

Design and experimental study of a hemispherical solar cooker: application to food cooking

Abstract

The present work is an experimental study of a glazed hemispherical solar cooker. It consists of a hemispherical concentrator made of reinforced concrete with a smooth inner part lined with a self-adhesive aluminium mirror film with a reflectivity of 95%. This reflector enables all the sun rays to be reflected onto the absorber. The hemisphere has a radius of 0.59 m, a height of 0.46 m and an exposure area of 0.1535 m² for the half angle of the apex of the focus with the axis passing through the centre. Experimental data on the evolution of the temperature of the air trapped in the device on October 26, 2022 showed a maximum temperature of 63°C. The temperature under the glazing indicates a maximum value of 51°C, for an ambient temperature of 35°C. The maximum irradiation of 700 W.m⁻² obtained around 11:45 a.m. The second test, carried out on October 28, 2022, was designed to heat 1.5 litres of water. The results indicate a maximum temperature of 91.7°C for the water, obtained from 10.45 a.m and 1.33 p.m. However, the air temperature under the glazing gave a maximum value of 67°C. The ambient air temperature was 37°C. The day of April 21, 2023 is devoted to experimental studies on cooking and frying sweet potatoes. The maximum temperature was 97°C, obtained from 11:30 a.m, for an air temperature of 80°C under the glazing, obtained from 10:50 a.m. with maximum irradiation of 957.1 W.m⁻². A value of 130°C is obtained at 13:21 p.m for the oil heating test and a maximum temperature of 68°C for the internal air at an ambient temperature of 32.9°C. The irradiation value reached a maximum of approximately 306.8 W.m⁻².

Key words: Irradiation, reflector, hemispherical, solar cooker, concentration

1. Introduction

Findings indicate that over 900 million people in sub-Saharan Africa still use traditional unprocessed solid biomass fuels for cooking [1]. This presents a significant risk, as these fuels generate high levels of toxic particles and biomass smoke and 95% of the world's population use wood, charcoal and agricultural waste [2]. Wood fuels account for around 90% of energy consumption in most households in developing countries (FAO, 2010). In Burkina Faso, 85.5% of households use biomass (wood energy, agricultural residues) [3]. This is

accelerating desertification in Sahelian countries. Given these difficulties, the various nations have no choice but to diversify their energy resources in view of the energy, environmental and security context. Solar energy will be an important alternative for sub-Saharan countries such as Burkina Faso. Our country is one of the 25 countries in the world with a large solar deposit, and this opportunity could help to reduce the use of petroleum products for cooking. At a time when energy savings and ecological issues are important, the use of solar cookers seems to be a good compromise in sunny developing countries [3]. To work at high temperatures, the incident optical flux needs to be increased, which could be achieved by concentrating solar radiation.

These systems generally include a reflective surface designed to concentrate solar energy on an absorbent surface, resulting in a large increase in heat. The advantage of this method is that high temperatures can be reached, making it ideal for heating water in solar kitchens [3]. The first historical use of solar energy to cook food was published by the Swiss Scientist Horace de Saussure(1767). However, the real development of solar cookers began in 1950. Since then, several different types of solar cooker have been developed and have been the subject of theoretical and experimental studies throughout the world. A solar concentrator is defined as a device that concentrates the sun's rays on a target in order to recover maximum energy. The main purpose of the concentrator depends on the application [4].

There are several solar cooking systems, including : concentration-type solar cooking systems such as paraboloid cookers [5], indirect-type solar cooking systems [6], [7], [8], [9], [10], [11]. They work like dryers with the collector separate from the receiver. Box-type solar cooking systems [12], [13], [14], [15], [16]. These systems are not intended to reflect the sun's rays accurately, but the rays that penetrate the box help to raise the internal temperature to a cooking level. The use of solar cookers should be a common means of cooking in Burkina Faso, located in the sub-Saharan region where 900 million people do not have their own cooking appliances [17]. Because of its geographical location, this country benefits from an annual solar flux of 1024 kWh.m^{-2} [18]. The SRTA (Stationary Reflector/Tracking Absorber) concept was created in 2008 by Berland [19] . According to this concept, a spherical concentrator always concentrates solar radiation along a line passing through the centre of the sphere, as shown in Figure1. The SRTA system, built and experimentally tested by Shay Cohen et al [20], has demonstrated the applicability of this system for collecting solar heat at intermediate temperatures. The efficiency achieved was virtually independent of operating temperature, over a wide range up to 200°C . Higher temperatures up to 300°C were achieved

