GEOMETRIC DESIGN AND OPTIMIZATION OF A LINEAR FRESNEL SOLAR COLLECTOR

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Abstract. *The linear Fresnel solar concentration technology differs from others solar concentration technologies existent in the market for its low costs and greater simplicity of manufacture. However, this technology is relatively new and more studies in this subject must be carried out. Following this line of thought, the LEPTEN laboratories is studying the implementation of a linear Fresnel solar collector on the roof of one of its facilities. In order to get the most promising configuration for the collector, taking into account physical and technical constraints of the laboratory, a series of algorithms were developed to optimize its parameters. These algorithms simultaneously vary parameters such as the number of mirrors, mirror spacing, mirror width, absorber element height and the aperture. The model developed obtains the best configuration for the collector varying the position of the sun over a day. This model was validated using the software SOLTRACE, from the National Renewable Energy Laboratory (NREL), and has the advantage that it allows a quick and automatic change in the parameter in order to reach the optimum configuration.*

Keywords: *Linear Fresnel, Renewable Energy, Solar Energy, Monte Carlo Ray Tracing, Solar Concentrators*

1. INTRODUCTION

Actual concerns related to environmental impacts caused by fossil fuel burning, increasing energy demand and the need for diversification of the brazilian energy matrix is highlighting the importance of renewable energy generation. In this context solar energy is getting attention due its great potential. It is been predicted that solar energy generation will be larger than fossil fuel generation in next decades. Therefore, researches are taking place to increase solar systems efficiency, cost reduction and technical viability.

Solar to electric energy conversion can be made by two distinct technologies: photovoltaic and thermosolar. Thermosolar generating systems uses concentrating collectors. These collectors use mirrors or lens to focus the sunbeams into the absorber element, which in turn transfers this energy to a working fluid rising its enthalpy (Duffie & Beckman, 2006).

Linear Fresnel Solar Concentrators is one of the concentrating collectors type and is the object of analysis of this paper. Several lines of flat or near-flat mirrors rotates tracking the sun along the day in one axis, each on its own axis of rotation, to reflect the sun's radiation to the receiver, (Abbas et al, 2013). The receiver is positioned above and parallel to the mirrors. The radiation is concentrated in a linear.

The absorber element of the receiver can be made of one or a bundle of tubes. The absorber is located inside a cavity insulated on its aperture by a high transmissivity glass window, which allows the radiation to get in and avoid heat losses, due to the greenhouse effect. Some receivers works with secondary reflectors (Zhu et al., 2013). The choice of the type of receiver is based upon the collector's objectives like maximum working temperature, pressure, radiation concentration ratio, costs and others variables (Flores Larsen et al. 2012).

The main advantage of linear Fresnel concentrators is its cost reduction potential compared to others CSP technologies, such as parabolic troughs. This cost reduction is mainly due to the possibility of simplify and automatize its manufacture. Linear Fresnel concentrators are becoming a preferred option for small-scale steam generation plants for industrial process heat.

In this project, two of the most relevant research fields of the LEPTEN laboratories are present: boiling and solar energy. The main objective is to study the direct steam generation in a linear Fresnel concentrator which is being implemented in one of the laboratories facilities.

The present work focuses on the development of the collectors designing tools to achieve its best optical and geometrical efficiencies restrained by physical and cost limitations. For this purpose, a Monte Carlo Ray Tracing (MCRT) routine was developed in Matlab to simulate and evaluate several collectors configurations.

2. MONTE CARLO RAY TRACING MODEL

The MCRT routine implemented in Matlab works by first defining the energetic weight of each ray, its position and direction using probabilistic functions. For each ray, its interaction with the collector parts is analyzed, respecting its properties of reflection, absorption and transmission (Delatorre et al, 2014). This method uses geometrical relations and optical properties to obtain optical and geometrical efficiencies of the collector (Zhu, 2013). In this paper the geometrical efficiency is analyzed. In the collector total efficiency there are still other effects like thermal losses to be included which are not described here.

