

Solar Energy Conversion Devices and Plants: Exercise 4

In this exercise, you will evaluate the optics of a solar concentrating facility. You are asked to use the Monte Carlo method to estimate the performance of the facility and compare it to the theoretical prediction. This is an individual work that will be graded. Submission deadline of code and short report is October 27, 2023, 14:15, by email to Prof. Haussener.

Analysis of 3-D Parabolic Dish – CPC – Receiver System

A Stirling engine system consists of a parabolic dish concentrator, coupled to a 3D CPC, and a cavity receiver. The cavity receiver is assumed to be a perfectly insulated blackbody, and the system is aligned such that all rays reflected from the dish are accepted by the inlet of the CPC and delivered to the receiver aperture. Figure 1 depicts the dish-CPC-receiver system. The system tracks the sun on two axes throughout the day, and useful work is extracted from the cavity receiver as it heats up.

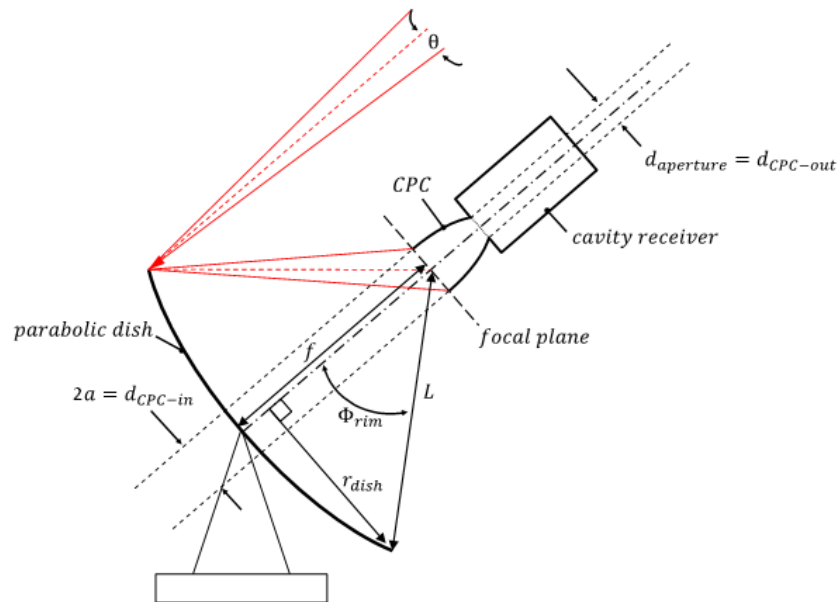


Figure 1: Cross-section schematic of a parabolic dish-CPC-receiver system.

Assumptions:

- Dish surface's reflectivity is $\rho_{\text{dish}} = 95\%$ (independent of wavelength and direction).
- CPC surface's reflectivity is $\rho_{\text{CPC}} = 90\%$ (independent of wavelength and direction).
- Beam normal irradiance is $G_{\text{bn}} = 890 \text{ W/m}^2$.
- Shading losses on the dish by the receiver, η_{shading} , remain constant during the day.

- Half acceptance angle, including tracking errors, is $\theta = 0.5^\circ$.
- The parabolic dish has rim angle $\phi_{\text{rim}} = 40^\circ$ and focal length $f = 4.5$ m.

Questions:

- Based on the alignment of the dish-CPC-receiver system stated in the description (all rays reflected from the parabolic dish are accepted by the receiver cavity), calculate the CPC entrance area $A_{\text{CPC-in}}$, and cavity aperture area A_{aperture} . Hint: use the relationship that the dish rim length L (length between the parabolic dish edge and focal point) is given by: $L = 2f/(1 + \cos \phi_{\text{rim}})$.
- Assuming that the ratio of receiver cavity diameter to receiver aperture diameter is 10:1, and that the ideal blackbody receiver has zero thickness walls, determine the shading losses (η_{shading}) by considering the projection of the receiver onto the projected dish area.
- Perform an energy balance on the Stirling engine system to determine the useful energy \dot{Q}_{useful} extracted from the receiver assuming that it is operated at $T_{\text{receiver}} = 2000$ K. Assume that the only energy loss by the receiver is due to re-radiation, and what remains is useful energy.
- Implement a ray tracing program and calculate the flux distribution in the focal spot of the dish (i.e. inlet area of CPC) and the flux distribution at the inlet of the cavity (i.e. outlet area of CPC). What are the peak and average concentrations at these two locations?

Hint: Each ray should start at a random point on the dish surface, which can be described by $z = \frac{x^2+y^2}{4f}$. A uniform point on the dish can be generated using $r = r_{\text{dish}}\sqrt{u_1}$, $\phi = 2\pi u_2$ with $u_1, u_2 \in [0, 1]$. The incoming direction can be sampled within a cone of half-angle $\theta = 0.5^\circ$ around the $-z$ axis. Reflections at the dish follow the mirror law $\mathbf{r}_{\text{out}} = \mathbf{r}_{\text{in}} - 2(\mathbf{r}_{\text{in}} \cdot \hat{\mathbf{n}})\hat{\mathbf{n}}$, where $\hat{\mathbf{n}}$ is the surface normal. Intersect the reflected ray with the plane $z = f$ to obtain the CPC inlet hit point.

- How do your Monte Carlo calculations compare to theoretical predictions of a typical flux distribution in the focal plane of a dish? Comment on the flux distribution at the receiver inlet.

Hint: More details on the Monte Carlo method and its application to parabolic dishes and compound parabolic concentrators can be found here: Dai et al., [Numerical investigation of the solar concentrating characteristics of 3D CPC and CPC-DC](#), Solar Energy, Vol. 85, Pages 2833-2842, 2011. Please note: In eq. 5, there is a typo in the coefficient of B1. The fourth term in the coefficient of B1 should be $2(m_1x_0 + m_2y_0)t$.