using thermal oil as **high-temperature fluid**(HTF) . The prototype solar cooker in the form of a box equipped with an asymmetrical CPC with an acceptance angle of 60° was built by A. Hamim et al, using resources and materials available in Adrar. The internal dimensions of the box housing the cooking utensils are $0.7 \times 0.28 \times 0.14 \text{ m}^3$. The objective was to heat 4.5 litres of water. The test started at 11:06a.m with an initial temperature of 20.8°C and an ambient temperature of 17.4°C . The boiling temperature was reached after 198 minutes [21]. A system has been designed, produced and tested for solar cooking[22]. It uses a spherical reflector as a concentrator, mounted on two frames for better orientation towards the sun. The system's engineering enables it to achieve a theoretical average geometric concentration of 720 and a theoretical efficiency of 0.42. As a result, the system is easy to handle, since only one azimuth angle is tracked. An optional tilting of the reflector also enables the system to be used in equatorial and tropical zones when the sun is close to the zenith. A series of tests was carried out around 20 November in Ouagadougou, Burkina Faso, at an angle of latitude of 12.21° . Tests for heating oil in a pot successively reached a maximum temperature of 184°C at 1:00 p.m. on the first day and 221°C on the second day at 1:30 p.m. Boiled sweet potatoes, fried sweet potatoes, spaghetti and fish dishes were cooked within a reasonable time

2 Description of the **studied** device

We present here a glazed hemispherical solar cooker. It has been designed at Thermal and Renewable Energy Laboratory (L.E.T.RE). Experimental work has been carried out on it, which consists of recording changes in the air temperature inside and outside our device during the cooking of various foods in the course of irradiation. Fig 1 and 2 shows the device used for our study.



Fig 1 :experimental device



Fig2: hemispherical reflector

It consists of a hemispherical concentrator made of reinforced concrete with a smooth inner surface lined with a self-adhesive aluminium mirror film with a reflectivity of 95%. This reflector enables all the sun's rays to be reflected onto the absorber, the cooking pot. The hemisphere has a radius of 0.59m, a height of 0.46m and an exposure area of 0.1535 m² for the half angle of the apex of the focus with the axis passing through the centre. The opening surface is closed by a glass pane that lets the irradiation rays through, and this pane has the property of trapping infrared rays inside the appliance. This raises the temperature inside the concentrator, making cooking easier.

An under-glazed hemispherical concentration system differs from other systems, which first heat a black plate with or without fins, then recover heat from the plate with a fluid by convection. The device that we propose uses the sunspot corresponding to the actual image of the sun formed in the focus of a hemispherical concentrator which by effect of concentration, generates a very hot zone. The heat from that zone can be directly transmitted to the circulating air. The device proposes to heat the air and cooks the food using the combined effects of the greenhouse effect and concentrated radiation, without solar system tracking. One more advantage of the hemispherical concentrator with reference to Fig3, is that the portion of the axis on which it concentrates is always in the bowl of the hemisphere.

The hemispherical portion, corresponding to a hub, is closed by a transparent glazing intended to cause a greenhouse effect trapping the infrared rays, while the reflecting surface of the hemisphere causes a concentration. This system as described does not use any receiver. The air is directly absorbing the heat produced by the concentrator. The concentration effect can be considered as a burning spot actually corresponding to the real image of the sun, and this spot may directly heat the surrounding air. Furthermore, inside the concentrator is a mobile iron fireplace where a pot or a frying pan can be placed (absorber). This absorber can be painted in black to absorb as much of the reflected rays as possible. The choice of this hemispherical concentrator cooker is simply justified by its quality and efficiency of permanent concentration throughout the day, whatever the position of the sun. The glass used allows the action of wind speed and other external parameters to be neglected, and also contributes to increasing the temperature inside the enclosure through the greenhouse effect. The moving focus allows us to manually track the sun's spot (focal point) inside. The reflector is permanently positioned with a 12° inclination corresponding to the latitude of the site. It is

the fireplace that will be moved to follow the focal point. The following table gives the estimated cost of the system

Table 1: Cost analysis of the prototype is shown in the following table

Materials	Price
Reinforced concrete hemispherical concentrator	\$30
self- adhesive reflector	\$77
Metal support for cooking pot	\$23
Black painted cooking pot	\$8
Glazing + coverage structure	\$142
Manpower	\$50
Total cost	\$330

3 Definition and operating principle

A solar concentrator is defined as a device that concentrates the sun's rays on a target in order to recover maximum energy. A hemispherical concentrator cooker does not focus on a single point, but on an axis parallel to the sun's rays and passing through the centre of the sphere. It is on this axis that an absorber or receiver should be placed [23]. The study on the hemispheric concentrator and the type of receiver to be placed on the focal axis showed that for an aperture half-angle of less than 23°, a cavity receiver is recommended, whereas for a larger aperture half-angle, a conical receiver is suggested [24].

