Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES18, 19–21 September 2018, Athens, Greece

Geometric, optical and thermal analysis for solar parabolic trough concentrator efficiency improvement using the Photogrammetry technique under semi-arid climate

Massaab El Ydrissi a,b,*, Hicham Ghennioui a, El Ghali Bennouna b and Abdi Farid a

a Laboratory of Signals, Systems, and Components, Sidi Mohamed Ben Abdellah University, Fez, Morocco
b Research Institute in Solar Energy and New Energies, Rabat, Morocco

Abstract

The investment of renewable energy, especially the solar energy, seems to be the real alternative and the potential solutions for the classical fuel energy due to its pollutant and limited source. Therefore, the cost and performance are the main criteria to assess a solar power plant. The purpose of this work is to evaluate the optical and thermal efficiencies of a solar Parabolic Trough Concentrated (PTC) installed in the Green Energy Park (GEP) research platform in Benguerir, Morocco. In order to improve the optical efficiency of the system, an optical qualification is necessary because of the difficulties of handling the glasses and the deformations from the ideal design. In this sense, an experimental study was carried out using the robust Photogrammetry measurement technique to perform the geometrical and optical errors of the solar concentrating system. Slope error, misalignment error, and receiver position error has been identified and analyzed. Moreover, the intercept factor and the optical efficiency of the PTC system according to the experimental measurements given by the Photogrammetry technique were determined. Finally, the thermal efficiency of the PTC according to results obtained and the weather conditions climate of Benguerir city extracted by an accurate meteorological station have been performed and analyzed. The results obtained show the relevant impact of the optical efficiency on the thermal energy and the plant performance.

© 2019 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
Selection and peer-review under responsibility of the scientific committee of Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES18.

Keywords: Photogrammetry; Optical efficiency; Slope errors ; Intercept factor; Solar concentrator ; Thermal efficiency.

* Corresponding author. E-mail address: massaab.elydrissi@usmba.ac.ma

10.1016/j.egypro.2018.11.272
1. Introduction

Renewable energy generation is becoming more dominant recently due to the limited fossil fuels source and to the impact of the dioxide emissions on the global climate change. The solar energy is a clean, affordable and abundant source to cover the big electrical demands of the society and the industrial sector. In this sense, the Concentrated Solar Power (CSP) technology is the most promising candidate to provide the majority of this renewable energy sources which widely used in many applications such as the electrical production, solar desalination, solar cooling, hot water supply, and others applications [1–3]. The solar collectors can produce a high temperature (up 400 °C) reached high thermal efficiency especially in the countries with a high solar irradiation level as Morocco [4,5]. The main commercially CSP technologies are separated into two kinds: the line focus technology as the Parabolic Trough Collectors (PTC) and the Linear Fresnel Collectors (LFC). The second kind is the point focus technology presented by the parabolic dish and central receiver tower [6–8]. Moreover, the PTC technology is the most used for heating the HTF at high temperature (over 400°C) and also for others applications that require medium temperture [100 to 250°C] such as cooling, evaporating and cooking. The principal idea of this technology is to collect the sunlight received in aperture area of the collector and then concentrate the parallel solar radiation on the focal line which a tube absorber is located. The heat energy of the HTF circulate inside the receiver will then converted to thermal energy and finally to electrical energy.

The thermal efficiency of a solar concentrator is affected by several parameters leading to significant optical losses and then reducing the thermal energy reached by the receiver. Moreover, the investigations and analyzes of the geometric parameters and the optical proprieties of the materials composing the collector are important for evaluating the geometric concentration ration and characterizing the optical losses of the mirrors used. Furthermore, while the solar concentrators are located in the open field and exposed to real strong conditions, the wind effects, tracking errors and soiling phenomena also have an impact on the thermal efficiency of the solar collectors and then on the whole power plant efficiency since the solar field constitute up 60% of the total investment part of the plant. According to the literature, the wind effect on the thermal efficiency was studied by Hachicha et al [9], the influence of the design parameters and the manufacturing factors on the technical performance of the PTC was analyzed by Clark [10]. In additions, some optical studies have been proposed, including optical errors and their effect on the optical and thermal energy losses. Binotti et al.[11] proposed the FirstOPTIC tool to evaluate and simulate the impact of the geometric and optical performance of a PTC system. However, the various optical studies give only an optical simulation using the ray tracing algorithms or models and not taking into account the real imperfections and aberrations of the mirrors used. For this, the necessity of a robust technique such as the photogrammetry or the deflectometry technique is important to experimentally calculate the real slope errors and deviations from the ideal design. A few of studies in this sense have been carried out, El Ydrissi et al.[12] proposed a geometric and optical study of a PTC system using the Deflectometry technique, in which the optical errors were determined and analyzed giving their impact on the thermal efficiency.

