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Research Article

ENGINEERING DESIGN AND OPTICAL INVESTIGATION OF A CONCENTRATING COLLECTOR: CASE STUDY OF A PARABOLIC TROUGH CONCENTRATOR

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ABSTRACT

In this paper, an optical investigation study of a solar radiation collector has been treated through a precise model, which it has integrated all the geometrical characteristics of the concentrator to determine the optimal conditions of its operation. The type of solar collector chosen is the parabolic trough concentrator (PTC). This concentrator comprises a single mirror in the form of a half cylinder (cylindrical-parabolic) and a single receiver tube. A mathematical model has been introduced for the calculation the various optical factors, such as concentrator ratio "C", intercept factor "γ" and incidence angle modifier factor "K (θ)". The collector optical efficiency has exceeded 61 % with an external diameter of the receiver tube equal to 0.07 m, a focal distance equal to 3.76 m, a rim angle equal to 90° and a concentration ratio equal to 68.39.

Keywords: solar energy; parabolic trough concentrator; optical factors; modeling.

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1. INTRODUCTION

Depending on the research done previously, the systems using parabolic trough solar concentrators (PTCs) are able to produce operating temperatures above 450 ° C [1-13]. The PTCs have been designed for conversion of solar energy by thermodynamic pathways to thermal energy [1-9, 11-13]. In this concentration system, the direct solar radiation is received by a large area called the opening surface (A_o) and then the radiation directed towards an absorber tube (or more) which has a very small absorbent surface area (A_r). Generally, the direct solar radiation (DNI) is defined as radiation coming directly from the solar disk alone, this means that this direct radiation is absent in the absence of the sun [10-13]. The study of solar radiation is necessary for the choice of the best site for an installation of a solar collecting system, where the radiation received by a solar collector also depends on the level of sunshine of the site under consideration and its orientation relative to the sun [1-9, 11-13].

The optical study of the solar collectors is something that is necessary to determine the efficacies of these collectors. The PTCs are the most important collector in the field of a solar energy conversion to a thermal or an electrical energy [1-7].

In general, when solar radiation reaches the collector, a large amount of energy is lost for three reasons: geometric, optical and thermal. Many of the scientific researches related to the optical modeling of the PTCs have been published in refereed scientific journals, where W. Huang et al., (2016), have studied optical three-dimensional of a parabolic trough solar concentrator, they used the solar concentrator to heat the air, they have done a calculation of an interception and a efficiency of their collector [14]. S. M. Akbarimoosavi et al., (2014), have done a calculation the optical efficiency of parabolic trough solar concentrator by using ANSYS[15]. D. Canavarro et al., They have done new optical designs for a parabolic trough solar collector [16]. C. Tzivanidis et al., (2015), they have done an optical investigation and optical modeling of a parabolic trough solar collector [17].

The main objective of this paper is to conduct an in-depth optical study on a PTC solar concentrator in order to determine the concentrator dimensions, the concentration ratio “C”, the intercept factor “γ”, the incidence angle modifier factor “$K(\theta)$, the incident solar flux and the distribution of solar flux on the receiver tube surface.

2. ENGINEERING DESIGN OF THE PARABOLIC TROUGH SOLAR CONCENTRATOR (PTC)

It is known that to determine the incident flux on the receiver tube, it is necessary to consider the optical efficiencies and the variable optical losses that change with the position of the sun. The total incident irradiation is a function of the opening surface of the reflecting mirror, the force of the insolation and the angle at which irradiation enters the plane opening. The equivalent opening area refers to the total reflection area of the collectors, which is projected onto the opening plane of the concentrator; this area is distinct from the reflective curved surface. The area of the gaps between the mirrors and the non-reflective structural components is not included in the aperture area. When the solar radiation is not normal to the plane of collector opening, the losses are calculated taking into account the incidence angle "θ, (°)", this angle is formed between the direct sunbeam on a surface and the normal at the same surface.

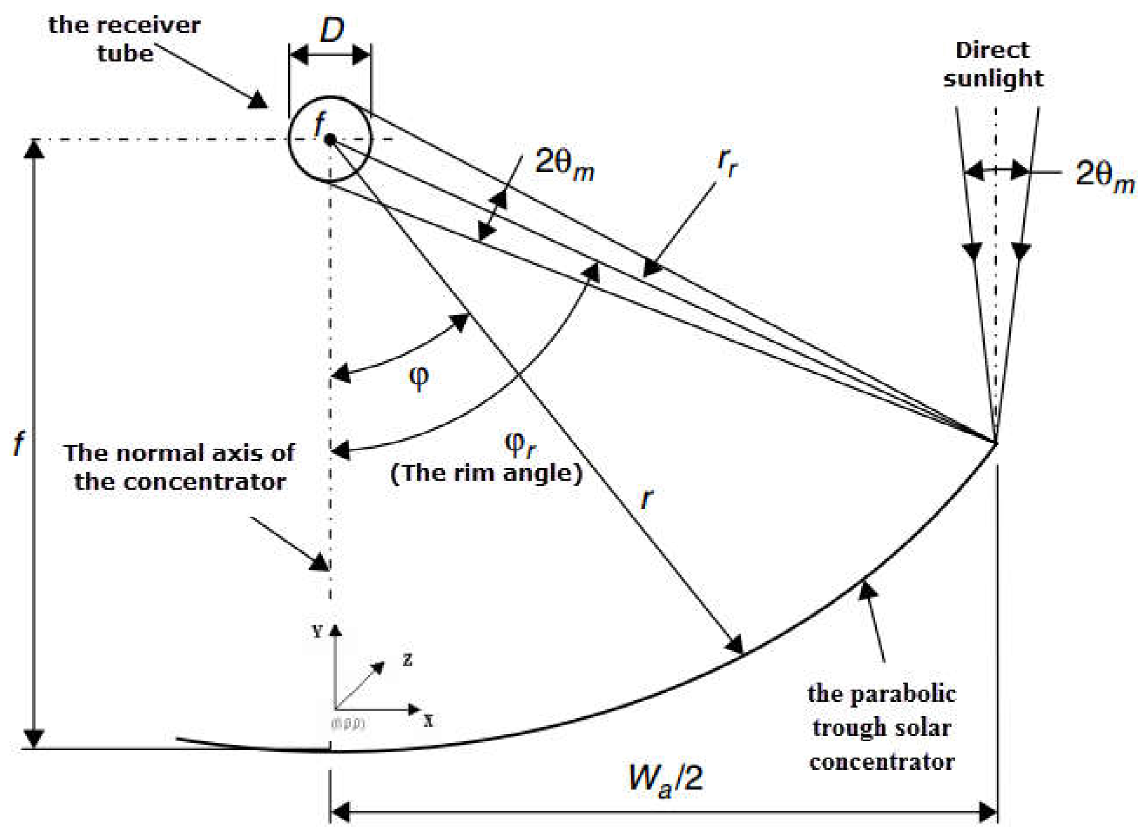

Fig. 1. Transversal-section of a cylindrical-parabolic concentrator with a tubular receiver

The Cartesian coordinates of cross-section of a parabolic trough collector in terms of Waypoint "x" and Waypoint "y". Equation (1) illustrates the curvature in Cartesian coordinates of a parabolic trough concentrator [18-20].

$$x^2 = 4fy \tag{1}$$

Where f is the focal distance between the parabolic center and the absorber tube, their unit is meter (m).

