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Research Paper 研究論文

Assessment of the Tilt Effect and the Truncation Effect on the energy collection performance of the MultiPro-CPCs in Tokyo

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Abstract

Although compound parabolic concentrators (CPCs) are widely used for solar concentration, they only have one degree of freedom in the design of their acceptance angle. To overcome this limitation, a new type of concentrator called MultiPro-CPCs has been developed. These three-dimensional concentrators have multiple compound parabolic profiles, combined with elliptical and rectangular receivers, enabling them to have multiple directional acceptance angles. In this study, the tilt effect, and the truncation effect on the energy collection performance of the MultiPro-CPCs in Tokyo is presented with a comparison to the three-dimensional CPC through ray tracing simulation. The MultiPro-CPCs with an elliptical receiver showed the highest performances, up to twice the collected energy per receiver area of the 3DCPC. Moreover, all truncated MultiPro-CPCs show higher peak performance compared to the non-truncated 3DCPC. The outcomes show the MultiPro-CPCs as better options in the field of concentration when considering high-cost receivers and concentrator height limits.

***Keywords*:** Compound Parabolic Concentrator, Elliptical receiver, Rectangular receiver, Truncation, Tilt

1. Introduction

The amount of energy that falls on the Earth in just one hour of sunlight surpasses the energy consumption of the entire world for a whole year(1). Therefore, an efficient use of all this solar energy can solve the problems of energy access and energy security with environment-friendly solar technologies. Nevertheless, solar installations require significant land areas and tracking systems to achieve high temperatures due to their dependency on the momently movement of the sun. To overcome these efficiency limits, solar concentration using mirrors or lenses to concentrate the solar rays on a receiver is shown as a solution. The compound parabolic concentrator (CPC)(2) designed by Winston et al. and consisting of a combination of two parabolic mirrors, is a core technology in the field of solar concentrator. The CPC has the function of advancing obliquely incident rays to the receiver, but it has only 1 degree of freedom in designing the half acceptance angle at which it can receive rays(3). The shapes created by rotating the CPC curve around an axis are called three-dimensional CPC (3DCPC) and the ones created by translating the CPC curve in a direction are called two-dimensional CPC (2DCPC). It has been also proven that the energy concentration ratio of the 3DCPC is found to be the square of the one of the 2DCPC (4). Two-dimensional and three-dimensional solar concentrators are used for heat generation(5-7), thermodynamic power generation(8,9) and photovoltaic power generation(10,11). Since the sun's position changes with time, momently tracking technologies are still used to concentrate the solar rays with high energy collection ratios.

To overcome these limits, the author previously developed the MultiPro-CPCs(12) which are non-momently tracking three-dimensional solar concentrators. This appellation comes from the fact that the MultiPro-CPCs have a CPC profile at any diagonal cross-section and changeable receiver shapes. In this previous study, multiple CPC profiles with different directional acceptance angles, and elliptical and rectangular receiver shapes are assumed. Based on simulations considering solar incidence and axial angles, it has been demonstrated that the MultiPro-CPCs can achieve an optical concentration ratio which can be up to 10 times higher compared to the conventional CPCs when their receiver major length is equal(12). Furthermore, assuming a mirror reflectance of 95%, the highest optical efficiency of 95% occurs when both the longitudinal and transversal incidence

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angles are 0°, meaning the emitter is directly above the concentrator. In MultiPro-CPCs, the efficiency decreases when the directional incidence angles increase. Compared to conventional CPCs, MultiPro-CPCs have moderate filtering, especially in the longitudinal direction. In addition, MultiPro-CPCs with rectangular receivers, capture wider oblique incidences than MultiPro-CPCs with elliptical receivers[12]. Nevertheless, the energy collection performance in a specific location during a specific period is yet to be clarified.

