

Three-Dimensional Analysis of a Concentrated Solar Flux

David Riveros-Rosas

Centro de Investigación en Energía,
Universidad Nacional Autónoma de México,
Avenida Xochicalco S/N,
Temixco, CP 62580 Morelos, México

Marcelino Sánchez-González

Solucar R&D,
Buhaira 2,
41018 Sevilla, Spain

Claudio A. Estrada

Centro de Investigación en Energía,
Universidad Nacional Autónoma de México,
Avenida Xochicalco S/N, Temixco,
CP 62580 Morelos, México
e-mail: cestrada@cie.unam.mx

In order to improve the durability of receivers used in solar concentrating systems, it is necessary to minimize thermal stress during their operation. A possible way to do that is to design receivers in which the radiative flux density is homogeneous at the surface. For this reason, a detailed 3D study has been carried out for the distribution of concentrated solar radiation in the focal zone of a parabolic concentrator. A computer program has been developed to obtain isosurfaces of solar irradiance and achieve a homogeneous radiation flux on the receiver surface. The algorithm of the program proposes a methodology to obtain flux isosurfaces for a great variety of optical configurations. The effect of the optical errors on the mirror surface has been studied, as well as the effect of the shape of the mirror, e.g., round, square, or faceted. The numerical calculations were made using the convolution ray tracing technique. [DOI: 10.1115/1.2807212]

Keywords: ray tracing, solar concentrators, numerical modeling, absorber design, irradiance isosurfaces

Introduction

It is important to measure the flux distribution of solar concentrating systems to optimize the receiver configuration. Different techniques have been developed to measure the flux distribution in a plane placed in the focal zone [1–4], many of them using charge coupled device (CCD) cameras [5]. However, the development of modeling tools is necessary to allow the detailed evaluation of the power density distribution in the focal region of the concentrator and thus optimize the design of solar concentrators and the receivers [2,3,6].

Solar concentrating technologies are convenient for power generation due to the high temperature achievable because of the higher power density. The durability of key components, as the solar receivers, is related to the use of homogeneous fluxes and the reduction of the thermal stress [7]. An idea to improve the durability of receivers is to reduce peak flux obtaining a homogeneous or almost homogeneous flux. This could improve the power

efficiency, reduce thermal stress caused by high temperature gradients, reduce possible damages to the receiver surface, and improve its durability. A starting point to reduce flux peaks can be the determination of a surface in the focal zone where the radiation density is homogeneous (isosurface). The distribution of solar power in the focal region depends entirely on the optical concentrator's design. For some simple cases, the form of the isosurfaces can be solved analytically, but usually numerical computation is necessary.

This paper presents a numerical algorithm and a computer program to calculate, with high accuracy, the regions in the focal zone in which a distribution of homogeneous radiative flux can be expected (isosurfaces). The program was used with several concentrators: A parabolic dish, a rectangular plate with parabolic curvature, and a concentrator of spherical facets with parabolic profile. The isosurface calculation was made for different values of mirror optical errors.

Methodology

A ray tracing program, which was called ISOS, was developed to search for isosurfaces using the convolution technique. The energy distributions were obtained in a plane located near the concentrator focal zone. Those radiative flux distribution curves were validated with CIRCE2 [8] and SOLVER (software package for concentrating systems developed by Solucar. Solucar is a Spain energy company). The sunshape chosen for the calculations was the one given in CIRCE2.

Initially, we look to determine irradiance isosurfaces for the case of a parabolic solar concentrator. The concentrator is assumed to have the focal axis on a vertical position, and the incidence of solar radiation is parallel to the focal axis, see Fig. 1. As a first step, the energy concentration is calculated on a plane located perpendicular to the focal axis; later, we scanned the planes away from the concentrator's focal point. This procedure gives us a set of planes where irradiance distributions are known. Therefore, it is possible to calculate, by interpolation, all those points that correspond to the same irradiance level and generate a surface as shown in Fig. 2(a), we call this surface a protosurface. Nevertheless, this protosurface would not have a homogeneous radiation flux. We must keep in mind that the irradiance flux not only depends on the position but also on the direction of the plane used for that calculation. Thus, the irradiance on tangential planes of the protosurface will have different values compared with those of the horizontal planes.