The absorber tube diameter "D, (m)" is a function of the rim radius "r_r, (m)", and the half acceptance angle "θ_m, (°)" as it is evident in Figure (1). Equation (2) presents the procedure for calculating the inside diameter of the absorber tube [18, 20].

$$D = 2r_r \sin\theta_m \tag{2}$$

The local mirror radius "r, (m)" is the reflecting mirror radius; it is a function of the angle "φ, (degree)", where this angle is angle between the normal axis of the concentrator axis and a reflected beam at the absorber tube (focus). Equation (3) shows the relationship to calculate the local mirrors radius "r" [18, 20].

$$r = \frac{2f}{1+\cos\varphi} \tag{3}$$

Through the equation (3), it was conclude the rim radius and is calculated as follows [20]:

$$r_r = \frac{2f}{1+\cos\varphi_r} \tag{4}$$

Through Figure (1), it was conclude a lot of geometric characteristics, and including:

$$\begin{cases} \varphi \in [0, \varphi_r] \\ r \in [f, r_r] \end{cases} \tag{5}$$

Where "φ_r" is the rim angle, it is the angle between the normal axis of concentrator and the rim radius.

The aperture width "W_a, (m)" of the parabolic trough was calculated according to the equation (6), it is a function of the rim angle "φ_r" and the rim radius "r_r" [20].

$$W_a = 2r_r \sin\varphi_r \tag{6}$$

Compensation the equation (4) into the equation (6), where the equation (6) becomes:

$$W_a = 4f \frac{\sin\varphi_r}{1+\cos\varphi_r} \tag{7}$$

Therefore, the opening width relation of the parabolic trough concentrator is as follows [19, 20]:

$$W_a = 4f \times \tan(\frac{\varphi_r}{2}) \tag{8}$$

There is a very important element in the design of the parabolic trough collector; this element is the curve length “L, (m)” of the reflecting mirror. This dimension “L” can be determined using the equation (9) [20].

$$L = \frac{lr_P}{2}\left[\sec\left(\frac{\varphi_r}{2}\right)\tan\left(\frac{\varphi_r}{2}\right) + \ln\left[\sec\left(\frac{\varphi_r}{2}\right) + \tan\left(\frac{\varphi_r}{2}\right)\right]\right] \tag{9}$$

Where “lr_P, (m)” is the latus rectum of parabola, their equation is:

$$lr_P = 4f \times \tan(\frac{\pi}{2}) \tag{10}$$

3. OPTICAL INVESTIGATION OF THE PARABOLIC TROUGH SOLAR CONCENTRATOR (PTC)

There are several methods for increasing the concentration of the radiation flux at the receiver tube. Some of these methods are:

- The use of the lenses;
- The use of refractory surfaces;
- Depending on the quality of the installation of the solar collector, and its orientation towards the sun, this can be achieved good choice of materials manufacturing solar concentrator.

The primary characteristic of the concentration is the geometric concentration ratio “C”. The most common definition of this factor “C” is based on the notion of surface; it is given as the ratio of the surface of the opening (A_o) to the receiver area (A_r) [20, 21].

$$C = \frac{A_o}{A_r} \tag{11}$$

For a cylindrical receiver tube, the concentration ratio is assumed as [20, 22]:

$$C = \frac{W_a}{\pi D} \tag{12}$$

By the compensation of the both factors “D” and “W_a” with equation (2) and equation (8), respectively, the equation (12) becomes [16, 20, 22]:

$$C = \frac{\sin \varphi_r}{\pi \sin \theta_m} \tag{13}$$

The solar energy incident on the opening surface of a solar concentrator depends on two parameters: the direct normal insolation “DNI, ($W.m^{-2}$)” and the relative position of the sun with respect to the opening of the collector.

The reflecting mirror optical properties of the parabolic trough concentrator are characterized by [1-6, 8, 9, 11-13, 18, 22-27]:

- The reflection coefficient “ρ_m”;
- The Transmission coefficient “τ”;
- The intercept factor “γ”;
- The receiver absorptance coefficient “α_C”.

In general, there are two types of errors that have relation to the reflecting surface; these types are [20, 22-27]:

- Random errors which are caused by environment factors where the existing the solar concentrator (error of the geometrical accuracy of the reflector, error of the reflectivity of the reflector, error caused by the presence of dust on absorber and reflector) [25].
- Non-random errors are directly related to the optical parameters, which depend on the properties of the materials used, the arrangement of the absorber in the focal plane and the angular errors of the reflecting surfaces [20, 22-27].

According to H. M. Guven et al., (1986), the both types of errors (random and non-random) of a parabolic trough concentrator can be combined in a relation; this relation is the relationship that grouped the geometric parameters of the parabolic trough concentrator (PTC), to determine error parameters universal to all concentrator geometries [20, 22-26].

The intercept factor “γ” is the most complicated optical factor in calculating the optical performance of a parabolic trough concentrator; it represents the ratio between the energy intercepted by the absorber and that reflected by the reflective surfaces. For a receiver extends from A to B, the intercept factor "γ" is given as [18, 21]:

$$\gamma = \frac{\int_A^B I_{SR}(R)dR}{\int_{-\infty}^{+\infty} I_{SR}(R)dR} \tag{14}$$

With "R, (m)" is the radius of the absorber tube and "I_{SR}, $(W.m^{-2})$" is the reflected radiation that is incident on the absorbing surface of the receiver.

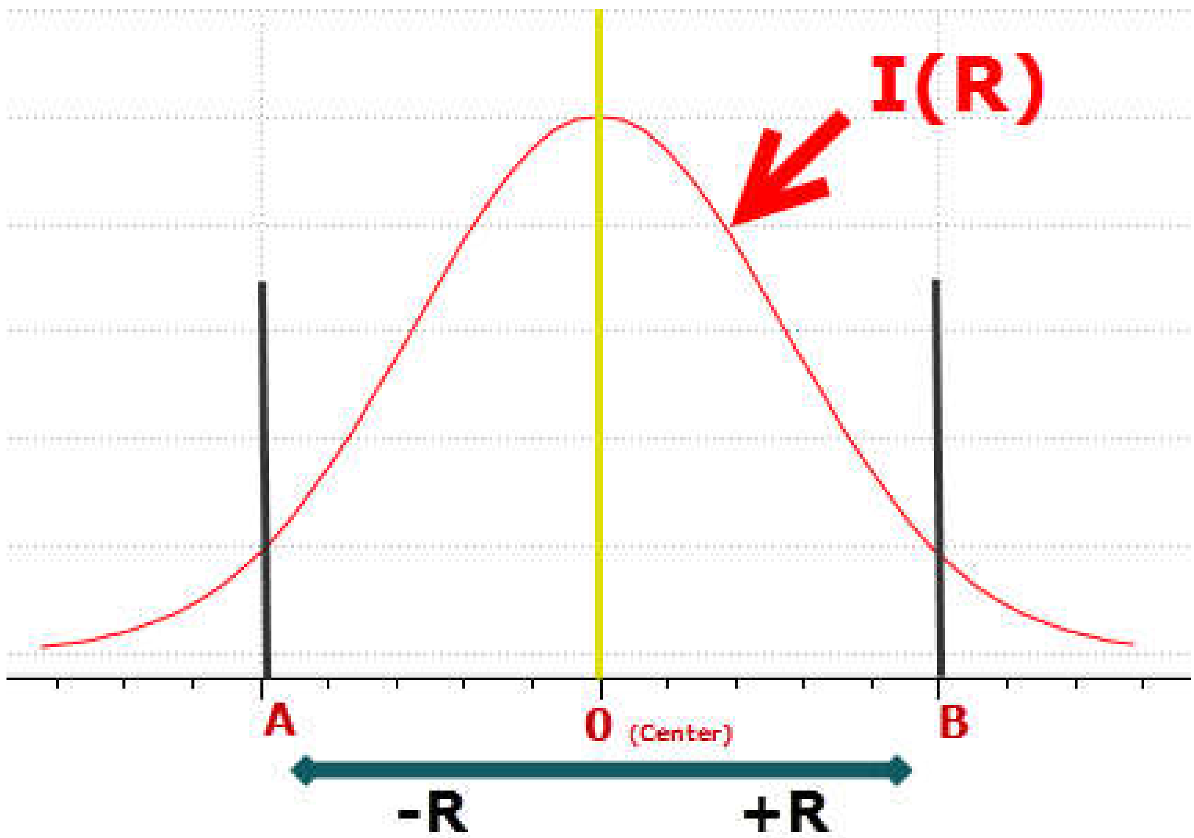

Fig. 2. Solar radiation distribution in the focal plane of a parabolic trough concentrator

