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Study, Design, Realization of a Domestic Solar Cooker in Tropical Climatic Conditions

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ABSTRACT
Cooking food is done mainly by the use of fossil fuels (coal, gas, oil) or wood with emissions of greenhouse substances, where Benin enjoys good sunshine. The valorization of solar energy through the equipment of concentration of solar radiations can contribute to a cooking with low impact on the environment. This project consists in the realization of a solar cooker, usable in Benin. A solar cooker is a heating system that works from solar energy by concentrating this energy in a specific place on which a container is placed in the corn that it heats. The project includes a first part of modeling of the cooker and a second of realization. This research simulates the mechanical operation of the cooker made essentially with recycled materials. The mass of the cooker is 6Kg and it can support up to 2Kg of load in its hearth. The latter has two joints to accurately track the position of the sun. We simulated the thermal performance of the concentrator made from reflective aluminum film using COMSOL software. The theoretical time to bring 1 liter of water to the boil taking into account heat losses is 669 seconds (11 minutes, 9 seconds). The maximum temperatures reached in the focus and in the water during the experiments are 161°C and 91°C respectively.

Key words: Solar cooker; Parabolic concentrator; Cooker weight; Maximum temperature

INTRODUCTION

Studies carried out by some research institutes show that the energy consumption of developing countries will increase significantly, especially after the globalization of trade and exchanges between States [1].The sun represents a huge potential for meet the countries' growing energy needs. Energy is defined as the ability to do work for any physical system that is very necessary for our environment [2]. Many researchers are working to solve problems related to energy and its consumption that directly affect human life. Fossil energy resources have a higher share in energy consumption [3]. There are several problems created by using fossil fuels like pollution of the atmosphere, greenhouse effect and global warming, increase in fuel cost and rapid depletion of fossil resources [4]. Due to the rising cost of cooking gas, fossil fuels, the majority of people in rural and urban areas still use firewood for cooking [5].

Due to several problems with fossil fuels, researchers have turned to renewable energies including the sun. This solar energy can be transformed into heat at low temperature, by flat collectors, using both absorption by a selective surface and the greenhouse effect created by the glazing [6].

To reach high temperatures, it is necessary to increase the incident optical flux, which can be achieved by concentrating solar radiation [7]. This is achieved using collectors called solar concentrators. Among this type of concentrators, there are parabolic solar concentrators (paraboloid of revolution). The use of solar cooking would not only eliminate or at least reduce respiratory illnesses resulting from exposure to smoke, but could also be used to defeat another scourge of the developing world, contaminated water [8].

Safa Skouri worked on a geometric and thermal study of a parabolic solar cooker [9]. Lentswe Katlego, Mawire Ashmore and Owusu Prince designed, fabricated and performed thermal analysis of parabolic solar cooker for cooking purposes and concluded that thermal performance of parabolic solar cooker is better than box type [10]. Kaushik C. and Gupta M. performed a comparative study between community-sized parabolic solar cooker and household-sized parabolic cooker. Based on its thermal performance, it was concluded that the thermal efficiency of community size is better than that of household size [11].

Mullick et.al worked on the parabolic solar cooker to evaluate the thermal performance of the solar cooker and found that the thermal performance of the solar cooker does not depend on climatic variables [12]. Ozturk et.al built a low cost parabolic type solar cooker (SPC) and tested it to calculate energy and exergy efficiency, experimentally [13]. Pohekar et.al studied the multicriteria of cooking appliances with particular reference to the usefulness of the parabolic solar cooker. It was concluded that the household cooking energy demand can be met by a parabolic solar cooker [14]. Kumar Manish and Singh Dheerand discussed simple exergy analysis of cylindrical parabolic solar cooker and provided detailed exergy analysis methodology of SPC and exergy loss distribution of cooker surfaces [15]. Draou MD performed an experiment on a parabolic solar cooker with a two-axis automatic sun tracking system. The tracking problem has been solved, which is the main drawback of concentrating solar cookers with manual tracking [16]. Ouannene et.al studied the design of the parabolic solar cooker and suggested that the best cooking time using a parabolic solar cooker is from 1:30 p.m. to 2:30 p.m. [17]. Zamani H., Moghiman M. and Kianifar A. discussed an idea to optimize the geometry of reflective surfaces of double exposure parabolic solar cookers [18]. Panwar NL worked on the experimental thermal performance of the parabolic solar cooker [19]. Dasin Dahiru Yahya et.al suggested that the new global standard procedure can be used to test solar cookers to determine the thermal performance of parabolic concentrating solar cooker. The new standard defines the limits of the environmental conditions, specifies the test method and the performance in terms of cooking power [20].

