Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking

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Abstract

Two similar storage cooking pots are experimentally evaluated and compared during solar cooking and storage off-sunshine cooking periods. One storage pot has sunflower oil as the sensible heat storage material, while the other has erythritol as the phase change material (PCM). To test their thermal performance during off-sunshine periods, the two pots are placed in insulated wonderbag slow cookers. Water and sunflower oil are used as the cooking fluids in the experimental tests. The sunflower oil cooking pot shows better performance during the solar cooking periods since it shows shorter cooking times (1.8 - 5.6 h) compared to the erythritol PCM pot (3.8-6.6 h). The sunflower oil pot also attains higher maximum storage temperatures (124 - 145 ^{o}C) compared to the erythritol PCM pot (118 - 140 ^{o}C). Storage efficiencies for the sunflower oil pot (3.0 - 7.1 %) are also greater than those of the PCM pot (2.5 - 3.7 %). During the storage cooking periods, the erythritol based phase change material cooking pot shows better performance as evidenced by the lower temperature drops (0.1 - 9.7 ^{o}C) from the maximum cooking temperatures compared to 8.3 to 34 ^{o}C for the sunflower oil pot. The heat utilisation efficiencies for the erythritol pot (4.8 - 14.3 %) are also greater compared to the sunflower oil pot (3.7 - 6 %).

Keywords: *Erythritol; Solar cooking; Storage cooking pots; sunflower oil; Thermal performance*

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1. Introduction and literature review

Solar cookers are environmentally friendly devices that use energy from the sun to cook food. Recent comprehensive reviews on solar cookers have presented different designs, applications and approaches for the evaluation cookers to improve their efficiency (Muthusivagami et al., 2010; Saxena et al., 2011; Cuce and Cuce, 2013; Yettou et al., 2014; Nkhonjera et al., 2017; Herez et al., 2018; Aramesh et al., 2019). The four main 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). Recent work on solar cookers has focussed on improvements of the design of these cookers to achieve higher operating temperatures by using reflectors and changes in the design of the solar cookers and cooking pots, improving the efficiency of solar cookers (Esen 2004; Saxena et al., 2018; Saxena and Agarwal, 2018; Guidara et al., 2017; Saxena et al., 2020; Sagade et al., 2020; Khallaf et al., 2020). The efficiency improvement, however, does not guarantee operation during non-sunshine periods, for example, at night to cook dinner. Oven and panel cookers have lower efficiency, achieve lower temperatures, and take a longer time to cook food compared to concentrating solar cookers and indirect solar cookers, although they are cheaper and easier to construct (Aramesh et al., 2019). On the other hand, the indirect type of solar cookers alleviate the problem of cooking when the sun is not available by using thermal energy storage (TES), but they are rather expensive for mass production compared to the concentrating type of solar cookers (Aramesh et al., 2019).

A widely available and highly efficient type of concentrating solar cooker is the parabolic dish solar cooker (Panwar et al., 2012; Kumar et al., 2018; Sagade et al., 2018). Different studies have been done recently, improving, characterising, and evaluating its thermal performance. An eco-friendly concentrating solar cooker for extraction of cashew nut shell oil and household cooking was presented by Mohod et al., (2010). The parabolic concentrating solar cooker (SK-14) was evaluated for cooking and generation of heat for cashew nut shell liquid (CNSL) extraction. A no-load temperature of 320 ^{o}C was achieved inside the extractor, and the average oil recovery was reported to be 55-70 %. Panwar et al., (2012) presented an experimental investigation of energy and exergy efficiencies of a domestic sized parabolic dish solar cooker. The heat output of the cooker varied between

46.67 and 653.33 W, whereas its exergy output varied between 7.37 - 46.46 W. An experimental study of solar cooking using heat storage in comparison with direct heating was done by Mussard et al., (2013). For the SK14 direct solar cooker, the cooking pot was placed on the focal point of a parabolic dish. The system was compared to a parabolic trough system where heat was transported from an absorber to a storage unit using a self-circulation loop filled with thermal oil. The system with heat storage was slower than the SK14 cooker for boiling water even with a standard pot. However, the quality of the heat transfer could be significantly improved with an amelioration of the contact surface of the heat storage unit. Thermal analysis of solar parabolic dish cooker with back reflection was presented by Kedar et al., (2017). The thermal performance of this type of solar cooker was better than a solar box cooker. The design, modelling, energy and exergy analysis of a parabolic cooker for Nigerian conditions was presented in the work of Onokwai et al., (2019). The solar cooker was fabricated using inexpensive, and locally available materials in Nigeria. The average energy and exergy efficiencies of the parabolic cooker were about 39 % and 44 %, respectively. The major problem with the parabolic dish solar cooker, as with all solar cookers, is that it cannot be used at night or during cloudy periods.

