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ORIGINAL RESEARCH ARTICLE

# DESIGN AND EXPERIMENTAL TESTING OF A SOLAR BOX COOKER WITH PARAFFIN WAX AS THERMAL ENERGY STORAGE USING MAIDUGURI WEATHER CONDITION

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ABSTRACT

*The performance of paraffin wax as phase change material (PCM) for thermal energy storage (TES) was investigated using a Solar Box Cooker (SBC) exposed to Maiduguri weather condition. Temperature and energy generated by SBC were experimentally established. The result shows tremendous improvement in energy storage compared to SBCs without TES in existence within Maiduguri and environs. The measured temperature and energy generated by the PCM in the experiment were 118oC and 4164.5KJ respectively, an adequate temperature and energy for cooking during off-sunshine hours and beyond. First figure of merit (F1) and second figure of merit (F2) were deduced to be 0.13 and 0.44 with overall SBC efficiency (η) of 63% qualifying the SBC to grade A based on the Bureau of Indian Standards (BIS)*



## 1.0 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 (Elsebaii et al., 2011).

Over the last century, many studies have been performed on the development of various types of solar cookers and on the evaluation of the performance and economic aspects of solar cookers. There have also been several attempts to increase the performance and efficiency of cookers in non-tropical regions (Oturanc et al. 2002). Different types of solar cookers (Box type, direct or concentrating type and indirect type) were modified and investigated by researchers (Elsebaii et al., 2011). Some researchers have investigated the performance of a solar cooker for possible use in different applications,

with modifications in outer-inner reflectors (Elsebaii, 1997); different insulating materials (Mishra et al., 1984 and Nahar, 2001), various booster mirrors (Mirdha and Dhariwal, 2008), absorber plate (Amer, 2003 and Harmim et al., 2010), a hybrid solar system (Prasanna and Umanand, 2011 and Nahar, 1993) 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). The use of a PCM results in shorter cooking times (Sharma et al., 2005). It is 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 (Elsebaii et al., 2009). Also, these PCM are rather expensive when high temperatures are concerned. In addition, Sharma et al. (2002) found that paraffin wax showed 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: highly sensitive heat capacity and heat of fusion, stable composition, high density and heat conductivity, chemical inert, non-toxic and non-inflammable, reasonable, and inexpensive (Sharma et al., 2009).

Several attempts have been made to increase the performance and efficiency of solar cookers developed and tested in Maiduguri and environs (Ngala et al., 2015). 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). Despite the enormous solar energy potential of Maiduguri solar cookers are not widely used. Available literature shows that no investigation dealing with PCM use in solar cooker has been carried out in the study area hence, this work intends to develop an experimental 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).

## 2 Materials and Methods

The design materials (parameters) considered included the energy requirements, daily average insolation, the Thermal Energy Storage Material (Paraffin Wax), ambient temperature and other thermo-physical properties of Paraffin Wax as highlighted in Table 1. The experimental temperature measurement was performed in selected points using The T-type thermocouples of Cu-Ni (Copper-Nickel) with a temperature range of 185°C to 300°C.

### 2.1 Design Considerations

The design parameters considered included the energy requirements, daily average insolation, and size of PCM container, ambient temperature and melting temperature of



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the PCM. The experimental temperature measurement was performed in selected points. At the wall surfaces: convective and radiative heat transfer conditions were applied to all outer walls and to the feeding glass (receiver). Heat flux to the wall was given by Bird et al. (2001) in eqn. 1 as:

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

where: hf is the local heat transfer coefficient of air (w/m$^2$k), Tw is the wall surface temperature (k), $T_f$ is the local air (fluid) temperature (k) and, qrad is the radiative heat flux (W/m$^2$). Air, which consists of nitrogen, oxygen, a 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 W/m$^2$k (Birds et al., 2001).

