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GEOMETRICAL PARAMETRIC ANALYSIS TO FIND OPTIMUM CONFIGURATION OF A SOLAR CONCENTRATOR WORKBENCH USING LINEAR FRESNEL TECHNOLOGY

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Abstract

In this study, a numerical model was developed in order to obtain the optical efficiency of a solar collector with a linear Fresnel concentrator. This model was build based on the ray-tracing and Monte Carlo methods. The goal was to use this model to obtain the parameters required to build a linear Fresnel workbench in our laboratory. With this model it was possible to obtain the optimum configuration of a linear Fresnel workbench taking into account physical and financial constraints.

Keywords: *Renewable Energy, Solar Energy, Numerical Model, Linear Fresnel, Concentrated Solar Power*

1. Introduction

Linear Fresnel solar concentration technology is associated with lower costs and greater simplicity of manufacture when compared to other solar concentration technologies available in the market (Muñoz-Antón et al, 2014). However, this technology is relatively new and more studies on this subject need to be carried out. In this regard, the implementation of a linear Fresnel solar collector workbench on the roof of one of our facilities is being investigated in our laboratory. In order to obtain the most promising configuration for this workbench, in terms of fulfilling our objectives, taking into account the physical and technical constraints of the laboratory, a series of algorithms was developed to evaluate the influence of the geometric parameters on the performance. In these algorithms parameters such as the number of mirrors, mirror spacing, mirror curvature, height of the absorber element and the aperture area of the absorber element are varied. With the model developed the geometric efficiency of the collector was evaluated with the position of the sun varying during the day. This model was validated using the software SolTrace, developed by the National Renewable Energy Laboratory (NREL, 2015). The linear Fresnel workbench will be used to study direct steam generation (DSG) and the associated technical thermal issues. The profile of the distribution of the solar radiation flux on the absorber element was determined since this parameter is of great importance regarding DSG technologies.

2. Linear Fresnel Solar Concentrators

The linear Fresnel collector is a type of concentrated solar power (CSP) technology. There are four main types of CSP technologies in the market: the solar tower and the parabolic dish (which involve punctual concentration), and the linear Fresnel and the parabolic trough (which involve linear concentration). Each technology has its particular characteristics, with advantages and disadvantages. Currently, the use of linear Fresnel technology for direct steam generation seems to be favored (Muñoz-Anton et al., 2014). In 2012 there were 29 CSP plants installed around the world and 31 plants under construction (Pavlovic et al., 2012). In most of these the parabolic trough concentration technology is used. Despite the increasing number of plants being installed, the viability of this technology still relies heavily on government incentives and an increase in production levels, which would result in a cost reduction (Wagner, 2008).

The linear Fresnel collector is composed of several elements. One of these is the absorber assembly, which is composed of an absorber element and often a cavity in which the absorber element is mounted. The absorber element usually consists of a single metal tube or a bundle of tubes with a spectrally selective coating to absorb

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as much of the concentrated radiation as possible and minimize the emission in the infrared spectrum (Duffie and Beckman, 2006). These tubes are generally made of stainless steel and the working thermal fluid flows inside. The cavity serves to promote the greenhouse effect and thus reduce thermal losses. It can work with a secondary reflector (Zhu et al., 2013).

Next to the ground are the rows of mirrors that reflect radiation to the absorber assembly. These may be flat or have a slight concavity to improve the concentration rate (Abbas et al., 2013). The rows of mirrors are generally orientated in a north-south axis, and they follow the sun's movement during the day, from east to west. The influence of the mirror curvature on the profile of the concentrated radiation was studied in this paper.

3. Geometric Model Using Monte Carlo Ray-Tracing

In order to evaluate the Fresnel configuration a routine was implemented in Matlab. In this routine the Monte Carlo Ray-Tracing (MCRT) method was used, in which the trajectory and energetic weight of each ray are defined using probabilistic functions. The MCRT method is a powerful tool for analyzing the optical characteristics of solar concentrators (Cheng et al., 2014).

The interactions of each ray with the collector elements have been analyzed, and the optical proprieties of these elements, such as reflection, absorption and transmission, can be taken into account (Delatorre et al, 2014). The optical efficiency of the collector is obtained when these parameter are included in the simulation (Zhu, 2013).

However, since this paper focuses on the analysis of the geometric efficiency, parameters such as the mirror reflectivity, the glazing transmissivity and the selective coating of the absorber element are not considered in the primary analysis. This simplification does not represent the real absorber, but it provides the distribution of the radiation concentration in the aperture plane, which will be useful later for thermal evaluations (Facão and Oliveira, 2011). To determine the geometric efficiency of the collector, aimed at obtaining the best configuration for the workbench, this approximation provides good results with great simplicity.

Another simplification is made by considering the absorber assemble as a flat surface which represents its aperture area. The objective is to obtain the concentrated radiation profile in this aperture area and the total concentrated radiation.

