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RESEARCH ARTICLE

THERMAL PERFORMANCE OPTIMIZATIONS OF A HEMISPHERICAL SOLAR COOKER WITH ALUMINUM SHEET CONCENTRATORS: APPLICATION TO FOOD COOKING

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Abstract

Cooking is a method of transforming food by exposing it to heat. Solar cookers allow us to cook food using the heat generated from the sun's rays. In this work, we present an experimental study of a hemispherical solar cooker tested with and without glazing. In the context of sustainable development, in order to reduce environmental impact, the SDGs, in their Goal 7, advocate the use of renewable energy to ensure access for all to reliable, sustainable, and renewable energy services at an affordable cost. This work is an experimental study of a hemispherical solar cooker. The hemisphere, made of reinforced concrete, has a radius of 0.59 m, a height of 0.46 m, and an exposed surface area of 0.1535 m². The smooth inner part is covered with aluminum sheet reflectors with a reflection coefficient of 92%. This reflector allows the sun's rays to be directed toward the absorber located at the focus. The no-load tests without glazing and with glazing showed satisfactory results. The maximum oil and water temperatures during the test without glazing were 186.7 °C and 99.5 °C, respectively, with maximum irradiances of 572 W/m² and 575 W/m². With glazing, we obtained maximum oil and water temperatures of 172.6 °C and 98.5 °C under maximum irradiances of 557 W/m² and 550 W/m². During all these tests, the oil temperature remained between 150 °C and 173 °C for more than 3 hours, demonstrating the system's performance in frying. The maximum water temperatures reached demonstrate the system's capacity for cooking. The potato fries were cooked within a reasonable amount of time and were ready for lunch.

Introduction:-

Studies have shown that in sub-Saharan Africa, more than 900 million people still use traditional unprocessed solid fuels for cooking food and 95% of the world population uses wood, charcoal, and agricultural waste. This poses a significant risk, as these fuels generate high levels of toxic particles. [1][2].

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In Burkina Faso, most households use wood and agricultural residues for cooking, thereby contributing to the acceleration of desertification. In a context of sustainable development and in a world facing a severe security and economic crisis, no one doubts the necessity of protecting the environment. To meet these requirements, different nations must diversify their energy sources by promoting renewable energies. Solar energy thus appears as an important alternative for sub-Saharan countries, particularly for Burkina Faso, which enjoys significant sunshine. Solar cookers are a sustainable and economical solution for cooking food, particularly in regions with high levels of sunshine and limited access to energy. In Burkina Faso, the annual solar flux is 1024 kWh m^{-2} [3]. These systems generally include a reflective surface designed to concentrate solar energy onto an absorbing surface, resulting in a significant increase in heat. The advantage of this method is that it allows high temperatures to be reached, making it ideal for heating water and cooking food in solar kitchens [4].

Solar cookers are classified into two (2) groups with or without storage [5]. Three technologies generally compete to meet solar cooking needs:

-Concentrating solar cooking systems such as parabolic cookers, cylindro-parabolic cookers [6], spherical cookers [7], the RAC (Ring Array Concentrator) cooking system [8], [9], the Scheffler-type cooking system [10], [11], and cooking systems using Fresnel reflectors Process[12] [13].

- Indirect solar cooking systems [14] [15] [16] [17] [18] [19] that function like dryers, in which the collector is separate from the receiver. It is very often fixed or barely mobile, with a network of tubes containing a fluid that collects heat and transfers it to the cooking chamber.

- Box-type solar cooking systems [20] [21] [22] [23] [24] [25].

In this study we proposed a hemispherical concentrating system for cooking.
To work at high temperatures, the incident optical flux must be increased, which could be achieved by concentrating solar radiation. This is why we propose in this work the use of a hemispherical solar cooker with and without glazing for cooking food. More specifically, we want to observe the effect of glazing on the device's performance, but also to improve this performance by using aluminum sheet as a concentrator. This device proves to be an appropriate solution for the socio-economic context of Burkina Faso in that it is easy to build and use, and can be designed using local materials [26].

