Investigating the Effect of Different Heat Storage Media on the Thermal Performances of Double Exposure Box-type Solar Cookers

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Abstract- This paper investigates the effect of some heat storage materials on the thermal performances of double exposure box-type solar cookers. Benzoic acid, stearic acid and palm olein oil were used in storing heat in double exposure box-type solar cookers. Using standard methods, some thermal performance parameters were evaluated and compared to that of a control design (no heat storage). The use of benzoic acid increased the average cooking power by 12, 3.6 and 3.4 W for 1, 1.5 and 2 kg of water respectively. Similarly, stearic acid was observed to increase the average cooking power by 1.6 W only for 1 kg of water and palm olein oil was observed to increase the cooking power for only 2 kg of water by 3.2 W. The average first figure of merit were; 0.13, 0.14, 0.12 and 0.11 ℃ m^{-2} W^{-1} for the cooker with benzoic acid, the control cooker, cooker with stearic acid and the cooker with palm olein oil, respectively, while their respective second figure of merit were; 0.45, 0.40, 0.10 and 0.12. Benzoic acid influenced a higher thermal performance, while stearic acid and palm olein oil had a reduction effect. Benzoic acid and palm olein oil had significant effect on the cooking power of the solar cookers, while stearic acid had effect on the first figure of merit.

Keywords Cooking power, figures of merit, solar cookers, heat storage, thermal performance.

1. Introduction

Cooking with the sun has gained the attention of several researchers owing to the need for a clean, safe and affordable energy. Based on this, different types of solar cookers with different features have been designed. This wide variety of solar cookers necessitated the need for regulation, comparison and classification. The three major testing standards currently in use globally are; American Society of Agricultural Engineers Standard (ASAE S580), Bureau of Indian Standards (BIS) Testing Method and European Committee on Solar Cooking Research (ECSCR) standard [1, 2]. Also, Kundapur and Sudhir [3] and Shaw [1] have developed other standards for solar cookers. Generally, these test and evaluation procedures were not only aimed at comparing and categorising different solar cookers but also in identifying ways of improving their performances.

In other to improve the thermal performance of box type solar cookers, different factors have been investigated using different test standards. Some of the factors which have been identified to influence the thermal performance of solar cookers include;

1. Cooker's geometry [4 – 6]
2. Type of insulation material [7, 8]
3. Auxiliary heating [9]
4. Sun tracking [10, 11]
5. Number of exposed surfaces [12]
6. Type and design of cooking pot
    a. Fins [13, 14]
    b. Lid with reeds [15]

   c. Depressed lid [16]
   d. Parallelepiped pot [17]
   e. Central cylindrical cavity [18]
7. Number and angle of reflectors [19, 20]
8. Type of glazing material [21]

In order to ensure the availability of heat in the evening, several heat storage systems have been developed making use of different types of heat storage materials such as rocks [22], stearic acid [23, 24], acetamide [25], acetanilide [26], common salt [27], erythritol [28, 29], $NaNO_3$-KNO_3 [30], benzoic acid [31], paraffin wax [20, 32], magnesium nitrate hexahydrate [33] etc.

Despite the fact that the performances of individual systems were reported, the effect of these materials on the cookers has not been adequately evaluated experimentally. Lecuona et al. [34] developed a mathematical model in order to explain the conventional figures of merit to characterize the performances of solar cookers with heat storage. They observed that the figures of merit were the same with those without heat storage, but with different interpretations and extra tests required.

To this effect, this paper is aimed at experimentally evaluating and comparing the effect of some selected heat storage media on the thermal performance of double exposure box-type solar cookers using two different testing standards.

2. Methodology

2.1. Description of Systems

Four double exposure box-type solar cookers (DEBSCs) which contained different heat storage materials were designed and fabricated. The cookers which were labelled 1-4 contained benzoic acid; air (as control, indicating no heat storage material); stearic acid and palm olein oil as heat storage media respectively. The amount of the heat storage materials required to store energy needed to boil 2 kg of water from 25 ^oC was added, which are; 4.5 kg of commercial grade benzoic acid (latent heat of fusion: 142.8 kJ/kg), 4 kg of commercial grade stearic acid (latent heat of fusion: 160 kJ/kg) and 6 litres of palm olein oil (specific heat capacity: 169 kJ/ kg and density: 900 kg/m^3).

Table 1 shows the components of the cookers, their dimensions and the materials they were made of. These materials (wood, aluminium, aluminium foil, mild steel, saw dust and tempered float glass) are readily available and have a good balance of cost and effectiveness. Figure 1 represents a typical double exposure box-type solar cooker showing the arrangement of the various components. The box type solar cookers which are have permanently positioned cooking pots surrounded by an annular cavity containing the heat storage material. The cookers were covered at the top with a double glazing cover and they have three plane reflectors to boost the collection of solar insolation. The bottom of the cookers was opened for exposure to solar radiation from a parabolic reflector placed below the cooker.

