

PERFORMANCE EVALUATION OF A SOLAR BOX COOKER WITH PALM OIL AS A PHASE CHANGE MATERIAL USING MAIDUGURI WEATHER CONDITION

M.B. Maina, A.T. Abdulrahim and S. Shodiya

Department of Mechanical Engineering, Faculty of Engineering P.M.B. 1069 University of Maiduguri Nigeria,

*Corresponding author email: m.muhammad@unimaid.edu.ng

ABSTRACT

The performance of palm oil 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 107°C and 383.3KJ respectively, an adequate temperature and energy stored by the PCM for cooking during off-sunshine hours. First figure of merit (F_1) and second figure of merit (F_2) were deduced to be 0.12 and 0.38 with overall SBC efficiency (η) of 33% qualifying the SBC to grade 'A' based on the Bureau of Indian Standards (BIS).

Keywords: Solar Box Cooker, Phase Change Material, Energy.

1 INTRODUCTION

Solar cooking is fast becoming a preferred method of cooking food considering the potential of saving significant amounts of conventional fuel and mitigating substantial environmental problems. The major challenge that limits the solar system in cooking application is that it can only be use during the day when sunshine is available. The need for solar cooking systems to have energy storage to extend it usage away from day time and overcast periods through the night and possibly beyond is imperative. 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. [1] Reported that many studies on the development and performance evaluation of various solar cookers were carried out including their economic aspect. There have also been several attempts to increase the performance and efficiency of cookers in non-tropical regions. Different types of solar cookers 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, 5], various booster mirrors [6], absorber plate [7, 8], a hybrid solar system [9, 10] among several other modifications. In recent times, 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 [11]. Acetanilide is a promising PCM for cooking indoors with aluminum among the in-organic PCMs; but it exhibits some corrosion in contact with steel. However, magnesium nitrate hexa-hydrate 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 [12]. Also, these PCM are rather expensive when high temperatures are concerned. The ideal PCM to be used for latent heat storage system must meet following requirements: high sensitive heat capacity and heat of fusion, stable composition, high density and heat conductivity, chemical inert, non-toxic and non-inflammable, reasonable, and inexpensive, [13]. Several attempts were made to increase the performance and efficiency of solar cookers developed and tested around Maiduguri and environs, [14]. 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, [15]. Despite the enormous solar energy potentials of Maiduguri solar cookers are not widely used.

Palm oil is an edible vegetable oil derived from the reddish pulp of the fruit of the oil palms. It is one of the few highly saturated vegetable fats and is semisolid at room temperature. It also forms the basis of soap products, industrial lubricant and palm oils physical property is slightly similar to that of paraffin wax, as shown in table 1. 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 an experimental model of a solar box cooker with TES (palm oil) 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 energy availability, especially for cooking purposes in the study area (Maiduguri). The cooker for this study is as depicted in Figure 1 which basically conforms to a box within a box with transparent double glazing and access door by the side.

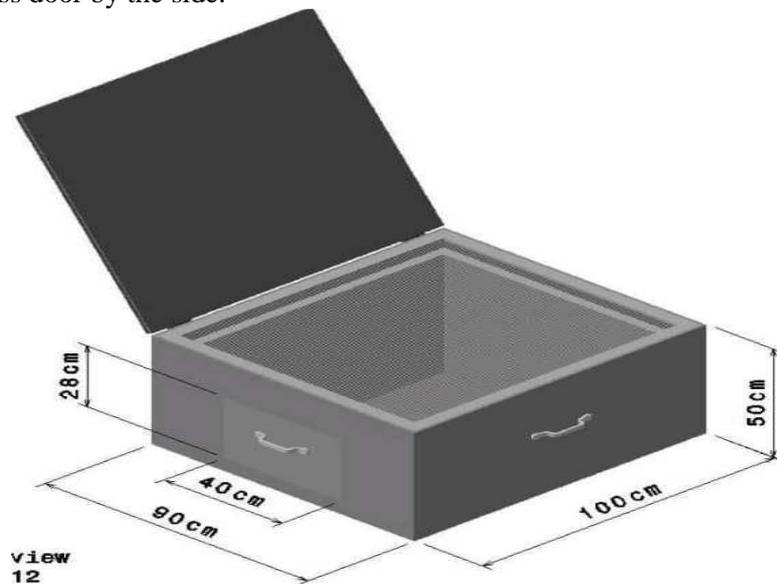


Figure 1: A double glazed Solar Box Cooker (SBC) with a booster mirror.

