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Manufacturing of Low-Cost Parabolic Dish Concentrators with Manual Dual-Axis Tracking

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***Abstract*—The increased rate of energy crises around the world results in expanding the role of Concentrating Solar Power (CSP) technology for different applications, comprising heating process and power generation applications. The Parabolic Dish Concentrator (PDC) with its large concentration ratio and its modular capacity attracts researchers' efforts. In this research work, we have designed and developed a PDC with back silvered mirrors as reflector material. Then we have sized the following geometric parameters: the dish diameter, the focal length, the aperture area, the rim angle, the geometric concentration ratio, the receiver material, and the receiver diameter. Furthermore, a dual-axis manual tracking system has been built for this PDC. It should be mentioned that the different components of the PDC have been recycled from a scrap yard to develop a low-cost PDC system. Finally, we have investigated the temperature evolution as a function of time at the focus spot. The maximum temperature obtained is 112 °C for the PDC with mirror. The findings of the study reveal the possibility of building a low-cost solar concentrator with good performance and high quality, only by employing recycled materials, and it could be operated in various applications.**

***Index Terms*—Geometric parameters; Low-cost; PDC; Tracking system; Temperature.**

I. INTRODUCTION

The most abundant resource of all renewable energy potentials is solar energy. The Sun emits its radiation in all directions, and the Earth receives an average power of $1,7x10^{14}$ kW for a surface perpendicular to the Earth-Sun direction [1], [2].

The solar energy can be harvested and transformed into heat at medium temperature by flat receiver using Concentrating Solar Thermal (CST) technology, using together the absorption by a selective surface and the greenhouse effect created by the glazing. Generally, these collectors have been adapted for buildings; in the meantime, they have attracted great attention in both the industrial and academic sectors [3]. The Parabolic Trough Concentrator (PTC) is the most advanced and deployed one compared to all existing CSTs. The advantage of such concentrator technology is its possibility of reaching high temperature levels that are well suited for the heating process and electricity generation [4]. The Compound Parabolic Collector (CPC) could capture and concentrate solar radiation within the range of acceptance angle without tracking. This makes it provide a medium temperature heat. Winston initially introduced CPCs as optical concentrators for thermal and photovoltaic (PV) applications [5]. In the last two decades, CPCs have been known as the best static low-concentrating systems for PV applications [6]. The advantages of CPCs over other concentrating systems are: the high optical efficiency, the capability to collect both direct and diffuse solar rays without a tracking system, and finally, its ability to provide medium temperature heat [6]–[8].

In recent years, Parabolic Dish Concentrator (PDC) systems and heliostat field systems have also been developed for use in solar power generation. PDC is a type of solar energy collection device that uses a parabolic mirror to reflect and concentrate sunlight on a receiver with dual-axis tracking system [9]. The latter mentioned system is necessary to move and adjust the angle of the PDC in both axes (i.e., the horizontal and vertical axes) to track the movement of the Sun and maintain optimal alignment for maximum energy collection throughout the day [10]. These systems usually have a reflecting surface with a parabolic form designed to concentrate the solar energy on an absorbent surface, which allows varying the temperature from 100 °C to 2000 °C and reaching high temperatures that could be applied in high thermal applications (i.e., heating sterilisation and water, producing steam), as well as electrical power generation [11]. The association PDC-tracking system (i.e., with a concentration ratio in the range of 600 to 2000) has more efficiency than a fixed PDC [12].

Taking into account the operating principle, the sun-tracking systems can be classified into manual- and automatic-based. Furthermore, two main types of trackers are known, which are *single-axis tracker* and *dual-axis tracker*.

Single-axis trackers are employed to track the movement of the Sun either from east to west or north to south, whereas dual-axis trackers are used to track both the altitude angle and azimuthal angle of the Sun [11]–[13].

Researchers around the word have addressed the design and fabrication aspects of various types of PDCs. For

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example, Palavras and Bakos [14] developed and evaluated a low-cost dish solar concentrator and discussed its application in zeolite desorption. The PDC consists of an old recycled satellite dish in which a polymer mirror film is used as a reflecting surface. The authors also used the sun-tracking system based on an electronic circuit that is equipped with a set of sensors and actuator that drives the dish.

