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Finite Element Modeling of a Solar Box Cooker: Temperature and Fluid Velocity Distributions

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Abstract

We studied the temperature distribution and fluid velocity in a box-type solar cooker by using the Finite Element Method (FEM) in Ziguinchor southern of Senegal. Indeed, this is one of the sunniest countries in the world: more than 3000 hours of sunshine per year with an average temperature of around 30˚C. This abundant and exploitable solar energy contributes to the development of more efficient, profitable and clean sources of energy. This will help to satisfy the increasing demand of energy. This numerical model was validated by comparing the numerical results with those of the experiment carried out on a single day. The relative error obtained is below 3%. The model results confirmed the performance of this cooker as its cooking temperature is available for more than seven hours. They have shown that the temperature and internal fluid velocity fields are not homogeneous. The results, although preliminary and encouraging, are a first step towards the complete simulation of a solar cooker integrated into a drying column.

Keywords

Solar Cooker, Box-Type, Finite Element Method, Heat Transfer Model, Experimental Validation

1. Introduction

In recent years, the use of fossil fuels has been questioned both in terms of their sustainability and their impact on climate change. Indeed, the limitation of the quantity of these reserves, the successive oil crises and the increasingly high energy demand in all countries of the world have led developing countries to seek and develop new sources of energy supply [1]. Solar energy is one of them. It is a real chance for humanity especially for Africa where it is almost inexhaustible. Africa is very sunny compared to other continents. Also, cooking sector is considered as one of the major energy consuming sectors in developing and underdeveloped countries. Among the technologies using solar energy, we can mention the solar cooker. There are several forms of cookers (parabolic, panel, box-type, etc.) even though the principle of operating is almost the same [2].

Various studies have been carried out with the aim of reducing cooking time by increasing the cooking temperature and/or by reducing heat losses. In Nigeria, the performance of solar cookers was studied [3]. Others results of the literature have shown the difference in performance between a solar cooker with and without reflectors [4] [5]. To reduce the cooking time too, the modeling and the numerical simulation of the operation of solar cookers were carried out with finned cooking vessel, a new shape of cooking utensil [6] [7] [8]. Another study focuses on the analysis of heat loss from a trapezoidal shaped solar cooker cavity [9].

The choice relates to the solar box cooker, which is explained by the fact that it is cheaper and easier to build. Several simulation studies aiming to know its performance were done. However, most of these studies have considered the behavior of the materials constituting the solar cooker as homogeneous [10] [11] [12]. But, physical parameters of the system change in time as well as in space [13] [14] [15].

The objective of this work is to build a predictive model of the operation of a box-type solar cooker with a single external reflector allowing a better exposure to solar radiation. This is based on the Finite Element Method (FEM). This approach, which has already been used in other applications, will make it possible to calculate the spatial and temporal distribution of variables such as the temperature or the velocity of the fluid. The validity of the model will be made by comparing the results of the experiment carried out under natural sunlight with the numerical results.

2. Modeling

The main goal is to calculate the temperature and velocity distributions in the solar cooker. A non-isothermal incompressible laminar flow is performed using Comsol Multiphysics, a finite element method software. This model is constructed as follows:

2.1. Geometry and Materials Properties

A two-dimensional model is used to simulate the behavior of the solar cooker.

- At the top portion, a transparent glass cover allows the entry of solar radiation in the oven.
- At the bottom of the solar cooker, a plate is coated in black matt paint. This absorber plate generates thermal energy and heats the interior air of the system.
- Different layers of insulators that limit heat losses surround the solar cooker. Two layers of red wood are in contact with the outside air and the inside air for the side faces. For the horizontal faces, they are two layers of plywood.

These layers are interspersed with a layer of wood chips.

- An external reflector and four other internal ones which allow radiation to concentrate on the absorber plate.

The dimensions of the various elements of the solar cooker are given in Figure 1. Their physical properties are mentioned in Table 1 except those of the fluid taken directly from the software library.

