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Comparative analysis of the Performance of Solar Box Cookers with Kapok and Saw Dust Insulators

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Abstract

The necessity for the search for available and affordable alternative source of energy to supplement the use of firewood for food cooking cannot be over emphasized. The present work is aimed at development of solar box cookers which employed two different natural thermal insulators namely Kapok wool and Saw dust, their performance evaluation were compared. The method employed was; the two thermal performance parameters called figures of merit (F_1 and F_2) associated with testing box-type solar cookers as per Bureau of Indian Standards (BIS). The First Figure of Merit, F_1, was determined from a stagnation test under no-load condition while the Second Figure of Merit, F_2, was determined from test under full-load condition, taking water as the load. The results obtained were subjected to statistical analysis using F-test, which clearly indicates that there are no significant differences in both the stagnation (no load) test (F_1) since F value is 1.116678 which is less than the F Critical value of 1.98376 at 5 % level of significance and 24 degree of freedom. And for the boiling (load) test (F2), the F Test value is 1.034856 which is less than the F Critical value of 2.576927 at 5 % level of significance and 13 degree of freedom for both cookers. The results for no load test (F_1) were found to be (0.123 Km^2W^{-1}) and (0.124 Km^2W^{-1}) for cookers with Kapok wool insulator and Saw dust insulator respectively, while results of the load test (F_2) were 0.057 and 0.056 for cooker with Kapok and Saw dust insulator respectively. The study on Kapok wool and Saw dust insulators reveals a promising future for the natural insulators in term of better insulation and low conduction losses and a better cooking ability of both cookers as the value obtained surpasses the standard given by Bureau of Indian Standards (BIS).

1. Introduction

In Nigeria and many other developing countries commercial fuels like coal, kerosene, cooking gas and electricity are very expensive beyond the reach of common man. Majority of the people depend on fuel wood for cooking purposes. Cutting down of trees for fuel wood has led to fast and rapid depletion of our forest therefore increased fuel wood price which imposes economic and social burden on the people as well as cause environmental and ecological problems. The necessity for the search for available and affordable alternative source of energy to supplement the use of firewood

for food cooking cannot be over emphasized. Solar energy through solar cooking offers a possible solution to these problems [1].
Cooking accounts for the major amount of energy consumption in the rural areas of developing countries. In rural areas, most of the cooking energy requirement is met by firewood (69.96 %), Kerosene (26.55 %), Charcoal (0.84 %), Gas (1.11 %) and Electricity (0.52 %) as shown in figure 1. Poor villagers have to forage in search of firewood; cutting of firewood also causes deforestation. Utilization of solar energy for cooking can solve the problem of deforestation to an extent. [2].

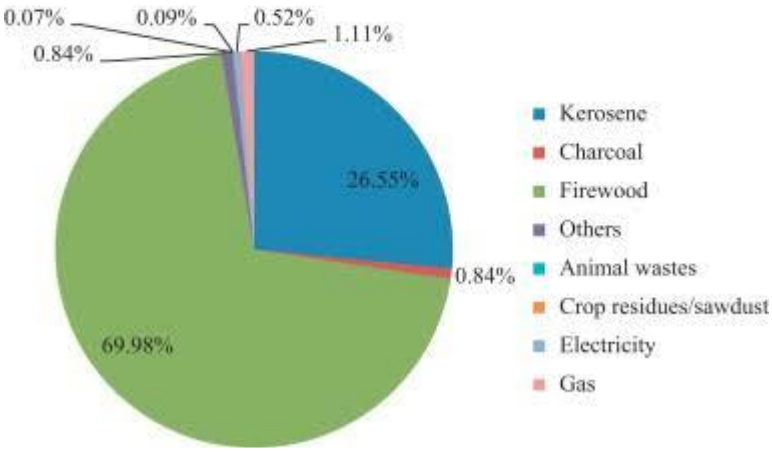

Figure 1: Cooking energy utilization in Nigeria.

