Comparative Study of Optical Efficiency and Concentration Factor for Box-Type and Parabolic Solar Cookers

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Abstract. Solar energy is rapidly expanding across various fields worldwide. Among its applications, solar cookers represent a promising solution for harnessing this renewable and inexhaustible energy source. This article presents a study of the optical performance of a box-type solar cooker and a parabolic solar cooker, conducted over two representative days of the year, one in winter and the other in summer. The objective of this optical simulation is to analyze the amount of incident flux concentrated on the absorber for these two configurations, while also evaluating their optical efficiency and concentration factor, which are key characteristics of these systems.

1 Introduction

The use of solar rays for cooking dates back to ancient times. In 1774, Horace-Bénédict de Saussure studied the thermal effects of solar rays using his heliothermic thermometer, a device with insulating walls and one or more glass panels that allowed light to pass through, thus creating a greenhouse effect. This instrument could reach temperatures of about 80°C. His research laid the foundation for the development of solar ovens. A century later, Augustin Bernard Mouchot invented the first solar cooker. In 1875, he presented a study on a pot heated by a cylindrical reflector. This prototype was able to cook a one-kilogram stew in four hours. Since then, many models of solar cookers have been developed and spread worldwide, offering a natural and effective way to cook without using gas or electricity. These devices are based on the direct use of sunlight to heat or cook food without emitting greenhouse gases. Solar cookers come in various shapes, each characterized by its design and functionality. They are known for their ease of construction, using commonly available materials such as wood (as an insulating material to reduce heat losses), aluminum, and glass. The literature contains several studies on the experimental performance of these cookers. Among these, we can cite [1] Navven Kumar et al conducted tests on a glazed box-type solar cooker, determining performance factors F1 and F2 as 0.1171 C m²/W and 0.4671 °C m²/W, respectively. They experimented with tilting the cooker, aligning the glass surface with the sun, and observed a

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lower stagnation temperature of the absorber plate at 112°C compared to the horizontal case at 119°C. [2] They designed and tested a truncated pyramid solar cooker and dryer. Their tests showed that the cooker could reach temperatures of up to 140°C with no load. A.A. EL SEBAII et al. [3] developed a box-type solar cooker by adjusting the internal mirrors at different angles relative to the horizontal to improve thermal efficiency. Their results showed that this cooker achieved a thermal efficiency of 30% and could be used three times a day in summer and once a day in winter. A new hybrid solar cooker, coupled with photovoltaic panels, was developed by S.B. Joshi et al. [4]. The goal was to reduce cooking time using the photovoltaic energy generated by these panels. This prototype can prepare multiple meals throughout the day in less time and at an affordable cost. Abhishek Saxena and Nitin Agarwal [5] developed and tested a solar cooker to enhance heat flux rate and reduce cooking time. Their approach integrated a trapezoidal duct, a 200W halogen lamp and 450 small hollow copper balls for forced convection. Operating under solar radiation, Configurations 1 and 2 were tested to determine merit factors ($F1=0.12$ m² °C/W, $F2=0.41$ m² °C/W). In Configuration 3, modifications included the addition of a duct and copper balls within the absorber plate, both tested with and without a load. In the fourth configuration, which involved an increased load, all copper balls achieved high temperatures, effectively generating hot air. A comparison revealed a 7% improvement in solar cooker efficiency and a 12% enhancement in the heat transfer coefficient, attributed to the added duct for forced convection. Additionally, an optical study was conducted for two types of solar cookers in this article. The objective was to determine their optical efficiency and enhance the concentration of rays on the absorber, even under unfavorable meteorological conditions. A. Harmim et al. [6] developed a new type of solar cooker coupled with a parabolic solar concentrator used as a reflector to enhance its thermal performance. Antonio Lecuona et al. [7] designed a new type of parabolic solar cooker using a hollow cylindrical utensil coupled with a phase change material (PCM) thermal storage unit. This system allows cooking outdoors during sunlight hours and indoors when there is no solar radiation. Tests showed that this type of cooker can prepare three meals a day, whether in summer or winter. In a context of increasing demand for sustainable and accessible energy This study presents an optical analysis of the performance of different types of box cookers rectangular (H = 35 cm), trapezoidal (H = 10 cm), triangular (H = 0 cm) as well as parabolic solar cookers, using the Trace Pro optical software, considering the weather conditions in Oujda for a sunny day in July, to compare their ability to concentrate solar radiation. The results show that the amount of incident flux is higher for the parabolic solar cooker than for the box-type, as demonstrated by the concentration factor and optical efficiency calculation curves.