As a second step, we considered a different direction and calculated the energy concentration on the planes located perpendicular to the previous direction; later, we scanned the planes away from the concentrator's focal point and, as before, we generate a second protosurface, as shown in Fig. 2(b). This procedure is repeated for several directions to obtain a set of protosurfaces.

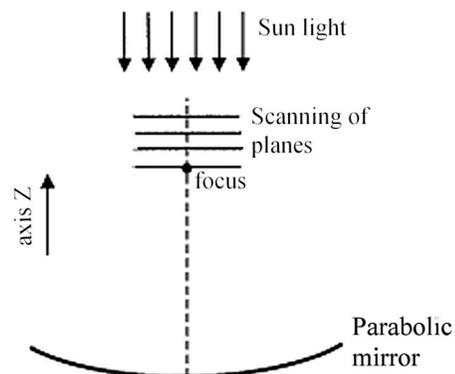


Fig. 1 Schematic of the concentrator, the focal point, and the scanning planes

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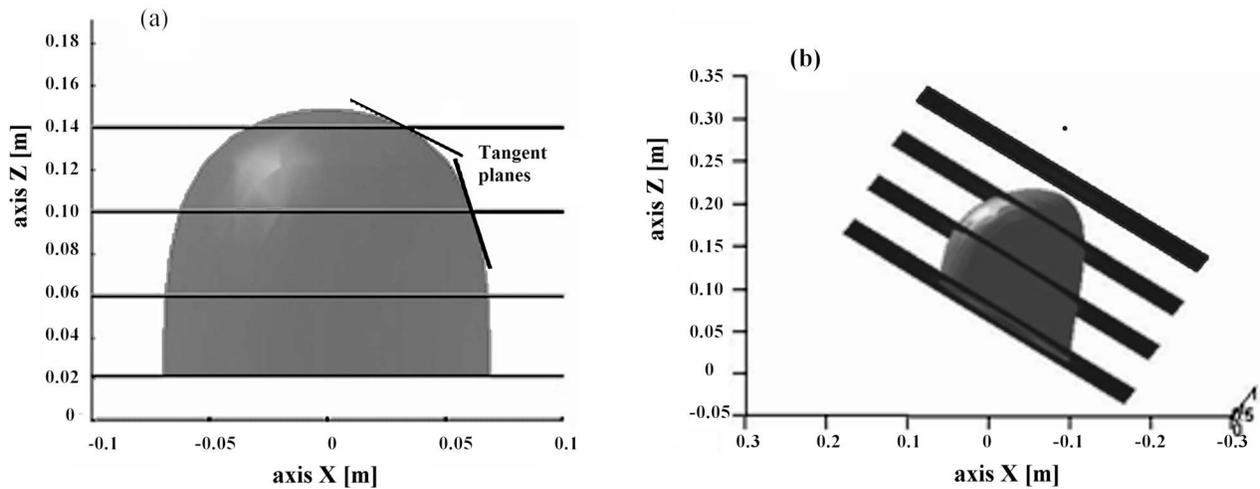


Fig. 2 (a) A protosurface of homogeneous irradiance from a set of horizontal planes and (b) a protosurface of homogeneous irradiance from a set of nonhorizontal planes

If we superpose all the protosurfaces calculated for each set of planes and directions, the surface that encloses all these protosurfaces will also have a uniform irradiance (Fig. 3), with the advantage that the tangential planes will be the nearest to the direction of the plane, which is where the irradiance was calculated. This can be seen when you compare the tangent plane in Fig. 2(a) with the tangent plane in Fig. 3. We will call this surface near the focal axis an isosurface. For this geometry (parabolic dish), and due to its axial symmetry, it is enough to calculate the set of protosurfaces for only one azimuthal direction. Figure 4 shows the superposition of all protosurfaces thus calculated.