The receiver was simplified in this study, being considered as only a plate, representing its aperture area plane. This simplification does not represent the real absorber but it provides the radiation concentration distribution in the aperture plane, which is useful for later thermal evaluations (Facão and Oliveira, 2011). To determine the geometric efficiency this approximation provides good results with great simplicity.

The simulation model was validated with the software SOLTRACE of the NREL (National Renewable Energy Laboratories). SOLTRACE is a top rated software for this purpose and it was validated with several experimental works. SOLTRACE, however, is not an optimization tool and is not suitable for analyzing several conditions.

The important variables in this optimization procedure is the several dimensions of the collector represented in figure 1. W_r is the width of the receiver, Wm is the width of each mirror, W_{col} the width of the collector h_r is the receiver height, C_m is the spacing between adjacent mirror lines e n is the number of mirror lines.

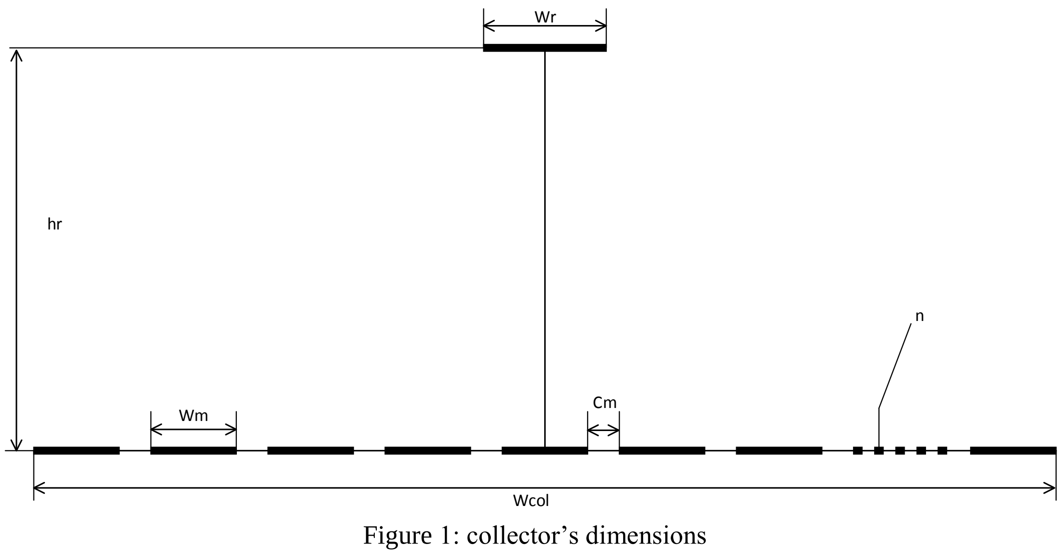

Figure 1: collector’s dimensions

To begin with the optimization some physical constraints must be known. As the collector will be built in the roof of the lab’s facilities the first constraint is the collector's total width and length. The total available width is 6m, so the collector was limited in 5m wide (W_{col} = 5m). The length of the collector was limited in the same way by 12m. For safety and operational reasons the receiver's height was limited to a maximum of 4m. Respecting the collector's width and the maximum receiver's height the other variables can be changed in order to analyze its behavior.

The geometric efficiency is defined as the ratio between the amount of rays that impinges in the receiver’s aperture width and the rays reaching the entire collector’s width.

3. SENSITIVITY ANALYSIS

It was observed in the first simulations that some of the variables could be kept constant without great influence in the final geometric efficiency. First it was analyzed the influence that the mirrors line spacing has on the efficiency. For this analysis the mirror width was fixed in 300 mm, the receiver height in 3500 mm and the receiver width was defined as $1.1*W_m$. The number of mirrors was varied between 11 and 16 and the spacing between mirror lines was varied from zero to the maximum allowed in the collector's width. Figure 2 shows the results obtained. For most numbers of mirrors analyzed the maximum efficiency is reached with the largest mirror spacing possible. Only in the casa of 10 lines of mirrors there is a maximum in the curve which it is not at the maximum spacing. However, in this case, the filling factor, equation 1, is too low and so is the power output for the collector purpose. The filling factor is a relation between the mirror field area and the total collector's area.

$$ff = W_m * n / W_{col} \tag{1}$$

It can be concluded that for all the cases that will be analyzed the maximum spacing between mirror lines will give the best results.

