Interception on Solar Absorbers: Ray Tracing for Comparison between a Parabolic Reflector and a Compound Parabolic Concentrator

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Abstract

A Compound Parabolic Concentrator (CPC) can direct incoming rays on an upper aperture to pass through a lower smaller aperture, giving a concentration ratio typically in the order of 4-5, depending on the acceptance angles of the CPC. The case for consideration here is for an absorber to be positioned inside the CPC, where a heat transfer fluid will circulate for heat absorption and further transport to a heat storage. Continuous solar tracking is to be avoided but tilting the concentrator 2-3 times during a day can be accepted.

A 3D CPC is compared with a normal Parabolic Reflector (PR) for similar concentration ratios. The comparison is made using ray tracing, where the sun angle is scanned over the acceptance angles and the interceptions on a cylindrical absorber are compared between the two systems. For low concentration ratios, the performances of the two reflectors are comparable, with about 10% improvements in interception ratios with the CPC over the PR. The concentration ratios for a CPC are limited. For the PR, an optimum can be considered, between increasing the concentration ratio but at the cost of decreasing the interception ratios.

Keywords: Compound Parabolic Reflector, ray tracing, optical efficiency, concentrating solar thermal, solar heat absorber

1. Introduction

Solar concentrators are lenses or reflectors which concentrates incoming solar rays on a large area (the aperture) onto a smaller area (the absorber). Solar concentration is in particular useful in solar thermal systems, where solar radiation is converted to heat. A range of direct heat collector systems are available for low temperature applications (typically flat panels or evacuated tube collectors for hot water systems). For higher temperature needs, typically, above 200 degrees C, concentrating solutions are required.

Reflectors, or lenses, which converge solar rays onto an absorber, require solar tracking with accuracies depending on the concentration ratios of the system. The geometrical concentration ratio is defined as:

$$C_r = \frac{A_{in}}{A_{abs}} \qquad \text{(eq. 1)}$$

where A_{in} is the aperture area for the incoming solar rays and A_{abs} is the area of the absorber. If the concentration ratio is high, the solar tracking must be accurate, as even small misalignments with the sun direction (often less than one degree) can shift the focal area away from the small absorber area. The range of sun angles where the incoming solar rays still terminate on the absorber can be called the acceptance angle. High concentration ratios then lead to small acceptance angles.

When designing a concentrating system for solar thermal energy collection, the temperature requirements at the absorber needs to be balanced by the precision requirements of the solar tracking system. Although solar tracking solutions are available, there are cases where the demand for robustness excludes solar tracking systems. The question then is what level of performance can be achieved with a concentration system based on minimal requirements for solar tracking (e.g., 2-3 adjustments of a concentrator during a day). A CPC can potentially meet these requirements.

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The aim is to achieve both high energy efficiency and high temperatures at a thermal absorber positioned at the focal area of a solar reflector. The temperature rise on the absorber due to the solar radiation is:

$$\rho A_{abs} \delta c \frac{dT}{dt} = P_{abs} - Q_{loss} \qquad \text{(eq. 2)}$$

An absorber shell with area A_{abs} (m^2), thickness δ (m), heat capacity c (J/Kkg) and density ρ (kg/m^3) obtains a rate of change of temperature (dT/dt) due to the solar power onto the absorber $P_{abs}(W)$, minus the thermal losses to the ambient and/or to a heat transfer medium at the absorber $Q_{loss}(W)$. With no optical losses, the power on the absorber is equal to the incoming solar power on the aperture of the concentrator. Optical losses are due to imperfect reflectivity on the concentrator surface, to rays not hitting the absorber as a result of surface irregularities and to the geometrical design of the concentrator system. The cases for analysis here are the geometrically based losses, the design aspects which leads to interception ratios less than one. The interception ratio, η is defined as the ratio of the sun rays hitting the absorber to the incoming rays on the reflector opening. The power on the absorber then becomes:

$$P_{abs} = P_{in}\eta = I_{sun}A_{in}\eta \qquad \text{(eq. 3)}$$

$P_{in}(W)$ is the sun power into the concentrator, $I_{sun}(W/m^2)$ is the sun intensity and A_{in} is the aperture area of the concentrator.