Table 1. Components of the DEBSCs

S/N	Component	Dimension	Material
1	Outer box	670 mm × 670 mm × 195 mm	25 mm thick Drum wood
2	Inner box	530 mm × 530 mm × 120.50 mm	3 mm thick plywood
3	Insulator	50 mm thick	Sawdust
4	Double glazing	650 mm × 650 mm	3 mm tempered float glasses
5	Three plane reflectors	670 mm × 670 mm	Aluminium foil on 3 mm plywood
6	Parabolic reflector	Focal length: 85 cm; Diameter: 82cm and Depth: 5 cm	Aluminium foil on 3 mm hard board
7	Absorber plate	520 mm × 520 mm × 116 mm	1.4 mm gauge mild steel sheet painted with epoxy black
8	Cooking pot	210 mm diameter and 90 mm height	Aluminium
9	Annular cavity	40 mm, 52 mm and 65 mm thickness from pot for benzoic acid, stearic acid and palm olein oil respectively	Aluminium
10	Stand	820 mm height	Mahogany wood

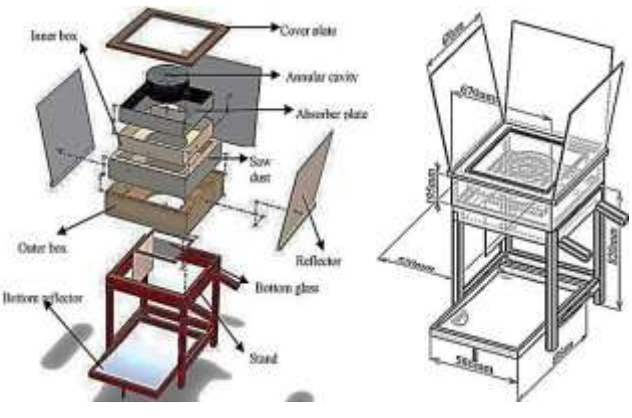


Fig. 1. Double exposure box-type solar cooker (DEBSC)

2.2. Experimental Setup, Instrumentation and Procedure

Experiments were conducted at the Department of Agricultural and Environmental Engineering, University of Ibadan, Ibadan, Nigeria located at 7.4417^o N and 3.9000^o E. The instruments used for this experiment were; a digital anemometer (AM-4812), k-type thermocouples, multichannel temperature logger (REED Thermometer SD-947) and indicator (Supco EM60), solar meter (Dr Meter Solar Power Meter SM206) and digital weighing balance (METRA TL-5000). The DEBSCs were set up as shown in fig. 2. The hot ends of k-type thermocouples were located (through a hole on the pot cover) at the midpoint of the water level in the pots while, their cold ends were attached to a multichannel temperature logger which recorded the temperature. The ambient temperature was monitored with a temperature indicator while, the solar meter was used in measuring the solar intensity in (W/m^2). These experiments were carried out between 12:30 pm and 2:30pm local time.

Transmittance, stagnation and water heating experiments were carried out according to the standard method in ASAE S580 [35] and IS13429 [36 – 38]. During the transmittance test, five sample readings of the solar intensity on the top of the cover plate (glazing) and below cover plate (inside the cooker) were taken within 30 minutes for each of the four solar cookers. The ratio of the two readings was estimated. The transmittance test was necessary so as ascertain that the difference in the thermal performances of the DEBSCs was not due to the glazing cover.

Stagnation test was carried out for three days, but, the day with the most favourable ambient condition was selected for analysis. During this test, the pots in the DEBSCs were left empty. The DEBSCs were exposed to solar radiation, while the pot and ambient temperatures were recorded alongside the solar intensity.

Three different quantities of water (1, 1.5 and 2 kg) were heated on different days for the water heating test. During this test, the pots in the DEBSCs were filled with water and the DEBSCs were exposed to solar radiation. The temperature of the water and ambient were recorded alongside the solar intensity.

Fig. 2. Experimental Setup

2.3. *Thermal Performance Evaluation*

The performances of the solar cookers were evaluated based on the following standards.

i. **American Society of Agricultural Engineers Standard ASAE S580**: This standard was used in evaluating the cooking power, standardized cooking power and temperature difference using equation (1) – (3), respectively.

$$P_i = \frac{(T_{w2}-T_{w1})M_w C_w}{600} \quad (1)$$

$$P_s = P_i\left(\frac{700}{I_i}\right) \quad (2)$$

$$T_d = T_w - T_a \quad (3)$$

Where, I_i is the interval average solar insolation (W m^{-2}); P_s is the standardized cooking power (W); P_i is the interval cooking power (W); T_a is the ambient temperature (ºC): T_w is water temperature (ºC); T_{w1} and T_{w2} are the water temperatures at state 1 and 2 (ºC); T_d is the temperature difference (ºC); M_w represents the mass of water (kg) and C_w is the specific heat capacity of water (kJ kg^{-1} k^{-1}).

