



Construction, Modeling and Simulation of Solar Box Cooker using Phase Change Materials (PCMs) for enhanced cooking method in Maiduguri, Nigeria

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ABSTRACT

Thermal energy storage (TES) systems provide several alternatives for efficient energy use and conservation. Phase change materials (PCMs) for TES are materials supplying thermal regulation at particular phase change temperatures by absorbing and emitting the heat of the medium. With abundant solar energy that can be tapped in Maiduguri from North East (NE) of Nigeria in average annual insolation of 755W/m^2 with temperature range as high as $38\text{-}45^\circ\text{C}$ the development of more efficient, cost effective and clean sources of energy has been an area of much research interest and technological development to fill the growing gap between energy supply and demand. Three phase change materials (PCMs), namely: Paraffin Wax, Palm Oil and Groundnut Oil were used as latent heat storage material in Solar Box Cookers (SBCs) with a single booster mirror for cooking during the day and at off-sunshine hours in Maiduguri Nigeria. ANSYS 19.0 simulation package was used to develop the SBC geometry and carry out numerical simulation while the Bureau of Indian Standards (BIS) was used to experimentally validate the numerical data. Paraffin Wax SBC F_1 and F_2 were found to be 0.13 and 0.44, Palm Oil SBC F_1 and F_2 were found to be 0.12 and 0.38 and Groundnut Oil SBC F_1 and F_2 were found to be 0.13 and 0.4 respectively qualifying all SBCs to grade 'A' based on the BIS evaluation standard. While the energy efficiencies were found to be: for Paraffin Wax SBC as (η) 33%, Palm Oil SBC efficiency (η) was 34% and Groundnut Oil SBC energy efficiency (η) was 32%. The simulated oven temperatures were experimentally validated and were found to agree within 5% error of mean for Paraffin Wax SBC (96°C and 98°C), 7% error of mean for Palm Oil SBC (96°C and 93°C) and 4% error of mean for Groundnut Oil SBC at 94°C and 91°C .

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INTRODUCTION

Today in the 21st century, about 2.7 billion people in developing countries

are facing energy poverty and rely on the burning of biomass for their primary cooking fuel as reported by the



International Energy Agency (2010). Some studies show that the number of people relying on this fuel for cooking will increase over the next twenty years unless new policies are introduced to mitigate its use (Shan *et al.*, 2014; Kumar, 2011). Cooking with biomass causes adverse consequences on health, the environment, social and economic development, currently, 1.5 million people, mostly women and children, are dying every year because of indoor air pollution from inefficient biomass combustion of cooking stoves, (IEA and WHO, 2010). With fossil energy nearing exhaustion as well as its green-house effect and air pollution being more severe, utilization of renewable energy technologies are increasingly gaining great importance, (Salah *et al.*, 2014 ; Zhou *et al.*, 2009).

Present day Maiduguri is populated with over 3.5 million people (SEMA, 2018). These include both household residents and those residing in the internally displaced person's camps (IDPs). The recent security challenge faced by the entire north-east (NE) with Maiduguri at the heart of the scourge has stressed the difficulty faced by the society in search of energy particularly for cooking and other household uses (Maina *et al.*, 2016).

Several attempts were made to increase the performance and efficiency of solar cookers developed and tested in Maiduguri and environs, (Abbas *et al.*, 2014; Ngala *et al.*, 2015; Musa *et al.*, 2016). 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, Maina *et al.*, (2016). Available literature on the use of solar box cooker within the study area (Maiduguri in North-Eastern Nigeria) has shown that no work with latent heat storage was carried out; as a result SBCs can

only be used during the day when the sun shines. The limitations in use of SBCs have affected their acceptance for use by the society; therefore, this study intends to bridge the gap (limitation) by using latent heat storage materials namely: Paraffin wax, Palm-oil and Groundnut-oil to extend the use of SBCs beyond sunshine period (off sunshine).

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).

MATERIALS AND METHODS

Experimental Material

Ansys 19.0 simulation package was used to generate the SBC Model geometry with thermal energy storage using different PCMs (Paraffin wax, Palm-oil and Groundnut-oil) for numerical analysis, while design and construction of solar box Cooker with thermal energy storage tank having manual tracking device was also carried out using appropriate empirical formulae and locally available material. Meteorological information of the study area (ambient conditions, solar radiation, wind speed, humidity etc.) was obtained from Nigerian Meteorological Agency (NIMET) and made use of in analysis of the SBC. The performance parameters of SBC with the three (3) different PCM candidates had also been investigated while Procedural testing of the solar box cooker (SBC) was carried out using the Bureau of Indian standard (BIS). Respective equations were used to deduce first figure of merit (F_1) and second figure of merit (F_2), with thermal cooker efficiency (η) of the solar box cooker as well as compare the figures of merit with BIS standards to deduce the classes of the SBCs.

SOLAR BOX COOKER SYSTEM

The block diagram of the cooking setup is shown in fig 2.1. This consists of mainly a single reflector, the glazed surface (receiver), outer box, inner box shown in fig 2.2(a), PCM Storage Tank (rectangular or slab model) shown in fig 2.2(b). The energy extracted from the sun is stored in the storage tank. Energy from sun is absorbed by the receiver depending on the insolation. This is utilized to raise the temperature of

the air that is being circulated convectively within the cooking chamber and the PCM in the tank. The average temperature of the PCM in the tank increases gradually as temperature in the chamber is being risen by the input solar power. Heat gets transferred to the load by air losing its temperature. If this energy is not sufficient, the remaining energy for cooking is supplied directly from thermal storage source (fig 2.2b).

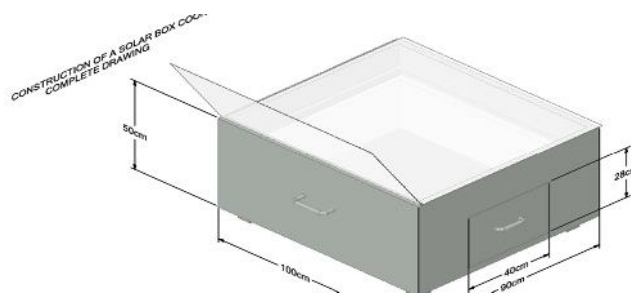


Fig 2.1: Solar Box Cooker (SBC) with single Booster Mirror

METHODS

Modeling

Design and modeling of the SBC structure with single booster mirror (fig 2.1) was performed using Ansys Space Claim Design Modeler (SCDM). The model of the system is proposed in order to predict its dynamic behavior. This can be used to predict the behavior of the system for different input parameters. Different techniques have been adapted to model solar cooking systems. Basic types of cookers like the box type are modeled using mathematical model based on direct heat

