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NUMERICAL AND EXPERIMENTAL STUDY OF A SOLAR COOKER

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ABSTRACT

A numerical and experimental study of a solar cooker with parabolic collector is presented. The established transfer equations are derived from thermal balances at each component of said cooker. The experimental set-up was designed and carried out at Bangui University (Central African Republic). A numerical code simulating the temperatures of the solar cooker has been developed. It was validated by comparison with the experimental results in which We had heated 1.5 liters of water, cooked 0.5 kg of potato, 200g of rice and 150g of yam. It emerges that after 55min, one liter of water reaches their boiling point, for the cooking of the rice, the maximum temperature reached is 101°C after 1h30min exposure of the concentrator, 107.5°C for cooking of the potato after 1h10min and 105°C after 1h20min for the cooking of the yam.

Keywords: *digital-experimental-solar cooker-solar concentrator.*

I. INTRODUCTION

Solar concentrating systems can contribute to the supply of thermal energy for cooking food. It was designed in 1767 by the Swiss Horace BENEDICT [1] and allowed him to cook vegetables in a parallélipipédique whose one of the walls is composed of a glass. Subsequently, the French engineer Augustin Bernard MOUCHOT developed a solar cooker concave solar concentrator in 1860 in Algeria [2].

Thus, many works (numerical and experimental) on different types of solar cookers were at the center of reflection of several researchers. Like multi-reflector box type solar cookers with and without trackers that have been the subject of several experimental works [3]-[13]. The type K and type T thermocouples for the water temperature measurements, and the various components (windows, walls) of the solar cooker are positioned in different places of the cooker. Type 2CM11 and Kipp & Zonen pyranometers for solar flux measurements were used. The results presented relate to the thermal efficiency, the cooker wall and water temperatures, the overall heat loss coefficient, the temperature difference between the ambience and the temperature in the cooker, and the cooking time. After no-load tests, tests under load every 10 seconds or 5 minutes are performed.

This experimental work is also intended for determining the energy efficiency of the solar cooker, the temperature of the water and other foodstuffs (potato, corn ...), the cooking time have been carried out [25]-[39]. These experiments were made in particular under a density of solar flux between 600W / m² and 900W / m².

The results presented show that the solar irradiance varies between 600 and 916.3 W / m², the difference between the temperature of the atmosphere and that of the air inside the cooker is between 44.8°C and 60.5°C. In addition, the maximum temperature of the air in the enclosure of the cooker is equal to 140°C. The energy efficiency is 55% with a thermal performance of 30.5% and the overall heat loss coefficient is estimated at 6W / m

For the numerical works, the studies are based on the numerical resolution of the equations of transfer, obtained by the nodal method by MATLAB software [14]-[17]. In addition, the thermal efficiency and the maximum temperature of the air inside the cooker are respectively equal to 33.9% and 140°C.

Reflectorless cookers have also been the subject of numerous numerical and experimental work. Digital work is based on the resolution of transfer equations [18]-[24]. One of the aims of this work is the analysis of the transient behavior of the solar cooker.

In the light of this literature review, we discover that the concentration of solar flux is one of the most promising alternatives in the current energy context for solar cookers. It is viable in the long term, it does not produce greenhouse gases. The box-type solar cookers are, by their simplicity of design and construction and their maneuverability, well adapted to areas devoid of conventional sources of energy. They do not present any particular disadvantage (burn). This bibliographic study shows that the two basic models of solar cookers most used are box type and parabolic concentrator. The box type cooker can be used directly or indirectly. The cooking time is longer than that obtained using wood as fuel, the maximum temperature of the air inside the cooker can reach 140°C. For the parabolic cooker the temperature is higher, up to 250°C and the cooking time is lower than that of the box-type cooker. However, it has a particular disadvantage (burn) and the design is complex. In addition, it requires regular monitoring during its operation. The cooking time of a box-type solar cooker is between 2 and 3 hours; it is reduced from 1 to 2 hours for the cooker with an air temperature between 82°C and 140°C depending on the type of cooker. For this cooker, the energy efficiency varies between 8.5 and 55%.