2 Methodology

This article aims to evaluate the solar flux incident on the absorber of different types of solar cookers: a box-type design with a height of H = 35 cm (rectangular), progressively reduced to H = 0 cm for the triangular configuration, and a parabolic concentrator, in order to optimize their optical performance. These technologies are characterized by their simple design and the use of readily available materials. The box-type cooker features an aluminum structure that acts as a reflector, directing sunlight onto the absorber, along with an insulating layer to minimize heat loss. It also includes a horizontal glass opening that allows solar rays to enter, increasing the temperature inside the cooker and enabling it to achieve very high temperatures.

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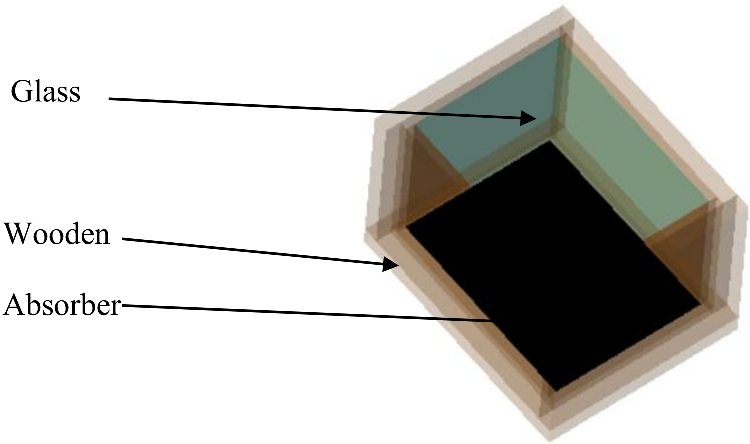

Fig. 1 Solar box cooker designed with SolidWorks

The second design, a parabolic solar cooker, is characterized by its ability to concentrate sunlight onto a single point, relying on two fundamental principles. The first principle is the reflection of sunlight by the parabolic reflector, which is specifically designed to direct solar rays toward a focal point where energy is concentrated. The second principle is the greenhouse effect, made possible by a transparent glass cover. This cover allows sunlight to enter while trapping heat inside the cooker and directing it toward the base of the cooking pot. As a result, the temperature within the cooker rises significantly, creating an efficient environment for cooking.

