

# EXPERIMENTAL AND NUMERICAL MODELING OF A SOLAR BOX COOKER WITH PARAFFIN WAX AS THERMAL ENERGY STORAGE MEDIUM UNDER MAIDUGURI WEATHER CONDITIONS

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## ABSTRACT

*The performance of paraffin wax as phase change material (PCM) as thermal energy storage (TES) was investigated using a Solar Box Cooker (SBC) exposed to Maiduguri weather conditions; Temperature and Energy generated by SBC were experimentally established. The developed model geometry was generated with a single reflector in Ansys 19.0 and temperature changes were simulated in the cooking chamber which was compared with the experimental results. The results show an acceptable agreement between the numerical and measured temperatures within 5% variation. Also in the experiment 118°C and 4164.5Kj of temperature and energy were respectively generated by the PCM, an adequate temperature and energy for cooking during off-sunshine hours and beyond in the study area (Maiduguri).*

**Keywords:** Solar Box Cooker, Phase Change Material, Energy, off-sunshine.

## 1 INTRODUCTION

With the rapid development in civilization, man has increasingly become dependent on natural resources to satisfy his needs. Cooking food is one of those indispensable processes that require natural resources in the form of fuels. Solar cooking is fast becoming a preferred method of cooking food considering the potential of saving significant amounts of conventional fuel. The major factor that limits the solar energy for cooking application is that it is a cyclic time dependent energy source. Therefore, solar systems require energy storage to provide energy during the night and overcast periods. In addition, one of the major requirements in using solar energy for cooking application is the development of a suitable cooking unit, which should be fast and energy efficient.

Over the last century, many studies have been performed on the development of various types of solar cookers and evaluation of their performance. There have also been several attempts to increase the performance and efficiency of cookers in non-tropical regions [1]. Different types of solar cookers (Box type, direct or concentrating type and indirect type) were modified and investigated by researchers [2]. Some researchers have investigated the performance of a solar cooker for possible use in different applications, with modifications in outer-inner reflectors [3] different insulating materials [4 and 5], various booster mirrors [6], absorber plate [7 and 8], a hybrid solar system [9 and 10] among several other modifications.

Recently, some studies have been performed concerning the use of phase change materials (PCMs) integrated with solar cookers as thermal energy storage (TES). For this purpose, magnesium nitrate hexahydrate [11], stearic acid [11 and 12], acetamide [13], acetanilide [14], erythritol [15] and engine oil [16] have been used as a PCM storage medium. A theoretical investigation on the

performance of PCM (magnesium nitrate hexahydrate, stearic acid, acetamide, acetanilide, and erythritol) has also been conducted by [17]. Results of these studies showed that these applications increase the average efficiency of the cookers. The use of a PCM results in shorter cooking times [15]. It was concluded that, acetanilide is a promising PCM for cooking indoors with aluminum; but it exhibits some corrosion in contact with steel. However, magnesium nitrate hexahydrate is not stable during its thermal cycling due to the phase segregation problem; therefore, it is not recommended as a storage material inside solar cookers for cooking indoors [18]. Also, these PCM are rather expensive when high temperatures are concerned. In addition, [19] found that paraffin wax has shown reasonably good thermal stability in their melting temperature as well as variations in their latent heat of fusion. The ideal PCM to be used for latent heat storage system must meet the following requirements: high sensitive heat capacity and heat of fusion, stable composition, high density and heat conductivity, chemically inert, non-toxic, non-inflammable, and inexpensive [20]. Paraffins appear particularly well suited for applications related to energy conservation in buildings and solar energy [21]. The evaluation and selection of PCM for solar cooker systems and applications in the field of solar energy are described in detail by [20 and 22].