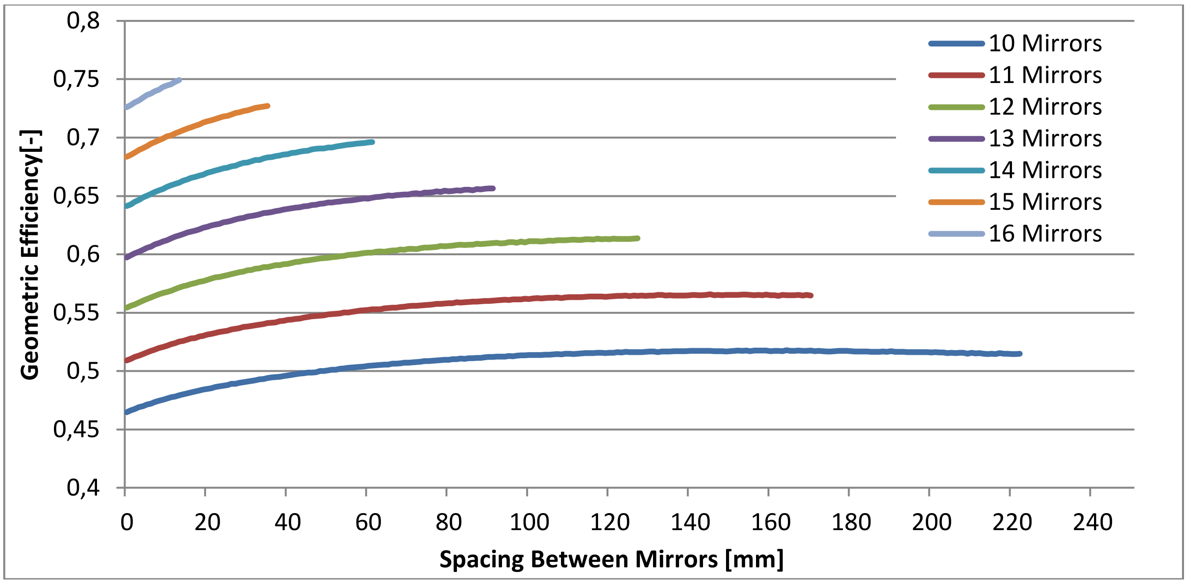

Figure 2: influence of number of mirror lines and spacing in the geometric efficiency

The next step was to check the receiver to mirror width ratio influence in the efficiency. The results are shown in figure 3. As the receiver width increase the efficiency increases because it can intercept more rays reflected from the mirrors. However the large the receiver gets the large is the shadow it makes in the mirror field. For that reason the curve reaches a maximum at approximately $W_r=1.1*W_m$. In this analysis the receiver height is fixed in 3.5m and the largest spacing is used. The same analysis was made for different mirror width and for all cases the same result was achieved. So the relation $W_r=1.1*W_m$ was maintained constant in all the other analysis.