The standardized cooking power, P_s, was plotted against the temperature difference, T_d, for each time interval. A linear regression of the plotted points was used to find the relationship between cooking power and temperature difference in terms of intercept "a" (W) and slope "b" (W ºC^{-1}) (i.e. $P_s = a + bT_d$). The single measure of performance was estimated by computing the value of the standardized cooking power, Ps, (W) for a temperature difference, T_d, of 50 °C using the regression relationship found. All these were done for 1, 1.5 and 2 kg of water.

ii. **Bureau of Indian Standards**: These standards were used in estimating the first and second figures of merit using equation (4) and (5). The first figure of merit at 100 ºC plate temperature (X) was determined using equation (6) while the standard boiling time (t_{boil}) was calculated for different values of X using equation (7). A plot of t_{boil} versus X was drawn.

$$F_1 = \frac{T_p - T_a}{I_o} \quad (4)$$

$$F_2 = \frac{F_1 M_w C_w}{A_s \Delta t}\ln\left[\frac{1-\frac{1}{F_1}\left(\frac{T_{w1}-T_a}{I_o}\right)}{1-\frac{1}{F_1}\left(\frac{T_{w2}-T_a}{I_o}\right)}\right] \quad (5)$$

$$X = \frac{(100 - T_a)}{I_o} \quad (6)$$

$$t_{boil} = \frac{-F_1 M_w C_w}{60 F_2 A_s}\ln\left[1 - \frac{X}{F_1}\right] \quad (7)$$

Where, I_o is the incident solar intensity (W m^{-2}); F_1 represents the first figure of merit (℃ m^{-2} W^{-1}); X is the first figure of merit at 100 ºC plate temperature (℃ m^{-2} W^{-1}); F_2 is the second figure of merit (no unit); T_p is the temperature of the absorber plate (during stagnation) (ºC); T_a is the ambient temperature (ºC); T_{w1} and T_{w2} are the water temperatures at state 1 and 2 (ºC); A_s is the area of the solar cooker aperture (m^2) and t_{boil} is the standard boiling time (min).

2.4. *Statistical Analysis*

In ascertaining the differences in the observed performance of the four cookers, the following statistical analyses were carried out;

1) **Analysis of variance (ANOVA)**: This was used in investigating whether there was any significant

difference between the transmittance of the four cookers at 5% level of significance. A p-value higher than 5% will imply that the transmittances of the cookers have no significant difference, while values lower than 5% will imply otherwise.

2) **t-test**: This was used in comparing some of the thermal performance parameters (cooking power and first figure of merit) of each cooker with heat storage to the control cooker at 5% level of significance. A p-value higher than 5% will imply that a heat storage material has no significant effect on the performance of the cooker while a value lower than 5% will imply otherwise.

3. Result

3.1. Transmittance

The result of the transmittance tests for each of the cookers is presented in table 2. An average transmittance of around 0.66-0.68 was observed. These values were as a result of the double glazing used and were above 0.65 which is the minimum transmittance ratio set by IS 13429 – 2 [37].

Table 2. Transmittance ratio through solar cookers' glazing

Samples	Cooker 1	Cooker 2	Cooker 3	Cooker 4
A	0.67	0.73	0.78	0.61
B	0.67	0.56	0.63	0.72
C	0.72	0.65	0.64	0.65
D	0.63	0.78	0.67	0.69
E	0.60	0.67	0.68	0.63
Average	0.66	0.68	0.68	0.66

Key: cooker 1- cooker with benzoic acid; cooker 2 - control cooker; cooker 3 - cooker with stearic acid; cooker 4 - cooker with palm olein oil

Further statistical analysis of the result of the transmittance test from the ANOVA revealed that there was no significant difference between the transmittance ratios of the solar cookers at 5% level of significance as shown in table 3. Hence, the glazing had no effect on the performance of the cookers; therefore, it does not contribute to the difference in the thermal performance parameters.

Table 3. ANOVA of transmittance ratio (5% significance level).

Source of Variation	SS	DF	MS	F actual	P-value	F critical
Between Cookers	0.01	3	0.004	1.271	0.318	3.239
Within Cookers	0.06	16	0.003			
Total	0.07	19				

3.2.Ambient Conditions

Table 4 shows the average values of the ambient conditions during the experiments. The conditions were favourable for evaluating the thermal performances of the solar cookers. The results of day 3 of the stagnation were used in the analysis because it had the lowest wind speed and the highest solar intensity.

Table 4. Average ambient conditions during experiments (between 12:30 pm and 2:30pm local time).