This gives information of the irradiance in space for any point in the focal region and any direction of the plane.

The third step consists in obtaining an approximation for the superposition of protosurfaces from all the points that are on the irradiance isosurface. To do that, the points farthest to the focal plane were calculated, assuming that those points belong to the isosurface. Figure 4 shows some of those points in black, and if we rotate the interpolated curve of the black points, the isosurface is generated.

The ISOS code makes all the calculations and generates the isosurfaces in a few days. This depends on the geometry and number of facets. The majority of the time is taken up calculating the irradiance on the planes with different orientations. When these calculations are completed, the time to obtain the isosurfaces only takes a few minutes.

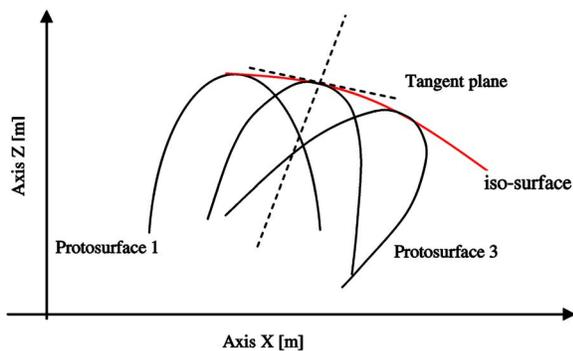


Fig. 3 An exaggerated view of the protosurface superposition to generate an isosurface

Results

The first case solved corresponds to the isosurfaces for a parabolic dish concentrator because this is the most typical geometry for a mirror concentrator. The concentrator of 12 m in diameter and 8 m in focal length was modeled for different optical errors. Figure 5 shows the cross section of isosurfaces for different irradiances with a mirror optical error of 4 mrad. The points in the graph adjust to a parabolic profile (solid line) with a standard deviation inferior to 5%. As the isosurface is located closer to the focal point of the concentrator, the flux density increases, whereas the area of the isosurface decreases. This is predictable because once the focal point is surpassed, the solar radiation diverges diminishing its power density.

Also, a study of the mirror optical error effect was carried out for isosurfaces of certain irradiance. Figure 6 shows the isosurfaces for three different optical errors for the concentrator, for a power density equal to 400 W/cm^2 . It can be observed that as the errors increase, the isosurface is nearer to the focal point.

We made a numeric verification for the isosurfaces corresponding to levels of $8 \times 10^5 \text{ W/m}^2$ and $1 \times 10^6 \text{ W/m}^2$. In Fig. 7, we

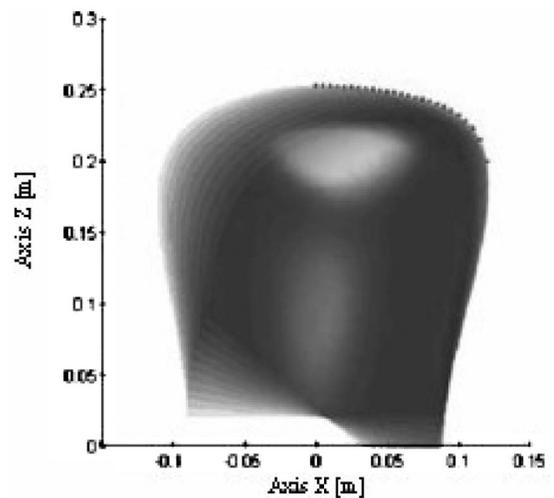


Fig. 4 Superposition of protosurfaces along the positive X axis in which the irradiance is homogeneous