Solar cooking can be classified into four categories based on the required temperature range: baking (85 to 130°C), frying (150 to 250°C), and grilling (over 300°C) [26]. Considering the potential of solar energy for developing countries, particularly for sub-Saharan countries, more specifically Burkina Faso, due to its significant solar resource.

The system originally designed and tested by Ky et al [27]. was made for air heating. The concentrator used was imported chrome stickers. Later, Kossi et al. carried out cooking tests on this same device [26]. They obtained satisfactory results. In order to ensure local use of the device and to provide assurance regarding the availability of materials used for its construction, we repeated the tests on this device, replacing the chrome sticker concentrator with aluminum sheet, which is easily accessible locally and at a lower cost.

Materials and Methods: -

In our work, we used type K thermocouples with a shielded sheath to measure the temperatures of water, oil, and air inside the glazing; as well as the ambient air. They are the margin of error is ± 0.05% of the measured value for temperatures between -200˚C and 2000˚C.

A SR03-05 type pyranometer from the brand Hukseflux with a margin of error of ±1.5% of the measured value for, 0 to 1600 W.m^2, installed on the platform of the renewable thermal energy laboratory at Joseph KI-ZERBO University, continuously records the incident solar radiation on the horizontal plane at the study site at 1-minute intervals. An automatic data recorder called a data logger, Midi LOGGER GL200A from the brand GRAPHTEC, 100 to 1730°C ± (0.1% freading+0.3°C) programmed at 5-minute intervals, was used to connect the thermocouples.

Figure 1:**Measuring equipment, experimental setup with and without glazing**

The average thermal efficiency of the device is calculated using formula 1 or 2.

$$\eta_{th} = \left(1 - \frac{\sigma T_{oil}^{4}}{I_{RD} \times C_g}\right)\left(1 - \frac{T_{amb}}{T_{oil}}\right) \quad (1)$$

T_{amb} is the ambiant average temperatue, σ Stefan–Boltzmann constant = 5.667 $\times 10^{-8}$ W m^{-2} K^{-4}, T_{oil} oil average temperature, I_{RD} the direct solar irradiance in W/m^2 and C_g the geometric concentration of the system .

$$\eta_{th} = \frac{\left(m_{pot} \times C_{p_{pot}} + m_{oil} \times C_{p_{oil}}\right) \times \Delta T}{\Delta t \times C_g \times S_{pot} \times I_{RD}} \quad (2)$$

$$\Delta T = \overline{T}_{oil} - \overline{T}_{amb}$$

ΔT : Oil heating time(s)

m_{pot} : the weight of the pan (kg)

$C_{p\,pot}$: the heat capacity of the oil (kJ.kg^{-1}.K^{-1})

m_{oil} : mass of oil (kg)

$C_{p_{oil}}$: the heat capacity of the oil (kJ. $Kg^{-1}.K^{-1}$)

S_{pot} : the pan area (m^2)

$$I_{RD} = 0.90 \times I_G$$

I_G the average incident solar irradiance in W/m^2 of the day

We will used formula 1 of Steinfeld's [28] because it takes concentration into account and better presents the efficiency percentages. Indeed, we can see here that the second term represents Carnot's efficiency.

Description of the device:-

In this work, we present a hemispherical solar cooker. It was designed at the Laboratory of Renewable Thermal Energies (L.E.T.RE). The device consists of a hemispherical concentrator made of reinforced concrete whose smooth interior surface is covered with a sheet of polished aluminum with a reflectivity of nearly 92%. This reflector allows the sun's rays to be directed onto the absorber, the cooking pot. The hemisphere has a radius of 0.59 m with an opening area of 1.09 m². The height is 0.46 m and the exposure area is 0.1535 m² for the half-angle of the apex of the focal point with the axis passing through the center [26]. The installed hemisphere is tilted at 13°, corresponding to the latitude angle of Ouagadougou, and is precisely aligned to the North. Tests were carried out both with and without glazing, empty and under load. Figure 3 show the experimental setup with glazing.