The temperature rise on the absorber then increases both with increasing interception ratios and concentration ratios (neglecting Q_{loss} for simplicity).

$$\rho \delta c \frac{dT}{dt} = I_{sun} \frac{A_{in}}{A_{abs}} \eta = I_{sun} C_r \eta \qquad \text{(eq. 4)}$$

When designing a concentration system with relaxation on the tracking accuracy, a larger absorber gives less interception losses (higher η) and higher concentration ratios (C_r). A smaller absorber may give higher temperatures, although overall lower energy efficiencies.

The performances of two types of reflectors are presented in this study: a Parabolic Reflector (PR) and a 3D Compound Parabolic Concentrator (CPC). The comparisons are made using an in-house ray tracer named TraceIt, varying the solar angles and the concentration ratios (size of the absorber). A cylindrical shaped absorber was chosen, as this will be easier to encapsulate with a glass cover (for reduction of convective heat losses) than for a spherical shaped absorber.

2. Parabolic reflector

A parabolic reflector (PR) focus incoming parallel rays along the z axis, on a focal point f (m) from the base of the PR. The shape of the reflector is given by:

$$z = \frac{r^2}{4f} \qquad \text{(eq. 5)}$$

For a two dimensional reflector (2D trough), r = x, and for a three dimensional reflector (3D dish), $r = \sqrt{x^2 + y^2}$. The depth h of the dish is related to the diameter of the dish, d, for a given focal length f by (follows from geometrical considerations):

$$h = \frac{d^2}{16f} \qquad \text{(eq. 6)}$$

3. Compound Parabolic Reflector, CPC

A CPC is the combination of two parabolic reflectors (PRs) as shown in Fig. 1. Early descriptions of CPCs are given in (Winston and Hinterberger, 1975) and (Rabl, 1976). A review of various applications of CPCs is given in (Tian et al., 2018). A particular CPC application for concentrating Photo Voltaics is provided in the review by (Parretta et al., 2003).

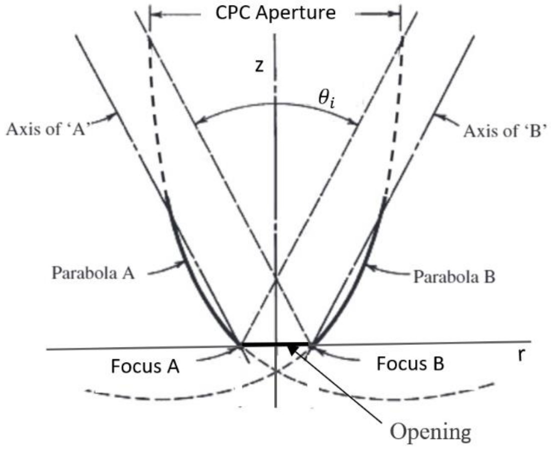


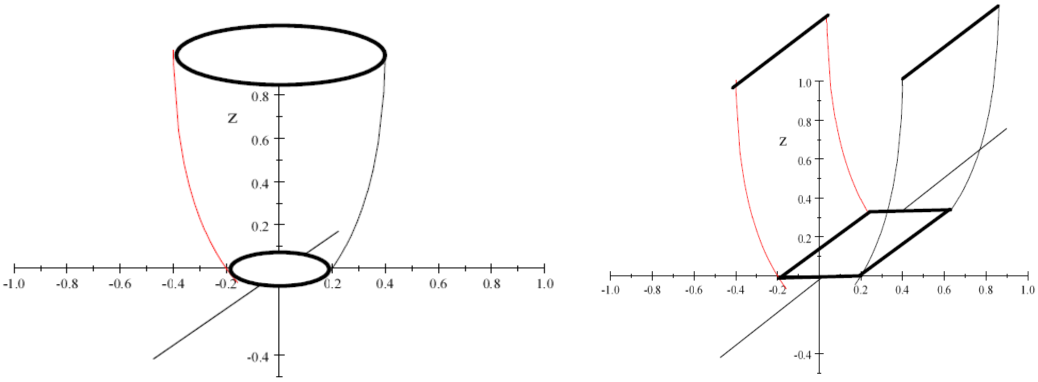
Fig. 1: The CPC (Lwiwa and jørgen Nydal, 2022)

The two parabolas are rotated and shifted opposite along the r axis, such that the focal point of one parabola is at the surface position of the other parabola. The parts of the parabola walls between the Aperture and the Opening constitutes the CPC. The magnitude of the rotation determines the half acceptance angles. Increasing the rotation gives larger acceptance angle but smaller concentration ratio (smaller A_{in}). The incoming rays with angles within the acceptance angles will go through the lower opening of the CPC for the 2D case (η = 1). For the 3D case, where the surface results from a revolution around the z-axis, the interception ratio becomes less than one when the solar angles deviates from the symmetrical vertical case.