Sahu, Arjun Singh, and Natarajan [12] developed a low-cost PDC with 12.6 m^2 aperture area associated with a dual-axis manual tracking system and back silvered mirrors that are used as a reflector. In addition, an economic analysis of the system was provided.

Numerous theoretical and numerical studies [1], [12], [14] have been carried out with the aim of evaluating the geometric parameters and concentration ratio of different PDCs.

Overall, the development of parabolic concentrators has been driven by the need for solar energy to be harnessed in an efficient and cost-effective way. In order to do this, various types of concentrators have been created, each one designed for a specific application and setting.

In this context, the main objective of this paper is to contribute in the design and fabrication of a very low-cost dish concentrator compared to the existing ones [12], [14]. This aim was achieved by using recovery materials from the Higher School of Signals (HSS) deposit for the PDC realisation purpose. This PDC was associated with a manual dual-axis tracking system to be used for thermal or electrical power generation. To the best of our knowledge, our PDC, with such characteristics and considerations, has never been made before. The design and fabrication process are discussed in detail in the following section.

II. THEORETICAL STUDY

A. Geometry Definitions and Sizing

In solar concentrators, the main property of the parabola is its ability to focus the sunrays onto a single point known as the *Focal Point* (*FP*). *f* is the distance between the FP and the vertex. The parabola is a two-dimensional arc, whereas the paraboloid is derived from the parabola (i.e., the surface shape given to dish concentrators that has a similar property of symmetry) [15]–[19]. As can be seen from Fig. 1, the parabolic concentrator cross section comprises a circular arc that is symmetrical about the y-axis (i.e., the latter axis is also known as the *optical axis*).

Various parameters must be adopted to design the parabolic concentrator [12]. Our design pays particular attention to the most important parameters, which are:

– The aperture area (Aper) is the concentrator's overall area upon which the sunrays are intercepted.

– The aperture diameter (D) or the dish diameter which is denoted by D in Fig. 1.

– The focal distance (f) is the distance existing between the vertex and the focus.

– The rim angle (ϕ_R) is the angle that arises from the intersection of the y-axis with the line between the focus and the physical edge of the concentrator.

– The dish height (h) is the maximum distance starting from the vertex to a line drawn across the parabola aperture.

– The Arc length (s) is obtained by integrating the differential fragments of the parabola-curve across both the perimeter and height.

– The acceptance angle (θ_s) is defined as the angle at which the incoming sunlight can be moved, meanwhile, still converging to the receiver.

To obtain the aforementioned parameters, rigorous mathematical development is needed, as follows [12], [15], [16].

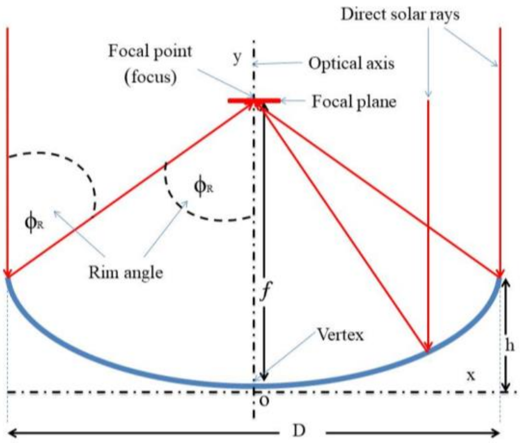


Fig. 1. The arc-parabola schematic diagram, the parallel incident rays to the y-axis are thoroughly focused on the focal point.

If the origin is taken at the vertex "o", the functional relationship of the arc (i.e., parabola) with its axes (i.e., x and y) can be defined as follows

$$y = \frac{x^2}{4f}. \tag{1}$$

If the origin is displaced to the focus *f*, meanwhile, the vertex is shifted to the left of the origin, and the parabola equation becomes

$$y = \frac{x^2}{4f} - f. \tag{2}$$

Similarly, for a paraboloid that has axes that coincide with the z-axis, its equation is

$$z = \frac{r^2}{4f} = \frac{x^2 + y^2}{4f}, \tag{3}$$

where *r* is the parabolic radius (i.e., it refers to the distance from the focus *f* to the curve).

