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Radiation Performance of a Cavity Receiver for a Parabolic Dish Solar Concentrator System

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Abstract. The radiation performance of a modified cavity receiver for a low-cost concentrating solar power plant is studied. The optical phenomenon taking place is modelled by using a ray tracing technique based on a finite element approach. This design is also compared to a flat receiver. Corrections for sunlight and optical errors of the parabolic dish are included. Its efficiency is analysed by varying some geometrical parameters of the receiver, maximizing the total power absorbed. It is found that the flux density on the cavity walls is less than on the flat receiver walls, hence decreasing heat losses. Also, in order to reach a maximum radiation performance the receiver is to be placed closer to the concentrator from the focal position. However, the aperture does not improve notably its efficiency, although it has an important role in the convection heat losses as shown in previous works. Finally by varying the cavity diameter it is possible to improve the efficiency when it is well adjusted to the radiation performance of the concentrator on the focal point.

Key words

Radiation performance, Solar Collector, Geometrical optics, Cavity Receiver, Flux Distribution

1. Introduction

Nowadays there exists an increasing interest in the development of technologies for the use of renewable energy sources. This is mainly because renewable energy technologies are intended to face the foreseeable threats of conventional energy sources, such as fossil and nuclear energy, or the growing global energy demand. Thus the effort in the development of renewable energy technologies is being focused in designing cost-effective facilities to turn renewable energy sources into a feasible energy [1].

The most abundant and sustainable source of energy is the Sun, in particular the energy of the solar irradiation at the Earth's surface. It is cleanly available in sunny areas with high *Direct Normal Irradiation* (DNI). However it is not controllable and it is subject to severe disturbances, for example, irregular cloud passage or sunset. Consequently these yield in a decrease of the effective available energy [1]-[2]. For these reasons solar energy technologies are often integrated in conventional power plants together with a control technique to overcome its drawbacks.

Actually there are two major solar energy technologies [3]-[4]: *Photovoltaic* (PV) and *Solar Thermal Power* (STP). We are concerning about process heating applications which the *Concentrating Solar Power* (CSP) technology is actually being more used for. In particular we relate to the *Parabolic Dish Concentrator* (PDC) technology. A sketch of the PDC system under study can be seen in Fig. 1. The main reasons why CSP technology is being more used in process heating applications are that radiation can be concentrated and converted efficiently into heat, and large amounts of heat can be easily stored unlike electricity storage [5]-[6].

As a general rule heat transfer and radiation losses take down the efficiency of a collector. Traditionally, flat receivers are known to have a poor overall efficiency. Cavity receivers increase the system efficiency by decreasing radiation, thermal radiation and convection heat losses. However some trade-offs between these loss mechanisms exist when optimizing the overall efficiency [7].

The aim of this paper is to analyze a modified cavity receiver [8] and optimize its radiation performance by varying some of its geometrical features. The receiver considered is a conventional cylindrical receiver - a cavity one - modified with a narrow aperture and a curved bottom. Fig. 2 shows an axisymmetric cut of the receiver. This design is intended to improve its performance by modifying the conventional receiver geometries taking advantage of the dependency of optical behaviour on the system geometry.

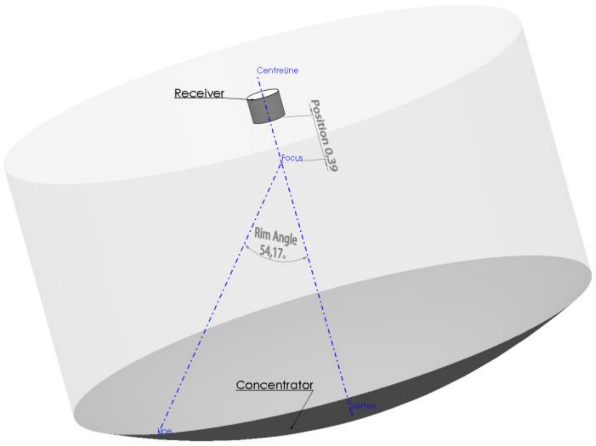

Fig. 1. A sketch of the parabolic dish concentrator under study. The length unit is the meter. The focal distance is 2.2m and the concentrator radius is 2.25m, giving an intercepting area of 15.9m