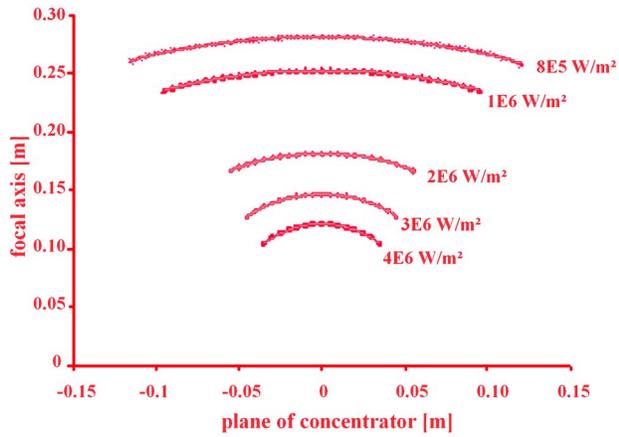


Fig. 5 Cross section of irradiance isosurfaces considering a parabolic dish concentrator

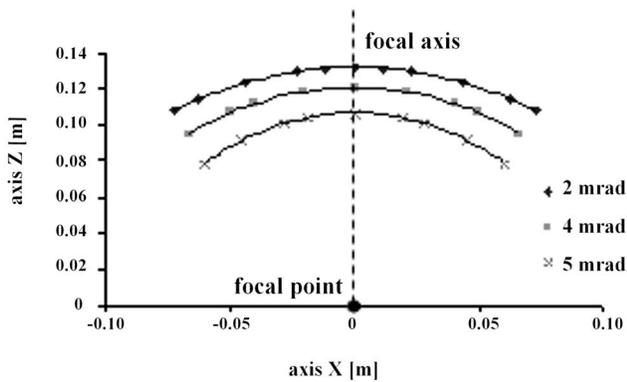
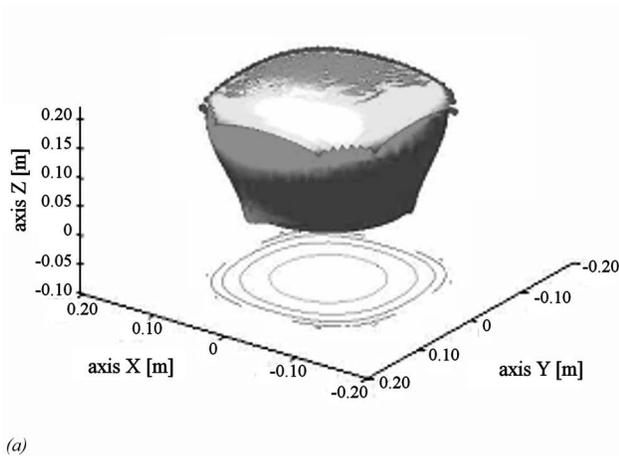


Fig. 6 Cross section of irradiance isosurfaces assuming different mirror surface errors

can observe that the level of irradiance remains almost constant for the two irradiances. The figure shows that the irradiance for a flat receptor located at the distance corresponds to the isosurface of $8 \times 10^5 \text{ W/m}^2$. We can observe that at this plane, the irradiance varies significantly from the irradiance for the isosurface.



(a)