Several attempts were made to increase the performance and efficiency of solar cookers developed and tested in Maiduguri and environs [23]. Solar cookers are expected to contribute considerably towards meeting the requirements of domestic cooking energy with 8-9 hours of sunshine hours in Maiduguri and environs [24]. Despite the enormous solar energy potentials of Maiduguri solar cookers are not widely used. Available literature shows that no investigation dealing with PCM use in solar cooker was carried out in the study area hence, this work intends to develop experimental and numerical model of a solar box cooker with TES (paraffin wax) a phase change material using the weather conditions of Maiduguri. This will also increase the reliability of the solar box cooker as it improves operational performance of the system to be used for off-peak periods. It is also an approach and or solution for bridging the gap between solar energy availability and demand, especially for cooking purposes in the study area (Maiduguri). The approach used for the design was to create a mathematical model of the cooker; The cooker for this study basically conforms to a box within a box with transparent double glazing and access door by the side as shown in Figure 1.

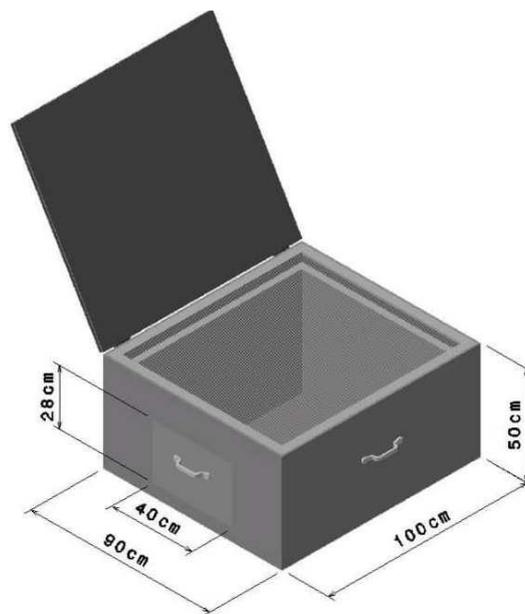


Figure 1. A double glazed Solar Box Cooker (SBC) with a Booster Mirror

## 2 MATERIALS AND METHODS

### 2.1 Experimental Modeling

The box unit consists of a double walled box. The inner and outer boxes were made of plywood. The dimensions of the outer box are 100×90×50 cm and of the inner box are 88×78×35 cm. [25] suggested that the depth of the inner box should not be more than 10-15 cm. The space between the two boxes was maintained at 6 cm and was filled with sawdust insulation obtained from local carpenters. The inner box was painted black for optimal heat absorption. Figures 2 and 3 show the inner box and thermal energy storage tank respectively.

Experimental tests were conducted after constructing physical model of the SBC as shown in plate 1 under various weather conditions to determine the viability of using paraffin wax as TES in comparison to the numerical data obtained by simulation. To evaluate the performance of the solar box cooker in Maiduguri the measured parameters include ambient temperature, solar irradiance, cooking chamber temperature, plate temperature, and PCM temperature.

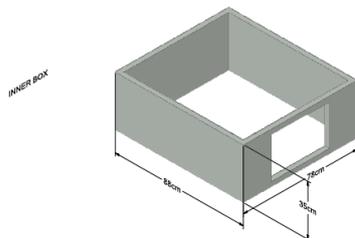


Figure 2. Inner Box

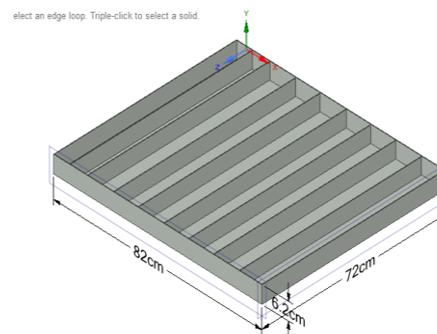


Figure 3. Thermal Energy Storage Tank



Plate 1. Box unit with PCM tank before (a) and after glazing(b)

### 2.2 Numerical Modeling and Validation

### 2.3 Numerical Model

Design and modeling of the structure of the SBC was performed using Ansys Spaceclaim design modeler (SCDM) which was also included in the graphic user interface (GUI), used to create and modify the geometry, [26]. For solar box cooker the Model equations employed are simple equations with closed form solution that are easily solved allowing the calculation and prediction of the internal temperature of the cooker cavity. Subsequently, the equation of the performance index was written and solved and used as basis for the actual design of a specific Cooker.