In an attempt to reduce the costs associated with the construction of solar cookers in order to make them accessible to populations in tropical regions, the researchers suggested the use of local and recyclable materials. Recycling of materials has become an essential feature of waste management with efficient reuse of waste not only in buildings but also for manufacturing.

Our work is devoted to the manufacture of a light and efficient solar cooker from recyclable materials. In this study, the modeling of the parabolic solar concentrator, the theoretical estimation of the temperature at the level of the receiver and then the comparison with the experimental results collected during various tests which took place on March 21 and 23, 2022 were made.

MATERIALS AND METHODS

In this present work, the parabolic type solar cooker is constructed for an experiment which is shown in Fig. 1. Bright anodized aluminum sheets are used as the reflective material of the parabolic type solar cooker because of its reflectivity, which is 85% [21]. The experimental installation consists of a parabolic antenna concentrator having an opening diameter of 1.05 m, a depth of 0.085 m. Cooking vessels coated with black paint are used so that their outer surface acts as an absorber. The focal length of the concentrator is calculated as 0.95 m.

Description of the Parabolic Solar Cooker

The experimental setup of the manufactured solar cooking system is presented schematically and illustrated as shown in Figures 1, 2 respectively. It mainly comprises four components, namely: the parabolic solar reflector, arm supporting the focus, focus, support frame.

Parabolic reflector: The reflector was made from TV panel and aluminum foil.

Hearth: The circular shaped hearth was made with a sheet of sheet metal 2mm thick

Support: It is made with concrete iron bars 12mm in diameter and recycled materials such as the footrest of a fan.

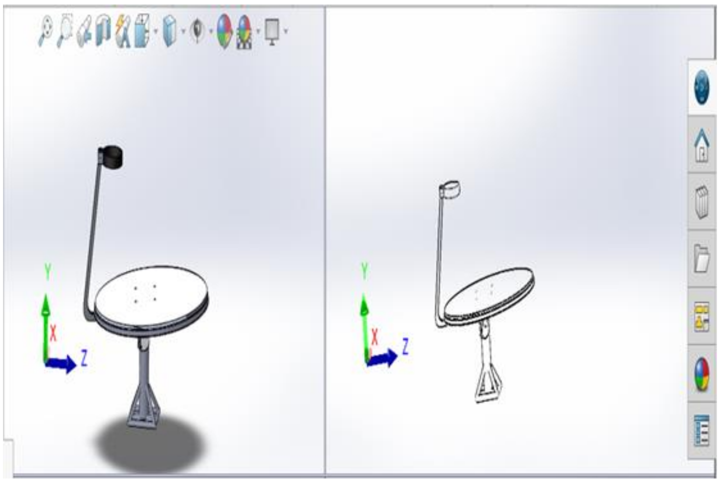

Fig. 1 (a) Cooker hearth (b) Concentrator (c) Support

Fig. 2 Solar cooker produced

Sizing of the support

The support is composed of 5 main beams and a connecting flange (reinforcing elements). After modeling, here is the diagram obtained:

