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ORIGINAL RESEARCH ARTICLE

APPLICATION OF STEARIC ACID FOR SOLAR THERMAL ENERGY STORAGE IN A DOUBLE COMPARTMENT SOLAR BOX COOKER

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ABSTRACT
Energy storage in some form is the need of the hour to even out the mismatch between energy supply and demand. Thermal Energy Storage (TES) system employing a phase change material (PCM) has been widely considered as an effective way to store and retrieve energy due to its high heat storage capacity at almost constant temperature during the phase change. In this work, an energy storage system was designed to study the heat transfer characteristics of stearic acid (as a phase change material in a double compartment solar box cooker (DCSBC) fabricated using wooden materials with high thermal energy storage system. In order to analyze the various characteristics of the PCM, the Bureau of Indian Standards (BIS) was used throughout the experiment. Investigations were performed to determine the first and second figure of merits (F1 and F2) of compartments 1 and 2 (C1 and C2) simultaneously. The results for F1 were found to be (C1= 0.14 and C2= 0.15) and F2 were (C1=0.47 and C2= 0.4) while the overall thermal efficiency of the cooker after water boiling test for C1 with 2.5kg and C2 with 3kg of water were deduced to be 77% for C1 and 92% for C2 after six hours of the load test, showing considerable temperature increase and extension of heat retention making possible to cook the dinner and even breakfast the next day.

1.0 Introduction

Related emissions of carbon dioxide will be doubled by 2050 and Fossil fuel demand, supply and utilization has increase over the years with its unsustainable use environmentally, economically and socially (International Energy Agency, 2015). Researchers most often get involved in finding materials and systems to make sure that alternative energy supply and use with appropriate technology in various domestic sectors, transport and industry were attained to support energy security and climate change goals. Among these are the different energy storage technologies, thermal energy storage (TES) is considered a key technology to reduce the mismatch between energy demand and supply on a daily, weekly and even seasonal basis, increasing the potential of implementation of renewable energies and reducing the energy peak demand, (IEA 2015).

Thermal energy storage (TES) is defined as the temporary holding of thermal energy in the form of hot or cold substances for later utilization (Abedin, 2011). Energy demands vary on daily, weekly and seasonal bases.These demands can be matched with the help of TES systems that operate synergistically and deals with the storage of energy by cooling, heating, melting, solidifying or vaporizing a material and the thermal energy becomes available when the process is reversed.TES is a significant technology in systems involving renewable energies as well as other energy resources as it can make their operations more efficient, particularly by bridging the period when energy is harvested and periods when it is needed. That is, TES is helpful for balancing between the supply and demand of energy (Abedin, 2011 and Pavlov, 2012). TES systems have the potential for increasing the effective use of thermal energy equipment and for facilitating large-scale fuel commutating (Pavlov, 2012). The selection of a TES system for a particular application depends on many factors these includes; storage duration, economics, supply and utilization temperature requirements, storage capacity, heat losses and available space (Dincer, 2011). The main types of TES are sensible and latent. Sensible TES systems store energy by changing the temperature of the storage medium, which can be water, brine, rock, soil, etc. Latent TES systems store energy through phase change, e.g. cold storage water/ice and heat storage by melting paraffin wax. Latent TES units are generally smaller than sensible storage units but can store large amount of energy.

The present study intends to give an experimental account of the application of stearic acid as a phase change material (PCM) technology for TES in a double compartment solar box cooker (DCSBC).It also seeks to increase the reliability of the solar box cooker using animal based fat as TES toimprove operational performance of the system to be used for off-peak periods. It is also an approach or solution for bridging the gap between solar energy availability and demand, specifically reducing the increasingenergy cost and scarcity for cooking purposes in the study area (Maiduguri).The use of solar box cooker is not popular among the dwellers in Maiduguri and environs. The objectives of this work are to test and evaluate the thermal performance of a low cost, doublereflector- based solar box cooker with TES (PCM) in Maiduguri, Nigeria and determine its suitability for cooking during high and low solar irradiation.

2.0 Materials and Methods

2.1 Materials and Equipment

The design materials(parameters) considered included the energy requirements, daily average insolation, the phase change material (Stearic Acid), size of PCM container, ambient temperature and other thermo-physical properties of the PCM 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 temperature range of 185°C to 300°C.

Thermo-physical Properties of Stearic Acid

The thermal properties of the stearic acid used and other physical properties were as given in table 1.

