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Storage and heat utilisation efficiencies of two solar storage cooking pots using different cooking loads

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ABSTRACT
Two storage cooking solar pots are compared experimentally during solar and storage cooking periods. For off-sunshine storage cooking periods, the pots are placed inside insulated wonderbag slow cookers. The first storage pot contains sunflower oil as the storage material, while the second pot contains erythritol as the storage material. Storage and heat utilisation efficiencies are evaluated using five different water heating loads (0.5, 1.0, 1.5, 2.0 and 2.5 kg). The sunflower oil pot shows slightly higher storage efficiencies (3.2-4.4 %) compared to the erythritol pot (2.5-3.9 %). The storage efficiencies reduce marginally for both pots with an increase in the load. Heat utilisation efficiencies increase significantly with the load for both storage cooking pots. The erythritol storage pot shows higher heat utilisation efficiencies for most of the investigated loads (1.3-49 %) compared to the sunflower oil pot (17-46 %). The change in the cooking load has a more significant effect on the heat utilisation efficiency compared to the storage efficiency.

Keywords: Erythritol; Heat utilisation efficiency; Storage cooking pots; Storage efficiency; Sunflower oil

1. INTRODUCTION

To alleviate the negative impact on the environment caused by fossil fuel based cookers, different types of solar cookers have been designed and implemented in recent years as discussed comprehensively in recent reviews [1-2]. The four major types of solar cookers are: oven solar cookers (box type), panel cookers, concentrating cookers (e.g. parabolic dish solar cookers) and indirect type of solar cookers (e.g. evacuated tube solar cookers with thermal energy storage). With the exception of the indirect solar cookers with thermal energy storage (TES), most types of solar cookers need a TES unit to operate during non-sunshine periods [2]. Indirect solar cookers are expensive to fabricate for mass production as compared to the other types of solar cookers [2]. Although box type solar cookers and panel cookers are less expensive to design and manufacture as compared to concentrating solar cookers, most of them achieve lower temperatures which may not be sufficient for high temperature cooking processes such as frying or roasting [1]. Concentrating solar cookers are thus ideal for high temperature cooking processes, and they can be combined directly with an appropriate TES to enhance their usefulness during non-sunshine hours.

In a recent study by Ahmed et al. [3], three low cost parabolic dish solar cookers showed good thermal performances. These solar cookers were suitable for refugee camps and rural households. The solar cookers only operated during sunshine hours, which is also a problem of most concentrating type of solar cookers. To address this problem, different types of parabolic dish solar cookers with indirect TES have been designed in recent years [4-6]. Indirect storage solar cookers with TES are rather expensive, and more heat losses occur due to the extra number components which include pipes for transporting heat to and from the storage system.

A cheaper and more affordable option is to integrate the storage system into the cooking pot as reported in recent work [7-13]. Chaudhary et al. [7] performed experiments on a storage receiver for a parabolic dish solar cooker using acetanilide as the phase change material (PCM). The storage receiver that was painted black with glazing performed better compared to the receiver which was not painted and had no glazing.

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Rekha and Sukchai [8] experimentally evaluated a storage cooking pot constructed from a hollow concentric cylinder, with heat transfer oil filling the gap between the cylinders. The outer layer of the pot was surrounded by vertical cylindrical PCM tubes. Reasonably good cooking temperatures were obtained during multiple discharging cycles. Magnesium chloride hexahydrate was used in a storage cooking vessel in which 500 g of rice was cooked in 30 min using around 100 ml of water. The heat utilisation efficiency was slightly over 30 %. In another study, Yadav et al. [9] used latent heat storage combined with different sensible heat materials in their storage cooking pot. The PCM-Sand and PCM-Stone pebble cases stored 3 to 3.5 times more heat compared to the PCM-Iron grits and PCM-Iron ball combinations. A parabolic dish solar with a storage cooking vessel using PCM was experimentally and numerically evaluated by Lecuona et al. [10]. The results obtained showed that the storage cooking unit could be used for indoors cooking incorporating an insulation box. The storage cooking pot cooked dinner and could retain enough heat for breakfast cooking. Nayak et al. [11] presented a solar storage pot charged with an evacuated tube collector. Two PCMs were used in the study namely; acetanilide and stearic acid. Acetanilide performed better than stearic acid in terms of the heat utilisation efficiency. Solar salt was used by Bhave and Kale [12] for a solar cooking receiver for a parabolic dish collector. The stored heat from the receiver was able to fry potato chips in 17 mins. Erythritol was used as the storage medium in a portable solar box cooker by Coccia et al. [13]. The performance of the box cooker improved during non-sunshine hours due to the usage of the TES unit.

