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Research paper

Evaluation of the design and optical errors for a parabolic trough collector field in an Algerian desert region: Gassi-Touil as a study area

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ABSTRACT

Solar energy of its renewable nature is considered the best alternative for offering effective solutions to the energy and environmental challenges faced by the world. This study is carried out to optically model a parabolic trough collector (PTC) field and study the influence of Gassi-Touil climate on its optical and thermal efficiency. The study allowed the completion of the MATLAB code that allows the calculation of all design and optical parameters of the studied solar collector, taking into account the instantaneous change of incidence angle that has a direct impact on the change in design and optical errors. For the PTC efficiencies, its average optical performance found, is 75.15% and its average thermal efficiency is 70%. Besides, the average rate of total heat loss coefficient is 7.95 W/m^{2}K, the average rate of local concentration ratio on the receiver tube surface is 40.65 and the average rate of heat flow intensity is 36823 W/m^2. The obtained results are very encouraging to exploit this effective solar technology, which will help in preserving fossil resources and progress towards sustainable development in Algeria.

1. Introduction

With the high demand for energy needs worldwide and the growth of environmental concerns, the search for renewable energy sources that are efficient and inexhaustible is an obligation and not an option. Many technologies that allow the exploitation of renewable energies (Bellos and Tzivanidis, 2020a; Rahman et al., 2022; Kallio and Siroux, 2022; Qazi et al., 2015), especially solar energy (Bellos and Tzivanidis, 2020b; Ghodbane et al., 2021c, 2022c; Qazi et al., 2019), which are defined as the best solution to the global energy problem, are exploited by adopting solar collectors such as linear Fresnel reflectors (Bellos, 2019; Ghodbane et al., 2021a, 2016b), parabolic trough collectors (Bellos et al., 2020; Bellos and Tzivanidis, 2019; Ghodbane and Boumeddane, 2017), flat collectors (Said et al., 2016a,b; Ghodbane et al., 2016a), solar dishes (Rafiei et al., 2020; Loni et al., 2020; Basem et al., 2022), heliostat collectors (Pfahl et al., 2017; Hu et al., 2020; Ghodbane et al., 2020a) and evacuated tube collectors (Kalogirou, 2009, 2004; Mehmood et al., 2019). The aforementioned solar collectors can be exploited in daily life such as water heating (Hussain and Hasanuzzaman, 2022b; Fayaz et al., 2018b; Venugopal et al., 2022; Qazi et al., 2014), water distillation and desalination (Fayaz et al., 2022b; Pannucharoenwong et al., 2021; Radwan et al., 2020), cooling and air conditioning (Al-Yasiri et al., 2022; Ghodbane et al., 2022; Hu et al., 2022), electricity production (Fayaz et al., 2019a,b; Barbón et al., 2022), cooking (Khatri et al., 2021; Qazi et al., 2021) and drying (Muruganantham

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Nomenclature

A_a	Solar collector opening area (m^2)
A_b	Lost area resulting from shading (m^2)
A_e	Lost opening area (m^2)
A_f	Geometric factor (/)
A_l	Total loss in the opening area without taking into account the incidence angle (m^2)
A_{shaded}	Shaded area of reflective mirror (m^2)
A_{TL}	Total loss in opening area in terms of incidence angle (m^2)
CL	Curve length of reflective mirror (m)
$D_{A,ext}$	Outside diameter of receiver tube (m)
$D_{A,int}$	Inner diameter of receiver tube (m)
$D_{G,ext}$	Outer diameter of glass cover (m)
$D_{G,int}$	Inside diameter of glass cover (m)
DNI	Direct-Normal Irradiance (W/m^2)
F	Focal distance (m)
h_P	Parabola depth (m)
h_S	Sun height angle (°)
$K(\theta_i)$	Coefficient of the incidence angle modifier (/)
ℓ	Mirror length (m)
$L_{spacing}$	Distance between each two consecutive rows (m)
Op_{error}	Overall average optical error (mrad)
PTCs	Parabolic trough collectors (/)
Q_{DISP}	Distribution of the incident solar power (W/m^2)
R	Outer radius of the receiver tube (m)
r_r	Rim radius (m)
SONATRACH	National company for the research, production, transport, transformation and marketing of hydrocarbons
S_{SA}	Shaded area rate (/)
W	Opening width of the reflective mirror, m (m)

Greek letters

τ	Glass tube transmittivity (/)
γ	Intercept factor (/)
ε_{Ab}	Receiver tube emissivity (/)
ε_G	Glass tube emissivity (/)
α_{Ab}	Receiver tube absorptivity (/)
α_S	Solar azimuth angle (°)
η_{opt}	Optical performance (/)
$\eta_{endloss}$	End loss factor (/)
ρ_m	Mirror reflectivity (/)
φ_r	Rim angle (°)
θ_i	Incidence angle (°)
θ_Z	Zenith angle in a PTC solar power plant (°)
β	Peripheral absorber angle (°)

et al., 2021; Attia et al., 2021). Currently, many valuable scientific studies encourage the use of nanoparticle technology as an enhancer of the heat convection coefficient of heat transfer fluids in solar collectors (Ghodbane et al., 2020b; Bellos et al., 2018; Said et al., 2021a), whereas, the nanoparticles dispersed in the working fluid allow improvement of its thermophysical properties (Rahman et al., 2019; Said et al., 2015; Hussein et al., 2020; Said et al., 2022b; Fayaz et al., 2022a). So renewable and abundant solar energy is the finest and most effective alternative to energy and environmental challenges because energy demand is constantly increasing and the depletion of fossil fuels continues to threaten the environment and energy security (Fayaz et al., 2018a; Filimonova et al., 2021; Nassar et al., 2019; Zhar et al., 2021).

