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HELIOSTAT FIELD SIMULATION IN A SOLAR TOWER POWER PLANT

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Abstract. *The Solar tower power plants are one of Concentrating Solar Power (CSP) systems, formed by large heliostat fields, which concentrate the solar direct normal irradiance (DNI) into a receiver located in a tower. The design and characteristics of these mirrors and the tower are directly related to the plant performance. Therefore it is convenient to develop mathematical models to simulate these systems behavior and their possible energy loss mechanisms. In this work a numerical algorithm based on 2D polygon clipping techniques is developed that is valid for heliostats and towers with arbitrary position, orientation and size. In order to show the performance and feasibility of a solar power plant, this program maps the heliostat field and computes blocking, shadowing, according to the sun position. By using the 2D clipping method, the algorithm provides a graphical output of the heliostat reflecting area, enabling the user to follow the losses by blocking and shadowing interactively. In this paper, it is made an analysis for a heliostat located at a latitude 40.08º at 12h and 15h 15min of 21st of January, on which were calculated an efficiency of 0.764 and 0.362, respectively. These results were compared with other theoretical work and presented small discrepancies with them. In this way, the algorithm shows to be feasible for a heliostat field simulation.*

Keywords: *concentrating solar power, solar tower plant, 2D clipping*

1. INTRODUCTION

In the last decades due to recurrent oil price crises and emerging global environmental problems, countries around the world are increasingly investing in clean renewable energy sources. In this context, solar energy plays an important role in replacing fossil fuels. Currently, the use of photovoltaic panels for domestic use is already a reality and there are large plants that show the feasibility of Concentrating Solar Power for the large-scale electricity production.

Concentrating solar power (CSP) is an electricity generation technology that uses heat provided by solar irradiation concentrated on a small area. Using mirrors, solar energy is reflected to a receiver where heat is collected by a thermal energy carrier and subsequently used to power a turbine and generate electrical energy. CSP systems are particularly promising in regions with high DNI (Zhang *et al*., 2013). DNI is an essential component of global irradiance and represents the amount of irradiation received from the sun without having been scattered by the atmosphere (Duffie and Beckham, 2013) and focused on a plane normal to the sunlight direction (Blanc *et al*., 2014).

Among the CSP technologies, solar tower systems have a prominent place to present the plants with the highest installed capacity. The Central Receiver System (CRS) or Solar Tower Plant (STP) is a concentrating solar power application that produces electrical power using an extremely high flux – concentrations on the order of one-thousand the middle irradiation per unit area on the earth surface – on a relatively small receiver. A Heat Transfer Fluid (HTF) is used to absorb thermal energy from the receiver and can be used to generate electricity through traditional thermodynamic cycles like Rankine or Brayton (Wagner, 2008).

One of the main challenges in converting solar energy into electricity is to design an optimized power plant project. At these stations, the irradiation collector subsystems (heliostats and receivers) represent a very important part of the structure costs and play a key role in the energy efficiency of the entire system. Numerically, the heliostat field, the main focus of this study, typically contributes about 50% to the total cost of the plant and results in power losses of 40% (Collado and Guallar, 2012). Therefore, the use of efficient computational programs is of great interest to optimize the plant design.

In this work, the techniques of 2D clipping are used to discretize the heliostat field of a solar tower power plant and, in this way, to calculate the loss mechanisms by blocking and shading of this system. According to Wagner (2008), blocking occurs when the reflected image from a heliostat is obstructed from reaching the receiver by an adjacent heliostat, and shading occurs when one or more heliostats in the field is partially obscured from incoming solar irradiation by a neighboring heliostat.

Unlike conventional algorithms, which use equations to calculate analytically each heliostat optical efficiency, this algorithm simulates what happens in real time in each mirror and shows graphically the area that reflects the sunlight to the receiver, using strategies of image processing, which are already widely used in other areas, such as video games (Ramos and Ramos, 2014).

Thus, the algorithm stands out from conventional methods, because it is valid to estimate the efficiency of a field at any point on the Earth's surface (chosen by the user) and for heliostats of arbitrary size, position and orientation. In addition, it provides a graphical output of the reflected surface area, which enables a more realistic view of the loss mechanisms.