The main objectives of this work are the geometric and optical efficiency study of a solar parabolic trough collector installed and assembled at the GEP research platform in Benguerir, Morocco. The accurate photogrammetry measurements technique was used to experimentally calculate and identify the slope errors and the deformations from the ideal design. These results are then used to determine the intercept factor and the optical efficiency of the system taking into account the real imperfections of the mirrors used to compose the collector. Moreover, the DNI data extracted by an accurate meteorological station installed at the research platform is used to analyze and evaluate the thermal energy of the system.
Nomenclature

- \( L \): Length of the collector
- \( \rho \): Reflectivity of the mirror
- \( \tau \): Transmittance of the receiver glass envelope
- \( \alpha \): Absorptance of the absorber tube
- \( \gamma \): Intercept factor
- \( \Psi \): Rim angle
- \( f \): Focal length
- \( D_0 \): Aperture width
- \( c_l \): Cleanliness factor
- \( K \): Incident Angle Modifier or IAM
- \( A_{SF} \): Net collecting surface
- \( X_{field} \): Availability of the solar field
- \( n_{endloss} \): Optical endloss efficiency
- \( n_{shadow} \): Efficiency from mutual shadowing
- \( n_{opt,0} \): Optical efficiency for perpendicular sun on the collector

VSHOT: Video Scanning Hartmann Optical Tester
FirstOPTIC: First-principle OPTical Intercept Calculation
NREL: National Renewable Energy Laboratory
GEP: Green Energy Park
HTF: Heat Transfer Fluid
PTC: Parabolic Trough Collectors
LFC: Linear Fresnel Collectors
CSP: Concentrated Solar Power
DNI: Direct Normal Irradiation

2. Geometric analysis of Parabolic Trough Concentrator

A parabolic trough collector was installed, assembled and tested at the GEP platform research in Benguerir city, Morocco. The GEP has several CSP projects installed on the site: 1MWe solar power plant based on Fresnel technology with thermal storage, test loop system based on parabolic trough collector for testing and characterizing different HTF, and various other projects such as hybrid applications. The idea to develop a PTC with important geometrical parameters in order to improve the geometric concentration ratio was done. The proposed parabolic trough collector has a focal line equal to \(2.75\, m\), an aperture area \(16.886\, m^2\) and \(0.208\, m^2\) for receiver area. The geometric concentration ratio corresponding to the ratio of the aperture area and the receiver area is \(81\). The PTC is composed of four facets, each facet having a geometric dimension equal to \(3230 \times 1000 \, mm\) and mounted on strong structures able of supporting the weight load of these long mirrors and prohibiting the handling of the glass (see Fig. 2). Especially, the exposed collector with a large aperture area is more affected by the wind loads and may affect the accuracy of the sun tracking unit. So, the collector has to be constructed in such a way to avoid the important geometrical deviations from the ideal shape design that causes optical efficiency losses. Therefore, a preliminary study of the geometric of the parabola is important to reach the geometric concentration ratio and to define the shape of the parabola and length of the module desired. The main geometric parameters of a PTC are as follows (Fig. 1):
- The collector length \((L)\).
- The focal length \((f)\) which present the distance between the vertex of the parabola and the focal point.
- The rim angle \((\Psi)\) described by the angle between the optical axis and the line connecting the focus to edge of the parabola.
- The aperture width \((D_0)\) is the distance between one rim and the other which describe the opening of the parabola.