Table1: Properties of PCM (stearic acid) used

M melting temperature	52°C
D density	847-965 (kg/m^3)
A appearance	White solid (waxy)
St storage temperature	2–9°C
Re refractive index	1.429
Th thermal conductivity	0.29 (W/m K)
La latent heat of fusion	169.0 (kJ/kg)
Sp specific heat	1.590 (kJ/kg K)

(Source: Hussein et al., 2008)

2.1.1 The double compartment solar box cooker (DCSBC)

The double compartment solar box cooker was made of inner and outer casing of the oven compartment (Figure1)and was fabricated with plywood of thickness 0.02m. The dimension for the inner casing constructed of flattened aluminum roofing sheet is 0.37m x 0.44m x 0.3m, fixed directly beneath the Aluminium casing serving as absorber plate (painted black) is the PCM storage tank having the same size as the base of the inner Al casing (0.37m x 0.44m x 0.05m) filled with 2kg of stearic acid for charging and dis-charging purposes, while the outer casing has dimension 0.87m x 0.7m x 0.43m. A 0.21m x 0.27m two rectangular openings were cut on each compartment side of the box to serve as a door. These allow for independent cooking purposes rather than the uniform cooking obtained in most solar cooking units, due to the cooking traditions of the test area (Maiduguri and environs) usually food and soup (Tuwo and Miya) were independently cooked. Thus, the SBC was also designed to provide opportunity to cook both food and soup simultaneously without affecting the progress of each other. The independent compartment also reduces amount of heat losses compared when the pots were in the same compartment as obtained in literature (Saxena et al., 2013). The aforementioned design and versatility of the SBC was to increase the acceptability of the SBC in the community as compared to the existing versions. The inner casing was then inserted in the oven box and nailed at the sides using 2mm nails. The whole assembly was turned upside down after which the space was filled with saw dust and then finally covered with plywood. Two 4mm thick, silver plated mirrors, 0.66m x 0.66m in dimension were each mounted on 0.7m x 0.65m plywood with the aid of clips and hinged by the opposite sides of the box cooker as reflectors. The reflectors were held at the sides using flat bars, with one end permanently fixed to the midpoint of the adjacent side on the collector and the other end sliding on the 3mm hole along the angle bar screwed to the plywood as shown in Figure 1.

Figure 1: Double Compartment Solar Box Cooker (DCSBC)

The aperture area of the box cooker is 37.41cm^2; the volume stands at 1608.63cm^3 while the oven weight was deduced to be 62.1N.

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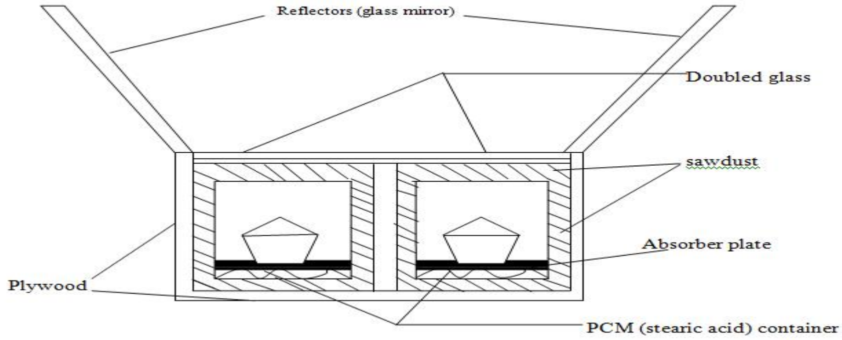

Figure 2: Sectional view of the double compartment SBC showing PCM container

2.2 Methods

2.2.1 Thermal performance Test

Difficulties in assessing numerous designs of solar cookers have led to the creation of three major testing standards for evaluating solar cookers throughout the world. They include: American Society of Agricultural Engineering (ASAE) Standard S580, the standard developed by the European Committee on Solar Cooking Research (ECSCR) and the Bureau of Indian Standards, based on work by Mirdha and Dhariwal (2008). Though, the three standards have their shortcomings, Indian standards provide testing standard based on thermal test procedures for box-type solar cookers. The performance of the reflector based solar box cooker implemented in this study was done based on the Bureau of India standard, IS 13429: 2000, Ayoolaet al. (2014). The standard highlighted two methods of test: a stagnation test (test without load) where F1shall be determine as the cookers optical efficiency and a load test (boiling water test) where F2 shall also be determine as the cookers heat transfer efficiency alongside the overall cooker efficiency (ɳ).