2.2. Coupled Equations

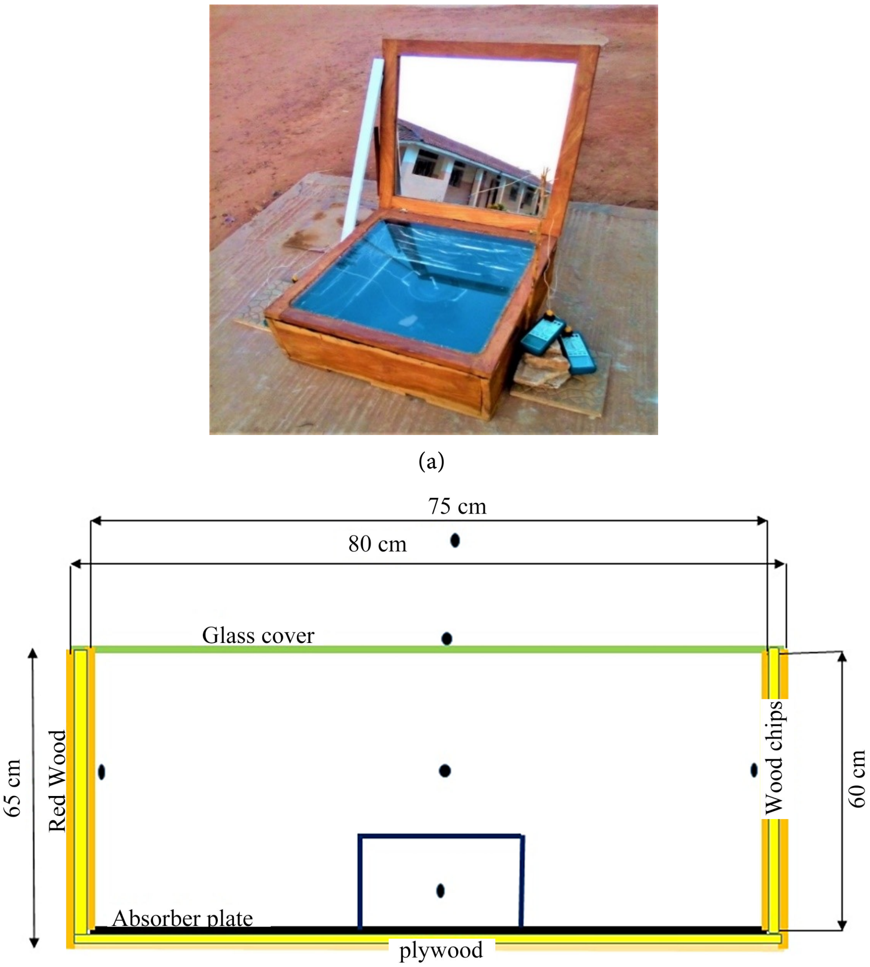
As the behavior of the temperature and the fluid flow are related to each other, three coupled equations needed to be solved.

Energy conservation is given by the following equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = 0 \tag{1}$$

Mass conservation (continuity equation) is given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho u \right) = 0 \tag{2}$$



(a)

(b)

Figure 1. (a) Photograph of the solar box cooker (b) Schematic of the solar box cooker.

Table 1. The properties of red wood, glass, plywood, wood chips and aluminum sheet [10] [12] [16].

Properties	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)	Heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Emissivity (−)
Red wood	0.12	873	2220	0.83
Glass	1.4	2530	840	0.92
Plywood	0.10	404	1850	
Wood chips	0.04	120	2300	
Aluminum sheet	238	2700	900	

Momentum conservation (Navier-Stokes equation) is given by:

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla \cdot \left[-pI + \mu \left(\nabla u + (\nabla u)^{\mathrm{T}} \right) - \frac{2}{3} \mu (\nabla \cdot u) I \right] + \rho g \qquad (3)$$

with $q = -\kappa \nabla T$, T the temperature, t the time, C_p ($J \cdot kg^{-1} \cdot K^{-1}$) the heat capacity, κ ($W \cdot m^{-1} \cdot K^{-1}$) the thermal conductivity, u ($m \cdot s^{-1}$) is the velocity of the air, ρ ($kg \cdot m^{-3}$) the density, μ (Pa·s) the dynamic viscosity, p (Pa) the pressure and g ($m \cdot s^{-2}$) the gravitational acceleration.