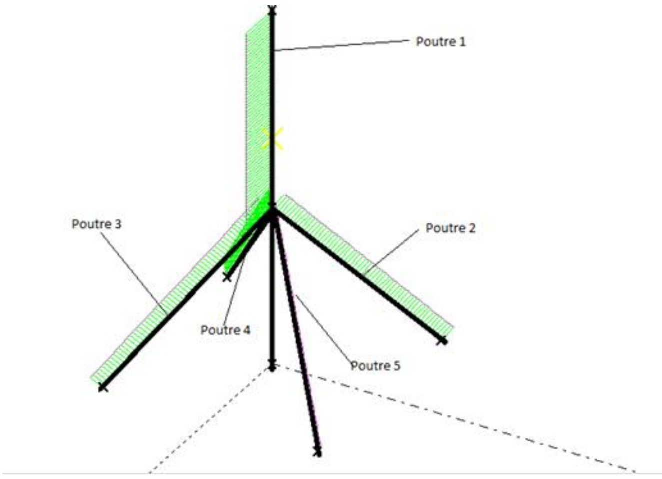

Figure 3: Modeling of the support

Beam 1 is subject to a single constraint: A compression.

The resistance condition can then be written as follows [22]:

$$\frac{N}{S} \leq R_{pe} = \frac{R_e}{s} \qquad 1$$

Where S: is the section of the beam;
N: is the force in the beam;
Re : the elastic limit of the material;
Rpe : the practical limit to the extension
With P= $40\ N\ R_E = 480\ MPa\ \ pour\ l'acier, on\ prends\ s = 3$
S is the cross-sectional area of a ring with an outer diameter of 27 mm and a thickness of 2 mm
$\sigma_{adm} = 0.25\ MPa$ gold $R_e = \frac{480}{3}$=120 MPa.
$\frac{N}{S} \leq R_{pe} = \frac{R_e}{s}$ is therefore verified so beam 1 is safe. Thus we conclude that there is security.
Beams 2, 3, 4 and 5 are subject to the same constraints: a stress composed of bending and compression. Thus, the equilibrium condition can be written as follows [22]:

$$\sigma_{adm} = \frac{N}{S_2} + \frac{M_{f\times y}}{I} \leq \frac{R_e}{S} \qquad 2$$

Here the section of its beams is S_2=10 mm. With RDM 7 we have:
σ_adm=0.18 MPa≤120 MPa. Beams 2, 3, 4 and 5 are therefore stable.
Conclusion : the support is therefore stable.

Sizing of the Hearth

We choose to evaluate the maximum displacements after application of the stresses on the focus using SolidWorks . Indeed, the weight of the kettle is 20N or 0.002 on the wall supporting the kettle. Here are the results obtained

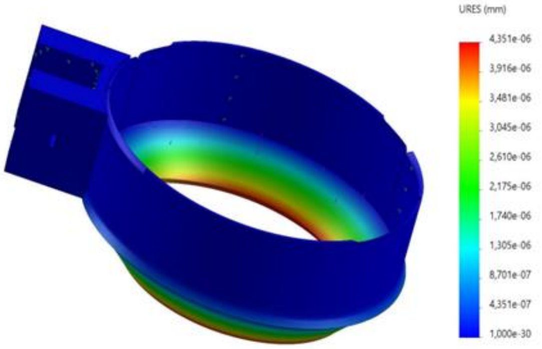

Figure 4: Displacement diagram

Considering the following criterion for choosing the thickness $f\ \max \leq \frac{1}{2}e$ [23]: We admit that the 4mm thickness of our focus largely ensures the stability of the device.

Experimental test procedure

Water boiling tests were carried out in March 2022 between 12:00 p.m. and 1:00 p.m. to evaluate the performance of the integrated cooking system of the tracking device. The experiment site was, located at 6.41° N latitude and 2 .33° E longitude. Boiling water tests were performed to determine the thermal response of the system. The time, date, and water temperature in the pot and other locations in the cooking system data were at 10 min intervals. The measuring device is a digital thermometer.

Theory and analysis

Parabolic concentrator: In our work we decided to recover satellite dishes from TV to make the concentrator of our solar cooker. This is the real crux of the work. Giving a second life to used television dishes will not only contribute to a low cost of the cooker and also to protect the environment.

Diameter	d = 1.05 m
Size	h = 0.08 m
The opening angle	ψp = 30.80°
Focal distance	f = 0.95 m
Opening area	Aa = 0899 m 2

Thermal modelling: The available energy is partly absorbed by the cooking fluid while the rest is lost to the environment by convection and radiation. The energy balance equations for various components of the cooking system namely: the parabolic reflector, the pan, the water have been written.