The intercept factor "γ" reflects the fact that [18, 22-27]:

- Some solar rays can be returned to the outside of the concentrator;
- The reflected rays of the sun don't pass to the absorber tube when the reflecting surfaces has defects in the irregularities;
- The absorber is incorrectly positioned in the focal plane.

Therefore, it depends on the optical properties of the materials used. There are also some errors may appear in the concentrator construction or tracking system.

The optical efficiency "η_{opt}" is the quantity of radiation absorbed by the absorber tube divided by the quantity of direct normal radiation "DNI" incident on the aperture area "A_a, (m^2)". The optical efficiency "η_{opt}" is given as [1-6, 8, 9, 11-13, 18, 20, 22-27]:

$$\eta_{opt} = \rho_m.\gamma.\tau.\alpha_C.K(\theta) \tag{15}$$

In practice, optics is not perfect. To make the model better represent reality, optical errors are taken into account. The incidence angle "θ, (°)" of the sun with respect to an inclined solar collector plays an important role in determining the amount of energy transmitted to the solar collector [18, 28, 29]. This angle "θ" varies along the day, so the daily performance varies concurrently. The incidence angle in terms of the different angles defining the sun position, hence the direct dependence of the absorbed energy, which is according to the factor of incidence angle modifier "K(θ)" [18, 20, 28, 29]. They are of several natures of optical errors. The relationship of incidence angle modifier factor is given by [18]:

$$K(\theta) = 1 - \frac{f}{\ell}\left(1 + \frac{W_a^{\ 2}}{48f^2}\right)\tan\theta \tag{16}$$

Where "ℓ, (m)" is the trough length (trough length=receiver length).

A program has been designed using an Engineering Equation Solver (EES) in order to make the engineering calculations, and optical modeling. The results will be presented and discussed are the specific day for the month of January

4. RESULTS AND DISCUSSION

The parabolic trough concentrator having a reflective mirror of parabolic shape disposed cylindrically. This geometry allows it to focus the incident solar energy along a linear generatrix in which an absorber tube is placed in which circulates a heat transfer fluid. The parabolic trough concentrator is generally provided with a solar tracking to adapt the inclination of the concentrator so that the incident solar radiation is always perpendicular to the plane of concentrator opening. Table (1) shows the optical characteristics of the components of the parabolic trough solar concentrator.

Table1. Optical characteristics of the components of the solar concentrator

Parameter	Value
Optical overall average error ($\sigma_{optique}$)	03 mrad
Mirror reflection coefficient (ρ_m)	0.92
Transmissivity of the glass	0.945
Absorbion coefficient of the absorber tube (α)	0.94
The emissivity of the absorber tube (ε_A)	0.12
The emissivity of the glass (ε_V)	0.935

The absorber tube is the main component in the parabolic trough concentrator, which has the function of absorbing the incident solar radiation, converting it into heat and transmitting this heat to a heat transfer fluid. Table (2) illustrates the diameters dimensions of the receiver tube.

Table2. Diameters dimensions of the receiver tube

Dimension	Value [m]
External diameter of the absorber tube ($D_{A,ext}$)	0.070
Internal diameter of the absorber tube ($D_{A,int}$)	0.065
External diameter of the glass tube ($D_{V,ext}$)	0.115
Internal diameter of the glass tube ($D_{V,int}$)	0.109

For the length of the tube absorber "ℓ", it will take as a variable in the rest of the study. For the dimension of the concentrator reflecting mirror, would be calculated based on the equations (2-10). Figure (3) presents the results of the dimensions calculate of the reflecting mirrors depending on variation in the focal distance "f", with an external diameter tube "$D_{A,ext}$" equal to 0.07 m and the rim angle equal to 90°.

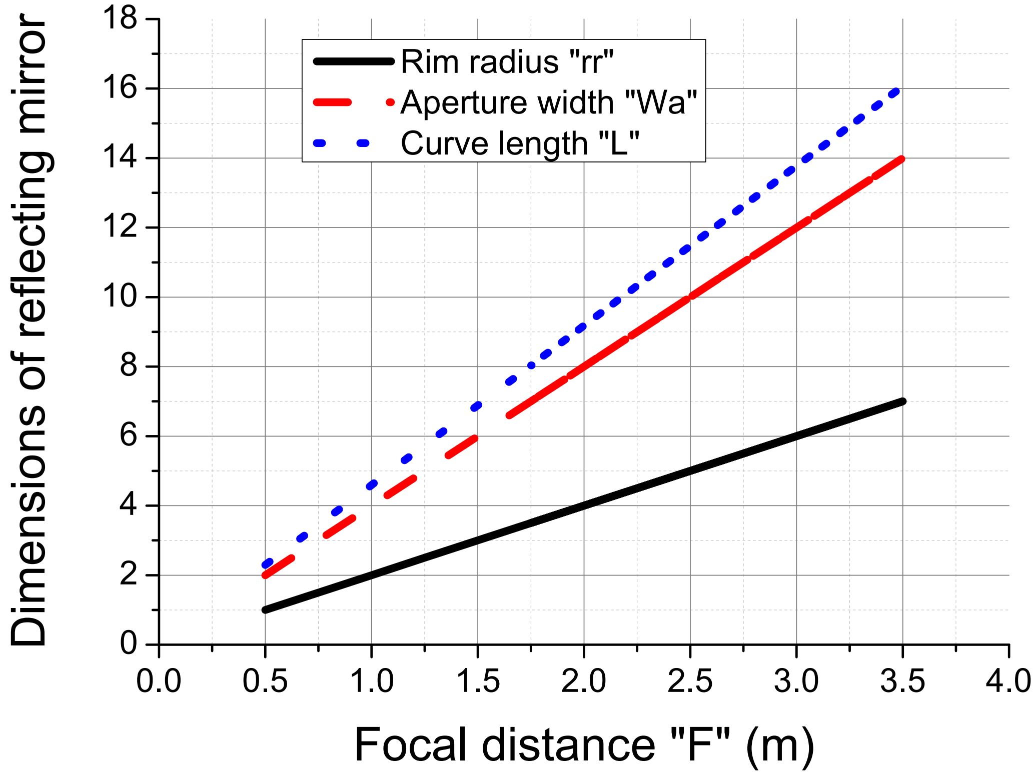

Fig. 3. Dimensions of reflecting mirror in function of the focal distance “f”, with $D_{A,ext}$=0.07 m and φ_r=90°