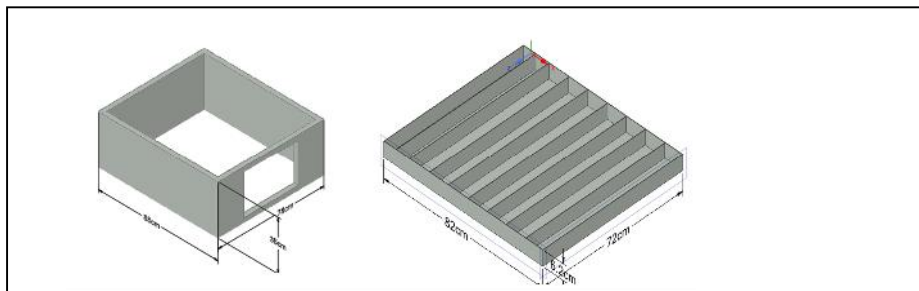
balance equations as reported by Garg *et al.*, (1983). Therefore, Ansys 19.0 Simulation tool is used in this study to obtain quasi-steady simulation model of the solar thermal systems using different phase change materials (Paraffin Wax, Palm oil and Groundnut oil) where partial differential equations are solved for this solar box cooker, the Model equations employed are simple equations with closed form solutions that are easily solved allowing one to calculate and predict the internal temperature of the cooker cavity.

fig 2.2 (a) Innera Box

(b) Rectangular model TES Tank

Modeling Assumptions and Boundary

Conditions





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. 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.

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. 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

(Nussbaumer, 2003). 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 (1):

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

Where, h_f is the local heat transfer coefficient of air ($\text{W/m}^2\text{K}$), 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 approximately $13.0 \text{ W/m}^2\text{K}$ (Birds *et al.*, 2001).

Model Equations

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

$$\frac{\partial k}{\partial t} + (U_j) \frac{\partial k}{\partial t_j} = V_T \left[\left(\frac{\partial (U_j)}{\partial t_j} + \frac{\partial (U_j)}{\partial t_i} \right) \frac{\partial (U_j)}{\partial t_j} \right] - s k \dot{S} + \frac{\partial}{\partial t_j} \left[\left(V + \frac{V_T}{t_k} \right) \frac{\partial k}{\partial t_j} \right] \quad (2)$$



$$\frac{\partial \dot{S}}{\partial t} + (U_j) \frac{\partial \dot{S}}{\partial t_j} = r \frac{\dot{S}}{k} V_T \left[\left(\frac{\partial (U_j)}{\partial t_j} + \frac{\partial (U_j)}{\partial t_i} \right) \frac{\partial (U_i)}{\partial t_j} \right] - s \dot{S}^2 + \frac{\partial}{\partial t_j} \left[\left(v + \frac{V_T}{\tau_s} \right) \frac{\partial \dot{S}}{\partial t_j} \right] \quad (3)$$

Where $\frac{\partial}{\partial t}(U)$ describes infinitesimal linear energy flow with respect to time in (i) and (j) directions, $\frac{\partial \omega}{\partial t}(U)$ describes infinitesimal angular energy flow with respect to time in (i) and (j) directions and the turbulent viscosity is calculated from $V_T = \frac{K}{S}$.

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 (Andersson *et al.*, 2009)

With steady state airflow within the box cooker, the heat transfer mechanisms are described mathematically by the equations of mass conservation, eqn.4, (continuity equation), momentum conservation, eqn. 5 (navier–stokes equation) and energy conservation, eqn.6

Mass conservation (continuity equation) is given in eqn 4:

$$\frac{\partial \dots}{\partial t} = - \left(\frac{\partial}{\partial t} \dots v_t + \frac{\partial}{\partial y} \dots v_y \right) \text{-----} (4)$$

Where $\frac{\partial}{\partial t}$ is the partial derivative of energy density with respect to time along x, y, directions

Momentum conservation (Navier- stokes equation) is given in eqns 5 and 6

$$\begin{aligned} \frac{\partial}{\partial t} \dots v_t &= - \left(\frac{\partial}{\partial x} \dots v_x v_x + \frac{\partial}{\partial x} \dots v_y v_x \right) - \left(\frac{\partial}{\partial x} \tau_{xx} + \frac{\partial}{\partial x} \tau_{yx} \right) - \frac{\partial p}{\partial x} + \dots g_x \\ \frac{\partial}{\partial t} \dots v_y &= - \left(\frac{\partial}{\partial x} \dots v_x v_y + \frac{\partial}{\partial x} \dots v_y v_y \right) - \left(\frac{\partial}{\partial x} \tau_{xy} + \frac{\partial}{\partial x} \tau_{yy} \right) - \frac{\partial p}{\partial y} + \dots g_y \end{aligned} \text{-----} (5)$$

Energy conservation is given in eqn 6:

$$\begin{aligned} \dots c_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} v_y \frac{\partial T}{\partial y} \right) &= k \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] + 2 - \left[\left(\frac{\partial v_x}{\partial x} \right)^2 + \left(\frac{\partial v_y}{\partial y} \right)^2 \right] \\ &+ - \left[\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right)^2 \right] - \frac{2}{3} \left[\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} \right] \end{aligned} \text{-----} (6)$$

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: Thermo-Physical Properties of Material in Use (20-25°C)

Material	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	T_M (°C)	ϵ	LHF(Kj/kgk)
plywood	850	1.250	0.150	-	0.8	-
Mirror	1.19	-	6.7	-	-	-
aluminum	2707	896	229	-	-	-
glass	2700	840	0.76	-	0.94	-
air	0.7	1034	0.037	-	-	-
Saw Dust	210	0.00176	0.06	-	-	-
Paraffin Wax	900	2.9	0.2	-	-	189
Palm oil	890	1.692	0.1726	35	-	185
Groundnut oil	920	2.000	3	-	-	187

Source: Maina *et al.*, (2016)

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PERFORMANCE ANALYSIS

PCM Heating Power

From performance point of view every element of a solar cooker has significant importance and directly affects its performance in any climate conditions (Saxena *et al.*, 2011). In order to compare the characteristic of different types of (PCM) solar box cookers, power and efficiency, the average heating power of the PCM used in solar box cooker can be calculated as follows

$$Q_{PCM} = M_{PCM} [C_{PCM} (T_m - T_a) + L + C_{PCM} (T_{PCM} - T_m)] \quad (7)$$

Where Q_{PCM} is heat stored by PCM (Kj), M_{PCM} is mass of PCM (kg), C_{PCM} is specific heat of PCM (Kj/kg°C), T_m is melting temperature of PCM (°C), T_{PCM} is temperature of PCM at 4:00pm (°C) and L is latent heat of fusion of PCM (Kj/Kgk).

To assess the actual performance of box type solar cooker, two figures of merit, i.e., F_1 and F_2 are to be calculated according to the Bureau of Indian Standards (BIS).