These data will serve as a reference in the analysis of the thermal performance of our cooker under the climatic conditions of the experimental site (Bangui).

II. DESCRIPTION OF THE SOLAR COOKER

2.1- Synoptic diagram

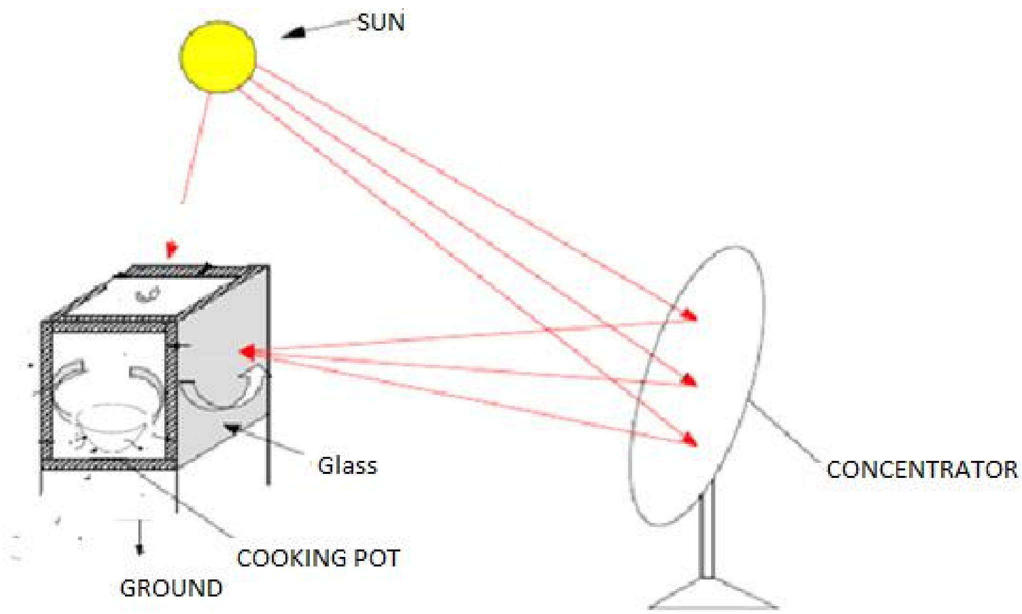

Figure 1 : Synoptic diagram of the solar cooker

The solar cooker model chosen is based on the analysis of the different solar cookers. This solar cooker is composed of a solar concentrator and a parallelepipedic enclosure in which the pot containing the food to be cooked is arranged. The pot in which the food is placed is a semi-spherical tank whose outer face is painted black.

The concentrator consists of a parabolic reflector (0.65 m diameter) designed to focus the solar flux in its focal length. The walls of the parallelepipedic enclosure with the exception of the one facing the concentrator are made of wood 0.65m × 0.50m × 0.50m and 30mm thick load glass wool for insulation. A glass 4 mm thick allows the transfer of a portion of the solar flux reflected by the concentrator to the kettle disposed in this chamber. Access to the interior of the enclosure is provided by one of the vertical walls adjacent to the wall of the glass.

2.2- Principle of operation

The solar flux reflected by the concentrator is transmitted inside the enclosure through the glass and a portion is absorbed by the wall of the kettle. This results in heat flow by conduction through the wall of the semi-spherical tank towards the inside of the pot and, consequently, heat supply to the fluid and the food contained in the pot.

2.3-Mathematical formulation

In order to deflect uncertainties the simplifying assumptions about the device are listed.

- **Simplifying hypotheses**

-The sky is likened to a black body,
-The soil temperature is taken equal to the ambient temperature,
-The properties of the materials are constant,
-The walls on each side of the box are thermally insulated,
-The temperatures of the components of the solar cooker and that of the fluid in the kettle are uniform,
-The various elements (walls) constituting the system are at uniform temperatures.
-The velocity of the fluids in the parallelepiped enclosure and the pot are supposed to be very low,
-The solar flux captured by the concentrator is uniformly distributed,
-The optical properties (reflectivity, absorptivity) are uniform over the entire reflecting surface,
At the ends of the concentrator, the heat losses by radiation are negligible,
-The heat losses by convection and radiation between the concentrator and the atmosphere are negligible,
-The loss of heat by conduction through the walls of the concentrator are neglected.