The rim angle (ϕ_R) is an important parameter that can affect both the efficiency and the performance of the PDC. Its equation can be written as

$$\tan\phi_R = \frac{D/2}{f-h} = \frac{4f(D/2)}{4f^2 - (D/2)^2}, \tag{4}$$

where *D* is the diameter of the parabola and *h* is the height of the parabola on the rim.

By shifting the origin to the focus *f*, one can measure the angle φ_R from the optical axis to the parabolic radius *r*, the equation that describes r is as follows

$$r = \frac{2f}{1+\cos\phi_R}. \quad (5)$$

The dish height is given by

$$h = \frac{D^2}{16f}. \quad (6)$$

The arc length S can be computed by the following equation

$$S = \left[\sqrt{\frac{D}{2}\left(\frac{4h}{D}\right)^2+1}\right]+2f\ln\left[\sqrt{\frac{4h}{D}\left(\frac{4h}{D}\right)^2+1}\right]. \quad (7)$$

Equation 8 expresses the cross-sectional surface of the enclosed space between a parabola and a line across its aperture and normal to the axis

$$A_x = \frac{2}{3}Dh. \quad (8)$$

B. *Derivation of the Concentration Ratio*

The incoming sunbeams on the dish reflector will be reflected as a cone of rays that corresponds to the angular distribution of the solar source with a half-angle is θ_s. When this cone falls on a flat target within the focal plane (shown in Fig. 2), one can get a spot. It should be emphasised that the rays hitting the dish edges are the main reason for a wider spot, as shown in Fig. 2.

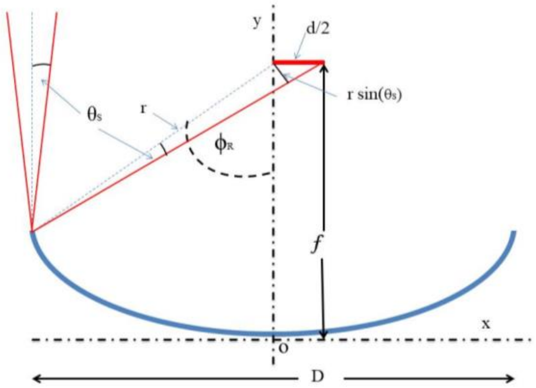


Fig. 2. Concentration of solar rays with a perfect parabolic mirror on a flat receiver.

The distance X of the reflection point from the optical axis is defined as

$$X = 2r\sin\phi_R. \quad (9)$$

The equation that describes the focal spot width on the focal plane is as follows

$$d = \frac{2r\sin\theta_s}{\cos\phi_R}. \quad (10)$$

The term "concentration ratio" describes the ratio between the surface of the gathered sunlight and the surface of the solar receiver onto which it is concentrated. Typically, two main concentration ratios are used in the PDC assessment:

1. Optical Concentration Ratio (CR_0): It can be computed as follows

$$CR_0 = \frac{1/A_r\int I_r dA_r}{I_0}, \quad (11)$$

where A_r is the receiver area, I_r is the averaged irradiance (radiant flux), and I_0 is the insolation that hits the collector aperture. The optical concentration ratio depends on both the lens or reflector quality; however, the receiver surface aera of most collectors is larger than the concentrated solar image.

2. The Geometric Concentration Ratio (CR_g): It can be defined as the ratio of the collector aperture area (A_c) to the receiver surface area (A_r) [12]

$$CR_g = \frac{A_c}{A_r}. \quad (12)$$

Repeat this analysis for a paraboloidal dish with flat receiver

$$CR_g = \frac{A_c}{A_r} = \frac{\frac{\pi}{4}W^2}{\frac{\pi}{4}d^2} = \left(\frac{W}{d}\right)^2 = \left(\frac{\sin 2\phi_r}{2\sin\theta_s}\right)^2. \quad (13)$$