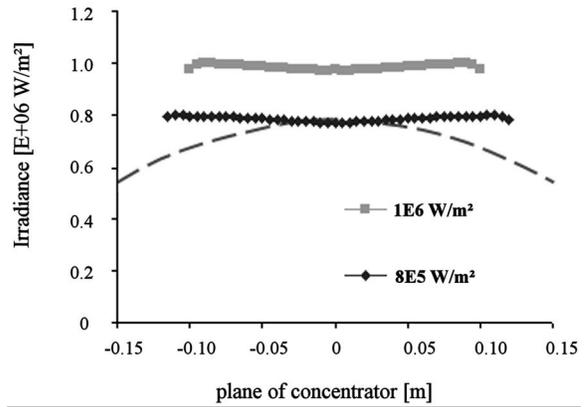


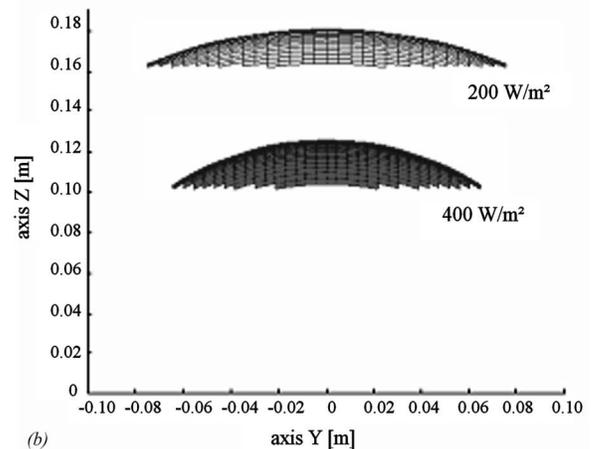
Fig. 7 Comparison between the irradiance level on the isosurface for $8 \times 10^5 \text{ W/m}^2$ and a flat plane receptor located at the same distance of the isosurface

As an example of a practical application, the above mentioned procedure was applied to calculate the irradiance isosurfaces for a parabolic concentrator of square shape, with a dimension of $12 \times 12 \text{ m}^2$, having the same focal length as the previous example. The total error of the concentrator was fixed to 4 mrad. Figure 8(a) shows a 3D view of the irradiance isosurface for 200 W/cm^2 level. The red surface corresponds to the superposed protosurfaces and the blue surface corresponds to the isosurface. Figure 8(b) shows a lateral view of isosurfaces of irradiances of 200 W/cm^2 and 400 W/cm^2 . The shape of the isosurfaces checked out, they correspond to parabolic profiles, as in the previous case.

The case of a concentrator system formed by spherical facets with a parabolic profile was also studied. The focal length of the parabolic concentrator was 7.45 m and the radius of every facet was 15 m with an optical error of 4 mrad, see Fig. 9(a). Figure 9(b) shows the isosurface obtained for this concentrator. This case was studied due to the fact that its geometry is very similar to other geometries, like a solar furnace or dish-Stirling systems. This allows the ISOS code to be used in those systems.

Conclusions

A methodology was developed to obtain approximated irradiance isosurfaces for solar concentrators. For the cases of concentrators with a parabolic profile, it was observed that the form of



(b)

Fig. 8 (a) 3D view of an irradiance isosurface of 200 W/cm^2 and (b) lateral view of isosurfaces of irradiances of 200 W/cm^2 and 400 W/cm^2

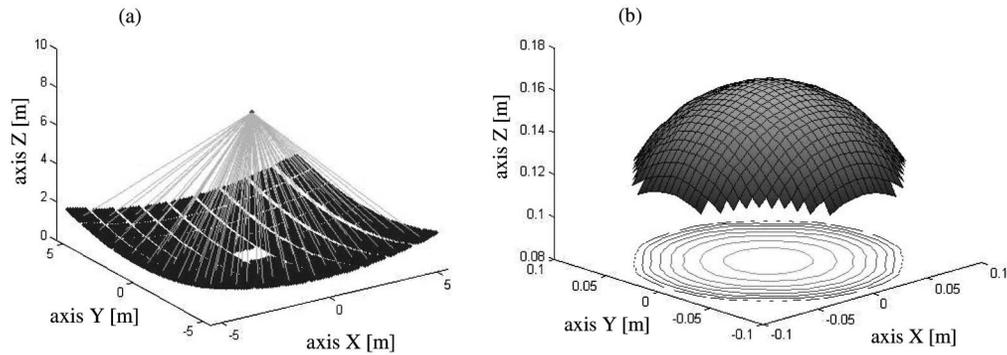


Fig. 9 (a) Schematic of the facet distribution and the incidence of reflected rays in the vertex of each facet and (b) 3D view of an irradiance isosurface, 200 W/cm^2

the isosurfaces also corresponds to a quasiparabolic profile. Other geometries can also be solved. The case of a concentrator formed by spherical facets with a parabolic profile has been used as an example.

This new procedure can be applied to a wide variety of solar concentrating system and can be used to help in the design and optimization of solar receivers.

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