The following assumptions were made:

Conditions to the limits

Before moving on to the actual calculation, we will make some approximations to simplify the problem.

- The temperature of the water is equal at all times to the temperature of the saucepan;
- All the water heats up at the same time without there being a temperature gradient. This is a good approximation given the high conductivity of water and the small volume;
- The thickness of the pan is negligible and will not undergo a temperature gradient;
- The absorptivity of iron is equal to 0.8. Here our iron pan is patinated. We cannot know the exact value of patinated iron but we will assume equal to 1. This implies that the pan absorbs all the energy and does not reflect any rays.

Initial conditions: The initial temperature is that of the ambient air (300K), the atmospheric pressure is 1 atm and the wind speed is zero.

Let's analyze the different heat transfers at the level of the iron pan.

Kettle energy balance

$$\Delta U_{mar} = \Phi_{mar} + \Phi_{lip} + \Phi_{con} + \Phi_{ray} \quad 3$$

ΔU_{mar} Average thermal power used to heat the pot.

$$\Delta U_{mar} = m_{mar} \cdot cp_{fer} \frac{\partial T_{mar}}{\partial t} \quad 4$$

Φ_{mar} Power absorbed by the pot.

$$\Phi_{mar} = \alpha_{mar} \cdot r_p \cdot S \cdot F_g \quad 5$$

Φ_{liq} Power exchanged with the liquid to be boiled.

$$\Phi_{liq} = m_e \cdot cp_e \cdot (T_{mar} - T_e) \quad 6$$

Φ_{conv} Power due to the exchange by convection between the ambient environment and the pan.

$$\Phi_{con} = h \cdot S_{con}(T_{mar} - T_{air}) \quad 7$$

Φ_{ray} Power radiated by the pan into the surrounding environment.

Standard cooking power

The amount of heat that enters the cooking vessel to raise the temperature of a given amount of water in a certain interval of time is called standard cooking power (Psc)[23]. It can be obtained as:

$$P_{sc} = m \cdot cp \cdot \frac{T_f - T_i}{t} \quad 8$$

where m is the mass of water (kg); Cp is the specific heat of water (4.182 kJ/kg ÿ); Tf is the final water temperature; Tw is the initial water temperature; t is the time(s).

Calculation of boiling time

- **Input of energy from solar rays (incident flux on the reflector)**

Let F be the solar flux arriving at the solar cooker. The parabolic mirror of the solar oven captures part of the rays whose power is given by the product of the flux with the surface S of the opening of the parabola. These rays are then reflected by the aluminium. At this level, there is a loss of power since 10% of the rays are absorbed by the metal (the reflection coefficient of aluminum is equal to 0.9). The power arriving at the receiver is therefore equal to:

$$P_r = r_p \cdot F \cdot S = r_p \cdot F \cdot \pi \left(\frac{D^2}{4}\right) \quad 9$$

r_p : Reflection coefficient;
D: Diameter of the parabola;
F: Solar flux arriving on the parabola.
To know the power really absorbed by the pan, we must appeal to the absorptivity of the metal of the receiver. The pan will thus absorb the energy and see its temperature increase. By convection of the water, therefore by the natural movement of the water, the heat will gradually be transmitted to the totality of the liquid.
The power absorbed by the pan is given by:

$$P_{abs1} = \alpha \cdot P_r \quad 10$$

α : Absorptivity coefficient of the metal;
P_r : Power reaching the pan.