The optimal rim angle for a parabolic dish is the derivative of the Geometric Concentration Ratio with respect to Φ_r

$$\frac{dCR_g}{d\phi} = \frac{d}{d\phi}\left(\frac{\sin 2\phi}{2\sin\theta_s}\right)^2 = \frac{\sin 2\phi_r\cos 2\phi_r}{\sin^2\theta_s} = 0. \quad (14)$$

Equation 14 results in a maximum geometric concentration ratio at φ = 45 °; therefore,

$$CR_{g,dish,flat,\max} = \frac{1}{4\sin^2\theta_s} = 11.600. \quad (15)$$

1. *The Optical Efficiency*

The optical efficiency of a dish concentrator is typically expressed as a percentage and is determined by the ratio of the concentrated solar energy received by the receiver over the total solar energy hitting the concentrator's aperture. Numerous factors can affect optical efficiency, we can mention from them the reflectivity transmissivity and absorptivity of the mirror surface, the accuracy of the dish shape and the tracking system, shading effect and the presence of dust or other debris on the mirror surface, receiver-cover transmittance, cosine loss of the absorber, and solar beam incidence effects [17]. Typical dish concentrators have optical efficiencies in the range of 0.6 to 0.7. Thus, the optical efficiency of the dish reflector can be computed by using the following mathematical relationship [11]

$$\eta_{opt} = \lambda \times \rho \times \tau \times \alpha \times \gamma \times \cos\theta, \tag{16}$$

where λ is the shading factor, ρ is the reflectivity, τ is the transmissivity, γ is the intercept factor, α is the absorptivity, and θ is the angle of incidence.

2. *The Thermal Efficiency*

The thermal efficiency of the collector indicates how well it is able to convert concentrated solar energy into thermal energy. Thermal conversion system with Heat Transfer Fluid (HTF) is often used for the extraction of thermal energy from the receiver. It is typically expressed as a percentage and is determined by evaluating the ratio of the useful thermal energy delivered to the heat energy incident over the concentrator aperture [11]. Many factors have a direct impact on the thermal efficiency of a dish collector, such as the receiver design, as well as its material, the working fluid temperature, the ambient temperature, and the wind velocity. The thermal efficiency of the collector system can be calculated as follows [12]

$$\eta_c = \frac{Q_u}{Q_s}. \tag{17}$$

III. Design Procedure for a Solar Parabolic Concentrator System

Before starting the fabrication of the PDC system, many steps forward should be considered during the design procedure. Firstly, we have started by determining the specifications of the system, such as the desired level of concentration, the size of the collector, and the location where the system will be installed. Then we select the appropriate type of PDC tracking system (single-axis or dual-axis system), and we choose the appropriate materials for the collector and the support structure, taking into account factors such as cost, durability, and weight, ensuring that it is strong enough to withstand wind and other environmental loads.

In this section, we describe the experimental facility, fabrication of each part of the PDC system:

– Concentrator (dish parabolic and reflector);
– Receiver;
– Base support;
– Dual-Axis Manual Tracking System (DAMT).

In our project, the design and fabrication of a dual-axis tracking parabolic concentrator system are carried out on campus of the Higher School of Signals, Kolea, Tipaza, Algeria.

A. Concentrator (Dish Parabolic)

The most important components of a parabolic solar concentrator system are the dish concentrator, the reflective surface, and the sun-tracking system. The costliest part of such a system is the dish concentrator [14]. To overcome this problem, we have looked for a low-cost damaged satellite dish to be reused. The dish concentrator used in this study was recycled HSS deposit, which went through a reform process to restore it to its original form. In addition to the advent of their cost, we have benefited from their lightness and durability because they are made of an aluminium alloy.

The geometric and concentration characteristics of the PDC are summarised in Table I.

TABLE I. GEOMETRIC AND CONCENTRATION CHARACTERISTICS OF BOTH PARAPOLIC DISH SOLAR CONCENTRATOR.