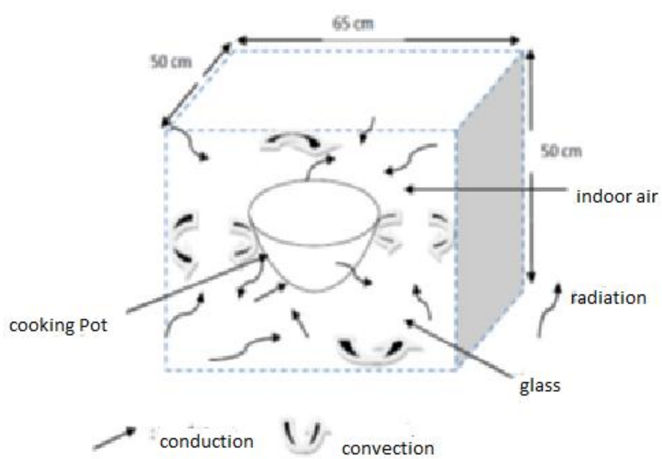

Figure 2 : Synoptic diagram of the cooking box

2.3.1-Transfer equation

The equations governing the heat transfer in the parallelepiped enclosure and the pots are based on the analogy between heat transfer and electrical transfer

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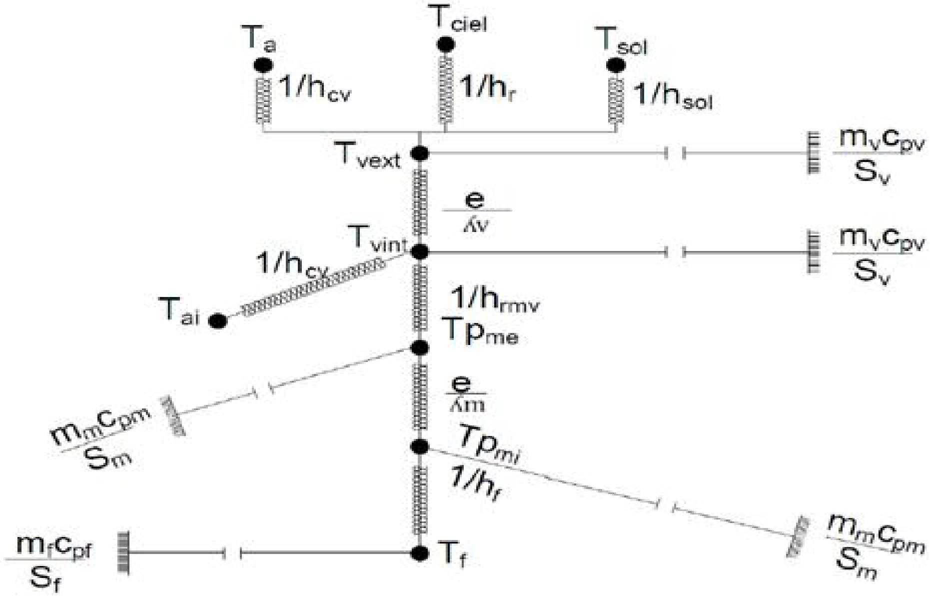

Figure 3 : diagram of the electricity network

The energy balance at the level of each component of the solar cooker is equal to the algebraic sum of the densities of the heat flux exchanged between the different components.

The general equation of this balance sheet verifies the expression:

$$M_i C_{pi} \frac{dT_i}{dt} = \varphi_{sol} \times S_i + \sum_{k=1}^{m} \sum_{j=1}^{n} h_{r,j-k} + h_{cv,j-k} + h_{cond,j-k} (T_k - T_j) \quad 1$$

Or

$h_{r,j-k}$: Radiation transfer coefficient between components j and k

$h_{cv,j-k}$: Coefficient of convective transfer between components j and k

$h_{cond,j-k}$: Coefficient of transfer by conduction between the components j and k.