- **Input of energy from the sun's rays (incident flux on the pot)**

The pot of the solar cooker captures a certain part of the solar radiation whose power in (W) is given by the product of the solar flux with the surface s of the pot. To be more rigorous, it is necessary to deduct from S the surface of the pot which does not receive any direct radiation from the sun.

$$P_{abs2} = \alpha_{fer} \cdot I_g \cdot S \quad 11$$

Overall energy input from the sun's rays on the pot

$$P_{absg} = P_{abs1} + P_{abs2} \quad 12$$

- **Heat loss due to thermal radiation**

The pan will, while heating, lose a certain amount of heat due to its thermal radiation.
The thermal radiation is given by:

$$P_{ray} = \varepsilon \cdot \sigma \cdot S_{ray} \cdot (T_r' - T_{air}^4) \quad 13$$

ε : Emissivity of aluminum;
σ : Boltzmann constant;
T_r : Temperature at the surface of the metal;
T_{air} : Ambient air temperature;
S_{rar} : Contact surface between the pan and the air.

- **Heat loss due to natural convection**

There will also be heat loss due to natural convection between the pan and the surrounding air. We have seen that this power lost by convection could be written:

$$P_{con} = h \cdot S_{con}(T_r - T_{air}) \quad 14$$

S_{con} : exchange surface between the air and the saucepan;
Tr: Pan temperature;
T_{air} : Ambient air temperature;
h : air surface exchange coefficient.
The coefficient h depends on a certain number of parameters such as the viscosity, the conductivity, the diffusivity, the density of the air.

- **Differential heat balance equation**

Let us equate the power needed to bring a liter of water to a boil and the various incoming powers.

$$P_{nec} = P_{abs} - P_{ray} - P_{con} = \frac{m \cdot cp(T - T_0)}{T} \quad 15$$

m : mass of water;
C_p : heat capacity of the water.
To do this calculation, we must introduce a differential equation since, when the temperature increases, the various heat losses also increase. We therefore have an inhomogeneous differential equation at T:

$$m \cdot cp\frac{dT}{dt} = \alpha \cdot P_{cas} - \varepsilon \cdot \sigma \cdot S \cdot T^4 - h \cdot S(T - T_{air}) \quad 16$$

Calculation of boiling time without heat losses

$$\frac{mcpdT}{dt} = \alpha P_{cas} \Leftrightarrow mcp \int_{T_0}^{T} dT = \alpha P_{cas} \int dt \Leftrightarrow mcp(T - T_0) = \alpha P_{cas} t \qquad 17$$

By isolating t, we get:

$$t = \frac{mcp(T - T_0)}{\alpha P_{cas}} \qquad 18$$

Now let's apply the formula we just got with
m = 1 Kg (mass of water to be boiled);
C_p = 4186 J/ Kg.K (heat capacity of water);
T=100°C (boiling temperature of water);
$T_0 = T_{air}$ = 32° C.;

$$S = \pi \frac{d^2}{4} + \pi dH$$

(Surface of the saucepan with diameter d=15cm And height h=10cm without taking the lid).
We obtain a boiling time without taking heat losses into account of **586 seconds (9 minutes and 45 seconds)** .
Many factors affect the cooking time in a solar cooker, including the time of year, the time of day, the amount of sunlight, the type of container used and the amount of food prepared.

Calculation of boiling time with heat losses

To calculate the boiling time taking into account the heat losses we have to solve the complete differential equation.
We solve it numerically thanks to Matlab which provides us with the function of temperature as a function of time. A graph (Figure 5) represents this function (in yellow). We can see that the boiling time, taking into account heat losses, is 669 seconds (11 minutes, 9 seconds).

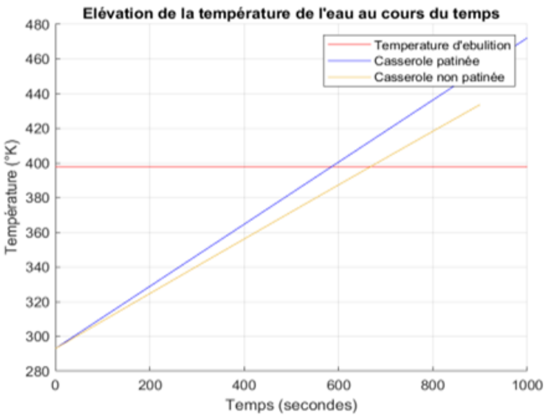

Figure 5: Rise in water temperature over time in MATLAB

RESULTS AND DISCUSSION

Temporal evolution of the temperature at the hearth and in the water under Comsol

According to our calculations and the numerical model the boiling point of water can be respectively reached.