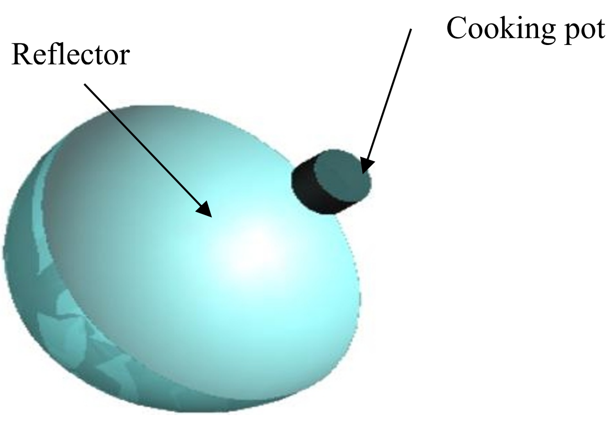

Fig. 2, Solar cooker parabolic designed with SolidWorks

3 Optical simulation

The operation of solar cookers relies on several physical phenomena, including absorption, convection, and confinement of solar radiation. The solar rays, after striking the cooker's receiver surface, are absorbed by a black-painted absorber designed to maximize absorption through its specific optical properties, thus converting solar energy into heat. The generated heat is then trapped inside the cooker, where the convection phenomenon helps evenly distribute the heat within the enclosed space, ensuring homogeneous cooking. Additionally, the use of thermal insulating materials helps reduce heat loss to the external environment, thereby maintaining very high temperatures. The optical study presented in this paper was conducted using Trace Pro software, following the design of the two solar cookers in SolidWorks, which were then imported in STEP format. We simulated the trajectory of solar rays' incident on the absorber for both selected cookers. Using the ray-tracing method, the light beam was represented by a 1300 x 1300 ray matrix. For the box-type solar cooker, before starting the simulation, it is necessary to define the light source for our concentration system, which, in our case, is the sun. This requires first calculating its position, which varies throughout the day, by applying the trigonometric relations [6] presented in the equations (1)-(2)-(3)-(5)

The sun height h is the angle between the sun direction and the horizontal plane on Earth, it varies between 0 and 90°. At sunrise and sunset, the height is 0°. It is given by the Following relation:

$$\sin(h) = \cos(\varphi) \times \cos(\delta) \times \cos(\omega) + \sin(\varphi) \times \sin(\delta) \tag{1}$$

With φ is the latitude of the site, δ is the declination and ω the hour angle, given by:

$$\delta = 23{,}45 * \sin(\frac{360}{365} * (284 + N)) \tag{2}$$

$$\omega = 15(t - 12) \tag{3}$$

The azimuth (Az) is the angle formed, on the horizontal plane, between the projection of the sun direction and the south direction. It is measured positively towards the west and negatively towards the east, with zero at noon. It is given by the following relation:

$$\mathrm{Cos}(Az) = \frac{\sin(\varphi)\times\cos(\delta)\times\cos(\omega)-\cos(\varphi)\times\sin(\delta)}{\{[\cos(\varphi)\times\sin(\omega)]^2+[\sin(\varphi)\times\cos(\delta)\times\cos(\omega)-\cos(\varphi)\times\sin(\delta)]^2\}^{\frac{1}{2}}} \tag{4}$$

The optical efficiency is a measure of how effectively a system captures and concentrates the incident light energy onto a receiver, It takes values between 0 and 1It is defined as

$$\eta_0 = \frac{Q_{abs}}{G*A_{receiver}} \tag{5}$$

For this simulation, two days were selected: one sunny and the other characterized by low sunlight, in order to observe the performance of the cookers under these two conditions. The following figure shows the global irradiation for these two days. The values of Global Horizontal Irradiance (GHI) used in this study were obtained from a meteorological data file provided by the Oujda Meteorological Station, ensuring realistic representation of local solar conditions.The first simulation will be performed on the solar cooker with a horizontal receiver surface (conventional geometry) for both selected days. Then, we will run the same simulation, but this time with an additional glass wall to study the effect of ray concentration on the absorber with the addition of this glass wall. Finally, we will simulate a parabolic solar cooker to compare it with the box-type cooker.

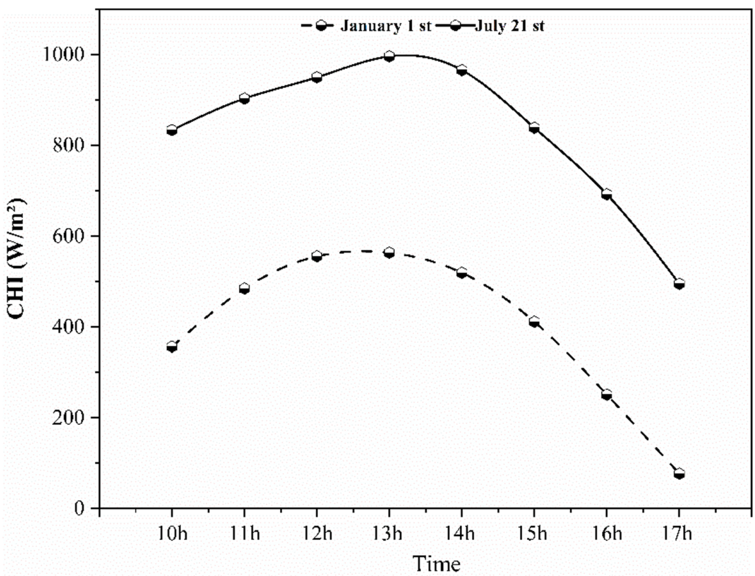

Fig. 3 Global solar irradiance for the simulation days

The basic parameters of a parabolic solar cooker are [7]-[8]:

$$X2=4\ f\ y \tag{5}$$

$$h = R^2/4.f \tag{6}$$

$$f = D^2_{ap} \ /\ 16.h \tag{7}$$

Where X is the distance along the horizontal axis, f is the focal point, D $_{Ap}$ the aperture diameter of the parabolic reflector.

We then proceed to calculate the reflector area and the receiver area to determine the concentration factor of the two selected cookers, by applying relations (4), (5) and (6) or A $_{Ap}$

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and A_{AB} representing the aperture area of the parabolic solar cooker and the box-type solar cooker, respectively.

$$AP = \pi * D_{AP}^2 / 4 \tag{8}$$

$$A_{AB} = \pi * D_{AB}^2 /4 \tag{9}$$

The purpose of determining the geometric concentration factor is to assess the amount of energy concentrated on a small surface (the focal point) for the parabolic solar cooker, as well as the energy captured by the box-type solar cooker. A high value of this factor indicates an intense concentration of energy, allowing for the achievement of very high temperatures

$$C_{GEO}=A_{AP}/A_{AB} \tag{10}$$

According to these relations, Table 1. presents the dimensions of the two cookers: the parabolic and the rectangular ones

Table 1. Dimensions of solar cooker

The dimensions of solar cooker (cm)	
Parabolic	Box
D_{AP}=100	H=35
f =100	L=50
ep =5mm	L=40

(a) (b)

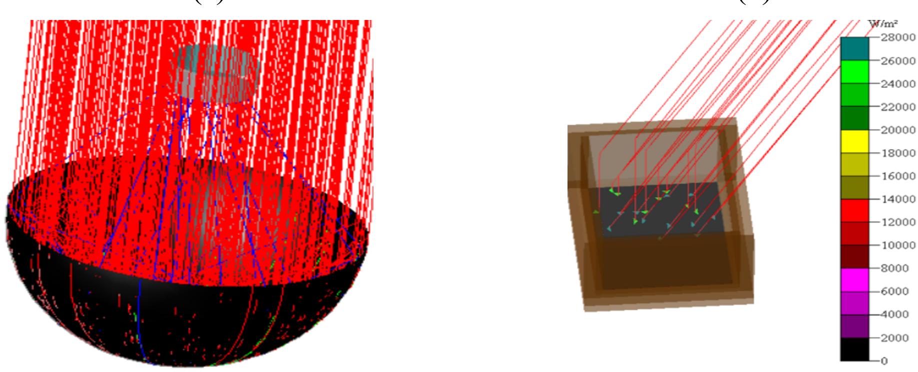

Fig. 4, Optical simulation for the two types of solar cookers: (a) solar box cooker, (b) solar parabolic cooker

4 Results and discussion

4.1 Optical simulation for solar cooker box and parabolic:

The study conducted using Trace Pro is based on an optical simulation designed to determine the incident light flux on the absorber for both a parabolic solar cooker and a box-type solar cooker. The goal is to compare the efficiency of the two cookers in terms of solar ray concentration and evaluate their optical performance throughout the two selected days for the simulation. This simulation enables the analysis of how the geometry of each cooker affects the distribution and intensity of the concentrated solar flux. Fig 5. clearly shows the amount of incident rays concentrated at the absorber at the focal point of the parabolic solar cooker, which can concentrate a maximum flux of about 1300 W/m² at 1:00 PM. The figure clearly illustrates the difference in the amount of incident flux concentrated on the two solar cookers. This variation is due to the nature of the geometries chosen for this study. As previously mentioned, the parabolic solar concentrator captures solar radiation over a small surface area, allowing it to achieve high levels of concentrated flux throughout the day. In contrast, the box-type solar cooker receives lower flux values compared to the parabolic concentrator. This difference is due to its conventional design, characterized by horizontal, non-inclined front walls, which create shadowed areas on the absorber surface, thereby reducing the concentration of solar flux throughout the day.