Geometrique and concentration characteristics	**1st PDC(with mirrors)**
Diameter of dish aperture W (m)	0.715
Aperture area	
Focale distance f (m)	0.4828
Depth (m)	0.065
Rim angle (°)	40.63
Arc length (m)	1.13
Focal length and diameter ratio	0.28
Surface (m^2)	0.765
Opening area of the parabola (m^2)	0.402
Ideal solar image width (m)	0.031
Ideal concentration ratio	20537
Reflector	Back silvered glass mirror
Reflectivity (%)	90
Thickness of glass (mm)	3
Facet size	0.03 m × 0.03 m
Profile geometry (mm)	y = x2/1930

B. Reflector

This element allows the incident solar energy to be focused on its focal point *f*. In this study, the reflector consists of several back silvered glass mirrors that cover the interior surface of the parabola (Fig. 3).

Fig. 3. Mirrors of square pieces (30 mm × 30 mm × 3 mm) used as a reflector for our PDC.

Mirrors must have bright sides in front of the Sun. The improvement in the use of this type of mirror for a parabolic dish concentrator lies in the thickness of the glass plate. The lower the thickness is, the higher the reflectivity of the mirror will be, thus allowing them to bend to obtain the desired parabolic shape and maximise the efficiency. This type of surface can reach a reflectivity of 90 % [14]. To keep the parabolic shape, we cut the mirror into small square pieces (30 mm × 30 mm × 3 mm). We stuck these pieces of mirrors on the surface of the dish concentrator using resin glue.

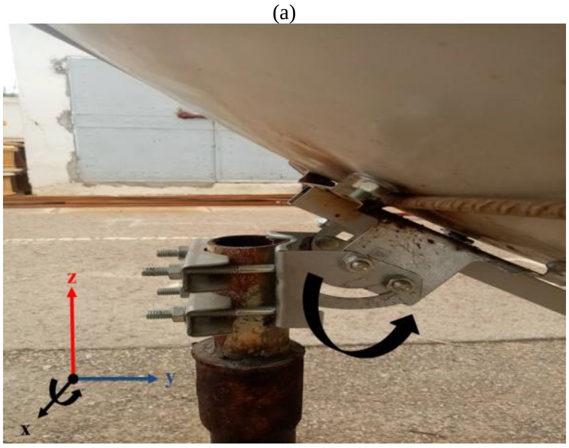
C. Dual-Axis Manual Tracking and Base Support

Manual dual-axis tracking is a mechanical device on which the parabolic dish concentrator is fixed. IT is typically performed by a system of gears and motors that is controlled by an operator who manually adjusts the position of the solar concentrator to collect maximum solar radiation throughout the day [14]. This method is often used in small-scale or experimental solar projects because it is less expensive and less complex than automated tracking systems.

It is important to note that dual-axis tracking is not necessary for all types of solar project and may not be cost-effective for small-scale systems. Before deciding to implement dual-axis tracking, it is important to consider factors, such as the cost of the system, the amount of energy that will be generated, and the location of the installation [12].

The support is an element that carries the device. It is made of round tubes welded to an electric arc to reduce weight and facilitate mobility and storage. The parabolic concentrator requires a tracking system to reach the maximum solar flux. We adopted a very simple tracking mechanism based on one (cylinders and a rotating axis) to turn the dish to the position of the Sun at all times. The tracking system has two degrees of freedom, as can be seen in Fig. 4.

(a)



(b)

Fig. 4. The manual tracking system for (a) the azimuthal angle and (b) the solar altitude angle.

D. Receiver

The solar receiver converts concentrated solar radiation into usable heat. The receiver is the hottest component of the solar concentrator system. The efficiency of the solar receiver reflects its ability to transfer the maximum incoming radiative power to the heating plates at working temperature by supporting minimal thermal losses. The active element of the receiver is on the heating plate.

The receiver surface must have the following characteristics:

– Good conductivity and thermal diffusion;

– An absorption factor, as close to the unit as possible.

Our study is concerned with medium temperatures (above 100 °C.) We have chosen copper (whose thermal conductivity is around 360 W/mk). It is a 100 mm long square plate, placed in the focal plane of the parabola as presented in Fig. 5.

Fig. 5. The receiver used for both PDCs.