2.3. Initial and Boundary Conditions

Initial and boundary conditions, which are considered to numerically solve the differential equations are the followings:

- Thermal losses by convection are considered on the exterior glass. The corresponding heat flux by convection is expressed by:

$$q = h \left(T_{ext} - T \right) \qquad (4)$$

with h ($W \cdot m^{-2} \cdot K^{-1}$) the convection coefficient, T_{ext} (K) temperature of the face in contact with the ambient air. The convection coefficient value (h) is estimated to be around 15 $W \cdot m^{-2} \cdot K$ from a confrontation between numerical calculations and experimental measurements of temperature.

- Thermal losses by radiation at the horizontal outer surfaces of the glass are considered by the Stefan-Boltzmann relation:

$$-\boldsymbol{n} \cdot q = \varepsilon \sigma \left(T_{amb}^4 - T^4 \right) \qquad (5)$$

with ε the emissivity and σ is the Stefan-Boltzmann constant. Inner surfaces are subjected to surface-surface radiation.

- The other surfaces are thermally insulated:

$$-\boldsymbol{n} \cdot q = 0 \qquad (6)$$

with $\boldsymbol{n}$ the normal to the outer surfaces.

- The initial temperature is about 20˚C throughout the system and the velocity is equal to 0 $m \cdot s^{-1}$.

3. Experimental

A simple solar box cooker with absorber area has been designed and fabricated as shown in Figure 1. It is a flat plate solar collector with double glasses cover on the top. To minimize the heat loss by convection, the envelop of the solar box cooker is composed by a series of insulated materials (wood chips, plywood, red wood).

Some thermocouples of type K are connected to different data loggers and placed at different positions: the exterior air temperature, the temperature of the surface of the glass, the interior air temperature, the water temperature, and the temperature of the inner surfaces as shown in Figure 1. Temperatures are measured with a time step of 10 minutes from 7:00 to 8:00 local time and with a time step of 1 hour from 8:00 to 18:00 local time. All experiments were conducted on April 2020 at Assane Seck University in Senegal. The uncertainty of the measurements of the multimeters is ±3%.

4. Results and Discussion

A non-uniform meshing of about 52,000 tetrahedral elements was used. To facilitate the convergence of computation, a temporal solver with a progressive time step was used. Comsol employs the finite element method for solving the mass, momentum, and the energy conservation equations in laminar regime.

4.1. Numerical Validation

The validation of the numerical model is carried out by comparison of the experimental and numerical temperatures. The absorber temperature and the exterior air temperature were used as inputs for the numerical model as shown in Figure 2.