These geometrical parabolic trough parameters are necessary to characterize the form, size and the section of the parabolic trough. A small rim angles require a longer focal length and make a flat trough, contrariwise to a large rim angles that make a curved cross-section with a small focal length, generally the parabola with a large rim angles reach high level of concentration related to the parabola with a longer focal length which the beam spared is important. The mathematical equation of the parabola is presented bellow and the geometric parameters of the PTC studied are mentioned in Table 1.

\[
z = \frac{1}{4f} y^2
\]

**Table 1. The geometric parameters of the PTC.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length module</td>
<td>2.61</td>
<td>m</td>
</tr>
<tr>
<td>Focal length</td>
<td>2.75</td>
<td>m</td>
</tr>
<tr>
<td>Aperture width</td>
<td>6.47</td>
<td>m</td>
</tr>
<tr>
<td>Facet dimension</td>
<td>3230*1000</td>
<td>mm</td>
</tr>
<tr>
<td>Number of facets used</td>
<td>4</td>
<td>--</td>
</tr>
</tbody>
</table>

**3. Optical evaluation of Parabolic Trough Concentrator**

**3.1. The optical proprieties**

The optical proprieties of the mirrors used and the tube absorber are very important for increasing the concentration ratio and reaching a high level of temperature inside the tube absorber in order to increase the reflectivity of the mirrors and to reduce the thermal losses on the tube absorber. Nevertheless, by choosing an
appropriate geometric parameters and structure design, the optical proprieties remain the most determining parameter for optical efficiency and intercept factor which represents the percentage of the radiation reflected by the concentrator and that reaches the absorber. In CSP applications, reflectivity is the main appropriate mirror materials which indicate the fraction of incident solar radiation reflected by the mirror. In general, there are two different kinds of reflection: the first one is the specular reflection, which means that incoming radiation in one direction will be reflected by the surface or the mirror into a single outgoing direction. The other kind is the diffuse reflection kinds of reflection: the first one is the specular reflection, which means that incoming radiation in one direction will be reflected by the surface or the mirror into a single outgoing direction. The other kind is the diffuse reflection representing a broad range of directions reflected when a light reaches the surface in one direction. In solar concentrators systems, only the specular reflectivity is interesting since the directions of reflected sunlight should be defined. On the other hand, the choice of the tube absorber diameter and the optical properties of the glass tube are also significant, an optimization study to find the appropriate absorber diameter is necessary in order to achieve a high average intercept factor minimizing the thermal energy losses produced by convective and conductive heat loss.

The studied PTC assembled at the GEP platform research is under test for evaluating its optical efficiency, the PTC is covered with high reflectivity values of the glass used up 96 % and adequate optical proprieties of the absorber tube and the glass covering it. The Fig. 2 shows the PTC studied composed of four parabolic facets mounted on a solid structures supporting their weight loads and minimizing the geometrical deviations.

![PTC Image](image)

**Fig. 2.** The parabolic trough collector assembled at the GEP

The optical efficiency is strongly affected by the optical errors due to the manufacturing and the installation errors, the difficulties in handling the glass and make a parabola form are a challenging task and require a high precision equipment. Small deviations from the ideal design can have a large impact on the intercept factor reducing the ratio of the concentrated sunlight on the tube receiver. According to the literature, the overall optical error can be expressed by the summation of the specularity error, slope error, and misalignment error called also shape error (Equation 2) [13]. The specularity error is referred to the quality of the glass used or exactly to the degree of which the collected rays respect to the law of reflection. The slope errors are directly linked to the manufacturing errors and to the local ripples or the aberrations on the mirrors. Moreover, the shape errors are generally caused by the misalignment of the facets that compose the collector, the geometrical deformations of the structures due to the wind, mirrors and tube weight loads are the main sources of shape error, especially at the operation time where the climates conditions are strong. In additions, others errors also affect the optical efficiency such as the tube receiver position error, the tracking error, and the soiling phenomena. In this work, we only consider the optical errors since the mirrors under test are clean and no tracking errors are counted.

