In this work, the thermal efficiency of a dual-operated solar cooking and drying system that may be utilized for domestic use was examined. An analysis of the system’s thermal performance was conducted at Sokoto Energy Research Centre (SERC) using the Bureau of Indian Standards (BIS). Sampling cooking and drying tests were carried out, and the potential for extended cooking time for brine solution and animal fat was conducted. The results showed that the first figure of merit (F1) value agrees with the standard value of 0.12 and the second figure of merit (F2) value is in close correspondence with 0.25 (BIS Standard). The system was able to dehydrate 89% of the moisture content of banana slices weighing 118 g which is of uniform thickness and the second figure of merit (F2) value agrees with the standard value of 0.12. The findings indicate the potential of this dual-operated system for domestic applications.

Keywords: solar cooking, solar drying, first figure of merit, second figure of merit, thermal storage
electricity, as well as in solar water heating systems, solar space heating for buildings, and drying processes (Tesfay and Venkatesan, 2013). Solar thermal technology stands out as one of the most adaptable and effective forms of renewable energy (Asif and Muneer, 2013). Consequently, solar cooking and thermal storage systems encompass a range of technical considerations, encompassing aspects such as material choice, insulation, methodologies, and thermal transportation.

MATERIALS AND METHODS

The methods used for the conduct of the study are described as follows:

**Determination of Stagnation Temperature for Solar Cooking Application (1st Figure of Merit F1)**

The solar cooker was positioned to face the direction of the sun. The cooker's orientation was such that the lid reflector (mirror) was occasionally adjusted to reflect the sun's rays directly into the cooking chamber. Thermocouple wires were connected to a data logger thermometer and placed on the cooker's absorber plate and the solar collector (glazing material) to measure their temperatures. The cooker was then securely shut. The ambient temperature around the cooker was monitored using a digital thermohygrometer, and the solar insolation of the sun's rays was measured using a pyranometer. Measurements were taken every ten minutes until the temperature reached stagnation. This was repeated for two days.

![Plate 1: Stagnation Temperature under Cooking Condition](image_url)

**Determination of Stagnation temperature for solar drying applications**

The experimental setup was the same as described in paragraph 2.1, except that the two venting ports (inlet and outlet) are kept open. The variation in solar radiation, ambient temperature, solar collector temperature and temperature of the absorber plate were measured at intervals of ten minutes. The experiment was carried out until stagnation was reached. This was repeated for two days.
Determination of Water Boiling Test (2nd Figure of Merit $F_2$)

The experimental setup for this determination is the same as described in paragraph 2.1, however, 0.51 kg of water was loaded into the cooker. Water temperature inside the pot, ambient temperature, solar collector temperature and solar radiation were recorded at intervals of ten minutes. The experiment was carried out until water temperature reached 100°C. This was repeated for two days.

Plate 3: Experimental Set-up of Water Boiling Test

Determination of Figures of Merit

The first figure of merit ($F_1$) is the ratio of optical efficiency to heat loss factor while the second figure of merit ($F_2$) is heat transfer capacity of the cooker interior. ($F_1$) was determined by monitoring the time and temperature of the solar box cooker under no load condition while $F_2$ was determined under full load condition. Hence according to Mullick et al. (1987), $F_1$ and $F_2$ can be determined using equation 1 and 2, respectively.

\[ F_1 = \frac{F'_\eta}{F'_UL} = \frac{T_{ps} - T_{as}}{H} \]  

\[ F_2 = \frac{F_1(MC_w)}{A_t} \ln \left[ \frac{1 - \frac{1}{F_1(T_{w1} - T_a)}}{1 - \frac{1}{F_1(T_{w2} - T_a)}} \right] \]  

Where

- $F_1$ = stagnation temperature (first figure of merit)
- $F'_\eta$ = system optical efficiency
- $F'_UL$ = overall heat loss coefficient.
- $T_{ps}$ = stagnation plate (tray) temperature ($^\circ$C),
- $T_{as}$ = average ambient temperature ($^\circ$C)
- $MC_w$ = product of the mass of water and its specific heat capacity.
- $A_t$ = the aperture area of the box-type solar cooker per the time interval during which water temperature rises from $T_{w1}$ to $T_{w2}$.
- $F'$ represents the heat exchange efficiency factor.
- $T_{w1}$ = water temperature
- $H$ = solar radiation level (W/m$^2$)
- $T_a$ = ambient temperature.

Sample Cooking and Drying Application Evaluation Tests

Cooking Test

An aluminum cooking pot of 200 mm diameter × 100 mm height was used to evaluate the cooking performance of the cooker. Six pieces of eggs were boiled in 0.51 kg of water, taking note of the temperature range and time it took the eggs to be cooked. However, the system was heated up to the minimum cooking temperature range ($72 ^\circ$C – $82 ^\circ$C) before loading the cooking materials into the system. The eggs were considered to have been cooked when the temperature of the water reached $82 ^\circ$C. Additionally, the amount of time it took to cook the eggs was recorded. Water temperature inside the
pot and absorber plate temperature was taken with the aid of thermocouple wires and digital data logger thermometer.