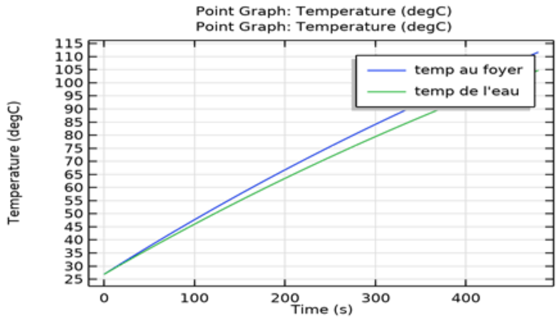

Figure 6: Temperature variation in focus and water in Comsol

Experimental results obtained

We took advantage of two sunny days to test our solar oven around 1 p.m. We removed some observations from these tests. First of all, the transport of the solar oven is quite easy thanks to its light weight.

We show in figures 5-1 and 5-2 the variation of the temperature at the level of the hearth and of the water for the concentrator which follows the movement of the sun during one hour and on different dates. These temperatures are measured by a digital display thermometer.

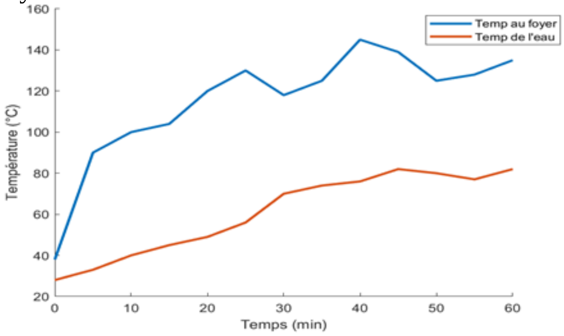

Figure 7: Comparison of the evolution of the temperature in the focus and in the water on 03/21/22 .

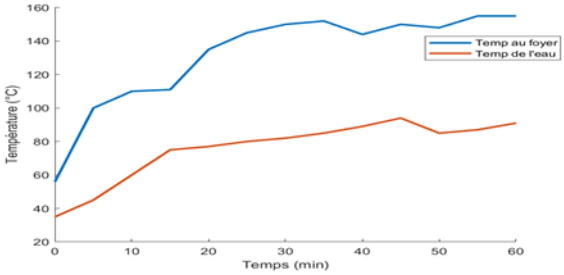

Figure 8: Comparison of the evolution of the temperature in the focus and in the water on 03/23/22 .

We notice that after a few minutes under the sun the temperature at the level of the hearth increases significantly more quickly than that of the water. It should also be noted that after a certain time the temperature in the fireplace and in the water both stabilize at one value. Also we observe temperature drops which are due to the disturbance of the solar flux because of the clouds and the wind. The weather conditions clearly affect the efficiency of the cooker. The maximum temperatures reached in the focus and in the water during the experiments are 161°C and 91°C respectively. We were able to cook an egg with the cooker.

Figure 9: Egg preparation with cooker.

Possible improvements to the realized solar cooker

Some improvements are possible to decrease the boiling time:

- To improve the convergence of the rays, we should improve the shape of our reflector so that it is more like a paraboloid. With the means at our disposal, we think we can do it;
- A larger patinated iron pan would capture the maximum number of rays and therefore energy;
- A correctly placed screen would protect the pan from the wind responsible for a large part of the losses.

CONCLUSION

This work made it possible to compare the numerical results via a comparison with those obtained by direct measurement with thermocouples placed at different positions in the solar oven. Then the spatial distribution of temperature, occupying the inner part of the pan gave us an insight into the non-homogeneous distribution of this parameter during the solar heating process. The modeling of this process with an additional element (pan) has almost been validated by comparing the numerical and experimental temperature inside the pan filled with water. The results would prove to be very promising for the future if we take into account the physical factors responsible for the different thermal losses of the solar cooker. We also obtain reasonable heating times which approach 12 minutes for 1 liter of heated water.

Acknowledgements

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