One of the most important areas of the exploitation of solar energy is the production of electricity using solar concentrators (Ghodbane et al., 2019; Wei et al., 2020; Ghodbane et al., 2021b). These systems are known as concentrated thermodynamic solar systems that are considered the most important in the world. These systems generate solar energy using mirrors or lenses to focus a large amount of solar radiation or solar thermal energy on a small area in order to exploit the heat flux intensity later in several industrial applications such as electricity production (Hussain and Hasanuzzaman, 2022a). For example, solar electricity can be produced thermally when the concentrated solar beam radiations are converted into heat, which results in a steam turbine connected to an electric power generator or a thermochemical reaction. Indeed, electricity production through thermodynamic solar power plants has been a real success since their first appearance dating back more than thirty years. This credit goes to the research efforts carried out by several countries such as Germany, Spain, and the USA, etc., that the thermodynamic power plant projects, are enjoying great and real success today (Peinado Gonzalo et al., 2019; Behar, 2018). Among the power plants that are currently adopted globally, the thermodynamic stations that use the parabolic trough collector “PTCs” are the most famous and most effective solar stations that are used to convert the sun’s energy into thermal energy from most of the electricity generation. The emergence of PTC thermoelectric power plants dates back to the 1980s, located exclusively in the United States in the Californian desert with an installed capacity of 354 MWe (Awan et al., 2020; Fernández-García et al., 2010). According to Awan et al. currently, there are 87 PTC plants in service around the world, located mainly in Spain (45 power plants) with a total capacity exceeding 2225 MWe, followed by the United States (15 power plants) with a capacity of around 1361 MWe (Awan et al., 2020). Many PTC thermal plants operate in many parts of the world, there are currently 5 power plants in South Africa, 4 in each Morocco and India, 2 in each the UAE and Italy, one in each Algeria, Saudi Arabia, Kuwait, Egypt, Thailand, Denmark, Mexico, Canada, and Israel (Awan et al., 2020). Among the countries which plan to seriously embark on this type of project, China is leading a very heavy investment, for the construction of six PTC power plants with a total capacity of 414 MWe, plus one station that has been operating since October 2018. For information, many solar power plants in Spain operate continuously day and night since they provide between 7 and 9 h of production after sunset, utilizing the thermal storage system technology (Awan et al., 2020). For PTC plants that are not equipped with a storage system or which are not hybridized with another renewable energy source, a backup of fossil fuels is used to ensure operation during cloudy periods or periods not sunny during the night, but the use of the backup system is limited in the USA and Spain, where the production using fossil fuels must not exceed 25% of the annual production of the PTC power plant in the USA and 15% in Spain (Romero-Alvarez and Zarza, 2007).

The PTC steam temperature can easily exceed 500 °C and the conversion efficiency is generally high compared to linear Fresnel reflector technology (Ghodbane et al., 2021f; Said et al., 2021b; Ghodbane et al., 2021g), it is varied between 62 and 82% (Bellos, 2019; Bellos and Tzivanidis, 2019; Ghodbane and Boumeddane, 2018), where the parabolic trough solar concentrators depend on the use of beam radiation "DNI, (W/m^2)". This study aims to track the optical behavior of a model of a parabolic trough collector from a field collector intended to generate electricity at a power station. Despite the advancement of simulation methods for solar concentrators, mathematical modeling has not been fully elucidated because of the physical phenomenon complexity. This complexity focuses mostly on two factors, the random modeling of beam radiation concentrated on the circular surface of the receiver tube, and the simulation to determine the optical and thermal parameters of the studied system. In this regard, Sandá et al. conducted a review work on simulation and modeling tools for direct steam generation using PTC solar collectors. This study has allowed addressing several important points such as the presentation of technological progress for direct steam generation in the PTC field, while presenting the current challenges (Sandá et al., 2019). They also discussed the methods of thermo-hydraulic and mathematical modeling that govern simulation and modeling tools for direct steam generation in PTC technology (Sandá et al., 2019). In addition, Naveenkumar et al. have provided a comprehensive picture of the various parameters that have a direct impact on the optical and thermal efficiency of PTC-type solar concentrators, and the techniques by which they can improve their efficiency and reduce their costs (Naveenkumar et al., 2021). It was also found that Qin et al. conducted a study that proved that the use of direct-absorption PTC using nanofluids doubles the optical efficiency and reduces the heat loss of the PTC solar collector, as a reflective coating has been applied to the upper half of the outer surface of the inner glass tube to double the length of the optical path (Qin et al., 2019). As for Subramaniyan et al. (2021), they conducted an optical efficiency examination of a PTC-type solar collector with a secondary reflector, allowing its optical efficiency to be improved by 20% compared to a conventional PTC. So, PTC solar collectors are under a continuous development in terms of optical and thermal efficiency, which makes them a suitable technology for exploitation and use in the regions rich in solar radiation such as Algeria.

Algeria seeks to exploit renewable energy sources, as the issue of exploitation and investment in renewable energies is one of the topics that receive great attention from the Algerian government as well as its society. This interest from the Algerian government is due to the reason that country has the potential to push renewable energy sources as an alternative to fossil energies (oil and gas) of limited quantity and known for its damage to the environment, as the exploitation of fossil energy sources in Algeria (oil and gas) in recent years has caused severe damage to the environment, especially in terms of the emission of gases that have polluted the air and the water. In addition, all the centers of extraction, production, exploitation, and treatment of gas and oil are located in the south of Algeria. These centers are known for their presence in isolated desert areas and are known for their large consumption of electricity and hot water, meaning that SONATRACH has to pay imaginary sums to the Algerian company for the production and distribution of electricity. Accordingly, the Algerian government has considered alternative proposals, the most important of which is relying on alternative renewable energy, especially solar energy, which can be exploited on a large scale in the regions of southern Algeria due to its availability of huge amounts of sunlight. Therefore, the good exploitation of solar energy in Algeria can allow the production of sixty times the need of European countries for electric energy and four times the equivalent of the world's need, and this is because Algeria has a vast desert and large amounts of sunlight. As a result, the Algerian state speeds up the launch of projects in southern Algeria that allow the exploitation of solar energy for use in heating water and producing electricity, thermal and photovoltaic, and also encourages to work hard to give ideas and projects that allow rationalizing energy consumption, rationalizing it and tightening its means to achieve economic prosperity and material progress. This paper is one of the projects that can embody SONATRACH in one of the regions of southern Algeria known for its gas and oil processing centers, where a detailed optical analysis of a PTC solar field will be presented that allows converting direct sunlight into heat energy that is exploitable in several fields, resulting in a significant reduction in the electricity bills paid by SONATRACH.

Table 1
Dimensions of the studied solar collector.

Dimension	Value
Focal distance (F)	0.6 m
Glass inside diameter ($D_{G,int}$)	0.0175 m
Glass outer diameter ($D_{G,ext}$)	0.02 m
Mirror curve length (CL)	1.2481 m
Mirror length (ℓ)	12.27 m
Mirror opening width (W)	1.2 m
Parabola depth (h_p)	0.15 m
Receiver inner diameter ($D_{A,int}$)	0.0142 m
Receiver outer diameter ($D_{A,ext}$)	0.016 m
Rim angle (φ_r)	53.13°
Rim radius (r_r)	0.75 m

Table 2
Optical characteristics of the studied solar collector.