2.2.3 Stagnation Temperature Test

The experiment was carried out on the 9th of June 2017 at the University of Maiduguri Engineering teaching workshop, to show the variation in the solar radiation and ambient temperature and their effects on the stagnation temperature observed in the absorber plate of the double compartment solar box cooker.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 (Ta) and absorber plate temperature (Tp) were measured for different time of the day between 10:00 am and 4.00 pm during operation of the cooker using 1.6mm diameter thermocouple with Elix digital thermometer (LX-6500) capable of reading temperature between -50°C and 300°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).

2.2.3 Water boiling Test (Load Test)

The loading 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 3.0 kg of water in the first day, 2.5 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 10:00 am and 4:00pm daily. The absorber plate temperature (T_p), ambient temperature (T_a), water temperature (T_w), solar radiation (H_s), PCM temperature and wind speed (v) were measured using the instrumentation described earlier in this section

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2.2.4 Performance Evaluation

The performance evaluation of the double compartment solar box cooker involve estimation of the First figure of merit (F1), Second figure of merit (F2) and cooker's efficiency (ɳ) as earlier highlighted in 2.2.1

2.2.5. First Figure of Merit

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

$$F1 = \frac{n_0}{U_L} \tag{1}$$

Experimentally,

$$F1 = \frac{T_{ps} - T_{as}}{H_s} \tag{2}$$

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.

2.2.4 Second Figure of Merit

The second figure of merit (F2) is evaluated under full load condition and can be representedby the expression given by Mohod (2011) as follows:

$$F2 = \frac{F1(M_w C_w)}{At} In \left\{ \frac{1 - \frac{1}{F1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F1}\left(\frac{T_{w2} - T_a}{H}\right)} \right\} \tag{3}$$

where: F1 is first figure of merit (Km^2 w^{-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) while F2 signifies the cookers heat transfer efficiency.

2.2.3. Cooker Efficiency

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

$$\eta_u = \frac{M_w C_w \Delta T}{I_a V A_c \Delta T} \tag{4}$$

where:ɳu represents overall thermal efficiency of the solar cooker; M_w, mass of water (kg); C_w, Specific heat capacity of water (J/kg/°C); ΔT, 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 (min); I_{av}, the average solar intensity (W/m^2) during time interval Δt.

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3.0 Results and Discussion

3.1 Stagnation Temperature test

The result of stagnation temperature under no load condition is shown in Figure 3.The average ambient temperature for the test day was 41°C. Maximum absorber plate temperature of 158°C was recorded at 4:00 pm for compartment 1 and at an average insolation value of 838 W/m^2 and 166.7°C at 4:00pm for compartment 2 at 838 W/m^2, the plate temperature increases despite decreasing insolation up to 4:00 pm. The result shows that heat loss from absorber plate of the cooker is negligibleand the absorber plate temperature was retained for a long time due to energy stored in the PCM (stearic acid) embedded below the absorber plate.This is desirable for heating since major mode of heat transfer to the cooking vessels is by conduction from absorber plate, Adewole et al. (2015).

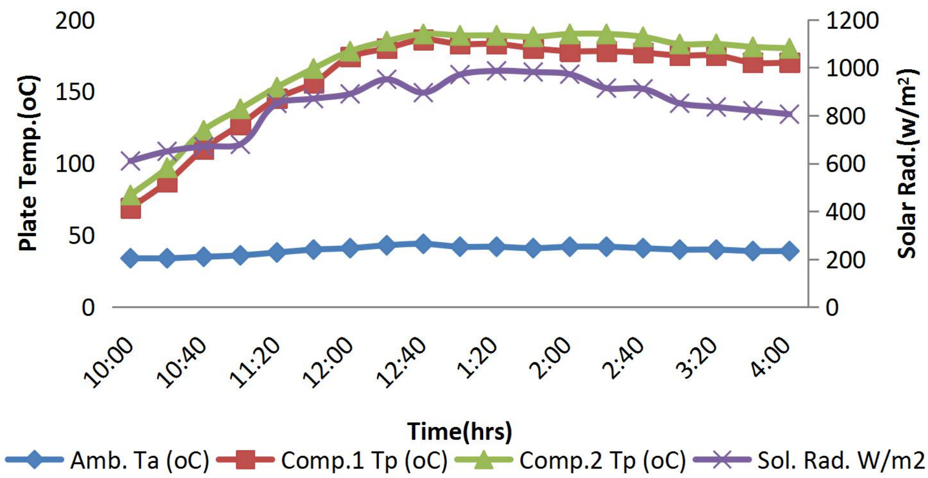

Fig. 3: performance curve of double compartment solar box cooker under Stagnation Temperature condition