2. COMPUTATIONAL PROCEDURE

The algorithm described in this work was developed in MATLAB and uses some functions of this platform in order to calculate some processes described in the literature.

2.1 Relative position of the sun

In all solar energy systems, the basic resource is the Sun. Therefore, to begin the plant efficiency calculations it is necessary to know the relative position of the Sun for each day and time. Conventionally, two angles are used to define the apparent movement of the sun relative to the earth's surface: solar height (α) and azimuth angle (γ). The solar height is defined as the angle between the horizontal plane and the imaginary line that join the Sun to the point where is the observer and the azimuth is the angle of the horizontal plane measured clockwise from the North to the projection in the horizontal plane of the center of the Sun axis (Eustáquio, 2011). The values of these angles are functions of the observer's position on the earth's surface, according to its respective latitude and longitude and also the day and time. The equations for describing the solar height and azimuth angles used in the code were taken from Stine and Geyer (2001) and Duffie and Beckham (2013).

To obtain the solar height and azimuth angles, the program calculates other parameters through the day and time values. First, the Eq. (1) calculates the Declination, i.e., the angular position of the sun at noon with respect to the equatorial plane.

$$\delta = 23.45 \sin\left(360 \cdot \frac{284 + n}{365}\right) \tag{1}$$

Where n is the day of year.

The Equation (2) calculates the hour angle (ω), which is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15º per hour:

$$\omega = 15\left[(h - 12) + (m/60)\right] \tag{2}$$

Where h is the current hour and m is the current minute. After calculating these two angles and knowing the latitude value (ϕ), it is possible to calculate the solar height by Eq. (3) and the azimuth by Eq. (5). The Eq. (4) refers to the zenith angle, that is, the complement of the solar height.

$$\sin\alpha = \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega \tag{3}$$

$$\theta_z = 90 - \alpha \tag{4}$$

$$\gamma = sign(\omega)\left|\arccos\left(\frac{\cos\theta_z \sin\phi - \sin\delta}{\sin\theta_z \cos\phi}\right)\right| \tag{5}$$

2.2 Coordinate systems

In the analysis made by the algorithm are used two different coordinate systems. One is the local coordinate system of the plant, which has the tower base as the origin with the positive X axis pointing to the north, the positive Y axis pointing to the West and the Z axis being the height. In this reference system ($S = XYZ$) the sunlight direction is given by the unit vector from Eq. (6):

$$\overrightarrow{u_s} = \left[-\cos\alpha\cos\gamma,\ \cos\alpha\sin\gamma,\ \sin\alpha\right] \quad (6)$$

Besides the sunlight direction vector, was defined the vector $\overrightarrow{u_t}$ as the unit vector that points from the heliostat to the receiver. This vector was obtained by the difference between the tower position vector ($\vec{T}$) and the position vector of the center of the heliostat ($\vec{C}$), divided by the module of the same difference, as follows Eq. (7). Thus, the normal heliostat vector that defines the Z axis of the reference system is given by the difference between the vector $\overrightarrow{u_t}$ and the solar position vector - Eq. (8):

$$\overrightarrow{u_t} = \frac{\vec{T}-\vec{C}}{\left|\vec{T}-\vec{C}\right|} \quad (7)$$

$$\vec{n} = \overrightarrow{u_t} - \overrightarrow{u_s} \quad (8)$$

The second is the heliostat reference system, denoted by *S' = X'Y'Z'*, which has the origin in the center of the heliostat and the *Z'* axis being normal to the mirror surface. To perform the change between coordinate systems, the algorithm uses geometric transformations described in Ramos and Ramos (2014). First, a rotation matrix is defined using the Euler angles in the *ZXZ* convention – Eq. (9). Then, the matrix is conditioned to the values of the normal vector and the heliostat slope (β) – Eq. (10).

$$R(\alpha,\beta,\gamma) = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (9)$$

$$R(\vec{n},\beta_h) = R\left(\arctan\left(\frac{n_1}{-n_2}\right),\ \arctan\left(\frac{\sqrt{n_1^2+n_2^2}}{n_3}\right),\ \beta_h\right) \quad (10)$$