In order to cater for the mismatch between the supply and demand of solar energy for cooking purposes, TES systems can be integrated with solar thermal solar cookers and other solar thermal devices (Esen and Ayhan 1996; Esen et al., 1998; Esen, 2000; Schwarzer and da Silva, 2003; Mawire et al., 2008; Mawire et al., 2010; Kumaresan et al., 2012; Saxena and Karakilcik, 2017; Cuce et al., 2020). A recent comprehensive review by Omara et al. (2020) highlighted the advantages and drawbacks of using solar cookers based on latent heat storage using phase change materials (PCMs), and they concluded that organic PCMs were the most commonly used in solar cookers due to the lower cost and high latent heat capacity as compared to other PCMs. Latent heat storage based on PCMs have recently been used in solar cookers to cook during non-sunshine periods due to the associated high thermal energy storage densities and quasi-isothermal storage and release of thermal energy (Buddhi et al., 2003; Chen et al., 2008; Hussein et al., 2008; El-Sebaii et al., 2009; Saxena et al., 2013; Kumar et al., 2018; Cuce et al., 2020).

The parabolic dish solar cooker offers reasonably good thermal performance at a relatively low cost, and can be fabricated with locally available materials at reasonable costs, as recently investigated by Ahmed et al., (2020) who fabricated cheap parabolic dish solar cookers for refugee camps and rural households. However, as already highlighted, this type of cooker cannot be used to cook food during non-sunshine hours. To alleviate the problem of cooking during non-sunshine hours, recent works have investigated using TES indirectly combined with parabolic solar cookers (Prasanna and Umanand, 2011; Musard and Nydal, 2013; Kumaresan et al., 2016; Saini et al., 2016; Mbodji and Hajji, 2017; Kumar and Panadian, 2019; El Moussaoui et al., 2020). These are rather expensive and inefficient methods with more components required and result in additional heat losses from piping that is required for transporting heat to the storage system.

Integration of the cooking pot directly with thermal energy storage (TES) has recently been developed, which ischeaper and more efficient than indirect methods. Lecuona et al., (2013) investigated a portable solar cooker of a standard concentrating parabolic dish cooker that incorporated a daily TES utensil. This utensil was formed by two conventional coaxial cylindrical cooking pots consisting of an internal one and a larger external one. The space between the two coaxial pots was filled with PCM forming an intermediate jacket. The results indicated that retaining the utensil inside an insulating box indoors allowed it to be used to cook food in the evening, whilst also retaining enough heat o cook breakfast the next morning. An experimental investigation of a parabolic solar cooker with a receiver incorporating a PCM storage unit was carried out by Chaudhary et al., (2013). During the day, acetanilide (PCM) stored solar heat, and during the evening, the solar cooker was kept in the insulator box where the phase change material delivered heat to the food. To enhance the performance of the solar cooker, three cases were considered namely; an ordinary solar cooker, a solar cooker with the outer surface painted black, and a solar cooker with the outer surface painted black and with glazing. It was observed that the solar cooker with the outer surface painted black with glazing performed better compared to the other cases. It was also found out that the PCM in the solar cooker with the outer surface painted black stored 26.8 % more heat as compared to the PCM in the ordinary solar cooker. In addition, the PCM in the solar cooker with the outer surface painted black with glazing stored 32.3 % more heat in comparison to the PCM in the ordinary solar cooker. The design of a PCM based domestic solar cooking system for both indoor and outdoor cooking applications was presented by Rekha and Sukchai (2018). The receiver was formed as a hollow concentric cylinder, with heat transfer oil filling the gap between the cylinders. The outer layer of the receiver was surrounded by vertical cylindrical PCM tubes. The optical efficiency factor of the solar cooker with the PCM receiver was double that of the receiver without PCM. The results also concluded that the design of the PCM solar cooking system could expand the applicability of solar cookers as a compatible cooking solution for cooking applications instead of using fossil fuel-based cooking systems. The study by Bhave and Thakare (2018) carried out an experimental investigation of a concentrating type solar cooker using magnesium chloride hexahydrate as the thermal storage material designed for boiling type of cooking. The time required to cook 50 g of rice with 100 ml of water was approximately 30 min, and the heat utilisation efficiency above 100 ^{o}C was 32.66 %. The thermal performance evaluation of solar cooker with a latent and sensible heat storage unit for evening cooking was evaluated by Yadav et al., (2015). The research presented an investigation on the thermal performance of PCM in combination with different sensible heat storage materials (SHSMs) in a solar cooker based on a parabolic dish collector for evening cooking. During sunshine hours, the storage cooking pot was placed on the focal region of the parabolic dish to store heat. In the evening, the solar cooking storage pot was placed inside an insulated box and loaded with food. Heat transferred from the PCM was used to cook the food. It was found that 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 cases. The PCM assisted in cooking while the outer sensible heat material assisted the PCM to maintain its performance.