Through Figure (3), is very clear that there is a proportional relationship between:

- The rim radius “rr” and the focal distance, where the variation of the dimension “r_r” is a linear form, with a positive tendency. Can be expressed on this equation is as “rr=2f” because “cos90°=0”;
- The aperture width “W_a” and the focal distance “f”, there a linear relation with positive tendency between the both parameters. Their relation is “W_a=4f” because “cos90°=0 and sin90°=1”;
- The curve length “L” and the focal distance; observed that the linear relationship between the two dimensions. This relationship expressed by the equation:

$$L = 4.5912 \times f + 7 \times 10^{-7} \tag{17}$$

However, to determine the appropriate dimensions of the parabolic trough concentrator should be considered the value of concentration ratio “C”. With regard to this kind of solar concentrator and according to the equation (13), the maximum value of the concentration ratio will not exceed the value "C_{max}".

$$C_{max} = \frac{\sin(\varphi_r)}{\pi \sin(\theta_m)} = \frac{\sin(90°)}{\pi \sin(0.2666667°)} = \frac{1}{\pi \sin(0.2666667°)} = 68.39206554 \quad (18)$$

Therefore, it is necessary to know the influence of the focal distance variation on the concentration ratio. Figure (4) shows the evaluation of the concentration ratio in function of the focal distance.

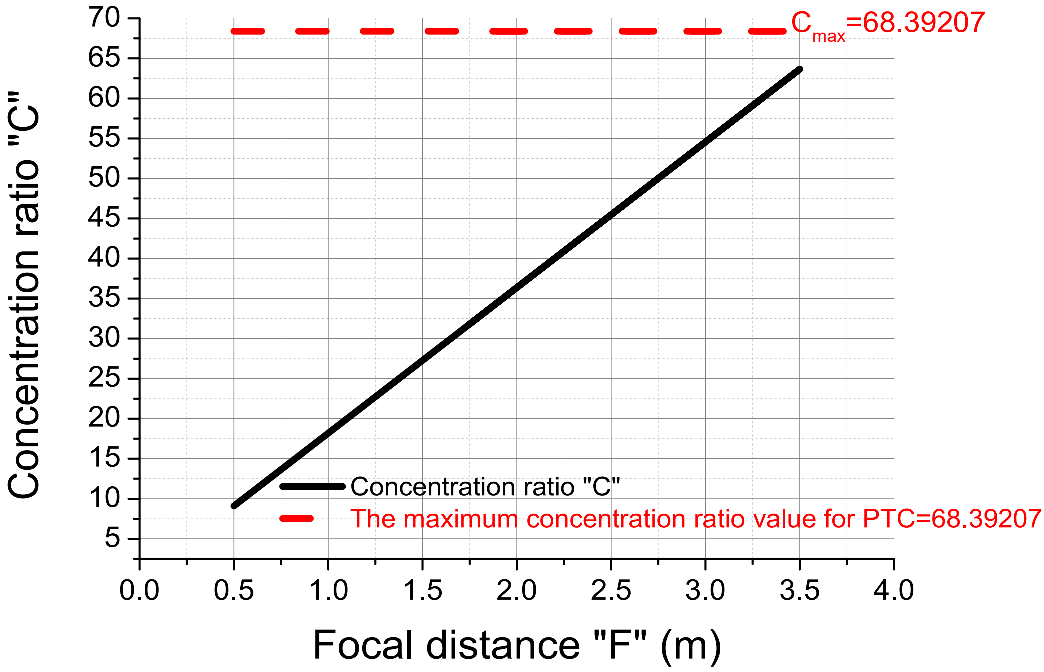

Fig. 4. Evolution of concentration ratio "C" depending of the focal distance "f", with $D_{A,ext}$=0.07 m and φ_r=90°

From the Figure (4), is very clear that the linear proportional relationship between the concentration ratio "C" and the focal distance "f". This can be expressed on a positive tendency linear equation of concentrator ratio "C" as follows:

$$C = 18.189 \times f + 4 \times 10^{-7} \quad (19)$$

Equation (19) enables us to calculate the greatest focal distance "f" that we can get the greatest value of the concentration ratio "C_{max}". Therefore, the value of the greatest focal distance "f" is equal to 3.760078352 m. Table (3) shows the dimension of a solar concentration prototype after the optimization.

Table3. Dimension of a solar concentration prototype after the optimization.

Dimension	**Value**
External diameter of the absorber tube ($D_{A,ext}$)	0.070 m
The rim angle (φ_r)	90°
The focal distance (f)	3.760078352 m
The rim radius (r_r)	7.520156704 m
The opening width (W_a)	15.04031341 m
The curve length (L)	17.26317509 m
The concentration ratio "C"	68.39206554

Figure (5) shows the cross-section of the parabolic trough solar concentrator with the dimensions obtained by numerical calculation.

