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Experimental study of a parabolic solar concentrator

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Abstract - *In this present work, a parabolic solar concentrator has been experimentally studied. The experimental devise consists of a dish of 2.2 m opening diameter. Its interior surface is covered with a reflecting layer, and equipped with a disc receiver in its focal position. The orientation of the parabola is ensured by two semi-automatic jacks. Experimental measurements of solar flux and temperature distribution on the receiver have been carried out. These experimental results describe correctly the awaited physical phenomena.*

Résumé – *Dans ce présent travail, un concentrateur solaire parabolique a été expérimentalement étudié. L'expérimentation est effectuée sur un disque de diamètre d'ouverture de 2.2 m. Sa surface intérieure est recouverte d'une couche réfléchissante, et équipée d'un récepteur à disque dans sa position focale. L'orientation de la parabole est assurée par deux vérins semi-automatiques. Des mesures expérimentales du flux solaire et de la distribution de température sur le récepteur ont été effectuées. Ces résultats expérimentaux décrivent correctement les phénomènes physiques attendus.*

Keywords: Solar energy - Dish - Receiver - Solar flux.

1. INTRODUCTION

Thermal radiative transport continues to emerge as an important energy transfer mechanism in a wide variety of practical systems such as high-temperature heat exchangers, boilers, rocket propulsion systems and solar concentrators. Two forms of solar energy are distinguished, direct radiation and diffused radiation.

Solar high temperature designs require concentration systems, such as parabolic reflectors. Solar thermal power plants with concentration technologies are important candidates for providing the bulk solar electricity needed within the next few decades. Four concentrating solar power technologies are developed: parabolic trough collectors (PTC), linear Fresnel reflector systems (LF), power towers or central receiver systems (CRS) and dish engine systems (DE) [1].

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Many researches related to parabolic concentrators are found. Kleih [2] has been setting up a test facility for parabolic dish systems with power conversion unit in their focus, R.Y. Nuwayhid *et al.* [3] realised a simple solar tracking concentrator for university research applications.

Draou *et al.* [4] have been realised a study, conception and experiment of tracking system. Pérez-Rabago *et al.* [3] treated heat transfer in a conical cavity calorimeter for measuring thermal power of a point focus concentrator.

As an alternative application, David *et al.* [6] have been realized projects of Coupling sun concentrator and a Stirling engine. The manufacture of these systems remains enough expensive seen the quality of materials, the dimensions and the preciseness. Some authors made researches with applications targeted to reduce cost [7, 8].

Quincy [9] has been shown that a focus point of solar concentrator can be made from two troughs collectors by orienting their longitudinal axes in perpendicular directions and separating them by the difference of their focal lengths along the optical axis.

Jaramillo *et al.* [10] have been analyzed the thermal transfers in a calorimeter to go back up to the concentrated stream. The concentrated flux has been determined by using several calorimeters of different geometries (Shuai *et al.* [11]).

In this work, a solar concentrator system has been constructed and tested by using two discs as receivers. The first experience consists to place a thick disc in the focal position in order to carry out the solar temperature distribution on the lighted face of the thick disc. In a second step, a thin disc was placed in the focal region in order to determinate solar flux concentrated and efficiency of our system.

Different compounds of this design are described. An acquisition data system is adapted to measure temperature profile over the receiver in the experiment conditions.

A theoretical and experimental study of the thermal transfers is realized for better conception of the solar energy installation. Experimental measurements in this stage describe correctly the awaited results. Several practical applications could so be allocated to this concentrator.

2. EXPERIMENTAL EQUIPMENT

2.1 Reflector

The reflector of our experimental device consists of a parabolic concentrator of 2.2 meters opening diameter. Its interior surface is covered with a reflecting layer. Which reflect solar rays on the face of a receiver placed at the focal position of the concentrator. The concentrator is posed on a directional support according to two axes to ensure the follow-up of the sun.

The equation for the parabola in cylindrical coordinates is:

$$z = \frac{r^2}{4\,f} \tag{1}$$

The diameter of the opening parabolic surface is d, and the focal distance of the parabola is f. The surface of this parabola is given by:

$$S = \frac{8\pi}{3} f^2 \left\{ \left[1 + \left(\frac{d}{4\,f} \right)^2 \right]^{3/2} - 1 \right\} \tag{2}$$

The cross-section of the opening parabola is:

$$S_0 = \frac{\pi\, d^2}{4} \tag{3}$$

The focal distance is given by the following expression:

$$f = \frac{d^2}{16\,h} \tag{4}$$

where, h is the depth of the dish.