$$\sigma_{opt}^2 = \sigma_{spec}^2 + \sigma_{slope}^2 + \sigma_{shape}^2$$  \hspace{1cm} (2)
3.2. Photogrammetry quality tests

The performance of solar concentrating collectors is strongly sensitive to the optical errors. The geometric precision of the reflectors, the quality of the mirrors used, the tube receiver placement, and the support structures have a significant impact on the concentrator efficiency and thus on the overall performance of the collector’s plant. Therefore, the necessity of a tool to measure the slope errors with adequate precision is important, especially any small deviation from the ideal design can lead to important optical losses. In this sense, a variety of practical techniques have been proposed: The VSHOT system developed by the Sandia and the NREL laboratories using a laser beam scanner and a camera to record the images of the mirror under test, then the software calculates the slope errors and the deviations from the ideal design[14]. As the implementation of the VSHOT for large surface still difficult, the deflectometry technique proposed by the German Aerospace Center (DLR) by Ulmer et al [15] is a robust technique for measuring rapidly the slope errors based on the fringe reflection theory which usually used in the automobile sector to evaluate the specular surfaces. Moreover, the arrangements difficulties when changing the type of reflector to be qualified can be exceeded by using the robust photogrammetry technique developed by Shortis and Johnston[16]. This technique uses the image processing algorithms with which the collector is covered by a various number of marks to locate the mirrors and supports positions and then determine the slope errors. The main advantages of this later are the possibilities of outdoor utilization in the field and the facilities to adapt rapidly the arrangements for different types of reflectors.

In this work, the photogrammetry technique was used to asses and evaluate the optical quality of the PTC under test in order to determine the slope deviations and the surfaces deformations from the ideal design. The method is based on the implementation of many flat retro-reflecting targets and specialized adapters on the mirror supports, mirror panels and on the other control points (Fig. 3). Then, the use of a high-definition camera with self-calibration allow the registration of the 3D coordinate of these object points in several images taken from different shooting positions. Therefore, the collector’s specifications will be added to the inputs of the software algorithms and then automatically calculate deviations of the actual mirror shape (interpolated between measurement points) to the design mirror shape. After the measurement objects are prepared with the measurement targets, the photogrammetric measurement process takes between 3 to 5 min to achieve the necessary accuracy. The Fig. 4 presents the Photogrammetry setup of the PTC under evaluation, the four facets were covered by the coded and Non-coded targets in order to evaluate the geometric precision and the panel orientation of the collector. In addition, the scale of the pictures taken by the camera cannot be determined from the image as it not contains objects of known size. So, including the scale bars of known length in the scene is important and facilitates to detect automatically the camera locations and orientations when the photogrammetric measurements are processed.

Fig. 3. Collector targeting: Non-Coded targets (Left) and Coded targets (Right).
Generally, the reflective behavior of the concentrating mirrors and the absence of the natural points are the main problematic and cause to use the targets points arranged on a concentrator surface. These targets are automatically detected by the photogrammetric software during the evaluation work. As each mirror is mounted to the collector structure at a certain number of points, small deviations and angle errors in these mirror support positions can change strongly the mirror panel orientation and thus lead to significant losses of the light intercepted on the absorber. For that, usually on each mirror mounting point position a Non-coded target is stuck. Moreover, the others targets are distributed over the mirror allowing the identification by the software and ensuring greater precision.