Parameter	Value
Overall average optical error (O_{perror})	3 mrad
Mirror reflectivity (ρ_m)	0.92
Glass tube transmittivity (τ)	0.945
Receiver absorptivity (α_{Ab})	0.94
Receiver emissivity (ε_{Ab})	0.12
Glass tube emissivity (ε_G)	0.935

Therefore, the main objective of this work is to calculate the optical coefficients of the PTC solar collector in terms of its engineering dimensions and climatic conditions for 21/03/2022 at the Gassi-Touil region in Algeria. This region (latitude 30°31′00″ North, longitude 6° 28′00″ East, and altitude 195 m) is characterized by its strong solar radiations all year round, but also by its desert climate and its particularly strong winds of sand in autumn and spring.

This study relies on the numerical simulation of the optical behavior equations that govern the studied solar collector model. MATLAB code is used as a programming tool. Water has been used as a heat transfer fluid. The simulation allows the identification of all the important PTC optical coefficients, i.e. the cosine effect of the incidence angle, the optical losses at the ends of the receiver tube, the shading effect, the blocking effect, the coefficient of incidence angle modifier, the intercept factor, the optical efficiency and the local concentration ratio (LCR). In addition, the distance between each consecutive row of field collectors will be determined.

2. Materials and methods

As shown in Fig. 1, Parabolic Trough Concentrator generally includes a reflective mirror and a receiver tube through which a heat transfer fluid circulates, where the dimensions shown in Fig. 1 represent the dimensions of the studied solar collector.

Table 1 contains the PTC dimensions, while Table 2 contains the optical properties of the PTC components.

The direct normal irradiance reaching the reflective mirror is reflected and focused on the outside surface of the receiver tube where the radiant energy is converted into thermal energy.

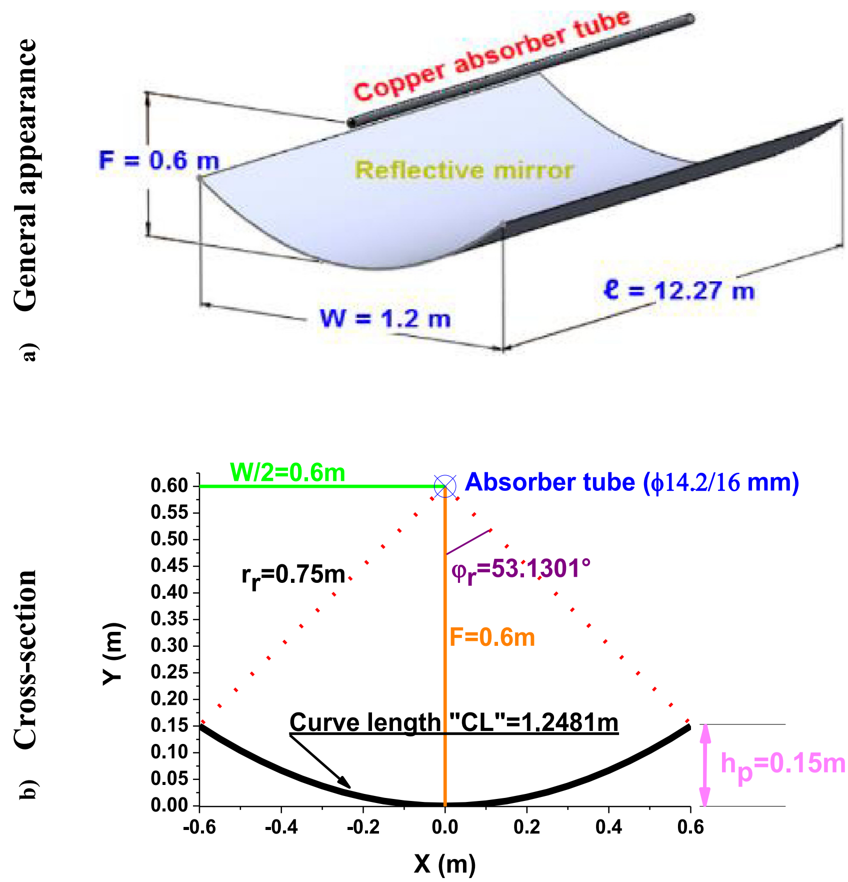

Fig. 1. Dimensions of the studied collector: (a) Longitudinal view (Bellos et al., 2018), (b) Cross-section.

For the existing optical losses, there are two types, the first is related to design errors and the second is related to uncertainties in the optical coefficients related to weather conditions and operating conditions. These losses arise from one of the following factors:

- Deformation of the metal structure, scratch of the reflective mirror breakage of the glass tube, which can occur due to the violence of sand winds and storms;
- Fouling of the mirrors and glass tube due to the deposition of sediments, dust, and grains of sand on them; causing the degradation of the optical characteristics of the PTC components such as the mirror reflectivity, the glass cover transmissivity, thus influencing the optical and thermal efficiency, i.e. the overall performance and total production of the power plant;
- Bad weather conditions reduce the hours of operation of the solar field even in the presence of strong solar irradiation, which affects the efficiency of the power plant and reduces its solar energy contribution capacity, which results in an excessive consumption of fossil fuels.

Therefore, the direct solar radiation incidence angle has an effect on the change in the optical performance of the studied collector, so it has to be the best choice for the optical and design parameters of the studied field of PTC solar collectors. With regard to direct solar radiation, its quantity varies spatially and temporally (change of place and time) according to several factors, the most important of which are the incidence angle of the sun's rays, the difference in the length of the day (change of seasons), the transparency of the gas envelope, the difference in terrain, and the albedo. With regard to the incidence angle of solar rays on the ground, it affects the amount of rays received by the PTC solar collector, because the vertical or semi-vertical rays are more powerful and more focused, due to the distance they travel is shorter than the oblique rays. Therefore, they are less likely to be lost by absorption, reflection, and diffusion. Also, the vertical rays are distributed over a small area, while the oblique rays are distributed over a larger area, which makes them weaken and become less focused than the vertical rays. Hence, the smaller the incidence angle of the sun's rays, the greater the value of the direct solar rays reflected in the PTC reflective mirror. Accordingly, the incidence angle modifier allows correcting and approximating the values of the amounts of solar radiation reflected by the PTC mirror and absorbed by the receiver tube. In addition, the PTC optical efficiency is calculated as the product of various optical parameters such as the absorber absorptivity, the PTC mirror reflectivity, the glass tube transmittivity, and the intercept factor. In addition, an extra parameter, the incident angle modifier is used to take into consideration the optical efficiency variation for the different sun positions, as the PTC collector needs a single-axis tracking mechanism to track the sun position correctly.