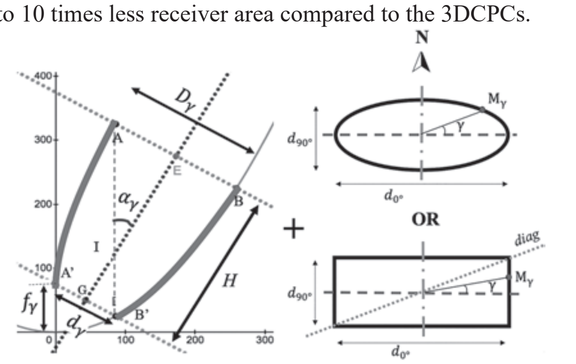
The objective of this study is to complement the assessment of the MultiPro-CPCs, spatiotemporal raytracing simulations in Tokyo in 2022. The assessment index is the energy collection per receiver area obtained through optical simulation. Moreover, the tilt effect and the truncation effect on the energy collection performance of the MultiPro-CPCs are presented.

Nomenclature

D_γ [mm]	Diameter of the aperture of the CPC at a profile
d_γ [mm]	Diameter of the receiver of the CPC at a profile
f_γ [mm]	Focus length of the CPC at a profile
H [mm]	Height of the CPC
M_γ [-]	Point of the receiver at γ
t_γ [°]	Angular parameter of the receiver at γ
x [mm]	x-axis coordinate
y [mm]	y-axis coordinate
α_γ [°]	Half acceptance angle of the CPC at a profile
$\alpha_{0°}$ [°]	Longitudinal direction half acceptance angle
$\alpha_{90°}$ [°]	Transverse direction half acceptance angle
γ [°]	Angle between a profile plane and the east-west direction
γ_{diag} [°]	Value of γ at the diagonal plane of the rectangle

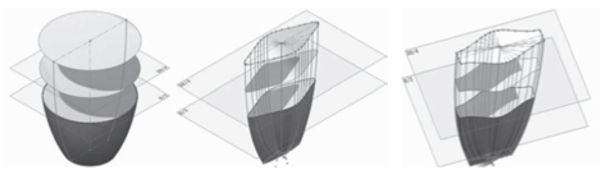
2. Design Method of the MultiPro-CPCs

The MultiPro-CPCs are new kinds of three-dimensional concentrators having a compound parabolic concentrator (CPC) shape at each profile with multiple acceptance angles in all directions and elliptical or rectangular receivers as shown in Fig. 1. Here, γ represents the angle between the profile plane and the longitudinal direction, α_γ the half acceptance angle, D_γ the aperture diameter, d_γ the receiver diameter, and H the concentrator height. The point M_γ represents a position on the receiver at γ. The MultiPro-CPCs can be reproduced by using the formulas and by following the steps mentioned in the previous study[12]. In this study, the longitudinal direction (γ=0°) corresponds to the East-West direction and the transverse direction (γ=90°) to the North-South. The half acceptance angle in the longitudinal direction is set to 15° and 45°, and the half acceptance angle in the transversal direction to 10°, and all receiver major axes are equalized. Here, in addition to their original size, the shapes are tilted from the horizontal every 15° from 0 to 90° and truncated at 3/4 and 1/2 of their heights H. In total, 3 types of concentrator are compared when truncated and not truncated: the MultiPro-ECPC with an elliptical receiver, the MultiPro-RCPC with a rectangular receiver, and the 3DCPC with a circular receiver and the same $\alpha_{0°}$, $d_{0°}$ and H value as the MultiPro-CPCs. The geometric concentration ratio represents the magnification factor at which a concentrator can concentrate solar energy without losses, assuming that the emitter is positioned directly on top of the concentrator. It is obtained by dividing the aperture area by the receiver area. Fig. 2 shows the 3DCPC, the MultiPro-ECPC, the MultiPro-RCPC, their truncated derivatives when $\alpha_{0°}$=15° and $\alpha_{90°}$=10° and the truncation settings. Here too, all heights of the concentrators and the longitudinal receiver diameters are equalized. Concerning the geometric concentration ratio, the maximum value is 22.0 which is obtained with the non-truncated MultiPro-ECPC when $\alpha_{0°}$=15° and the minimum value of 1.76 is obtained with the truncated 3DCPC when $\alpha_{0°}$=45°. In Fig. 3, the variation of the receiver area ratio normalized to the receiver area of the 3DCPC for each shape and axial half acceptance angle combination is represented. The conventional 3DCPC has a fixed circular receiver area due to the fixation of the longitudinal receiver diameter to 50 mm. It is noticeable that the receiver area of the MultiPro-CPCs decreases with $\alpha_{0°}$ and increases with $\alpha_{90°}$. Furthermore, the MultiPro-RCPCs have the second-largest receiver area for each case and up to 10 times less receiver area compared to the 3DCPCs.