Experiments	Solar intensity (W/m^2)	Ambient temperature (°C)	Wind speed (m/s)
Stagnation (day 1)	538.8	33.0	0.8
Stagnation (day 2)	512.6	32.2	0.5
Stagnation (day 3)	606.3	33.5	0.4
Water heating (1 kg)	764.8	35.7	1.2
Water heating (1.5 kg)	454.3	32.1	0.7
Water heating (2 kg)	800.0	34.9	0.0

3.3. Water Temperature

Figures 3-5 show the results of the water heating tests carried out for 1, 1.5 and 2 kg of water respectively. Considering these results alongside table 4, it was observed that the performance of the solar cookers varied with amount of water, insolation intensity and wind speed. The solar cookers performed best in heating 1kg of water given an insolation of 764.8 W/m^2. The temperatures attained by all the pots were suitable for cooking. Cooker 3 and Cooker 4 performed poorly in heating 1.5 kg of water. Although this could be attributed to the low solar intensity (454.3W/m^2), the poor performance can also be traced to the thermal properties of the heat storage materials. The four solar cookers performed better in heating 2 kg compared to 1.5 kg of water because the environmental conditions were better and favourable (higher solar intensity and still air movement). These values are in line with the values reported by Gavisiddesha *et al.* [39], Rikoto and Garba [14] and Adedipe and Abolarin [40] who reported values ranging between 93°C to 97°C.

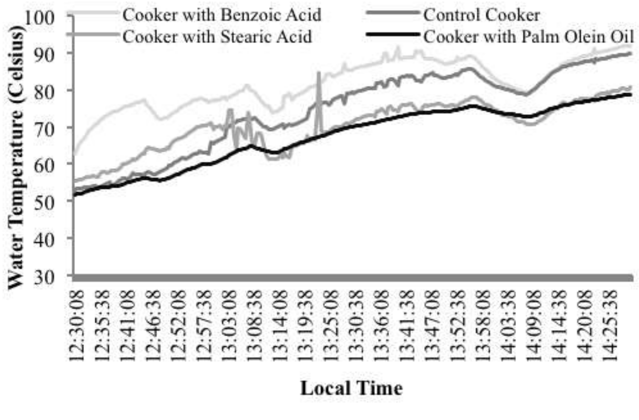


Fig. 3. Water temperature during heating test (1 kg).

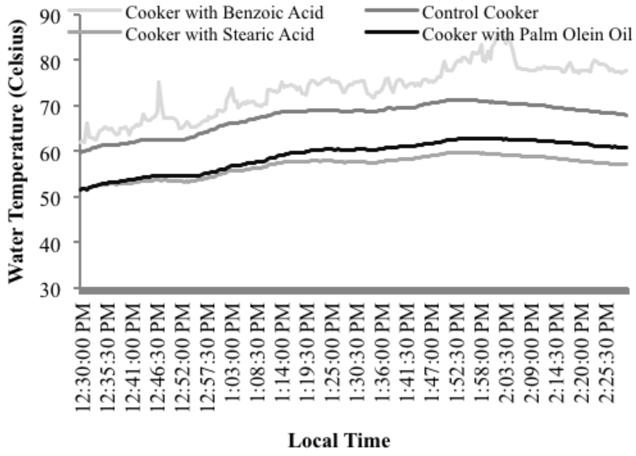


Fig. 4. Water temperature during heating test (1.5 kg).

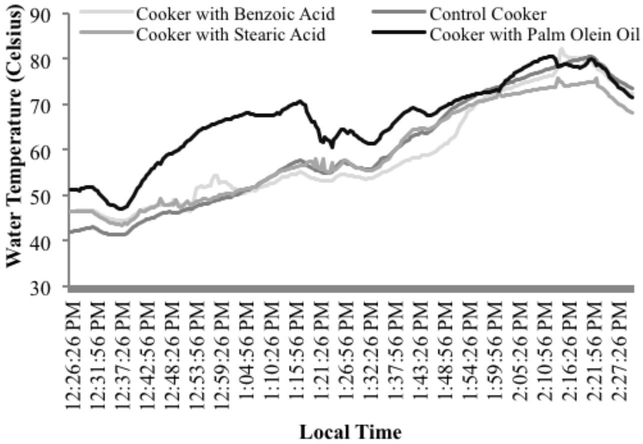


Fig. 5. Water temperature during heating test (2 kg).

3.4. Thermal Performance (ASAE S580 Standard)

3.4.1. Cooking Power

Table 5 shows the average cooking power attained by the solar cookers during the water heating test. Cooker 1 had the highest average cooking power of 47.1 W for 1 kg of water while values lower than 30 W was attained for 1.5 and 2 kg of water. Cooker 2 and 3 attained values higher than 30 W for 1 kg of water but lower than 20 W for 1.5 and 2 kg. Cooker 4 had the lowest cooking power except for 2 kg of water. Benzoic acid was observed to influence a higher thermal performance in the cooker. The use of benzoic acid increased the average cooking power by 12, 3.6 and 3.4 W for 1, 1.5 and 2 kg of water respectively. Similarly, stearic acid was observed to increase the average cooking power (by 1.6 W) only for 1 kg of water and palm olein oil was observed to increase the cooking power for only 2 kg of water by 3.2 W. Hence, the latent heat storage materials influenced a higher cooking power especially for smaller quantities of water compared to the sensible heat storage material used. Arabacigil et al. [20] confirmed the influence of heat storage material (paraffin wax) on the efficiency of a solar cooker.