## 2.4 Modeling Assumptions

Basic thermodynamics states that the energy flowing into the cooker must be equally balanced by the energy that flows out of the cooker otherwise the cooker/oven would continue to heat up to an infinitely-high temperature. In formulating an appropriate model for this type of cooker the following assumptions were made: The SBC reflector angle inclination was neglected and the cooker was considered as a plane solar collector operating under stationary conditions. Steady flow without any chemical reaction was assumed for the flow of gases within the solar box cooking chamber.

The turbulent flows are characterized by fluctuating velocity fields primarily due to the geometry and/or high flow rates hence the navier-stokes equations can be solved directly for laminar flows since turbulent flows on direct numerical simulation (dns) with full solution of the transport equations at all lengths and time scales is too computationally demanding.

The reynolds-averaged navier-stokes (rans) equations were assumed to represent the transport equations for the mean flow quantities, and are derived by splitting the instantaneous properties in the conservation equations into two parts; mean and fluctuating components.

## 2.5 Boundary conditions

At the heat source: the receiver (glass) was only included in the modeling to provide a realistic flow pattern into the solar box cooker therefore, the heat absorbed by the receiver was modeled as a heat source in the cooking chamber to increase the temperature of the resident air (310K). The temperature had a range of (380-519K) measured experimentally on the heat source leading into the cooking chamber using an air flow which corresponds to an amount of excess air between 2 and 4 [27]. Heat losses were modeled as heat transfer through the box wall by conduction. The velocities were calculated from the average air velocity of the study area. The experimental temperature measurement was performed in selected points. At the wall surfaces: convective and radiative heat transfer boundary conditions were applied to all outer walls and to the feeding glass (receiver). Heat flux to the wall was computed as in equation 1:

$$q = h_f (T_w - T_f) + q_{rad} \quad (1)$$

Where,  $h_f$  is the local heat transfer coefficient of air ( $w/m^2k$ ),  $T_w$  is the wall surface temperature (k),  $T_f$  is the local air temperature (k) and,  $q_{rad}$  is the radiative heat flux ( $w/m^2$ ). Air, which consists of nitrogen, oxygen, small amount of carbon dioxide and other gases, has been found not showing absorption band in those wavelength regions of importance to radiant heat transfer. The walls are insulated with Saw dust. The heat loss which was calculated from the overall heat transfer coefficient that combines convection and conduction was estimated as being approx.  $13.0 w/m^2k$  [28].

## 2.6 Model Equations

A mathematical model that was used to describe the flow pattern at this condition was based on the following equations 2 and 3 respectively for model k and model  $\omega$ . used as a length determining quantity; this quantity is defined by  $\omega \bar{a} \varepsilon/k$ , and it should be interpreted as the inverse of the time scale on which dissipation occurs.

$$\frac{\partial k}{\partial t} + (U_j) \frac{\partial k}{\partial \chi_j} = V_T \left[ \left( \frac{\partial(U_j)}{\partial \chi_j} + \frac{\partial(U_j)}{\partial \chi_i} \right) \frac{\partial(U_j)}{\partial \chi_j} \right] - \beta k \omega + \frac{\partial}{\partial \chi_j} \left[ \left( V + \frac{V_T}{\sigma_k} \right) \frac{\partial k}{\partial \chi_j} \right] \quad (2)$$

$$\frac{\partial \omega}{\partial t} + (U_j) \frac{\partial \omega}{\partial \chi_j} = \alpha \frac{\omega}{k} V_T \left[ \left( \frac{\partial(U_j)}{\partial \chi_j} + \frac{\partial(U_j)}{\partial \chi_i} \right) \frac{\partial(U_i)}{\partial \chi_j} \right] - \beta \omega^2 + \frac{\partial}{\partial \chi_j} \left[ \left( V + \frac{V_T}{\sigma_\omega} \right) \frac{\partial \omega}{\partial \chi_j} \right] \quad (3)$$