The storage cooking pot needs an insulation container or vessel to store heat for usage during off-sunshine periods. The wonderbag has been found to be useful for slow cooking of preheated food [14]. In our recent work (See Figure 1(b)), we used the wonderbag with solar storage cooking pots for off-sunshine cooking, and good results were obtained with sunflower oil and erythritol as the storage materials [15]. The paper also proposed testing storage and heat utilisation efficiencies with different loads as future work. The objective of the study is to evaluate the solar cooking storage and off–sunshine heat utilisation efficiencies using 5 different water heating loads (0.5, 1.0, 1.5, 2.0, and 2.5 kg) to determine the effect of the load experimentally. This research was mentioned as future work in [15], and it extends the results presented in [15] by evaluating the effect of the cooking load on the storage and heat utilisation efficiencies. There have been no previous studies done on the effect of the load on the storage and heat utilisation efficiencies. This work will add to the body of knowledge on storage cooking pots of which there is very limited literature. Storage cooking pots are also a good innovation for the developing world where the rural dwellers use fossil fuels for cooking especially wood which leads to global warming as well as smoke related lung diseases.

2. EXPERIMENTAL METHOD AND ANALYSIS

2.1 Experimental method

The experimental method and materials have been reported in detail in our previous related work [15]. A 1.2 m parabolic dish solar cooker was used for the solar cooking experiments, and it has been reported in more detail in our previous work [15]. It uses manual tracking, and the photograph of the dish is shown in Figure 1 (a). For the storage cooking periods, the pots were placed inside the wonderbag insulated slow cookers shown in Figure 1(b). The properties of the wonderbag have been reported in more detail in [15].

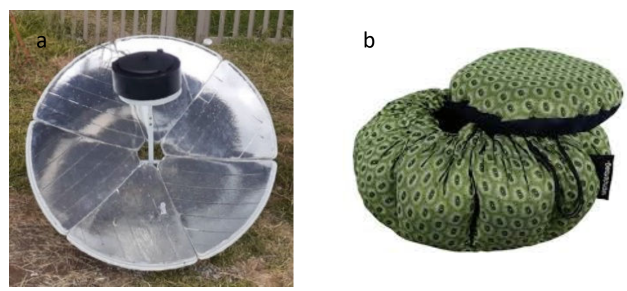

Figure 1: Photographs of (a) the parabolic dish solar cooker used in the solar cooking tests, and (b) the wonderbag slow cooker used in the off-sunshine storage cooking tests.

The storage cooking pot that was placed on the parabolic dish solar cooker is shown in Figure 2. More details of the pot have also been reported in our recent paper [15]. Sunflower oil and erythritol were used as the TES materials in two different storage cooking pots. Three K-type thermocouples measured the temperatures in the storage materials at 0.024 m, 0.06 m and 0.09 m from the base of the pots. Another K-type thermocouple measured the water temperature inside the storage pot during cooking. The properties of these two TES materials are shown on Table 1. Equal volumes of erythritol and sunflower were placed in the storage cavities shown in Figure 2(b), although the masses were different due to their different densities. The erythritol storage pot weighed more than the sunflower oil storage pot due to the higher density of erythritol.

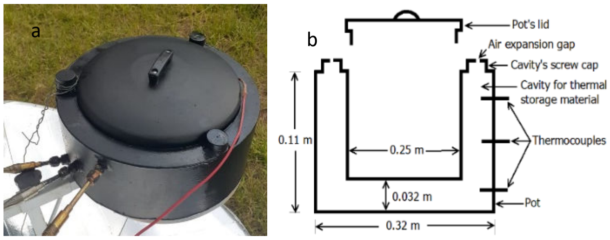

Figure 2: (a) A photograph and (b) schematic diagram of the solar storage cooking pot.

Table 1: Thermophysical properties of the two storage materials used in this study

Property	Erythritol	Sunflower Oil
Melting Temperature (°C)	118.4 - 122.0 [15]	N/A
Specific Heat Capacity (kJ/kgK)	1.38 (20 °C), 2.76 (140 °C) [15]	$c = 2.115 + 0.00131T$ [15]
Phase change enthalpy (kJ/kg)	310.6 [15]	N/A
Density (kg/m³)	1480 (20 °C), 1300 (140 °C) [15]	$\rho = 930.62 - 0.65T$ [15]
Thermal conductivity (W/mK)	0.733 (20 °C), 0.326 (140 °C) [15]	0.17 [15]
Volume of storage material in the pot (litres)	3.780	3.750
Mass of storage material in the pot (kg)	5.438	3.438

Two experiments were carried out each with water heating loads of 0.5, 1.0, 1.5, 2.0 and 2.5 kg making a total of 10 experiments. The experimental conditions for the test are shown in Table 2 with the standard deviation of the solar radiation and the wind speed. The average solar radiation varied from 630-944 W/m^2, and the wind speed from 0.1-1.6 m/s in the experiments. The solar heating periods varied from 3.8-4.2 h, while the total storage heating periods varied from 1.7-1.9 h.

