Optical Analysis for a Honeycomb Solar Receiver Using a Point-Focus Concentrator

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Abstract

In this work we present an optical analysis for three different hydraulic diameter honeycomb receivers used to elevate working fluid temperature using concentrated solar radiation provided by a point-focus solar concentrating system. The analysis was carried out in order to determine the amount of concentrated solar radiation received in the volumetric receiver as well as the radiation distribution inside of it, also to determine the length of it. The study which determines the location of the receiver in the optical axis of the concentrating system is also presented, as well as the ray independence study to secure the reproducibility and repeatability of the results. The simulation was done in Tonatiuh software considering the physical characteristics of the point-focus concentrating system and the volumetric receivers. As results, it was revealed that around 96% of the concentrated solar radiation arrives to the receiver – inside and in the front side-, the rest of it is attributed to the losses due to different factors.

Keywords: *Honeycomb solar receiver, Optical analysis, Point-Focus concentrator*

I. INTRODUCTION

Obtaining heat through the excessive use of fossil fuels to facilitate the production processes of fuels and materials is a serious problem today; however, a feasible alternative is the use of renewable resources and materials. Solar Thermal Energy is the most important in the type of solar energy and represents one of the most important sources of technology and electricity production used in various applications such as buildings, mobility and manufacturing [1]. The heat necessary for medium-high temperature processes can be obtained through the production of Concentrated Solar Radiation, this heat is obtained through systems with optical arrangements that involve the use of lenses and / or mirrors, which have the function of re-directing the sun's rays to an area smaller than the catchment area, thus increasing its energy density several times. There are different types of solar concentration technologies that achieve this process through different operating bases such as the parabolic disc, parabolic channel, linear fresnel reflector, central tower and solar oven[1]. Solar concentration technologies are still under development and are not accessible like conventional photovoltaic modules compared to the ease of operation of the latter[2]. However, its development provides significant advantages over conventional devices such as greater efficiency, high temperatures for energy production and to be used as process heat.

The transformation of RSC into thermal power is carried out using receivers, whose geometries and construction materials vary depending on their application. Volumetric receptors (Figure 1 (a)) are porous structures of different materials such as metal or ceramics. This type of receptor is very promising due to the volumetric effect; this effect causes the temperature of the irradiated part to be lower than the temperature in the final part of the receiver, causing less heat losses by radiation and making the process more thermodynamically efficient [3], it also reduces the local points high temperature that could damage the material and harm the process in general[4]. Despite this, there are significant difficulties in RV design due to the complexity of the volumetric effect. The heat transfer phenomena that occur within the structure - radiation, convection and conduction - are affected by each other, so the radiative and thermal study of RVs requires a large computational load[4].

The distribution of radiative flux has a significant impact on the temperature field of the receiver [5], that is why their study provides necessary information on its operating limits. Said study is carried out by applying the ray tracing method, which considers that light moves from a light source describing a path in the form of a line until it hits a surface that, depending on its assigned physical properties, can modify its direction by reflection or refraction. Ray tracing can be performed using three different techniques: Simple Ray Tracing Method, Convolution Ray Tracing Method and Monte-Carlo Method.

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The simple ray tracing method refers to a systematic ray distribution of rays by mesh and ray projection of the solar cone individually; While convolution ray tracing is a mesh ray distribution and calculation of the degraded solar cone by the mathematical convolution technique, only the central ray is projected, and the cone is reconstructed in the receiver. On the other hand, the Monte Carlo Method, which is a numerical method that allows solving physical and mathematical problems by simulating random variables, is a statistical simulation of the radiative transfer phenomenon based on the behavior of the emission, the reflection and the absorption of the surfaces of the optical system [6].

Studies have been reported in the literature that reveal the distribution of radiative flux in RV, through the application of the MCRT Method, where the source of CSR considered is a point focus concentrator [7–9], some reported works combine the X-ray computed tomography technique to reconstruct a realistic porous absorber with the MCRT to obtain the RSC distribution[10], while in other works theoretical assumptions are made to simulate the operating conditions of the receiver[11].