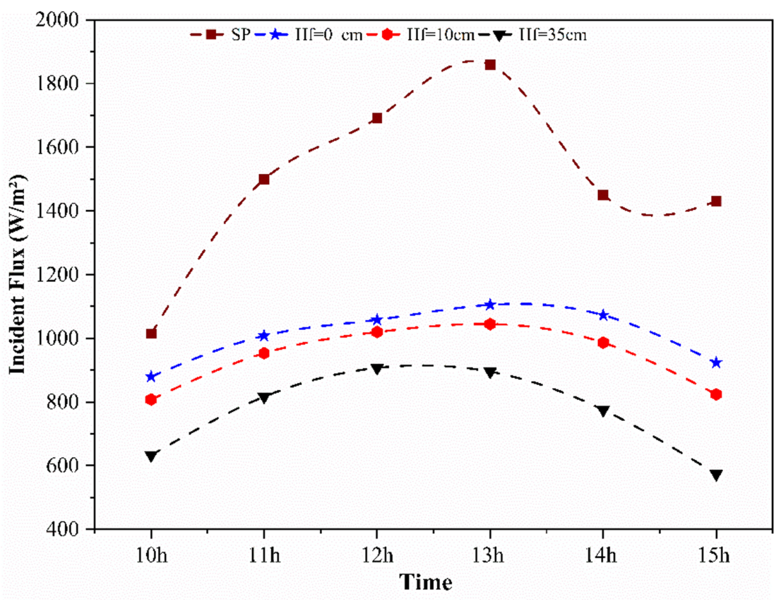

Fig. 6, Comparison between incident flux for box-type cooker and parabolic solar cooker

Fig 6. illustrates the difference in the amount of concentrated rays on the absorber between the box-type solar cooker and the parabolic solar cooker. This difference is primarily due to the nature of the cookers' geometries. Indeed, the surface onto which the rays are concentrated differs between the two cookers. For the parabolic cooker, all rays are directed toward a single focal point, the pot, which has a relatively small surface area. In contrast, the box-type solar cooker captures solar rays over a larger surface, that of the absorber. Furthermore, the geometry of the parabolic cooker allows it to concentrate more rays, as it reflects all rays parallel to its axis of symmetry toward a single focal point.

4.2 Optical efficiency and concentration factor

4.2.1 Optical simulation for solar box cooker

Defining the optical efficiency of a solar concentration system is crucial for assessing its ability to capture and focus solar rays, converting them into heat while considering energy losses caused by phenomena like reflection and absorption on optical surfaces. Optical efficiency is expressed as the ratio of the flux absorbed by the absorber to the incident flux on the receiving surface [5], as illustrated in Fig 5.