Table 2: Test conditions using water as the heating load

Test No and Date	Average solar radiation (W/m²)	Average wind speed (m/s)	Total solar heating period (h)	Total storage heating period (h)	Heated load (kg)
1-22/05/20	630±318	0.1±0.4	4.1	1.9	0.5
2-27/05/20	944±34	0.5±0.9	3.8	1.8	0.5
3-28/05/20	945±33	0.4±0.9	3.8	1.7	1.0
4-29/05/20	916±33	0.6±0.7	4.0	1.8	1.0
5-11/05/20	743±234	0.0±0.0	4.1	1.8	1.5
6-12/05/20	848±40	0.2±0.5	4.0	1.8	1.5
7-14/05/20	962±27	0.9±1.4	4.0	1.8	2.0
8-15/05/20	916±28	1.6±2.0	4.1	1.8	2.0
9-20/05/20	892±26	0.7±1.1	4.2	1.8	2.5
10-21/05/20	872±23	1.0±1.2	4.2	1.8	2.5

2.2 Experimental analysis

The total solar energy incident on the dish aperture area for the solar cooking period can be estimated as [10];

$$Q_{inc} = \sum I_{av} A_c \Delta t \qquad (1)$$

where I_{av} is the cumulative moving average solar radiation at each time interval during the solar cooking storage period to cater for fluctuations in the solar radiation, A_c is the dish aperture (~1.12 m^2, estimated from the diameter of the dish, d =1.19 m) and Δt is the data-logging time interval of 10 s. The cumulative moving average solar radiation is calculated as;

$$I_{av} = \sum_{i=1}^{N} \frac{I_i}{N} \qquad (2)$$

where N is the number of samples taken during the measurement interval. The total energy stored during the solar cooking period is estimated as [15];

$$Q_{ust} = \sum m\, c_S \Delta T \qquad (3)$$

where m is the mass in the storage pot, c_S is the specific heat capacity of the storage material and ΔT is the moving average temperature difference between the next and previous time step interval Δt. The solar energy storage efficiency is thus given by the ratio total energy stored to the total solar incident energy as [15];

$$\eta_{storage} = \frac{Q_{us}}{Q_{inc}}. \quad (4)$$

During the storage cooking period, the total heat utilisation can be estimated by considering the total heat delivered to the cooking fluid, and it is expressed as [15];

$$Q_{uti} = \sum m_l \, c_l \Delta T \quad (5)$$

where m_l is the mass of the cooking fluid and c_l is the specific heat capacity of the cooking fluid (water = 4187 J/kgK). The heat utilisation efficiency can be estimated from the ratio of the total heat utilisation to the total energy stored, and it is given as [15];

$$\eta_{uti} = \frac{Q_{uti}}{Q_{us}} \quad (6)$$

The specific heat capacities of sunflower oil and erythritol are temperature dependent. Their temperature dependence equations are given as [10];

$$c_{av} = 2115.00 + 3.13T_{av} \quad (7)$$

and

$$c_{av} \ (J/kgK) = 1269 + 4.10T_{av}, \quad (8)$$

for sunflower oil and erythritol, respectively, where T_{av} is the moving average temperature calculated from the number of samples measured.

4. RESULTS AND DISCUSSION

Figure 3(a) shows the variation of the solar radiation and the wind speed (at 30 min intervals) during the solar cooking period for a 1 kg load of water. The solar radiation is around 950 W/m^2 from the start of the experiment at around 11:10 h to around 12:30 h after which it drops slowly to around 850 W/m^2 at the end of the solar cooking period at around 15:15 h. The wind speed fluctuates up and down during from the start of the experiment to around 14:00 h showing a maximum value of 1.5 m/s at 12:00 h. From 14:00 h to the end of the experiment there is no wind.

The temperature profiles of the two storage pots during both solar and storage cooking periods are shown in Figure 3(b). The solar cooking period is around 4 h, while the storage cooking period is close to 2 h. The sunflower oil pot shows higher temperatures both in the storage and in the heated water due to its lower thermal mass compared to the erythritol pot. The sunflower oil pot attains a maximum temperature of around 118 °C in its storage tank while the erythritol pot only attains a maximum temperature of just above 100 °C in the storage tank which is below its melting temperature. Similar trends are also seen with heated water whereby the sunflower oil pot shows higher cooking temperatures compared to the erythritol pot. More fluctuations are seen with the erythritol pot due to more instances of adjusting the cooker manually to track the sun as a result of non-uniform heating of the erythritol pot. Even though the erythritol pot attains lower temperatures during the solar cooking period, it shows a lower temperature drop of storage material compared to the sunflower oil pot signifying more effective heat utilisation during the storage cooking period as reported in [15]. Both storage pots attain the same temperature of around 65 °C at the end of the storage cooking period.