The characteristics of the solar concentrator are shown in **Table 1**.

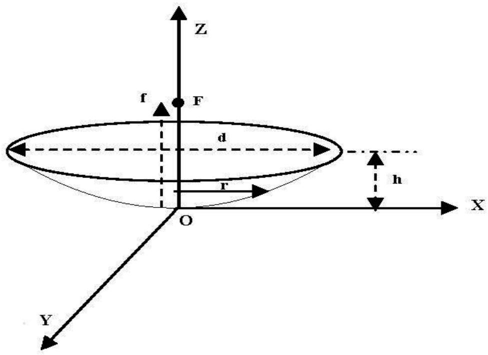

Fig. 1: Geometrical parameters

Table 1: Characteristics of the solar concentrator

Diameter of opening of the parabola	2.2 m
Surface collecting of the parabola	3.8 m^2
Depth of the parabola	0.4 m
Focal distance f	0.75 m

The reflecting film covering the surface of the parabola is a stainless steel layer with a reflecting coefficient near 0.85.

2.2 Receiver

The receivers have a diameter of 120 mm, and are covered with a thin coat of black paint with an absorption coefficient near 0.9 and are located in the focal zone of the parabola.

The characteristics of receivers are shown in **Table 2**.

The geometrical concentration of this model is

$$C_g = \frac{S_0}{S_a} \tag{5}$$

where, S_a is the lighted area of the absorber

Table 2: Characteristics of receiver

	Thick disc	Thin disc
Material	Stainless steel	cupper
Receiving diameter	0.12 m	0.12 m
Thickness	0.02 m	0.0005 m
Receiving surface	0.012 m^2	0.012 m^2
Geometrical concentration factor	336	336
Thermal conductivity λ	20 W/mK	380W/mK

2.3 Follow-up of the sun

The follow-up of the sun is ensured by two commanded electric jacks. The concentrator is oriented in front of sun according to two freedom degrees. (hour angle and declination). First jack ensure the follow up of the hour angle. The second one permits movement of the concentrator according to declination angle.

This command system permits us to obtain a circular shape of sunspot. The present design is equipped by a moving support in order to have the possibility to place our system in the best site.

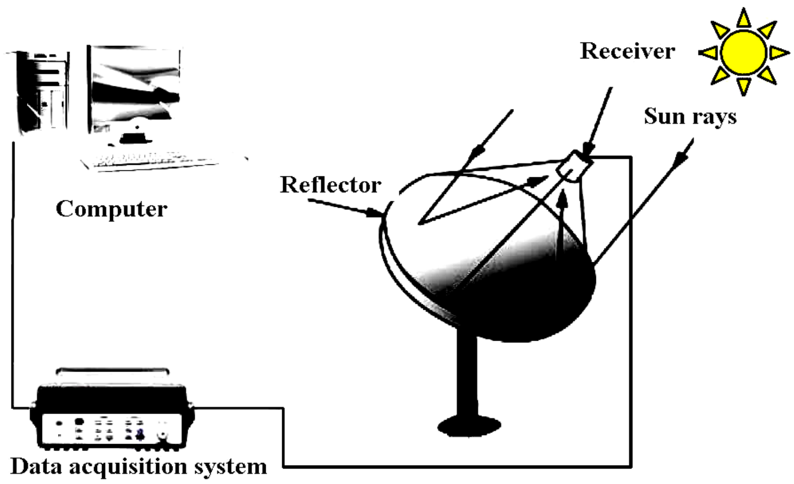

Fig. 2: Experimental design

3. EXPERIMENTAL MEASUREMENT AND RESULTS

3.1 Solar flux density

The experiment is made at 29/01/2008 during the period from 12h to 15h. To determine the space-time evolution of the disk temperature, seven thermocouples were installed in equidistant positions along its diameter.

A data acquisition system (Fig. 2) makes it possible to follow the evolution of the temperature given by each thermocouple every five minutes.

Solar flux and the ambient temperature are given by a weather station installed on the site.