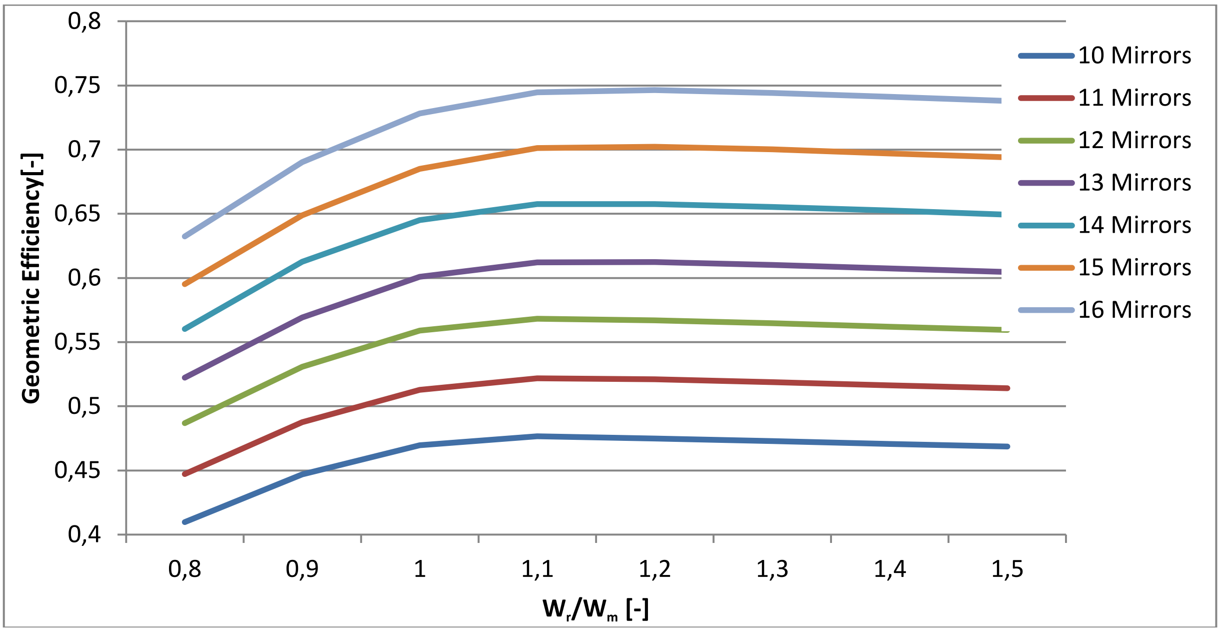

Figure 3: Relation between collector and mirror width

The receiver height influence on the geometric efficiency was analyzed by fixing the mirror width in 300mm and using the largest possible spacing between rows. Figure 4 shows the results obtained. This graph shows that increasing the receiver height increases the efficiency. As the mirror width was fixed the filling factor rises as the number of row rises, so in these results one should compare only the influence of the receiver height for same number of rows. It can be concluded that the receiver height has a very little relation with the other variables.

I was observed that as the receiver gets higher so does the efficiency. This is due to the fact that this analysis is two dimensional. This means that this geometrical efficiency obtained is in fact a transversal geometric efficiency. In a three dimensional case, taking into account the collector's length, there is another type of losses called end losses. The actual literature separates these two effects like it is done in this paper. A real scale Fresnel collector must be long enough so that these end losses are minimal. Because the analyzed collector is short, 12 m long, these losses are big when the sun is low in the sky, like in the winter. The collector is a prototype, so it will have a system to move the receiver to minimize these losses, being possible to have more realistic results along the year.

In figure 4, one can notice that for receiver height larger than 3500mm the increase in the efficiency are minimal, especially for lowest number of lines. For practical and safety reasons the receiver height was then determined as 3500mm.