The glass is used to increase the temperature through the greenhouse effect. It allows sunlight to pass through, thereby trapping infrared rays. A hemispherical concentration system under glass differs from other systems that first heat a black plate with or without fins, then recover the plate's heat using a fluid by convection. The device we propose uses the solar spot corresponding to the real image of the sun formed at the focus of a hemispherical concentrator which, through the concentration effect, generates a very hot area (the focal point) where the pot, painted black here, should be placed to maximize heat absorption. Inside the concentrator there is a mobile iron support on which the pot is placed. The mobile support allows us to manually track the solar task (focal point) inside the cooker. Table 1 shows the cost analysis of the prototype.

Table 1: Prototype Cost

Material	**Price**
Reinforcedconcretehemisphericalconcentrator	$30
Metal support for cooking pot	$23
Black painted cooking pot	$8
Glazing +coverage structure	$142
Aluminumreflectivesheet	$54
Workforce	$50
Total cost	**$307**

Results and Discussion:-

In order to evaluate the thermal performance of the device, water and oil heating tests were carried out without glazing and with a glazed cover.

Water and oil heating test without glazing

Tests conducted without glazing on 1 liter of water and oil produced satisfactory results, showing that the device is very efficient. During these tests, a maximum water temperature of 99.9°C was reached at 10:37 AM with an ambient temperature of 36.8°C. The maximum radiation was 575 W/m² at 10:38 AM. There was a plateau from 10:17 a.m. to 1:12 p.m., lasting nearly three hours, during which the water temperature remained at or above 90°C.These results further show that the device can be used for preparing meals. A maximum oil temperature of 186.7°C was reached at 12:25 PM with an ambient temperature of 33.7°C. The maximum radiation was 572 W/m² at 11:53 AM. It is noted that the oil temperature remained between 150°C and 186.7°C from 9:35 AM to 2:15 PM, for more than 3 hours, demonstrating that the device can be used for frying. Figures 2, 3, 4, and 5 shows the evolution of sunlight exposure, oil temperatures, and water temperatures during the tests on water the 04/12/2024 and on oil the 05/12/2024. These results are comparable to those of Kossi et al. [26].

Figures 2 and 3 shows typical bell-shaped sunlight curves with irregularities suggesting cloudy periods during these days. Analysis of the temperature curves (Figures 4 and 5) shows a similar trend to that of sunlight, demonstrating the device's dependence on climatic conditions. The temperature rises steadily from the morning, reaches maximum values around which it stabilizes for nearly 3 hours, then decreases to reach minimum values in the evening.