Nigeria is one of the densely populated countries in Africa with approximately 218.5 million people in an area of 923,768 km^2[3]. The country lies within a high sunshine belt and thus has enormous solar energy and other solar related potentials. The resources in the Northern part of the country, in particular, provide a more viable potential for solar use with solar insolation of up to 7 kWh/m^2/day and an average sunshine hours of about 9 hours per day [4]. Hence, the country does have rich potentials for renewable energy (solar power production in particular).

Solar cooking presents an alternative energy source of cooking, which is simple, safe and convenient without consuming fuels, and not polluting the environment. Utilization of solar cookers provide many advantages with no recurring costs, high nutritional value of food, potential to reduce drudgery and high durability, [5]. Also, solar cookers have many advantages, on the health, time and income for the users and on the environment. Also, solar cooking is a better substitute for cooking by fuel or wood in Nigeria. Solar energy has become one of the most promising alternative energy resources because it is free, environmental friendly and available in abundance.

From the last few decades, solar energy is utilized in the field of cooking using different types of collector such as box type solar cooker, parabolic dish collector, parabolic trough collector and evacuated tube collector, [6].

Several research works were conducted in different areas of solar cooking that includes thermal testing and performance evaluation of different types of solar cooking devices. Such devices include concentrating solar cookers, [7]. Parabolic solar cookers, panel solar cookers, Hot Box Solar Cookers, square and rectangular box type solar cookers of [8]. Double exposure solar cookers, solar cookers with thermal storage and many others by various authors with the aim of improving the efficiencies of these cookers were carried out. [9] have worked on the Performance Tests and Thermal Efficiency Evaluation of a Constructed Solar Box Cooker at a Guinea Savannah Station (Ilorin, Nigeria), the results obtained showed that a maximum temperature of 88^{o}C was attained for the water boiling tests and the average collector efficiency of the solar box cooker has been estimated to be about 47.56 %. [10] have studied potential use of box type solar cooker for developing countries. They have studied the parameters of box type solar cooker like Stagnation temperature, Figures of merit, thermal efficiencies and cooking power of different types of solar cookers. [1] conducted a comparative analysis on solar cooking using box type solar cooker with finned cooking pot, the analysis revealed clearly that fins improved the heat transfer from the internal hot air of the cooker toward the interior of the pot. Recently, [11] studied an assessment of solar box cooker (SBC) with kapok fiber insulator under Maiduguri weather conditions, the result of the study showed that solar box cookers can perform well under Maiduguri weather condition with a thermal efficiency of (η) = 44 % and cooking power of 14.

The present study is aim at comparative analysis of the performance of solar box cookers with two different natural insulating materials namely; kapok wool and saw dust as thermal insulators in term of figure of merits specified by Bureau of Indian Standards [12].

2.0 Materials and Method

2.1 Solar box cookers

For solar cooking purpose two similar solar cookers were developed (cookers A and B). Both cookers A and B consist of a double walled hot box made of ¾ ply wood. The specific dimensions of the outer and inner box were approximately 700 × 700 × 445 mm and trapezium shape inner dimensions are 400 × 400 × 360 mm inclined at an angle of 21^0respectively. The space between the inner tray and outer box were filled saw dust for A and Kapok wool for the other solar box cooker B. The thermal conductivity of Kapok wool was determined by [13] using Degiovanni model ranges between 0.03 -007 W/m^{o}K. [14] Stated that the thermal conductivity of saw dust ranged from 0.185 – 0.240 W/m^{o}K. The inner trays made of aluminum painted dull black to absorb maximum solar energy. The leakage from the box to the surroundings was minimized by having a rubber gasket (1.5 mm thick) in between the triple glass cover (25 mm glazing) and the box. The cooking vessels used in this study were bought from the local market, it is made of Al alloy (18 cm in diameter and 10 cm in height) in a cylindrical shape and painted black to allows for high absorption of solar radiation designed to kept cooking, filled with water and equipped with a black cover, one each was placed into each of the solar box cookers. Three clear window glass panes of 4 mm thickness were fixed over the box. The space between these three panes of glass is critical. The air gap also acts as an insulator. A three layers glazing with 25 mm gap was used to transfer the direct radiation to the absorber trays. As shown in figure 2. The two solar box cookers had strictly identical designs except for the different in insulation materials.