**Table 1:** Thermo-physical property of materials in use

| Material | ρ [kg/m$^3$] | cp [J/kgK] | λ [W/mK] | ε 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 | - | - | - | - |
| Paraffin Wax | 0.900 | - | 0.2 | 189 |

Source: Mishra et al. (1984)

### 2.2 Solar Box Cooker Description

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.

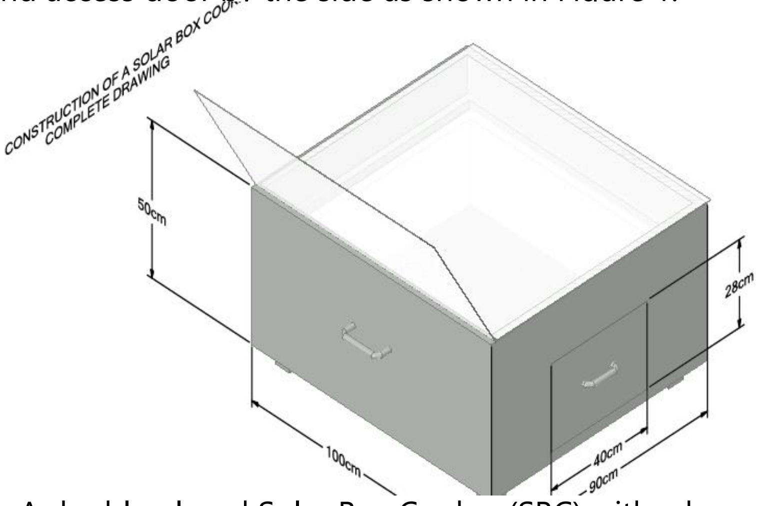
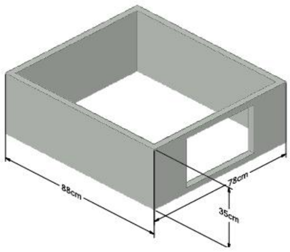



Figure 1: A double glazed Solar Box Cooker (SBC) with a booster mirror.

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 were 100 × 90 × 50 cm and those of the inner box are were 88 × 78 × 35 cm. Kundapur (2009) 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 in Maiduguri, Borno State Nigeria. The inner box was painted black for optimal heat absorption. The box geometry was designed and generated using Ansys Design modeler as shown in fig Figures 2 and 3 respectively.



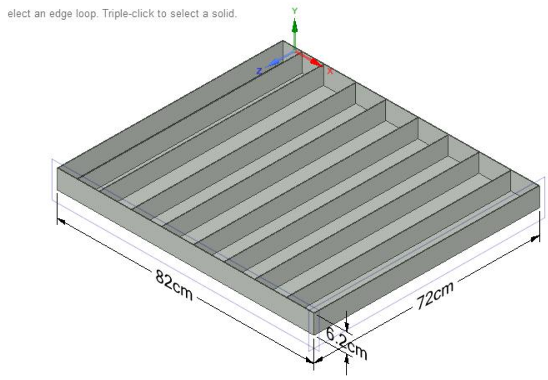




Figure . 2: 1nner Box Figure. 3: Thermal Energy Storage Tank

Experimental tests were conducted after constructing a physical model of the SBC as shown in fig Figure 4 under various weather conditions to determine the viability of using paraffin wax as TES. 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. 4: Box unit with PCM tank before and after glazing

## 3.0 Methods

Thermal performance tests were conducted under various weather conditions to determine the viability of using paraffin wax a phase change material (PCM) as TES, to evaluate the thermal performance of the solar box cooker in comparison with non-PCM box cooker used around Maiduguri environs. The measured parameters include temperature, solar irradiance and the wind speed. The cooking power tests were done according to the Bureau of Indian Standards, BIS (2000) as one of the best standards for the evaluation of Solar Box Cookers. All the measured parameters were recorded at intervals of ten minutes. According to Funk (2000) the ten minutes is long enough time



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that the minor fluctuations in heat loss due to ambient temperature and wind variability are expected to be negligible. Ten minutes is short enough time that the heat gain variability due to gradual sun angle changes may be considered constant during the interval. The T-type thermocouples of Cu-Ni (Copper-Nickel) with a temperature range of 185 °C to 300 °C were used to measure the temperature distribution inside the PCM storage unit, the temperature inside the cooking vessel, the absorber temperature and the ambient temperature. The SBC was operated under load and no-load situations to establish parameters for its evaluation.