Apply equation (1) to the different components of the cooker.

- **Glass**

- **External face**

$$mC_p \frac{\partial T_{ve}}{\partial t} = I\alpha_v S_v + h_{rv} S_v (T_{ciel} - T_{ve}) + h_{rvsol} S_v (T_{sol} - T_{ve}) + h_{cv} S_v (T_{amb} - T_{ve}) + \frac{\lambda_v S_v}{e} (T_{vi} - T_{ve}) \quad 2$$

Internal side

$$mC_p\frac{\partial T_{vi}}{\partial t} = I\alpha_v S_v + h_{rmv}S_m\left(T_{pme} - T_{vi}\right) + h_{cvv}S_v(T_{ai} - T_{vi}) + \frac{\lambda_v S_v}{e}(T_{ve} - T_{vi}) \quad 3$$

Air inside

$$m_{ai}\, C_{pai}\frac{\partial T_{ai}}{\partial t} + m_{ai}C_P V_{ai}\frac{dT_{ai}}{\partial x} = h_{cvai}\, S_v(T_{vi} - T_{ai}) + h_{cvm}\, S_m\left(T_{pme} - T_{ai}\right) \quad 4$$

Absorber
External face

$$mC_p\frac{\partial T_{pme}}{\partial t} = I\tau_v\alpha_m + h_{cvm}\, S_m\left(T_{ai} - T_{pme}\right) + h_r S_m\left(T_{vi} - T_{pme}\right) + 2\pi\lambda_m\left(\frac{R_2 - R_1}{R_2.R_1}\right)\left(T_{pmi} - T_{pme}\right) \quad 5$$

Internal side

$$mC_p\frac{\partial T_{pmi}}{\partial t} = 2\pi\lambda_m\left(\frac{R_2 - R_1}{R_2.R_1}\right)\left(T_{pme} - T_{pmi}\right) + h_f S_m\left(T_f - T_{pmi}\right) \quad 6$$

- **Fluid**

$$m_f C_{Pf}\frac{\partial T_f}{\partial t} + m_f C_{Pf} V_f\frac{\partial T_f}{\partial x} = h_f S_m\left(T_{pmi} - T_f\right) \quad 7$$

2.4-Evaluation of the thermal performance

The evaluation of the thermal performance is done by calculating the thermal efficiency and the thermal power of the cooker thanks to the various parameters of the cooker.

Thus the thermal power is calculated by the relation established by FUNK [1999]:

$$P_{th} = \frac{M_{eau}C_{peau}(T_{f(eau)} - T_{i(eau)})}{dt} \quad 8$$

FUNK has introduced the term of the thermal power of standard cooking by the expression:

$$P_{th} = \frac{700M_{eau}C_{peau}(T_{(eau)f} - T_{(eau)i})}{600\bar{I}_s} \quad 9$$

He proposed the method of calculating the thermal efficiency of a solar cooker by the relation:

$$\eta_{th} = \frac{(m_{water} \times C_{Pwater} + m_m \times C_{Pm})(T_f - T_i)}{S \times I \times \Delta t} \quad 10$$

The specific boiling time (Khalifa et al 1985) is calculated by the relation:

$$t_s = \frac{A_c \times \Delta t}{M_{eau}} \quad 11$$

2.5- Numerical study

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Methodology

The system of equations (2-7) is solved by the Gauss method coupled to an iterative procedure because the convective and radiation heat transfer coefficients depend on the temperatures of the different media which are unknowns. Thus for a given time step, we assign an arbitrary value to the temperatures of the different media by the calculation of the natural convection heat transfer coefficients and radiation and the resolution of the system of algebraic equations, the values of the calculated temperatures are compared. Arbitrary values; if the deviation is greater than the desired precision (0.5°C), the arbitrary values are replaced by the calculated values and the calculation procedure described above is resumed until the accuracy is reached. In this case, the calculations are resumed at the next time step and this procedure continues over time until the desired operating time is reached. Thus the heat transfer in the solar cooker can be represented by a thermal resistance network.