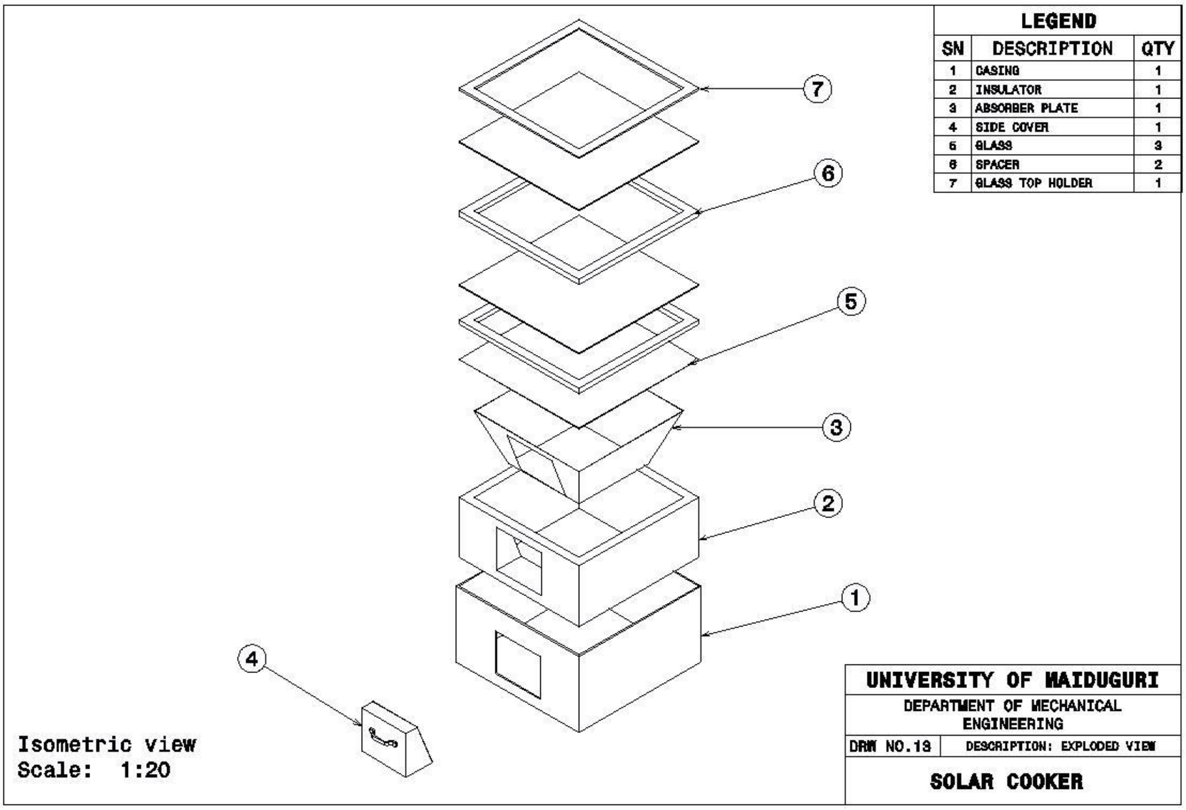

Figure 2: Exploded view of the developed solar box cooker

2.2 Procedure of Experimentation and Evaluation

For the evaluation of the performance tests of the solar box cookers, the cooking device were positioned in the open space at Centre for Entrepreneurship and Enterprises Development (CEED) University of Maiduguri. The thermal system was placed in such a way that it was free of shadows throughout the period of investigation. Following the standard international procedures developed by the Bureau of Indian Standards (BIS) [12] which has been further revised by [15]. The test procedure provides performance characteristics of solar cookers, more or less independent of climatic variables. There are two thermal performance parameters called figures of merit (F1 and F_2) associated with testing box-type solar cookers as per [12]. The First Figure of Merit, F_1, is determined from a stagnation test under no-load condition while the Second Figure of Merit, F_2, is determined from test under full-load condition, taking water as the load. First Figure of meritF_1, (^oC m^2/W) or stagnation test is defined as: [12].