This model is equipped to analyze both plane and curved mirrors and its validation was carried out applying two different approaches. First, a plane mirror model was obtained and validated using the software SolTrace of the NREL (National Renewable Energy Laboratory). SolTrace is a highly rated software program designed for this purpose and it has been validated in several experimental studies (SolTrace, 2015), (Wendelin, 2003), (Wendelin et al. 2013), (Maliage and Roos, 2012). However, SolTrace is not an optimization tool and it is not suitable for analyzing several conditions in a row.

Later a model of an existing collector, the FRESDEMO, was developed and the concentrated radiation profile in the absorber was compared with that obtained by Abbas et al. (2013). In this case, the mirrors were slightly curved.

Figure 1 shows several of the dimensions of the collector: the width of the receiver (Wr), the width of each mirror (Wm), the width of the collector (Wcol), the receiver height (hr), the spacing between adjacent mirror lines (Sm), the number of mirror lines (n) and the mirror curvature (Cm).

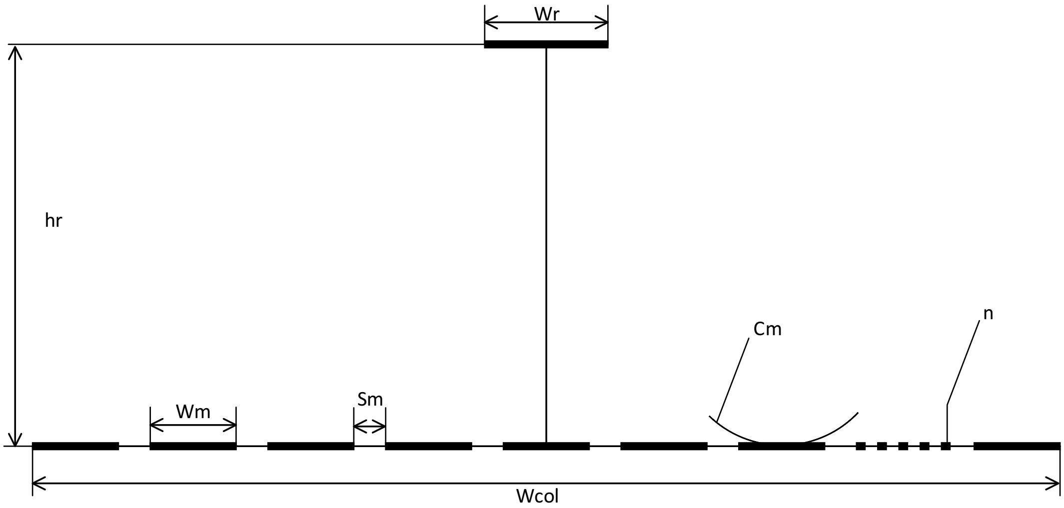

Figure 1: Dimensions of the collector.

4. Results

Since the experimental Fresnel collector is to be installed on the roof of one of the LEPTEN laboratory facilities, spatial and financial constraints must be taken into account. The first constraints are the total width and length of the collector. The area were the Fresnel will be installed is 6m wide and 12m long and thus it is limited to a width of 5m (W_{col} = 5m) to allow easy access for installation and maintenance. The length of the collector was similarly limited to 12m. Considering the collector width limit the other variables can be changed in order to analyze the geometric efficiency.

The geometric efficiency is defined as the ratio between the amount of rays (or energy) that impinge on the width of the receiver aperture and the rays reaching the entire collector width, as shown in equation 1, where η_g stands for the geometric efficiency while n_{r_abs} and n_{r_coll} are the number of rays produced by the MCRT that hit the absorber and the collector aperture, respectively. A useful relation to characterize the Fresnel collector is the filling factor defined in equation 2. This is the relation between the mirror field area and the total area of the collector.

$$\eta_g = n_{r\_abs}/n_{r\_coll} \quad \text{(eq. 1)}$$

$$ff = W_m * n/W_{col} \quad \text{(eq. 2)}$$

The first simulations showed that some of the variables can be kept constant without significantly influencing the final geometric efficiency. This initial analysis is of qualitative rather than quantitative importance. The influence of the spacing between mirrors on the efficiency was the first factor analyzed. In this analysis the mirror width and height were fixed at 300mm and 3500mm, respectively, and the receiver width was defined as 10% greater than the width of the mirrors. The number of mirror rows varied between 10 and 16, and the spacing between mirror lines varied from zero to the maximum allowed respecting the collector width. As shown in Figure 2, for most of the numbers of mirror rows analyzed the maximum efficiency was reached with the largest mirror spacing possible. The only case where the maximum efficiency was not observed at the maximum spacing was 10 rows of mirrors. This is because greater spacing between the mirrors reduced the losses due to shading and blocking, but a limit was reached when significant shadowing and blocking were no longer present. On the other hand, greater mirror spacing means that the mirrors at the extremities will be even farther from the absorber assembly, increasing the loss due to its increased inclination.