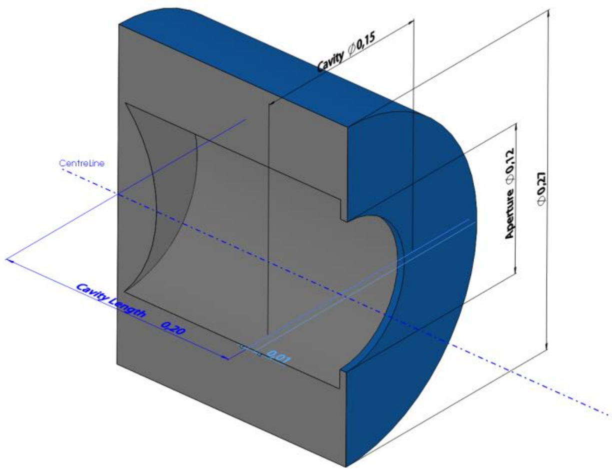

Fig. 2. Cut of the cavity receiver. The length unit is the meter. The main features are shown with its nominal values.

The characterization of the receiver can be theoretically estimated by modelling the optical phenomena occurring in the system, including the Sun and the atmosphere. We use a model based on geometrical optics. Then we simulate the model to compute the radiation performance of the system under certain conditions.

Radiation performance can be measured as the ratio of energy flux, i.e. total power, entering the system to the flux absorbed by the receiver walls participating in the energy transfer to the *Heat Transfer Fluid* (HTF). Also, this value can be used to estimate the radiation losses i.e. radiation leaving the receiver cavity by optical effects.

In the next sections we will consider the radiation performance as the main objective value in the optimization process of the cavity performance. Finally, we will end up concluding some guidelines for a good design of the receiver studied.

2. System Structure and Design Approach

The system under consideration is a typical PDC system. Fig. 1 shows a sketch of the system modelled. Basically it consists of a parabolic mirror and a receiver placed near the focus. Hence, when the Sun is placed along its centre-line axis, radiation density increases substantially on the focal plane.

The cavity receiver is shown in Fig. 2. The main features over convectional designs are the curved bottom and the narrow aperture. A simplified analysis of this type of receiver was presented in [7].

This design is devised to improve the overall efficiency of more elementary shapes like planar, cylindrical cavity or other simpler geometries. The highest energy losses are those coming from heat transfer mechanisms. Convection and thermal radiation have an important role in the energy loss of the overall system. The cavity is intended to reduce these losses and the curved bottom in intended to reduce thermal radiation losses, as well.

On the other hand, the cavity design helps to improve the radiation performance. The curved bottom is intended to reflect the rays to the walls. Also, the mean free path of the rays in the cavity is reduced. On the other hand some of the rays that otherwise would leave the cavity will also be reflected back by the narrow aperture. Nevertheless some other rays will be absorbed by the aperture reducing the amount of radiation entering the cavity. Hence, we can expect that there will be an optimal aperture size for a maximum radiation performance.

We base our input data in a concentrator already installed and the specifications of this system will be used in the simulation set up.

3. Process Modelling

We assume a geometrical optics model of the system. It can be solved with a low computational effort and it holds good for the underlying electromagnetic phenomenon taking place, since for any wavelength of the electromagnetic radiation involved 300 - 2000 nm (the light intensity in the infrared-C (IRC) sub-spectrum from 3mm to 1mm is negligible [3]), it is much smaller than the smallest distance of any edge or any aperture (~ mm.)

In a medium with uniform refractive index the ray trajectories can be calculated as straight lines.

A. Sunlight and optical errors

Non-ideal sunlight and optical errors of the parabolic dish concentrator can yield a bigger hot spot in the focal region and a local overheating in the cavity receiver. The effects taken into account in our model are as follows.