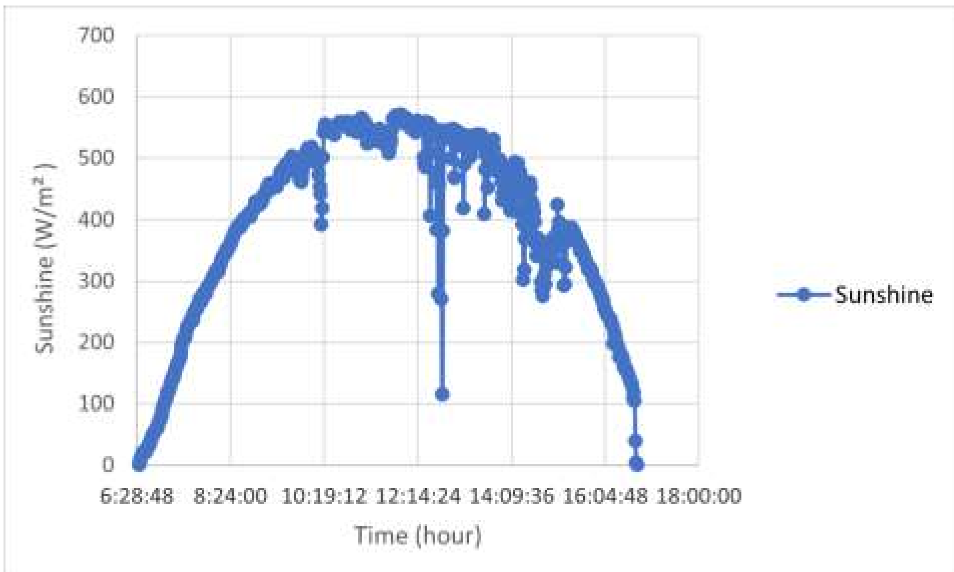

Figure 2: Curve showingthe variation in solar radiation during the day on December 4, 2024