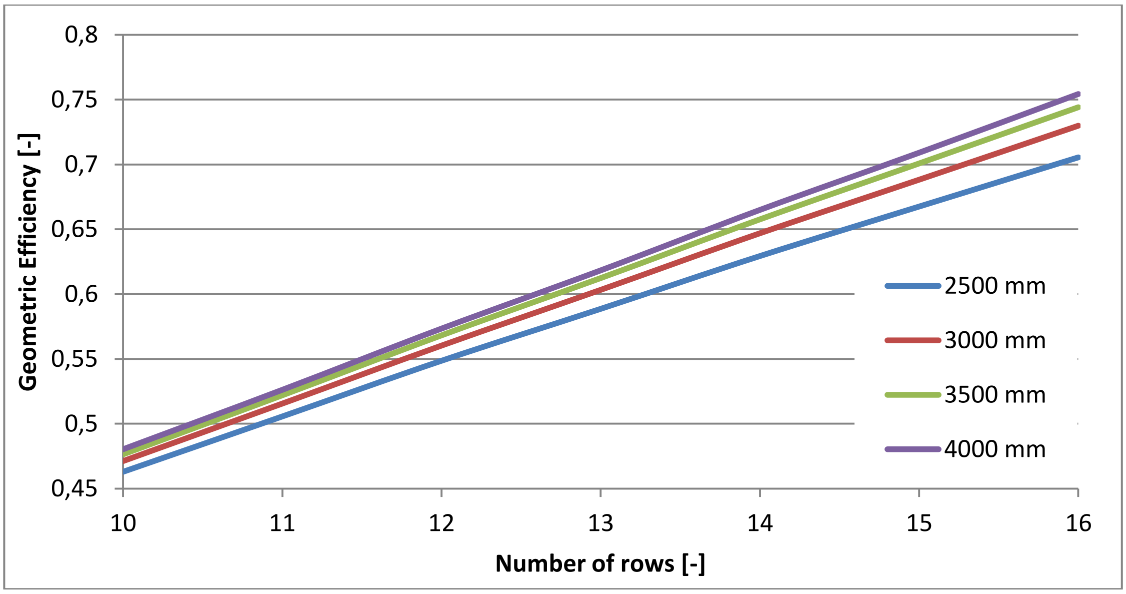

Figure 4: Receiver height influence on the geometric efficiency

The last analysis was made evaluating the relation between the number of lines and the mirror's width, using the largest possible spacing, receiver height of 3500mm and the relation $W_r=1.1*W_m$. The filling factor defines a relation between the number of mirror lines and mirror width, as it was defined in equation 1. So making curves for different numbers of mirrors lines, varying the filling factor is enough to characterize the collector geometry. Figure 5 shows the results obtained.

As expected the large the filling factor the large is the efficiency. The same happens for larger number of lines. Although the higher efficiency, these cases are not always practical or economically feasible. Large number of lines means large number of components like tracking devices, axis, mirrors and control devices.

Other important observation in figure 5 is that, for low filling factors the efficiency rises fast as the filling factor rises, and for filling factors close to unity the increase in efficiency rises slower. This analysis shows that one can operate with filling factor between 0.9 and 0.95 with efficiency only 3% lower than the maximum efficiency. This gives some flexibility to deal with costs and building issues in the project.