$$F_1 = \frac{T_p - T_a}{I_s} \quad (1)$$

Where T_p, T_a, and I_s are absorber plate temperature, ambient temperature and solar intensity on a horizontal surface at a time stagnation temperature is reached respectively. Second Figure of merit F_2 or water heating test is defined as:[12].

$$F_2 = \frac{F_1 m_w c_w}{At} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w_1} - T_a}{I_s}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w_2} - T_a}{I_s}\right)} \right] \quad (2)$$

where F_1 is the First Figure of Merit, M_w is the mass of the water, C_w is the specific heat of water, T_{w1} is the initial temperature of water (≡ 60^{o}C), T_{w2} is the final temperature of water (≡ 90^{o}C), t is

the measured time difference in which the water temperature rises from T_{w1} to T_{w2}, T_a is the average ambient temperature over the time period t, H is the average solar radiation intensity incident on the aperture of the cooker, and A is the aperture area of the solar cooker.
During all experiments, the instruments used in measuring the evaluation parameters are shown plate 1and describe in Table 1. The BIS test standard requirements for temperature range and insolation were applied for the solar box cookers on each day**.** Plate 1 shows the experimental set up of the two similar solar box cookers; namely solar box cooker with kapok wool insulator and solar box cooker with saw dust insulator,

Plate 1: Experimental set up of the two similar solar box cookers

Table 1: Apparatus Table

Description	Purpose
Digital pyrometer (SPM-1116SD)	Solar radiation intensity (W/m^2)
Measuring cylinder	Water volume (m^3)
Digital anemometer (ABH-4224)	wind speed (m/s) and Ambient Temperature (^{o}C)
Digital thermometer (MTM-3801) and thermocouples	Water temperature and absorber plate temperature (^{o}C)

3.0 Results and discussion

Figure 3 depicts the variation between the Absorber Temperature of solar cooker with kapok wool insulator and the Absorber Temperature of solar cooker with saw dust insulator with corresponding solar radiation/solar time. The tests were conducted from 10:00am to 14:00pm noon. These temperatures were recorded at an interval of 10 minutes. It was observed that absorber plate for initial temperatures of cooker with kapok insulator was 81.5^{o}C and saw dust was 74.8°C. These temperatures were found to be increasing till 13:20 and then started to fall. The maximum temperatures attained were 145.7^{o}C for the cooker with kapok wool insulator which was recorded at 13:20 while that for cooker with saw dust insulator was 146.6°C at 13:20. Low ambient temperature and low solar radiation can lower down the temperature of the absorber plate. The result shows that heat loss from absorber plate of the cooker is minimal and the absorber plate temperature

is retained for a long time. This is desirable for heating water since major mode of heat transfer to the cooking vessels is by conduction from absorber plates as reported by [16].
Equation (1) was used to compute F_1 and the obtained value of F_1 is 0.123 $Km^2W^{-1}$for cooker with kapok insulator and 0.124 Km^2W^{-1} for cooker with saw dust insulator, the allowed standard test specified by [12]. States; that if the value of F_1 is ≥ 0.12, the cooker is marked as A-Grade solar cooker and if ≤ 0.12 the cooker is marked as a B-Grade solar cooker, The high value of first figure of merit is as a result of high insolation, as well as low conduction loses from the cookers. F_1 value attained for the experiment was similar to value found by [16] and [11].