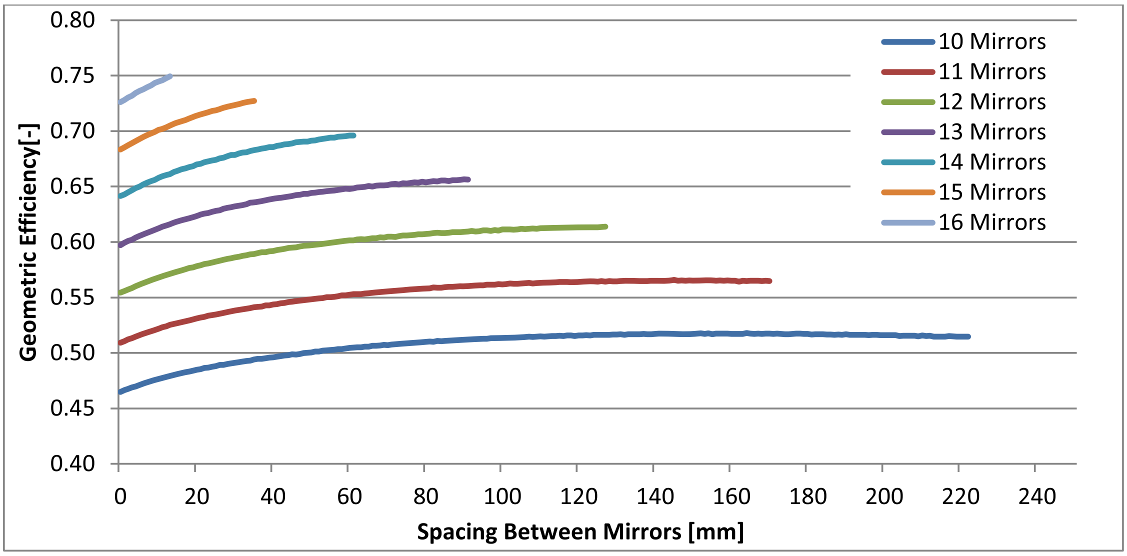

Figure 2: Influence of the number of mirror lines and the spacing on the geometric efficiency.

Therefore, it can be concluded that for all of the cases to be analyzed the maximum spacing between mirror lines will give the best results.

The next step was to determine the influence of the receiver width to mirror width ratio on the efficiency and the results are shown in Figure 3. The efficiency increases with the receiver width as the receiver can intercept more rays reflected from the mirrors. However, the larger the receiver is the larger the shadow it produces on the mirror field will be. For this reason, there comes a point where the efficiency begins to decrease with an increase in the area of the receiver aperture. The curve reaches a maximum at approximately$W_r = 1.1 * W_m$. In this analysis the receiver height is fixed at 3.5m and the spacing between mirrors is set as larger as possible. The same analysis was carried out for different mirror widths and for all cases the same result was achieved. Thus, the relation $W_r = 1.1 * W_m$ was maintained constant in all other analyses. All of these studies were carried out considering plane mirrors. Later, it is shown that for curved mirrors this ratio is far lower, and the receiver width is smaller than the mirror width.

The influence of the receiver height on the geometric efficiency was analyzed by fixing the mirror width at 300mm and using the largest possible spacing between rows. It was observed that on increasing the receiver height the efficiency also increased. It was also concluded that the receiver height has a very weak relation with the other variables.

The analysis is bi-dimensional, which means that the geometrical efficiency obtained is in fact a transversal geometric efficiency. In a three dimensional case, taking into account the collector length, there is another type of loss called end losses. A real-scale Fresnel collector must be sufficiently long to ensure that these end losses are minimal. Because the collector analyzed is short (length = 12m) these losses are large when the sun is low in the sky, for instance, during winter. For flat mirrors, for receiver heights larger than 3500mm the increase in the efficiency is minimal.