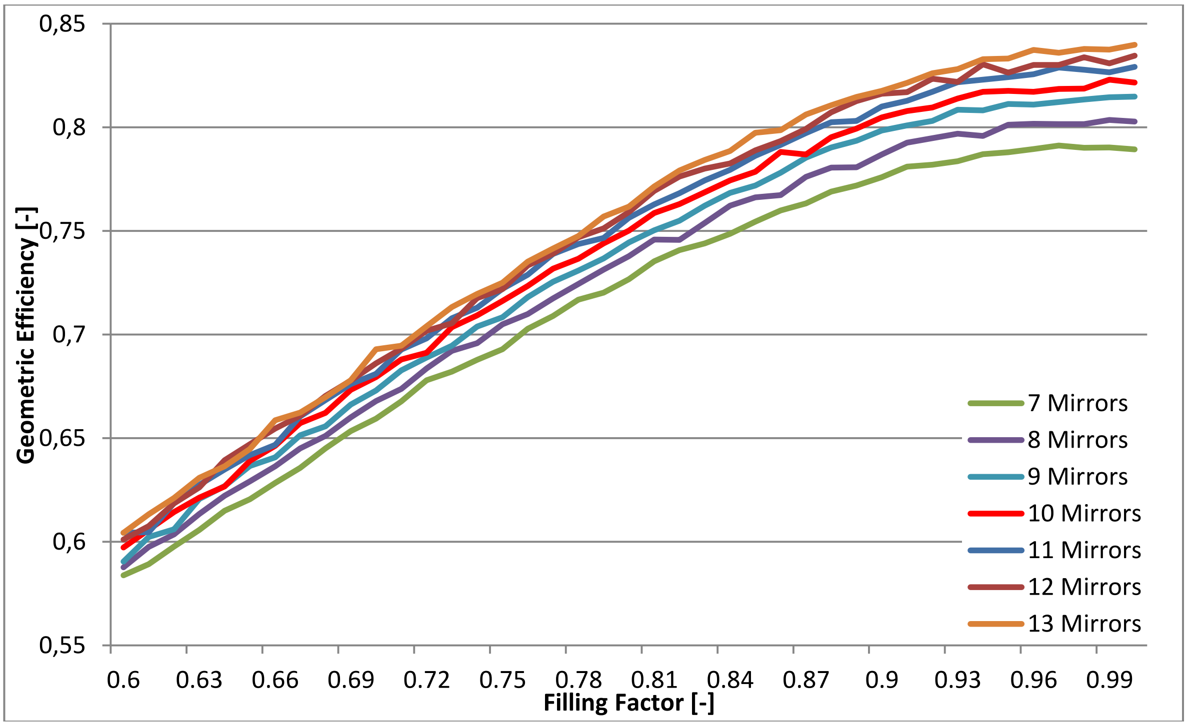

Figure 5: Filling factor and number of mirror lines influence on efficiency

4. MODEL VALIDATION

The model in Matlab was validated using the SOLTRACE software. Some of the collector's configurations were implemented in SOLTRACE and compared with the Matlab results for an entire day. Figure 6 shows these comparisons. These validations were made in both transversal and longitudinal directions. The longitudinal direction represents the end losses.

For all cases the collector is oriented in the north-south axis and tracks the sun in the east-west direction along the day. The maximum difference of the concentrated radiation heat flux obtained by the developed model 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 angle which will almost never happen in the real application.