2.6-Materials used

- A mini DVS-1.4 weather station that allows us to read the ambient temperature, the wind speed and the solar flux.
- An Agilent 34970A multiplexer that is connected to a computer for data acquisition.
- A HLD precision scale, to weigh the mass of food products
-
- Five K-type thermocouples for measuring temperatures at different points on the cabinet and a computer for data processing.
- An Arduino microcontroller that measures fluid temperature using the DS18B20 sensor

2.7-Experimental procedure

This experimental procedure has a main purpose. It is a question of comparing the experimental results to those given by our numerical model to validate it. At the end of this confrontation, we will be able to judge the reliability of the predictions of the computer program developed and we can then consider using it to predict the performance of the cooker with another configuration.

The scheduled tests are stagnation tests, performed without any charge and with charge.
For the purposes of our study, a prototype was made as previously described.

During the various experimental tests, the prototype of the box solar cooker is installed on the experimentation area of the Laboratory of Energétique Carnot and is exposed to the natural sunshine.

Figure 4 : Photo of solar concentrator with solar concentrator

Figure 5 : Photo of the box containing the pot

During the tests the cooker is exposed to the sun and follows the course of the sun with a blind pursuit every 15 minutes. We measure:

- Room temperature,
- The temperature of the wall of the external and internal kettle,
- The temperature of the glazing,
- The temperature of the air in the cooker enclosure,
- The temperature of the fluid in the enclosure of the pot.

Vacuum tests

Empty measurements were made every 5 minutes, when the cooker is exposed to the sun during the experimental period.

Tests to load

Test 1: The container filled with 1.5 kg of water;
Test 2: cooking the potato,
Test 3: cooking rice
Test 4: cooking yams

III. RESULTS AND ANALYSIS

We present in this section, the experimental results that will be confronted to the numerical results in order to analyze the relevance of our cooker.

Figures 6 and 7 illustrate the results of the amount of heated water. We note that the water temperature reaches 98°C at 12h when the solar flux density indicates 850W / m².

Cooking food

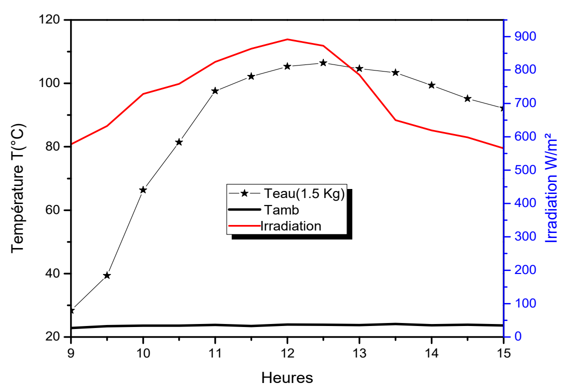

Figure 6 Temperature evolution for 1.5Kg of water (25/10/2017)

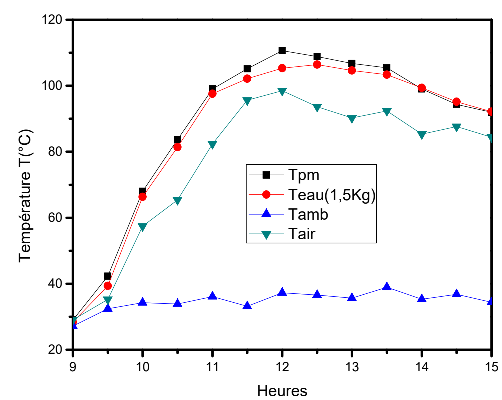

Figure 7: Temperature evolution for 1.5 kg of water (25/10/2017)

Figures 8-10 shows the hourly evolution of the temperatures of the outer and inner faces of the wall of the pot, the atmosphere, the temperature of the different foodstuffs and that of the solar flux. The tests started at 10h (TL), we observed that the water-food mixture begins to boil after 30 min of solar irradiation.