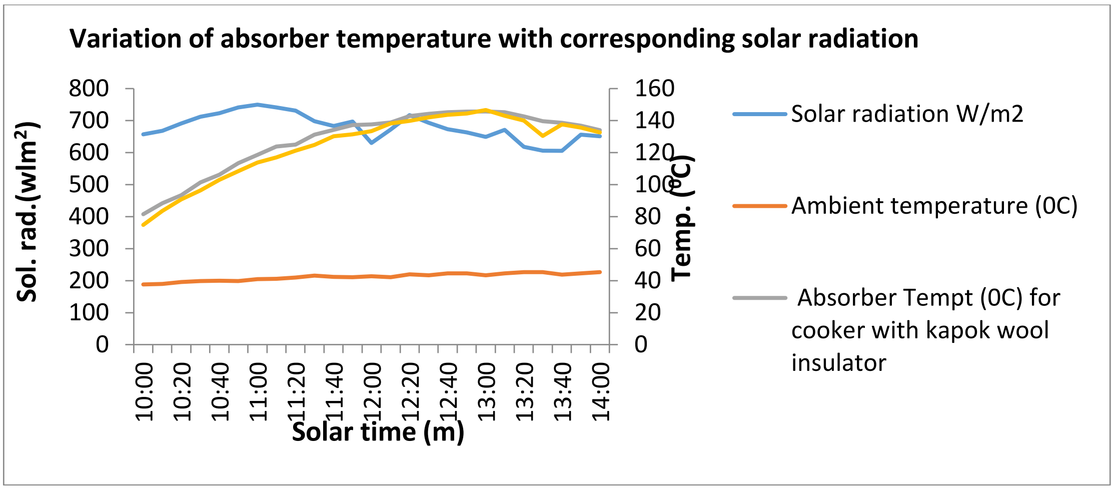

Figure 3: Variation between the Absorber Temperatures of the two solar cookers with corresponding solar radiation/solar time.

The statistical tool used to test for the significant difference between the solar cooker with Saw dust insulator Absorber Temperature and the Absorber Temperature of solar cooker with Kapok wool insulator is in Microsoft Excel, F Test as shown in Table 2, in the F Test, the F value is 1.116678 which is less than the F Critical value of 1.98376 at 5 % level of significance and 24 degree of freedom. This shows that there is no significant difference between the two absorber plate temperature outputs.

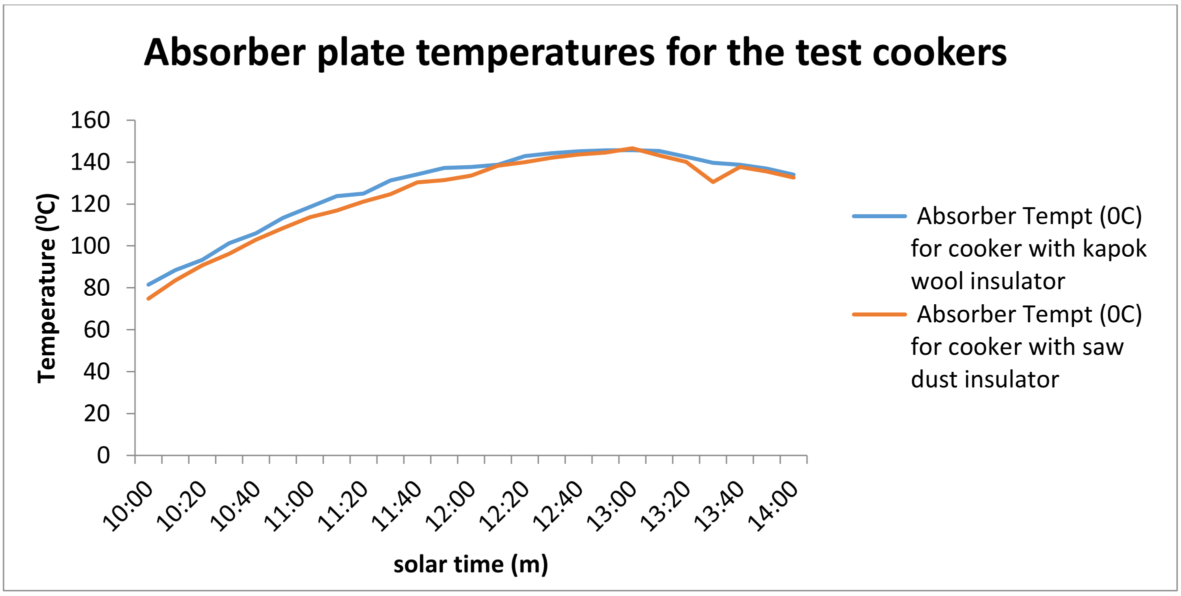

Figure 4: Similarity of Absorber Temperatures of the two solar cookers with corresponding solar time.