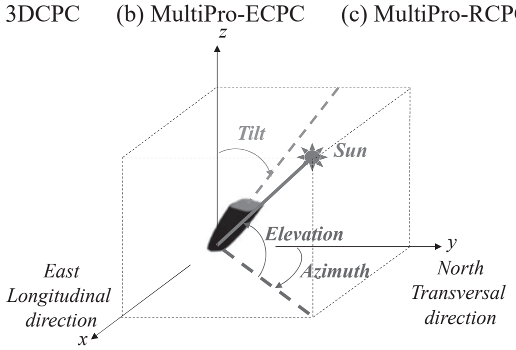


(a) Profile shape (b) Receiver shapes

Fig. 1 Structure of the MultiPro-CPCs



(a) 3DCPC (b) MultiPro-ECPC (c) MultiPro-RCPC



(d) tilt settings

Fig. 2 Compared solar concentrators and tilt settings

3. Simulation Method: Raytracing

The raytracing simulation software used in the simulation is TracePro which is based on the Monte Carlo ray tracing method(13). As for the concentration device, the reflectance of the mirror is set to 95% and the absorptance of the receive to 100%. Concerning the emitter, 140000 rays are launched from a plane surface with an intensity of 1 kW/m^2. The light is monochromatic with a wavelength of 550 nm. The ray tracing simulations are done in Tokyo throughout the year 2022. For each month, the 1st and the 15th are simulated. In the simulation, all concentrators are tilted from the horizontal every 15° from 0° to 90°. The evaluation index is the collected energy per receiver area [MJ/m^2] which is an important driver when considering a high-cost receiver. Concerning the emitter, 140000 rays are launched from a plane surface with an intensity of 1 kW/m^2. The light is monochromatic with a wavelength of 550 nm. The ray tracing

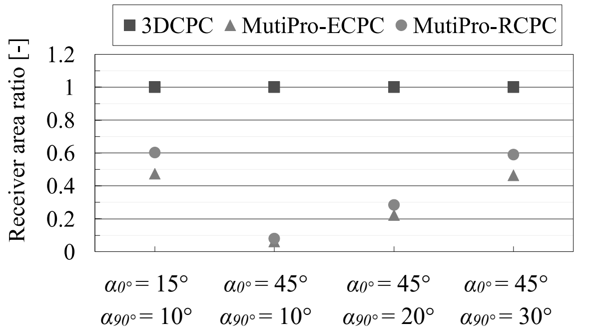
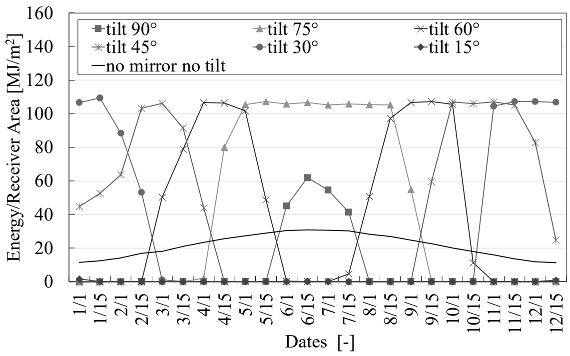
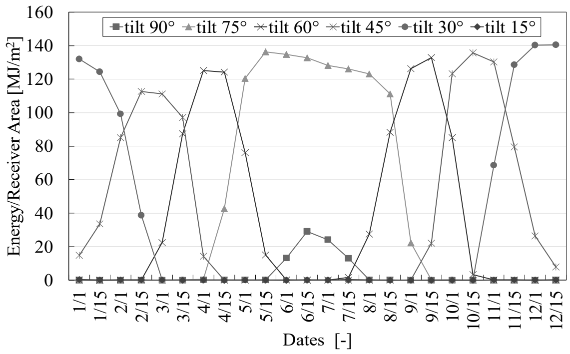