First of figure of merit (F_1): is the ratio of optical efficiency to the heat loss factor by the bottom absorbing plate and is a measure of the differential temperature gained by the absorbing plate at a particular level of solar insolation. The second figures of merits F_2 , is more or less independent of climatic conditions and gives an indication of heat transfer from the absorbing plate to the water in the containers placed on the plate (Kumar *et al.*, 2011). First figure of merit F_1 is determined by stagnation test at no load conditions and it is expressed mathematically as in (8):

$$F_1 = \frac{\eta_0}{U_L} = \frac{(T_p - T_\infty)}{H_s} \quad (8)$$

Where, T_p , T_∞ and H_s are stagnation plate temperature, average ambient temperature and intensity of solar radiation respectively

Second figure of merit (F_2) is to be obtained with full load conditions and is mathematically expressed as follows:

$$F_2 = \frac{F_1 (M_w) w}{A(t_1 - t_2)} \ln \left[\frac{1 - \left(\frac{T_{w1} - T_\infty}{F_1 I_a} \right)}{1 - \left(\frac{T_{w2} - T_\infty}{F_1 I_a} \right)} \right] \quad (9)$$

Where, F_1 is first figure of merit (Km^2w^{-1}), M_w is the mass of water as load (kg), C_w is the specific heat capacity of water (J/kg°C), T_∞ is the average ambient temperature (°C), I_a is the average solar radiation incident on the aperture of the cooker (W/m^2), T_{w1} is the initial water temperature (°C), T_{w2} is the final water temperature (°C), A is the aperture area (m^2) and t is the time difference between T_{w1} and T_{w2} (s). The higher value of factors F_1 and F_2 is desirable for better cooker. The value of water temperature T_{w2} should be in the range of 90–95°C. The initial water temperature T_{w1} can be selected at same value midway between the ambient and the boiling point temperatures (Mohammed, 2000).

Energy efficiency of the solar cooker: is the ratio of energy output to the energy input of the cooker and it is calculated as follows:

$$\eta = \frac{E_o}{E_i} = \frac{M_w C_p (T_w - T_{wi})}{I_t \cdot t \cdot A_{sc}} \quad (10)$$

Where η is energy efficiency, M_w is water mass, C_{pw} is specific heat capacity of water, T_{wf} is final temperature of water, T_{wi} is initial temperature of water, t is time, I_t is total instantaneous solar radiation and A_{sc} is intercept area of solar cooker.

RESULTS AND DISCUSSIONS

Stagnation Temperature Test

Figs. 3.1, 3.2 and 3.3 show the results of stagnation temperature tests under no load condition for all the three SBCs carried out concurrently on the 7th

Dec, 2019. Fig.3.1 shows the result of wax TES solar box cooker, the figure reveals the variation in the solar radiation and its effects on ambient temperature, oven temperature and plate temperature. Oven maximum temperature of 118°C with ambient maximum temperature of 33°C was observed at 11:45am with corresponding insolation of 915 W/m². The figure further shows plate maximum temperature of 135.7°C was achieved at 12:30 pm while stagnating at 135.1°C between 10:45am to 1:30pm with average solar radiation of 811 W/m² on the test day.

The average ambient temperature for the test day was 33°C being cloudy with intermittent rainfall (7th Dec, 2019). F_1 was deduced based on Eqn. (8) and was found to be 0.13 this value qualifies the SBC as grade A Cooker in accordance with the criteria set by BIS. The result shows that heat loss from absorber plate of the SBC was minimal and the absorber plate temperature increases irrespective of the fluctuations in solar radiation due to cloud cover, the findings are similar to the work of Mohammed *et al.*, (2013).

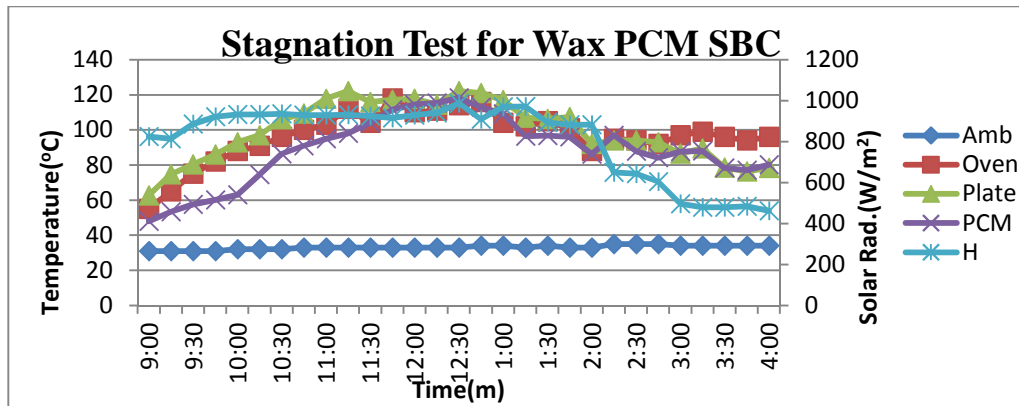


Fig 3.1: Thermal performance under Stagnation Test for Paraffin Wax PCM SBC (7th Dec, 2019)

The behavior of paraffin wax (PCM) to a varying solar insolation was also displayed under no load condition in fig 3.1. Maximum PCM temperature of 118.3°C was attained by 12:30pm to a corresponding insolation of 988W/m² while stagnating between 104°C and 109°C between 11:30am to 1:00pm. At the end of the test by 4:00pm PCM temperature of 80.2°C was recorded showing significant heat storage for off sunshine discharge.

Fig. 3.2 shows the results of stagnation temperature tests under no load condition for palm oil (PCM) TES solar box cooker. The figure reveals the variation in the solar radiation and its effects on ambient temperature, oven temperature,

plate temperature and the phase change material used as the TES (palm oil). The figure shows that maximum oven temperatures of 115°C with ambient maximum temperature of 34°C were achieved at 1:30 pm with corresponding insolation of 894 W/m², it has also established that oven temperature stagnates between 100°C and 115°C from the hours of 10:45am to 1:30pm. The plate maximum temperature of 128.7°C was achieved at 12:45 pm while stagnating from 103°C to 128°C between 10:15am and 1:45pm as shown in the figure with corresponding average solar radiation of 811 W/m² in the test day. F_1 was deduced based on Eqn. (8) and was found to be 0.12.