2 MATERIALS AND METHODS

2.1 Parts of the Solar Box Cooker (SBC)

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. [16] 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 Workshop. The TES Tank was painted black for optimal heat absorption. It was designed using Ansys Space Claim Design Modeller as shown in Figures. 2 and 3 respectively.



Figure 2. Inner Box

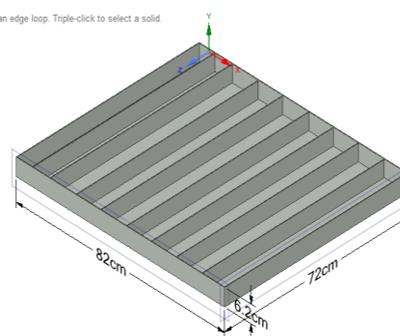


Figure 3. Thermal Energy Storage Tank

Experimental tests were conducted after constructing physical model of the SBC as shown in fig 4 under various weather conditions to determine the viability of using palm oil 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 where heat transfer takes place in position before and after glazing

2.2 Design Considerations

The design parameters considered included the energy requirements, daily average insolation, and size of PCM container, ambient temperature and melting temperature of 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 eqn 1[17].

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

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 coefficient that combines convection and conduction was estimated as being approximately. $13.0 W/m^2k$, [17].

Table 1. Thermo-physical properties of materials in use [4]

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	-	-	--	-	-
Palm Oil	890	1.692	0.1726	35	185

2.3 Methods

Experiments were conducted under various weather conditions to evaluate the viability of using Palm Oil 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 Bureau of Indian Standards, [3]. All the measured parameters were recorded at intervals of ten minutes. The T-type thermocouples of Cu-Ni (Copper-Nickel) with temperature range of 185 °C to 300 °C was used to measure the temperature distribution inside the PCM storage unit, the temperature inside the cooking vessel, the absorber temperature and the ambient temperature.

2.3.1 Thermal Performance Tests

2.3.2 Stagnation Test

The stagnation temperature (T_s), ambient temperature (T_a) and absorber plate temperature (T_p) were measured for different time of the day between 09:00 am and 4.00 pm during the operation of the cooker using 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).

2.3.3 Full Load Test

The boiling test was done by placing a water-filled cylindrical pot covered by a lid, in the cooker. The test was conducted for three days with 1.0 kg of water in the first day, 1.5 kg of water in the second day and 2.0 kg of water in 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

2.3.4 Performance Measurement

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

2.3.5 First Figure of Merit (F_1)

The first figure of merit (F_1) of a solar box cooker is defined as the ratio of optical efficiency (η_o) and the overall heat loss coefficient (U_L), [12].

$$F_1 = \frac{\eta_o}{U_L} \quad (2)$$

Experimentally,

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

Where T_{ps} , T_{as} and H_s are stagnation plate temperature, average ambient temperature and intensity of solar radiation respectively.

2.3.6 Second Figure of Merit (F_2)

The second figure of merit (F_2) is evaluated under full load condition and can be expressed by the expression given as follows:

$$F_2 = \frac{f_1 M_w C_w}{A t} \ln \left(1 - \frac{1}{f_1} \left(\frac{T_{w1} - T_a}{H} \right) \right) / 1 - \frac{1}{f_1} \left(\frac{T_{w2} - T_a}{H} \right) \quad (4)$$

Where F_1 is first figure of merit ($\text{K m}^2 \text{w}^{-1}$), M_w is the mass of water as load (kg), C_w is the specific heat capacity of water ($\text{J/kg}^{\circ}\text{C}$), T_a is the average ambient temperature ($^{\circ}\text{C}$), H is the average solar radiation incident on the aperture of the cooker (W/m^2), T_{w1} is the initial water temperature ($^{\circ}\text{C}$), T_{w2} is the final water temperature ($^{\circ}\text{C}$), A is the aperture area (m^2) and t is the time difference between T_{w1} and T_{w2} (s).