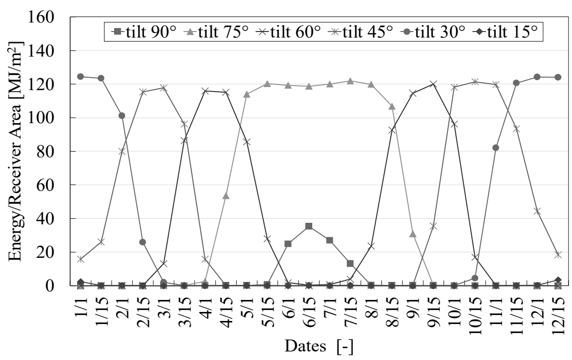
Fig. 3 Variation of the receiver area normalized to the flat receiver (Note: for 3DCPCs, $\alpha_{0°}$=$\alpha_{90°}$)



(a) 3DCPC and a flat receiver

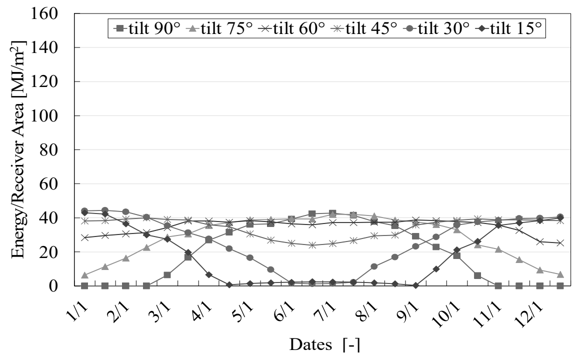


(b) MultiPro-ECPC

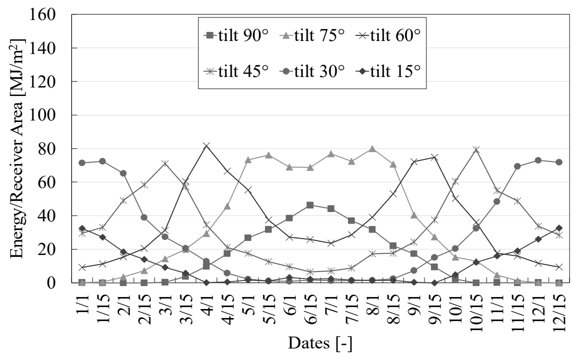


(c) MultiPro-RCPC

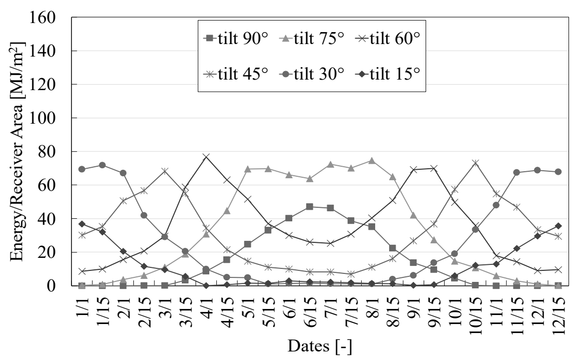
Fig. 4 Annual variation of the energy per receiver area for the tilted shapes with α=$\alpha_{0°}$=15° and $\alpha_{90°}$=10°



(a) 3DCPC



(b) MultiPro-ECPC



(c) MultiPro-RCPC

Fig. 5 Annual variation of the energy per receiver area for the tilted shapes with α=$\alpha_{0°}$=45° and $\alpha_{90°}$=10°

simulations are done in Tokyo throughout the year 2022. For each month, the 1st and the 15th are simulated. In the simulation, all concentrators are tilted from the horizontal every 15° from 0° to 90°. The evaluation index is the collected energy per receiver area [MJ/m^2] which is an important driver when considering a high-cost receiver.