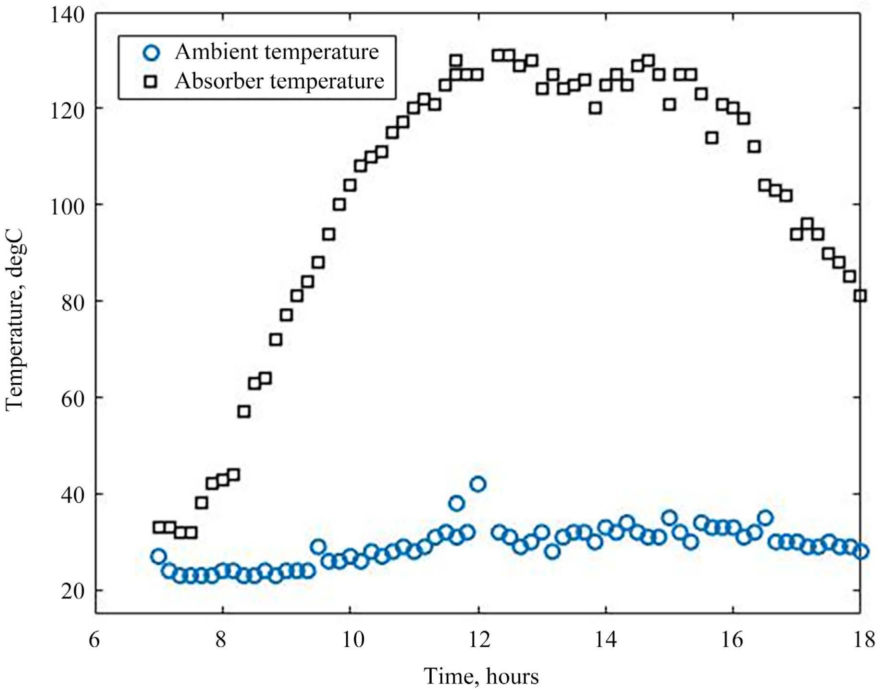
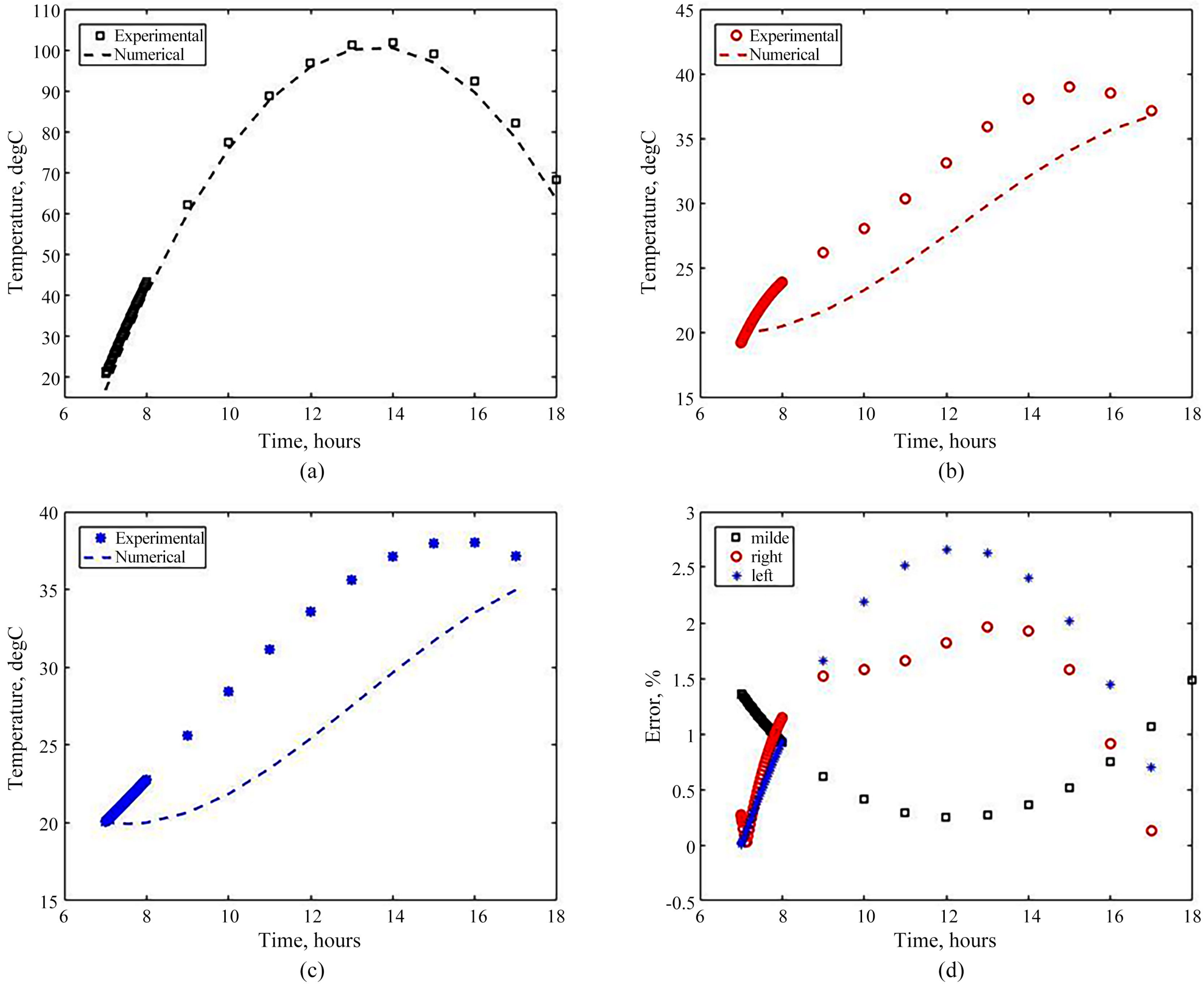


Figure 2. Exterior air and absorber plate temperatures as a function of time.