## 3.1 Thermal Performance Tests

### *3.1.1 Stagnation Test*

A number of tests without load were conducted on the cooker to determine its stagnation temperature and also to check the rise in temperature inside the cooker. The stagnation temperature, ambient temperature ($T_a$) and absorber plate temperature ($T_p$) were measured for different times of the day between 09:00 am and 4.00 pm during the operation of the cooker using Type K, mineral insulated grounded junction, 1.6mm diameter thermocouple with Elix digital thermometer (LX-6500) capable of reading temperature between -50°C and 350°C. Thermo Anemometer (PROVA Instrument, AVM 01) was used to measure wind speed (v) and solar radiation was measured using global radiation meter (GRM 100).

### *3.1.2 Full Load Test*

The loading test was carried out by boiling different volumes of water-filled in cylindrical pot covered with a lid and placed inside the cooker. The test was conducted for three days with 1.0 kg of water on the first day, 1.5 kg of water on the second day and 2.0 kg of water on the third day. Each test was carried out on a relatively sunny day between 9:00 am and 4:00pm daily. The absorber plate temperature ($T_p$), ambient temperature ($T_a$), Oven temperature ($T_o$), water temperature ($T_w$), solar radiation ($H_s$) and PCM temperature were measured using the instrumentation described in section 2.3.2

## 3.2 Performance Measurement

The performance evaluation of the solar box cooker involved estimation of the following parameters: First figure of merit ($F_1$), Second figure of merit ($F_2$) and cooker's efficiency (ŋ).

### *3.2.1 First Figure of Merit*

The first figure of merit (F1) of a solar box cooker is defined as the ratio of optical efficiency (ŋo) and the overall heat loss coefficient (UL) as given by Purohit, 2009.

$$F_1 = \frac{\eta_0}{U_1} \quad (2)$$

Experimentally,

$$F_1 = \frac{T_{ps} - T_{as}}{H_s} \quad (3)$$

where: $T_{ps}$,(°C) $T_{as}$,(°C) and $H_s$ (W/m$^2$) are stagnation plate temperature, average ambient temperature and intensity of solar radiation, respectively.

### *3.2.2 Second Figure of Merit*

The second figure of merit ($F_2$) was evaluated under full load condition and can be represented by the expression given by Mohod (2011) as follows:

$$F_2 = \frac{f_1 M_w C_w}{A_t} In \left[ \frac{1 - \frac{1}{f_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{f_1}\left(\frac{T_{w2} - T_a}{H}\right)} \right] \quad (4)$$

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), Ta is the average ambient temperature (°C), H 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).

### *3.2.3 Cooker Efficiency*

The overall thermal efficiency of the solar box cooker was expressed mathematically by Khalifa et al. (2005) and Olwi (1993) and reported by El-sebaii (2005) as follows:

$$\eta = \frac{M_w C_w \Delta T}{I_{av} A_c \Delta t} \quad (5)$$

where: ŋu represents overall thermal efficiency of the solar cooker; $M_w$, mass of water (kg); $C_w$, Specific heat of water (J/kg/°C); ΔT, the temperature difference between the maximum temperature of the cooking fluid and the ambient air temperature (°C); $A_c$, the aperture area ($m^2$) of the cooker; Δt, time required to achieve the maximum temperature of the cooking fluid (s); $I_{av}$, the average solar intensity ($W/m^2$) during time interval Δt.

## 3. Results and Discussion

Various test results as highlighted earlier are presented below graphically and discussed to draw inferences for or against" based on facts and figures established by the study. These include the stagnation test, the load test and the cooker efficiency test.