The work by Choudhari and Shende (2015) investigated a solar cooking pot with acetanilide as the PCM. In order to evaluate the internal behaviour of the PCM, a one-dimensional heat balance model was developed, and it was compared with the experimental results. The results obtained demonstrated that the PCM could absorb solar radiation throughout daytime periods and use the heat in evening cooking. Nayak et al., (2016) experimentally investigated acetanilide and stearic acid as PCMs for a storage cooking pot charged up with an evacuated tube solar collector. The circumference of the cooker was integrated with a heat exchanger, and the annulus area of the cooking unit was embedded with PCMs. The results revealed that the cooker was efficiently utilised for cooking during the evenings due to the use of PCM. The results showed that acetanilide was superior to stearic acid in terms of thermal performancewith a cooker utilisation efficiency of 31 % compared to 25 % for stearic acid. Senthil and Cheralathan (2019) presented the enhancement of the thermal energy storage capacity of a parabolic dish concentrated solar receiver using phase change materials. A parabolic dish collector with a reflector aperture area of 16 m^2 was used to test the performance of the solar receiver. Sugar alcohols were used as the PCMs. The average energy and exergy efficiencies of the receiver with multiple PCMs were 66.7 % and 13.8 %, respectively, for the heat transfer fluid (HTF) flow rate of 80 kg/h. The solar receiver acted as a thermal battery for meeting thermal needs even after sunset. Keith et al., (2019) conducted a feasibility study of a collapsible parabolic solar cooker incorporating phase change materials. This research proposed a collapsible parabolic solar cooker with 12 panels, and a PCM-incorporated cooking pot as a viable alternative to firewood. The PCM allowed food cooked during the day-time to be kept warm and subsequently consumed as an evening meal. Bhave and Kale (2020) recently developed a thermal storage unit for a solar parabolic dish using a solar salt which was embedded with the receiver. The TES unit was able to successfully store heat at its melting point of 220 ^oC with a charging time of 110 min. Frying temperatures of 170-180 ^oC using oil were easily obtained during indoors cooking, and 0.25 kg of potato chips were fried in 17 mins from one heat charging cycle. A portable solar box cooker coupled with an erythritol-based PCM storage system, was recently reported (Coccia et al., 2020). The TES unit was a double-walled stainless steel vessel, with the annular volume filled with 2.5 kg of erythritol. Results showed that equipping the portable solar box cooker with the erythritol-based TES allowed extending the average load cooling time, in the range of 125-100 °C, to around 351.16 %.

A recent innovation in cooking is the slow cooking wonderbag, which has been used to retain heat and cook food that has been initially slightly pre-cooked using electric cookers and liquefied petroleum gas (LPG) (Islam and Salehin, 2014). It is a stand-alone, non-electric insulated bag designed to reduce the amount of fuel required in the cooking of food in developing countries. Food is only brought up to the cooking temperature and then placed inside the wonderbag cooker instead of cooking for the whole period. Thermal insulation in the wonderbag retains the heat so that cooking continues slowly without the need for additional heat. One of the few scientific studies on wonderbag slow cookers carried out by Islam and Salehin (2014) revealed that the wonderbag reduced a significant amount of energy consumption in the induction cooker and the LPG stove. The tests showed a range of energy savings from 22-48 % for different food items. The wonderbag also helped to reduce the carbon footprint and reduced carbon-dioxide emissions by 45-189 g per kg of different foods. The food cooked during the tests was tasted, and it was found that the texture of the food cooked using the wonderbag was improved. The wonderbag was primarily designed for slow cooking in conjunction with electric cookers, biomass and LPG. However, to reduce the use of electrical energy, biomass and LPG for cooking, it can be combined with solar cooking pots with energy storage especially in rural areas of developing countries where there is no electrical grid connection. We are not aware of research into wonderbag together with solar cookers and storage cooking pots in recent literature searches , and so we will be disseminating novel and interesting research to the solar cooking and energy utilisation communities. Using the wonderbag with solar storage cooking pots can be a sustainable cooking solution for people in rural areas in the developing countries where there is an abundance of solar energy. However, the performance of solar storage pots and wonderbags could be limited by the amount of solar radiation available at a particular location and the prevailing weather conditions.