In the Gaussian approximation, when a light beam arrives parallel to the axis of the hemispherical concentrator, which is an astigmatic surface, all the reflected rays converge at the focus of the concentrator. In a zone called the aberration caustic, the reflected rays form a luminous spot at the plan the of the least confusion. The reflected rays are tangent to the surface of this zone [25], as shown in Fig 1 and 2. The parametric equation of the caustic known as the Nephroid equation is :

$$\begin{cases} R_d = R \sin^3 \varphi \\ Y = \frac{R}{2} \cos \varphi (1 + \sin^2 \varphi) \end{cases} \quad (1)$$



Fig 3 : Sunspot formation [25]

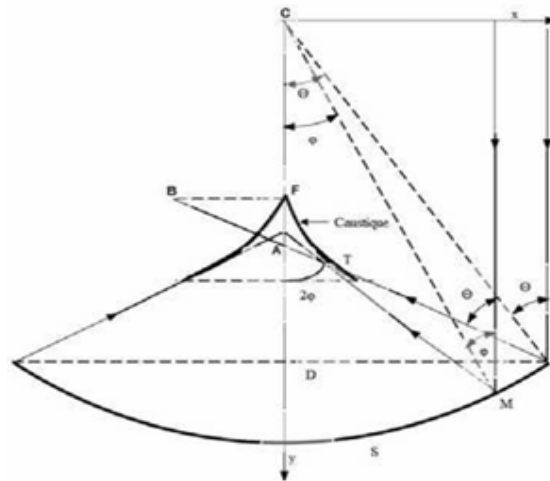


Fig 4: Caustics of a hemispherical or spherical concentrator [26]

Y position of the plane of least scattering

The reflection at point M of the ray forming an angle has the equation of a straight line (CM)Khaled [26].

$$R_d \cos(2\phi) + Y \sin(2\phi) - R \sin \phi = 0 \quad (2)$$

With R_d and Y the coordinates of the point of intersection (T) of the caustic and the line (CM). To position the receiving cavity on the y axis, we need to determine the coordinates R_d and Y of the point (T).

R_d : The radius of the plan of the least confusion(m) .

Y : Position of the plane of least confusion on the y-axis (m).

ϕ : The opening angle at the centre($^\circ$ C).

θ : The opening angle at the focus($^\circ$ C) .

Solving this equation involves replacing the expression for R_d and Y in equation (1) and for a value of $\phi=30^\circ$ we have $\theta=22^\circ$.

So with this value of φ , we obtain $R_d = 1.5610^{-2}m$ and $Y=0.33m$.

Taking into account the apparent diameter of the sun and to better calibrate the receiver, the radius R_a inside the receiver or the radius of the plan of the least confusion has the following expression:

$$R_a = (R \sin \varphi + R_d) * \frac{\cot(2\varphi)}{\cot(2\varphi + 0,266)} - R \sin \varphi \quad (4)$$

The hemispherical concentrator cooker we used has a radius $R= 0.59 m$ and we also know the value of $\varphi=30^\circ C$. Equations (1) and (2) give us

$$R_a = 3.4510^{-2} m \quad Y= 0.33 m \quad \text{et} \quad R_d = 1.5610^{-2}m$$

R_a : minimum radius of the cooking pot (m).

Y : position of the pot in relation to the reflecting surface (m).

The geometric mean concentration is calculated, using the equations (1, 2, 3 and 4):

$$C_{gm} = \left(\frac{R \sin \varphi}{R_a} \right)^2 \quad (5)$$

We obtain a geometric mean concentration $C_{gm} = 244$

Ky et al [27] have shown that following the apparent path of the sun, the plan of the least confusion describes a semicircle of radius Y inside a hemispherical concentrator, illustrated in fig 5. The value of the radius of the semicircle is close to half the value of the radius of the concentrator.