- ✓ **POTATO**

Figure 8 shows the hourly evolution of ambient temperatures, that of the internal and external faces of the wall of the kettle. As can be seen in this figure, with an average solar irradiance of 968 W / m², after 70min the sweet potato is ready.

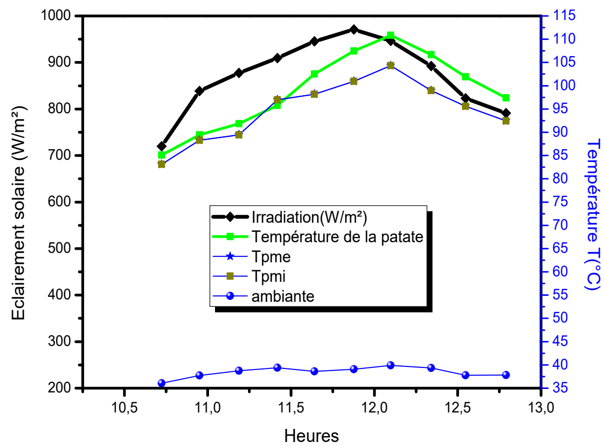

Figure 8: hourly evolution of temperatures during the cooking of the potato (20/01/17)

✓ **RICE**

For rice, the maximum temperature reached is 105°C for an average solar irradiance equal to 752W / m² after 130min the rice is ready.

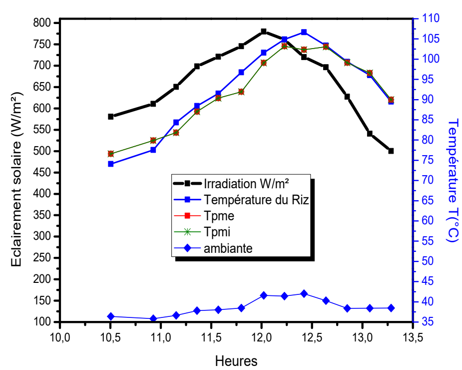

Figure 8 : Hourly evolution when cooking the water-rice mixture (05/02/2017)

✓ **YAM**

For an average solar irradiance of 972 W / m², the cooking of the yam requires a duration of 87 min. The drop in temperatures observed at 11am results in the passage of clouds covering the sky for a period of 15 min.

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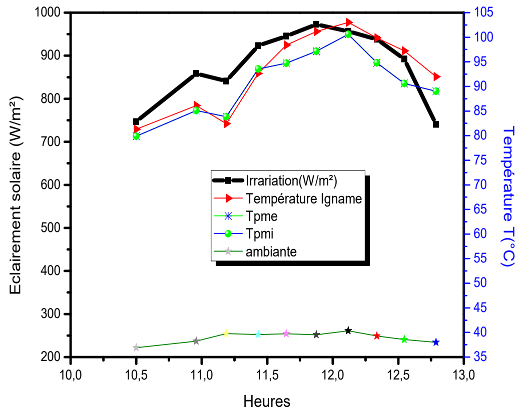

Figure 11 : Hourly evolution of the temperature of the cooker components during the cooking of the yam (24/02/2017)

We proceeded to the cooking of the yam, a duration of 1:27 min is enough for it to be well cooked under an average solar irradiance of 972W / m².

The drop in temperatures observed at 11am results in the passage of clouds covering the sky for a period of 30 min. We note that the time of cooking rice and yam are lower than that for cooking the potato. This is due to the density of solar flux when cooking the potato which is significantly higher than that of rice. During the cooking of the yam we observed a cloudy passage that lasted 15 minutes, which seems to be the cause of the delay of this cooking.

For these different tests, the durations of the various firings are in adequacy, with those reported in the works of Nahar and Harmim [8] and [10]. At the solar concentrator focus, the temperature reached 150 ° C compared to that of Sonune.