### 3.1 Stagnation Temperature Tests

Figures 5 and 6 show the result of stagnation temperature tests under no load condition for wax TES solar box cooker. The figures reveal the variation in the solar radiation and its effects on ambient temperature, oven temperature and plate temperature. In Figure 5 Oven maximum temperature of 105°C and maximum ambient temperature of 36°C was recorded at 12:30 pm with corresponding insolation of 768 $W/m^2$. Figure 6 shows maximum plate temperature of 135.7°C was achieved at 12:30 pm while stagnating at 135.1°C between 10:45am to 1:30pm with corresponding average solar radiation of 770 $W/m^2$. The PCM (Wax) temperature was maintained despite drastic fall in solar radiation



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between the hours of 12; 45pm to 1; 30pm as shown in Figure 7. The average ambient temperature for the test day was 35°C being cloudy with intermittent rainfall (7th-15th July 2018). First figure of merit (F1) was deduced based on Eqn. 3 and was found to be 0.13 this figure qualifies the SBC as grade A Cooker in accordance with the criteria set by BIS. The result shows that heat loss from the 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).

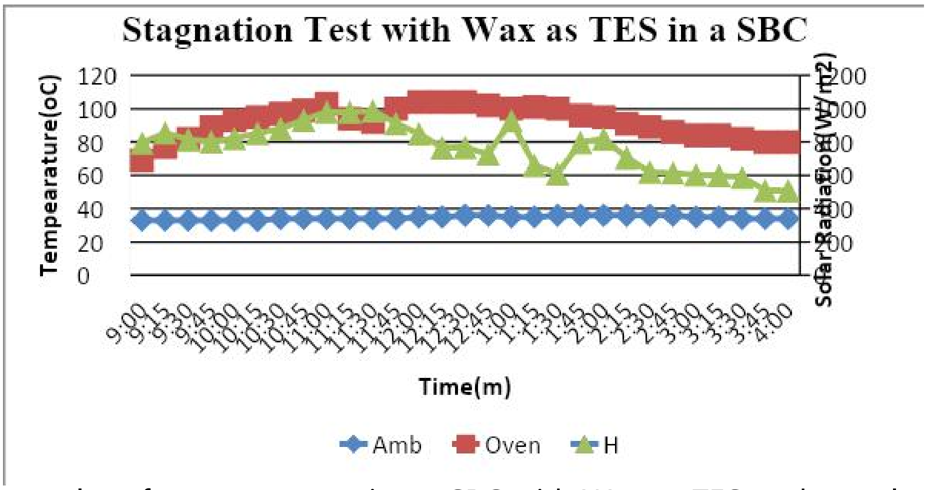


Figure 5: Thermal performance curve in an SBC with Wax as TES under no load condition in a test day showing ambient and oven temperature against corresponding solar radiation

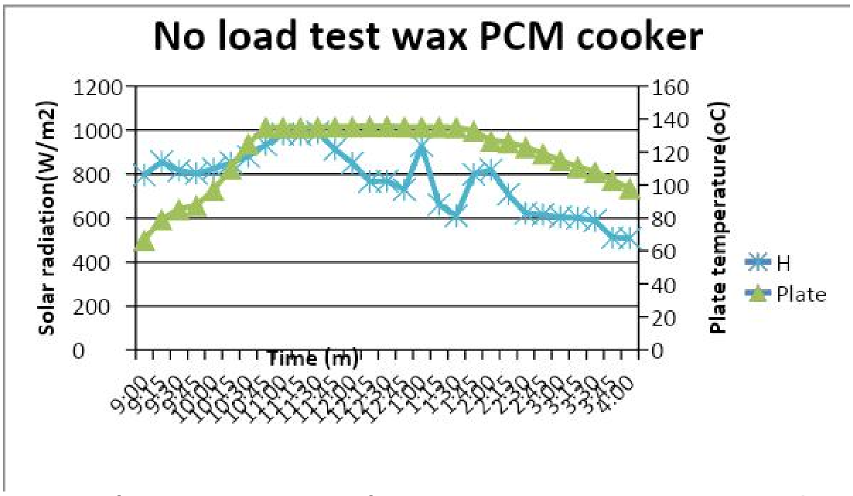


Figure 6: Thermal performance curve of plate temperature in SBC with Wax as TES in a test day