The emitting solar surface extension, as it is considered in most CSP models, distorts the flux distribution of an ideal parabolic mirror. The factor characterizing this effect is often given by $\theta_{\max}$, that is, the maximum angle of deviation of a ray coming from the Sun. It is equal to the maximum angle of the solar dish scoped from the Earth. It can be calculated by the following expression

$$\theta_{\max} = \tan^{-1}\left(\frac{r_{sun}}{d_{Earth-Sun}}\right) \quad (1)$$

where r_{Sun} is the solar radius and $d_{Earth-Sun}$ is the distance from the Sun to the Earth. This value can be calculated being approximately 4.65mrad.

The limb of the Sun appears darker than its centre. We also include the limb darkening of the Sun by means of an empirical law that can be found in [9].

On the other hand, the optical errors of the parabolic dish include manufacturing errors, assembling errors, etc. Considering that errors behave as random variables with normal distributions, the irregularities at the concentrator surface can be characterized by the standard deviation σ [8]. In [10] it is pointed out that σ = 3.45mrad whereas in [8] σ = 6.7mrad. We choose this uncertain value to be the former, since it is considered to yield a more representative focal flux distribution of that observed in the concentrator already deployed.

On the other hand, we consider that the sunlight wave front is planar. In reality, it has a spherical form when it gets to the Earth, although it is not considered an influential factor in any previous work, neither do we.

Moreover, we consider that the system is always pointing directly at the Sun. However, in real collectors a control system for tracking the Sun is often used since the maximum performance is reached only in that case.

We do not consider any atmospheric effects, thus assuming a clear sky conditions. In addition, the structure supporting the receiver shadows the parabolic dish, although it does not affect much to the final results, as pointed out in [7]. As a result, the geometry of our model will not include the supporting structure.

B. Cavity walls

At the receiver cavity walls rays are either absorbed or reflected. The rays being absorbed contribute to the total amount of energy of the surface element absorbing the ray. The probability of a ray being absorbed is given by the absorption coefficient α for sunlight. In general α depends on the coating material of the receiver surfaces and the electromagnetic spectrum irradiated. It is desirable materials with high absorption and low emission coefficients for sunlight.

The trajectories of the reflected rays are computed using the Lambert's cosine law that accounts an ideal diffusely reflecting surface.

4. Methodology

This model is solved using a *Finite Element Method* (FEM) approach [11]. This methodology allows for performing a ray tracing study on more general geometries that those available in some codes typically used for solar concentrator modelling, with relatively little effort.

On the other hand, we try to optimize the radiation performance of the cavity receiver. We consider the following dimensions as the design optimization parameters; see Fig. 1 and Fig. 2:

1) *Position to the focal point*. The receiver is positioned along the centre-line of the system.
2) *Aperture diameter*. This parameter can be varied up to the cavity diameter.
3) *Cavity diameter*. The bottom shape does not change when varying this parameter.

Moreover, regarding to the overall system efficiency, it is also desirable a uniform flux distribution on the receiver walls [10], because a highly varying flux distribution yields more thermal losses. Thus, we will also take this into consideration in the optimization process as far as possible.

The methodology employed in this analysis will give a stationary value of the radiation performance, as we simplify our model to characterize the optical phenomena of the system in ideal conditions.

A. Specific studies

The flux distribution on the focal plane is used to validate the model. To do so we calculate the concentration ratio of the flux at a point of the focal plane to the value of the DNI entering at the system, that is 1000W/m^2 [9].

Fig. 3 shows the radial average of concentration ratio distribution on the focal plane. More specifically, given a radius centred on the focal point, the value shown is the concentration ratio of the mean flux along that circumference.

In this computation we used 420000 rays. We can observe that it is in concordance with [7],[10],[12] where a MCM is used. Furthermore, Fig. 4 shows the contour map of the concentration ratio distribution. As we can see the flux distribution is not symmetric.