**Drying Test**

Solar drying performance test was evaluated by drying banana slices weighing 118 g. The banana was peeled and sliced into a uniform thickness of size 4 to 5 mm, it was then placed on the drying rack layer in the dryer. Following loading at 10:00 am, drying began right away and continued until the banana slices reached its minimum moisture content. A digital scale was used to monitor the sample’s weight loss at hourly intervals throughout the drying process. To allow the solar collector to efficiently absorb the most solar radiation throughout the drying process, the reflector’s location was modified in relation to the solar angle. Moisture content from the specimen was determined based on the wet basis analysis by using equation 3. Also, the time it took the banana slices to stabilize in weight were recorded as well as weight of the sample, and solar radiation at an interval of one hour.

\[
\%\text{MC}_{\text{wb}} = \frac{\text{Mass of the Product} - \text{Mass of the Fully Dried Product}}{\text{Initial Mass of the Wet Product}} \times 100
\]  

(3)

**Assessment of Brine Solution and Animal Fat as Storage Material**

The experimental setup used for this determination was the same as described in the stagnation test (F1). The potential of each thermal storage material in the system was determined by monitoring the length of time the system took to cool after heating to stagnation. This was carried out by putting the dual solar cooking and drying system to a close by covering it with its cover to block the penetration of solar radiation. During this procedure, temperature variations of the absorber plate were recorded over thirty minutes using thermocouple wires and a digital data logger. This was repeated for two days.

**RESULTS AND DISCUSSION**

**Stagnation Temperature for Solar Cooking Application (1st Figure of Merit F1)**

The first figure of merit (F1) was attained through the air stagnation temperature test of the passive solar cooking system. The test was conducted under variable solar radiation measured in W/m². The results of the (stagnation) tests are shown in Figures 3.1 and 3.2, shows the variations of the system temperatures until the stagnation conditions are achieved. The tests were conducted with and without a storage tank. Both tests have attained stagnation temperatures of 120.9 ºC and 130.8 ºC for the collector plate for a period of 2 hours 10 minutes and 2 hours 40 minutes respectively. The first test was conducted without the storage tank, and the test results showed stagnation temperature was attained in 2 hours 10 minutes at an ambient temperature of 22.9 ºC, 120.9 ºC of absorber plate temperature at corresponding solar radiation of 812 W/m². See Figure 3.1.
The second test was conducted with unloaded thermal storage tank, where the stagnation was achieved in 2 hours 40 minutes at an ambient temperature of 25.6 °C, 130.8 °C of absorber plate temperature at corresponding solar radiation of 868 W/m² (see Figure 3.2). A slight time increase of 30 minutes was recorded for the system to attain stagnation as the above test, without the tank. The time increase was due to sensible heat stored in the system within the introduced (empty) thermal heat storage tank. The thermal storage tank was introduced in the system to enable performance evaluation of the heat storage materials that could be used to store excess solar radiation to extend cooking and drying operation beyond the sunny periods.

A minimum temperature of 82°C is needed for the system to function for cooking purposes. In the F₁ stagnation test evaluation criterion, a minimum of 0.12 is needed for the cooking system to meet the cooking temperature. A high value of F₁ indicates that the system has high optical efficiency and a low heat loss factor (Aremu, 2013). Therefore the first figure of merit (F₁) was calculated as follows;

\[ F_1 = \frac{\Delta T}{H} = \frac{T_p - T_a}{H} = \frac{120.9 \text{ °C} - 22.9 \text{ °C}}{812} = 0.120 \]

Where \( T_p \) is the plate temperature (°C), \( T_a \) is the ambient temperature (°C), and \( H \) is the solar radiation (W/m²).

Therefore, using the F₁ equation, the system has passed the F₁ evaluation criterion.

**Stagnation Temperature Test for Drying**

Solar drying stagnation test was conducted with an unloaded thermal storage tank and venting ports kept opened. Stagnation was achieved over 4 hours at an ambient temperature of 30.1 °C, maximum absorber plate temperature of 125.2 °C, solar collector temperature of 73.1 °C, under a variable solar radiation level of 821 W/m². (Figure 3.3)
Water Boiling Test (2nd Figure of Merit $F_2$)
The water boiling test was conducted under variable solar radiation level with aluminium pot as a cooking utensil. From an initial ambient temperature of 22 °C, a 0.51 kilograms weight of water took 2 hours 30 minutes to reach a boiling point in the dual-operated solar cooker on the first day and took exactly 2 hours to reach boiling point on the second day. 131.7 °C and 98.7 °C were temperatures recorded for absorber plate collector and inner pot (water) respectively. In the $F_2$ stagnation test evaluation criterion, a minimum of 0.24 was needed for the cooking system to meet the cooking temperature (Mullik et al, 1987). However, second figure of merit $F_2$ was calculated to be 0.235. This value compared favorably with the ASAE value 0.25 (ASAE, 2002), a high value of $F_2$ indicates that the system has high heat exchange efficiency. (Figure 3.4)