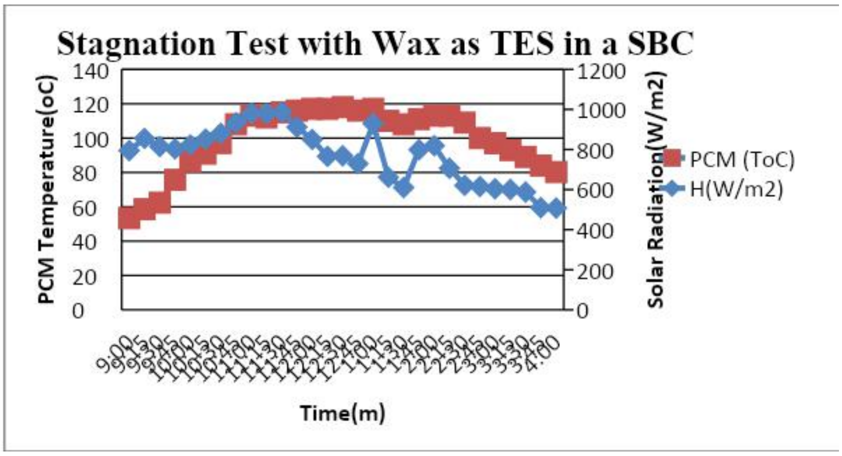


Figure 7: Thermal performance curve of PCM (Wax) temperature in SBC as TES in a test day

### 3.2 Full Load Test

The experiment was carried out during cloudy days of July (7th July 2018) in a rainy season from the morning through the evening hours (9:00am to 4:00pm) and the absorber's surface temperature increased with a single reflector (Booster Mirror) at an appropriate focusing angle. The Solar box cooker under full load condition was able to provide a hot environment adequate for cooking most food items and maintaining it hot/warm for long hours after completion of cooking as shown in Figure 8. The highest oven temperature of 131°C was attained by the box cooker at 12:30 with corresponding insolation of 861 W/m$^2$ and maximum plate temperature of 124.1°C with corresponding solar radiation of 876W/m$^2$ at 12:15pm as shown in Figure 9. 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 et al. (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 as shown in Figure 10. The amount of energy stored by the PCM (Wax) was determined to be 4167.5 kJ, an amount much higher than that obtained by Dormanski et al. (1995) and 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. Figure 11 shows the thermal behavior of pot due to a multifaceted heat gain existing in the SBC with adequate insulation to extend energy conservation and usage. Accordingly, the overall SBC efficiency with Wax as PCM was found to be 51% using Eqn. 5. However, higher efficiency may be achieved by modifying the thermal conductivity of wax and incorporation of solar tracking system, as demonstrated by Yuksel and Avci (2010). The maximum pot temperature during the water boiling test shown in fig. 11 was 98°C attained by 2:00pm with corresponding average insolation of 760 W/m$^2$; F2 was deduced to be 0.44 using Eqn. 4 above the minimum value of 0.4 set by BIS for proper assessment of SBCs as grade A SBC in terms of efficiency.