3.2 Water boiling Test (Load Test)

Variation in solar radiation, ambient temperature, plate temperature and water temperature during sensible heating test of 3.0kg of water for compartment 1 and 2.5kg of water for compartment 2 are shown in figure 4.The experiment was carried out on the 10th of June 2017 at the University of Maiduguri Engineering teaching workshop, Periodic overcast of weather caused fluctuation in the solar radiation, Folaranmi (2013). The maximum insolation of 973 W/m^2 at 1.00 pm and minimum of 602.4 W/m^2 at 4.00 pm were recorded. The average solar radiation and ambient temperature observed during the period of test for 3.0 kg of water were 837.9 W/m^2 and 41°C respectively.

The highest pot water temperature of 99°C between 1:00pm to 1:20pm for compartment 1 and 99°C between 1:00pm to 1:40pm for compartment 2 was observed. Mirdha (2008) reported that most food can be fully cooked at the temperature range of 60-90°C. The water temperature during the period of test reached temperature values between 60- 93°C for compartment 1 and 60-96°C for compartment 2 at 602.4 and 890.8W/m^2 between the hours of 12:00 PM and 4:00 PM. Figure 4 shows sensible heating test result for 3.0kg and 2.5kg of water in the different compartments of the SBC. The average solar radiation and ambient temperature during the period of boiling 2.5kg of water were 849.9 W/m^2 and 40.75°C respectively. The highest pot water temperature of 95°C and 99°C for compartment 1and 2 were observed between 1:00pm and 1:20 pm. The overcast of cloud during the period of test caused fluctuations in the value of plate temperature with the average value at 158°C and 166°C for compartments 1 and 2; this is similar to the report of Adewole et al. (2015). Despite the fluctuations in insolation, there was significant temperature retention up till 4:00 PM. F2 for both compartments were calculated based on Eqn. 3 and found to be 0.47 for C1 while C2 was found to be 0.40, both figures being above the minimum standard set by BIS for assessment of Solar Box Cookers. This shows the effect of the thermal energy storing mediumthat is Stearic acid (PCM) as an effective energy store for heat transfer to the cooking vessel through the absorber plate for period much longer after the sunshine hours. The results of the tests present the thermal behavior of major parameters in the DCSBC namely: solar radiation and ambient temperature among others. Despite high weather fluctuation during the period of test, water temperature increased significantly reaching maximum temperature of 94°C and 96°C, 95°C and 99°C at an insolation of 973 and 970 W/m^2, respectively for the two compartments. The plate and water temperature attained temperature suitable for cooking and increase considerably from 10:00am till 4:00 PM. This and other results discussed above demonstrated the suitability of the designed double compartment solar box cooker for cooking even during fluctuating weather conditions; this is similar to the work of El-amin (2015).

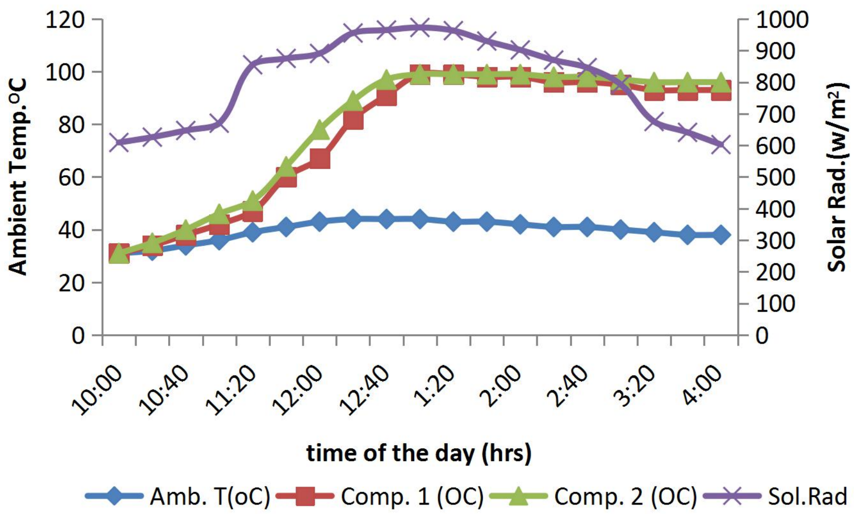

Fig. 4: Thermal performance curve of the double compartment solar box cooker during sensible heat test of 3.0kg of water in C1 and 2.5kg of water in C2 in a test day