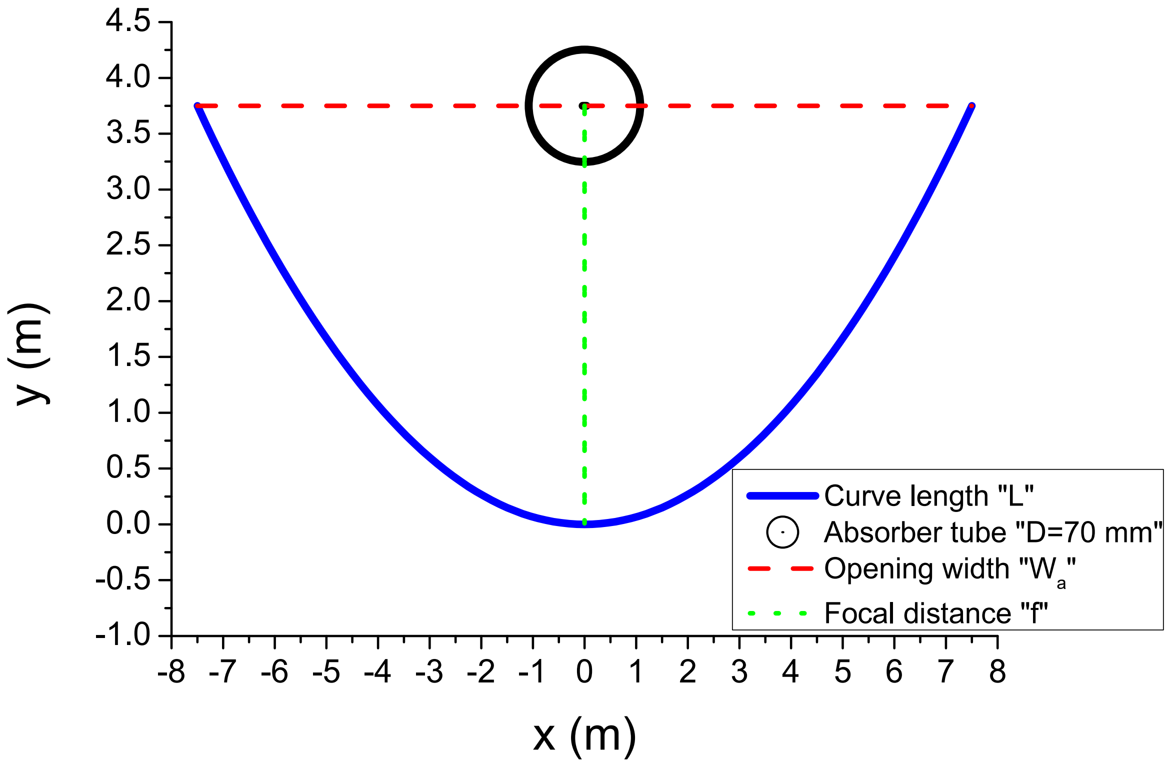

Fig. 5. Cross-section of the parabolic trough concentrator, with our dimensions

The solar illumination received by the parabolic trough solar concentrator is the direct radiation “DNI, (W.m^{-2})” [1-6, 8, 9]. The solar radiations (global, direct and diffuse) typically vary as shown in Figure 6 for the day chosen to take the measure. During a sunny day, the solar radiations increase from sunrise to a maximum at midday solar before decreasing again until sunset. The 16 Jan. 2017 was chosen as the day to make a measurement of solar radiation depending on the semi empirical approach of PERRIN DE BRICHAMBAUT [10]. El-Oued region (Oued souf) was chosen as an area in the Algerian desert to calculate solar radiation. According to the weather station of Guemar (elevation 61 meters, latitude 33.51 ° N and longitude 6.78 ° E); with and absence of wind, the high and the low ambient temperature are 06 °C and 16 °C, respectively, in the El-Oued region for the chosen day [30].

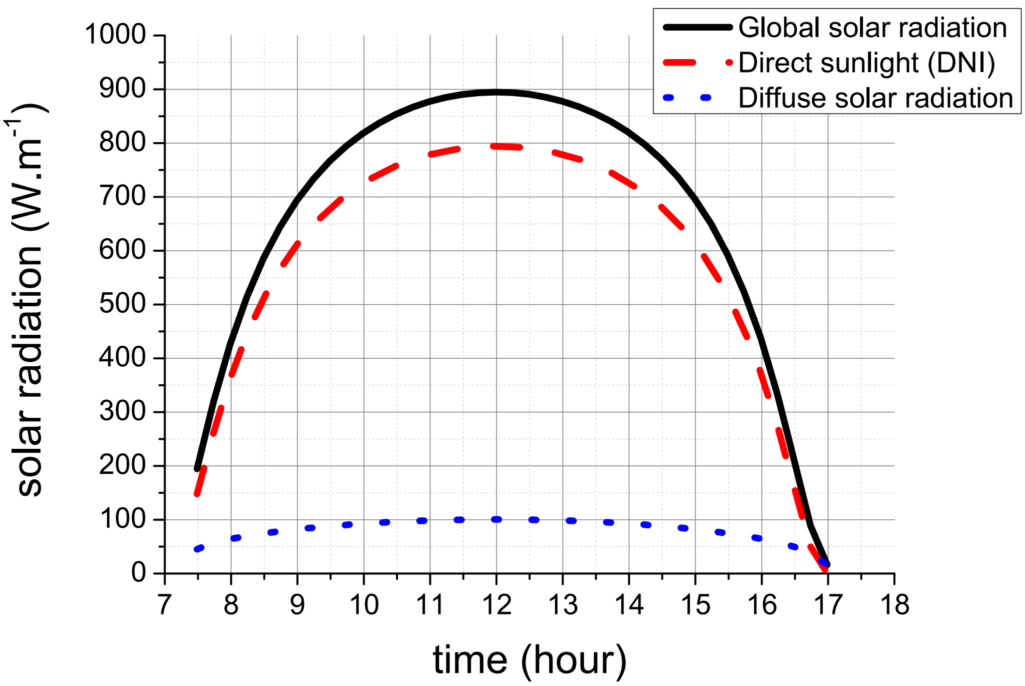

Fig. 6. Solar radiations variation at Jan.16th, 2017

Direct solar radiation is fixed between sunrise and sunset; it is a variable change the angle of the solar height “h, (°)” [10]. As noted in Figure (6), the direct radiation change versus the time, where the highest solar radiation value recorded at midday “DNI = 800 W.m^{-2}”. In Figure (6), the solar radiation for a day in the winter, this solar radiation is very strong, It means that the results is encouraging for the solar energy exploitation in many uses (industrial and domestic) in a El-Oued region.

We are going now to speak on the intercept factor (γ), this factor represents the fraction of the radiation reflected by the reflecting mirror and the radiation intercepted by the absorber tube. Figure (7) shows the variation of intercept factor in function of the incidence angle in the day of Jan. 16th, 2017. It is well known that the greatness value of incidence angle at sunrise and sunset "θ≈90°", and the minimum value of the incidence angle at midday. In our case, the maximum value of incidence angle is equal to 89.67°, and the minimum value of this angle is equal to 54.6°. Therefore, the intercept factor is approximately 62% at midday and is approximately 95.6% at sunset and sunrise. The effect of the solar tracking on the intercept factor evolution is varied as a function of the variation of the solar radiations (global, direct and diffuse) versus the time; all this is evident in Figure (8).

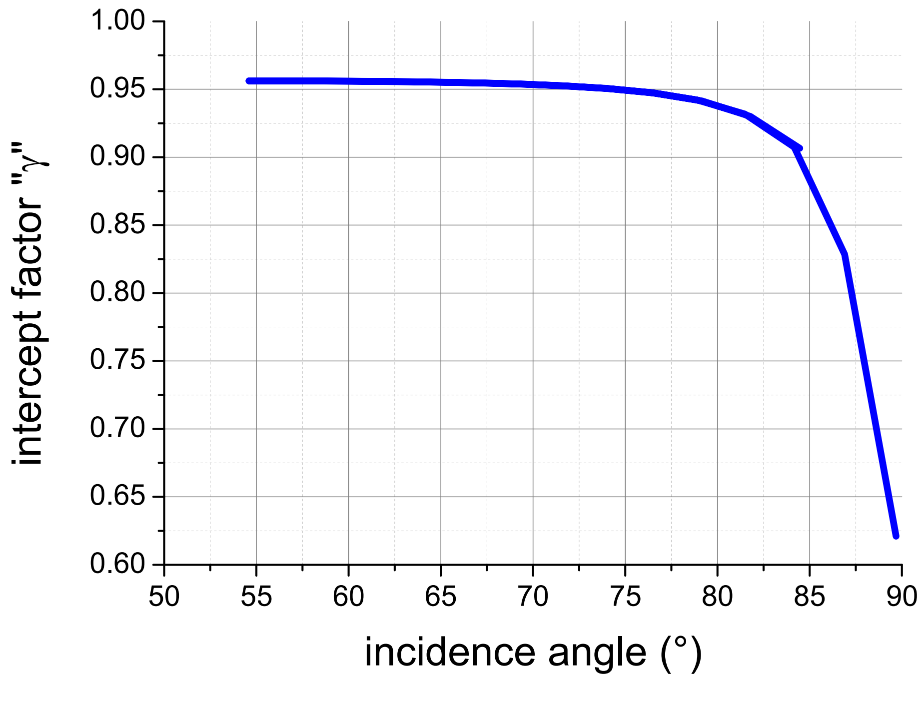

Fig. 7. Intercept factor evaluation (γ) versus the incidence angle (θ), with "$D_{A,ext}$=0.07 m" and "f=3.760078352 m"

The correlation for the intercept factor of the parabolic trough concentrator studied in this paper is given by equation (20).

$$\gamma = -5.01018 \times 10^{-6} \exp\left(\frac{(\theta - 57.64143)}{2.88583}\right) + 0.95473 \tag{20}$$

Increasing the interception factor will increase the fraction of input energy in the receiver tube. The increase in the interception factor leads to reducing the errors in the reflecting mirror of the parabolic trough concentrator, then an increase the performance of the concentration system.