From the ray tracing simulations, the energy passing the aperture and absorbed by the receiver is obtained. The collected energy per receiver area is calculated by dividing the absorbed energy per the receiver area. In addition, the contribution of the MultiPro-CPCs is also assessed through the normalization of its performance to the mirrorless receiver performance.

4. Results and Discussion

4.1 Effect of the tilt

Fig. 4 and Fig. 5 respectively show the annual variation of the collected energy per receiver area for the tilted shapes when $\alpha_{0°}$ =15° and when $\alpha_{0°}$=45° and a mirrorless flat receiver. The mirrorless flat receiver maintains its collected energy per receiver area between 10 and 32 MJ/m^2 with a peak in June and July. It is noticeable that when $\alpha_{0°}$=15°, 30° tilt, 45° tilt, 60° tilt, and 75° tilt correspond to common peak energy collection per receiver area obtained during 2 periods in the year for each tilt. For 90° tilt and 15° tilt, the peak values are only obtained with the 3DCPCs with $\alpha_{0°}$=45°, respectively between May 15th and August 1st, and between November 15th and January 15th. This is because these periods of the year correspond to solar elevation angles at Tokyo that vary between $\alpha_{0°}$ and $\alpha_{0°}$±25°[(14)]. Therefore, according to their acceptance range, the concentrators can collect in a larger or a smaller period. Nevertheless, the intensity will be proportional to their concentration ratio. This also explains the 60% decrease in the peak values of the 3DCPCs from the range of 100 MJ/m^2/day to 40 MJ/m^2/day when α increases. In contrast, the peak values of the MultiPro-CPCs decrease by about 43% from the range of 143 MJ/m^2/day to 80 MJ/m^2/day when α increases. Compared to 3DCPCs, the MultiPro-ECPCs show up to 50% higher peak values, followed by the MultiPro-RCPCs. The maximum energy per receiver area of 143 MJ/m^2. is obtained on December 15th by the MultiPro-ECPC with $\alpha_{0°}$=15°. Nevertheless, the MultiPro-CPCs show a necessity of 4 tilt angles throughout the year, whereas the 3DCPCs only need 2 tilt angles except when $\alpha_{0°}$ = 15°.

Fig. 6 represents the total annual energy per receiver area obtained with the 24 simulated days normalized to the mirrorless receiver performance. The MultiPro-ECPC with a total collected energy per receiver area of 2997.0 MJ/m^2 when $\alpha_{0°}$ = 15° obtains 5.8 times more energy per receiver area compared to the receiver-only case and 1.2 times more compared to the 3DCPC. In addition, when $\alpha_{0°}$=45°, the MultiPro-ECPC still obtains 3.3 times more energy per receiver area compared to the receiver-only case and 1.8 times more compared to the 3DCPC.

In Fig. 7, the energy per receiver area on January 1st for each shape at 30° tilt normalized to the mirrorless receiver performance on the same day is further analyzed on an hourly basis. It is noticeable that the performance of the concentrators mainly results from a collection during the 2 hours around noon when $\alpha_{0°}$=15°. That period of collection increases to 7 hours between 9 a.m. and 3 p.m. when $\alpha_{0°}$=45°, with a drastic decrease from 43 times to 10 times the normalized intensity obtained. On a daily basis and on an hourly basis, the MultiPro-CPCs generally show a better performance compared to the 3DCPC. Especially, when α=$\alpha_{0°}$=45°, the MultiPro-ECPC obtains up to 10 times more energy per receiver area compared to the receiver-only case and up to twice more compared to the 3DCPC.