The values given by the pyranometer represents the solar flux on horizontal surface (Fig. 3).

Figure 4 represents global solar flux variation measured by the meteorological station of the site during the sunning period of the day.

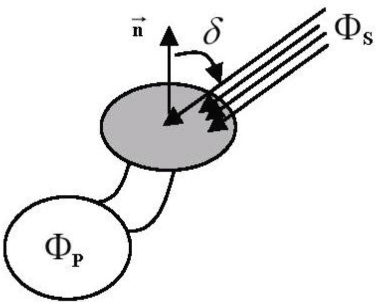

Fig. 3: Pyranometer

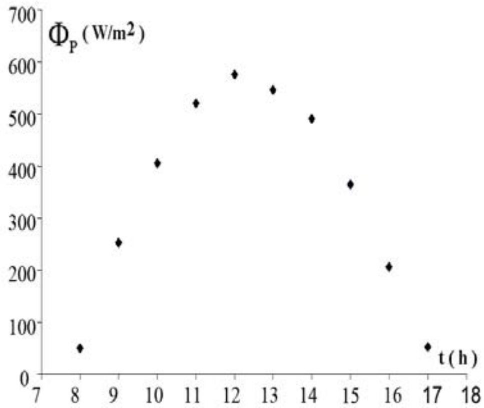

Fig. 4: Measured global solar flux density

Because of the sun flow up system which is assured by two jacks, the receiver disk is oriented in front of sun, that's way the effectiveness solar flux will be deduced from the measured flux density using a correction coefficient carried out from the disk orientation angle cosines (Fig. 5).

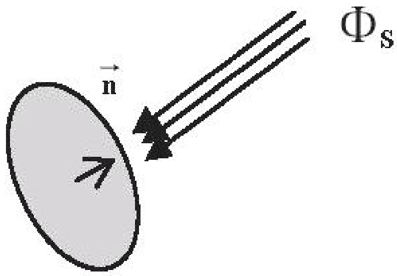

Fig. 5: Incident flux on the disk receiver

The **Table 3** gives global solar flux density measured by the pyranometer, angle declination, direct solar flux and incident solar flux on the receiver. The relation between incident and direct solar fluxes is given by the following expression:

$$\Phi_{incid} = \frac{\Phi_S}{\cos(\delta)} \tag{6}$$

Direct solar flux [12] is deduced from global solar flux measured by a pyranometer of meteorological station of the site and is represented by the figure 6.

The figure 7 represents the effective solar flux density received by the concentrator. As shown in this figure and **Table 3**, the flux density can reach in the experiment conditions 544 W/m² between 11h and 13h.

Table 3: Solar flux density vs. declinaison

t (h)	Φ_p (W/m^2)	δ (°)	Φ_S (W/m^2)	Φ_{incid} (W/m^2)
8	49.3	69	39	118
9	252.6	57	202	370
10	405.4	46	324	466
11	520,8	37	416	521
12	576,1	32	461	544
13	546,1	33	437	521
14	490,3	38	392	497
15	364,8	48	291	434
16	206,3	59	165	320
17	52.2	71	42	129

The mean ambient temperature given by the station is of 15 °C.

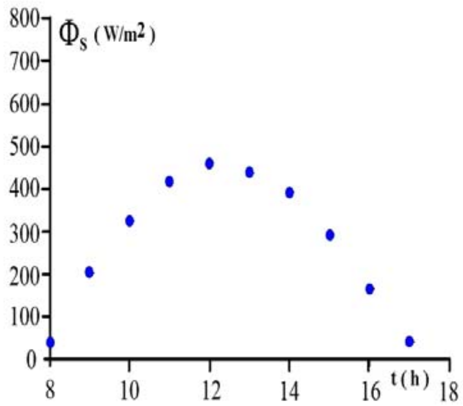

Fig. 6: Solar flux density received by the concentrator, solar rays normal to aperture

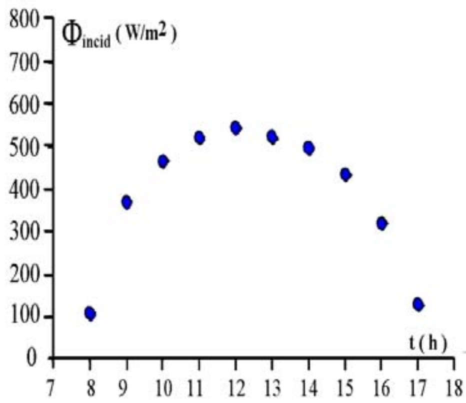

Fig 7: Solar flux density directly received on the concentrator

3.2 Results

3.2.1 Temperature measurement on a thick disc

Figure 8 represents temperature evolution of the disk centre. In the experimental conditions mentioned above, the temperature reaches an average value of 380 °C after 23 min which represents the heating time of the receiver.