In order to attain cooking temperature at the solidifying point of the PCM at discharging point the energy released by the PCM and the food should be equal to the energy loss from the cooker as given in equation 5 by [19].

$$Q_{PCM} = M_{PCM} [C_{PCM} (T_m - T_a) + L + C_{PCM} (T_{PCM} - T_m)] \quad (5)$$

Where, Q_{PCM} is heat stored by PCM (KJ), M_{PCM} is mass of PCM (kg), C_{PCM} is specific heat of PCM ($\text{Kj/kg}^{\circ}\text{C}$), T_m is melting temperature of PCM ($^{\circ}\text{C}$), T_{PCM} is temperature of PCM at 4:00pm ($^{\circ}\text{C}$) and L is latent heat of fusion of PCM (KJ/Kg).

2.3.7 Cooker Efficiency (η)

The overall thermal efficiency of the solar box cooker is expressed mathematically as follows, [8]:

$$\eta = \frac{M_w C_w \Delta T}{I_{av} A_c \Delta t} \tag{6}$$

Where η_u represents overall thermal efficiency of the solar cooker; M_w , mass of water (kg); C_w , Specific heat of water (J/kg $^{\circ}$ C); ΔT , temperature difference between the maximum

Temperature of the cooking fluid and the ambient air temperature; A_c , the aperture area (m 2) of the cooker; Δt , time required to achieve the maximum temperature of the cooking fluid; I_{av} , the average solar intensity (W/m 2) during time interval Δt .

3 RESULTS AND DISCUSSION

Various test results as highlighted earlier were presented in figures 1 to 7. These include the stagnation test, the load test and the cooker efficiency test.

3.1 Stagnation Temperature Tests

Figures 5, 6 and 7 show the results of stagnation temperature tests under no load condition for palm oil (PCM) TES solar box cooker. The figures reveal 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). Fig. 3 shows maximum oven temperatures of 115 $^{\circ}$ C with ambient maximum temperature of 34 $^{\circ}$ C were achieved at 1:30 pm with corresponding insolation of 894 W/m 2 . Fig 1 has also established that oven temperature stagnates between 100 $^{\circ}$ C and 115 $^{\circ}$ C from the hours of 10:45am to 1:30pm. The plate maximum temperature of 128.7 $^{\circ}$ C was achieved at 12:45 pm while stagnating from 103 $^{\circ}$ C to 128 $^{\circ}$ C between 10:15am and 1:45pm as shown in fig 2 with corresponding average solar radiation of 811 W/m 2 respectively. The average ambient temperature for the test day was 33 $^{\circ}$ C being cloudy with intermittent rainfall (7 $^{\text{th}}$ July, 2018). F_1 was deduced based on Eqn.3 and was found to be 0.12. This value qualifies the SBC as grade A Cooker in accordance with the criteria set by [3]. The result also shows that heat loss from absorber plate of the SBC had been negligible and the absorber plate temperature increases despite varying insolation due to intermittent rain drops and cloud cover as shown in fig 3 confirming adequate heat transfer from PCM to the plate (discharging), the findings with respect to this SBC (Palm oil PCM) were similar to the work of [20].

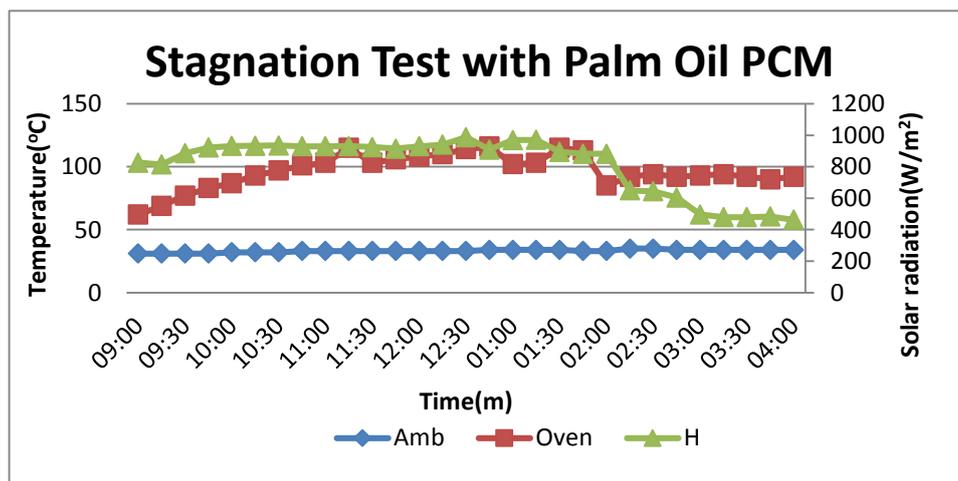


Figure 5. Thermal performance curve in a SBC with Palm oil as TES under no load condition in a test day showing ambient and oven temperature against corresponding solar radiation