This value qualifies the SBC as grade A by BIS.
 Cooker in accordance with the criteria set

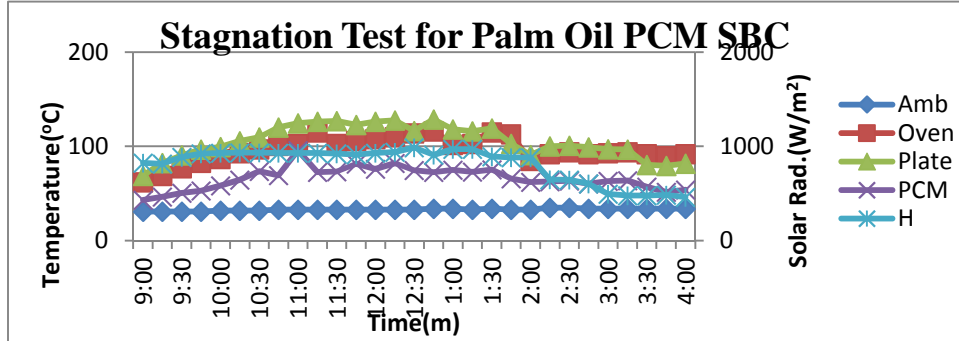


Fig 3.2 Thermal performance behavior of Palm Oil PCM SBC (7th Dec 2019)

Fig 3.2 further shows maximum PCM temperature of 131°C attained by 12:30pm to a corresponding insolation of 988W/m². The Palm oil PCM temperature stagnates from 105°C to 131°C between 10:45am and 2:30pm. At the end of the test by 4:00pm PCM temperature of 88°C was recorded showing appreciable heat storage for off sunshine discharge.

Fig. 3.3 show the results of stagnation temperature tests under no load condition for Palm oil (PCM) TES SBC, at the beginning of the temperature reading by 9:00am ambient temperature was recorded to be 31°C while oven temperature was 60°C with corresponding solar radiation of 825W/m². Oven temperature was raised to 102°C after 7200 seconds (2hrs) by

11:00am. The oven temperature varies between 102°C and 115°C for almost 3hrs (11:00am to 1:45pm) and later dropped to 93°C at the end of the test by 4:00pm with declining insolation. The figure further shows the maximum plate temperature attained during the test as 124°C by 12:45pm while the temperature was stagnating between 101°C to 124°C from 10:30am to 4:00pm when the last temperature was recorded to be 105°C. An average plate temperature of 105.9°C was maintained throughout the test period. F_1 was deduced based on Eqn. (8) and was found to be 0.13 qualifying the SBC as grade A Cooker in accordance with the criteria set by BIS.

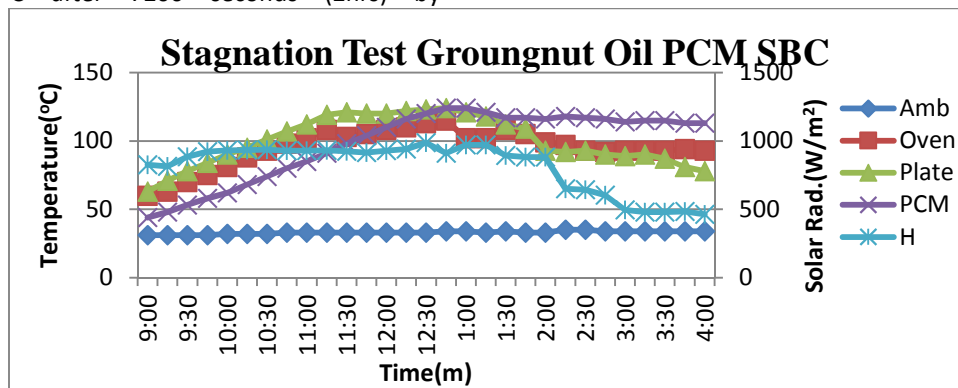


Fig 3.3: Thermal performance behavior of Groundnut Oil PCM SBC (7th Dec, 2019)

PCM thermal behavior for Groundnut oil SBC was also presented in fig. 3.3 where highest temperature of 137°C was attained by 2:15pm and dropped to 132°C at the end of the test. PCM average temperature of 105°C was maintained throughout the test period while highest insolation of 988 W/m² was recorded at 12:30pm on the test day. 137°C was a significant temperature stored by the PCM during charging while the last record of 132°C by 4:00pm will be a good point for discharging immediately after solar declination.

Water Boiling Test

The water boiling test experiment was carried out during the cloudy days of December (10th Dec, 2019) concurrently for all the three SBCs from morning through the evening hours (9:00am to 4:00pm). The Solar box cookers under full load (1kg water) condition were able to provide a hot environment adequate for cooking most food items and maintaining its hotness/warmness for long hours after completion of cooking as shown in Figs. 3.4, 3.5 and 3.6 respectively.

Water Boiling Test for Wax (PCM) SBC

The highest oven temperature of 131°C was attained by the Wax PCM SBC at 12:30 with corresponding insolation of 861

W/m² and maximum plate temperature of 124.1°C with corresponding solar radiation of 876W/m² during the boiling test at 12:15pm as shown in Fig. 3.4. Plate temperature was maintained at 124°C from 11:45am to 12:45pm when most food items can be cooked at 75°C as reported by Dormanski (1995). Maximum Temperature of 108.1°C was attained by the PCM (Wax) at 12:15 and 99°C by 4pm showing appreciable heat storage with declining solar radiation, water was found boiled at this condition. The amount of energy stored by the PCM (Wax) was determined using Eqn. (7) to be 4167.5 KJ an amount much higher than that obtained by Dormanski 1995; Yuksel and Avci 2010 showing that the Cooker can also be used to get other food items cooked through the night at off Sun-shine hours due to the heat storing capacity of the PCM under the prevailing weather conditions. Accordingly, the overall SBC Energy efficiency with Wax as PCM was found to be 31% using Eqn. (10). The maximum pot temperature during the water boiling test was 99.5°C attained by 1:45pm with corresponding insolation of 851 W/m² while F₂ was deduced to be 0.44 using Eqn. (9) above the minimum value of 0.4 set by BIS for proper assessment of SBCs.