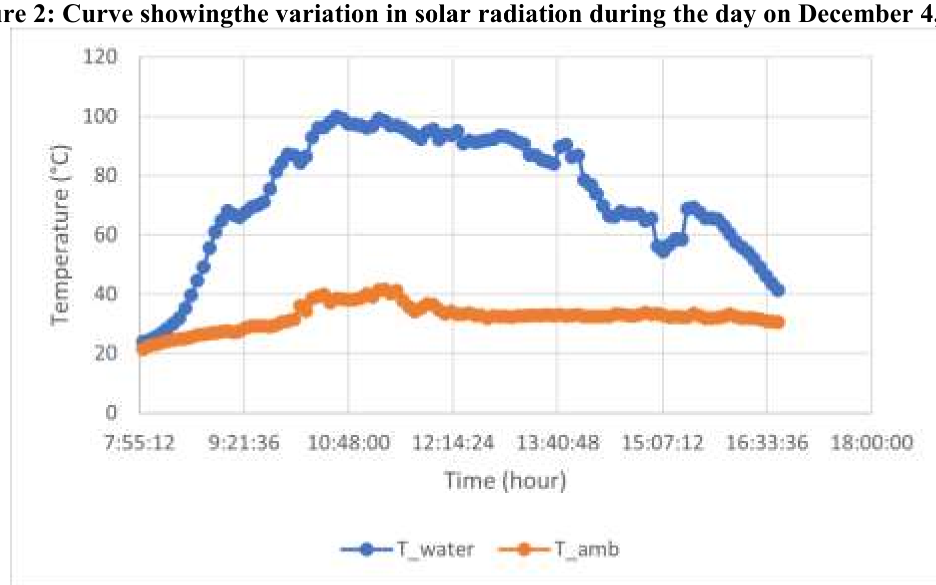

Figure 3 : Water temperature curve for the day of December 4, 2024

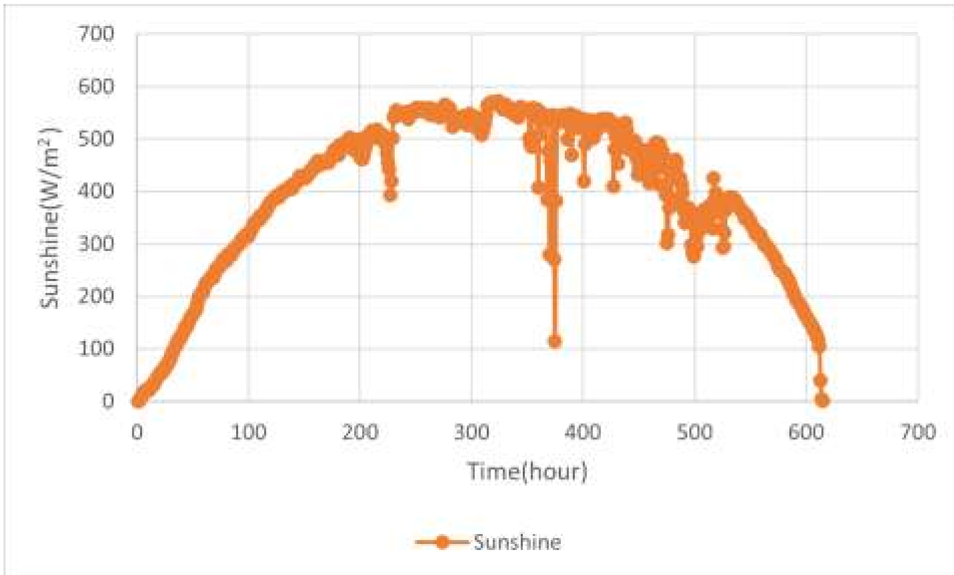

Figure 4: Curve showing the variation in solar radiation during the day on December 5, 2024

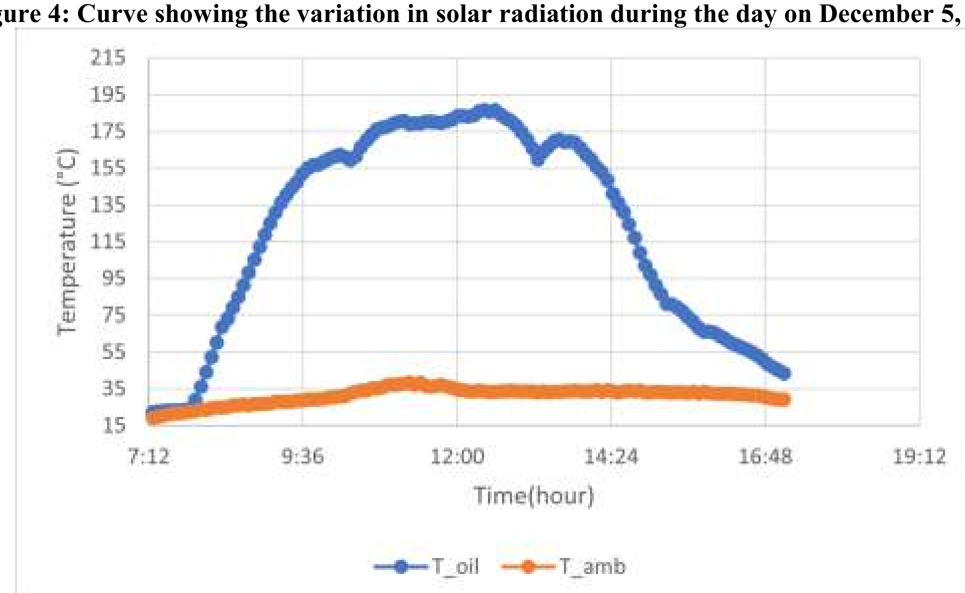

Figure 5: Oil temperature curve for the day of December 5, 2024

Water and oil heating tests with glazing

During the glazing tests for maximum sun exposures of 557 W/m² and 550 W/m² recorded on 08/12/2024 and 10/12/2024 respectively, we obtained maximum oil and water temperatures of 172.6 °C at 1:20 PM and 98.5 °C at 11:55 AM for ambient temperatures of 33.8 °C and 34.5 °C, under a maximum internal air temperature of 62.3 °C and 55.2 °C. These low values compared to the test without glazing can be explained by the fact that it is more difficult to focus the heat with the glazing, which is delicate to handle, but also because these days were very cloudy, resulting in significant fluctuations in sunlight, creating instability. Despite this, it is worth noting that we were able to reach cooking and frying temperatures, as the oil temperature remained between 150 °C and 172 °C for nearly 3 hours, which is sufficient for frying. Figures 6, 7, 8, and 9 show the curves representing changes in sunlight exposure and water and oil temperatures during the glazing test conducted on December 8 and 10, 2024.