Table 5. Average cooking power of the solar cookers.

M_w	Average Cooking Power (W)			
	Cooker 1	Cooker 2	Cooker 3	Cooker 4
1 kg	47.1	34.5	36.1	27.4
1.5 kg	23.3	19.7	14.1	14.4
2 kg	21.6	18.2	14.6	21.4

Key: cooker 1- cooker with benzoic acid; cooker 2 - control cooker; cooker 3 - cooker with stearic acid; cooker 4 - cooker with palm olein oil

Figures 6 – 8 show the variation in the cooking power for different amounts of water. The change in cooking power of the four cookers occurred at different rates especially during the few minutes after start-up. Generally, the trend in these graphs can be divided into three stages which are;

1) **Stage 1 (Rising rate)**: This stage spanned between 0 and 1200 sec. This is the stage at which the heat build-up in the DEBSCs occurred. At this stage, the quantity of water used had no effect on the rate of increase in cooking power. The presence and type of heat storage materials was the only factor observed to cause the variation across the DEBSCs.
2) **Stage 2 (Falling rate)**: At this stage, the cooking power of the cookers drops from the peak value which occurs usually after 1200 sec. This reduction is not only as a result of reduction in solar intensity but, also as a result of a reduction in the difference in the temperature of water at two consecutive intervals. The falling rate was observed to depend on the quantity of water. For 1 kg of water the falling rate lasted between 1200 and 7200 sec while for 1.5 kg of water it occurred at 1200 – 7800 sec. For 2 kg of water, the falling rate started from 1200 – 9600 sec. The heat storage materials had no effect at this stage.
3) **Stage 3 (Constant rate)**: At this stage, the cooking power can be assumed to be stable over a period of time. This stage started after 7200 sec for 1 kg of water and after 7800 sec for 1.5 kg but it was not observed while heating 2 kg of water until after 9600 sec. This is the period when the solar radiation is not completely responsible for the heating but, the heat storage material transfers heat to the pot at a uniform rate.

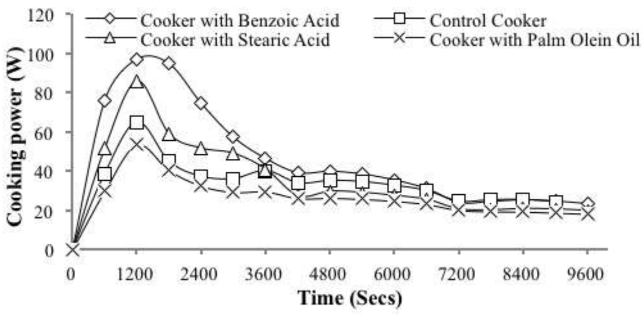


Fig. 6. Cooking power of the solar cookers for 1 kg of water.

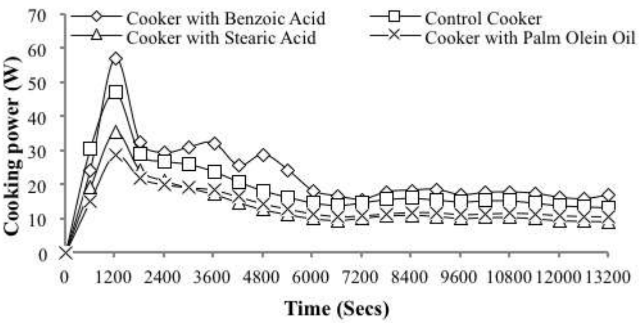


Fig. 7. Cooking power of the solar cookers for 1.5 kg of water.

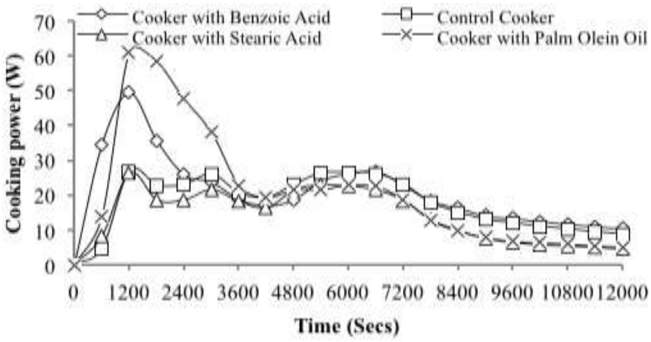


Fig. 8. Cooking power of the solar cookers for 2 kg of water.

From table 6, it can be seen that most of the heat storage materials had a significant influence on the cooking power for 1 and 1.5 kg of water in a double exposure box-type solar cooker. For 2 kg of water, it was observed that only stearic acid had effect on the cooking power.

Table 6. T-test comparison of the cooking power of DEBSCs containing heat storage media with that of the control DEBSC (cooker 2).