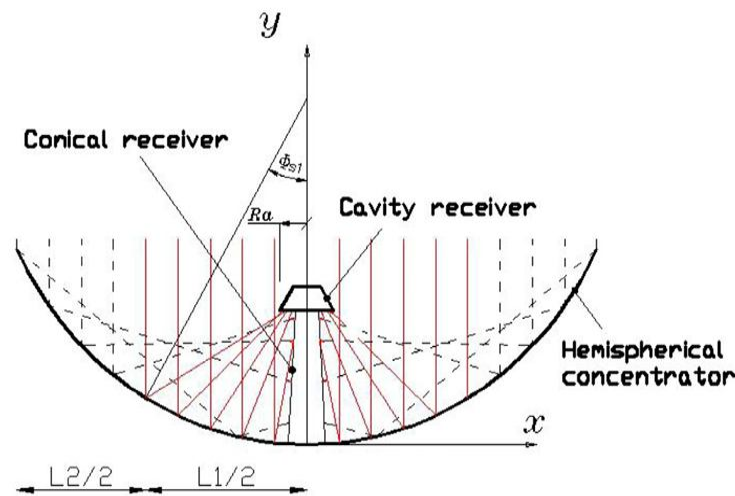


Fig 5: Hemispherical concentrator with mixed conical and cavity receiver [27]

3 Materials and Methods

In this work, we used type K thermocouples with armoured sheaths to measure the temperature of the receiver, the air inside the hemisphere, the ambient air and the outside and inside of the glass. A Hukseflux SR03-05 pyranometer used to measure incident solar irradiance on the horizontal plane. It is used to measure changes in direct illuminance on a horizontal plane. It has a sensitivity of $7.64\mu\text{V}(\text{W}\cdot\text{m}^{-2})$. A GRAPHTEC Midi LOGGER GL200A automatic data logger, programmed at a rate of 5 minutes, to which the thermocouples and pyranometer are connected. This device records changes in temperature using the thermocouples.

Table 1: Technical characteristics of the pyranometer, type K thermocouples and Midi logger

Tool	Temperature range	uncertainty
Type K thermocouple	-40 à 1000°C	±1.5%
SR03-05 pyranometer	0 à 1600 W.m ²	±1.8%
Midi LOGGER GL200A	-100 à 1730°C	±(0.1%reading+0.3°C)

GI200A

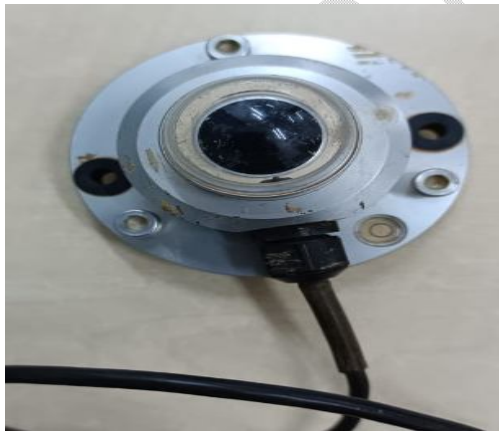


Fig 7 : SR03-5 Pyranometer

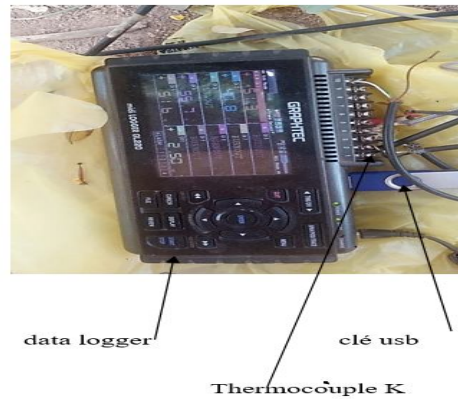


Fig 6: Midi LOGGER GL200A

A USB key is used to store recorded data. With the measurement equipment, an aluminum pot painted black on the outside was used during all tests. For temperature measurements, we used 3 type K thermocouples. The thermocouple measuring ambient air temperature is exposed to the open air. The thermocouple measuring the air temperature inside the device is suspended

inside the device. A thermocouple is always inserted inside the absorber to record the heating or cooking temperature of the food.

2 Experimental results

We carried out the first measurements without internal load, just to observe the evolution of the temperature of the air outside and inside the device.

Test 1. The aim of this first test is to measure the evolution of the air temperature trapped inside our hemispherical reflector. The evolution of irradiation during the day of October 26, 2022 is indicated by the following curve.