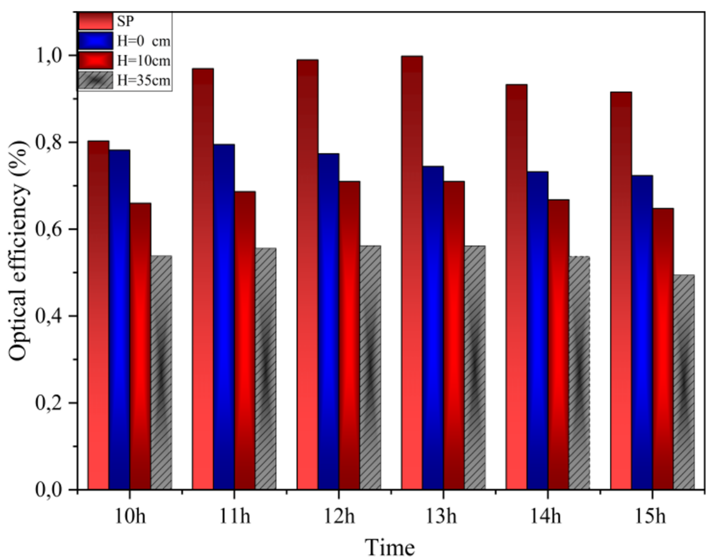

Fig. 9, Optical efficiency for solar box cooker and parabolic solar cooker

As shown by the two curves presented in Fig 4. the optical efficiency of the parabolic solar cooker is higher than that of the box-type solar cooker. These results align with the amount of concentrated flux for both types of cookers. The optical efficiency for both cookers increases throughout the day until it reaches the maximum values corresponding to the maximum concentrated solar irradiation. The maximum optical efficiency reaches 76% for the parabolic cooker, while for the box-type solar cooker, it stabilizes at 55%. This difference can be attributed to the geometry of the parabolic cooker, which allows for more efficient concentration of solar rays onto a smaller surface, thus increasing the efficiency of converting solar energy into heat.

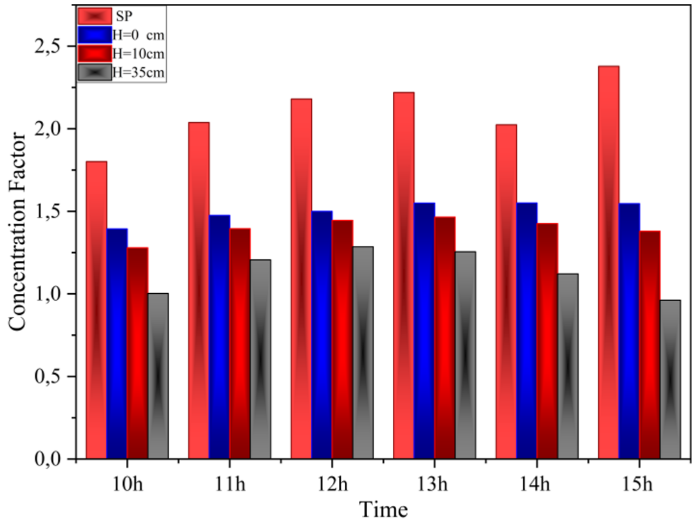

Fig. 10, Concentration factor for solar box cooker and solar parabolic cooker

For the concentration factor of the cookers, it can be calculated as the ratio of the incident flux on the glass surface to the incident flux on the absorber surface. Based on this definition, the concentration factor reaches a maximum value of 1.6 when an additional glass panel is added.

4.2.2 Flux distribution

The flux distribution on the parabolic receiver and the absorber of the box-type solar cooker is illustrated in fig 5. Fig 6. The two figures present the distribution of incident flux on the receivers for both solar cookers. In the case of the parabolic cooker, the flux is more concentrated at the center since the receiver is positioned at the focal point of the reflector. Conversely, for the box-type solar cooker, the flux distribution is more uniform. The area without radiation corresponds to the shadow cast by the walls on the absorber surface.