By performing the rotation and the translation of the parabolas (Eq. 5), the following equation for the CPC results (Dai et al., 2011):

$$((r+a)c+zs)^2 = 4a(1+s)(zc-rs+a) \qquad \text{(eq. 7)}$$

where $c = cos\theta_i$, $s = sin\theta_i$, θ_i, =acceptance angle, a= radius of exit opening. The illustrations in Fig. 2(a) are for a=0.1, θ_i= 15 degrees.



(a): 3D CPC **(b): 2D CPC**

Fig. 2: Schematic diagram of a 3D and a 2D CPC

4. Ray tracing

Ray tracing is the tracing of the individual paths of rays passing through the optical system with the purpose of finding their distribution pattern on the surfaces of interest. Each ray starts from a point of origin (the sun) and is tracked as it intersects with surfaces. A reflective surface will reflect the ray onwards and an absorbing surface will terminate the ray. The base problem is to find the interception point $\overrightarrow{P}$ with a surface f (x, y, z) = 0 for a ray with starting point $\overrightarrow{S}$ and with a direction unit vector $\vec{d}$.

$$\vec{P} = \vec{S} + u\vec{d} \qquad \text{(eq. 8)}$$

Inserting Eq. 8 on component form into Eq. 7 for the surface gives an equation for u, the distance from the origin of the ray to the interception point, (Jafrancesco et al., 2018) gives an overview of ray tracing programs.

In this work, an in-house program has been used (TraceIt is programmed in C++, Qt, OpengGL) as this gives the flexibility for direct programming of needed functionalities, see a short description in (Nydal, 2014). This tool includes the 3D model view of the data where panels can be selected for translation, rotation or deletion. Tracelt gives the user options to set up different type of geometrical shapes (eg. cylinder, flat panels, spheres, parabolas, CPCs, Scheffler, light guides, lens) which can be defined as reflectors or absorbers. The sun is user specified (sun angle, density of sun points and direction). These functionalities are missing in other commercial ray tracing tools. A screen capture of the program is shown in Fig. 3.

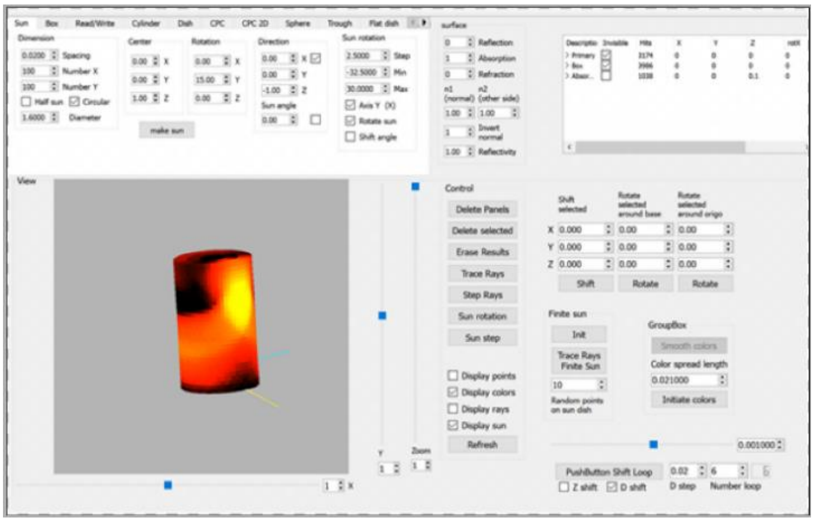


Fig. 3: A screen capture of the Tracelt program

Analytical solutions for u from Eq. 7 and Eq. 8 can be found for the classes of cylindrical, spherical, and parabolic surfaces as well as for the 2D CPC case. For the 3D CPC case, a bisect numerical solutions scheme was implemented. The results of the tracing can be exported for better graphical presentation than what is implemented in TraceIt, the result plots in this study are generated with Matlab.