In this work, the methodology and results obtained by ray tracing simulation carried out in three volumetric receivers of different hydraulic diameters are presented to determine the amount of concentrated solar radiation received in it, as well as the way in which it is received. and it is distributed within the structure in addition to establishing the length of the same receiver; and which are the three diameters it presents favors the radiative phenomenon to a greater extent. The CSR source considered is a point focus concentrator (Figure 1 (b)), developed and built by researchers from the University of Arizona in collaboration with Rehnu[12], whose characteristics are described in Table 1.

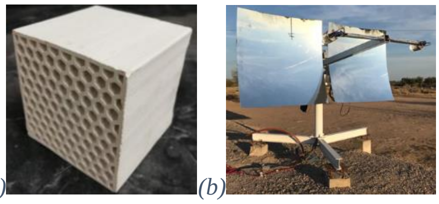

Figure 1. (a) Ceramic volumetric receiver with dimensions of 10x10x10, dh = 0.0078 m. (b) Point focus concentrator system located in the Hermosillo Solar Platform.

II. METHODOLOGY

The simulations were carried out in the free license software Tonatiuh v.2.2.4 with three volumetric receivers of different porosities with hexagonal cylinders (Figure 2); For an orderly application of the methodology, the cases described in sections a), b) and c) were established, in addition the specifications described in Table 1 were considered and the receiver input was located 1.47 m from the vertex on the optical axis of the parable - as determined in the next section - considering it as a black body.

The simulation strategy used consisted of approximating the hexagonal cylinders to circular cylinders through the use of the hydraulic diameter, in addition to considering all the cylinders that are within a flat area of 0.05x0.05 m2 at the entrance of the receiver; This is because the system to be simulated must be as similar as possible to the physical system (Figure 3), which is why it is important to include in the simulation, the structure of the concentrator system to determine if it has an effect on the distribution of radiation in the receptor.

To consider the results obtained from the simulation acceptable, a radiative balance was carried out considering that the sum of the radiation received in the RV, as well as that which passes through it and which is overflowed, must be equal to what is received in a area of 0.01 m2 (which is the total receiving area 1.47 m from the vertex).

a) Case 1: DH = 0.004 m, L = 0.10 m, No. of cylinders = 99, fraction of holes = 0.498
b) Case 2: DH = 0.0057 m, L = 0.10 m, No. of cylinders = 42, fraction of holes = 0.428
c) Case 3: DH = 0.0078 m, L = 0.10 m, No. of cylinders = 25, fraction of holes = 0.802

A. Study of ray independence

The study of ray independence is mandatory in TR simulations to ensure the repeatability and reproducibility of the results obtained, which is why it must be carried out before the development of the aforementioned methodology. For this, the mesh size parameter was set at 25x25 while the number of rays was considered as the variable and an uncertainty was established as a function of this and in relation to the maximum value of flux less than 4% for the three cases a study. As results, we found that for case 1, 10 million rays were used and for cases 2 and 3 5 million were used.

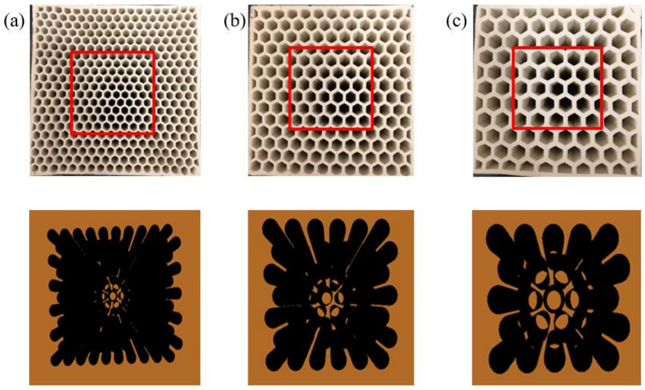

Figure 2. (a) case 1, (b) case 2, (c) case 3.

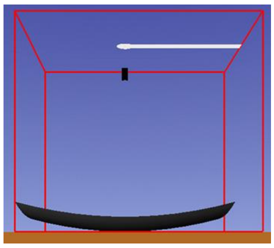

Figure 3. Physical system drawn in Tonatiuh software.