It is clear from the literature review that limited work has been done on solar cooking storage vessels or pots, and more work needs to be done in terms of improving the storage efficiency, finding suitable storage materials and improving heat retention properties. In addition to this, solar cooking pots need an insulating container for them to retain heat that will be used for cooking later effectively. This paper thus presents a novel study which will evaluate the performance of solar cooking pots with TES combined with wonderbag slow cookers for cooking during non-sunshine hours. This study has never been done, and will assist developing countries who have limited electricity supplies for cooking, where biomass is the major source of energy for cooking, but which presents hazards to the environment and to human beings. The two main viable storage options for solar cookers are latent heat storage using PCMs and sensible heat storage; thus, two storage cookers will be compared. Sensible heat storage has the advantage of being less expensive than latent heat storage, but has lower energy density for TES applications. Two solar cooking storage pots will be compared in this work. One storage cooker uses sunflower oil as the sensible heat storage material. Sunflower oil has been reported by recent studies to be a viable storage medium since it is food grade, inexpensive and readily viable, non-toxic and has comparable performance to other heat transfer oils (Hossain et al., 2010; Mawire, 2016; Hoffmann et al., 2018). The other storage cooker uses erythritol as the PCM which is an affordable, food-grade, non-toxic and a readily available PCM that has been proposed recently for solar cooking TES applications (Lecuona et al., 2013; Mawire et al., 2019; Anish et al., 2020; Coccia et al., 2020; Mawire et al., 2020a). Preliminary cooking experimental results are presented using the two storage cooking pots heated up with solar parabolic dish solar cookers combined with wonderbag slow cookers for off-sunshine cooking. This study will add invaluable information on solar cooking storage pots and wonderbag slow cookers where limited previous research has been reported on these two devices.

2. Materials and method

2.1. Parabolic dish solar cooker

A photograph for the parabolic dish solar cooker used in the experiments is shown in Figure 1. It has a diameter of around 1.2 m and a manual tracking mechanism to allow proper focusing of solar radiation on to a stand where the pot is placed. It is relatively inexpensive costing about R1500 (~USD 85), and is purchased locally in South Africa from SunFire Solutions (2020). The performance of this parabolic dish solar cooker has recently been evaluated using different non-heat storage cooking pots and fluids, and it was found to perform reasonably well (Mawire et al., 2020b).

Figure 1: A photograph of the parabolic dish solar cooker used in the cooking tests.

2.2. Solar cooking pot and storage materials

Different views of the storage cooking pot are shown in Figure 2. The storage cooking pot is made with stainless steel, and it has an internal cavity in which the storage material is placed. The pot is painted black in order to increase its absorbance of solar radiation, as shown in Figure 2(c). A standard cooking pot lid fits on the top of the storage pot, and is closed to increase its efficiency during cooking tests. The top of the pot has three air vents to allow for thermal expansion of the storage materials. Three K-type thermocouples are embedded on the sides of the pot to measure the temperature of the storage material, as shown in Figure 2(b). A K-type thermocouple is also placed inside the cooking pot to measure the cooking temperature. The K-type thermocouples all have an accuracy of ± 2.2 ^{o}C.

Figure 2: Photographs of the storage cooking pot; (a) plan view, (b) side view and (c) the storage cooker painted black in a solar cooking experiment.

The properties of two cooking pots used in the experiments are shown in Table 1. The masses of the erythritol and the oil cooking pots are nearly the same. Figure 3 shows a schematic diagram indicating the dimensions of the storage pot presented in Table 1. The three thermocouples are placed at vertical distances of 0.024 m, 0.06 m and 0.09 m from the base of the storage.