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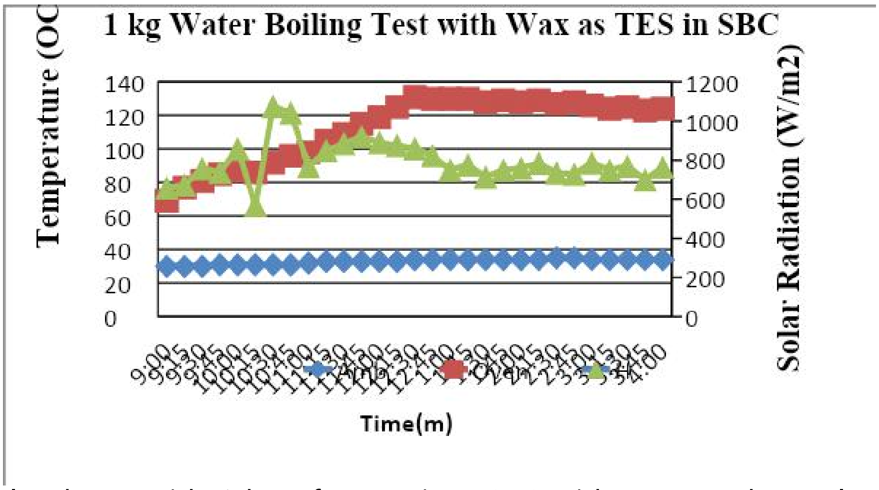


Figure 8: Full load test with 1 kg of water in a SBC with Wax as thermal energy storage showing ambient and oven temperatures against corresponding solar radiation in a test day

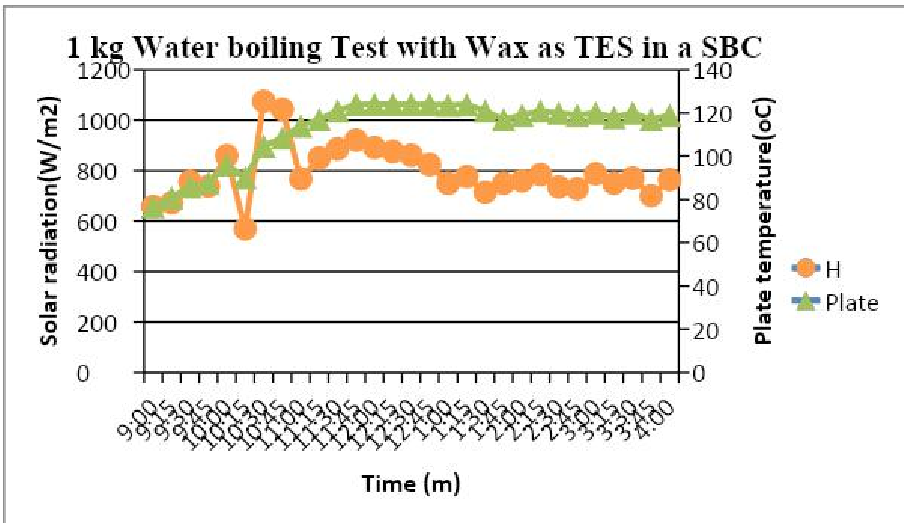


Figure 9: Full load test in a SBC with Wax as TES showing plate temperature behavior with corresponding solar radiation in a test day

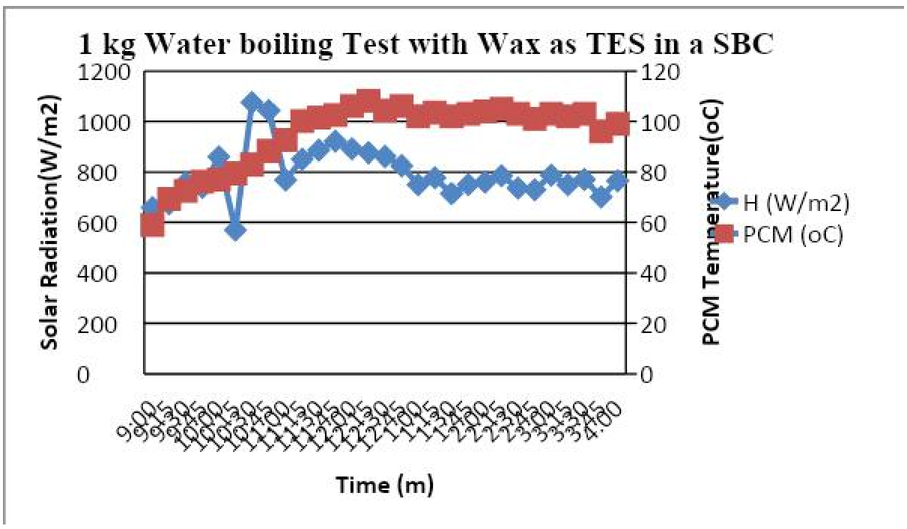


Figure 10: Full load test in a SBC showing PCM temperature behavior with corresponding solar radiation in a test day.