These trends reveal that the variation of the directional acceptance angles and the use of slender receiver shapes compared to the circular receiver have a leverage effect in terms of collected energy per receiver area.

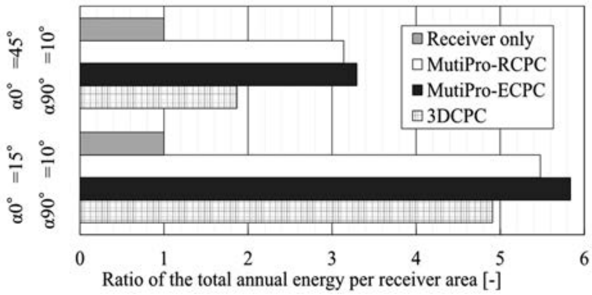
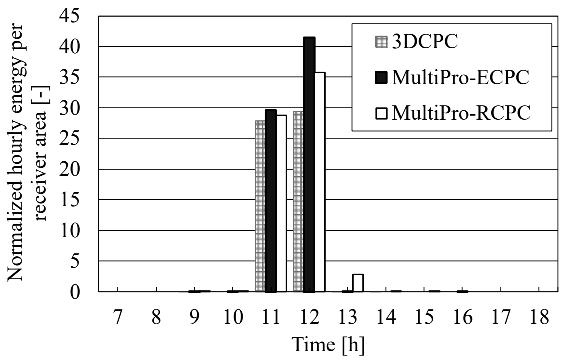
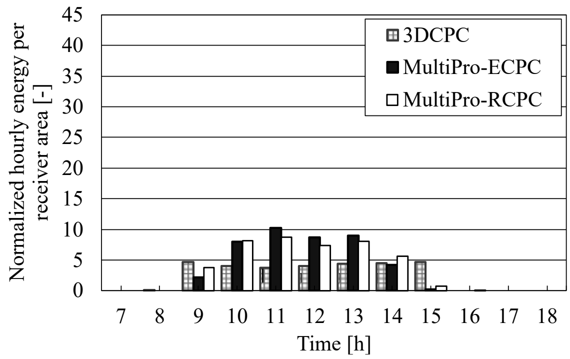


Fig. 6 Total annual energy per receiver area normalized to the mirrorless receiver performance



(a) α=$\alpha_{0°}$=15° and $\alpha_{90°}$=10°



(b) α=$\alpha_{0°}$=45° and $\alpha_{90°}$=10°

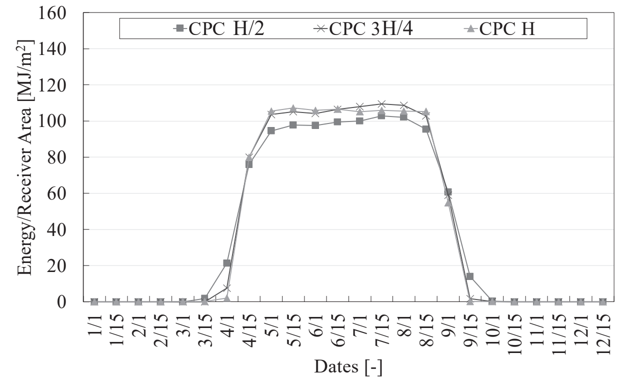
Fig. 7 Comparison of the hourly energy per receiver area at 30° tilt normalized to the mirrorless receiver performance on Jan 1st

4.2 Effect of the truncation

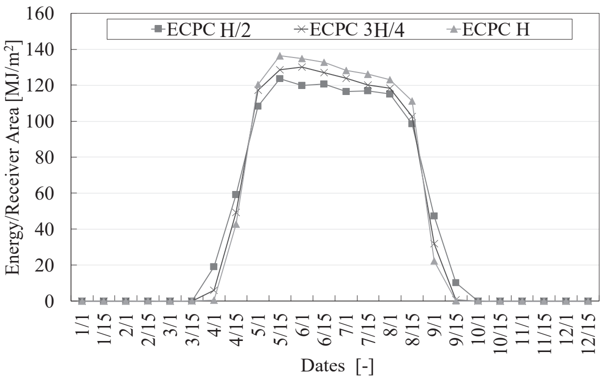
Fig. 8 and Fig. 9 respectively show the annual variation of the collected energy per receiver area for all shapes when their heights are equal to H, $3H/4$, and $H/2$ when α_{0°=15° and when α_{0°=45°. It is noticeable that with the 75° tilt setting used, energy collection is only possible between March 15th and September 15th. This is also due to the fact that in that period of the year, the solar elevation angle at Tokyo varies between 50° and 77°[(14)].