After the targets preparations that take an important care and time, the photogrammetric measurements are processed then by capturing several images in different positions and different viewing using an automatic rotary arm mounted at the top of the collector and capture about 80 images. Therefore, the software calculates the panel angle deviation and the slope deviations in X, Y and Z directions. The Fig. 5 shows the distribution of the slope errors on the collector surface, the green areas denote that no deviation from the ideal design is presented, so all the incoming rays will be concentrated on the center of the tube absorber. Furthermore, the positive sign defined by the red color indicate that the collected rays will be passed above the focal line and below the focal line for the negative value denoted by the blue areas. It may be noted that a negative deviation is presented on the edges of the left facets, and a positive deviation is located on the edges of the right mirrors, thus the RMS slope errors of the tested mirrors is 4.1 mrad. In practical, slightly slope deviations were located on the center of the mirrors contrariwise on the edges of the collector’s facets which significant negative and positive deviations were observed. Using these results, the performance and the geometric precision of the concentrator could be improved by readjusting the collector assembly on the structure. Therefore, using the open source ray tracing software SOLTRACE based on the Monte-Carlo algorithms developed by the NREL [17], the intercept factor is determined and equal to 0.67 which represents the ratio of the energy concentrated on the tube absorber and the total energy captured by the mirrors. Furthermore, the optical efficiency for perpendicular sun on the collector corresponding to the maximum performance that can be reached by the collector is expressed as the product of reflectivity of the mirrors, the transmittance of the receiver glass envelope, the absorptance of the absorber tube, and the overall intercept factor.

\[
\eta_{opt,0} = \rho \alpha \gamma \xi
\]  

(3)
Generally, the reflective behavior of the concentrating mirrors and the absence of the natural points are the main problematic and cause to use the targets points arranged on a concentrator surface. These targets are automatically detected by the photogrammetric software during the evaluation work. As each mirror is mounted to the collector structure at a certain number of points, small deviations and angle errors in these mirror support positions can change strongly the mirror panel orientation and thus lead to significant losses of the light intercepted on the absorber. For that, usually on each mirror mounting point position a Non-coded target is stuck. Moreover, the others targets are distributed over the mirror allowing the identification by the software and ensuring greater precision.

Fig. 4. The Photogrammetry setup: The PTC under test (Left) The retro-reflective targets captured by the camera (Right).

After the targets preparations that take an important care and time, the photogrammetric measurements are processed then by capturing several images in different positions and different viewing using an automatic rotary arm mounted at the top of the collector and capture about 80 images. Therefore, the software calculates the panel angle deviation and the slope deviations in X, Y and Z directions. The Fig. 5 shows the distribution of the slope errors on the collector surface, the green areas denote that no deviation from the ideal design is presented, so all the incoming rays will be concentrated on the center of the tube absorber. Furthermore, the positive sign defined by the red color indicate that the collected rays will be passed above the focal line and below the focal line for the negative value denoted by the blue areas. It may be noted that a negative deviation is presented on the edges of the left facets, and a positive deviation is located on the edges of the right mirrors, thus the RMS slope errors of the tested mirrors is 4.1 mrad. In practical, slightly slope deviations were located on the center of the mirrors contrariwise on the edges of the collector’s facets which significant negative and positive deviations were observed. Using these results, the performance and the geometric precision of the concentrator could be improved by readjusting the collector assembly on the structure. Therefore, using the open source ray tracing software SOLTRACE based on the Monte-Carlo algorithms developed by the NREL [17], the intercept factor is determined and equal to 0.67 which represents the ratio of the energy concentrated on the tube absorber and the total energy captured by the mirrors. Furthermore, the optical efficiency for perpendicular sun on the collector corresponding to the maximum performance that can be reached by the collector is expressed as the product of reflectivity of the mirrors, the transmittance of the receiver glass envelope, the absorptance of the absorber tube, and the overall intercept factor.

\[ Q_{inc} = n_{opt}^{n_{shadow}} n_{endloss}^{n_{DNI}} A_{SF}^{K} c_{l}^{x_{field}} \]

where the \( n_{shadow} \), \( n_{endloss} \), \( x_{field} \), and \( c_{l} \) are supposed equal to 1.