The temperatures of the interior air and the interior wood surfaces, estimated using the heat transfer model, were compared to experimental measurements, and illustrated in **Figure 3**. The convective coefficients presented in the model equations were estimated by minimizing the differences between the experimental and simulated values of these temperatures.

The relative error between the experiment and the simulation confirms that the numerical results are reliable. Indeed, its maximum value is about 2% as shown in **Figure 3**. It can be seen that the temperature distribution in the system can be predicted by simulation with very good precision. Based on this comparison, we can say that the numerical model is valid. Although these validation results are those of a single day, it should be noted that experiments on different days were made. Due to Senegal's geographical position, the experimental results seem to be similar. The validation with the numerical results does not show too many inconsistencies.



(a)

(b)

(c)

(d)

Figure 3. Comparison between the experimental and simulated temperatures (middle (a), right side (b), left side (c)) and the relative error between the model and the experimental temperatures in the middle, the right and left.

Temperature values above 100˚C can be seen in the middle of the solar cooker at the time when the sunshine is at its highest. We find that the maximum temperature of the absorber plate is 130˚C and it occurs at 12:20 local time. To analyze the performance of the solar cooker, the number of hours above which the temperature of the absorber plate is above 100˚C has been calculated and it is around five hours (between 10:00 and 18:00 local time). Indeed, this plate temperature guarantees that the cooking temperature is above 70˚C for more than 4 hours. This adapts to the culinary traditions of West African countries. This performance of the solar cooker could be highlighted in the fruit and vegetable drying process in the study region.

4.2. Temperature and Velocity Fields

The temperature and the air velocity fields are shown in **Figure 4** and **Figure 5** when the temperature is higher. It is observed that the temperature remains constant along the horizontal direction. Nevertheless, a significant change is observed near the absorbent plate and the glass. This is largely explained by the heat losses via the upper part of the solar cooker.

The behavior of the velocity is explained by the difference in density of the fluid. The hot fluid tends to rise because of its low density and the walls, being airtight and the buoyancy effects, we see this phenomenon of air circulation in the solar cooker which is in agreement with the results of the literature even if the number of vortices formed is more than those observed in the work of Nayak [9]. This could be explained by the larger dimension of the system studied here.

4.3. Application: Temperature of Boiling Water

In order to better assess the performance of the solar cooker locally, an experiment was carried out on an aluminum container loaded with 5 L of water. It shows that when the temperature of the absorber plate is about 120˚C, the water temperature is 100˚C as illustrated in **Figure 6**. The results showed that

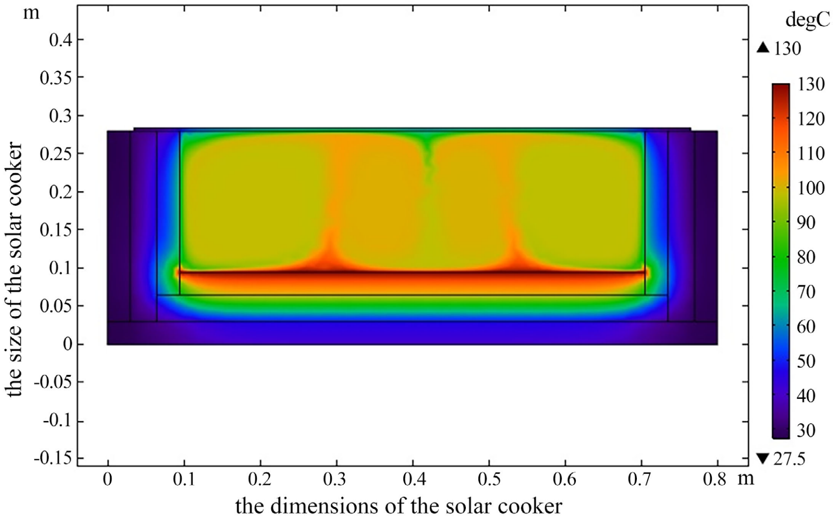


Figure 4. Temperature distribution simulated at 12:20 local time in solar cooker.