An advantage of this model compared to the more commonly used k-ε model is that it can predict the sub-layer near the wall more reliably and thereby eliminating the need to use wall functions except for computational efficiency. however, the low Reynolds k-ω model requires a very fine mesh close to the wall with the first grid below  $y^+=5$  [29]. With steady state airflow within the box cooker, the heat transfer mechanisms are described mathematically by the equations of mass conservation, equation 4 (continuity equation).

$$\frac{\partial \rho}{\partial t} = -\left(\frac{\partial}{\partial x} \rho v_x + \frac{\partial}{\partial y} \rho v_y\right) \tag{4}$$

Momentum conservation (Navier–stokes equation) is given in equations 5 and 6:

$$\frac{\partial}{\partial t} \rho v_x = -\left(\frac{\partial}{\partial x} \rho v_x v_x + \frac{\partial}{\partial x} \rho v_y v_x\right) - \left(\frac{\partial}{\partial x} \tau_{xx} + \frac{\partial}{\partial x} \tau_{yx}\right) - \frac{\partial p}{\partial x} + \rho g_x \tag{5}$$

$$\frac{\partial}{\partial t} \rho v_y = -\left(\frac{\partial}{\partial x} \rho v_x v_y + \frac{\partial}{\partial x} \rho v_y v_y\right) - \left(\frac{\partial}{\partial x} \tau_{xy} + \frac{\partial}{\partial x} \tau_{yy}\right) - \frac{\partial p}{\partial y} + \rho g_y \tag{6}$$

Energy conservation is given in equation 7:

$$\rho c_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y}\right) = k \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] + 2\mu \left[\left(\frac{\partial v_x}{\partial x}\right)^2 + \left(\frac{\partial v_y}{\partial y}\right)^2\right] + \mu \left[\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right)^2\right] - \frac{2\mu}{3} \left[\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y}\right] \tag{7}$$

Together with the initial boundary conditions (velocity, and temperature) and the physical properties of the materials used as shown in table 1 the equations were solved with fluent on ANSYS 19.0 workbench.

Table 1. Physical property of materials in use

Material	$\rho$ [kg/m <sup>3</sup> ]	$c_p$ [J/kgK]	$\lambda$ [W/mK]	$\epsilon$	LHF(Kj/kgk)
plywood	850	1.250	0.150	0.8	-
Mirror	1.19	-	6.7	-	-
aluminum	2700	896	229	-	-
glass	2700	840	0.76	0.94	-
air	0.7	1034	0.037	-	-
Saw Dust	300	-	-	-	-
Paraffin Wax	0.900	2.9	0.2	-	189

Source: Maina et al, 2016

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Experimental Results

Solar box cooker with wax was observed to achieve a good temperature to cook most kind of consumables like rice, beans, meat and fish. The experiment was carried out during cloudy days of October 2019 in a rainy season from the morning through the evening hours and the absorber’s surface temperature increased with a single reflector (Booster Mirror) at an appropriate focusing angle. The Solar cooker was able to provide a hot environment adequate for cooking most food items

as mentioned earlier maintaining hot/warm for long hours after completion of cooking (Figure 4). Plate temperature was maintained at over 80°C around 4pm when most food items can be cooked at 75°C as reported by [11], the highest oven temperature of 114°C was attained by the box cooker at 12:30 with corresponding insolation of 958 W/m<sup>2</sup> and maximum plate temperature of 122.2°C. Temperature of 118°C was attained by the PCM (Wax) at 12:30 and 80.2°C at 4pm having slight variation with the plate temperature at the same time. The amount of energy stored by the PCM (Wax) was (4167.5 KJ) an amount much higher than that obtained by [11 and 30] showing that the Cooker can also be used to get other food items cooked through the night at off Sun-shine hours because of heat storing capacity of the PCM. Accordingly, Wax as a PCM can be regarded as a high efficiency material due to the amount of energy stored. However, higher temperatures can also be achieved by modifying the thermal conductivity of wax and incorporation of solar tracking system, as demonstrated by [31]. Thermal curves of SBC with Wax as TES in a test day.