Table 1. Definition of parameters for TR simulation in Tonatiuh software

Definition of irradiance parameter	
Direct Normal Irradiance	1000 W/m^2
Sun Shape	Standard
CSR	0.02
Azimut	0°
Elevation	90°
Primary optical element	Parabolic mirror
Dimensions	1.65x1.65 m^2
Focal point	1.5 m
Reflectivity	0.9
Global optical error of the system	2.8 mrad

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B. Determination of the location of the RV on the optic axis

It was established that the area of the receiver is 0.05 x 0.05 m^2, so through the simulations it was determined that at a distance of 1.47 m from the vertex and on the optical axis of the parabola, the RSC with the highest concentration illuminates an area of 0.0025 m^2 while the total reception area is 0.01 m^2. According to the results of the TR simulations, the support structure does not have a significant effect on the distribution of the RSC as shown in Figure 4; where it is also established that the CSR presents a maximum peak of 2.5 MW/m^2 and an average of 236 kW/m^2.

Figure 5 shows the profiles of the distribution of concentrated solar radiation obtained from Figure 4, in the central part of the x and y axes, respectively. In the distribution profiles presented, it is observed that the shadowing effect of the structure on these is negligible, and that the flux value remains between 1.5-2.5 $x10^6$ W/m^2 in x, y = [- 2.5,2.5].

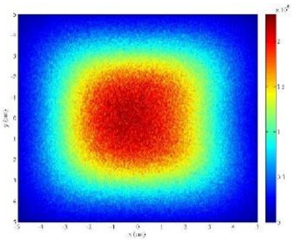
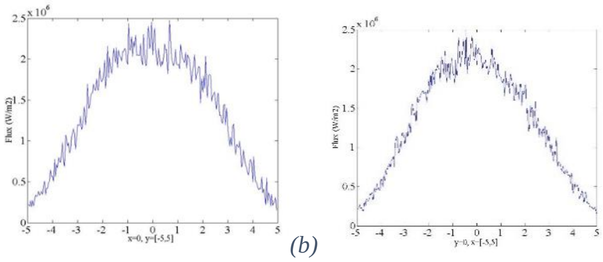


Figure 4. Spot of concentrated solar radiation obtained by simulation on the PPLR at 1.47 m from the vertex of the parabola. (The units of the color scale are W/m^2).



(a) *(b)*

Figure 5. Profiles in (a) x = 0; y = [- 5.5] y (b) y = 0, x = [- 5.5] of the distribution of concentrated solar radiation on the PPLR obtained by simulation.

III. RESULTS

A. Interpretation of results

For a proper interpretation of the energy balance, the following is established. "Received in the volumetric receiver" is understood as the radiation that is received in the frontal structure of the walls that are between the cylinders and that that is received in the interior walls. On the other hand, the radiation that overflows when reducing the area from 0.01 m2 to 0.0025 m^2 and that which leaves the receiver, whether a part of it has interacted with the interior walls, are considered as losses.

Before performing the energy balance within the volumetric receiver for the three cases, it is necessary to clarify what happens to the concentrated solar radiation when the receiver arrives. The solar rays can be intercepted by the frontal structure of the walls that is between the cylinders of the receiver as well as they can impact against the interior walls - reflect some percentage to hit another wall again depending on its direction - or pass through the cylinders without having directly interacted with the walls of the receiver; Another percentage of the rays may not even have reached the receiver and another percentage may overflow from the reception area. The radiation distribution that is observed in the following figures corresponding to this section are the result of the radiation phenomenon, because the physical properties of the receiver are considered, as well as the concentration system and the final scene of the phenomenon including optical system errors.

B. Results

Considering the total area of capture of solar radiation (2.7225 m2) and a normal direct irradiance of 1,000 W / m2, the radiation that would be received if a perfect concentrator were had would be 2,722.5 W; However, considering the global optical error of the system that has been determined previously, only 2.365 W are received, that is, 96% - in radiative terms - in a flat plate of 0.01 m^2 at 1.47 m and on the optical axis. From this, the balances presented above are determined.

The general and detailed energy balances presented in the previous tables are considered correct because, as expected, the sum of the energy received inside the cylinders is less than that received in a flat receiver. As can be seen in Tables 2, 3 and 4, there is no significant difference between one diameter size and another in terms of radiation received within the receiver or losses.

Regarding the distribution profiles of concentrated solar radiation formed on the interior walls of the volumetric receiver, only those corresponding to the central section are presented and analyzed in this section, while the rest of the graphs are found in the section of annexes. The foregoing is justified by corroborating that the radiation intensity was highest in the center of the receiver and decreases when moving away from the center, so reviewing the profiles at this location will provide sufficient information for the analysis.