2.1. Loss due to optical errors

Generally, the optical errors are divided into two classes, as follows:

- Random errors: they are caused by the environmental factors in which the studied PTC lies under, as it is directly affected by the engineering accuracy of the reflective mirror and its reflectivity, due to the presence of dust and dirt on the receiver tube and the mirror (Ghodbane and Boumeddane, 2018; Pierucci et al., 2014);

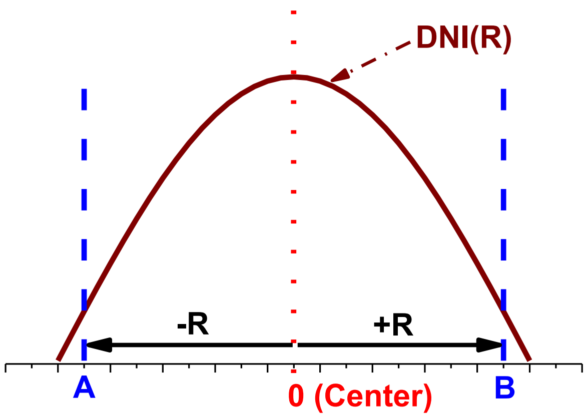

Fig. 2. Direct solar irradiance distribution over the receiver tube surface (Ghodbane et al., 2021e).

- Non-random errors: they are directly related to optical coefficients that depend on the properties of the materials used in the design of the studied PTC, the correct positioning of the receiver tube in the focal line, and the inclination angle errors of the mirror (Kalogirou, 2009; Ghodbane and Boumeddane, 2018; Pierucci et al., 2014; Breeze et al., 2009; Kalogirou et al., 1996; Kalogirou, 1996; Guven and Bannerot, 1986; Guven, 1986).

Generally, optical losses are associated with four parameters such as mirror reflectivity, the glass cover transmittivity, the receiver absorptivity, and the intercept factor "γ". The intercept factor is given by (Ghodbane and Boumeddane, 2018; Said et al., 2019) (see Fig. 2):

$$\gamma = \frac{\int_{A}^{B} \mathrm{DNI(R)dR}}{\int_{-\infty}^{+\infty} \mathrm{DNI(R)dR}} \tag{1}$$

Optical efficiency is defined as the ratio of the energy absorbed by the receiver tube and that reflected by the reflective mirror. It depends on the optical properties of the materials used, the geometry of the PTC, and the various imperfections due to its construction. It is given by (Ghodbane and Boumeddane, 2017; Ghodbane et al., 2021d):

$$\eta_{opt} = \rho_m.\gamma.\tau.\alpha_{Ab}.K(\theta_i) \tag{2}$$

With $k(\theta_i)$ represents the coefficient of incidence angle modifier, it is given by (Ghodbane et al., 2021e):

$$K(\theta_i) = 1 - (A_f.\tan(\theta_i).\cos(\theta_i)) = 1 - A_f.\sin(\theta_i) \tag{3}$$

2.2. Loss due to design errors

Design loss is directly related to the incidence angle "θ_i, (°)". As Figs. 3 and 4 illustrate, that there are many design loss coefficients. The geometric coefficient "A_f" can be calculated as following (Kalogirou, 2009; Jeter et al., 1983):

$$A_f = \frac{A_l}{A_a} = \frac{A_{TL}}{A_a.\tan(\theta_i)} \tag{4}$$

With "A_{TL}, (m^2)" represents the sum of the lost opening area "A_e, (m^2)" (Kalogirou, 2009; Jeter et al., 1983), and the lost area resulting from shading "A_b, (m^2)" (Kalogirou, 2009; Jeter et al., 1983; Jeter, 1986, 1987).

$$A_{TL} = A_e + A_b$$
$$\begin{cases} A_e = F.W.\tan(\theta_i)\left[1 + \dfrac{W^2}{48F^2}\right] \\ A_b = \dfrac{2}{3}W.h_P.\tan(\theta_i) \end{cases} \tag{5}$$
$$\Rightarrow A_{TL} = A_e + A_b = A_l.\tan(\theta_i)$$

As for the end loss factor "$\eta_{endloss}$" at both ends of the receiver tube, it is given by (Lippke, 1995):

$$\eta_{endloss} = 1 - \frac{F}{\ell}\tan(\theta_i) \tag{6}$$

In the PTC field collector, the solar collectors are arranged in parallel rows. The distance "$L_{spacing}$, (m)" between every two consecutive rows for a PTC solar power plant is given by:

$$L_{spacing} = \max\left[\frac{W.\cos(\theta_i)}{\cos(\theta_Z)}\right] \tag{7}$$

where "θ_Z, (°)" is the zenith angle in the field collector.

As is known, the shading area "A_{shaded}, (m^2)" on a reflective mirror decreases with the increase of the sun height angle "h_S, (°)", so it increases proportionally with the increase of the incidence angle. Therefore, the shading area factor "η_{shadow}" can be calculated as follows:

$$\eta_{shadow} = 1 - \frac{A_{shaded}}{A_a} = 1 - S_{SA} \tag{8}$$

With "$S_{SA} = A_{shaded}/A_a$" is the shaded area rate. As for the shading area, it is given by:

$$A_{shaded} = \ell\left(W - L_{spacing}\frac{\cos(\theta_Z)}{\cos(\theta_i)}\right) \tag{9}$$

The optical modeling is carried out through the digital program, which is established and written in the MATLAB language.

2.3. Thermal analysis

In 1986 (Jeter, 1986), Jeter et al. performed a mathematical analysis to follow the optical behavior of a PTC solar collector, where they arrived at analytical solutions of the density distribution of the concentrated flux on a cylindrical receiver as well as the local concentration ratio. According to Jeter (1986), the distribution of the incident solar power on the receiver tube is evaluated by the following relations:

- At the top of the receiver tube (Ghodbane et al., 2022a):

$$Q_{DISP} = DNI.\cos(\theta_i).\cos(\pi - \beta) \tag{10}$$

- At the bottom of the receiver tube (Ghodbane et al., 2022a):

$$Q_{DISP} = DNI.LCR \tag{11}$$

where the local concentration ratio (LCR) is given by (Jeter, 1986):

$$LCR = \frac{\frac{2F}{R}\cos(\theta_i)}{1 + \cos(\varphi_r)} \tag{12}$$

Regarding PTC thermal efficiency, it is given by (Ghodbane et al., 2021d):

$$\eta_{th} = \frac{Q_{gain}}{DNI.A_a} = \frac{\dot{m}.Cp_F\,(T_{out} - T_{in})}{DNI.A_a} \tag{13}$$

In Ref. Said et al. (2022a) there is all the detail of the mathematical model for analyzing the energy and thermal balance of the receiver tube.

