Thermal performance assessment of the novel solar system using Fresnel concentrated solar power system and assessing their impact towards environment: Preliminary study

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Abstract: - This work is concerned with assessing the thermal performances of a solar CSP system using linear Fresnel reflector (LFR). The main objective of this paper is validation the preliminary experimental work carried out in august 2023 on the concentrator in the climatic conditions of Algerian city “Bou Ismail”, where we did not used the heat carrier fluid. Growth energy demand, coupled with increasing energy security and climate change, is posing a challenging scenario for the future energy supply. Fossil fuels is the dominant energy source in the industrial sector, and their uses continues to grow, exerts negative influence on the environment. Hence, it is inevitable looking out for an alternative source that representing a powerful, clean, endless, and reliable source of energy meeting the requirements of the worldwide energy structure transformation. Renewable energy technologies, are increasingly gaining, among which solar energy will certainly play an important role in the future. Concentrated Solar Power (CSP) system is one of the promising kind of solar energy since it is clean sources of energy and contributes minor impacts toward the environment. The main objective of this study is validation the experimental work carried out in the summer of 2023 on the linear Fresnel reflector (LFR) in the climatic conditions of Algerian city “Bou Ismail” by a numerical simulation. The main contribution of this paper is the design and feasibility analysis of a novel LFR system made out of equi-spaced mirror elements of equal width with an innovative receiver and their energy applications for better management of energy needs in different areas and in both residential and commercial buildings. Indeed, the first prototype LFR CSP established at Solar Equipment Development Unit UDES produces heat reaching 250°C. Apart from the power applications, the device dramatically reduces the global warming by limiting the gases emissions compared to conventional process.

Key-Words: - Renewable energy, Solar energy, Concentrated solar, Environmental impacts, Power supply, Greenhouse gas

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1 Introduction

The excessive combustion of fossil fuel have become a global problem threatens the environmental [1-4]. Cov pandemic caused a severe decline in gross available energy worldwide in recent years which leads to dropping in the share of fossil fuels, while renewable energies grew [1]. Renewable energies produce energy from theoretically unlimited resources, or reconstitutable more quickly than they are consumed [5]. In recent years, renewable energy represented by solar energy has developed rapidly. Solar energy is an endless cleaning energy source that can mitigate the environmental issues brought by fossil fuel consumptions [6]. CSP present the most possibilities for exploitation due to their profitability in terms of performance, and the high yields, which can be, exploit it for consumptive and productive purposes [7]. Of the many feasible designs of CSP, the ones based on the Fresnel reflector configuration appear to possess good prospects. Otherwise, this approach has the advantage of ease of fabrication, is cheap and can usually withstand the normally encountered wind loadings. Notably the use of LFC technology for electricity production is an attractive alternative for the conventional one [8-9]. Regardless of the effectiveness of this technology, it requires costs lower investments compared to other solar concentrator technologies. Specifically, this study deals with LFC systems, in which a practical design of linear Fresnel concentrator made out of long narrow segments of flat mirrors arranged in planar configuration [10]. Such LFC configuration, as employed in this approach, is design out of equi-spaced of equal width mirrors tilted at an angle so as all incident solar rays falling on them formed an overlapping image of the sun on the absorber tube [10]. Moreover, a tracking system has added guaranteeing the reflection of solar beam to a receiver. In the case of ideal tracking, it is recommended that the linear Fresnel concentrator be constituted of a large number of flat mirror elements, each of which has a finite width and length equal to the length of the linear receiver. The collected heat will mainly exploited for consumptive and productive purposes such as to produce a steam to generate a turbine. With the intention of preventing the unwanted threats to the planet, this process limits the gases emissions and decreases the environmental impacts compared to conventional process.

2 LFC description and methodology

The LFC prototype manufactured at UDES for the experimental process was designed with the aim of generating electricity, warming water up and generating vapor. In Fresnel linear concentrator technology, the incident rays are reflected by the mirror field and focused on the linear receiver. Each flat plat mirrors follows the path of the sun throughout the day in an individual way. Mirror movement must be high precision to minimize optical loss [10-12]

2.1 System description

An overall description of the LFC is made followed by the explanation of the instrumentation used to obtain the experimental data. There are several systems of this type in the world, but each device stands out from the other by something new or original.