To begin the analysis of the results of the ray tracing simulation, a general description of Figures 6, 7 and 8 is made. The x-axis corresponds to the hydraulic diameter of each case described above, while the y-axis describes the length of the cylinder. The input of the concentrated solar radiation to the cylinder is at y = 0 and the output at y = 0.10. The origin of the coordinates is on the lower left side.

In Figure 7, the results for case 1 are shown and in a general appreciation, it is observed that the radiation does not reach beyond y = 0.02, which means that the highest concentration is in the first fifth of the volumetric receptor. The maximum estimated flux value is 6 MW / m2. Figure 8 corresponds to the results of case 2 and the radiation slightly exceeds the length of y = 0.02 in the positions that correspond to items 1 to 4, which means that the radiation has a penetration greater than 1/5 of the length of the receiver; the maximum estimated flux value is 7 MW / m2. Regarding Figure 9, the distribution profiles of the concentrated solar radiation corresponding to case 3 are described. The radiation penetrates up to a maximum length of y = 0.04 m, that is, it reaches 2/5 of the total length of the receiver and the maximum estimated flux value is 7 MW / m2.

In all three cases it is possible to appreciate the volumetric effect from the perspective of the radiation distribution inside the walls. From this, it is established that a length of 0.10 m is not necessary for the receiver - in any of the cases-, but it is recommended that it have a maximum length of 0.05 m.

Table 2. Energy balance for case 1

		Balance in General Terms	Percentage	
2365	W	Plane (0.01 m^2)	100.00	%
2273.7	W	Received in VR (0.0025 m^2)	96.14	%
91.3	W	Losses	3.86	%
		Detailed Balance	**Percentage**	
2365	W	Plane (0.01 m^2)	100.00	%

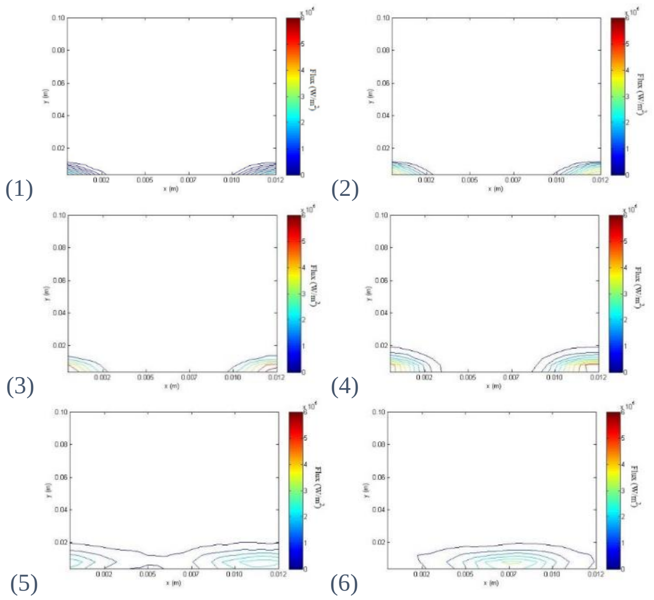
2279	W	Plane (0.0025 m^2)	96.36	%
86	W	Overflow	3.64	%
1299.8	W	Received within 99 cylinders	54.96	%
5.3	W	Come out of the receiver	0.22	%
973.9	W	Received in the structure	41.18	%

Table 3. Energy balance for case 2

		Balance in General Terms	Percentage	
2365	W	Plane (0.01 m^2)	100.00	%
2276.4	W	Received in VR (0.0025 m^2)	96.26	%
88.53	W	Losses	3.74	%
		Detailed Balance	**Percentage**	
2365	W	Plane (0.01 m^2)	100.00	%
2279	W	Plane (0.0025 m^2)	96.36	%
86	W	Overflow	3.64	%
1184	W	Received within 99 cylinders	50.07	%
2.53	W	Come out of the receiver	0.11	%
1092.3	W	Received in the structure	46.19	%