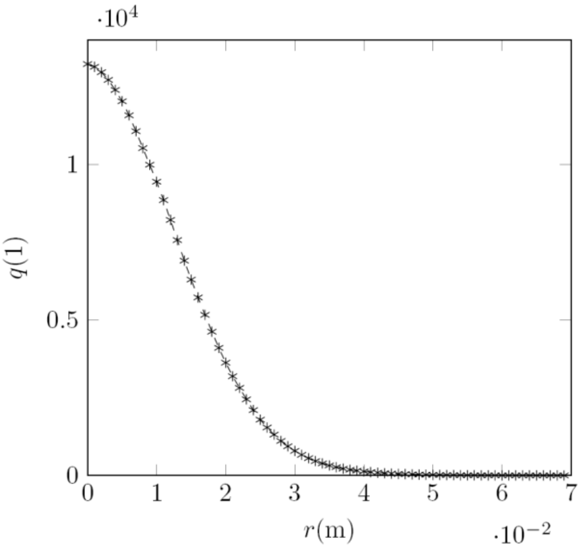

Fig. 3. Concentration ratio distribution on the focal plane with the radial distance from the focal point.

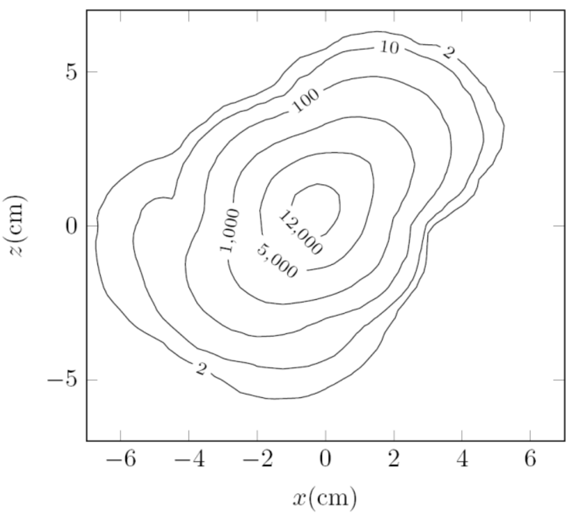

Fig. 4. Contour map of the concentration ratio on the focal plane.

5. Simulation

The boundary conditions on the cavity walls were set accordingly to a system already deployed. The dimensions of the concentrator are shown in Fig. 1. The cavity receiver nominal values are shown in Fig. 2. The flat receiver was model by a 25.4m^2 square.

To represent the absorptivity of the cavity walls, we set a probability of a ray being absorbed to the value of the absorptivity of the surface material. This value was set to 0.9 a representative value for black coatings. Moreover, as mentioned above, these walls were considered totally diffusive.

The concentrator surface was set to an emitting surface. Thus, the rays are released as they were coming from the Sun direction.

The remaining domain walls were set to a freeze condition, thus removing a ray from the simulation when it reaches the domain limits. This condition is applicable when a ray moving away from the receiver will not return back, although this might not be true if we considered reflections on the parabolic dish from rays leaving the receiver.

For an accurate computation of the flux distribution we needed a finer element size on them. This, in turn, increases the memory usage, so a balance has to be found. The minimum length of a surface element was set approximately to 2mm.

6. Results

First, we vary the position of the cavity receiver. We choose this parameter first because it is thought that a deviation from the focal position highly influences the efficiency. We compute the ratio of the total flux absorbed by the cavity receiver to the total flux absorbed by the flat receiver at the focal point. The total flux of the flat receiver on the focal point is 12.3kW. Fig. 5 shows this ratio with the cavity receiver position around the focal point, keeping the others parameters fixed to their nominal values. We can see that there is an interval in which the total flux absorbed does not change relatively so much. Also, we can observe that the ratio above the unity near the focal point, so the cavity receiver catches more energy than the flat receiver in those positions. Concretely, the cavity receiver improves the radiation performance in a 2.34% to the flat receiver.