The transformation from the local coordinate system to the heliostat coordinate system and its inverse transformation are described by Eqs. (11) and (12), respectively:

$$\begin{aligned} &T_h : S \rightarrow S' \\ &\overrightarrow{x'} = T_h(\vec{x}) = R(\vec{n},\beta_h)\left(\vec{x}-\vec{P}\right) \end{aligned} \quad (11)$$

$$\begin{aligned} &T_h^{-1} : S' \rightarrow S \\ &\vec{x} = T_h^{-1}\left(\overrightarrow{x'}\right) = R^T(\vec{n},\beta_h)\,\overrightarrow{x'} + \vec{P} \end{aligned} \quad (12)$$

The heliostat slope is the angle between the heliostat plane and the XY plane. It follows the sun position during the day and is a function of the solar height and the heliostat position. After obtaining the normal vector and the slope, the algorithm has all information to perform the coordinates change and then the graphical clipping to calculate the loss mechanisms.

2.3 2D polygon clipping

A closed polygon *P* is described by the ordered set of its vertices. It consists of all line segments consecutively connecting the points (Greiner and Hormann, 1998). In this work, the polygons are represented by giving the number of corners of the heliostat, and calligraphic letters are used to identify them. For the particular case of a rectangular heliostat with dimensions L_x x L_y, the coordinates of the corners in the coordinate system *S'* are described by Eq. (13):

$$\begin{aligned}\vec{P}'^{1} &= \left[-L_x/2, L_y/2, 0\right]\\ \vec{P}'^{2} &= \left[-L_x/2, -L_y/2, 0\right]\\ \vec{P}'^{3} &= \left[L_x/2, -L_y/2, 0\right]\\ \vec{P}'^{4} &= \left[L_x/2, L_y/2, 0\right]\end{aligned} \tag{13}$$

Thus, the inverse transformation from Eq. (12) can be used to obtain the coordinate of a heliostat in the S coordinate system:

$$\vec{P}^{a} = T_h^{-1}\left(\vec{P}'^{a}\right) \tag{14}$$

Where a represent the corners of a heliostat (from 1 to 4). After obtaining the corners in the S coordinate system, it is possible to perform the clipping algorithm.

The 2D polygon clipping is a computational tool that basically determines which portion of a figure covers another. In this work, an efficient 2D clipping algorithm is used to determine the blocking and shadowing efficiency of heliostats, since these loss mechanisms occur when one heliostat overlaps another. The only assumption made to use the algorithm is that the heliostat is flat and rectangular. To perform the clipping operation in the program, was performed the polygon subtraction through the function *polybool* from MATLAB.

This clipping algorithm will determine which reflecting surface fraction of each heliostat is not shaded or blocked by the tower and the other heliostats. For this, one must assume the dimensions of the heliostats and the tower. Then, the geographical position of plant and the position of each heliostat are entered. For each analysis, a heliostat will be chosen to be determined the reflecting surface fraction that is not blocked or shaded by a set of N heliostats.

2.4 Blocking and shadowing efficiency

After the input of the above data, the proposed algorithm works in three phases:

First, the vertices of each heliostat present in the field (or those heliostats that are closest to the one to be analyzed) are projected to the subject heliostat coordinate system. When this projection is doing from the sun point of view, the shadowing will be determined – Eq. (15), and when doing it from the tower point, the blocking will be determined – Eq. (16). After this first phase, 2N quadrilaterals will be formed in the subject's heliostat plane.

$$\overrightarrow{S^{a}} = \overrightarrow{P^{a}} + \left(\frac{\vec{n}\cdot\vec{C} - \vec{n}\cdot\overrightarrow{P^{a}}}{\vec{n}\cdot\overrightarrow{u_s}}\right)\overrightarrow{u_s} \tag{15}$$

$$\overrightarrow{B^{a}} = \overrightarrow{P^{a}} + \left(\frac{\vec{n}\cdot\vec{C} - \vec{n}\cdot\overrightarrow{P^{a}}}{\vec{n}\cdot\overrightarrow{u_t}}\right)\overrightarrow{u_t} \tag{16}$$

Where $\overrightarrow{S^{a}}$ are the corners of the shadowing polygon, and $\overrightarrow{B^{a}}$ are the corners of the blocking polygon.

Second, the 2D polygon clipping is performed through subtraction (set-theoretical difference) between the subject heliostat and the 2N quadrilaterals. After this stage, a polygon is obtained (in the general case of the whole field, there is a polygon for each heliostat) that represents effective reflecting surface of the heliostat.