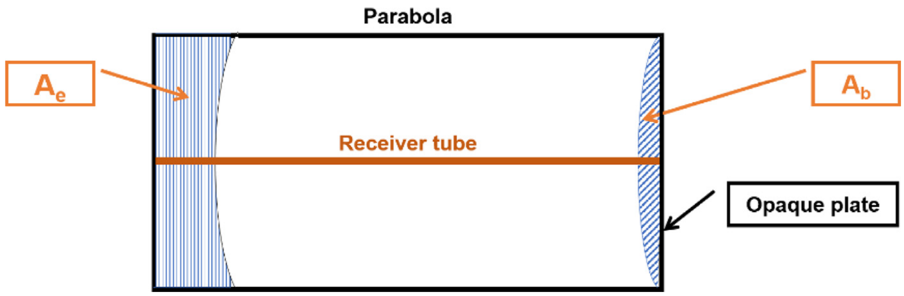

Fig. 3. Lost areas by the end effect and the blocking effect (Ghodbane et al., 2021e).

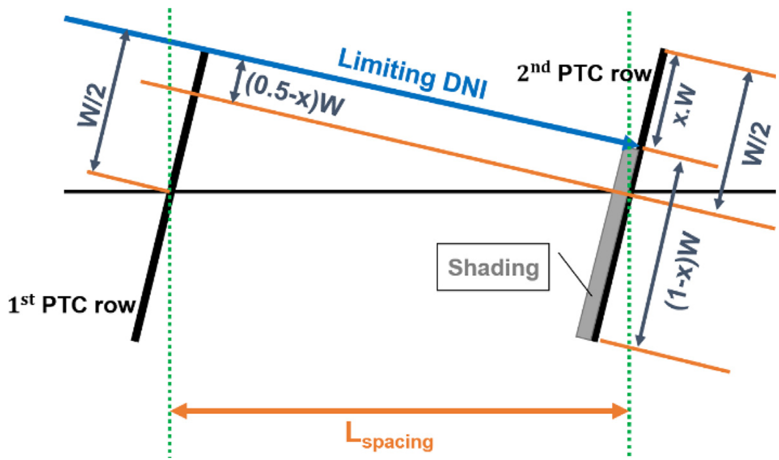

Fig. 4. Shaded area caused by two consecutive rows in a PTC field collector (Ghodbane et al., 2021e).

3. Results

In order to model the optical performance of any solar collector, it is important to define the geometric and optical characteristics of each subsystem that composes it. In order to achieve this, a MATLAB code has been implemented that allows calculating all engineering and optical parameters for the studied solar collector by adopting real weather conditions for the day 21/03/2022 in the Gassi-Touil region.

3.1. Weather data

Gassi-Touil is located 1000 km southeast of Algiers and 150 km south of Hassi-Messaoud. Gassi-Touil is an Algerian oil and gas exploration zone, which is part of the production division of the SONATRACH company, where all of the region's gas and crude oil production is transported by pipeline. Gassi-Touil is located in a harsh, desert environment subject to thunderstorms and sandstorms. Moderate winds are a major feature of this region, where the main wind direction is East, but generally, these winds do not cause sand uplift. Due to the difficult desert nature of this region, the renewable energy resources available here, such as solar energy, can be exploited in many industrial and living uses. Further, the solar radiations can be very strong in general throughout the year, especially in the summer, as this will lead to higher temperatures. These large amounts of solar radiations can be exploited in cooling, air conditioning, industrial applications, and electricity production by using solar collectors, including PTC collectors. Fig. 5 shows the change in the weather data for the studied area for March 21, 2022, where this day is the typical day for the month of March.

From Fig. 5, it is concluded that direct solar irradiance varies between 158.34 and 852.50 W/m^2 and its average rate is 667.44 W/m^2. As for the ambient air temperature, it varies between 287.41 and 298.75 K, and its average rate is 295.10 K. With regard to the change in wind speed, its highest value is 5.40 m/s, its lowest value is 2.70 m/s, and its average value is 4.33 m/s. Therefore, the weather data for the studied area encourages moving forward to exploit solar energy in particular and the rest of the energy types of renewable energy in general.

3.2. Optical coefficients assessment

The incidence angle is the angle formed by the incident direct solar radiations and the opening plane normal of the PTC collector. The DNI incidence angle is a very important factor, since the useful direct radiation fraction to the PTC collector is directly proportional to the cosine of this angle, where a non-zero incidence angle ($\theta i \neq 0$) can cause several optical losses. Fig. 6 shows the change in incidence angle vs. time for the studied day.

According to Fig. 6, the incidence angle varies in this study from 31.61 to 86.9°, where their values are greater than zero, i.e. there is an optical loss that will be determined by specifying the optical and design coefficients.

For optical coefficients, there are two, which are illustrated in Fig. 7. The first parameter is the intercept factor, which is the solar radiations fraction reflected by the reflecting opening of the PTC solar collector and intercepted by the receiver tube. From Fig. 7, it is concluded that the increase in incidence angle leads to a decrease in the intercept coefficient (inverse variation). For this study, the highest value of the intercept coefficient is 0.97, the lowest value is 0.92 and its average rate is 0.968.

The second optical factor is the coefficient of incidence angle modifier "K(θ_i)", it is less than 1 and decreases with the increase of the incidence angle "θ_i, (°)". This coefficient is directly related

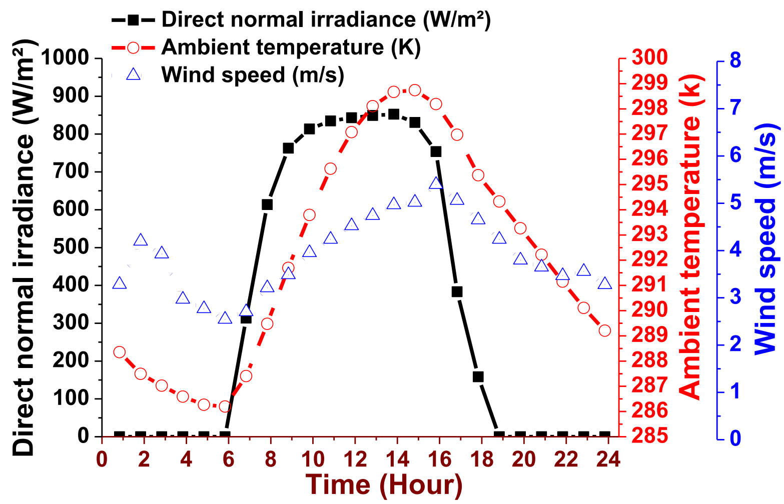

Fig. 5. Change in weather data (March 21, 2022).