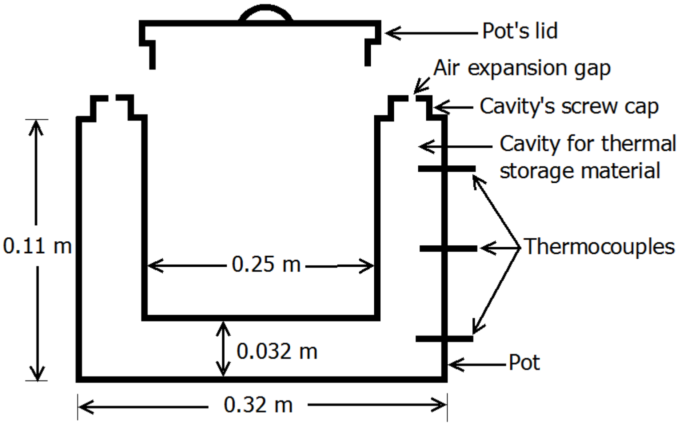

Figure 3: Schematic of the storage cooking pot showing the dimensions

Table 1: Properties of the cooking pots

Property	Value
Material of pots	Stainless steel
Thickness of stainless steel used for the pot (m)	0.003
Mass of oil pot (kg)	1.915
Mass of erythritol pot (kg)	2.020
External pot diameter (m)	0.320
Internal pot diameter (m)	0.250
Internal pot depth (m)	0.078
Outer pot depth (m)	0.110

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Thermophysical properties of the two storage materials, erythritol and sunflower oil, are shown in Table 2. Erythritol was purchased locally in South Africa from Faithful to Nature, and sunflower oil was also purchased locally from Shoprite. These are local supermarket stores in South Africa. Sunflower oil was poured in the cavity of the storage pot in its liquid form, whereas erythritol first had to be melted to be poured into the storage pot. Nearly equal volumes of sunflower oil and erythritol were poured into the cavities; 3.750 and 3.780 litres, respectively. It was opted to use equal volumes rather than equal masses so as to measure the temperatures in the storage cavity more accurately. Equal masses would have resulted in the top thermocouple of the erythritol pot being exposed to ambient conditions since its mass would have occupied a smaller volume because of its larger density. Erythritol has a larger density; thus, its storage mass of 5.438 kg was larger as compared to 3.438 kg for sunflower oil. Erythritol also shows a reasonably higher thermal conductivity both in the liquid and solid states compared to sunflower oil. The thermocouples connections had rubber seals connected to the ferrules to prevent any sort of leakages during heating of the pots. Each pot was electrically heated on a hot plate at maximum temperatures of up to 300 ^{o}C to test for leakages and the thermal expansion capability. No visible leakages through the thermocouples and the thermal expansion air vents were observed in both pots after electrical heating.

Table 2: Thermophysical properties of the two storage materials used in this study

Property	Erythritol	Sunflower Oil
Melting Temperature (ºC)	118.4 - 122.0 (Shobo and Mawire, 2017)	N/A
Specific Heat Capacity (kJ/kgK)	1.38 (20 ºC), 2.76 (140 ºC) (Gunasekera et al., 2018)	$c = 2.115 + 0.00131T$ (Mawire, 2016)
Phase change enthalpy (kJ/kg)	310.6 (Shobo and Mawire, 2017)	N/A
Density (kg/m^3)	1480 (20 ºC), 1300 (140 ºC) (Agyenim et al., 2010)	$\rho = 930.62 - 0.65T$ (Mawire, 2016)
Thermal conductivity (W/mK)	0.733 (20 ºC), 0.326 (140 ºC) (Agyenim et al., 2010)	0.17 (Hoffmann et al., 2018)
Volume of storage material in the pot (litres)	3.780	3.750
Mass of storage material in the pot (kg)	5.438	3.438

2.3. Wonderbag cookers

The wonderbag insulated slow cooker used for the off-sunshine cooking experiments is shown in Figure 4. The wonderbag is a stand-alone, non-electric insulated bag mainly designed to reduce the amount of fuel required in the cooking of food. Instead of placing a pot on electrical, fossil fuel-based or biomass stoves for the duration of the cooking period, food is instead only heated to up to a hot enough temperature and then transferred to the wonderbag. It then uses the principle of thermal insulation to continue cooking and keeps food warm without needing additional fire or heat. The wonderbag is estimated to save up to 30 % of the total fuel costs associated with cooking with kerosene (paraffin) alone. In developing countries, there are numerous advantages for the product, as it immediately helps ease deforestation of natural reserves, and it frees up those who would spend their time gathering extra wood for fire fuel (May 2015). The wonderbag consists of an inner layer of insulation containing recycled polystyrene balls, with an outer draw-string covering of polyester-cotton blended textiles (Islam and Sahelin, 2014). The polystyrene balls have a low thermal conductivity of 0.03 W/mK making them a good insulator. The dimensions of the wonderbag and the other technical details are shown in Table 3. The properties of the wonderbag used in the experiments are very similar to those reported by