Fig. 1 presents a prototype of a linear Fresnel concentration solar system with an innovative receiver. The main components of the LFR CSP system are the reflectors field or mirrors, receiver tubes and tracking system. Specifically, this paper deals with LFC reflector-concentrator, designed and fabricated for the present investigations, which is made from 12, 3-m long, narrow mirror strips arranged in a rectangular planar configuration flat frame and oriented so as to form a linear image of the sun on the receiver. The 12 strips are 0.5 m wide. The reflecting strips used for the present investigations are the commercially available back-coated mirrors (of reflectivity p = 0-6). The back-coated mirrors, despite their inferior reflectance, were preferred to avoid deterioration due to dust, environmental pollution, heavy monsoon rain, fouling by birds, etc. These geometrical parameters assume no shading of the mirror or blocking of the reflected light by the neighboring mirror elements. Each mirror element is pivoted at its two ends on easily steerable mounts such that it can be rotated freely about an axis along its length. The tilt of each constituent mirror element is chosen to form an overlapping image of the sun on the absorber tube guaranteeing that the maximum of the sun's rays laid out on the collector are reflected towards the receiver. These mirrors are tracked with Arduino microcontroller that tracks the Sunrays so that receives the maximum energy given out by the Sun. The concentrator has been designed such that the parallelepiped receiver can be held vertically above the mirror parallel with the length of the mirrors in order to receive the concentrated flux.

Fig. 1. LFC prototype for experimentation realized at UDES [10–12]

2.2 System description

The solar reflector adopted in this study has been designed and installed at UDES with a full surface of reflecting mirrors equal to 18m2.

Table 1 represents the dimensions of each mirror and the receiver according to the geometric parameters of our prototype.

Table 1. Dimensional of LFC prototype components'

Elements	Value
Mirror width	50 cm
Mirror length	3 m
No. of mirror row	12
Center focal length	3 m
Receive width	50 cm
Receive length	3 m
Receive height	20 cm
Copper absorber tube diameter	16 mm

2.3 Receiver Description

The receiver composed of 06 copper tubular of 0.016 m in diameter covered with an adapted a selective coating and 2 collectors at the inlet and outlet with a double- shelled absorber in aluminum which specially designed to increase the heat exchange surface for better performance [12]. For the experimental investigations, the vertical height of the receiver from the concentrator frame is kept constant 3 meters. It is a parallelepiped shape of 3m in length, 50cm in width and 20cm in height. The receiver is insulating on all sides except the lower face (a 5mm thick double-glazed glass win-dow) to protect the selective coating that decreases the emission losses and to make a greenhouse effect that benefits receiver performance. It also minimizes convection losses, due to the vacuum existing inside it (see Fig.2). This receiver uses a double-envelope absorber fixed by original methods. Its temperature can reach 250°C measured via thermocouples placed in different locations, namely: 2 thermocouples one at the inlet and the other at the outlet of the absorber and 3 others distributed on different points of its surface

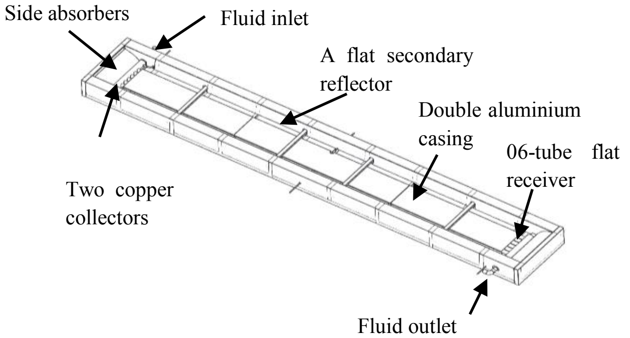

Fig. 2. Longitudinal section of the receiver realized at UDES [10–12]

2.4 Methodology and theoretical analysis

The concentrator consists of N mirror elements, with N/2 mirrors present on either side, which is located symmetrically. Each mirror of the field is defined by four key parameters: namely, mirror width, the position in the field of the primary mirror, the focal length, and the tracking angle. These four parameters are discussed in detail in this paragraph:

1. Mirror width: a more practical design of a LFC, which is easy and hence inexpensive to fabricate, can be made out of a finite and equal mirror width, each of which has a same length to the length of the linear receiver.
2. Position of the mirror: the mirror field consists of an even number of mirrors arranged symmetrically around an axis. The value x_i defines the position of the ith mirror in the field of the primary mirror. It is defined by:

$$x_i = \left(i - \frac{1}{2}\right)(L + e) \tag{1}$$

Where

e: the distance between two successive mirrors [m]
L: the mirror width [m]