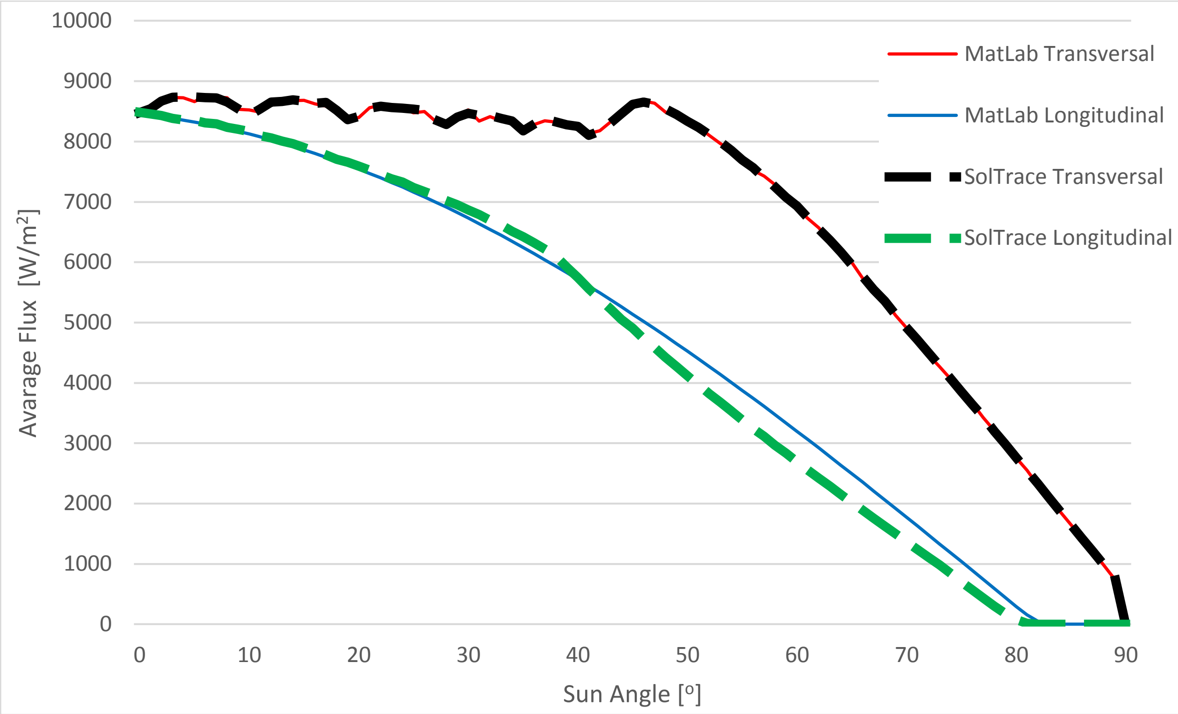

Figure 6: Model validation

5. RESULTS

The developed model showed good agreement with SOLTRACE. With this model, it was possible to simulate several collectors geometry, make comparisons and achieve the best configuration for some application. To simplify, a sensitivity analysis was made first and it showed that some variables does not have a strong relation with the others. These variables were then maintained fixed in the other optimization analysis.

One important conclusion is that the mirror row spacing should be the maximum allowed inside the collector's total width to achieve the best geometric efficiency. The receiver height was also analyzed and a value of 3.5m was selected as a good value for good efficiency and operational issues. The best relation achieved for the receiver to mirror width ratio was 1.1.

With the above parameters fixed the number of mirror rows and mirror width was analyzed by varying the filling factor. It was shown that for filling factors large than 0.9 the increase in the efficiency is small.

All the obtained results give a great overview to make the decisions regarding costs and efficiency.

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6. REFERENCES

Abbas, R., Muñoz-Antón, J., Valdés, M., Martínez-Val, J.M., 2013. High concentration linear Fresnel reflectors. Energy Conversion and Management. 72, 60-68.

Cheng, Z.D., He, Y.L., Cui, F.Q., Du, B.C., Zheng, Z.J., Xu, Y., 2014. "Comparative and sensitive analysis for parabolic trough solar collectors with a detailed Monte Carlo ray-tracing optical model". In Applied Energy 115 (2014) 559–572

CHEN, J. C. Physics of Solar Energy. Hoboken: John Wiley & Sons, Inc, 2011.

Delatorre, J., Baud, G., Bézian, J.J., Blanco, S., Calior, C., Cornet, J.F., Coustet, C., Dauchet, J., El Hafi, M., Eymet, V., Fournier, R., Gautrais, J., Gourmel, O., Joseph, D., Meilhac, N., Pajor, A., Paulin, M., Perez, P., Piaud, B., Roger, M., Rolland, J., Veynandt, F., Weitz, S., 2014. Monte Carlo advances and concentrated solar applications. Solar Energy 103, 653 – 681.

Duffie, J. A., Beckman, W. A., 2006. Solar Engineering of Thermal Processes. John Wiley & Sons, Inc. 3rd ed.

Facão, G., Oliveira, A. C., 2011. Numerical simulation of a trapezoidal cavity receiver for a linear Fresnel solar collector concentrator. Renewable Energy 36, 90-96.

Flores Larsen, S., Altamirano, M., Hernández, A., 2012. Heat loss of a trapezoidal cavity absorber for a linear Fresnel reflecting solar concentrator. Renewable Energy. 39, 198-206.

NREL. National Renewable Energy Laboratory. Information on the United States government agency NREL. Avaliable in: < http://www.nrel.gov>. Acessed in: 11 march 2015.

Zhu, G., 2013. Development of an analytical optical method for linear Fresnel collectors. Solar Energy 94, 240-252.

Zhu, G., Wendelin, T., Wagner, M. J., Kuntscher, C., 2013. History, current state, and future of linear Fresnel concentrating solar collectors. Solar Energy.

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