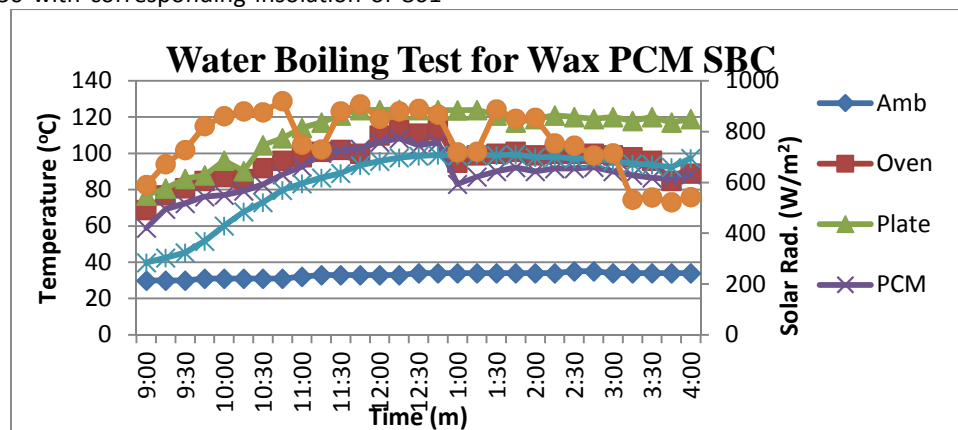


Fig 3.4: Thermal performance behavior of Wax PCM SBC (10th Dec, 2019)

The results of thermal performance of Palm oil PCM Solar Box Cooker under load (1kg water) condition were as recorded in fig. 3.5. The Figure shows the maximum oven temperature of 107°C attained by the SBC at 1:30pm with corresponding insolation of 880 W/m² while maximum plate temperature of 116.9°C with corresponding solar radiation of 868W/m² was recorded by 12:45pm as shown. Plate temperature was maintained above 100°C from 11:00am to 2:30pm when most food items can be cooked at 75°C as earlier reported by Dormanski

(1995). Maximum PCM temperature of 123°C was attained by 12:30pm and at the end of the test by 4pm, temperature of 101°C was recorded showing commendable heat storage despite declining solar radiation and water was found boiled and kept hot. The amount of energy stored by the PCM (Palm oil) was determined using Eqn. (7) to be 383.3KJ an amount much lower than that obtained by Dormanski (1995); Yuksel and Avci (2010), Accordingly, the overall SBC Energy efficiency with Palm oil PCM was found to be 33% using Eqn. (10).

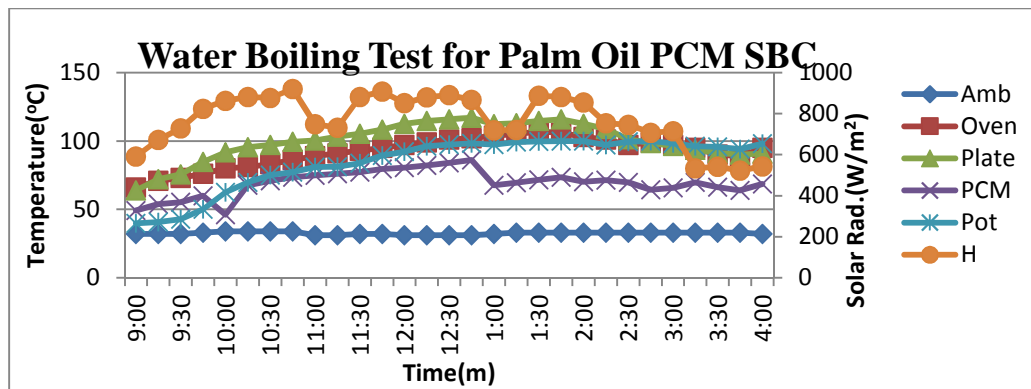


Fig 3.5: Thermal performance behavior of Palm Oil PCM SBC (10th Dec, 2019)

The pot temperature maintains between 92°C to 100°C up to the end of the test by 4:00pm when the last record was 98°C. Pot average temperature of the SBC was 85°C throughout the test while F₂ was found to be 0.38 using Eqn. (9) below the minimum value of 0.4 set by BIS for grade “A” cookers in the proper assessment of SBCs.

The Groundnut PCM Solar box cooker under full load (1kg water) condition was able to provide a hot environment adequate for cooking most food items and maintaining it hotness/warmness for long hours after completion of boiling as shown in Fig. 3.6. The highest oven temperature of 132°C was attained by the box cooker at 1:30pm with corresponding insolation of

888W/m² and maximum plate temperature of 125°C with corresponding solar insolation of 891W/m² at 12:30pm. Plate temperature was raised to 101°C from 10:30am and the temperature was maintained above 100°C up to the end of the test by 4:00pm when 118°C was recorded while an average plate temperature of 111.5°C was maintained throughout the test period. The maximum temperature attained by the PCM (Groundnut oil) at 2:45 was 142°C showing appreciable heat storage with declining solar radiation (707W/m²). The amount of energy stored by the PCM (Groundnut oil) was determined based on Eqn. (7) and was found to be 307 KJ showing that the Cooker can also be used to get other food items

cooked through the night at off Sun-shine hours under the prevailing weather conditions. Accordingly, the overall SBC

energy efficiency was found to be 32% using Eqn. (10)

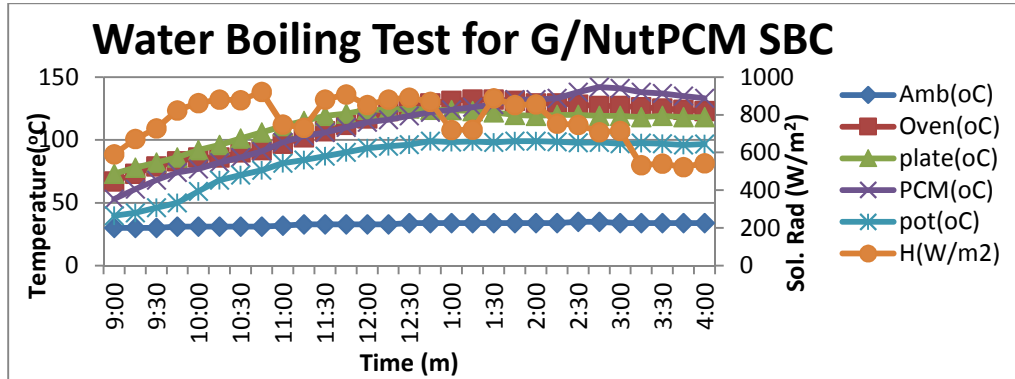


Fig 3.6: Thermal performance behavior of Groundnut Oil PCM SBC (10th Dec, 2019)

The maximum pot temperature during the water boiling test with Groundnut oil PCM SBC is as shown in fig 3.6 and it was recorded to be 99.1°C attained by 12:45pm at a corresponding insolation of 868 W/m² while F₂ was found to be 0.4 using Eqn. (9) equals the minimum value of 0.4 set by BIS as grade “A” cooker for proper assessment of SBCs.

Night Cooking Test

Figs 3.7 to 3.12 were the results of night cooking tests using the three respective SBCs, where 1kg of rice and 1kg of beans were cooked between the hours of 5:00pm to 8:00pm on the 13th and 15th of Dec, 2019. The figures showed similar thermal behaviours as it was observed that the PCM temperature reduces while plate and pot temperatures increases. The absence of solar insolation during off-sunshine reduces energy inflow to the SBC hence the reverse of stored energy flow

from the PCM to the pot through the plate.