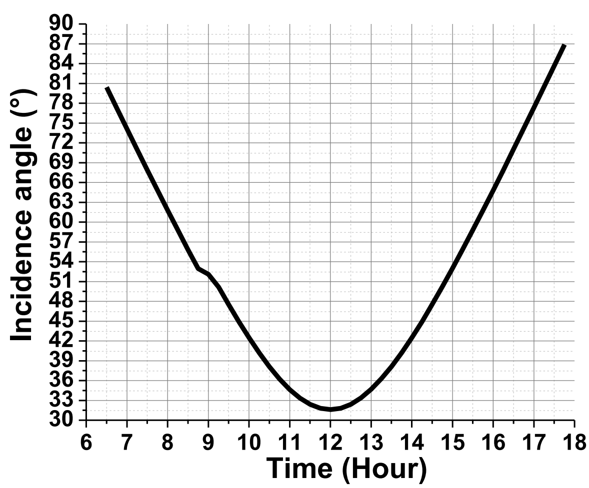

Fig. 6. Change in incidence angle vs. time.

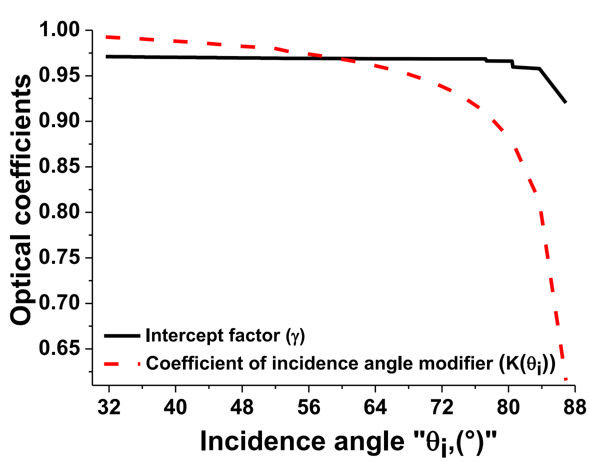

Fig. 7. Optical coefficients evaluation.

to the cosine variation of the incidence angle "θ_i, (°)". For this study, its maximum value is 0.9925 with "$\theta_i = 31.61°$", its lowest value is 0.6152 with "$\theta_i = 86.9°$" and its average rate is 0.957.

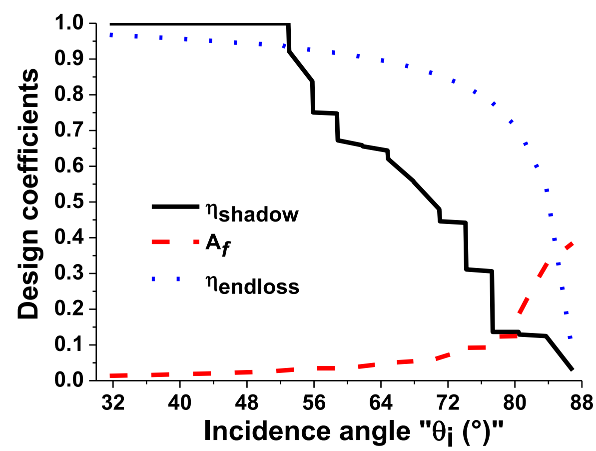

Fig. 8. Design coefficients evaluation.

Generally, the DNI incidence angle depends on the PTC orientation (i.e. its position relative to the Azimuthal plane) and the position of the sun in the sky (i.e. its sun height), so it depends on the day of the year and on each hour of the studied day.

3.3. Design coefficients assessment

The ultimate function of the specular mirrors that constitute a solar field is to collect and then reflect the maximum of incident radiation towards a solar receiver located at a well-defined position. However, there are always design errors that are defined by estimating design factors. These design parameters are the geometric coefficient "A_f", the shading area factor "η_{shadow}" and the end loss factor "$\eta_{endloss}$". In this study, a numerical model was developed in MATLAB language to predict the design coefficients. Fig. 8 illustrates the design factors variation vs. incidence angle.

From Fig. 8 it is concluded that:

- The maximum value of the geometric coefficient is 38.53%, while its lowest value is 1.35% and its average rate is 5.36%. In addition, the increase in incidence angle leads to an increase in geometric factor (Positive relationship);
- The maximum value of the shading area factor is 100%, while its lowest value is 2.9%. Its average rate is 76.44%. In addition, the increase in incidence angle leads to a decrease in the shading area coefficient (Inverse relationship);

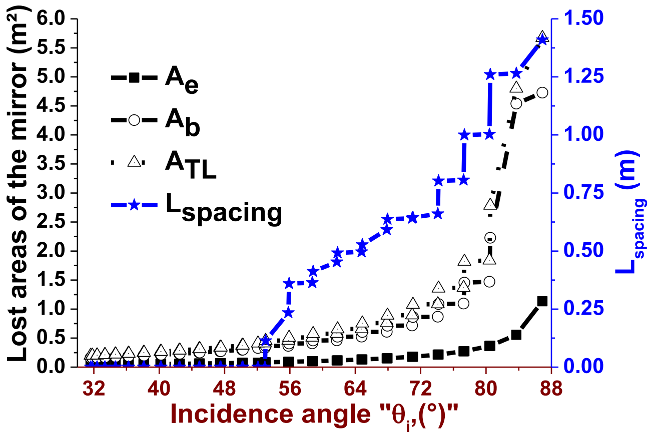

Fig. 9. Change in lost areas of the reflective mirror and $L_{spacing}$ vs. the incidence angle.

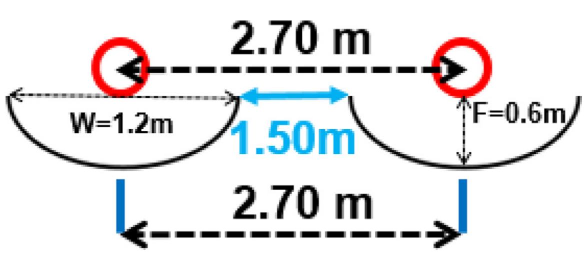

Fig. 10. The ideal distance between every two consecutive rows for the studied field collector.

- The maximum value of the end loss factor is 96.75%, while its lowest value is 7.52%. Its average rate is 88.70%. In addition, the increase in incidence angle leads to a decrease in the shading area coefficient (Inverse relationship).

Fig. 9 contains the change in the lost areas and the distance between two consecutive rows of mirrors inside the same solar field collector in terms of incidence angle.

