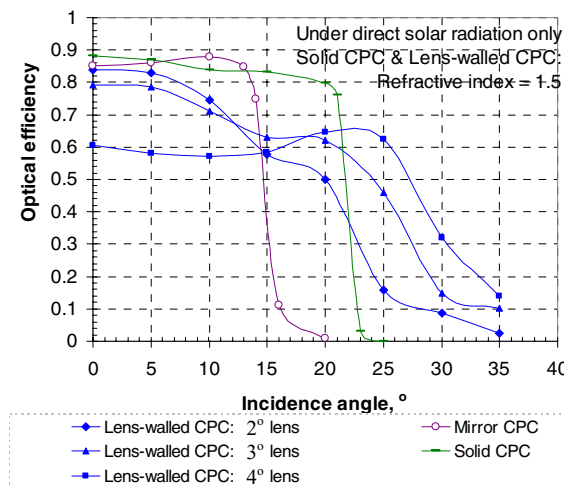


Figure 4: Optical efficiency versus incidence angle for the trough lens-walled CPC with different lens forming angle under direct solar radiation only.

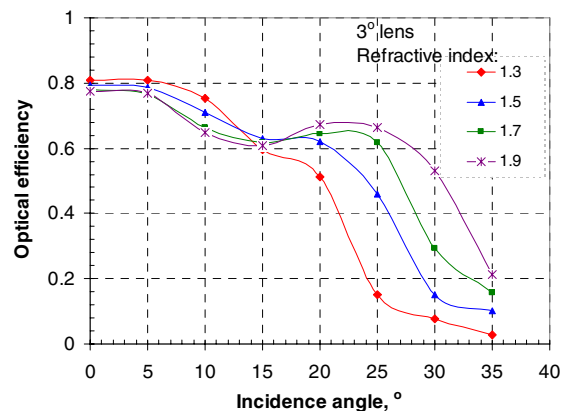


Figure 5: Optical efficiency versus incidence angle for the trough lens-walled CPC with different lens refractive index under direct solar radiation only.

Figure 4 shows the change of the optical efficiency with incidence angle for the trough lens-walled CPCs of different lens forming angles under direct solar radiation only. The simulation results for the mirror and solid dielectric CPCs are also given for comparison. The optical efficiency is the ratio of the solar radiation received at the base of a CPC relative to the incoming solar radiation at the front aperture

of the CPC. It is apparent that the lens-walled CPC has a much larger acceptance angle than the mirror CPC, but its optical efficiency is somewhat lower than the mirror CPC for the incidence angle within its half acceptance angle  $14.5^\circ$ . However, when the incidence angle is larger than  $14.5^\circ$ , the lens-walled CPC is great advantageous over the mirror CPC in terms of optical efficiency, and this becomes better when the lens forming angle changes from  $2^\circ$  to  $4^\circ$ . It is also clear that the lens-walled CPC even has a larger acceptance angle than the solid CPC though its overall optical efficiency may be slightly lower.

The results in Figure 4 also indicate the deviation of Radiance/Pmap simulation from the theoretical estimation. For example, the curve for the mirror CPC does not exhibit a straight vertical line at the incidence angle equal to  $14.5^\circ$  and is not quite flat when the incidence angle  $< 14.5^\circ$ . For the surface reflectance of 0.90, the mirror CPC is expected to have an optical efficiency slightly larger than 0.90. The simulation gave a value around 0.85, so the deviation is about 5.5% which is within the general deviation range found by Roland Schregle [9]. A similar deviation can be found for the solid dielectric CPC as the transmission coefficient of 0.9 was assumed. The deviation is obviously much larger at the incidence angle close to the half acceptance angle of the mirror or solid CPC. This is probably due to the reason of optical bias as encountered in ray-tracing simulation [8, 9]. At the incidence angle equal to the half acceptance angle  $14.5^\circ$ , the incoming light is theoretically expected to be concentrated on the edge line of the mirror CPC base. Because of optical bias in simulation, the light is actually focused on a narrow band, which is also evident in Figure 2. When the incidence angle equal to or slightly less than  $14.5^\circ$ , part of this optical band might be out of the CPC base and could not be counted on the numerical grid on the CPC base. Similarly, part of this optical band might be on the CPC base when the incidence angle close to but larger than  $14.5^\circ$ . This might be the reason why the curves for the mirror CPC do not exhibit a straight section at the incidence angle equal to  $14.5^\circ$ . However, the overall simulation accuracy was satisfactory and should be sufficient for comparison of the lens-walled CPC with the common CPCs.

Figure 5 shows the effect of the lens refractive index on the optical efficiency of the lens-walled CPC under direct solar radiation only. For the incidence angle less than the half acceptance angle  $14.5^\circ$  of the counterpart mirror CPC, the effect of refractive index is small. However, when the incidence angle  $> 14.5^\circ$ , larger optical efficiency of the lens-walled CPC may be obtained for larger refractive index of lens.

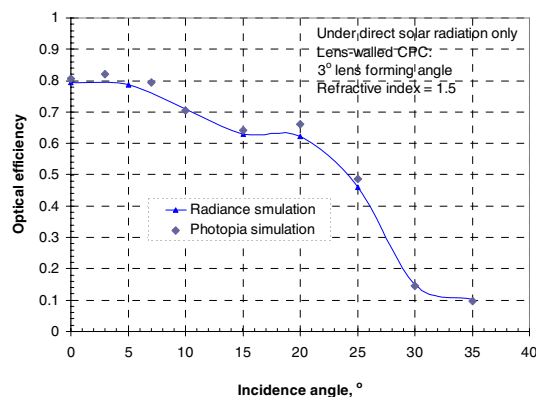


Figure 6: Comparison between Radiance/Pmap simulation and Photopia simulation

A comparison between the open source software Radiance/Pmap and a commercial optical analysis software Photopia for simulation of the lens-walled CPC was also conducted. It is evident from Figure 6 that the overall agreement between their simulation results is fairly good and the average relative

difference is within 5%. This further demonstrates that the reliability of Radiance/Pmap for simulation of the lens-walled CPC.

#### 4. Conclusions

A novel lens-walled compound parabolic concentrator (CPC) has been described and simulated using a well-known ray-tracing software Radiance/Pmap. The lens-walled CPC is formed by either attaching a thin CPC-shape lens on the inside of a mirror CPC or having a mirror coating on the outside of lens. The simulation results indicate that the lens-walled CPC has a much larger acceptance angle than its counterpart mirror and solid CPCs. The overall optical efficiency of the lens-walled CPC is larger than the mirror CPC and slightly lower than the solid CPC, but it has a light weight, so it could be a good alternative to the solid CPC for stationary concentrating PV applications. The comparison between the open source software Radiance/Pmap simulation and the theoretical estimation has shown a satisfactory accuracy of simulation. This has been further confirmed by comparing with the simulation given a commercial optical analysis software Photopia.

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