Table 2; F-Test Two-Sample for Variances

	Saw dust Absorber Tempt (°C)	*Kapok Absorber Tempt (°C)*
Mean	124.12	127.644
Variance	422.215	378.0992
Observations	25	25
df	24	24
F	1.116678	
P(F<=f) one-tail	0.39456	
F Critical one-tail	1.98376	

Figure 5 Shows variation between the Water Temperature of solar cooker with kapok wool insulator and the Water Temperature of solar cooker with saw dust insulator with corresponding solar radiation and solar time. The tests were conducted from 10:00 am to 14: 00 pm. These temperatures were recorded at an interval of 10 minutes. Initial temperature of water in the solar box cooker with kapok wool insulator and solar box cooker with saw dust insulator were 34.3°C and34.8°C respectively. Initially, the water temperature was almost same as the ambient temperature. The trend of the water temperatures for solar box cooker with kapok wool insulator and solar box cooker with saw dust insulator became nearly similar 99.8°C and 98.2°C at 12:00pm as can be seen from figure 5.The ambient temperature was initially 34.7°C which increased gradually up to the maximum of 45.1°C during the experiment. From figure 5, It was observed that solar box cookers were at low temperature in the morning hours from 10:00 am to 11.00 am at temperatures between 30°C and 70°C, which might not be good enough to boil water. However, the temperature begins to increase from 11.00 am. It maintains slightly high temperature enough to cook food from the hours of 11:30 am. This ensures that the best time to cook with the solar box cooker start at the hours of 11.00 on sunny days.

The thermal load tests were conducted to determine the second figure of merit (F_2) and they were evaluated under full load condition. The solar box cookers were loaded with 1 kg of water each. Equation (2) was used to compute F_2, the obtained F_2 values for cookers with kapok wool insulator and saw dust insulator were found to be 0.057 and 0.056 respectively and similar results were obtained by [17], [18] and [19].

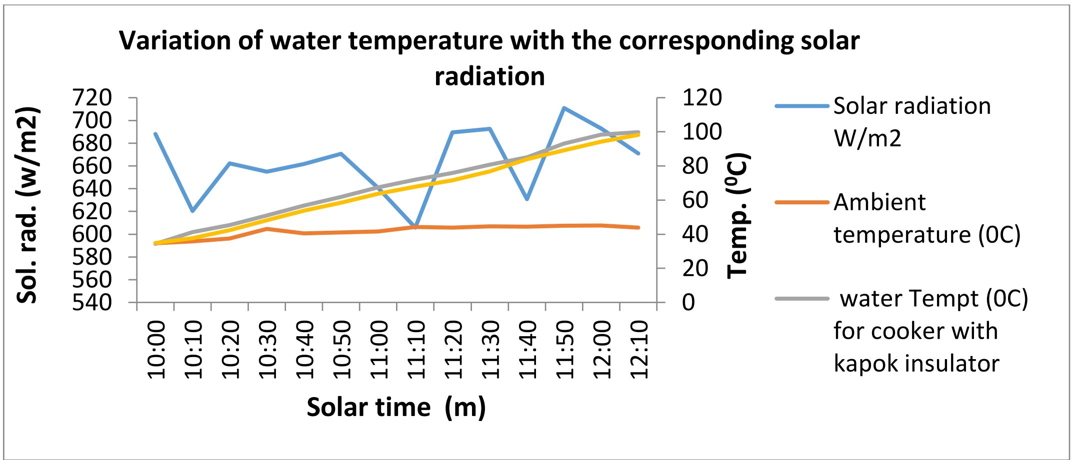

Figure 5: Variation between the Water Temperature of the two solar cookers with corresponding solar radiation/solar time

The statistical tool used to test for the significant difference between the two cookers water Temperature in Microsoft Excel is F Test as shown in Table 3. In the F Test, the test value is 1.034856 which is less than the F Critical value of 2.576927 at 5 % level of significance and 13 degree of freedom. This shows that there is no significant difference between the two cookers water temperature outputs.