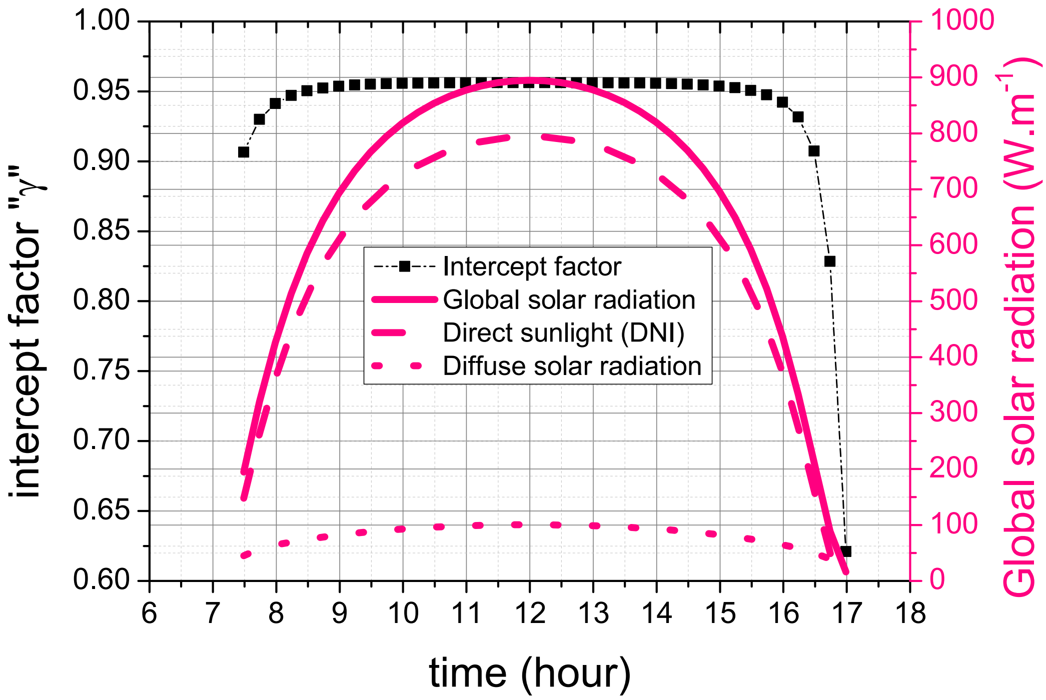

Fig. 8. Solar radiations and intercept factor evolution versus the time

In general, if the increase in the interception factor is accomplished by increasing the size of the aperture, there will be contradictory impacts; a study must be made to determine whether the increase in energy intercepted by the absorber tube is greater than the energy lost due to thermal losses.

Therefore, to obtain a high concentration level in the parabolic trough concentrator, it is necessary to make a precise study to determine the absorber tube dimensions and of the reflective mirror surface dimensions, and this is the main objective of this paper.

Now come to speak on a very important factor in determining the efficacy of a parabolic trough solar concentrator, this factor is the incidence angle modifier “K (θ)”, this factor describes how the optical efficiency of the concentrator changes as the incident angle changes. The value of this factor is less than one and decreases with the increase of the incidence angle "θ". Figure (9) illustrates the variation of the incidence angle modifier versus the incidence angle.

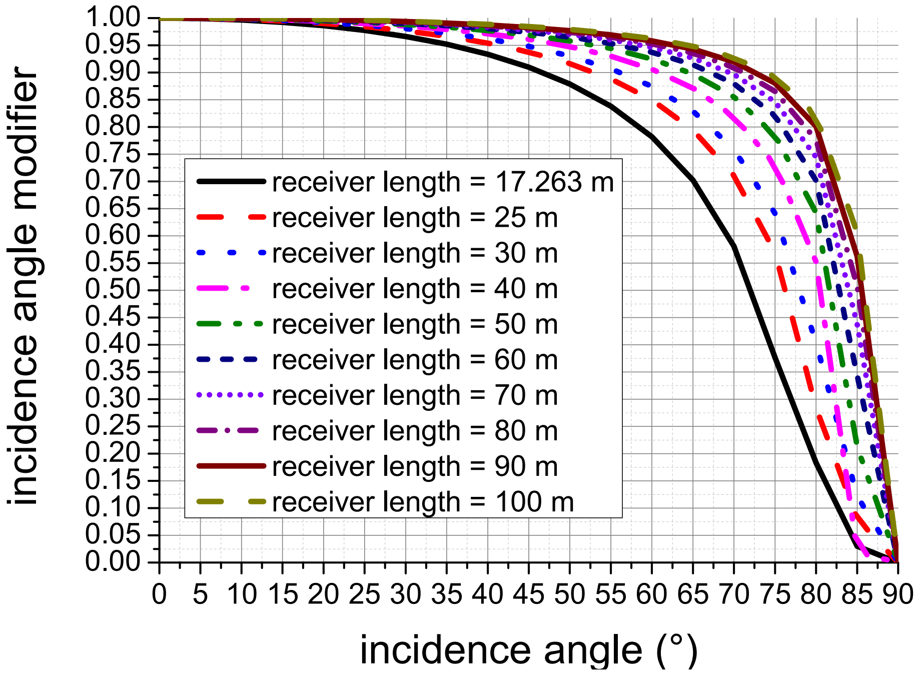

Fig. 9. Incidence angle modifier evaluation of the concentrator in function of receiver tube length and the variation of incidence angle "θ", with "$D_{A,ext}$=0.07 m" and "f=3.760078352 m"

Therefore, Figure (9), the incidence angle modifier is varied in terms of the incident angle and the length of the absorber tube. The greater the receiver tube length increased the value of the incidence angle modifier. The incidence angle modifier directly related to the value of the incidence angle cosine. It is found that the incidence angle modifier decreases noticeably with the increase of the incidence angle, so such a system of continuous tracking of the sun is necessary for the parabolic trough concentrator.

The optical efficiency is written as a function of the incidence angle modifier. Figure (10) shows the optical efficiency versus the time.

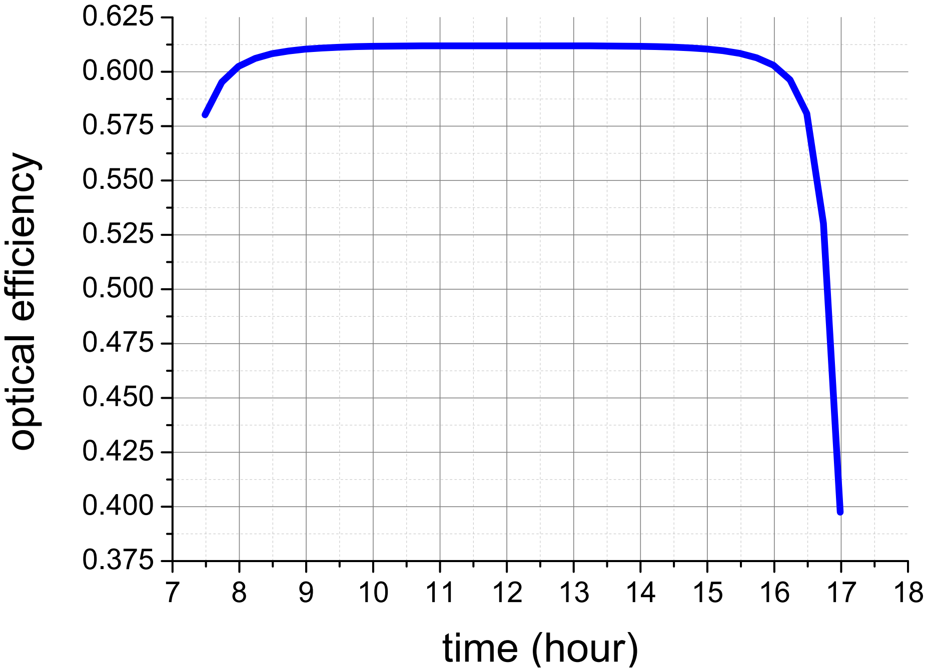

Fig. 10. Evaluation of concentrator optical efficiency versus the time

The optical calculations for the solar concentrator are extended to the determination of incident solar flux on the receiver tube. Very clear from the Figure 10, that the optical efficiency of the device up to 61.20 % at midday, this efficiency is very well.