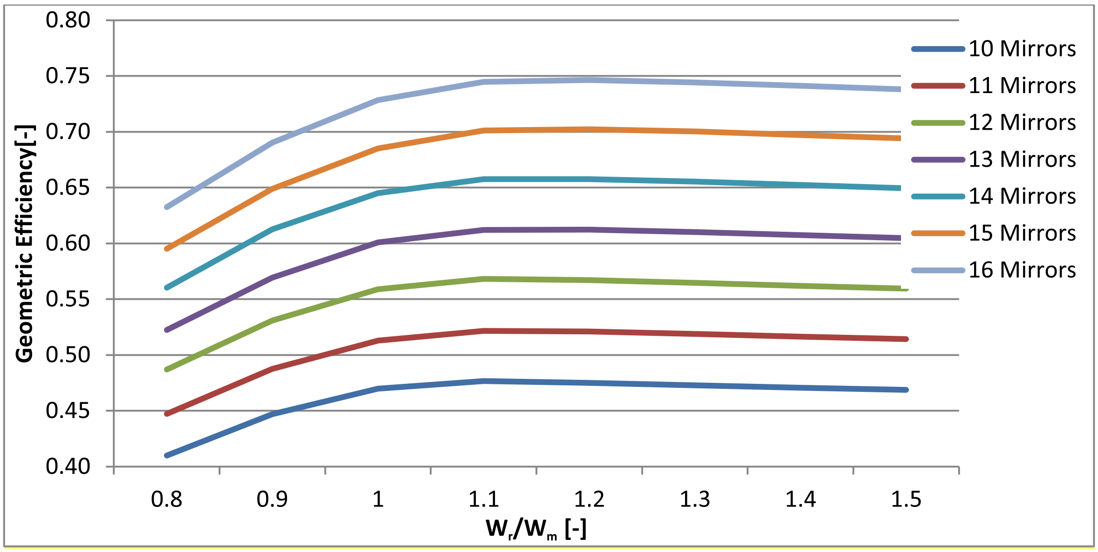

Figure 3: Relation between receiver width and mirror width.

This increase in the efficiency with the receiver height is even more difficult to observe for curved mirrors, as shown in Figure 4. This figure is for the specific case of a collector with 10-mirror rows, each mirror with a length of 450mm each, curved, with an average focus of 1.1 times the absorber height, and using the maximum spacing between mirrors. Other cases were studied and presented similar results.

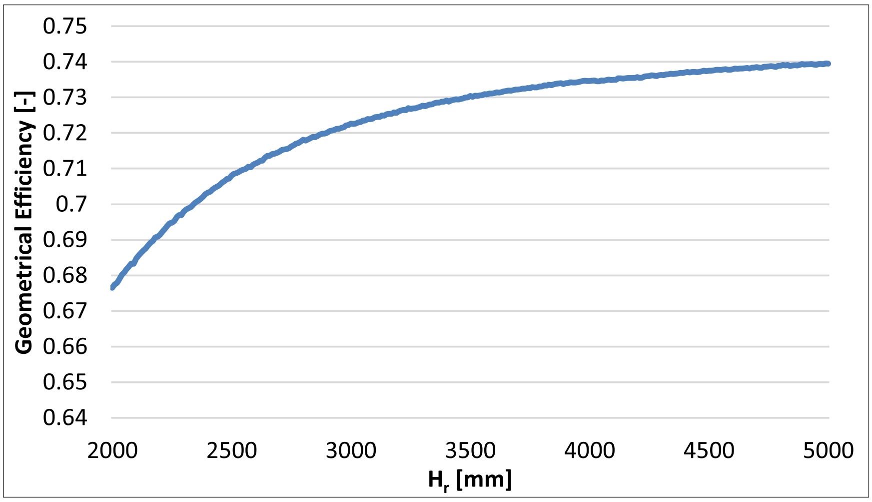

Figure 4: Influence of the receiver height on the geometric efficiency.

The relation between the number of mirror rows and different mirror sizes in the form of a filling factor was analyzed. Figure 5 shows the results for plane mirrors and $W_r = 1.1 * W_m$ using the largest possible spacing and a receiver height of 3500mm. The same analysis was performed for curved mirrors for different focus distances; however, by analyzing these results the conclusions were the same as in the case of flat mirrors.

The filling factor defines a relation between the number of mirror lines and the mirror width, as defined in equation 2. Thus, obtaining the curves for different numbers of mirror lines, varying the filling factor is sufficient to characterize the collector geometry.

As expected, the larger the filling factor the better the efficiency will be and the same is true for a greater number of lines. However, despite the higher efficiency, these cases are not always practical or economically feasible since a greater number of lines requires more components like tracking devices, axes, mirrors and control devices.

Another important observation in relation to Figure 5 is that for low filling factors the efficiency rises considerably with the filling factor, and for filling factors close to unity the increase in the efficiency is not as great. This analysis shows that one can operate with filling factors between 0.9 and 0.95 with an efficiency only 3% lower than the maximum efficiency. This allows some flexibility to deal with costs and building issues associated with the project.