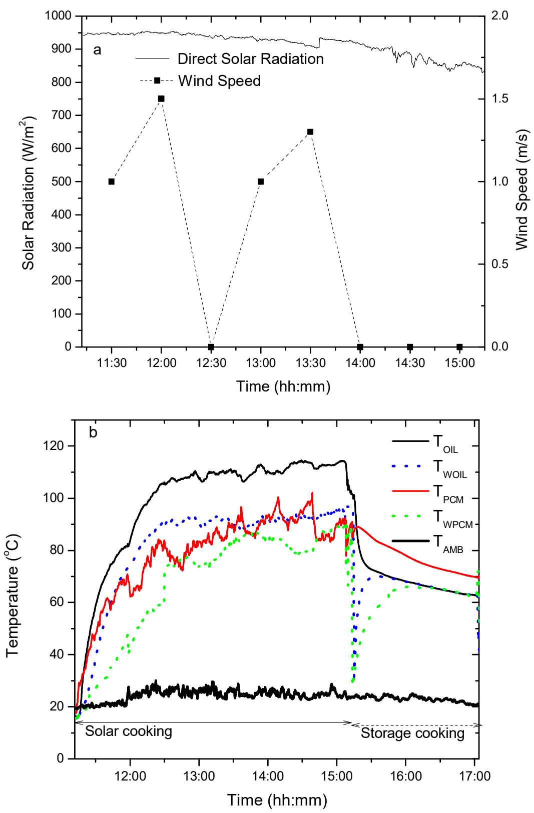

Figure 3:(a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for a 1 kg load of water on 29 May 2020.

Using similar solar radiation and temperature profiles depicted in Figure 3, the average storage and heat utilisation efficiencies were calculated using Eqs. 4 and 6. Table 3 shows the experimental results of the average storage and the heat utilisation efficiencies using different water loads. The average values were calculated for two experiments using each load. The sunflower oil storage cooking pot showed slightly higher average storage efficiencies which tend to slightly reduce with an increase in the load. This was due to its lower thermal mass compared to the erythritol pot. Both storage pots showed storage efficiencies that reduced marginally with the increase in the water heating load. The reduction in the storage efficiency was more pronounced for the erythritol storage pot (3.9-2.5 %) compared to the sunflower oil storage pot (4.4-3.2 %).

Table 3: Experimental results of the effect of the load on the storage and heat utilisation efficiencies

Cooking pot	Average solar heating time (h)	Heated load (kg)	Average storage heating time (h)	Average storage efficiency (-)	Average heat utilisation efficiency (-)
Erythritol					
Case 1	3.95	0.5	1.85	0.039	0.13
Case 2	3.90	1.0	1.75	0.032	0.29
Case 3	4.05	1.5	1.80	0.029	0.44
Case 4	4.05	2.0	1.80	0.028	0.47
Case 5	4.20	2.5	1.80	0.025	0.49
Sunflower oil					
Case 1	3.95	0.5	1.85	0.044	0.17
Case 2	3.90	1.0	1.75	0.043	0.21
Case 3	4.05	1.5	1.80	0.041	0.29
Case 4	4.05	2.0	1.80	0.038	0.35
Case 5	4.20	2.5	1.80	0.032	0.46

The erythritol storage pot showed higher heat utilisation efficiencies compared to the sunflower pot except for the lowest load. This was due the larger thermal storage mass, and also due to the release of latent heat during heat utilisation. However, for a load increase of 1.5 kg to 2.5 kg, the storage efficiencies of the erythritol pot only increased marginally (44-49 %), whereas for the sunflower oil pot, the efficiencies increased more significantly (29-46 %). The results suggest that more effective heat transfer occurs with larger loads during heat utilisation which is in agreement with previous work [14] on wonderbag slow cookers.

4. CONCLUSION

An experimental comparison of two solar cooking storage pots has been presented during storage and heat utilisation periods using five different water loads. The sunflower oil storage pot showed slightly better storage efficiencies compared to the erythritol pot. Heat utilisation efficiencies of the erythritol pot were higher than the sunflower oil pot for most of the cooking loads. The storage efficiencies reduced marginally for both pots with an increase in the load, while the heat utilisation efficiencies increased significantly with the load for both storage cooking pots. The solar storage cooking pot can be a viable cooking solution for both developing and developed countries since it is environmental friendly.

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