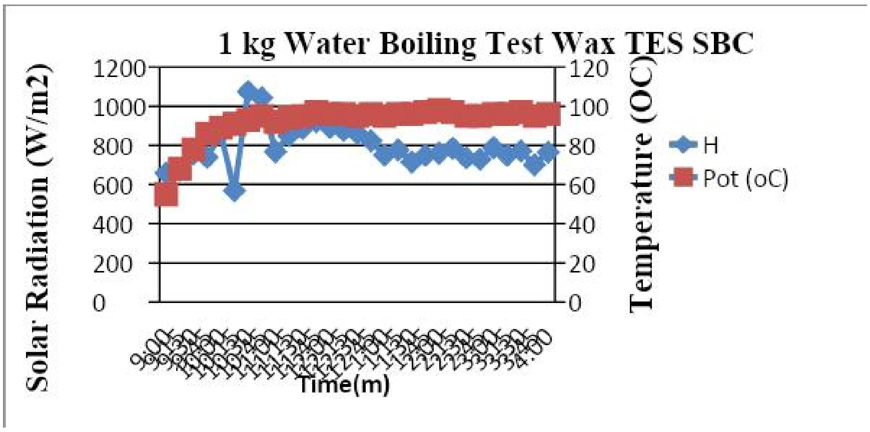


Figure 11: Thermal curve of Pot temperature in a SBC with Wax as TES.

**4.0 Conclusion**

In this study, the geometry of Box type solar cooker with single booster reflector was generated/ designed using Ansys 19.0, constructed, and experimentally tested under the weather conditions of Maiduguri. For the first time, the characteristics of wax as a PCM in Solar Box Cooker were investigated within the study area. Experiments were performed and the influence of different components was investigated from the experiments as shown in Figures 5 to 11. From the experimental results of the designed solar cooker 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 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.

It is also expected that an improvement in the cooker performance is possible with the choice of a storage unit, a PCM and the amount of radiation received from the sun looking at the present findings despite the intermittent solar radiation due to weather conditions during the test period.

The use of thermal energy storage in solar cookers play a pivotal role in a sustainable energy management based on solar energy as well as for energy conservation.

Solar cooking has the potential to reduce fossil fuel use and the release of $CO_2$ to the environment



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## References

Amer, EH. 2003, Theoretical and Experimental Assessment of a Double Exposure Solar Cooker Energy Conversion and Management, 44(16): 2651-2663.

Bird, RB., Stewart, WE. and Lightfoot, EN. 2001, Transport Phenomena, John Wiley & sons, Inc. (2nd Ed.) New York.

Bureau of Indian Standards (BIS) IS 13429:2000.

Domanski, R., El-Sabaii, AA. and Jaworsky, M. 1995. Cooking During Off-sunshine Hours Using PCM as Storage Media. Energy, 20(7): 607-616.

El-Sebaii, AA., Al-Heniti, S., Al-Agel, FAA., Al-Ghamdi, F. and Al-Marzouki, KK. 2011. One Thousand Thermal Cycles of Magnesium Chloride Hexahydrate as a Promising PCM for Indoor Solar Cooking. Energy Conversion and Management, 52(4): 1771-1777.

El-Sebaii, AA. 1997. Thermal Performance of a Box-Type Solar Cooker with Outer-Inner Reflectors. Energy, 22(10): 969-978.