According to Fig. 9, it is concluded that:

- The maximum value of the lost opening area "A_e, (m^2)" is 1.13 m^2, while its lowest value is 0.04 m^2 and its average rate is 0.14 m^2;
- The maximum value of the lost area resulting from shading "A_b, (m^2)" is 4.73 m^2, while its lowest value is 0.16 m^2 and its average rate is 0.65 m^2;
- The maximum value of distance "$L_{spacing}$, (m)" between every two consecutive rows is 1.41 m, while its lowest value is 0.001 m. Its average rate is 0.31 m. Despite these values of distance between two consecutive rows, a distance between the two rows should remain at midday ($\theta_i = 31.61°$) in order to facilitate movement in the maintenance event or any other circumstance worthy of interference, so the ideal distance as shown in Fig. 10 to be left between the centers of two consecutive rows is "W + 1.5 = 1.2 + 1.5 = 2.7 m", this distance will allow the disposal to the fullest extent of the loss caused by shading;
- The increase in incidence angle leads to an increase in "A_e, A_b and $L_{spacing}$" (Positive relationship).

As it is observed, all design and optical parameters have a direct relationship, either directly or inversely to the incidence angle.

3.4. Assessment of PTC efficiencies

The most important parameters to define when assessing the PTC solar concentrator performance are the optical and thermal efficiencies, which are dependent on the optical and thermal losses. For this study, the receiver tube and the glass cover are centered on the focal axis. In addition, the glass cover is considered opaque to infrared radiation and the temporal variations in the thickness of the receiver tube and the glass cover are negligible. Fig. 11 shows the change in the optical and thermal performance of the studied solar collector, as well as the change in the overall coefficient of the thermal loss.

The optical performance is based on the incidence angle, i.e. it is in terms of the incidence angle modifier. Through Fig. 11, it is concluded that:

- The maximum value of optical efficiency is 77.56%, while its lowest value is 70.54% and its average rate is 75.15%;
- The maximum value of thermal efficiency is 72.55% between 12h00 and 13h00, while its lowest value is 61.04% at 06h00 and its average rate is 70%;
- The maximum value of the total heat loss coefficient is 9.55 W/m^2 K, while its lowest value is 4.62 W/m^2 K and its average rate is 7.95 W/m^2 K.

So, the studied collector performances include all types of optical losses such as shading losses and geometric losses that occur at non-zero incidence angle solar radiations and which are counted through the incidence angle modifier.

The study was carried out for a PTC solar collector with a north–south rotation axis with a tilt angle of 31.61° towards the south in order to follow the trajectory of the sun from sunrise to sunset. Fig. 12 illustrates the distribution of heat flux intensity on the receiver tube surface with "DNI = 905.94 W/m^2" and an incidence angle "$\theta_i = 31.61°$". It is noted that the distribution of heat flux is not uniform in the circumferential direction of the tube, it is in terms of peripheral absorber angle "β, (°)".

In addition, the thermal flow is concentrated on the lower part of the circular surface of the receiver tube in the peripheral absorber angle field "β, (°)" from 91 to 269°. At the upper part of the receiver tube where the peripheral absorber angle field "β, °" from 0 to 90° and from 270 to 360°, the heat flow intensity is very low because DNI solar radiation reaches this part without concentration. Through Fig. 12, it is concluded that:

- On the bottom part: the maximum value of heat flux intensity is 113 186.5 W/m^2, its lowest value is 56 593.25 W/m^2, and its average rate is 73 212.84 W/m^2. For the local concentration ratio, the maximum value of "LCR" is 124.94; its lowest value is 62.47, while its average rate is 80.81. As it can be noted, the LCR value at the bottom of the receiver tube is high (LCR = 124.94) because the outer diameter of the receiver tube is small and a large number of direct solar radiations are focused on it, allowing the focus of this large number of rays in one point, which corresponds to the peripheral absorber angle "$\beta = 91°$ and $\beta = 269°$ ";
- On the upper part: the maximum value of heat flux intensity is 702.39 W/m^2, while its lowest value is 4.3×10^{-14} W/m^2 and its average rate is 434.79 W/m^2. For the local concentration ratio, the maximum value of "LCR" is 0.775, while its lowest value is 4.75×10^{-17} and its average rate is 0.48.

Therefore, the total average of the local concentration ratio on the receiver tube surface is 40.65, while the total average heat flux intensity is 36 823 W/m^2.

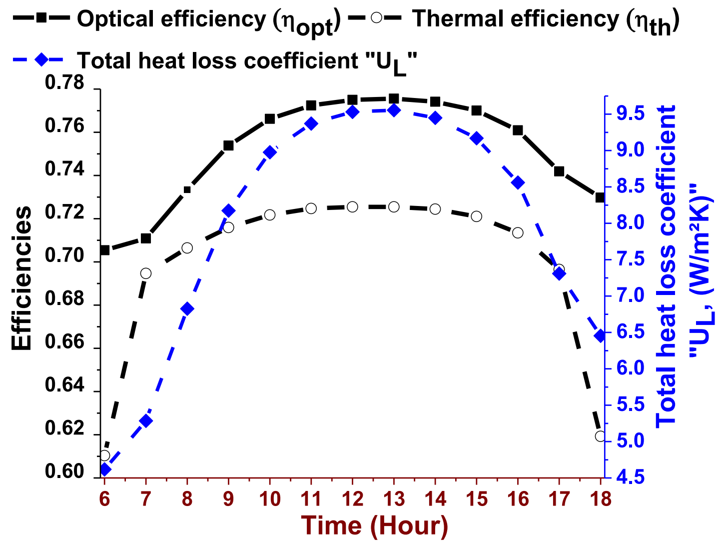

Fig. 11. PTC efficiencies evaluation.

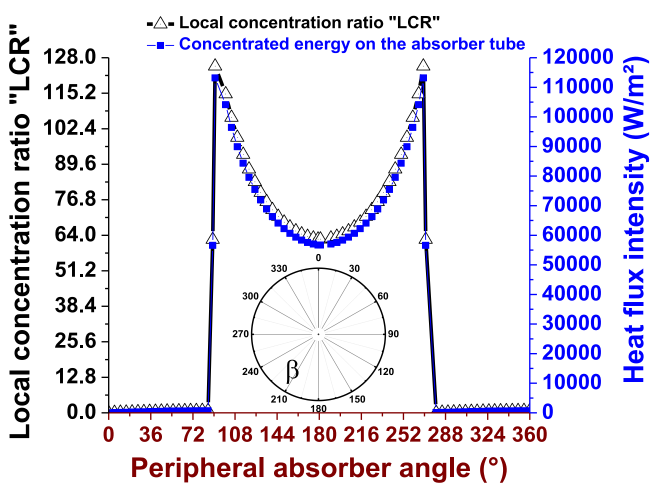

Fig. 12. Distribution of heat flux intensity on the receiver tube surface with "DNI $= 905.94$ W/m^2" and an incidence angle "$\theta_i = 31.61°$" vs. peripheral absorber angle "β, (°)".