5. Cases for comparisons

The cases for consideration in this study is for a cylindrical absorber to be positioned inside the CPC (Fig. 4) and the PR, varying the absorber length and the diameter.

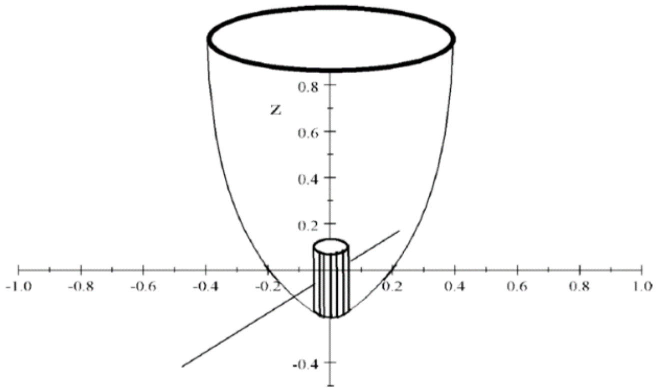


Fig. 4: Cylindrical absorber positioned inside the CPC for sensitivity analysis with changing diameter and length

A CPC is compared with a normal Parabolic Reflector (PR) for the same concentration ratios (same openings of the two reflectors and same absorber area). Loops were programmed in TraceIt for scanning of sun angles and geometrical changes (length and diameter of the absorber). The interceptions on a cylindrical absorber are compared between the two reflectors. The cases are:

- Reflectors: The CPC (acceptance angle 15 degrees) and Parabolic dish are used as reflectors. Aperture diameter=1.0 m
- Absorber length. A cylinder with length L=0.3 m and diameter D= 0.15 m is shifted downwards with step size of 0.04 m
- Absorber diameter. The diameter of a cylinder with length L=0.15 m is changed from D=0.1 m to D=0.2 m with step size of 0.02 m
- The Sun is an array of rays where each ray has a starting point and a direction. A given sun size gives better control on comparisons between cases than Monte Carlo methods. In Monte Carlo methods, rays are selected randomly and the user has to apply simulation times which are sufficiently long to give converging results. With a fixed sun, the number of sun rays are the same for both cases, and comparisons can be meaningful also with relatively few sun rays. The rays entering the reflector and the rays hitting the absorber determines the interception ratios. The applied sun dimension was a grid of 100x100 sun rays, with 0.02 m grid size of the sun ray density. This gives simulations with 10000 rays and the sun extends over a 2x2 m square region.

6. Qualitative comparisons

Fig. 5(a) illustrates the geometrical extent of the first reflected rays from a line sun (a one dimensional array of sun rays). A line sun gives the equivalent behaviour of a 2D CPC and is easier to visualize than a swarm of 3D rays. For incoming normal sun rays, the PR shows the rays passing through the focal point, whereas the CPC spreads the rays across the bottom area.

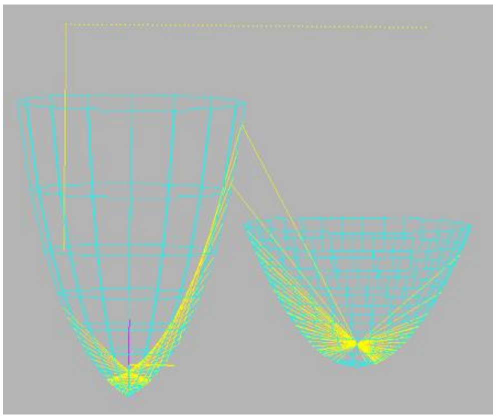


Fig. 5 (a): CPC and PR with the same concentration ratio showing the line sun and sun rays when the sun is vertical

For the maximum acceptance angle of 15 degrees, Fig. 5(b), the CPC focus the rays on the side of the reflector, which is according to the design principles of a CPC.