Night Cooking Test Wax PCM SBC

Fig 3.7 recorded the highest plate temperature of 134°C, while oven and pot temperature recorded highest temperature of 115°C and 107°C by 8:15pm respectively after about 26.5% heat discharge by PCM (136°C to 100°C) This results affirm the report of Sharma et al., (2000) in his design and development of a cylindrical PCM storage unit for a solar cooker that “PCM melting temperature should be in the range of 105°C to 110°C for night cooking”. Fig 3.8 describes the beans cooking test where highest plate temperature of 129°C was recorded at 8:15 pm while oven and pot temperature were 110°C and 100.3°C by the same time respectively. During both cooking tests it was observed that PCM has discharged appropriately as both food items were cooked at off-sunshine period with average temperature of 118°C.

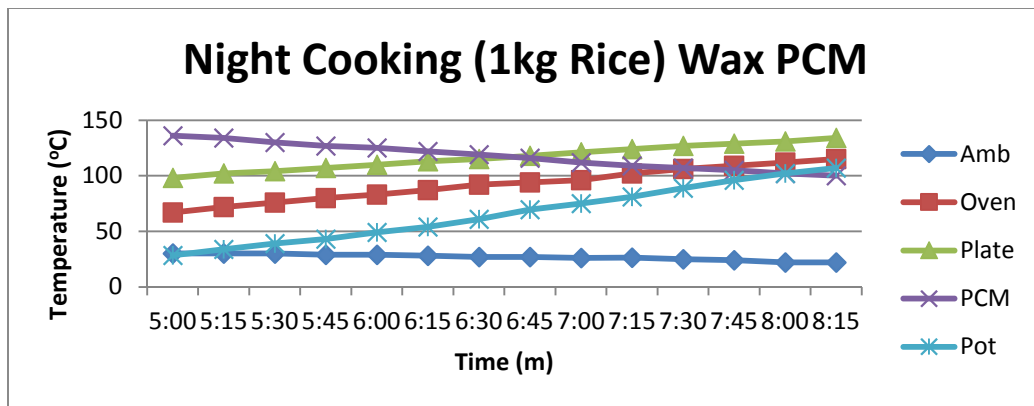


Fig 3.7: Temperature variation during discharge period of Wax PCM when cooking 1kg of Rice at off-sunshine hours on the 13th of Dec, 2019

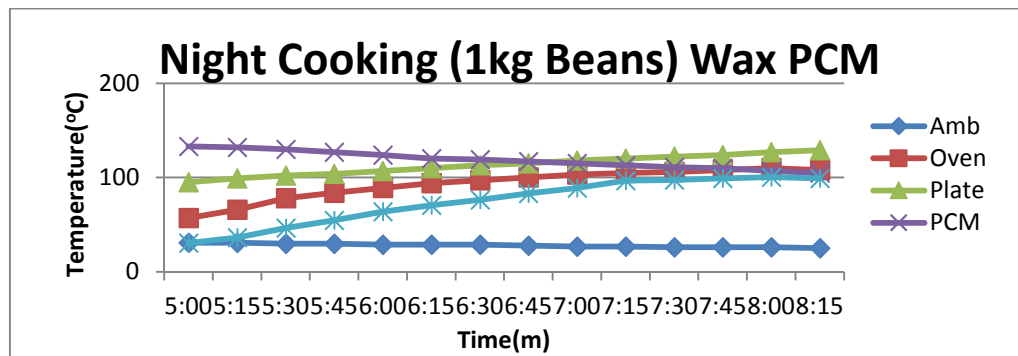


Fig 3.8: Temperature variation during discharge period of Wax PCM when cooking 1kg of Beans at off-sunshine hours on the 15th of Dec, 2019

Night Cooking Test for Palm oil PCM SBC

Figs 3.9 and 3.10 reported the various results of the component parts of the Palm Oil PCM SBC as recorded during the night cooking experimentation. During rice cooking average oven temperature of 89°C was observed from 5:00pm to 8:15pm while highest temperature was recorded as 131°C, plate temperature rosed from 62°C to 131°C between 5:00pm to 8:00pm as a result of heat transfer from the TES tank (discharging) as energy source to heat up the oven in absence of Solar radiation. Pot and PCM temperatures were recorded to have 72°C and 115.7°C as average

temperatures between 5:00pm and 8:00pm with highest PCM temperature of 130°C by 5:00pm immediately after solar declination (13th Dec,2019). The average oven temperature was well over 75°C that was the minimum temperature required for cooking most food items, Dormanski (1995). Fig. 3.10 highlights the thermal performance of the Palm oil PCM SBC during Beans cooking at off-sunshine period (5:00pm to 8:00pm). The oven temperature was recorded as 93°C as it average temperature while it rose from 55°C to 115°C from 5:00pm to 8:00pm. Highest plate temperature of 125°C was recorded

by 8:15pm while average plate temperature was 111.6°C whereas pot and PCM average temperature were measured as 114.7°C and

105°C with highest PCM temperature of 129°C by 5:00pm on the test day (15th Dec, 2019)

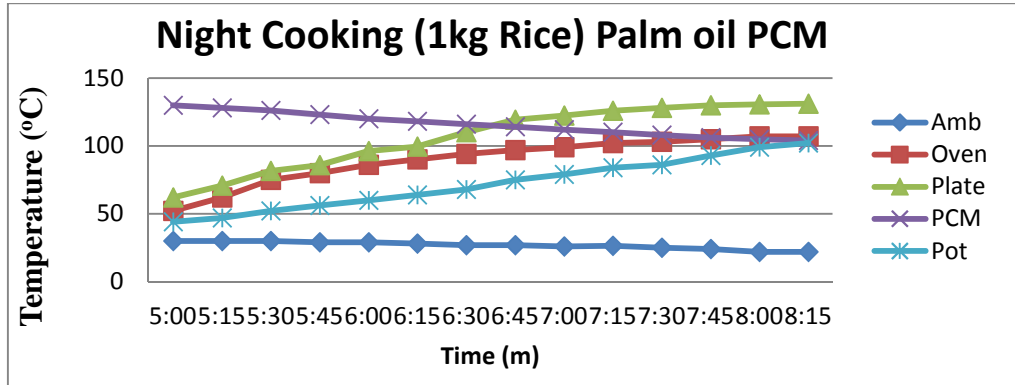


Fig 3.9: Variation of temperature during off-sunshine cooking (1kg Rice) with Palm oil PCM SBC (13th Dec, 2019)