	P-values		
	1 kg	1.5 kg	2 kg
Cooker 1	0.010	0.00	0.166
Cooker 3	0.525	0.00	0.001
Cooker 4	0.000	0.00	0.149

Key: cooker 1- cooker with benzoic acid; cooker 2 - control cooker; cooker 3 - cooker with stearic acid; cooker 4 - cooker with palm olein oil

3.4.2.Standardized Cooking Power (P_s)

Table 7 shows a summarized result of the maximum standardized cooking power. When the cooking power was standardized using a solar intensity of 700 W m^{-2}, cooker 1 had the highest cooking power for 1 and 1.5 kg of water but for 2 kg of water, cooker 2 had the highest power. For 1 kg of water, it was observed that using benzoic acid increased the standardized cooking power by 19.1 W and by 12.7 W when stearic acid was used. Using palm olein oil reduced the cooking power by 7.1 W. Similarly, for 1.5 kg of water, standardized cooking power was only increased by benzoic acid (13.5 W) but was reduced by stearic acid (13.9 W) and palm olein oil (16.5 W). For 2 kg of water, the standardized cooking power was reduced with the use of the three heat storage materials.

Table 7. Maximum standardized cooking power of the solar cookers.

M_w	Maximum Standardized Cooking Power (W)			
	Cooker 1	Cooker 2	Cooker 3	Cooker 4
1 kg	59.1	40.0	52.7	32.9
1.5 kg	77.4	63.9	50.0	47.4
2 kg	37.7	41.1	34.1	40.0

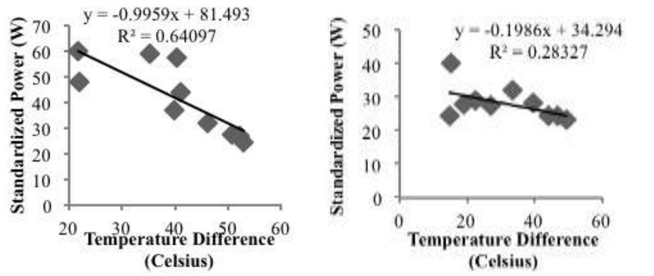
Key: cooker 1- cooker with benzoic acid; cooker 2 - control cooker; cooker 3 - cooker with stearic acid; cooker 4 - cooker with palm olein oil

3.4.3.Temperature Difference (T_d)

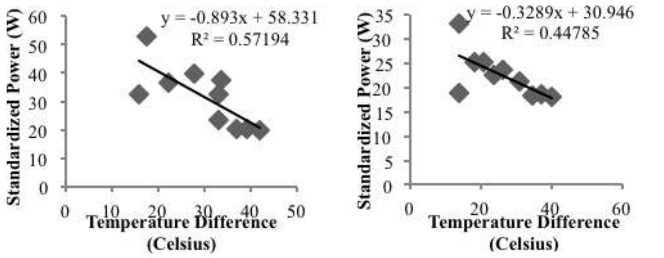
The difference between the temperature of 1 kg of water in cooker 1 and the ambient temperature varied from 21.9 – 57.6 ºC and lower values of 14.8 – 56.4 ºC; 15.7 – 46.8 ºC and 13.9 – 44.9 ºC were attained by cookers 2, 3 and 4, respectively. Lower temperature difference was observed for 1.5 kg of water which varied between 6.7 – 42.4 ºC; 6.4 – 38.0 ºC; 5.6 – 26.7 ºC and 3.2 – 29.6 ºC for cookers 1 – 4 respectively. For 2 kg of water, the temperature differences varied between 14.5 – 43.3 ºC; 21.3 – 43.2 ºC; 12.1 – 38.6 ºC and 20.7 – 43.6 ºC for cookers 1 – 4 respectively. Despite the discrepancies in the performance of the cookers, this result shows that the cookers performed relatively well in raising the temperature of water above that of the ambient.

3.4.4.Regression Plot

The regression plot and equation between the standardized power and the temperature difference in heating 1, 1.5 and 2 kg of water for the four cookers is depicted in Fig. 9 – 11, respectively. It was generally observed that the correlation coefficient reduces with increase in quantity of water for all the cookers. Cooker 1 had the highest correlation coefficient for the three amounts of water. This shows that benzoic acid ensures a higher correlation between the cooker's performance and the temperature difference. The correlation coefficient for the control cooker was lowest for 1 kg of water while cooker 4 had the lowest correlation coefficient for 1.5 kg and 2 kg of water. Generally, it was observed that heat storage materials reduce the rate of change of the temperature difference leading to a disproportionate increase compared to the increase in cooking power. This effect reduces with reduction in the quantity of water heated. Hence, with lesser quantities of water, the heat storage materials stabilize the cooking power and ensure proportionate increase as the temperature difference increases compared to a cooker without heat storage material.