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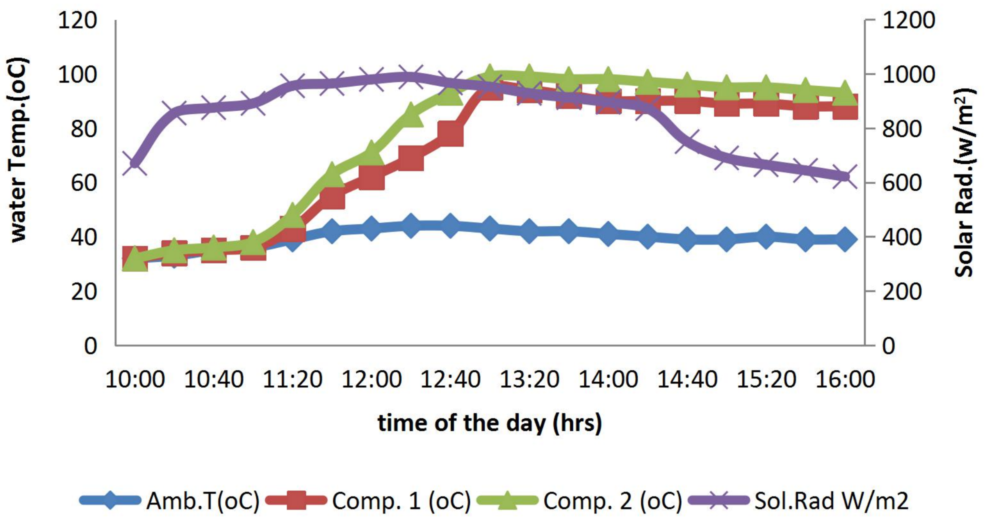

Fig. 5: Thermal performance curve of the double compartment solar box cooker during Sensible heat test of 2.5 kg of water

3.3 Thermal cooker efficiency (ŋ)

The cooker efficiency for both compartments (C1and C2) were determined using equation iv as 77% for compartment C2 with 2.5kg of water and 92% for compartment C1 with 3kg of water after six (6) hours of heating test, this is similar to the report of El-amin, (2015) where he obtains 77% as the efficiency of box cooker after evaluation in comparism to parabolic solar cooker and panel type cookers, it is also similar to the work of Adetifa and Aremu, (2016) with respect to heat storage where extension of heat storage increases temperature making it possible to cook dinner in late hours.

4.0 Conclusion

A double compartment solar box cooker was designed and produced with stearic acid as phase change material (PCM) serving as the energy storage medium using the weather conditions of Maiduguri (North-East Nigeria). The idea was to improve the performance of solar box cookers for better acceptability in the society and as a promising alternative (such that it can be used in the day and for late evening cooking that may not be possible with simple solar cooker without energy storage) this work also specifically intends to impact on the cost and scarcity of cooking energy in the study area.

The Bureau of Indian Standard (BIS, 2000) was used to evaluate the SBC and the values of first figure of merit (F1) for the two compartments (C1= 0.14 and C2= 0.15) indicates good optical efficiency and low heat lost factor going by the BIS which ranges between 0.12 and 0.16 depending on the climate of the test area (country). The values of second figure of merit (F2) for C1 and C2 (0.47 and 0.4) indicates good heat exchange efficiency factor, good optical efficiency (ŋo) and low heat capacity of the cooker interior and vessel with full load of water. The stagnation and full load test result shows that the double compartment SBC can be effectively used for methods of cooking obtained around the test environment,traditional food and soup (Tuwo and Miya) cooked around the locality can be adequately produced in the two different compartments having independent access and sizes to suit different volumes of food intended to be cooked. While students can use the DCSBC during the day and night as well appropriately due to energy storage facility incorporated to the cooker without affecting their time for academic and other activities. The result has also provided useful database for validation of theoretical models of box cookers using PCMs haven fulfilled the standard set by BIS for Solar Box Cookers assessment.

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