For the fields of cylindro-parabolic concentrators, the total solar radiation incident on the solar field is equal to the total normal irradiation available times the total opening area, multiplied by the cosine of incidence angle “θ”, this optical decommissioning is called "cosine loss" and is the main variable for the solar field loss.

Roughly speaking, the optical losses of a parabolic trough concentrator, which are dependent on the position of the sun, are applied as constant multipliers. Like tracking error, geometry defects, mirror reflectivity, mirror soiling, and other error that is not taken into account by other points. Because the model multiplies the loss factors to calculate a loss factor as a whole, the value of each individual loss factor is not significant.

Now, the solar flux distribution around the absorber tube and the flux intensity at the surface of the absorber tube were simulated using the SolTrace which is based on the use of the Monté Carlo method [31]. Figure (11) presents the schematization of our parabolic trough concentrator model with SolTrace.

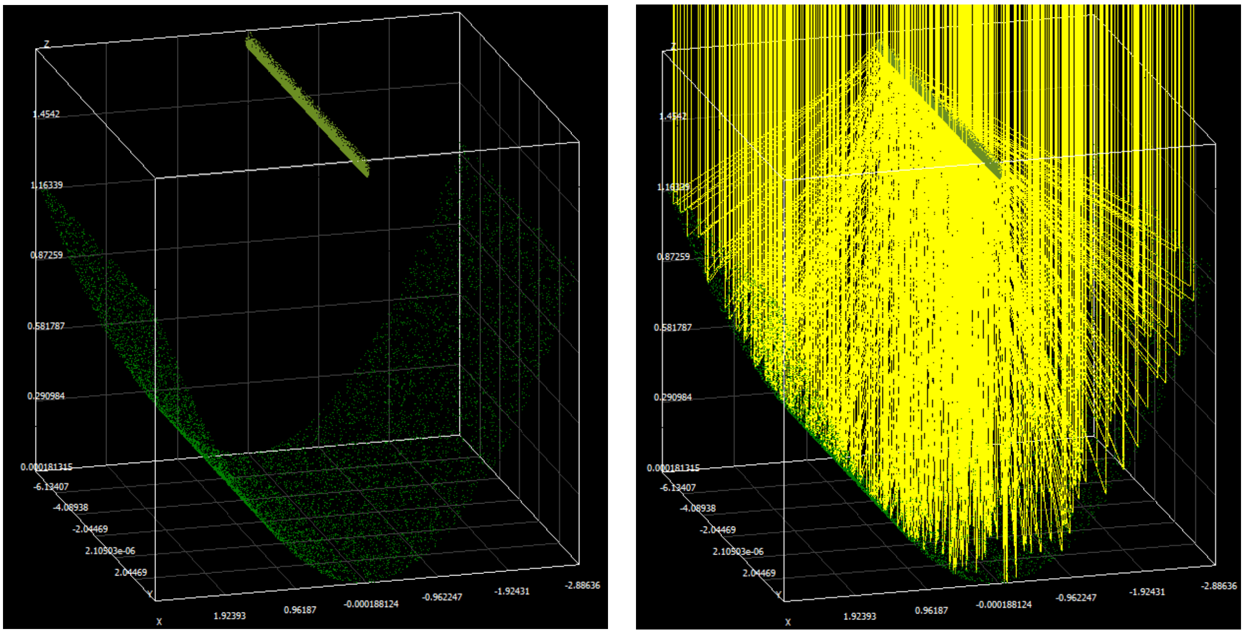

Fig. 11. Parabolic trough concentrator schematization by using SolTrace

Figure (12) illustrates the final intersections of three hundred solar beams with the absorber tube.

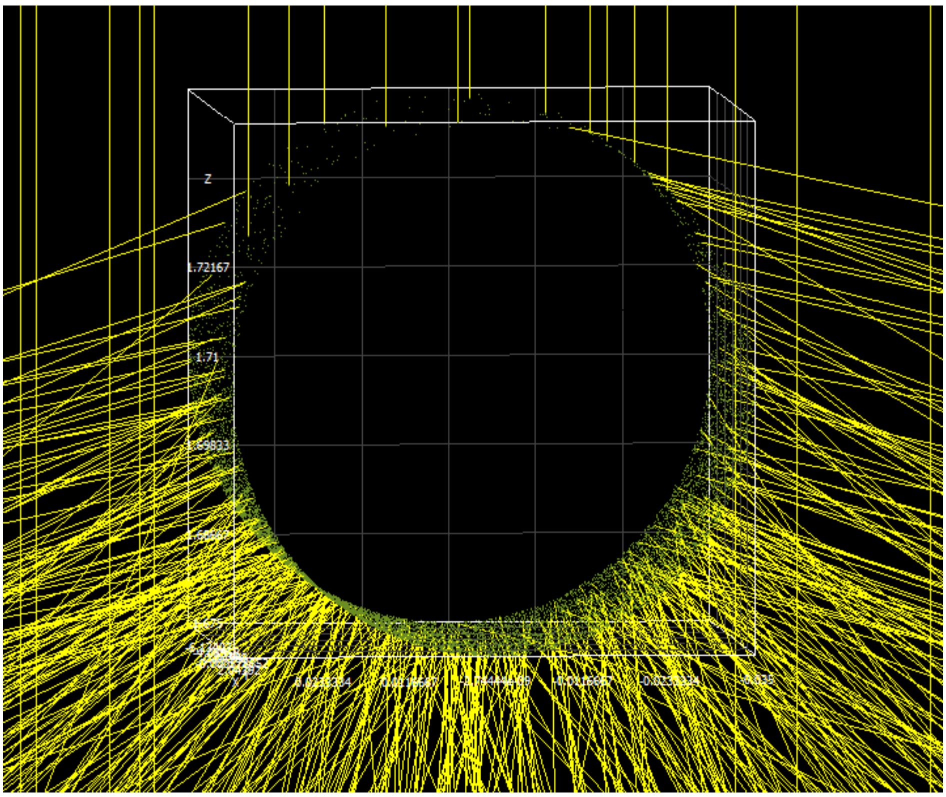

Fig. 12. Final intersections of the solar beams with the absorber tube

Figure (13) shows the flux intensity contour on the receiver tube surface with direct solar radiation equal to 800 W.m^{-2}, and three hundred solar beams.