As shown in figure 8, the mean temperature is maintained during two hours.

According to the energy distribution of light in the sun spot. The maximum of energy is concentrated in the centre. The temperature distribution over the disk having also the same profile as the awaited phenomena (Fig. 9).

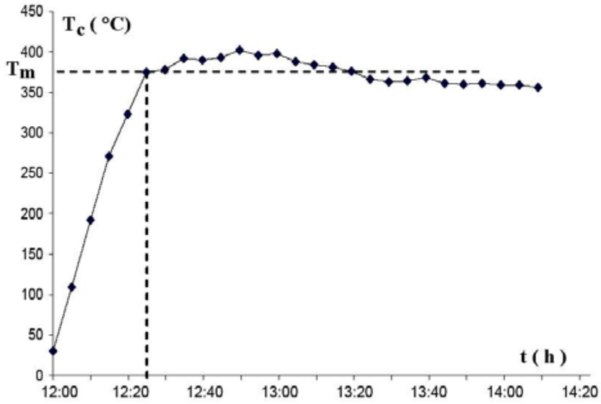

Fig. 8: Temperature profile of the disk center

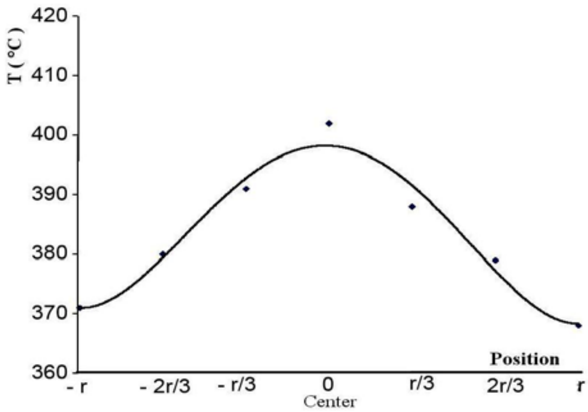

Fig. 9: Temperature profile over the disc at 12h50mn

3.2.2 Experimental measurement of the solar flux density by means of a thin disc

3.2.2.1 Theoretical study

The energy balance at the level of the receiver can spell under the following shape:

$$m.C_p.\frac{dT}{dt} = \Phi_{conc} + \Phi_{incid} - \phi_{conc} - \phi_{ray} \tag{7}$$

At the time $t = 0$, the receiver has the same temperature of the ambient, so the energy lost by the disk by convection and radiation is negligible. The concentrated solar flux is very important compared to the incident solar flux received by the disk directly from the sun, then equation (7) becomes:

$$m.C_p.\left(\frac{dT}{dt}\right)_{t=0} = \Phi_{conc} \tag{8}$$

To determine the concentrated solar flux, it is enough to estimate the tangent coefficient at the origin of time witch is:

$$a = \left(\frac{dT}{dt} \right)_{t=0} \tag{9}$$

The tangent equation at the origin of time is given by the following expression:

$$T = a.t + T_{\infty} \tag{10}$$

Then, the concentrated flux on the receiver is:

$$a.m.C_p = \Phi_{conc} \tag{11}$$

3.2.2.2 Experimental measurements and results

In order to determine the efficiency of the solar concentrator equipment, a company of measurements of temperature evolution on the thin disc are carried out. The determination of the efficiency and the characteristics of the studied concentrator give as the possibility of a truth study, conception and realization of high temperature designs.

To determine temperature profile on the disc, a thermocouple K was installed in the centre of the receiver and was linked with the data acquisition system. The temperature is scanned each 10 seconds. The experiment is made at May 07^{th} 2008, during the period from 12h to 13h.