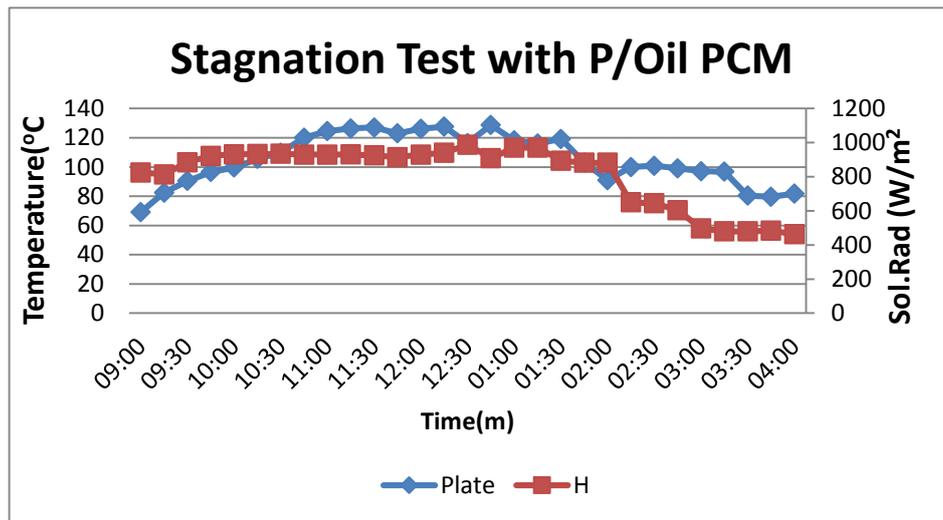


Figure 6. Thermal performance curve of plate temperature in SBC with Palm Oil as TES in a test day

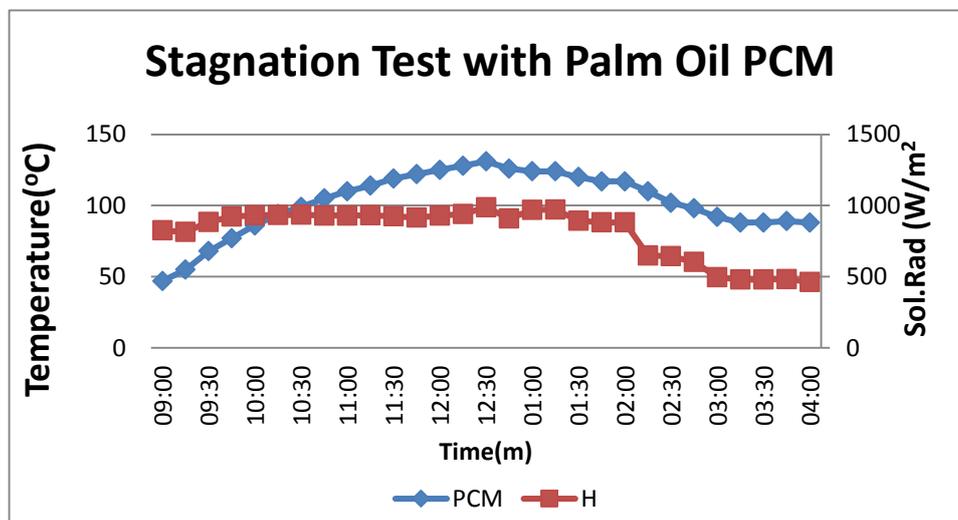


Figure 7. Thermal performance curve of PCM (Palm Oil) temperature in SBC as TES in a test day

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 boiling/cooking most food items and maintaining it hot/warm for long hours after completion of the test as recorded in Figures 8, 9, 10 and 11 respectively. Figure 9 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 in Figure 10. 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 [16]. 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. 4 to be 383.3KJ an amount much lower than that obtained by [16] and [15]. Accordingly, the overall SBC Energy efficiency with Palm oil PCM was found to be 33% using Eqn. 5. Fig7 shows the maximum pot temperature during the water boiling test as 100°C attained by 2:45pm with corresponding insolation of 707 W/m². While F₂ was found to be 0.38 using Eqn. 3 below the minimum value of 0.4 set by BIS for grade “A” cookers in the proper assessment of SBCs.