3. The focal length: this parameter is a function of the position of the mirror in the field of the primary mirror and the height of the receiver. It is defined by Eq.2:

$$f = \sqrt{x_i^2 + {h_{ref}}^2} \tag{2}$$

Where
f: the focal length [m]
h_{ref} : receiver height above the primary mirror field [m]

4. The tracking angle: each mirror admits its own tilted angle. The tilt of inclination ψ_i between the horizontal plane and the plane containing the reflecting mirror is defined by Rabl [13]: It is defined by Eq.3:

$$\psi_i = \frac{\phi_i - \theta}{2} \tag{3}$$

ϕ_i : the angle between the optical axis and the line that joins the mirror and the receiver [°]
θ: the angle of incidence [°]

During the process, losses can be observed at several levels namely the Concentrator, Receiver, Transport and Storage [14].

Determining the optical efficiency of LFC systems must be carried out with accuracy and precision depending of various factors, among which the following significantly stand out: the incidence angle, the radiation reflector, the losses due to shading, ratio and the geometric engineering dimensions of the real prototype components.

This thermal energy obtained is either directly used in a thermodynamic cycle to produce electricity, or for cogeneration. This energy is generally stored for later use.

The performance equation or instantaneous efficiency characteristic of this type of technology is as follows [15-16]

$$\eta_{FS} = \eta_{mf} * \eta_{rp} * \eta_{pb} \tag{4}$$

Where
η_{FS} : Fresnel system efficiency
η_{mf} : Mirror field efficiency
η_{rp} : Receiver efficiency
η_{pb} : Power block efficiency

$$\eta_{mf} = \frac{Q * A_{rec}}{DNI * A_{mf}} \quad (5)$$

Where
Q : Flux generated by the mirror field
A_{rec} : Receive tube area
A_{mf} : Primary reflector field area
DNI : Direct normal radiation

$$\eta_{mf} = \frac{m * C_p * (T_{out} - T_{int})}{I_b * A_{mf}} \quad (6)$$

Where
m : Fluid mass flow rate (Kg/s)
C_p : Specific heat of fluid (KJ/Kg/°C)
A_{mf} : Reflector field area (m^2)
T_{out}, T_{int} : Outlet and inlet fluid temperature respectively (°C)
I_b : Solar beam radiation (kW/m^2)

$$CR = \frac{\text{Number of rays concentrated on the receiver}}{\text{Number of rays reflected by the total area of the reflector}} \quad (7)$$

$$S_e = \sum_k^n L * \cos(\theta_t - \theta_n) \quad (8)$$
$$\delta = 23.45^{\circ} * \sin[0.98^{\circ} * (j + 284)] \quad (9)$$
$$h = arc\sin(\cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta) \quad (10)$$

θ_t : Angle in the transversal plane
θ_n : Slope angle of an nth mirror element.
φ : Latitude angle
ω : Hour angle

3 Research approach: numerical modeling and simulation

3.1 Modeling system and simulation

The temperature modelling is based on the energy balances, which are characterized by differential equations of the absorber temperature (T_{Ab}) and fluid temperatures (T_F). The thermal power emitted by the sun and received by absorber tubes (see Fig.3) is given by the following equations [17]:

$$Q_{Absorbed} = 0.7\alpha\, \rho_m \gamma * S_e DNI * \sqrt{1 - cos^2(\delta) sin^2(h)} \quad (11)$$

Where

α : Absorption coefficient of the absorber tubes

ρ_m : Reflectance factor of the mirror

γ : Interception factor

Se: Selective surface of mirror aperture

δ : Declination angle

h : Sun altitude

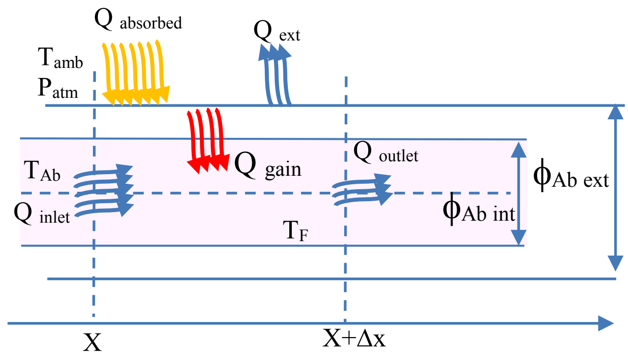

Fig. 3. Heat exchanges in the absorber tube

To evaluate the optical performance of the linear Fresnel concentrator, analyzing the distribution of the thermal flux intensity of the solar radiation reflected by the mirrors and concentrated by the absorber tubes, a specific optical evaluation and simulation process is carried out in this section applying free simulation tool (see Fig.4).