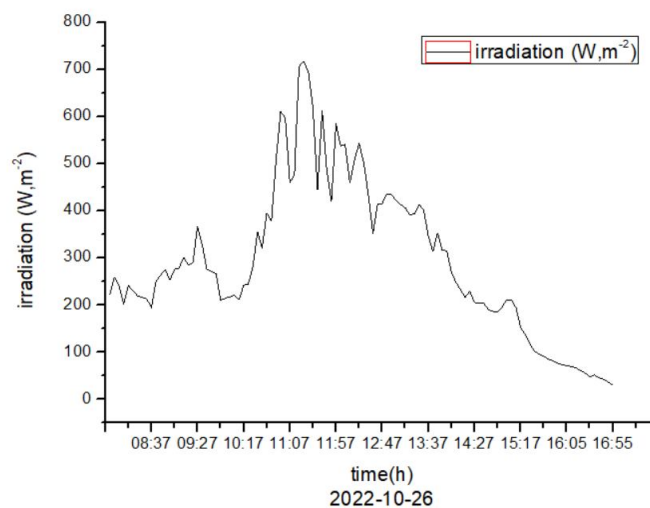


Fig 8: Irradiation curve for the day of 26 October 2022

Fig 8 shows the daily variation of irradiation obtained on this day. Maximum irradiance of 700 (W.m⁻²) at 11:45a.m; but the irregularities observed on the curve can be explained by the presence of clouds. The fig9 below, shows the various changes in air temperature in the system.

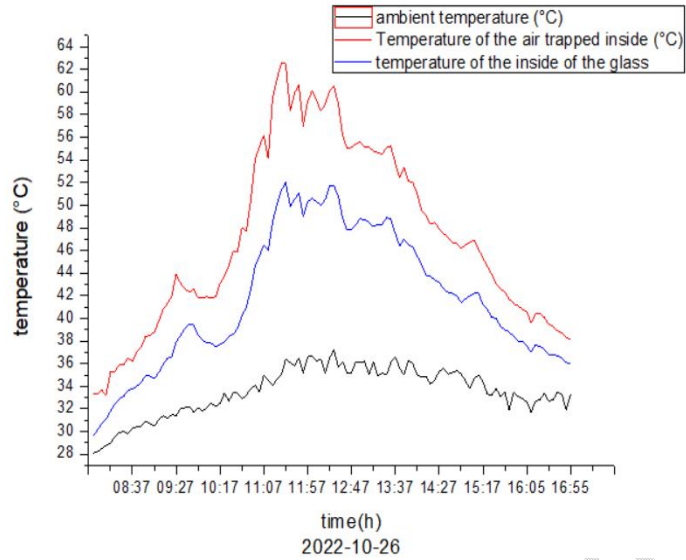


Fig 9: Curve of internal air temperature and ambient temperature as a function of time of day 2022-10-26

Fig9 shows the temperature evolution of the unloaded system. The results of measurements taken during the day on October 26, 2022 indicate a maximum temperature of 63°C for the air trapped in the hemispherical reflector, obtained from 11 a.m. onwards. The temperature on the inside of the glass pane reached a maximum of 51°C. However, the ambient air temperature is 35°C. These temperatures are obtained under the following radiation evolution during the day of October 26, 2022.

Test 2: The aim of this test is to heat water with the system. The device is used to heat water on October 28, 2022. The quantity of water heated is 1.5L. Fig 10 shows the evolution of hot water and outside air temperatures.

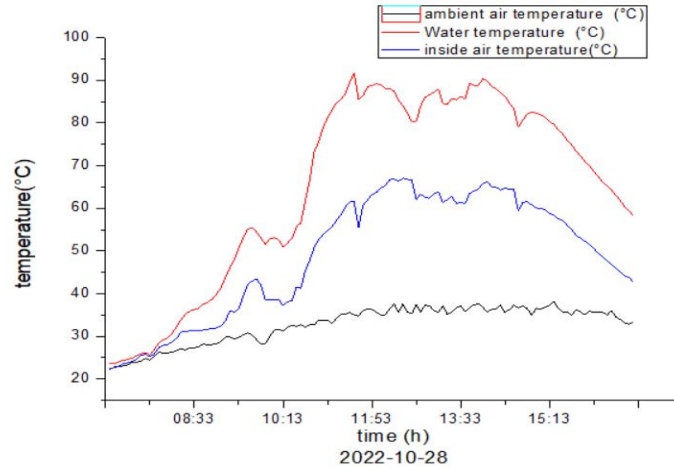


Fig 10: The evolution of hot water and outdoor air temperatures

Fig 10 shows that temperature values evolve progressively, with a maximum water temperature of 91.7°C reached at 10:45 am. This temperature was achieved in 30 minutes by Gianluca Coccia et al[20] using a new, low-cost solar cooker featuring a high-performance Fresnel lens. The temperature of the trapped air was 67.1°C at 11:53 am. The ambient air temperature is 37°C. This irregularity in the curves is justified by the presence of cloud shading.