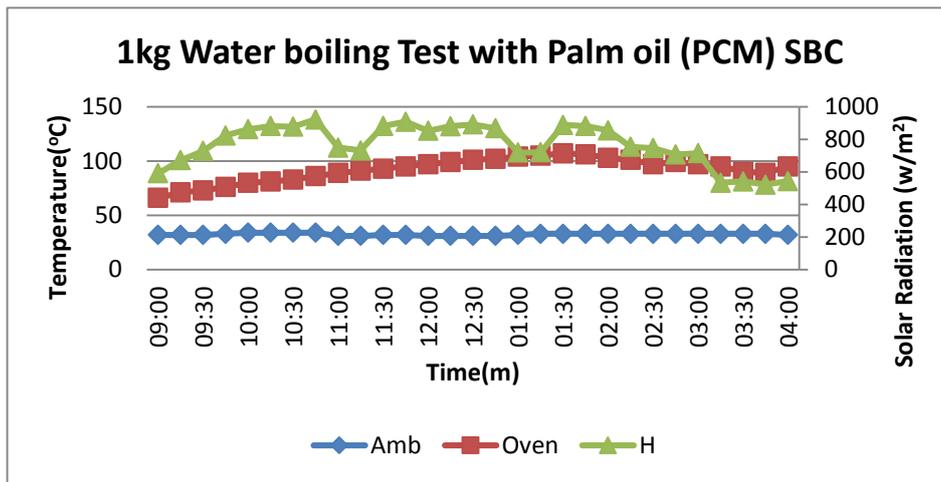


Figure 8. Full load test with 1 kg of water in a SBC with Palm Oil as thermal energy storage showing ambient and oven temperatures against corresponding solar radiation in a test day

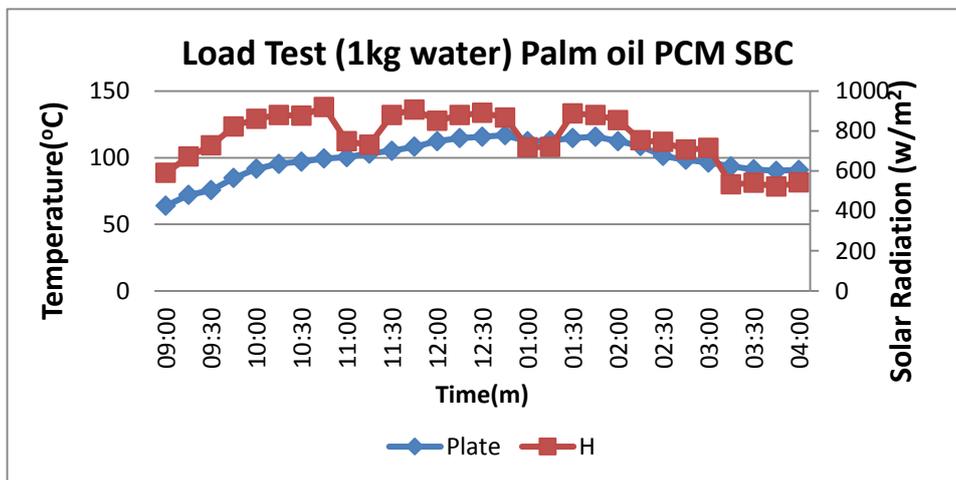


Figure 9. Full load test in a SBC with Palm Oil as TES showing plate temperature behavior with corresponding solar radiation in a test day

Heat transfer performance of Palm oil PCM during charging process with 1kg of water in the SBC is presented in fig 6, temperature variations inside the (PCM) with time as recorded shows no loss of heat despite dwindling Solar radiation observed on the test day (10th July, 2018). PCM temperature was raised to 107°C by 11:00am and maintained to the end of the test (4:00pm) to 101°C with an average insolation of 767W/m² on the test day. The PCM charging behavior has shown good characteristics of recyclability with the temperature recorded at the end of the test.