For each height, compared to 3DCPCs, the MultiPro-ECPCs show up to 50% higher peak values, followed by the MultiPro-RCPCs. In addition, when α_{0°=15°, except for the MultiPro-ECPC, the truncation of the concentrator from H to $3H/4$ does not change the collection intensity at peak. In the same case, the energy collection per receiver area of the MultiPro-ECPC during the peak period decreases by around 10 MJ/m^2 with the height of the concentrator.

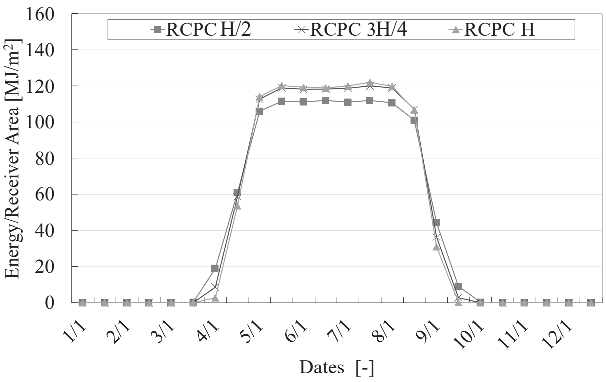
Furthermore, for all cases when α_{0°=15°, the truncation of the concentrator from $3H/4$ to $H/2$ decreases by up to 10 MJ/m^2 the energy collection per receiver area during the peak period. This is due to the decrease in concentration ratio caused by the truncation of the CPC profile which results in smaller aperture areas as shown in Fig. 2. In addition, when α_{0°=15°, the energy collection period increases by one month with the truncation. In contrast, when α_{0°=45°, for all cases, the truncation of the concentrator from H to $H/2$ does not change the collection performance except in June and mid-July where an