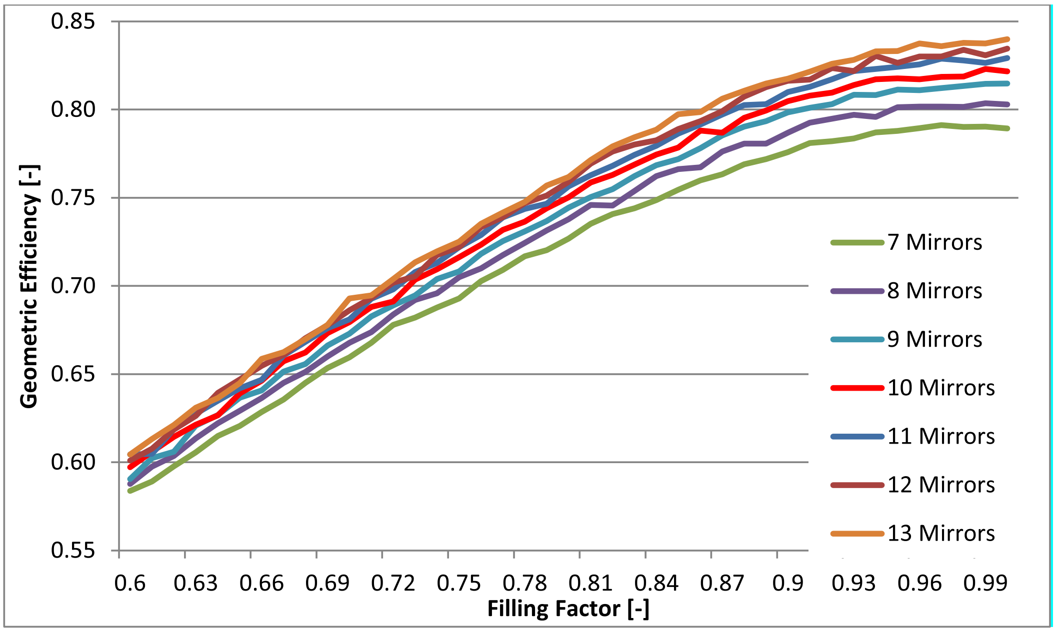

Figure 5: Influence of filling factor and number of mirror lines on efficiency.

The influence of the mirror curvature on the concentrated radiation which is focused on the absorber aperture was analyzed. The distribution of the concentrated radiation over the absorber aperture throughout the day, for different focal lengths, is shown in the Figures 6, 7 and 8. The focal length reported herein is the mean distance between the mirrors and the middle of the absorber aperture area. These figures relate to a collector with 10 mirror rows of 450mm, the absorber height is 3000mm and the maximum spacing between mirrors is applied. Three focal lengths were analyzed: 1.0, 1.1 and 1.2 times the receiver height.

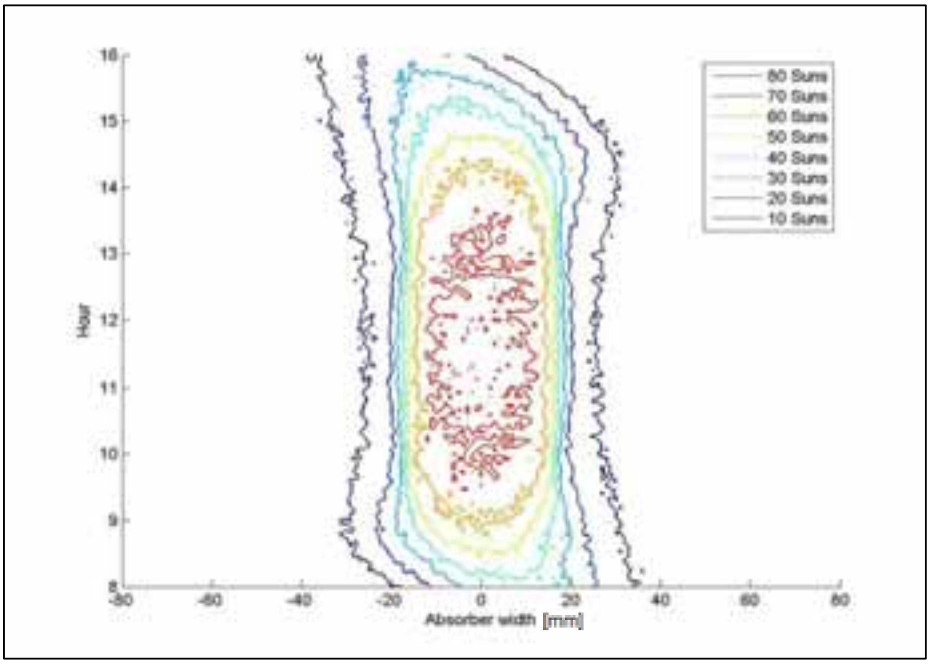

Figure 6: Profile of the concentrated radiation for a focal length 1.0 times the receiver height.