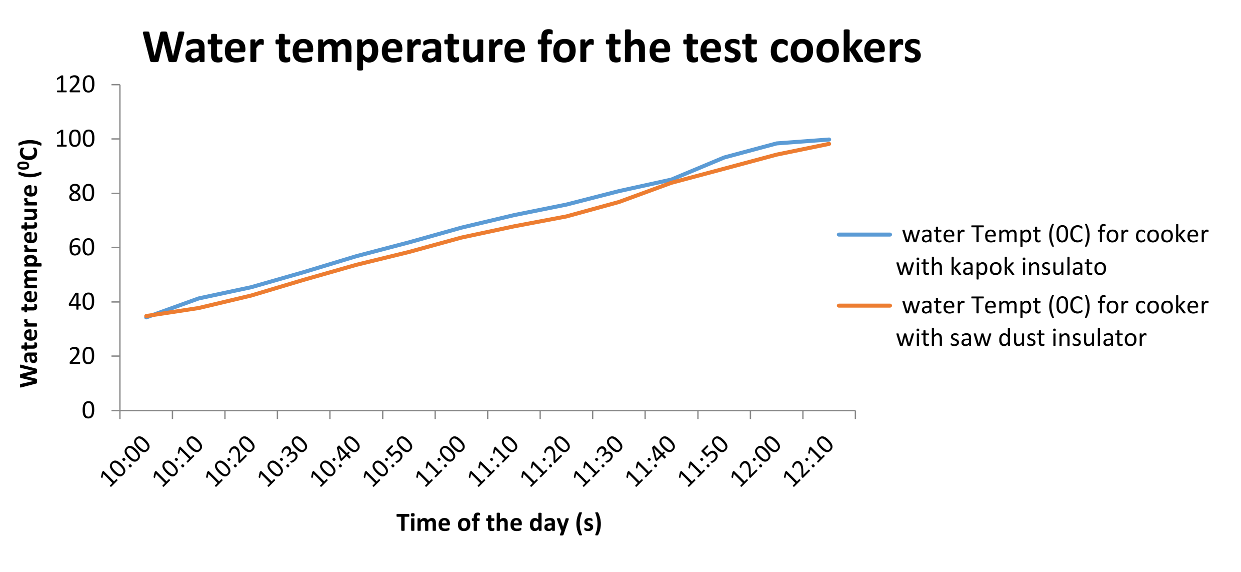

Figure 6: similarity of Water Temperatures of the two solar cookers with corresponding solar radiation/solar time

Table 3; F-Test Two-Sample for Variances

	Kapok water Tempt (ºC)	Saw dust water Tempt (ºC)
Mean	68.8	65.74286
Variance	454.3015	438.9996
Observations	14	14
Df	13	13
F	1.034856	
P(F<=f) one-tail	0.475842	
F Critical one-tail	2.576927	

4.0 Conclusion

Two different solar box cookers were developed, one with Kapok wool and the other with Saw dust insulation materials. The Performance of the cookers were experimentally evaluated and the results obtained were subjected to statistical analysis using F-test, which clearly indicates that there is similarity in both the stagnation (no load) test (F_1) with F value is 1.116678 which is less than the F Critical value of 1.98376 at 5 % level of significance and 24 degree of freedom, and boiling (load) test results (F_2), with F_2 value of 1.034856 which is less than the F Critical value of 2.576927 at 5 % level of significance and 13 degree of freedom for both cookers. No load test (F_1) results 0.123 $Km^2W^{-1}$and 0.124 Km^2W^{-1} for cooker with Kapok wool insulator and Saw dust insulator respectively reveals a promising future for the natural insulators in term of better insulation and low conduction losses. Load test (F_2) results of 0.057 and 0.056 for cooker with Kapok wool insulator and Saw dust insulator respectively, clearly indicates a better cooking ability of both cooker as the value obtained surpasses the standard given by Bureau of Indian Standards both cookers can be regarded as grade A cookers as specified by [12].

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