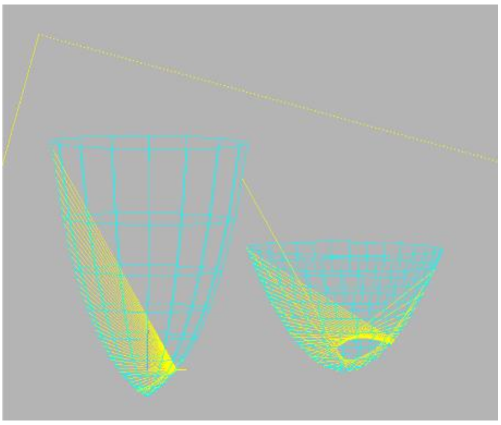


Fig. 5 (b): CPC and PR with the same concentration ratio showing the line sun and sun rays when the sun is tilted 15 degrees

With sun angles double the maximum acceptance angle, shown in Fig. 5(c), both reflectors show very large spread of the rays. The spread will be even larger with the sun rays covering the whole aperture, but the line sun serves to give an indication of how far a cylindrical absorber should extend into the reflectors.

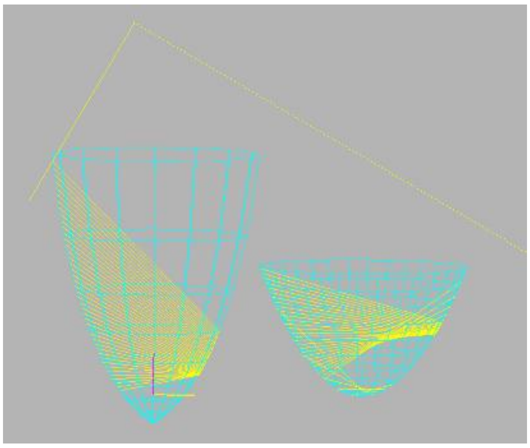


Fig. 5(c): CPC and PR with the same concentration ratio showing the line sun and sun rays when the sun is tilted 30 degrees

7. Sensitivity on absorber length

A 30 cm long cylinder with 15 cm diameter was shifted downwards and out of the reflectors in steps of 4 cm. This means the ray tracing is made with a decreasing length of the absorber. At each absorber position, the sun is scanned over a range of acceptance angles, and the accumulated averaged interception is computed for each step in sun angle. This cumulative interception at a given angle is then a measure of how much of the incoming sun rays have hit the absorber during the change in sun angle from zero to the given angle. It gives an indication of how much total energy can be collected at the absorber during the period when the sun traverses from zero to the given angle.

Fig. 6 shows the cumulative interception results for each position of the absorber. At sun angles normal to the reflectors, the interception is 1 for all absorber lengths. The upper curves are for the long absorber, and it is seen that a long absorber will accumulate more interceptions as the sun angles are increased from the zero position. As the absorber becomes shorter (as it is lowered out of the reflectors) the accumulated interception starts to decreases at earlier sun angles.

The comparisons between the CPC and the PR shows that the CPC performs better than the PR for low solar angles, although the differences are quite small for large absorbers. For higher sun angles, the PR performs somewhat better than the CPC.

We would often prefer small absorbers, in order to reach high temperatures at the absorber (high concentration ratios). At about 18 degrees sun angle, the total averaged interception for the smallest absorber is similar between the two reflectors. An optimal use of the CPC appears then to suggest reflector adjustments after 5-10 degrees change in sun angles. When the sun angle has reached 15 degrees, about 50% of the rays have been absorbed, for both the CPC and the PR.

The overall tendency is that the CPC and the PR can give similar interception values for sufficiently long absorbers (low concentration ratios). For shorter absorbers, the CPC performs better. The ray tracing also shows that the main illumination area for the CPC case is closer to the absorber base than for the PR case.