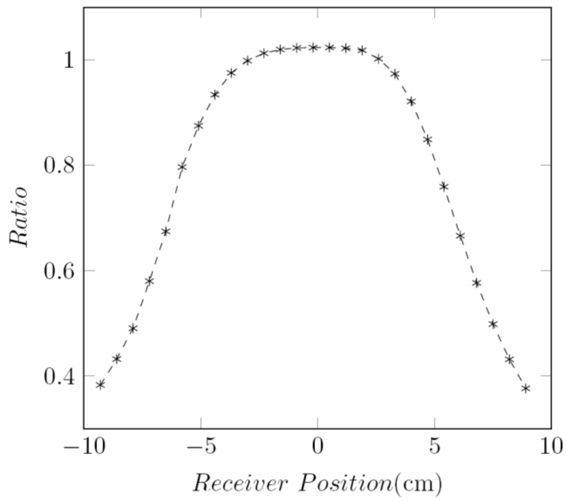

Fig. 5. Total flux ratio with the cavity receiver position. The remaining parameters are set to their nominal values. The receiver position is measured relative to the focal point of the concentrator. A positive value means a position further from the focus.

The flux distribution on the flat receiver surface is similar to that of the focal plane. The total flux absorbed is reduced due to the absorption coefficient of the surface. The maximum concentration ratio for the flat receiver is found to be 1.19×10^4.

On the other hand, Fig. 6 shows the concentration ratio on the cavity side wall along the centre-line, for different positions near the focal point. This is in concordance with the results in [10] for the cavity receiver considered there.

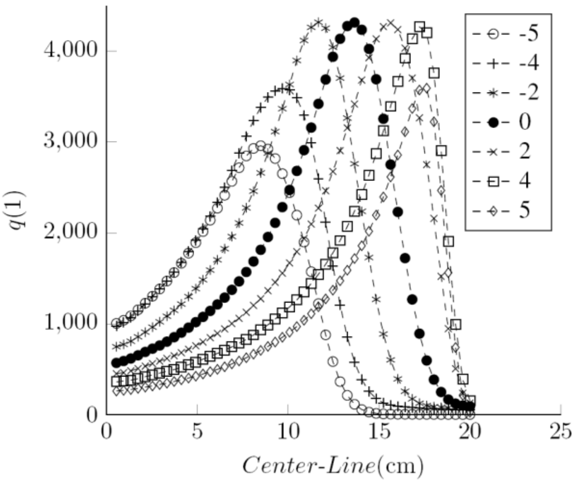

Fig. 6. Distribution of the concentration ratio on the cavity receiver side wall along the centre-line for different receiver positions. The origin is the bottom of the receiver. The receiver position is shown in centimetre. The remaining parameters are set to its nominal values.

The concentration ratio on the cavity bottom is shown in Fig. 7 for the same positions considered in Fig. 6. We observe that the maximum concentration ratio found is 4.3×10^3 so the cavity receiver reduces in a factor of 35% the maximum concentration ratio of the flat receiver.

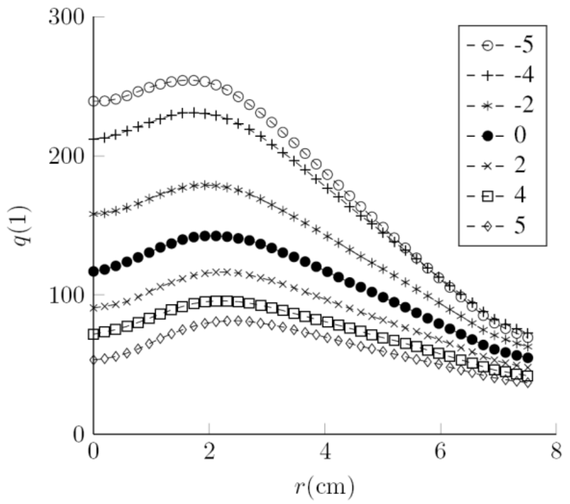

Fig. 7. Distribution of the concentration ratio on the cavity receiver bottom for different receiver positions. The origin corresponds to the centre-line intersection with the bottom. The receiver position is shown in centimetre.

Second, keeping the cavity receiver in the focus we vary its aperture diameter. Fig. 8 shows the total flux with the aperture diameter. It can be observed that the flux decreases as the diameter tends to 0, because, as it was to be expected, the receiver shadows itself. On the other hand we do not observe any improvement as the aperture tends to the cavity diameter. Note that although the aperture catches some rays otherwise leaving the cavity, it also prevents other rays from entering the cavity. Hence, it seems that the former effect is lower that the latter. Also note that we only consider the optical phenomena from sunlight so including other phenomena accounting for other energy loss mechanisms could yield in an effectively optimal aperture size, see [13].