4. Conclusion

The subject of this numerical study is about tracking optical behavior and the influence of design factors on the performance of a parabolic trough solar collector for March 21, 2022, in Gassi-Touil, Algeria. The rotation of the PTC collector is from East to West, where the collector makes a daily follow-up movement going from East at the start of each day to the West, where the system will end its daily follow-up run. The study enabled to identify all design and optical errors of the studied solar collector, where it is observed that:

- The average rate of intercept factor is 0.968;
- The average rate of the coefficient of incidence angle modifier is 0.957;
- The average rate of geometric factor is 5.36%;
- The average rate of shading area factor is 76.44%;
- The average rate of end loss factor ($\eta_{endloss}$) is 88.70%;
- The average rate of lost opening area "A_e, (m^2)" is 0.14 m^2;
- The average rate of the lost area resulting from shading "A_b, (m^2)" is 0.65 m^2;
- The ideal distance to be left between the centers of two consecutive rows is 2.7 m.

As for PTC efficiencies, its average optical efficiency is found as 75.15%, while its average thermal efficiency is 70%. With regard to the average total heat loss coefficient, it is estimated at 7.95 W/m^2 K. In addition, the average rate of local concentration ratio on the receiver tube surface is 40.65, while the average rate of heat flow intensity is 36 823 W/m^2.

In a conclusion, it can be said that the completed numerical model allowed for the calculation of all the aforementioned important design and optical factors, and gave very reasonable results. The results obtained are encouraging, where utilizing this effective solar technology will help greatly to reduce dependence on fossil resources and advance towards sustainable development in Algeria and other global regions with similar weather conditions and solar radiations. Currently, Algeria has established a national program for investing in renewable energy, by allocating a large financial envelope to the projects of concentrated solar power stations in order to establish its new energy policy.

CRediT authorship contribution statement

Mokhtar Ghodbane: Writing – original draft, Methodology, Software, Simulation, Supervision. **Boussad Boumeddane:** Investigation, Supervision, Simulation, Writing – review & editing, Formal analysis. **Fayaz Hussain:** Writing – review & editing, Methodology, Formal analysis. **Rania Zhar:** Writing – review & editing, Methodology, Formal analysis. **Khadija Lahrech:** Writing – review & editing, Methodology, Formal analysis. **Jahanzeb Bhatti:** Writing – review & editing, Methodology, Formal analysis. **Bo Zhang:** Writing – review & editing, Methodology, Formal analysis. **Hayati Yassin:** Writing – review & editing, Methodology, Formal analysis. **Liyanage C. De Silva:** Writing – review & editing, Methodology, Formal analysis. **Arsenio Barbón:** Review, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

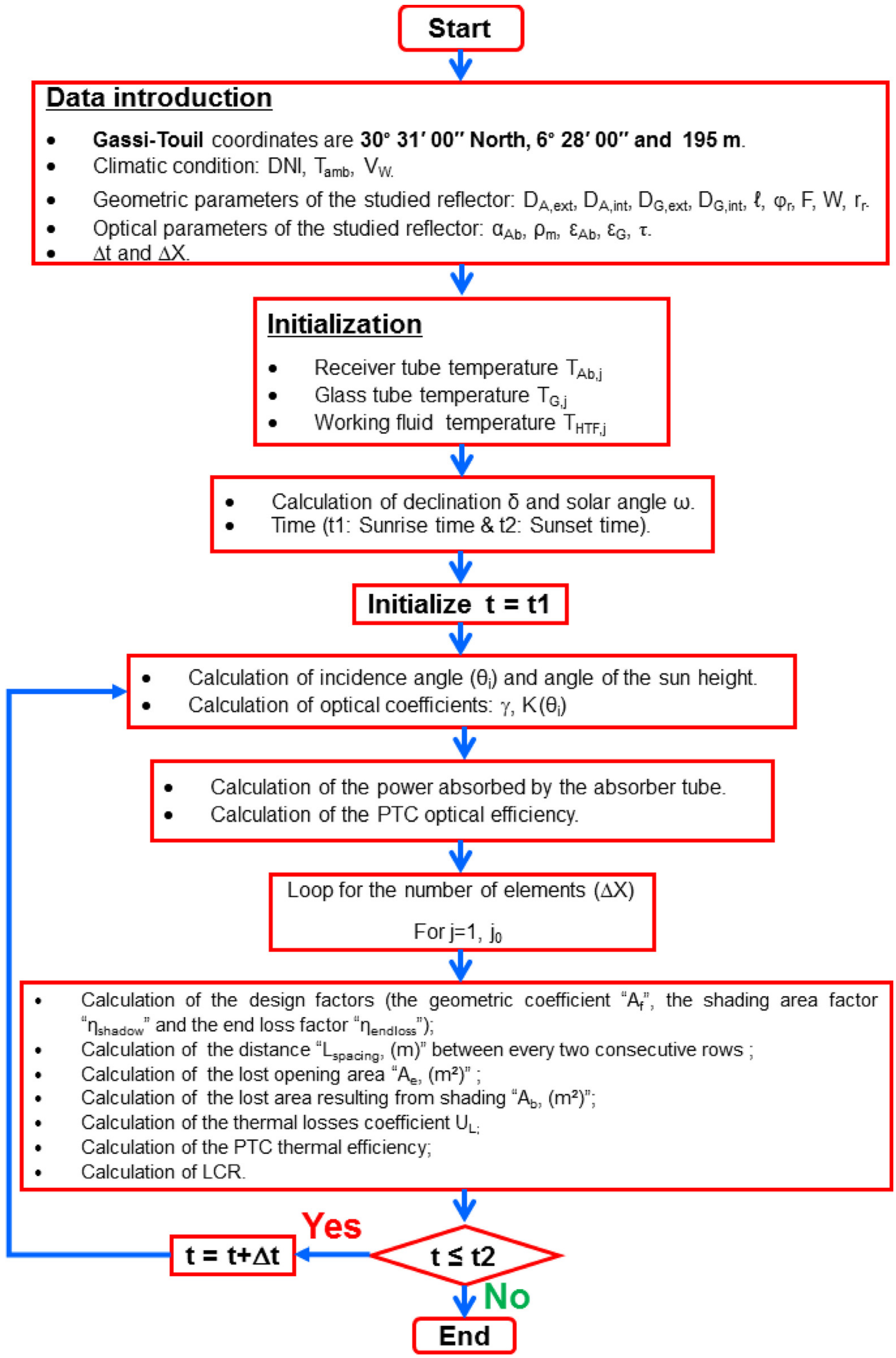

Fig. A.1. Flowchart of the optical and thermal balance of the studied PTC solar field.

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Appendix

See Fig. A.1.

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