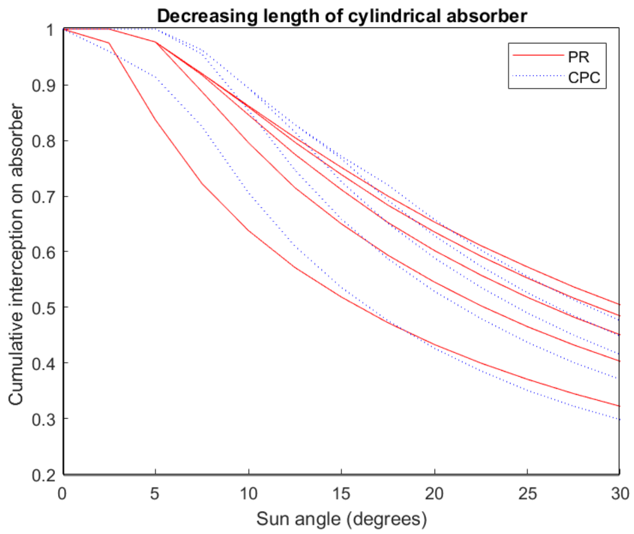


Fig. 6: Cumulative interception on sun rays on a cylindrical absorber (L=0.3 m, D=0.15 m) which is shortened in steps of 0.04 m for each curve. CPC (dashed) and PR (solid)

In order to minimize the absorber surface, an absorber length of L=0.15 m was selected for sensitivity tests on changing the absorber diameter.

8. Sensitivity on absorber diameter

A 15 cm long cylindrical absorber is positioned at the vertex of the CPC and the PR reflectors, and the diameter is changed in steps of 2 cm from an initial diameter 10 cm to the largest diameter of 20 cm. This gives a decrease in concentration ratios from about 14 to 6. Again, the solar angles are chosen to exceed the maximum acceptance angle (15 degrees) to see the effect of operating the CPC reflectors beyond the design regions as shown in Fig. 7.

If the absorber is kept in a constant vertical position, the pipe connections to the heat transfer loop can be static, as the absorber will not move. Large absorbers naturally have higher interception values, all rays are captured for a larger range of sun angles from the vertical. However, smaller absorbers are required to obtain higher temperatures (higher concentration ratios) and the interception values for smaller absorbers decay faster as the sun angles are increased.

The CPC is seen to perform better than PR at low solar angles, but somewhat worse than PR for higher solar angles, beyond the acceptance angle for the CPC.

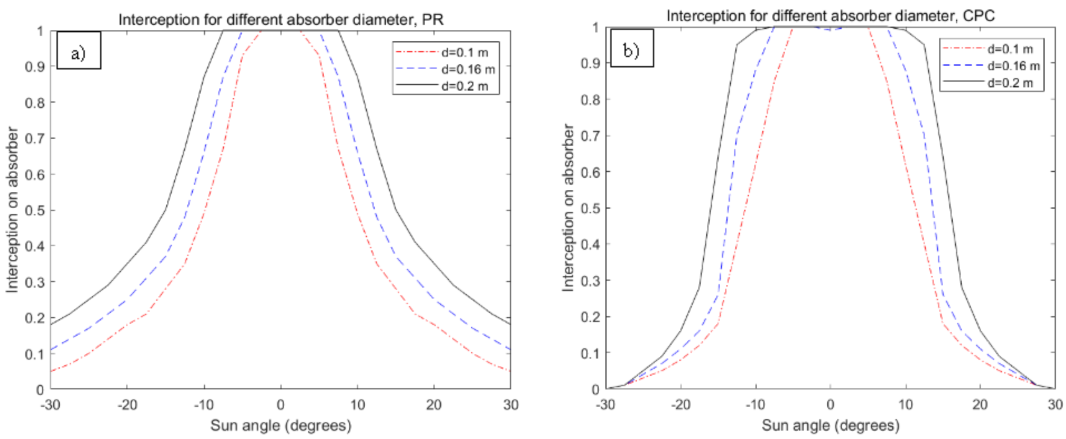


Fig. 7: Interception on cylindrical absorber with different diameters (0.1, 0.16, 0.2 m) and sun angles. a) and b) for absorber aligned with reflectors.

The accumulated interception values are shown in Fig. 8, for the symmetric cases with the absorber parallel with the sun rays at zero sun angle. The values in the figure are the averaged total interception in the intervals from zero solar angle to the actual angle on the x axis. The CPC maintains higher average interception ratios as the solar angle increases, but eventually performs weaker at very large sun angles.