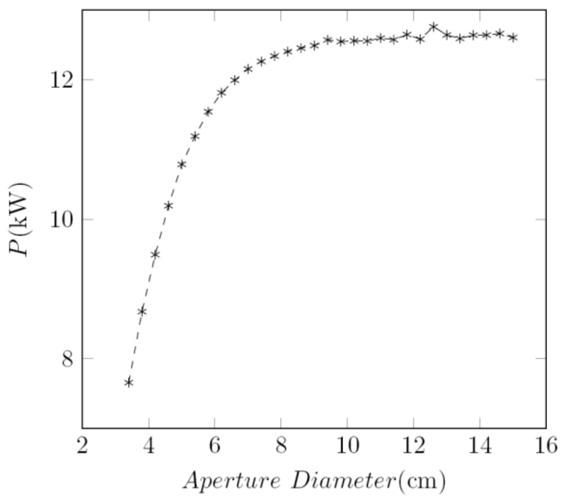

Fig. 8. Total flux with the aperture diameter. The receiver is placed in the focal position. The remaining parameters are kept fixed.

Finally, we vary the cavity diameter. The aperture diameter is also varied together with the cavity, keeping a linear relation between them. Concretely the variation rate of the aperture diameter is a 25% less than the variation rate of the cavity diameter. Fig. 9 shows the total flux varying these parameters together. As above, we do not observe any appreciable improvement.

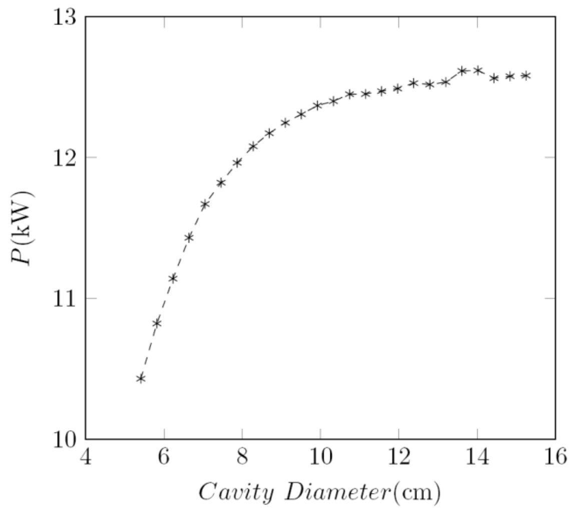

Fig. 9. Total flux with the cavity diameter together with the aperture diameter. The receiver is placed in the focal position. The remaining parameters are kept fixed.

7. Conclusions

It is found that the cavity receiver improves the radiation performance of the flat receiver in a 2.34%. Reflections in the cavity walls yield a lower mean free path of the rays upon entering the cavity, increasing the total number of reflections, therefore increasing the total flux absorbed. However reflections are considered ideally diffusive, hence a modified model with a specular reflection fraction of the rays reflected could produce different results for the cavity performance.

On the other hand, it is found that the cavity receiver is to be placed near the focal position to reach the maximum efficiency. In addition it is found that there receiver can be placed in the range between -3cm and 3cm approximately without diminishing significantly its radiation performance.

In addition, in order to reduce heat losses it is important to have a flux density distribution on the cavity walls as uniform as possible. From Fig. 6 we see that the peak flux density is lower between -4cm and -2cm, and from Fig. 7 we see that the peak increases. Thus the receiver could be placed closer to the concentrator while keeping an optimum performance, see Fig. 5.

Finally, varying the aperture and the cavity does not improve notably the radiation performance, although it has an important role in convection heat losses. However, for the maximum cavity diameter the radiation performance increases, because it intercepts the total flux coming from the concentrator. This has the drawback that the efficiency depends on the concentrator performance that highly degrades over time, resulting in a decreasing efficiency. Thus the variable aperture, together with a fixed cavity diameter allows a more robust design, since the variable aperture can be easily corrected or modified.

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