E. Concentrator Assembly

When the development of each part of the solar parabolic concentrator ends, we proceeded to assemble different components together in order to obtain the complete system, which is presented in Fig. 6. Our concentrators are now ready to be used and evaluated.

Fig. 6. The final achieved parabolic dish concentrator.

IV. THERMAL EVALUATION

To evaluate the performance of a PDC, important parameters must be identified, such as solar irradiance incident on the concentrator, wind velocity, ambient temperature, angle of inclination of the receiver from the horizontal, and so on. The ideal operation of a solar concentrator is when the solar radiation is parallel to its focus axis [20]. We have chosen a period of time when the sky is clear to avoid the shadow effect. The solar concentrator is facing the Sun. By using the manual tracking system, the PDCs are redirected to the Sun position (azimuthal and elevation angles) every 30 minutes. The solar rays are reflected at the focal point of the PDC, thus forming the sunspot, which should appear in front of the plate to be heated. To measure the temperature reached on the absorber surfaces, a thermocouple is placed on the surface of the plate receiver. Temperatures were measured every 30 minutes using a digital display thermocouple to study their evolution over time between 09:00 to 17:00 on the 29 May 2022. That day.

The meteorological data and geographic coordinates were as follows:

– Relative humidity: 50 %;

– Ambient temperature: 22 °C;

– Wind speed: 5 km/h;

– Longitude of the location: 2 °46’15’E;

– Latitude of location: 36 °37’46’N;

– Day Number: 140 days (29-05-2022).

The measurement of the temperature obtained from our PDC is presented in Table II.

From Fig. 7, we notice that the temperature evolution in respect to time follows the famous bell form, it increases rapidly at the beginning (from 9:00 am to 12:00 am) and then stabilises between 12:30 pm and 14:00 pm at about 110 °C. The maximum operation condition of a solar concentrator is between 12:00 pm and 14:00 pm. The maximum temperature achieved for both concentrators is at 13:00 pm when the Sun is at true south. Furthermore, the temperature at focus of the PDC is the highest. This is because the mirror has a reflexivity (more than 95 %). In addition, the diameter of the PDC is 0.72 m, which affects the surface of the parabola and thus the rays reflected on the focal spot.

TABLE II. MEASUREMENTS OF THE TEMPERATURES AT THE FOCUS OF BOTH SOLAR CONCENTRATORS (DAY OF 23/05/2022).

Time (hours)	**Concentrator temperature (°C)**
09:00	26
09:30	37
10:00	48
10:30	65
11:00	76
11:30	95
12:00	103
12:30	107
13:00	110
13:30	112
14:00	108
14:30	102
15:00	93
15:30	74
16:00	65
16:30	46
17:00	30

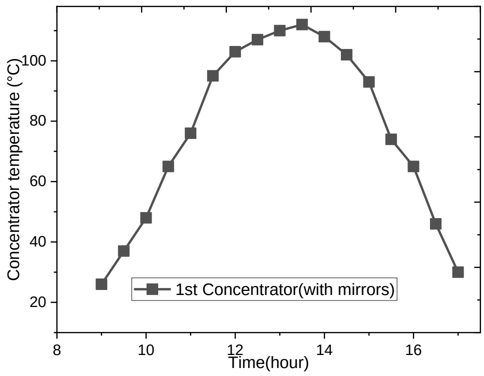


Fig. 7. The temperature evolution as a function of time for both concentrators.

V. Conclusions

In this research, we have carried out an experimental study on a PDC with a dual-axis tracking system. The main objective is to develop a system for harvesting solar energy in a low-cost manner, using recycled components. Investigating the temperature evolution as a function of time at the focus spot for PDC has had the famous bell shape with a maximum achievable temperature of 112 °C. Furthermore, we have demonstrated that the concentrator temperature at the spot focus depends on several factors, most importantly, the variation in sunlight that varies during the day and year. To improve the solar concentrator performance, it is recommended to combine it with an automatic sun-tracking system and investigate various reflector materials to increase the reflection rate. Finally, it should be mentioned that employing such systems will provide significant environmental and financial benefits. Thus, the solar concentrator can be successfully used for a number of solar applications.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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