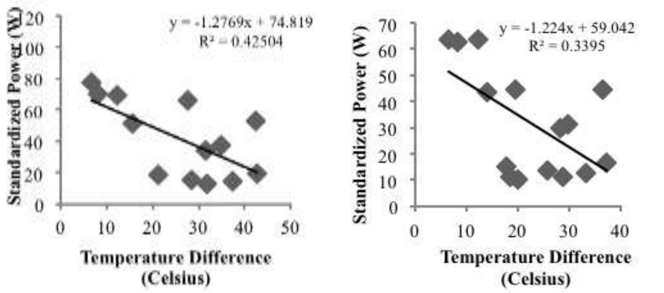


a: Cooker with benzoic b: Control cooker

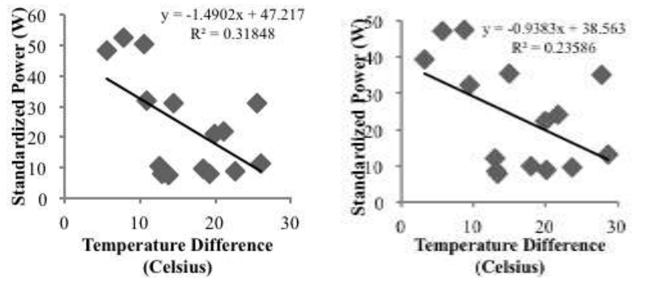


c: Cooker with stearic d: Cooker with palm olein oil

Fig. 9. Standardized power vs. temperature difference for 1 kg of water.

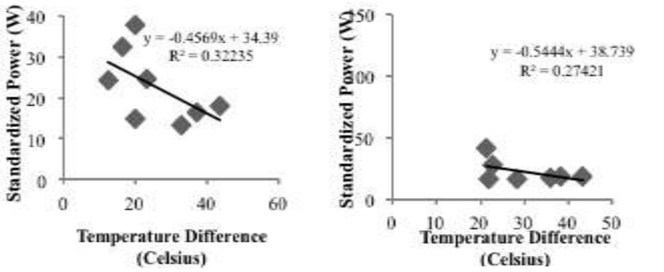


a: Cooker with benzoic b: Control cooker

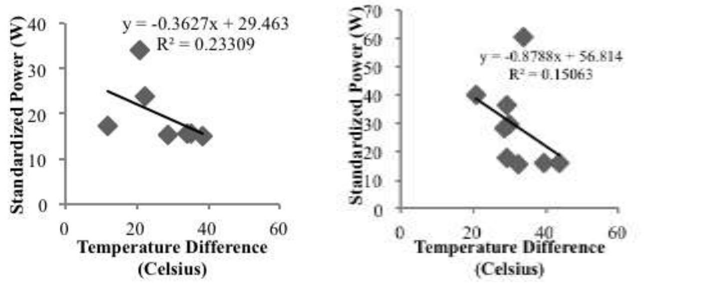


c: Cooker with stearic d: Cooker with palm olein oil

Fig. 10. Standardized power vs. temperature difference for 1.5 kg of water.



a: Cooker with benzoic b: Control cooker



c: Cooker with stearic d: Cooker with palm olein oil

Fig. 11. Standardized power vs. temperature difference for 2 kg of water.

3.4.5.Single Measure of Performance

Table 8 shows the predicted single measure of performance based on the regression equations developed between standardized power and temperature difference. The values ranged from 11.39 – 31.49 W for 1 and 2 kg of water. The heat storage materials had a negative effect on the single measure of performance for all the quantities of water except for 1 kg of water in which benzoic acid increased the value by 7.2 W.

Table 8. Single measure of performance at 50 ºC.

Solar Cookers	M_w (kg)	Slope (W/ºC)	Intercept (W)	Standardized Cooking Power at 50 ºC (W)
Cooker 1	1	– 1.00	81.49	31.49
	2	– 0.46	34.39	11.39
Cooker 2	1	– 0.20	34.29	24.29
	2	– 0.54	38.74	27.00
Cooker 3	1	– 0.89	58.33	13.83
	2	– 0.36	29.46	11.46
Cooker 4	1	– 0.33	30.95	14.45
	2	– 0.88	56.82	12.84

3.5.Thermal Performance (IS 13429 – 3)

3.5.1.First Figure of Merit (F_1)

Table 9 shows the result of the first figure of merit of the solar cookers. Cooker 2 had the highest first figure of merit which ranged from 0.13 – 0.15 ℃ m^{-2} W^{-1}. This can be attributed to the fact that the heat storage materials were the additional loads limiting the performance of the cookers compared to the control cooker. The F_1 of the four cookers agrees with the report by Aremu [15] whose values ranged from 0.10 – 0.15 ℃ m^{-2} W^{-1}. Based on the calculated averages, cooker 1, cooker 2 and cooker 3 can be classified to be grade A cookers according to the criteria given in IS

13429 – 1 [36], while cooker 4 can be classified to be grade B.

Table 9. First figure of merit of the DEBSCs.