The solar reflector adopted in this study is a linear Fresnel concentrator. Based on the data presented in Table 1, the simulation model of the LFR system is shown in Fig. 5. In this section, optical evaluation and simulation process is carried out applying free simulation tool to evaluate the optical performance of the linear Fresnel concentrator, analyzing the distribution of the thermal flux intensity of the solar radiation reflected by the mirrors and concentrated by the absorber tubes. The absorber tubes are made of Copper covered with an adapted a selective coating; they are placed along the focal line of the linear Fresnel concentrator. Generally, the heat exchange existing in the system takes place between the heat transfer fluid and the absorber tubes, but in our preliminary study, we did not introduce the transfer fluid.

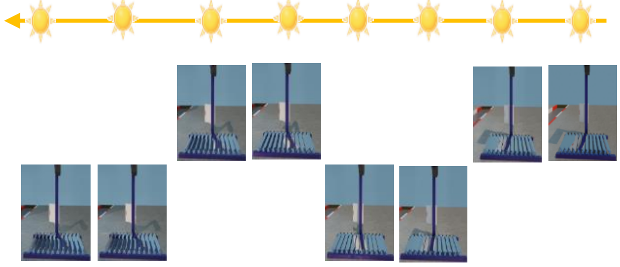

Fig. 4 : 3D modeling of kinematics solar tracking [11]

Preliminary tests were carried out in UDES with the following coordinates 7.0629152, -73.1380194. The mirrors were positioned at the angularity calculated at 8:00 am, in order to carry out the pertinent tests, knowing that the path of the sun begins in the east to the west, the module must be

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positioned in the operating coordinates and thus determine the degree of accuracy provided by the system mechanism.

The results obtained from the conditions of the system, the distribution of the mirrors and its automation; allow us to show more clearly, through simulations, the effects of incidence on the surface of the reflecting mirrors and the concentration at the point focus throughout the day, as shown below.

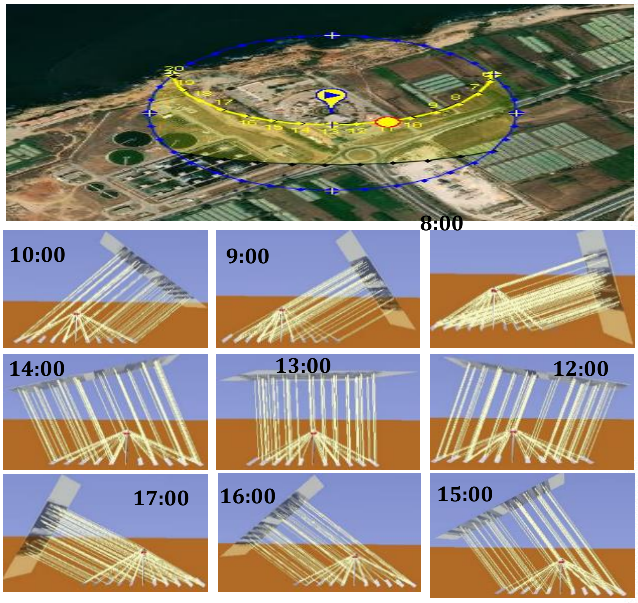


Fig. 5. Extract from SunEarth Tools for the UDES website and Ray simulation by Tonatiuh

4 Results and discussion

The experimental data, for the two days of the manipulation (June 19th and June 27th, 2023), obtained from the LFC was acquired during certain conditions operation of the prototype. In particular, the optimization work of the LFR CSP allowed solar tracking with accuracy less than 0.1°. The study led to the establishment of an autonomous control system, freeing itself from the occasional drops of sunshine.

During the experiments, some clouds were observed, specifically between 11:00 and 14:00 for the June 19th. In general, the direct solar radiation increases from sunrise to reach the maximum in the middle of the day and then it is back down in the evening.

Primary tests were carried out without introducing the Heat Transfer Fluid (HTF).

The experimental tests measured and recorded during the test days made it possible to plot the evolution of the different temperatures as a function of time, which is represented in the form of curves. Fig. 6 and Fig.7.

The temperature evolution as a function of time are shown in Fig. 6 without glass cover the receiver, and Fig. 7 relates to the temperature evolution with glass cover of the receiver.

From this figure, the recorded outlet temperature reaching 140 °C. The receiver temperature increase gradually until it achieving its maximum of 176 °C around 11:30 a.m., and then back down influenced by the lack of the quantity of direct solar radiation.