The calculated thermal efficiency is 28.34%. A comparison between our results with those of El-Sebaii [7], and Nahar [8] shows that the yield obtained is higher than those reported in this study. Indeed, they are 26% and 30.5% respectively. This difference is due to the latitude of the place, the design, the orientation and the choice of materials used to manufacture these solar cookers.

Validation of results

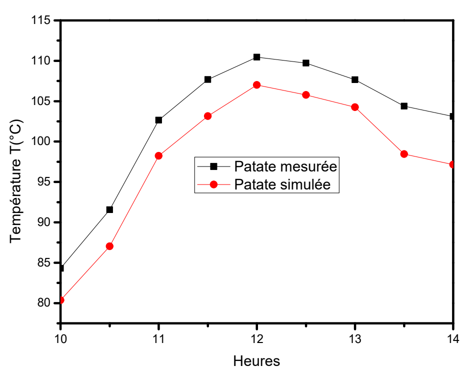

Figure 12: Hourly evolution of potato temperatures (measured and simulated)

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The two simulated and measured temperature curves in Figure 12 show a similar temperature variation. From 12 o'clock, we notice that there is a constant evolution of the two curves. The maximum difference is 1.8%.

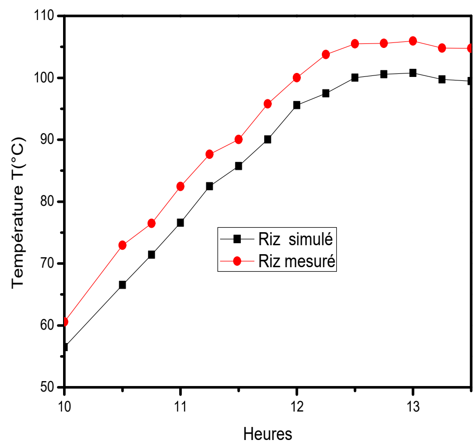

Figure 13: Hourly evolution of Rice temperatures (measured and simulated)

The simulation and experimentation curves of rice cooking give an appreciable look. In all cases, the time évolution of the two curves reaches their maximum temperature from 12 hours. The relative difference is 2.1%.

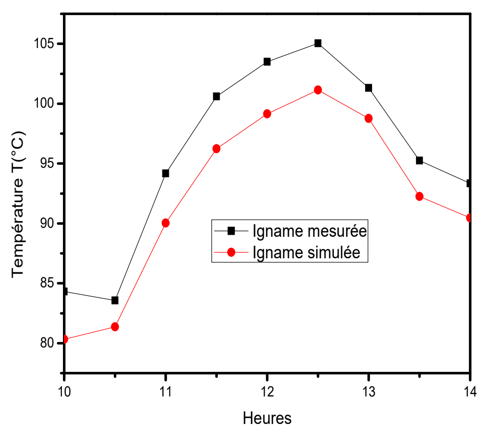

Figure 14: hourly evolution of yam temperatures (measured and simulated)

With regard to these two curves, we can say that the simulated and experimental results go hand in hand, and therefore it bodes interesting with a maximum relative difference of 3%.

IV. CONCLUSION

We conducted a numerical and experimental study of a solar cooker whose concentrator is parabolic. We have applied this cooker for cooking 3 widely consumed foods in the Central African Republic, potatoes, rice and yams. The validation of our experimental results was made by a comparison with the results of the simulation thanks to the meteorological data of the experimentation site. The experimental results seem to be efficient because they agree with the results of the simulation and are much higher than the results of the simulation. Faced with variable sunlight this cooker can keep the temperature for a while. With this record, we could estimate a twice-daily cooking of foodstuffs. The experimental analysis contributed to the validation of the calculation code, the evolution of the temperature of the various parameters of the cooker, measured and simulated is satisfactory with a maximum relative difference of 1.8%; 2 % and 3% successively of potato, rice and yam. Despite the relatively complex installation of this cooker, it is advantageous compared to other cookers because it acquires the performance of a concentrator cooker and a box-type cooker.

V. COMPETING INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

VI. ACKNOWLEDGMENT

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