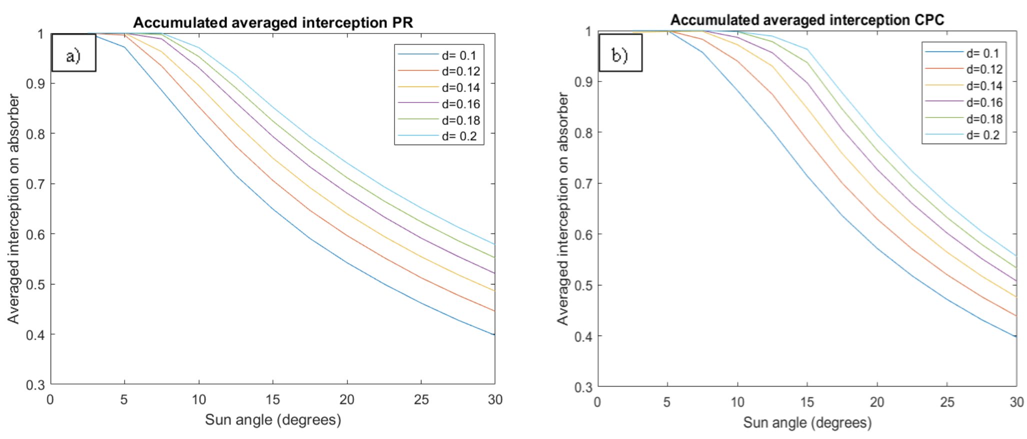


Fig. 8: Accumulated interception for sun angles deviating from the normal incident. (a) PR (b) CPC

The relative difference in accumulated interception for CPC and PR is shown in Fig. 9. The comparison is taken for selected diameters: 0.1 m, 0.16 m and 0.2 m. The differences in the interception values are quite low for lower sun angles and increases up to a maximum of about 12% for sun angle at 15 degrees (acceptance angle for the CPC).

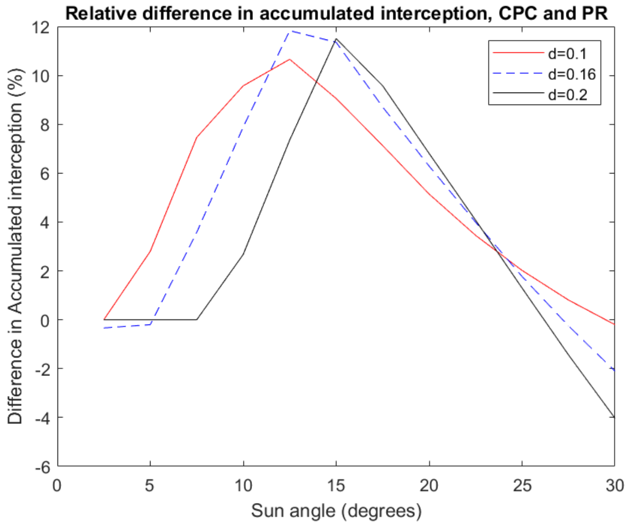


Fig. 9: Relative difference between accumulated interception of CPC and PR

9. Sensitivity on tilting the reflector

If a reflector (PR or CPC) is left to accumulate energy on a cylindrical absorber without solar tracking, the interception values with the varying sun angles have been shown above, with sensitivities on absorber length and on absorber diameter. It shows how the interception values decrease with the sun angles and will come to zero for sufficiently large sun angles. The practical use of such systems would then require some changes in the reflector angle towards the sun at some regular time interval. A solar tracking system gives continuous movement of the reflector with the sun and can then be designed to provide high concentration ratios. The benefit with a CPC is less dependency on solar alignment, but at the cost of lower concentration ratios.

As a test on the effect of tilting the reflectors on the interception ratios, the two reflectors were compared for a tilt angle of 15 degrees. This means that the absorber will be at an angle with the axes of the reflectors, and the case is no longer symmetrical as the sun angle vary.

The interception results with tilted reflectors are seen in Fig. 10, with similar diameter changes of the absorber as before. The interception values are somewhat reduced and the curves are slightly non-symmetric around the normal sun angles.