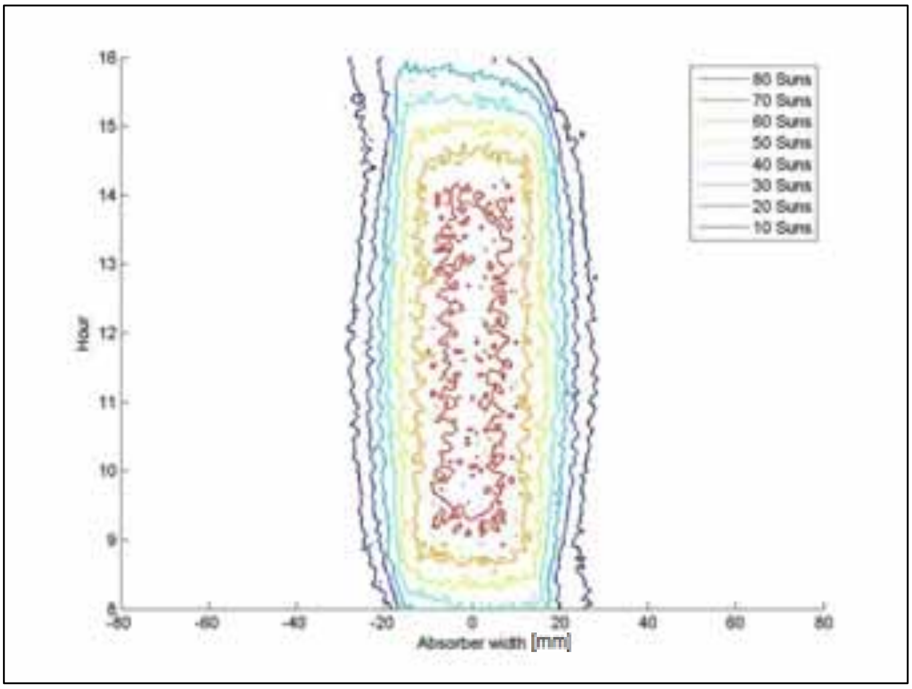

Figure 7: Profile of the concentrated radiation for focal length 1.1 times the receiver height.

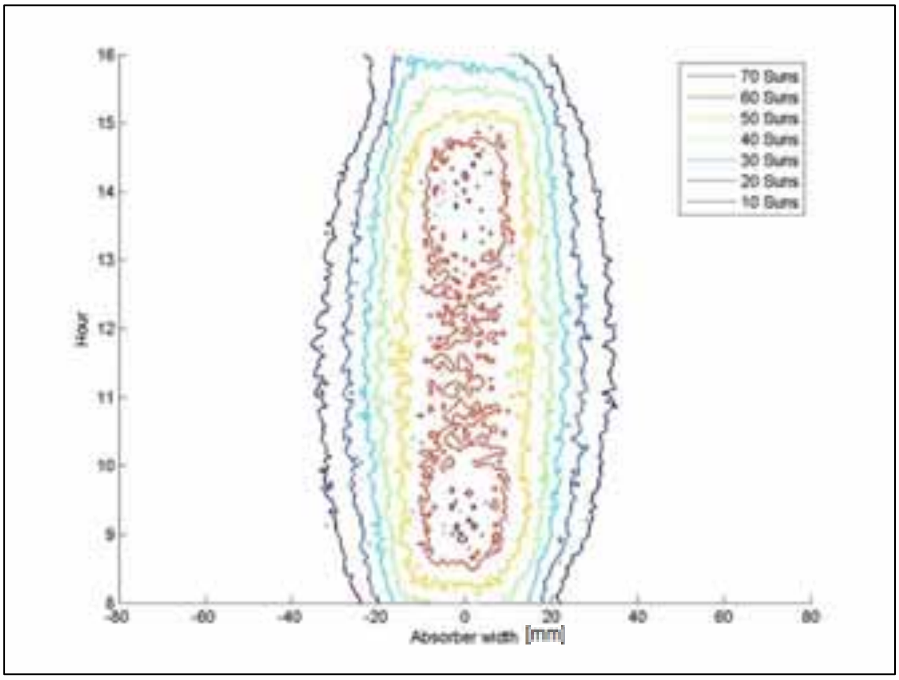

Figure 8: Profile of the concentrated radiation for focal length 1.2 times the receiver height.

It can be seen that for a focal length 1.0 times the receiver height the profile for the concentrated radiation on the absorber aperture area is more homogeneous during the day. This is of interest, since the collector operation will be steadier during the main solar hours of the day. These concentrated radiation profiles favor the use of a set of tubes in the absorber assembly, because this configuration provides good operational flexibility. Muñoz-Anton et al. 2014 demonstrated that in this configuration, for a set of four tubes in a DSG operation, one can set the flow to pass first through the outermost tubes to allow preheating and then through the inner tubes for the phase change. Other numbers of tubes and flow configurations can be used in order to obtain better use of the concentrated profile. The higher the number of tubes for the same flow the lower the diameters can be and, therefore, the heat exchange coefficient will be improved. However, lower diameters also lead to higher pressure losses (Abas et al., 2013).

Focal lengths of shorter than 1.0 and greater than 1.2 times the receiver height were also studied, but they produced a much more disperse profile than those shown in Figures 6, 7 and 8.

5. Model Validation

This model was validated using the SolTrace software, available from the National Renewable Energy Laboratories. The reliability of SolTrace has been validated via several experimental studies. However, this software does not allow the plant parameters to be changed automatically according to the time of day, making it difficult to generate an optimization routine.