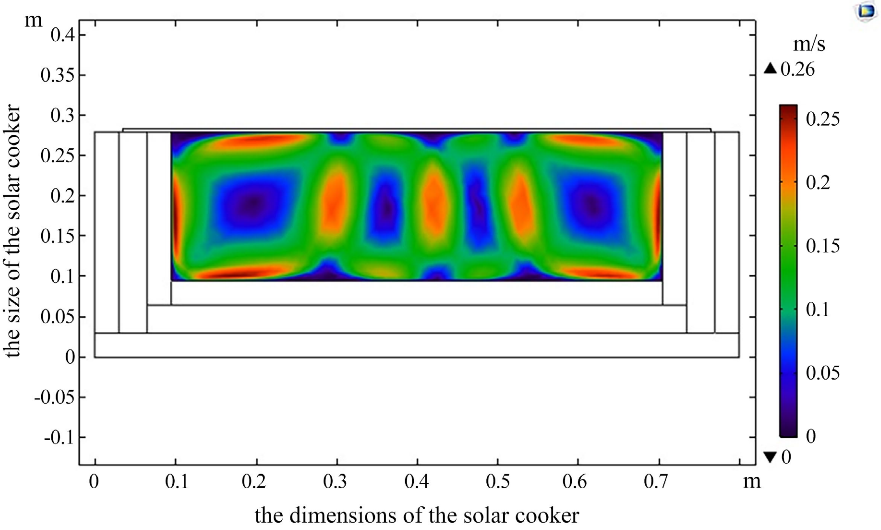


Figure 5. Interior air velocity distribution simulated at 12:20 local time in the solar cooker.

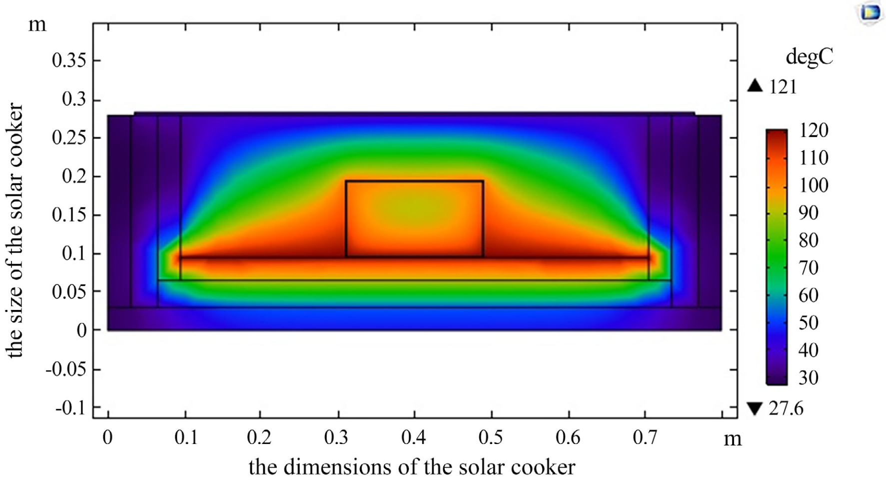


Figure 6. Temperature distribution simulated at 12:20 local time in solar cooker with water.

the water temperature remains equal to 100˚C for around 7 hours a day and this boiling time of water remains sufficient for a domestic use.

5. Conclusions

The modeling of the heat transfer in a solar cooker was carried out as well as the behavior of the fluid via the finite element method. This numerical approach takes into account the heterogeneity of the spatial distribution of the variables (temperature, velocity) unlike other approaches which consider homogeneous materials. The numerical results were first validated by comparing them with the results of the experiment on several positions of the system. The difference obtained is acceptable since it does not go beyond 2%, which is negligible. This confirms that the model developed is reliable.

Knowing that the two modes of heat loss are mainly radiation and part of convection, the thermal behavior of the fluid in the solar cooker and its velocity is in agreement with the results of the literature. The vortex behavior of the fluid in this cooker, larger than in its previous studies, shows more vortices.

The performance of the solar cooker has also been studied and gives ideal cooking temperatures for more than 8 hours. This is exceptional and could be valued in several applications in order to achieve energy self-sufficiency very quickly.

In this solar cooker, it would be interesting to integrate another compartment with a fan in order to predict the temperature distribution in this second space. This would be a good application for drying local products and setting up a suitable process.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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