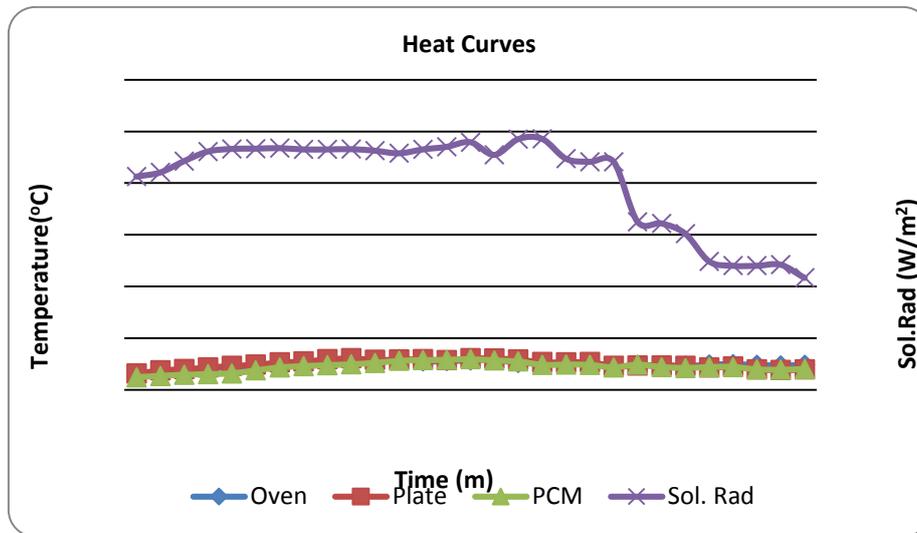


Figure 4. Thermal curves of Solar Box cooker during sensible heating test with wax as TES

### 3.2 Simulation results of Solar Box Cooker (SBC) with Wax as TES

Convergence history of solar box cooker (SBC) with Wax as thermal energy storage (TES), showing scaled residuals of iteration and the convergence curves as shown in Figure 5 after 3475 iterations.

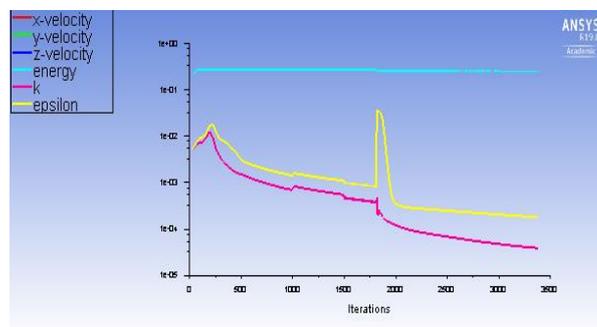


Figure 5. Convergence curve of SBC with Wax as TES

Figure 6 shows the result of the surface cluster temperature distribution in the TES (Wax) tank during heating. It can be clearly seen from the blue color seen in figure that the walls of the outer box do not transmit any heat. This means that a good insulation has been achieved with significant temperature increases within the thermal energy storage tank as shown in figure 6

described by the red and bright colors towards the central region of the TES tank. The required cooking temperature can be reached as long as the wax temperature at the bottom of the tank (base plate) is kept within the required temperature range; while Figure 7 describes the pressure situation of the TES tank after charging the PCM, a relatively constant pressure distribution throughout the TES tank after complete charging by the PCM depicting minimum or no heat loss in the TES tank which can also be attributed to adequate insulation of the Box Cooker.