In the last phase of the analysis, the blocking and shadowing efficiency is simply the result of the ratio between the effective reflecting surface over the total area of the heliostat. To calculate the reflecting surface polygon area has been used the function *polyarea* from MATLAB.

3. RESULTS AND DISCUSSION

As discussed in the computational procedure, this work consists in the elaboration of a algorithm that calculates optical losses by blocking and shadowing of a heliostat in a solar tower power plant. Therefore, this program has as data input the field geographical location, the day and hour in which the analysis is made, the tower height, the dimensions of the heliostats and their relative position to the tower.

In order to compare the results obtained by the program developed in this study, was selected the simple case to a subject's heliostat analysis published by Ramos and Ramos (2014). While the algorithm of this work was implemented in MATLAB, this second algorithm present in the selected literature was written in FORTRAN. For the case study, it has been considered a solar tower plant located at a latitude of 40.08º with a receiver situated at 100m of height. All heliostats have dimensions 10 m x 10 m. The blocking and shadowing efficiency has been computed of a heliostat *c* described in the local coordinate system at position:

$$c \equiv (108, 0, 5)\ m \tag{17}$$

This heliostat is surrounded by two other heliostats h_1 and h_2 described at positions:

$$h_1 \equiv (100, 8, 5)\ m \tag{18}$$

$$h_2 \equiv (100, -8, 5)\ m \tag{17}$$

Two analyzes were made for January 21, one at 12h and other at 15h 15 min. Figure 1 shows the reflecting surface area by the heliostat c at noon after the blocking and shadowing effects of heliostats h_1 and h_2 have been subtracted. This figure was obtained using the function *mapshow* from MATLAB and has its origin in the center of heliostat *c*. In this way, it describes the reflecting surface area in the heliostat coordinate system – *S'*. For this case, the algorithm calculated an efficiency in the value of 77.65%.

Figure 2 shows the result of Ramos and Ramos (2014) for this case. This second case, besides the reflecting area also shows the projection of the effects of heliostats h_1 and h_2. The efficiency obtained by this algorithm was 0.7640.

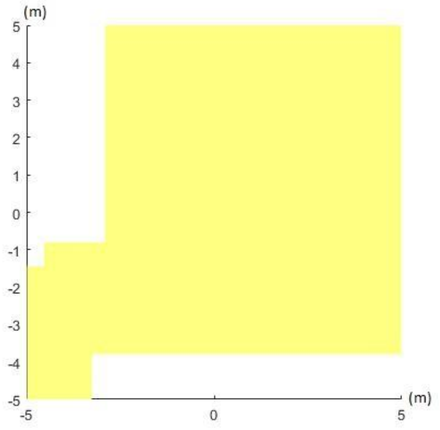

Figure 1. Reflecting surface area by heliostat *C* at 12h

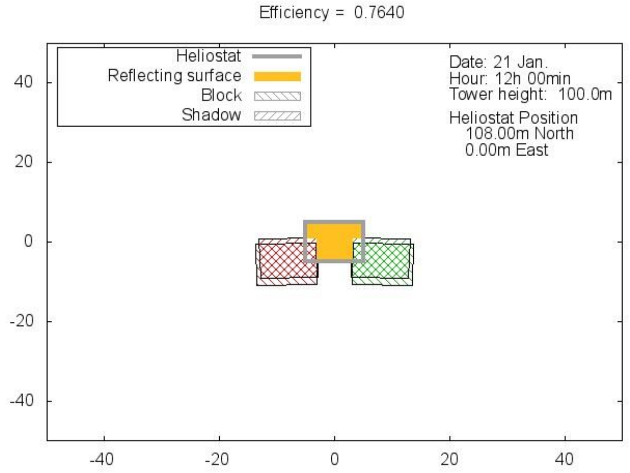

Figure 2. The subject heliostat *c* and the projection of the block and shadow from heliostats h_1 (red) and h_2 (green) at noon (Ramos and Ramos, 2014)

Figure 3 describes the reflecting area by the heliostat *c* for the analysis at 15h 15min. Note that in this case, the reflecting area by the heliostat *c* is much smaller than at noon, which has been already expected, because as can be seen daily at noon, bodies have practically no shadow in sunlight. The blocking and shading efficiency for this second case was calculated to be 0.3624.