Fig 11 shows the irradiation for the day of April 20, 2023.

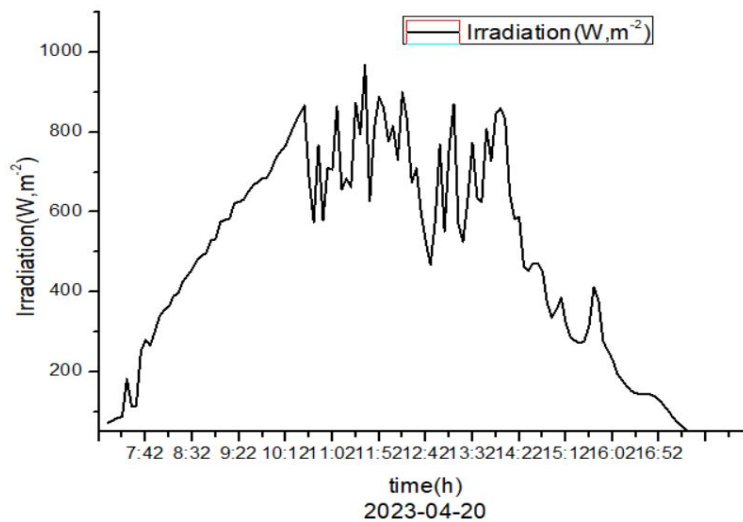


Fig11: irradiation trends for the day of 20-April 2023

Fig 11 shows the results of the experiment on April 20,2023. The results show a maximum irradiation of 957.1 W.m^{-2} at 11:52 a.m. The irregularities observed on the curve are due to the passage of clouds.

Test 3: the day of April21,2023 is dedicated to cooking and frying sweet potatoes

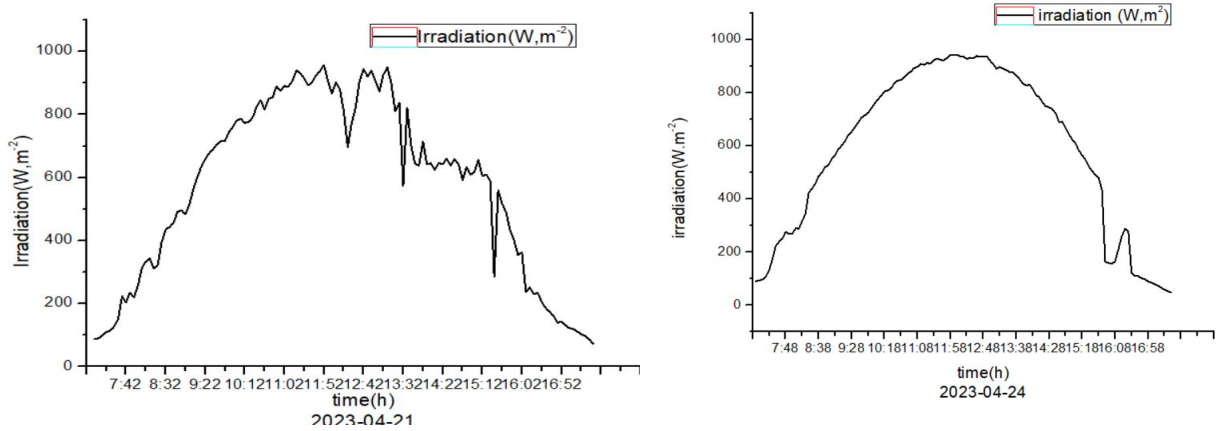


Fig 13: Irradiation during the day on April 2023, 21

Fig 12: Irradiation during the day on April 2023,24

Fig 12 and 13 show the results of the experiment on April 21, 2023 and April 24, 2023. The results show a maximum irradiation value of 950 W.m^{-2} for the day of April21, 2023 and a value of 960 W.m^{-2} for the day of April 24,2023. The irregularities observed on the curves are due to the passage of clouds.

Fig 14 shows the evolution of the cooking temperature of sweet potatoes.