(a) 3DCPC

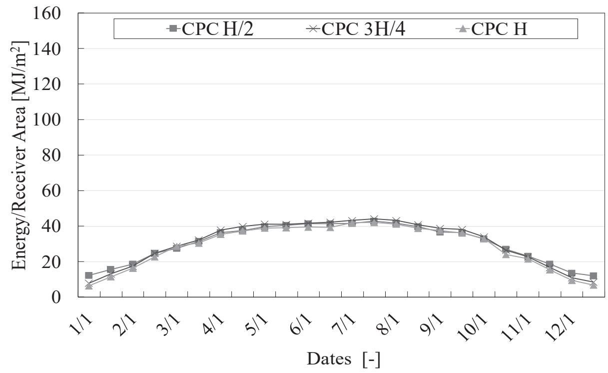


(b) MultiPro-ECPC

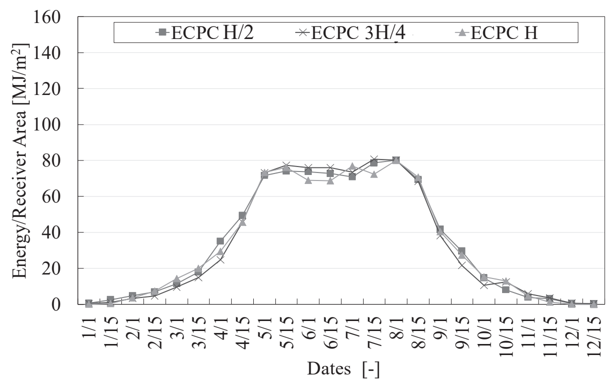


(c) MultiPro-RCPC

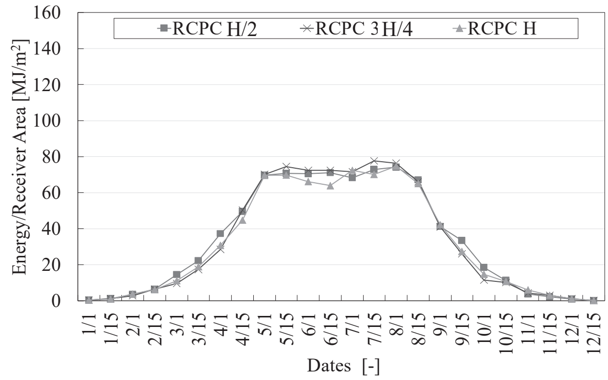
Fig. 8 Annual variation of the energy per receiver area for the truncated shapes tilted at 75° with $\alpha=\alpha_{0^\circ}$=15° and α_{90°=10°



(a) 3DCPC



(b) MultiPro-ECPC



(c) MultiPro-RCPC

Fig. 9 Annual variation of the energy per receiver area for the truncated shapes tilted at 75° with $\alpha=\alpha_{0^\circ}$=45° and α_{90°=10°

overcollection of up to 10 MJ/m^2 is noticeable with the MultiPro-CPCs. These results indicate that with the increase of $\alpha_{0°}$ from 15° to 45°, less difference in collection performance due to truncation is noticed for each shape. This is due to the wider range of acceptance provided by the truncation of the CPC profile shown in Fig. 1 which results in a bigger half acceptance angle compared to the $\alpha_{0°}$ of origin. Since 45° of half acceptance angle already covers most of the daily azimuth angle variation(14) in summer, a truncation that further increases the half acceptance angle does not bring as much increase in the incidence coverage compared to the case where $\alpha_{0°}$=15°.

For each combination of $\alpha_{0°}$ and $\alpha_{90°}$, all truncated MultiPro-CPCs have up to 50% higher peak values compared to the non-truncated 3DPCs. Nevertheless, the peak periods are the same for all MultiPro-CPCs, where they increase with $\alpha_{0°}$ for the 3DCPCs.

5. Conclusion

In this study, the tilt and truncation effect of the MultiPro-CPCs is assessed. This new family of concentrators with elliptical and rectangular receivers and various acceptance angles in all directions, is compared to the conventional 3DCPCs and the mirrorless flat receiver. Simulations in Tokyo showed that MultiPro-CPCs collect up to 50% more energy per receiver area at peak compared to 3DCPCs. Here, the MultiPro-ECPCs which has an elliptical receiver, generally collect more energy per receiver area followed by the MultiPro-RCPCs. In contrast, the MultiPro-CPCs showed a constant necessity of 4 tilt angles throughout the year whereas the 3DCPCs need 3 tilt angles when $\alpha_{0°}$ = 15° and 2 tilt angles when $\alpha_{0°}$ = 45°. Truncated MultiPro-CPCs generally outperform non-truncated designs, showing up to 50% more energy per receiver area even when truncated at half their heights. The wider range of acceptance provided by truncation results in less difference in collection performance with increasing $\alpha_{0°}$, indicating diminishing returns beyond a longitudinal half acceptance angle of 45°. This suggests the potential for optimizing CPC designs for enhanced energy collection with smaller heights.

These outcomes concerning the tilt effect and the truncation effect imply that the MultiPro-CPCs may provide new possibilities in solar concentration when considering stationary high-intensity concentration and limited concentrator height.

In this study, the MultiPro-CPCs are investigated in terms of single unit performance. In the case where the concentrators will be used in an array format, the units are arranged in a delimited area. With the resulting aperture shapes, there will be a space between the units, which will decrease the space efficiency at the apertures. Therefore, adoption of aperture shapes with straight edges for array formats is yet to be discussed.

Acknowlegments

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