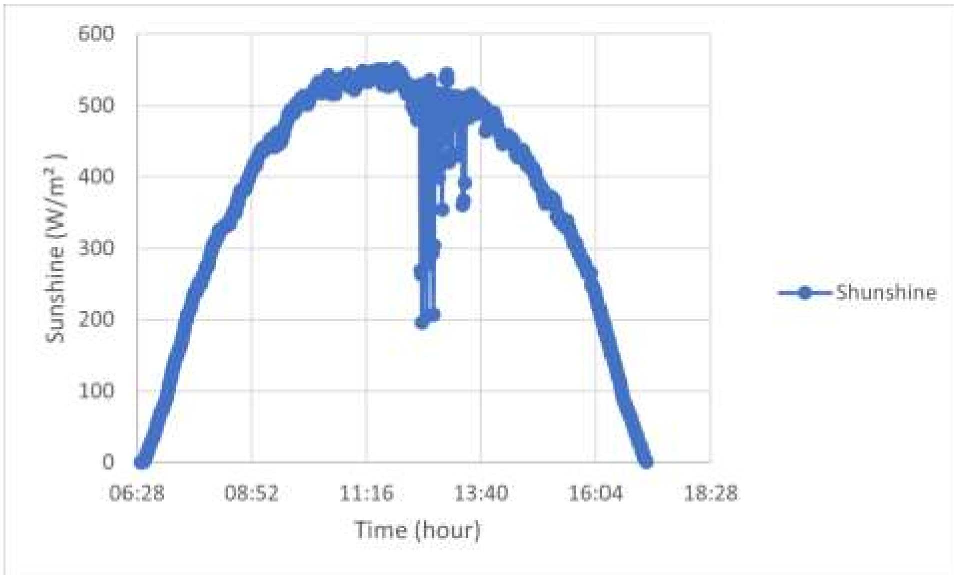

Figure 6: Curve showing the variation in solar radiation during the day on December 8, 2024