Table 4. Energy balance for case 3

		Balance in General Terms	Percentage	
2365	W	Plane (0.01 m^2)	100.00	%
2278.3	W	Received in VR (0.0025 m^2)	96.34	%
86.64	W	Losses	3.66	%
		Detailed Balance	**Percentage**	
2365	W	Plane (0.01 m^2)	100.00	%
2279	W	Plane (0.0025 m^2)	96.34	%
86	W	Overflow	3.64	%
1289.5	W	Received within 99 cylinders	54.53	%
0.64	W	Come out of the receiver	0.03	%
988.84	W	Received in the structure	41.81	%



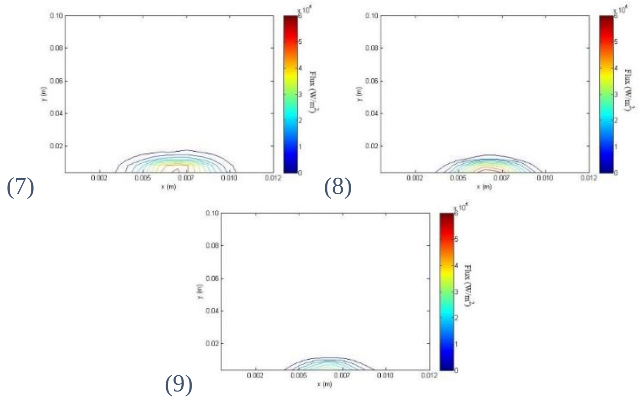


Figure 6. Distribution profiles of concentrated solar radiation on the interior walls of case 1.

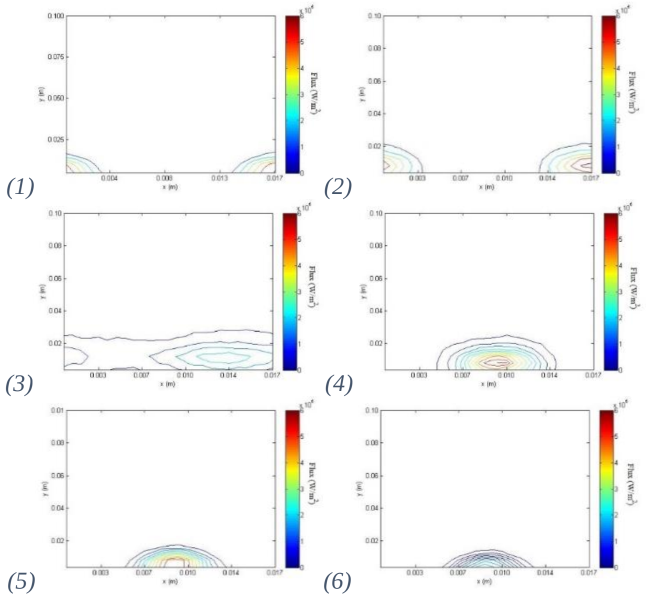


Figure 7. Distribution profiles of concentrated solar radiation on the interior walls of case 2.

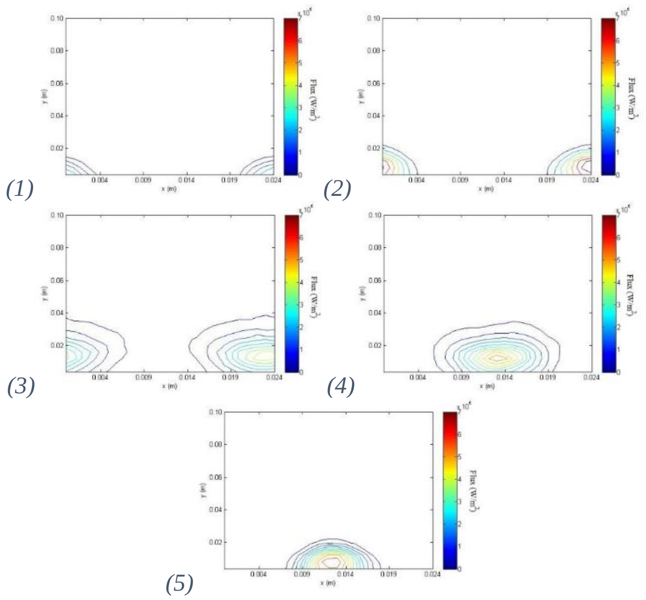


Figure 8. Distribution profiles of concentrated solar radiation on the interior walls of case 3.

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