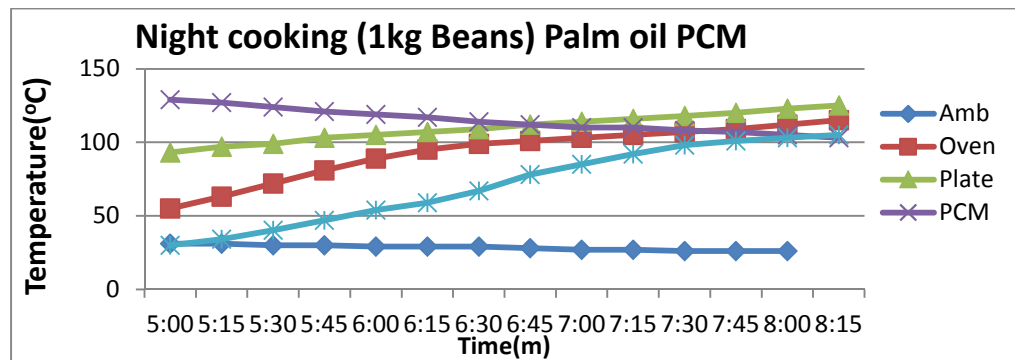


Fig 3.10: Variation of temperature during off-sunshine cooking (1kg Rice) with Palm oil PCM SBC (15th Dec, 2019)

Night Cooking Test G/Nut Oil PCM SBC

Figs. 3.11 and 3.12 show the various temperature profiles as recorded during the off-sunshine cooking test using Groundnut oil PCM SBC. In fig. 3.11 during rice cooking average oven temperature of 86.5°C was recorded between 5:00pm and 8:15pm while highest temperature was recorded as 107°C, plate temperature rosed from 62°C to 130°C between 5:00pm and 8:00pm as a result of heat transfer from the TES tank (discharging) as energy source to

heat up the oven in absence of Solar radiation. Pot and PCM temperatures were recorded to have 71°C and 117°C as average temperatures between 5:00pm and 8:00pm with highest PCM temperature of 131°C by 5:00pm immediately after solar declination (13th Dec, 2019). The average oven temperature was well over 75°C that was the minimum temperature required for cooking most food items, Dormanski (1995). Fig 3.12 shows the thermal performance of the Groundnut oil PCM SBC during Beans

cooking at off-sunshine period (5:00pm to 8:00pm). The average oven temperature was recorded to be 93°C as it average temperature while it ascends from 56°C to 113°C from 5:00pm to 10:00pm. Highest plate temperature of 131°C was recorded

by 10:00pm while average plate temperature was 111.6°C whereas the pot and PCM average temperature were recorded as 71°C and 117°C with highest PCM temperature of 133°C by 5:00pm on the test day (15th Dec, 2019)

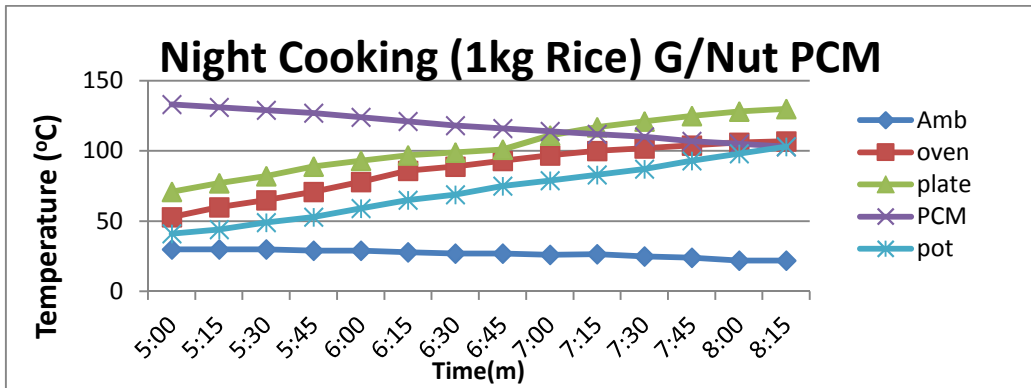


Fig 3.11: Variation of thermal curves during off-sunshine cooking (1kg rice) using Groundnut PCM SBC on the 13th of Dec, 2019.

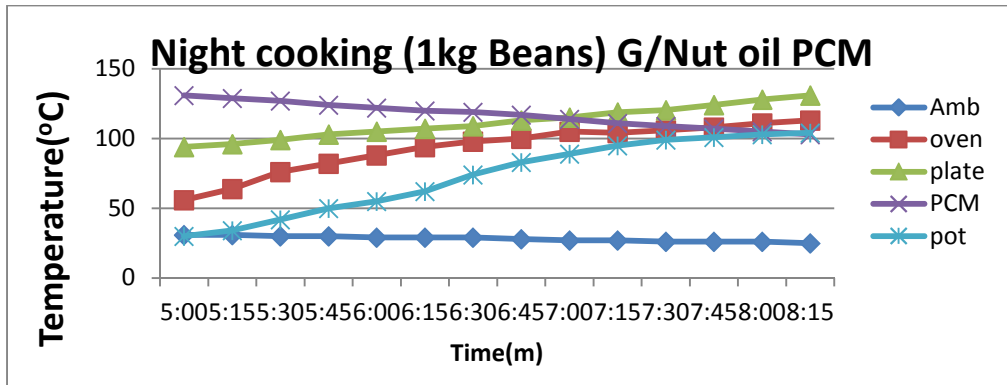


Fig 3.12: Variation of thermal curves during off-sunshine cooking (1kg beans) using Groundnut PCM SBC on the 15th of Dec, 2019..

Validation of Numerical Simulation with Experimental Data for Wax PCM SBC

Experimental and Numerical thermal curves of the solar box cooker (SBC) were drawn against each other in comparism as shown in fig. 3.13, it was observed that the temperature variation were in agreement within 5% error of mean when the analysis of variance (ANOVA) was carried out using SPSS with experimental

temperature having standard deviation of 14.23596 and mean error of 2.64355 while the numerical thermal curve generated a standard deviation of 15.06578 with mean error of 5.2915 for an average experimental and numerical oven temperature of 96°C and 98°C respectively which may be attributed to inexact boundary conditions that stands to be modified both analytically and numerically.