To validate the model, several Fresnel configurations were simulated under the same radiation conditions using both software programs. The results obtained with the model developed in this study were very close to those provided by SolTrace.

A commercial collector FRESDEMO was then modeled, considering curved mirrors, and the results compared with data available in the literature.

Initially, a collector configuration was implemented in SolTrace and compared with the Matlab results for an entire day, as shown in Figure 9. The validation was carried out in both the transversal and longitudinal directions. The longitudinal direction represents the end losses.

For all cases the collector was oriented along the north-south axis and it tracked the sun in the east-west direction during the day. The maximum difference in the values for the concentrated radiation heat flux obtained using the model developed in this study and SolTrace was 1.1%. Considering the end losses (the longitudinal case) this maximum difference was 18.5%. This large difference is observed for high incidence angles which will almost never occur in real applications.

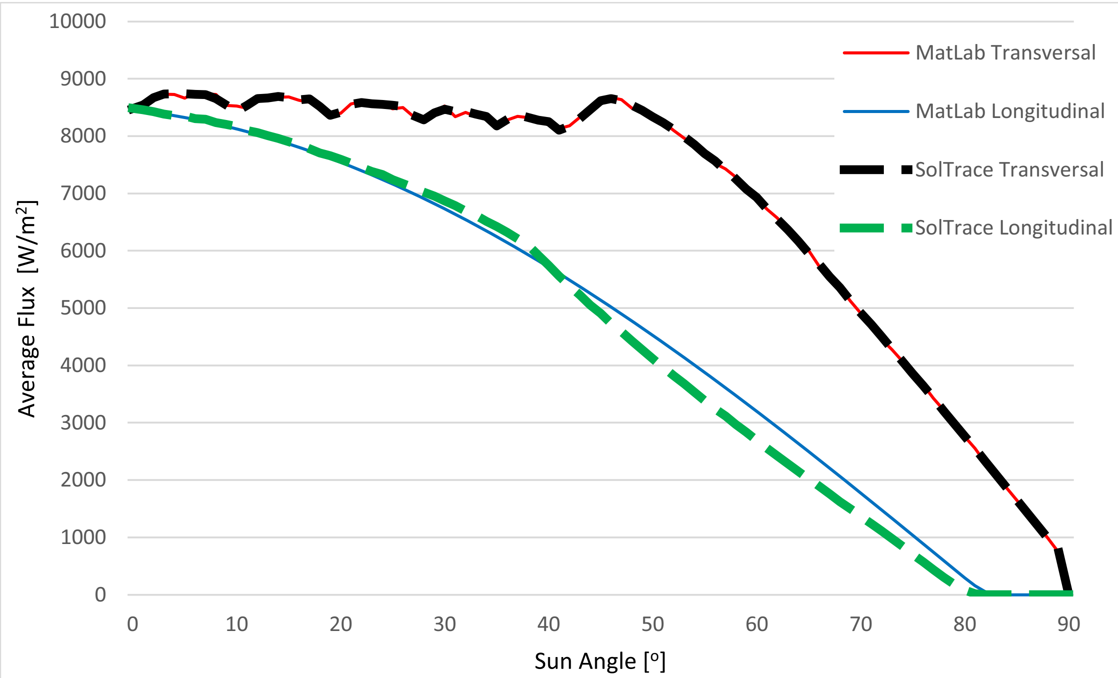

Figure 9: Comparison between the model and SolTrace results.

Figures 10 and 11 show a comparison between the results for the concentrated radiation in the absorber aperture plane for the FRESDEMO collector obtained by Abbas et al. (2013) and with the model presented herein. The focal length used by Abbas et al. (2013) was not reported and thus the focal length used in the model was 1.1 times the mean distance between the mirrors and the absorber. Our model showed good agreement with the radiation profile presented by Abbas et al. (2013). This simulation was carried out using the collector parameters reported by Abbas et al. (2013).

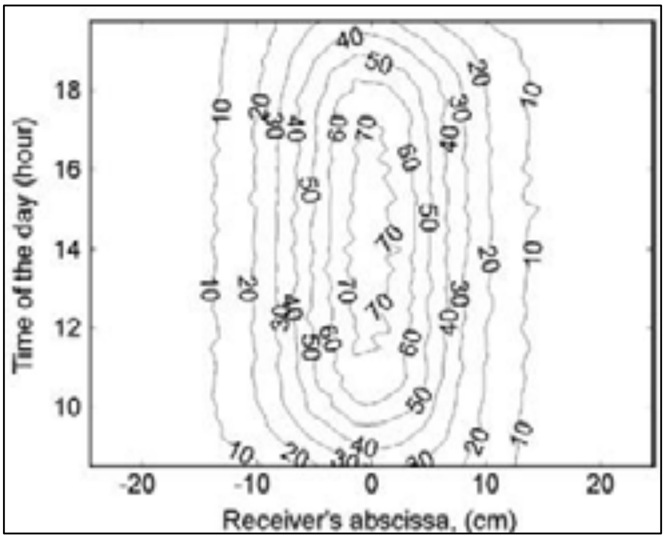

Figure 10: FRESDEMO concentrated radiation profile for the receiver (source Abbas et al., 2013).