The same application made in the algorithm from Ramos and Ramos (2014) is described by Fig. 4. The efficiency obtained in this case was 0.3080.

By comparing the obtained results, it is possible to conclude that for the first case, the heliostat efficiency value differed by 1.64% when compared to the literature. However, the output polygon representing the reflecting surface area for the receiver presented a shape divergence about one obtained in the algorithm in FORTRAN.

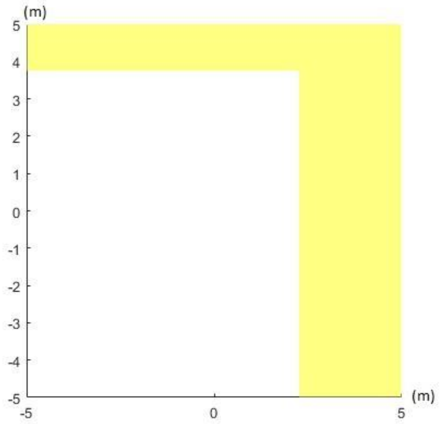

Figure 3. Reflecting surface area by heliostat *C* at 15h 15 min

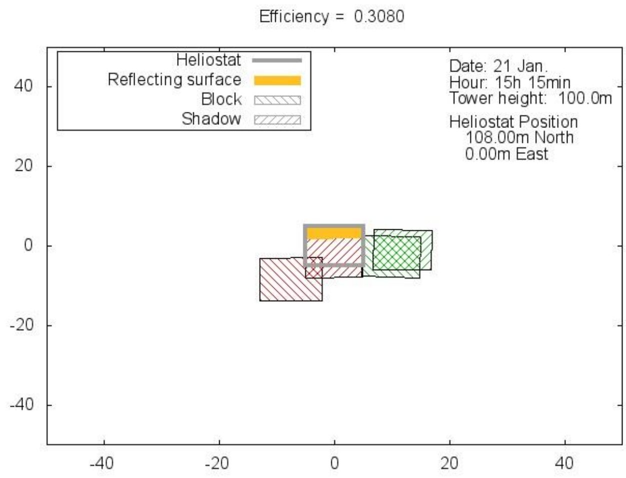

Figure 4. The subject heliostat *c* and the projection of the block and shadow from heliostats h_1 (red) and h_2 (green) at 15h 15min (Ramos and Ramos, 2014)

In the second case, the divergence between the value found by the program described in this study and the selected bibliography was 17.7%, which is considerably high when compared to the first case. There is also a difference of shape about the reflecting surface polygon.

This difference between the obtained values can be justified by the different equations that estimate the angles of sunlight direction and the orientation of the heliostat as to its azimuth and its slope relative to the local coordinate system, since these values are not explained in Ramos and Ramos (2014)

4. CONCLUSIONS

In this work a graphic-mathematical algorithm implemented in MATLAB was developed to estimate the blocking and shadowing efficiency of heliostats in solar tower power plants. This computational tool is based on projection of other heliostats present in the field to the subject heliostat coordinate system, both from the point of view of the sun (shadowing effect) and that of the tower (blocking effect). The projected figures form a set of 2D polygons that will be applied to a graphic clipping method in order to compute the loss mechanisms. To do this, functions available in the platform library has been used to solve the problem efficiently.

From the point of view from usability, this algorithm has practically no restrictions. The simulation can be done anywhere on the planet, since that this geographical location being defined by the user at the beginning of the program and the heliostats can be of different geometries and sizes and be located at different heights. The algorithm can also be easily modified to simulate fields with different towers and implementable in programs that calculate other loss mechanisms in solar tower plants.

When submitted to tests the algorithm outputted satisfactory results and presented a small discrepancy when compared to the consulted bibliography, presenting as an interactive and efficient alternative for the study of the loss mechanisms in solar tower power systems, which can make feasible the prospecting new projects for the production of clean energy.

The authors intend to extend the research to a whole field analysis and to add to the program the calculation of other loss mechanisms such as the cosine effect and the atmospheric attenuation, in addition to making some adjustments to improve the analysis and output of the results.

5. ACKNOWLEDGEMENTS

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