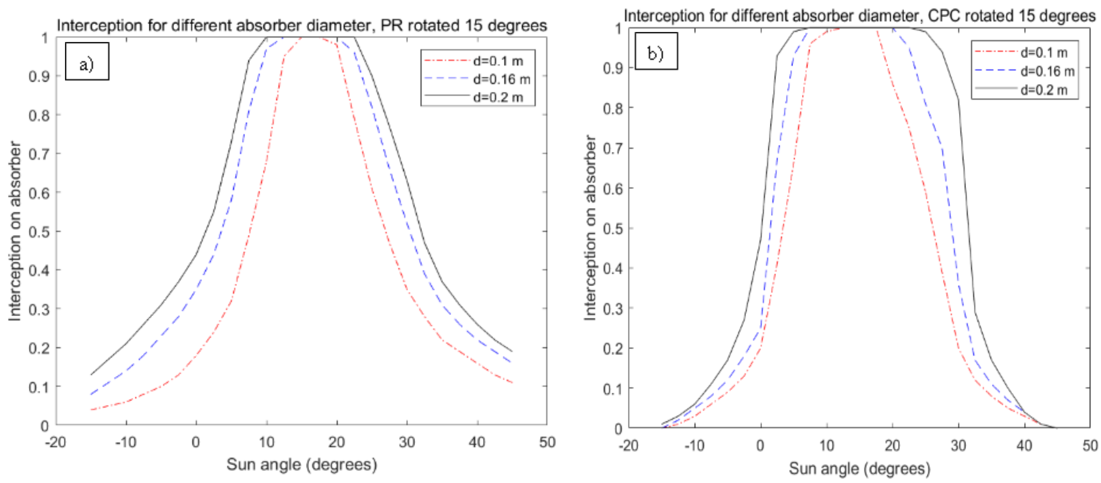


Fig. 10: Interception on cylindrical absorber with different diameters (0.1, 0.16, 0.2 m) and sun angles. a) for PR tilted 15 degrees b) for CPC tilted 15 degrees.

10. Conclusion

Ray tracing is used for comparison of a Compound Parabolic Concentrator (CPC) and a Parabolic Reflector (PR) with similar apertures (opening diameter). The cases are motivated in the application of solar cookers, where a concentrator can heat a storage in the focal area without elaborate solar tracking methods. The sensitivity of the interception ratio on the length and diameter of a cylindrical absorber positioned inside the CPC and PR is evaluated. With the quite large absorber dimensions applied in this work (concentration ratios varying from 14 to 6), the differences between the CPC and the PR are quite small, the CPC shows up to 12% better averaged performance than the PR. The CPC can tolerate shorter absorber lengths than the PR, as the intersection locations on the absorber is closer to the absorber base than for the PR. The concentration ratio for a CPC is limited (when the reflector walls become vertical) while a PR can be optimized more freely, taking into account the balance between the interception ratio and the concentration ratio.

11. Acknowledgements

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12. References

Dai, G.-L., Xia, X.-L., Sun, C. & Zhang, H.-C. 2011. Numerical investigation of the solar concentrating characteristics of 3D CPC and CPC-DC. *Solar Energy,* 85**,** 2833-2842.

Jafrancesco, D., Cardoso, J. P., Mutuberria, A., Leonardi, E., Les, I., Sansoni, P., Francini, F. & Fontani, D. 2018. Optical simulation of a central receiver system: Comparison of different software tools. *Renewable and Sustainable Energy Reviews,* 94**,** 792-803.

Lwiwa, C. B. & Jørgen Nydal, O. 2022. A Ray Tracer for optimizing solar concentrating systems: The case of discretized Compound Parabolic Concentrator. *Scandinavian Simulation Society***,** 15-18.

Nydal, O. J. 2014. Ray tracing for optimization of a double reflector system for direct illumination of a heat storage. *Energy Procedia,* 57**,** 2211-2220.

Parretta, A., Martinelli, G., Stefancich, M., Vincenzi, D. & Winston, R. Modelling of CPC-based photovoltaic concentrator. 19th Congress of the International Commission for Optics: Optics for the Quality of Life, 2003. International Society for Optics and Photonics, 1045-1047.

Rabl, A. 1976. Comparison of solar concentrators. *Solar energy,* 18**,** 93-111.

Tian, M., Su, Y., Zheng, H., Pei, G., Li, G. & Riffat, S. 2018. A review on the recent research progress in the compound parabolic concentrator (CPC) for solar energy applications. *Renewable and Sustainable Energy Reviews,* 82**,** 1272-1296.

Winston, R. & Hinterberger, H. 1975. Principles of cylindrical concentrators for solar energy. *Solar Energy,* 17**,** 255-258.