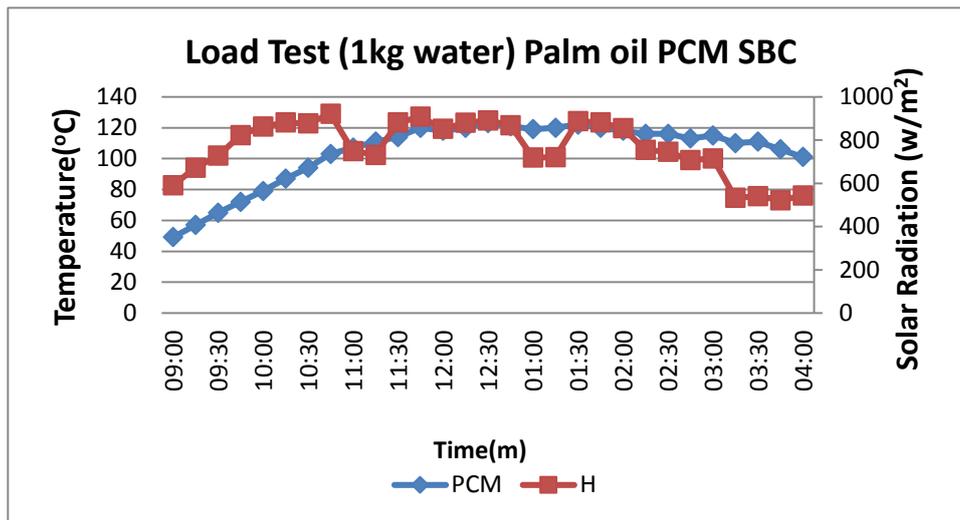


Figure 10. Full load test in a SBC showing PCM temperature behavior with corresponding solar radiation in a test day.

Pot temperature behavior for Palm oil PCM SBC at the beginning of the test record by 9:00am recorded 39.7°C to a corresponding Solar Radiation of 591W/m². Heat gained by the pot in the Palm oil PCM SBC was raised to temperature of 100°C by 2:45pm as the peak to a corresponding insolation of 701W/m². 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 with a standard error of mean of 3.63472 and standard deviation of 19.57357. The oven, plate and PCM temperatures of the SBC attained mean errors of 2.06325, 3.86482 and 2.56897 to a corresponding standard deviation of 11.11095, 20.81270 and 13.83431 respectively on the test day.

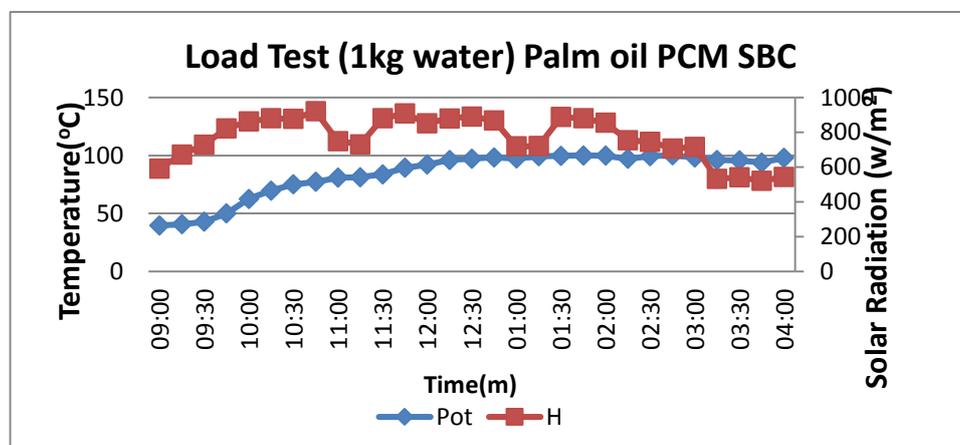


Figure 11. Thermal curve of Pot temperature in a SBC with Palm Oil as TES.

4 CONCLUSION

In this study, Box type solar cooker with single booster reflector has been designed using Ansys 19.0, constructed, and experimentally tested under the weather conditions of Maiduguri. For the first time, the characteristics of Palm Oil as a PCM in Solar Box Cooker were investigated within the study area. Experiments were performed and the influences of different components were investigated, Palm Oil was found to store adequate energy (383.3KJ) for off peak period with 33% efficiency. From the experimental results of the solar box cooker the following conclusions were drawn: The thermal efficiency of the solar cooker and the cooking times are found to depend strongly on the PCM, the reflector, insulation, and the solar intensity. Palm Oil can be used as a storage medium integrated with a Solar Box Cooker using Maiduguri weather conditions. It is obvious that the total Solar radiation on cloudy days is lower than that of the clear days; the solar cooker receives reflected radiation from only

a single reflector hence there is a possibility that high temperatures can be achieved by increasing the number of reflectors and incorporation of automatic 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 CO₂ to the environment

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