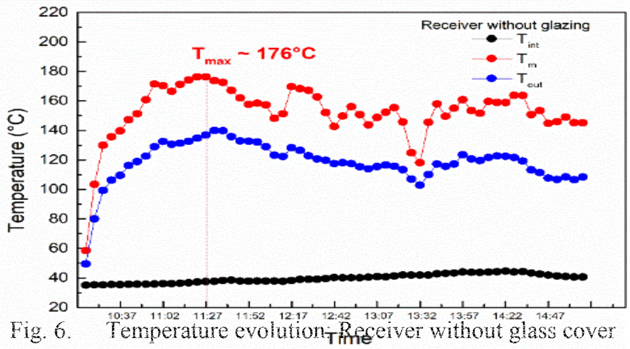


Fig. 6. Temperature evolution Receiver without glass cover

Based on the Fig. 7, similar trend is observed with considerable increases due the greenhouse effect, which promotes heat transfer between the absorber and the air

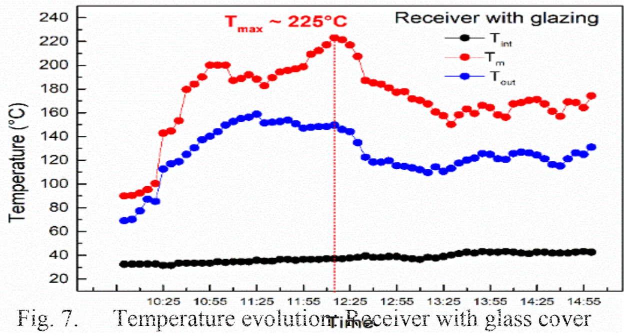
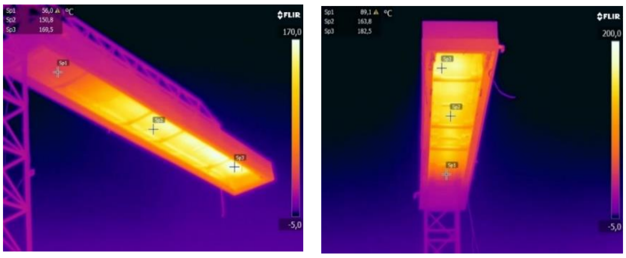


Fig. 7. Temperature evolution Receiver with glass cover

According to the Figs, the evolution is noticeable around solar noon 12.00 p.m.–14.00 a.m. In fact, the temperature reaching the receiver after the glazing is higher than that before the glazing shifting around 50°C. Undoubtedly, this shift due to the glass cover which allows very high temperatures to be reached by creating the greenhouse effect. From these Figs, the temperature depends mainly on the solar power received by absorber tubes, on the glass cover of the absorber, and on the tilt angle of the mirror

Fig.8 illustrates the temperature distribution in the receiver via the infrared thermal camera to enrich and highlight the results obtained. The results demonstrate good distribution except in the neighboring part of the structure where the temperature is significantly lower due to end losses.

The same behaviors are detected and match perfectly with the experimental measurement that recorded. So, by these results we can validate and confirm the reliability of the results of the acquisition system.



(a) Without glass cover (b) With glass cover

Fig. 9. Temperatures evolution recorded using the thermal camera : (a) without glazing and (b) with glazing.

5 Conclusion

The linear Fresnel reflector relies on solar energy, which is available throughout the year. The use of this device will solve many problems in many industrial and domestic areas preserving the environment by avoiding releasing the CO_2. This Preliminary study was carry out to validate the experimental and simulation results for the LFC solar prototype manufactured at UDES. The results of the above study have clearly shown that the LFC design offers a better performance in terms of concentration on both cases of the absorber (with or without glass cover of receiver). It is clear to see that the temperature variation has a direct relationship with the incident direct solar radiation. The temperature reaching the receiver has reached up to 176°C before cover the receiver and 225°C after cover the receiver increasing by around 50 °C.
In fact, the direct solar radiation, the geometric and optical characteristics of solar collector components and the climatic conditions of the site studied the performance of the solar reflector. Moreover, some quantity of the incidental solar energy absorbed by the receiver is not completely transmitted to the heat transfer fluid. They dissipated as heat loss between the absorber tubes and the ambient air. Undoubtedly, there is a relationship between the heat loss and the performance of the device.
As result, the linear Fresnel solar reflecting concentrator was found suitable for the objectives cited such as electrification, water-heating application, etc… The use of the linear Fresnel reflector as a solar electrification, heating system is an economical, efficient and sustainable towards environmental.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.