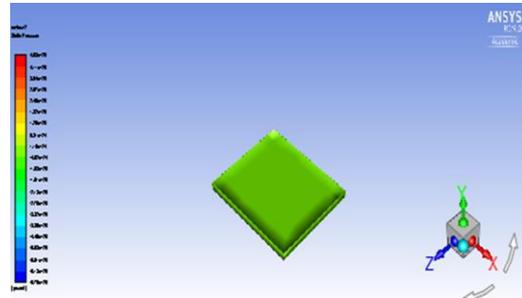
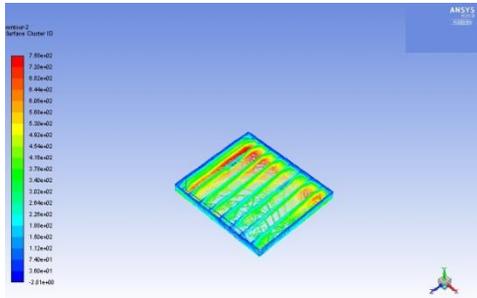


Figure 6. Contours of Temperature in TES Tank      Figure 7. Contours of pressure in TES Tank

### 3.3 Validation of Numerical Simulation

Experimental and Numerical thermal curves of the solar box cooker (SBC) were drawn against each other in comparison as shown in Figure 8.

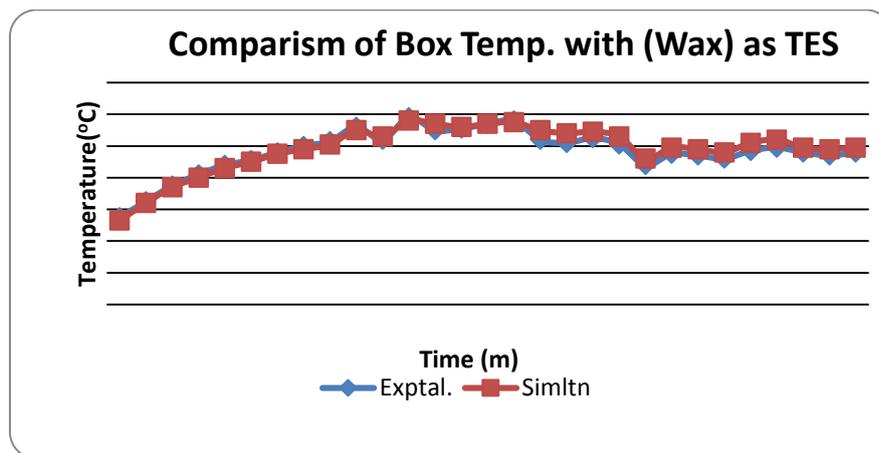


Figure 8. Experimental and Numerical thermal performance Curves of SBC with Wax as TES

It was observed that the thermal curves were in agreement within 5% error which may be attributed to inexact boundary conditions that stands to be modified both analytically and numerically.

## 4 CONCLUSION

In this study, Box type Solar Cooker with single Booster Reflector has been modeled and designed using Ansys 19.0, Constructed, and experimentally tested under the weather conditions of Maiduguri. For the first time, the characteristics of wax as the PCM in a Solar Box Cooker were investigated within the study area. Experiments were performed and the influence of the different boundary conditions was investigated for the experiments. From the experimental results of the designed solar cooker and the simulated results were compared and the error found was within 5% between the two results. The following Conclusions were drawn:

- The thermal efficiency of the solar cooker and the cooking times are found to depend strongly on the wax, the reflector, insulation, and the solar intensity.

- Wax can be used as a storage medium integrated with a Solar Box Cooker using Maiduguri weather conditions.
- Wax as a PCM can be regarded as a high efficiency material due to the amount of energy stored (4167.5Kj).
- It is obvious that the total Solar radiation on cloudy days is lower than that of the clear days; the solar cooker receives also reflected radiation from only a single reflector hence there is a possibility that high temperatures can be achieved by changing the amount of wax and incorporation of solar tracking system for further optimization.
- The use of TES medium (Wax) in Solar cooking within the test environment has the potential to reduce fossil fuel use and the release of CO<sub>2</sub> to the environment.

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