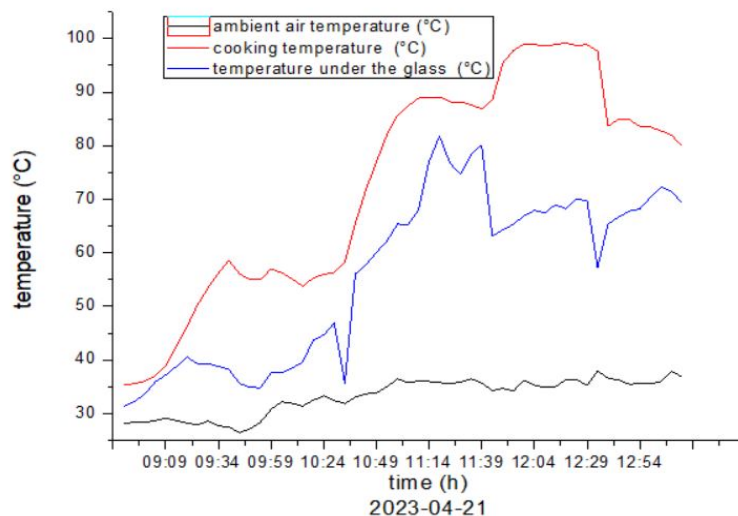


Fig 14: Evolution of cooking and frying temperatures for sweet potatoes

Fig14 shows the results of the experiment on April 21, 2023. The maximum temperature is 100°C, obtained at 11:30a.m, for an under-glazing temperature of 80°C obtained at 10:50 am with maximum irradiation of 957.1W.m⁻². The ambient air temperature has a maximum value of 35°C.



Fig 16 :sweet potato cooking (1Kg)



Fig 15: A dish of fried potatoes

Test4 for bean cooking

Fig 17 shows the cooking temperature for beans.

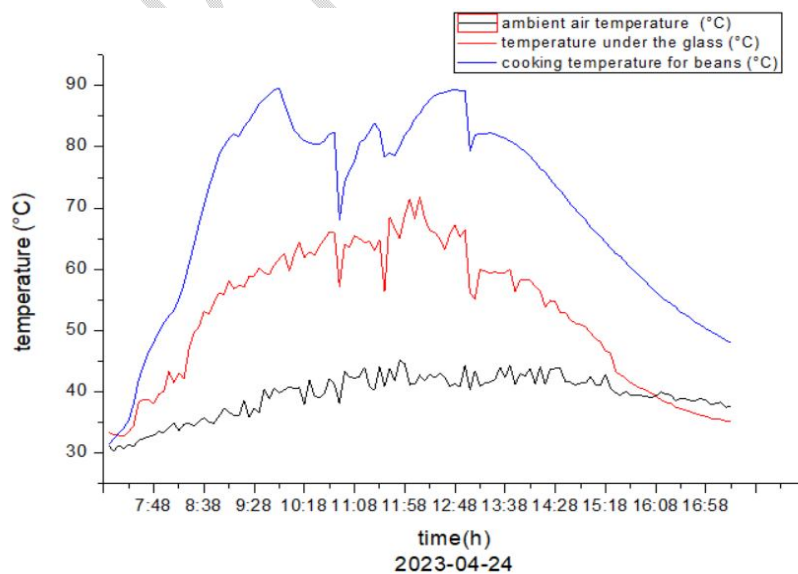


Fig 17: cooking temperature for beans.

Fig17, shows a maximum temperature of 90°C obtained from 9:28am to 12:48pm for bean cooking, with a maximum under-glass air temperature of 70°C obtained at 12:00pm. We have a maximum ambient air temperature of 40°C.



Fig 18:Baked bean dish

Test 5 aimed to heat 1 litre of oil

fig 19, shows the irradiation trend during heating the oil

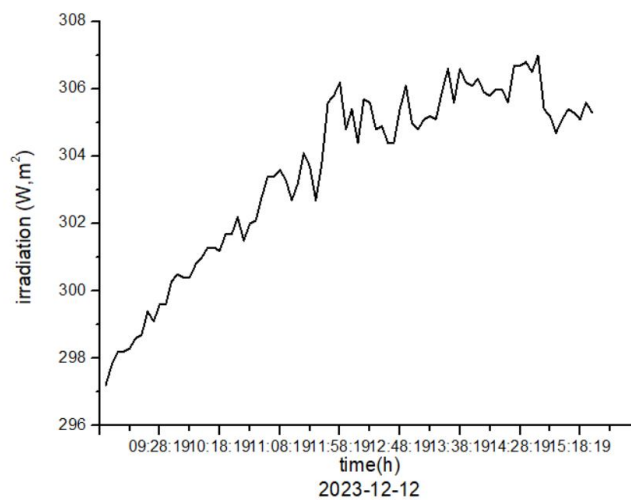


Fig 19:irradiation for day 2023-12-12

The maximum irradiation value on this day is 306.7 W.m², obtained at 2:33pm.