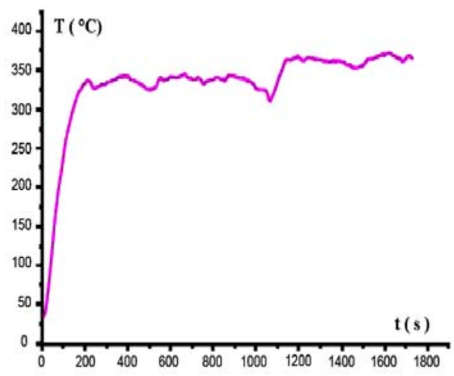

Fig. 10:Temperature profile

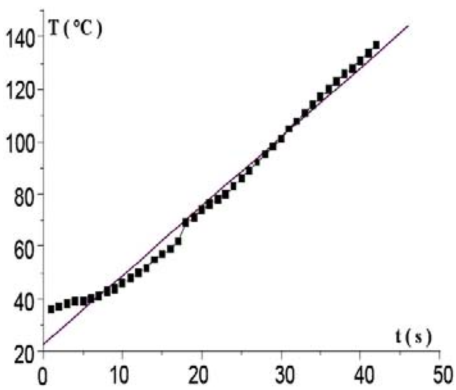

Fig. 11: Temperature profile at the beginning of experiment

The figure 10 represents the evolution of the temperature of the disc according to time. Experimental results show that the temperature attends 330 °C in few minutes and permanent regime is also established.

The temperature fluctuations around the mean value near 330 °C at permanent regime is due essentially to the effects of convection heat transfer fluctuations as the act of wind speed instability and the passage of small clouds which shadows partially the concentrator during small periods.

The figure 11 represents temperature variation with the time at the beginning of the experiment. The determination of the tangent gives us the following equation:

$$T = 2.81t + 25.64 \qquad (12)$$

The determination of the tangent also allowed us to find the ambient temperature which is 25 °C.

From equations (10) and (11), the concentrated flux Φ_{conc} and the solar density fluxes $q_{conc} = \Phi_{conc} / S_a$ are deduced and their values are given by the following **Table 4**.

Table 4: Solar flux concentrated and solar density flux measured

Concentrated Flux	Solar density flux (W/m^2)
167 W	14739 W/m^2

The efficiency of the studied solar concentrator is the ratio of the solar concentrated flux density and the solar flux density.

$$\eta = q_{conc} / \Phi_{incid} \qquad (13)$$

The experimental efficiency of the system is then about 27 %.

4. CONCLUSION

In this study, a solar concentrator design has been installed. This equipment is based on a reflector dish and a receiver disk. Experimental measurements of solar flux and temperature distribution on the receiver have been carried out. The solar flux concentrated on receiver has been experimentally determined. The obtained results describe correctly the awaited physical phenomenon. The temperature in the center of the disc reaches a value which is about 400 °C.

So that, a good quality of industrial high temperature equipments, can be obtained using this technology of solar energy concentration. The second result is the good efficiency of the studied solar concentrator witch can be increased by different interventions. In another term, using this solar equipment we can extract eventually 27 % of direct solar energy and convert it into thermal energy that can be used directly for several applications such us water heating, electricity generation using Stirling engine, vapour production, etc.

NOMENCLATURE

C	Geometrical concentration coefficient	Φ	Solar flux density, (W/m^2)
C_p	Specific heat, (J/(kg.K))	Φ_{conc}	Solar flux concentrated, (W/m²)
d	Parabola aperture, (m)	Φ_{incid}	Incidental solar flux, (W/m²)
f	Focal distance, (m)	Φ_{conv}	Solar flux lost by convection, (W/m²)
h	Parabola depth (m)		
m	Mass of the thin disc, (kg)	Φ_{ray}	Solar flux lost by radiation, (W/m²)
q_{conc}	Solar density flux, (W/m^2)	η	Efficiency,
r	Radial distance, (m)	T	Temperature, (°C, K)

S_0	Parabola area, (m^2)	T_∞	Ambient temperature, (°C,K)
S_a	Sa receiver area (m^2)		
z	Axial distance, (m)		**Indices**
	Greek letters	1	First face of the disc
δ	Declination angle, (°)	2	Second face of the disc
λ	Thermal conductivity, (W/m^2)	cd	Conduction
ray	Radiation	conc	Concentrated
e	Thickness	cv	Convection

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