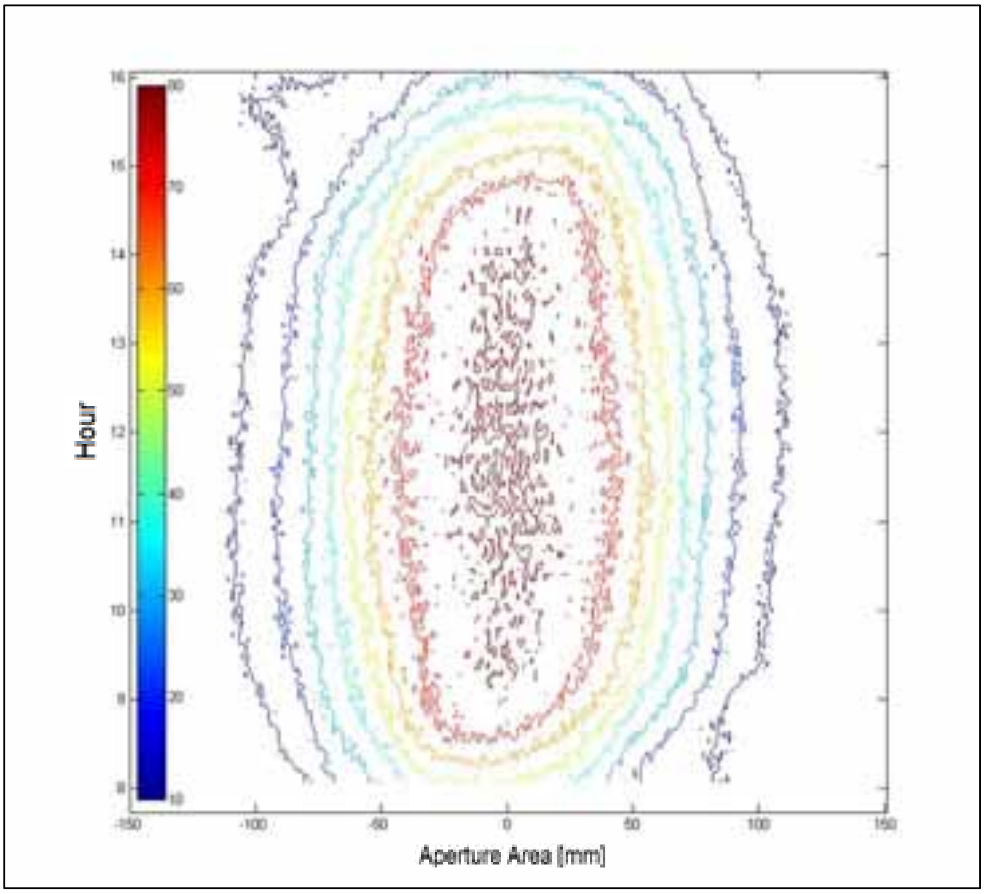

Figure 11: Concentrated radiation profile for the receiver obtained with our model.

6. Conclusions

The model described herein showed good agreement with SolTrace. With this new model it was possible to simulate several aspects of the collector geometry, to make comparisons and to achieve the best configuration for the proposed application. To simplify the work, sensitivity analysis was initially carried out and it was found that some variables do not have a strong relation with others. These variables were then maintained fixed in the subsequent optimization analysis.

An important conclusion is that the mirror row spacing should be the maximum allowed respecting the total collector width, in order to achieve the best geometric efficiency. The receiver height was also analyzed and 3.5m was selected as an appropriate value in terms of efficiency and operational aspects. For this receiver height and using flat mirrors the best value for the receiver width to mirror width ratio was 1.1.

Considering the constraints identified using the model developed it was possible to evaluate the influence of the geometric configuration of the Fresnel on its efficiency. This study allowed the final configuration of the workbench to be installed in the laboratory to be defined, that is, 10 rows of mirrors with a width of 450mm, with the absorbing assemble placed at a height of 3m. The absorber assembly adopted is the trapezoidal cavity, using a set of four parallel absorber tubes. The trapezoidal cavity was selected due to its technical and constructive advantages and the multitube absorber provides some flexibility in relation to the operational strategies.

The total width of the four tubes is 140mm. The reflective mirrors have a slight curvature which allows the absorber element width to be smaller than that of the mirrors. This bending increases the rate of concentration in the central area of the absorber element, as shown in Figures 6, 7 and 8.

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