El-Sebaii, AA., Al-Amir, S., Al-Marzouki, FM., Faidah, AS., Al-Ghamdi, AA. and Al-Heniti, S. 2009. Fast Thermal Cycling of Acetanilide and Magnesium Chloride Hexahydrate for Indoor Solar cooking. Energy Conversion and Management, 50(12): 3104–3111.

Funk, A. 2000. Evaluating the international standard procedure for testing solar cookers and reporting performance. Solar Energy, 68(1): 1-7.

Harmim, A., Merzouk, M. Boukar M and. Amar, M (2010), Design and experimental testing of an innovative building-integrated box type solar cooker. Solar Energy, 98, 422-433.

Khalifa, AMA., Taha, MMA. And Akyurt, M. 2005. Solar cookers for outdoors and indoors Energy, 10(7): 819–829.

Kundapur, A. and Sudhir, CV. 2009. Proposal for new world standard for testing solar cookers. Journal of Engineering Science and Technology, 4 (3): 272-281.

Maina, MB., Ngala, GM. and Abdulrahim, AT. (2016). Design, Fabrication and Performance evaluation of a Solar Brick Oven. International Journal of Engineering Research and Technology, 5(1): 176-182.

Mirdha, US. and Dhariwal, SR. (2008). Design Optimisation of Solar Cooker. Renewable Energy, 33(3): 530-544.

Mishra, RS., Sabberwal, J. and Prakash, SP. 1984, Evaluation of Solar Cooker Thermal Performance Using Different Insulating Materials. International Journal of Energy Research, 8 (4): 393-396.

Mohammed, IL, Ruma, UJ. and Abdulrahim, AT. (2013). Performance testing of a Truncated Pyramid Solar Thermal Cooker. Int. Journal of Engineering Research and Application, 3(4): 1174-1178.

Mohod, AG. and Powar, AG. 2011. Development and evaluation of multi reflector foldable type solar cooker. Agricultural Engineering International: the CIGR Journal.

Manuscript No. 1090.

Nahar, NM. 2001. Development and Testing of a Double Reflector Hot Box Solar Cooker with a Transparent Insulation Material. Renewable Energy, 23(2): 167-179.

Nahar, NM. 1993. Performance and Testing of Large-Size Solar Water Heater Cum Solar Cooker. International Journal of Energy Research, 17(1): 57-67.

Ngala, GM., Maina, MB. and Tela, MB. 2015. Design and construction of a high concentration solar cooker. International Journal of Research in Mechanical Engineering, 3 (1): 01-07.

Oturanc, G., Necdet, O. and Gungor, A. 2002. Performance Analysis of a Solar Cooker in Turkey. International Journal of Energy Research, 26(2): 105-111.

Prasanna, UR. and Umanand, L. 2011, Modeling and Design of a Solar Thermal System for Hybrid Cooking Application. Applied Energy, 88(5): 1740-1755.

Purohit, I. and Purohit, P.2009. Instrumentation error analysis of a box-type solar cooker,

Energy Conversion and Management, 50(2): 365-375.

Sharma, A., Buddhi, D. and Sharma S. 2002, Accelerated Thermal Cycle Test of Acetamide Stearic Acid and Paraffin Wax for Solar Thermal Latent Heat Storage Applications. Energy Conversion and Management, 43 (14):1923-1930.

Sharma, A., Chen, C., Murty, V. and Shukla, A. 2009. Review on Thermal Energy Storage with Phase Change Materials and Applications. Renewable and Sustainable Energy Reviews, 13(2): 318-345

Sharma, S., Buddhi, D., Sawhney, R. and Sharma, A. 2005. Thermal Performance of a Solar Cooker Based on an Evacuated Tube Solar Collector with a PCM Storage Unit. Solar Energy, 78 (3): 416-426.

Yuksel, N. and Avci, A. 2010, The Use of Solar Energy on the Cookers with Latent Heat Storage (in Turkish). Proceedings, 8th National Clean Energy Symposium, 2010 Bursa, Turkey, pp. 23-31



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