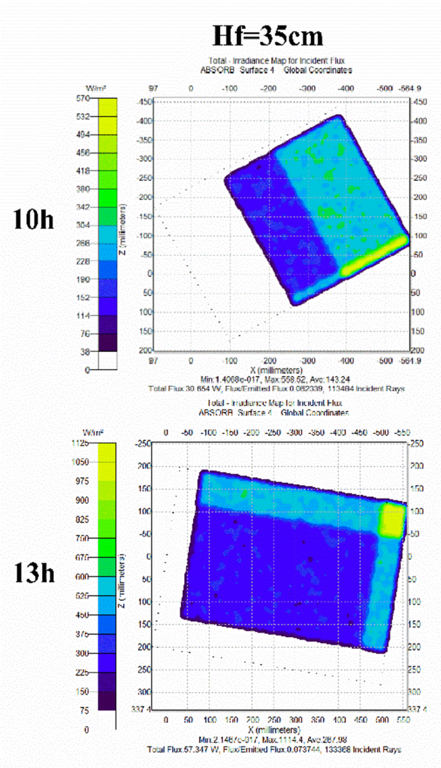

Fig. 10, Irradiance Map for solar box cooker January 1st

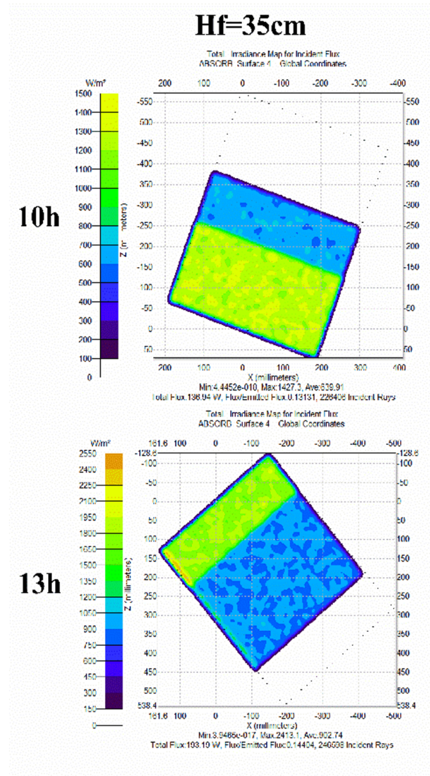

Fig. 11, Irradiance Map for solar box cooker July 21st

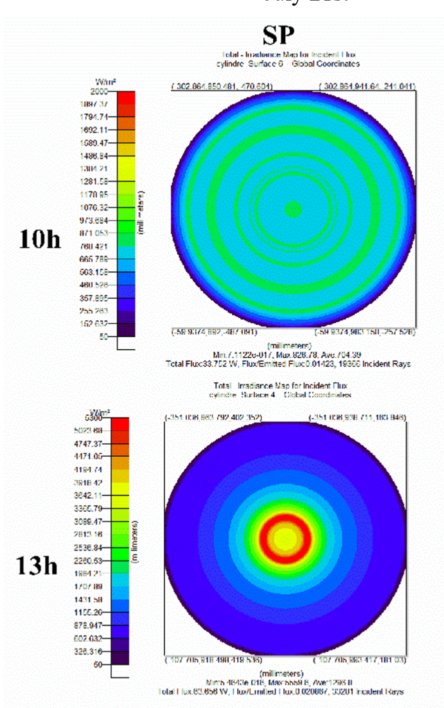

Fig. 12, Irradiance Map for parabolic solar cooker

Nomenclature

X: distance along the horizontal axis

Y: is the distance along the vertical axis

f: focal length

A_{AP}: Aperture area of parabola

A_{AB}: Aperture area of ABSORBER

C_{GEO}: The geometric concentration factor

L: The width of the box-type solar cooker

D_{AP}: The aperture diameter of the parabolic
D_{AB}: The aperture diameter of the Box cooker

h: depth of parabolic

I: The length of the box-type solar cooker

0V: Without a glass wall

1V: With a glass wall

Conclusion

In this article, the distribution of radiation flux on the absorber of a box-type solar cooker and a parabolic solar cooker was analyzed numerically using the Monte Carlo ray-tracing method with Trace Pro software. The simulations show that the parabolic solar cooker is able to concentrate more energy on the receiver than the box-type solar cooker. This difference can be explained by the functioning of the parabolic solar concentrator, which focuses the rays onto a single focal point, unlike the box-type cooker that disperses the rays over a larger surface. Adding additional reflectors improves the amount of incident flux on the Solar receiver, increasing the concentration of solar radiation and allowing higher temperatures to be reached, effectively meeting our energy needs. Furthermore, the calculation of two very important parameters for analyzing the optical performance of solar cookers was carried out. The results clearly show that the parabolic solar cooker concentrates a greater amount of solar radiation than the box-type cooker.

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