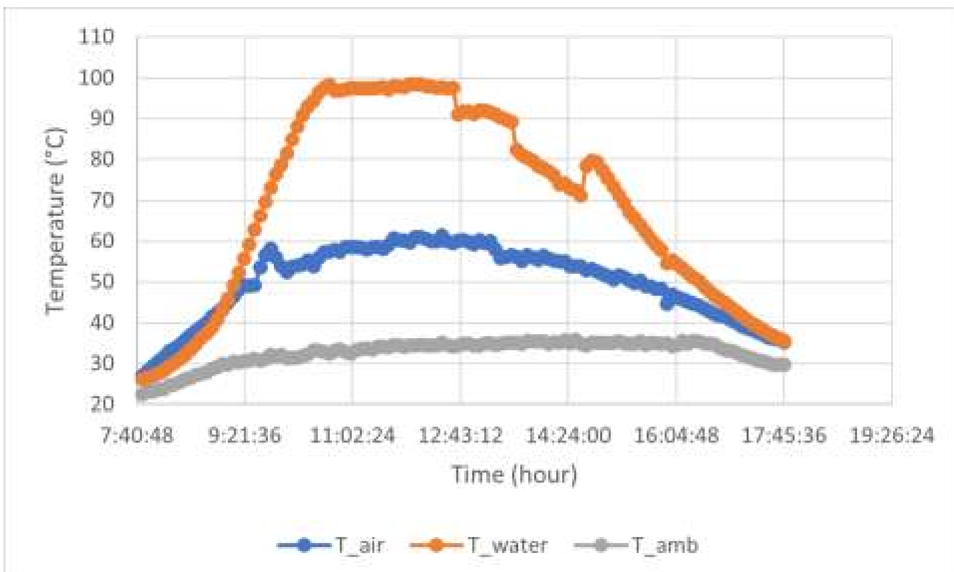

Figure 7: Water temperature curve for the day ofDecember 8, 2024

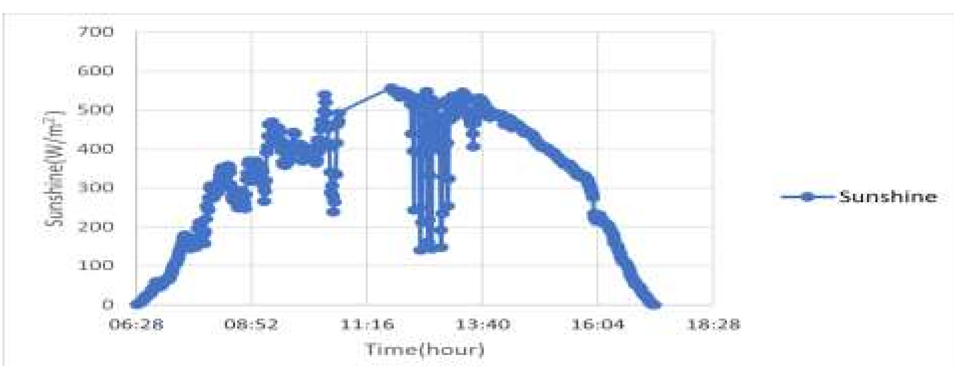

Figure 8: Curve showing the variation in solar radiation during the day on December 10, 2024

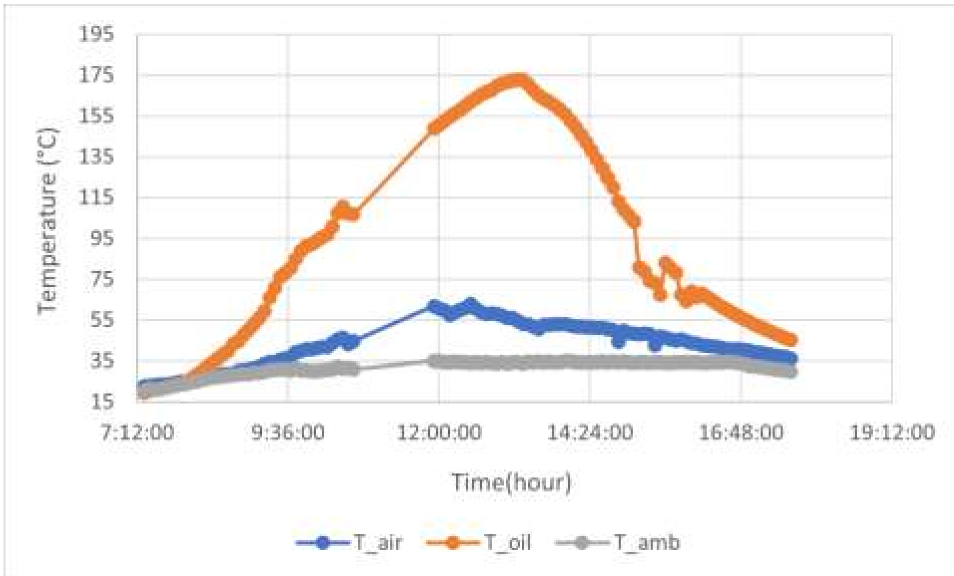

Figure 9: Oil temperature curve for the day of December 10, 2024

The dip observed in the curves on December 10 can be explained by the fact that there was a one-hour power cut, resulting in an interruption in data recording during that time.

Annexe:-

Figure 10: The potato fries

Conclusion:-

The system designed, built, and tested for outdoor solar cooking underwent a series of tests in Ouagadougou, Burkina Faso, at a latitude of 12.21°.

A series of tests was conducted in December 2024, when the sun is at its lowest possible position and the maximum horizontal irradiation values on the test days are approximately 575 W/m² and 572 W/m² for tests without glazing, and 557 W/m² and 550 W/m² for tests with glazing.

The calculation of the system's thermal efficiency using formula 1, gives an average efficiency of 21.17%, higher than that recorded by Kossi et al in their study [26].

Although the sun was at its lowest possible position, this allowed us to carry out cooking and frying tests. We can therefore say that this system is very efficient and can be used for cooking all year round.

Another test protocol for comparison purposes could be carried out during favorable periods such as March-April. This will allow us to make a comparison with the setup of Kossi et al. and draw a clear conclusion regarding the effect of glazing.

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