Day	First Figure of Merit (°C/m²W)			
	Cooker 1	Cooker 2	Cooker 3	Cooker 4
1	0.13	0.13	0.11	0.11
2	0.13	0.15	0.12	0.12
3	0.14	0.15	0.13	0.12
Average	0.133	0.143	0.12	0.11
Class	Grade A	Grade A	Grade A	Grade B

Table 10 shows the result of the t-test carried out on the first figure of merit. It was observed that at stagnation, using stearic acid as a heat storage material had effect on the thermal performance (F_1) since the p-value for cooker 3 was lesser than 0.05. On the other hand, using benzoic acid and palm olein oil had no effect on F_1 since their p-value was higher than 0.05; this is in line with the simulation result of Lecuona et al. [34].

Table 10. Comparison of F_1 of DEBSCs containing heat storage media with that of control DEBSC (cooker 2).

	P value	Significance at 5%
Cooker 1	0.607	Insignificant
Cooker 3	0.002	Significant
Cooker 4	0.465	Insignificant

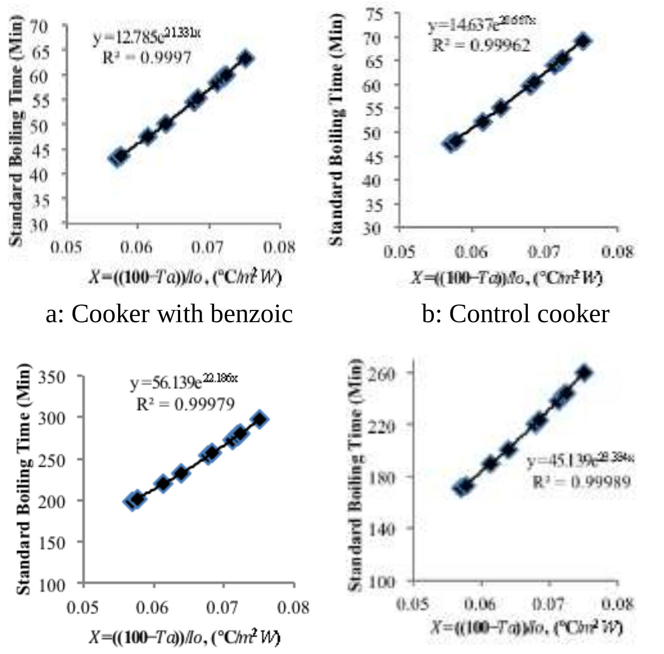
3.5.2. Second Figure of Merit (F_2)

In heating 1 kg of water, the calculated F_2 were 0.45, 0.40, 0.10 and 0.12 for cooker 1 – 4 respectively. The F_2 for cooker 1 and 2 satisfied the requirements of IS 13429 – 1 by having F_2 up to 0.40. It was also observed that the use of benzoic acid increases F_2 while stearic acid and palm olein oil reduces it.

The F_2 for other quantities of water were not estimated because 90 ºC was not attained during heating.

3.5.3.Standard Boiling Time (t_{boil})

Figure 12 shows the time required for 1 kg of water to boil. The time required for cooker 1 to boil 1 kg of water at the given ambient condition ranged from 47.7 – 63.2 min while it will take 48.1 – 68.9 min for cooker 2 to boil. Cooker 3 and 4 will take longer time to boil which are 198.6 – 296.3 min and 170.6 – 259.9 min, respectively. These values corroborate with the results obtained using ASAE standard for evaluating thermal performance which reiterates the poor performance of cooker 3 and 4 in water heating compared to cookers 1 and 2.



a: Cooker with benzoic b: Control cooker

c: Cooker with stearic d: Cooker with vegetable oil

Fig. 12. Standard boiling time vs. X for 1 kg of water.

4. Conclusion

In this paper, the effect of using benzoic acid, stearic acid and palm olein oil as heat storage materials on the thermal performance of a double exposure box-type solar cooker (DEBSC) was investigated. Water heating and stagnation experiments were conducted on DEBSCs based on the American Society of Agricultural Engineers Standard (ASAE S580) and Bureau of Indian Standards (BIS). The results of these experiments show difference in the thermal performance of the cookers with benzoic acid, stearic acid and palm olein oil compared to the cooker without heat storage material. Generally, the heat storage materials influenced a disproportionate increase in the temperature difference compared to the cooking power. The change in cooking power occurred in three stages – rising, falling and constant rates. The heat storage materials were observed to affect the rising rate and the falling rate. Benzoic acid caused a higher cooking power, standardized cooking power and second figure of merit, but it reduced the first figure of merit and the standard boiling time of the DEBSCs. On the other hand, stearic acid and palm olein oil reduced the values of the cooking power, standardized cooking power and the first and second figures of merit of the DEBSCs with increased standard boiling time. This paper reveals the type of effect and the extent of influence some heat storage materials have on the different parameters indicating the thermal performance of a DEBSC.

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