4. Thermal analysis of the Parabolic Trough Concentrator

In the last section, the slope errors were calculated using the robust photogrammetric measurements, the real imperfections and the shape orientation of the mirrors that compose the PTC are identified and calculated. The quality tests of the PTC under evaluation was repeated several times which the geometric precision and the collector structures are readjusted on each time to improve its performance and looking for the adequate geometrical parameters orientation. Once this later were done, the optical efficiency was performed using the Equation 3 taking into account the reflectivity value of the mirrors, the intercept factor, and the product transmittance/absorptance of the tube absorber. In this sense, the thermal energy of the studied PTC can be expressed by the Equation 4, where the main variables are the optical efficiency, the incidence angle modifier, the surface of the collector, and the DNI of the site which the concentrator will be installed. On the other hand, the DNI data used in this study is extracted by an accurate meteorological station installed at the GEP research platform. The meteorological station on this site measures the solar flux, ambient temperature, humidity, atmospheric pressure, wind speed, and direction. Indeed, the left part of Fig. 6 shows the monthly average variation of DNI data of one-year of Benguerir city which Mars, April and June have the maximum solar potential of the year. As the incidence angle modifier was calculated, the daily variation of thermal energy of the studied PTC is determined and presented in the Fig. 7, and also the monthly variation of its thermal energy is performed in the right side of the Fig. 6.
5. Conclusion
A parabolic trough collector installed at the Green Energy Park research platform (Benguerir, Morocco) was studied. The optical evaluation of the PTC using the photogrammetry technique were performed. Moreover, the main procedures of 3D processing and image capturing are presented. The optical analysis and the readjustments of the results obtained by the photogrammetric measurements are leading to identify the slope errors of the real imperfections of the mirrors used and determine the angles orientation deviations of the structure from the ideal shape of the PTC studied. Therefore, thermal performance analysis of the PTC was presented which the thermal energy was calculated according to the total optical error, the angle incidence modifier and the DNI data of one-year of Benguerir city extracted by an accurate meteorological station. The main relevance and results are the following:

- The optical evaluation of the PTC studied was carried out by the experimental photogrammetric measurements which the real imperfections and aberrations of the mirrors composing the PTC were determined, as well as the angles deviations errors of the panels orientations with respect to the ideal shape of the trough.

- The most intense slope errors were located in the edges of the trough, with a maximum value of 12 mrad and an RMS slope errors value of 4.1 mrad characterized the most part of the collector’s mirrors surface.

- The intercept factor determined was 0.67 and the optical efficiency of the PTC was 0.515 at normal incidence.

- The thermal evaluation of the parabolic trough collector was analyzed and performed according to the photogrammetric measurements of the slope deviations of the mirrors and the optical efficiency obtained. The one-year DNI data are used in this evaluation for analyzing the thermal efficiency of this collector under real conditions of Benguerir site. Moreover, some recommendations for the quality enhancement of the PTC were suggested such as the revision and readjustments of some mirrors, the tube absorber alignment and the glass envelope diameter.

References
5. Conclusion

A parabolic trough collector installed at the Green Energy Park research platform (Benguerir, Morocco) was studied. The optical evaluation of the PTC using the photogrammetry technique were performed. Moreover, the main procedures of 3D processing and image capturing are presented. The optical analysis and the readjustments of the results obtained by the photogrammetric measurements are leading to identify the slope errors of the real imperfections of the mirrors used and determine the angles orientation deviations of the structure from the ideal shape of the PTC studied. Therefore, thermal performance analysis of the PTC was presented which the thermal energy was calculated according to the total optical error, the angle incidence modifier and the DNI data of one-year of Benguerir city extracted by an accurate meteorological station. The main relevance and results are the following:

- The optical evaluation of the PTC studied was carried out by the experimental photogrammetric measurements which the real imperfections and aberrations of the mirrors composing the PTC were determined, as well as the angles deviations errors of the panels orientations with respect to the ideal shape of the trough.

- The most intense slope errors were located in the edges of the trough, with a maximum value of 12 mrad and an RMS slope errors value of 4.1 mrad characterized the most part of the collector’s mirrors surface. Then, the intercept factor determined was 0.67 and the optical efficiency of the PTC was 0.515 at normal incidence.

- The thermal evaluation of the parabolic trough collector was analyzed and performed according to the photogrammetric measurements of the slope deviations of the mirrors and the optical efficiency obtained. The one-year DNI data are used in this evaluation for analyzing the thermal efficiency of this collector under real conditions of Benguerir site. Moreover, some recommendations for the quality enhancement of the PTC were suggested such as the revision and readjustments of some mirrors, the tube absorber alignment and the glass envelope diameter.

References