Sample Cooking and Drying Application Evaluation Tests

Cooking Test
The solar cooking performance test was conducted using the same aluminium pot. Six pieces of eggs weighing 0.36 kg were boiled in 0.51 kg of water which was cooked under a variable solar radiation as above. The egg was cooked in a temperature range from 29.7 °C to 88.2 °C in 45 min with a maximum absorber plate temperature of 103 °C as shown in Figure 3.5

A similar cooking test was carried out by (Garba, 2009). Parboiled basmati rice was cooked in 0.70 kg of water and cooking was achieved in three hours within a temperature range of 82 °C to 95 °C with a maximum cooking pot temperature of 95 °C.
Drying Test
Banana slices of about 4 – 5 mm in thickness, weighing 118 g dried using the dual-operated solar cooking and drying system. The initial moisture content on a wet basis was found to be 100% before drying. And after drying, it was found that the dual-operated solar cooking and drying system was able to dehydrate 89 % of moisture content, achieving a stable weight of 12 g after 8 hours of drying. See Figure 3.6

This result comes in consistence with a similar drying test which was conducted by (Fernandes et al, 2022) using sliced foods which include; apples, mushrooms, zucchini, lemon peel, sweet potatoes, and bananas. These sliced foods were dried to a moisture level of less than 10 % in less than 6 hours, necessitating only one drying day. However, due to the tough serous peel that covers fruits such as tomatoes and blueberries, drying tomato quarters took at least two days, and drying full blueberries can take several days to dehydrate below 10 % of moisture content.

Determining the Potential of Brine Solution and Animal Fat as Storage Material
The results of the thermal energy retention test for the dual-operated solar cooking and drying system using Brine Solution and Animal Fat as heat storage materials, which can be used for both cooking and drying applications are presented in figures 3.7 and 3.8. Thermal energy stored in the system under cooking application was conducted on two dimensions, charging and discharging periods. This enabled the assessment of the thermal energy storage potential by monitoring the length of time the system took to cool to 30 °C after heating to stagnation of 126.1 °C and 128.3 °C for Brine Solution and Animal Fat respectively.

Brine Solution as a Potential Thermal Storage Material
The stagnation test shows that the system has taken 4 hours to heat to a stagnation of 126.1 °C at an ambient temperature of 31.8 °C and solar radiation of 807 W/m² and 4 hours 30 minutes to cool down to 26.9 °C. The stored thermal energy in the storage tank could enable a continued late evening cooking or a continued drying application using the thermal energy stored from the 4 liters of Brine Solution in the system.
Animal Fat as Potential Thermal Storage Material

Four liters of animal fat was used as heat storage medium, and it was evaluated under solar cooking conditions. The result shows that the plate temperature has reached 128.3 °C at an ambient temperature of 31.2 °C with corresponding solar radiation of 824 W/m² within 3 hours. It further shows that it took the system 5 hours to cool down to 28.8 °C. The stored thermal energy in the storage tank could enable a continued late-evening cooking or drying application.

Garba (2009) carried out a similar study determining the potential of four liters of used engine oil and two other organic storage materials. Table 3.1 shows the summary of the result.

<table>
<thead>
<tr>
<th>Material Quantity</th>
<th>Cooking Period</th>
<th>Cooling Period</th>
<th>Max. Plate Temp.</th>
<th>Storage Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 liters</td>
<td>2 hrs 30 min</td>
<td>5 hrs 25 min</td>
<td>82 °C</td>
<td>Organic Material</td>
</tr>
<tr>
<td>4 liters</td>
<td>1 hrs 30 min</td>
<td>4 hrs 27 min</td>
<td>82 °C</td>
<td>Encapsulated Material</td>
</tr>
<tr>
<td>4 liters</td>
<td>1 hrs 30 min</td>
<td>4 hrs 25 min</td>
<td>83 °C</td>
<td>Engine Oil</td>
</tr>
</tbody>
</table>

CONCLUSION

The first figure of merit (F₁) for the dual-operated solar cooker fell within the recommended range of 0.12-0.16 m² °C/W, indicating its functionality. The second figure of merit (F₂) was calculated to be 0.235, which aligns closely with the suggested range for a functional cooker. A solar cooking test successfully boiled six eggs in 45 minutes, with a temperature range of 29.7 °C to 88.2 °C. Drying tests demonstrated that banana slices can be dehydrated within a day, although the achieved temperature exceeded the recommended drying temperature. The use of brine solution and animal fat as storage materials showed promising results for extended cooking and drying periods, with brine solution enabling up to 4 hours and 30 minutes of cooking or drying, and animal fat allowing for 5 hours of operation. These findings indicate the potential of this solar cooking and drying system for domestic applications.

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