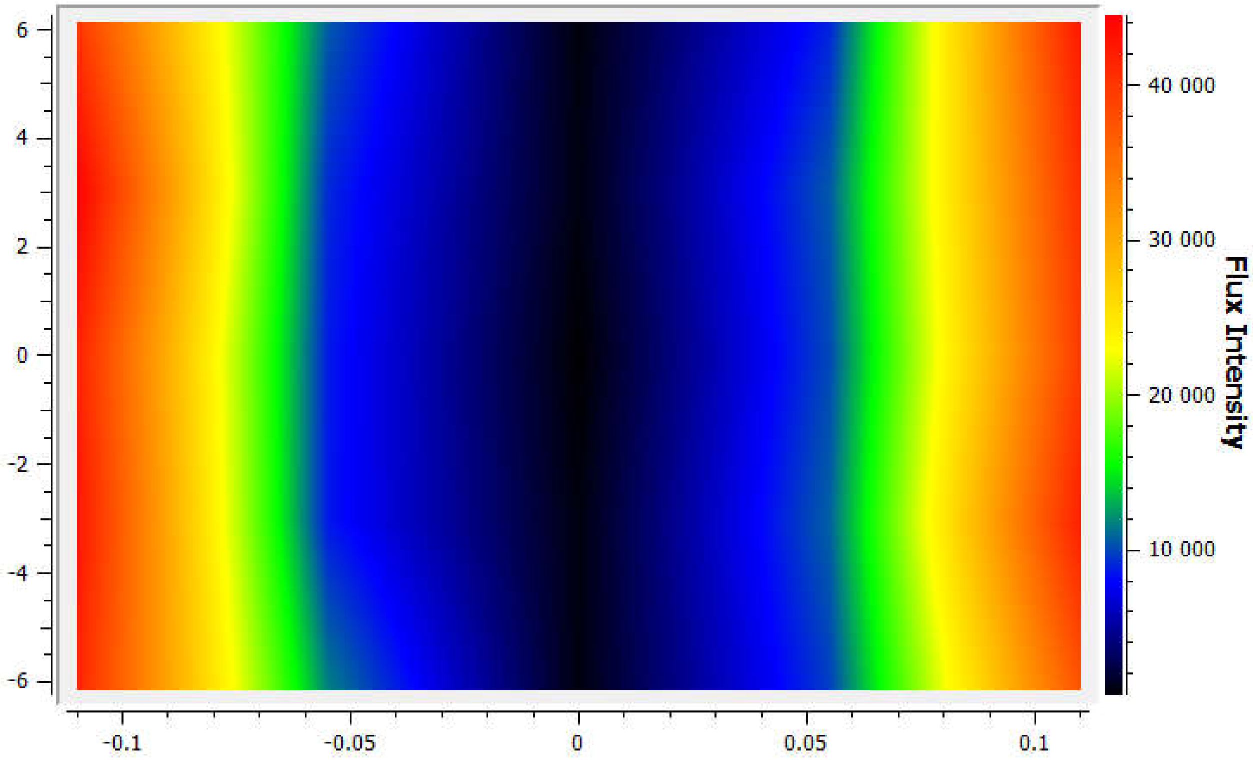

Fig. 13. Flux intensity contour on the receiver tube surface

The summary Figure (13) is the following:

- Peak flux equal to 44475.7 W.m^{-2};
- Minimum flux is equal to 574.217 W.m^{-2};
- Average flux is equal to 20640.5 W.m^{-2};
- Uniformity of the distribution of the flux intensity on the absorber tube surface is equal to 83.184 %.

Figure (14) shows the flux intensity distribution on the receiver tube surface with direct solar radiation equal to 800 W.m^{-2}, and three hundred solar beams.

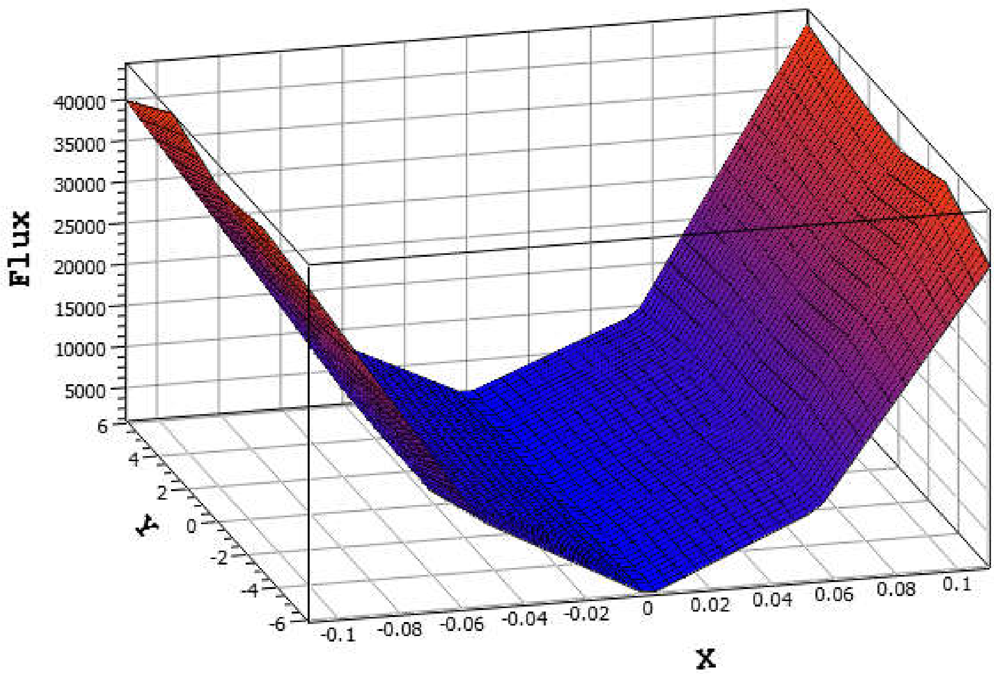

Fig. 14. Flux intensity distribution on the receiver tube surface

Through Figure (14), it seems clear that the obtained distribution is very logical; this explains where the three models of heat transfer, and are as follows:

- The heat transfer by radiation between the reflective mirror and the outer surface of the absorber tube;
- The conduction transfer in an distance element "Δy, (m)" between the outer surface and the inner surface of the absorber tube;
- The heat transfer by convection between the inner surface of the absorber tube and the heat transfer fluid.

Finally, the parabolic trough concentrator is described by three main factors: the concentration ratio "C", the intercept factor "γ" and the incidence angle modifier "K (θ), this is what has been discussed previously. Sure, every solar collector has the advantages and the inconvenients. For example, in the field of electricity generation, the advantages points of parabolic trough concentrator are:

- Good performance;
- Little mechanical movement compared to other heat stations;
- Less expensive than mirror concentration and Stirling dishes;

The inconvenients are:

- Always more expensive per watt compared to conventional photovoltaic panels;
- Not suitable for small installations;
- Energy changes on many occasions: risks of energy loss;

5. CONCLUSION

Renewable energy offers us many ways to generate energy; the most prominent of these renewable energies is the solar energy. The application of solar renewable energy systems, particularly solar concentration systems in the industrial and domestic sectors, can make a difference and solve many problems. This study shows that it is possible to exploit the solar energy in Algeria by the use of parabolic trough concentrator with an external diameter of the absorber tube “$D_{A,ext}$” equal to 0.07 m and a rim angle equal to 90°. This paper is the search for the design of a parabolic trough solar concentrator. In this work, it has been calculated the concentrator dimensions (the focal distance “f”, the opening width “Wa” and the curve length “L”), the concentrator ratio “C”, the factor intercept “γ”, the incidence angle modifier “K (θ)”. The optical efficiency of solar concentrator exceeded 61%, and the average flux intensity on the absorber tube surface is equal to 20640.5 W.m^{-2}.

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