Fig 20, shows temperature trend during heating oil

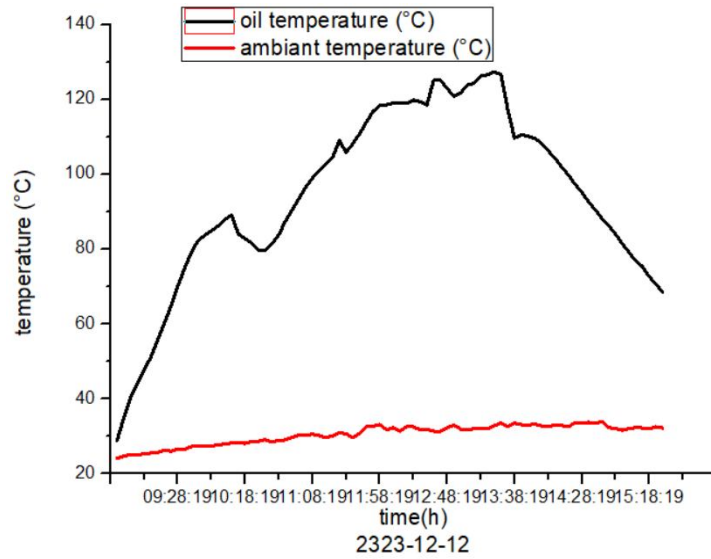


Fig 20:Oil heater (11 oil)

Fig 20 ,shows the progressive evolution of oil temperature, with a value of 130°C obtained at 1:21pm for the oil, a maximum temperature of 68°C for the internal air and an ambient temperature of 32.9°C. These temperatures evolve with the curve of irradiation.

Calculating the efficiency of our device

$$\text{Useful power, } P_u = \frac{(m_{pot} \times c_{p_{pot}} + m_{oil} \times c_{p_{oil}}) \times \Delta T}{\Delta t} \quad (6)$$

$$\Delta T = T_{Max \text{ of oil}} - \bar{T}_{am} \quad (^\circ\text{C})$$

Δt :oil heating time (s)

m_{pot} : the weight of the pan, (Kg)

$c_{p_{pot}}$: the heat capacity of the pot ($\text{Kj.Kg}^{-1}.\text{K}^{-1}$)

m_{oil} : mass of oil (Kg)

$c_{p_{oil}}$: the heat capacity of the oil ($\text{Kj.Kg}^{-1}.\text{K}^{-1}$)

Absorbed power (Pa):

$$P_a = S_{pot} \times \bar{I}_{RD} \quad (7)$$

We will suppose $\bar{I}_{RD} \approx \bar{I}_G \times 0.90$ (8)

This correlation takes into account the sky's cloud cover

S_{pot} : hemispherical reflector's exposure area (m^2)

\bar{I}_{RD} : Average direct irradiation for the day of measurement

\bar{I}_G : Average overall irradiance for the day of measurement.

We used the measurement data for oil heating because there was no oil evaporation during heating. The efficiency of our system is around 20%, which is quite low because not all the hemispherical reflector is reflecting on the absorber. We can also see that there is a great deal of heat loss between the hemisphere and the glass.

Conclusion

Solar radiation can be considered one of the most suitable energy sources for cooking food. It is therefore important to promote progress in solar cooking systems, particularly with regard to their efficiency and cooking times. In this work, we designed, built and tested a new low-cost solar cooker (designed from concrete under a glazing), underwent a series of tests carried out in Ouagadougou, Burkina Faso. We tested water heating, cooking of foods such as sweet potatoes, frying and bean cooking. We also recorded the evolution of irradiation during these experiments. The first test consisted on measuring the air trapped inside the unloaded hemispherical reflector. It was carried on October 26, 2022 under an irradiation of $700 W.m^{-2}$. We obtained an air maximum temperature of $63^\circ C$. The second test, carried out on October 28, 2022, was designed to heat 1.5 litre of water. Under an irradiation of $860 W.m^{-2}$. The results show a boiling water temperature of $91.7^\circ C$ obtained between 10:45am and 1:33pm. The day of April 21, 2023 was devoted to experimental studies on cooking and frying sweet potatoes under an irradiation of $950 W.m^{-2}$. The maximum temperature of cooking spot is $100^\circ C$, obtained at 11:30a.m, for an under-glazing temperature of $80^\circ C$ is obtained at 10:50 am. We succeeded in cooking bean with our system under irradiation of $306.7 W.m^{-2}$. The device is used to heat oil, under an irradiation of $306.7 W.m^{-2}$. The maximum temperature reached by the oil is $130^\circ C$. In terms of sustainability and durability, our solar cooker poses no serious environmental problems such as pollution, global warming and greenhouse gas emissions

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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