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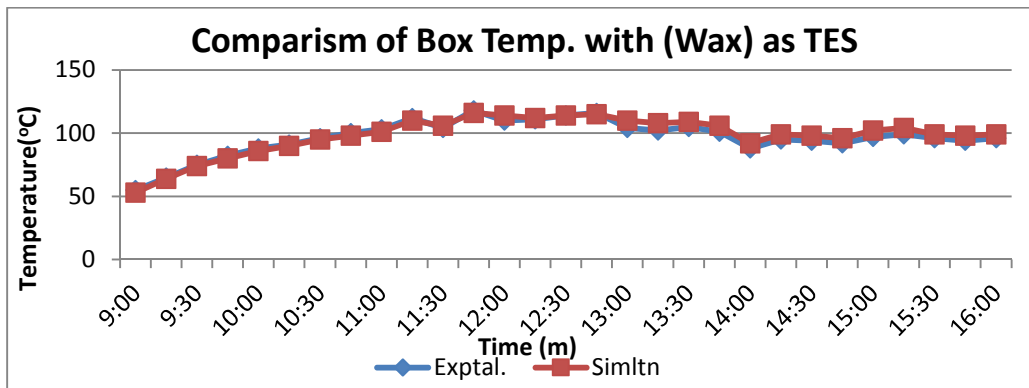


Fig. 3.13: Experimental and Numerical thermal performance Curves of SBC with Wax as TES

Experimental and Numerical thermal curves of the Palm oil (PCM) solar box cooker (SBC) were also drawn against each other in comparism as shown in fig. 3.14 the temperature variation with time were in close agreement within 7% error of mean when the analysis of variance (ANOVA) was carried out using SPSS with experimental temperature having standard

deviation of 13.51855 and mean error of 2.51033 while the numerical thermal curve generated a standard deviation of 14.84462 with mean error of 5.38516 for an average experimental and numerical oven temperature of 96°C and 93°C which may as well be attributed to inexact boundary conditions also.

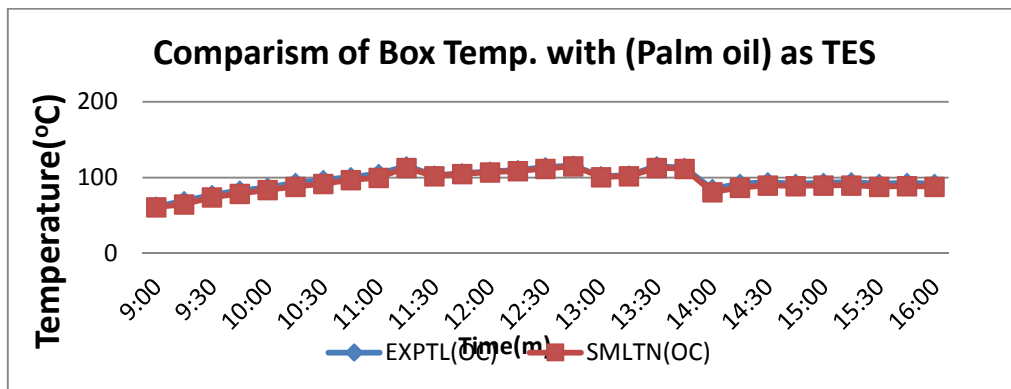


Fig 3.14: Experimental and Numerical thermal performance Curves of SBC With Palm oil PCM as TES

Experimental and Numerical thermal curves of the Groundnut oil (PCM) solar box cooker (SBC) were drawn against each other also for comparism as shown in fig. 3.15 the temperature variation with time were in close agreement within 4%

error of mean when the analysis of variance (ANOVA) was carried out with experimental temperature having standard deviation of 13.95012 and mean error of 2.59047 while the numerical thermal curve generated a standard deviation of 14.43931 with a mean

error of 5.38516 for an average temperature of 94°C and 91°C.
 experimental and numerical oven

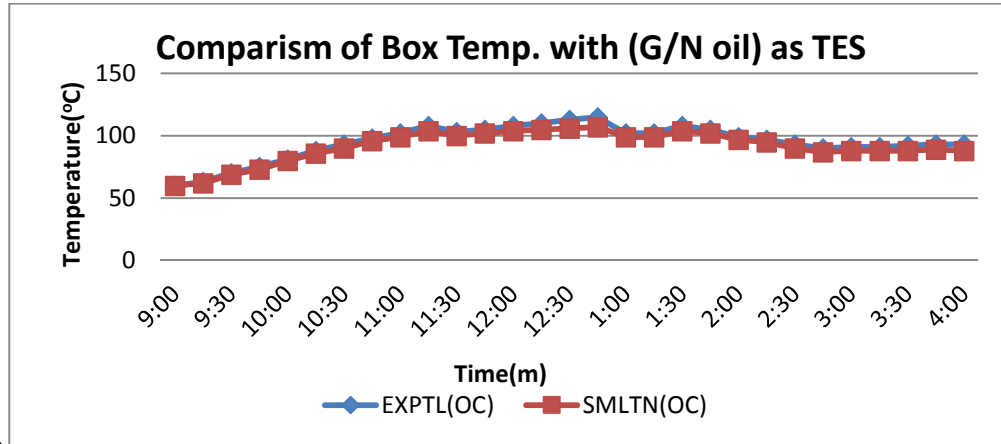


Fig. 3.15: Experimental and Numerical thermal performance curves of Groundnut oil PCM SBC.

CONCLUSION

The development of thermally responsive systems with high energy density for storing heat in a Solar Box Cooker (SBC) is a critical link between energy production and utilization in the effort to reduce overall energy demand. Phase change materials (PCMs) offer high energy storage capacity due to the latent heat storage. Three SBCs with different locally available Phase Change Materials (Paraffin Wax, Palm Oil and Groundnut Oil) were developed using ANSYS 19.0 Simulation Environment. The Bureau of Indian Standard for testing (SBCs) and reporting was used to experimentally establish the efficiencies of these SBCs. Numerical data of these SBCs were compared with the experimental result and it was found that they are in agreement within 3% error of mean. The study was used to identify the classes of the SBCs and the following conclusions were drawn:

1. SBCs using Latent Heat Storage media (Paraffin Wax, Palm Oil and Groundnut Oil) were developed based on the designed parameters and the following performance

parameters were obtained: Paraffin Wax SBC F_1 and F_2 were found to be 0.13 and 0.44, Palm Oil SBC F_1 and F_2 were found to be 0.12 and 0.38 and Groundnut Oil SBC F_1 and F_2 were found to be 0.13 and 0.4 respectively qualifying all SBCs to grade 'A' based on the BIS evaluation standard.

2. The modeling and Simulation of SBCs were carried out using the space claim Design (SCDM) modeler in Ansys 19.0 simulation environment, where SBC geometry was generated and simulation for Paraffin Wax SBC converged after 3475 iterations, for Palm Oil SBC converged after 2500 iterations and for Groundnut Oil SBC converged after 2725 respectively.
3. All the three SBCs were experimentally evaluated and the energy efficiencies were found to be: Paraffin Wax SBC overall energy efficiency (η) was 33%, Palm Oil SBC energy efficiency (η) was 34% and Groundnut Oil SBC energy efficiency (η) was 32% with



insignificant difference existing between them.

4. The simulated oven temperatures were experimentally validated and were found to agree within 5% error of mean for Paraffin Wax SBC (96°C and 98°C), 7% error of mean for Palm Oil SBC (96°C and 93°C) and 4% error of mean for Groundnut Oil SBC at 94°C and 91°C for experimental and numerical oven average temperatures.

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