Islam and Sahelin (2014). The storage cooking pots are placed in the wonderbag so that the stored heat can be transferred to the food placed inside the pots. The top cover is closed during the non-sunshine cooking experiments. Heat is conducted from the storage cavity to the food during the non-sunshine cooking experiments. Medium-sized wonderbags with capacities of up to 6 litres are used in the experiments. The wonderbags are manufactured locally in South Africa, and are inexpensive devices costing about R350 (~USD 20) per unit.

Figure 4: A photograph of the insulating wonderbag slow cooker used for heat retention cooking tests.

Table 3: Properties of the wonderbag cookers

Property	Value
Mass of empty wonderbag (kg)	1.700
Capacity (m^3)	0.008
External height without pot (m)	0.200
Internal height without pot (m)	0.140
Diameter fully open (m)	0.910
Diameter with pot inside (m)	0.500
Base diameter (m)	0.400
Thickness of insulation (m)	0.126
Thermal insulation	Polystyrene
Thermal conductivity (W/mK)	0.030

2.4. Experimental method

Temperatures in storage cooking pots, and the direct solar radiation were monitored during each test. Figure 5 shows the two storage pots in a solar cooking experiment using the parabolic dish solar cookers in an open space with no obstruction from trees and buildings. K-type thermocouples with an accuracy of ± 2.2 °C were used to monitor the temperature in the solar heating experiments. An Eppley normal incidence pyroheliometer with a solar tracker was used to measure the direct normal incidence (DNI) radiation (Eppleylab, 2020). It has a single point measurement uncertainty of less than ± 5 W/m^2 and a 95 % response time of 5 s. The ambient temperature was also measured with a K-type thermocouple during each experiment period. The minimum period for each experiment was at least 3 h in Mahikeng, South Africa as previously established by Mawire et al., (2020b). This minimum cooking period was deemed adequate for high enough temperatures to be achieved inside three different cooking pots without storage. The cookers used manual tracking based on shading of the pots, and the cookers were adjusted every 15 minutes so that maximum solar radiation was incident on the pots with minimal shading. The experimental tests were carried out at the same time and hence similar ambient conditions. A total of eight tests were carried out with different types of foods. The first four experiments, indicated in Appendix A, considered solar water heating experiments with the same load of 2.0 kg to store energy in the storage materials. Cooking experiments were then carried out with different types of food after water heating with the 2.0 kg load. The other four experiments are the main contents of this paper, which investigated solar and storage cooking using the same type and amount of food. Two cooking experiments were performed using water as the cooking fluid, and another two were performed using sunflower oil as the cooking fluid for both storage pots. The same amount and type of food, as indicated in Tables 5 and 6 was put in the storage cooking pots in each experimental test during the solar and storage cooking phases. The thermocouples and the pyrheliometer were connected to an Agilent 34970 A datalogger (Agilent 34970 A data logger, 2020) which logged the data to a computer every 10 s for each experimental cooking period. The wind speed was also measured manually every 30 mins with a handheld anemometer to get an idea of the prevailing wind speed conditions which affected the performance of the solar cookers (Benetech anemometer, 2020). The measurement interval was made 30 mins due to the manual nature of the wind speed measurement since only estimated values were required, and a detailed analysis of the wind speed effects was beyond the scope of this study.

The details of the instruments and sensors used in the experiments are shown in Table 4. The wind speed anemometer shows the lowest accuracy, and the data logger is able to measure the voltage signal from the pyrheliometer and temperature signals from K-type thermocouples with a good degree of accuracy. In terms of the wind speed measurement, the maximum uncertainty of ±0.2 m/s is obtained using its accuracy for a maximum wind speed of 3.1 m/s in the experimental tests. The average hourly solar radiation during the experimental tests ranges from 642 W/m^2 to 919 W/m^2, and the uncertainty is estimated to be in the range of ±6 W/m^2 to ±9 W/m^2 according to the accuracy of the pyrheliometer. From the temperature range of 25 ^{o}C to 150 ^{o}C in the experimental tests, and using the uncertainty of the K-type thermocouple, the average percentage uncertainty in the temperature readings is around ±2.5 %. The maximum percentage uncertainties in the measured values are at most 5 %; therefore, the measured readings are deemed to be acceptable and reasonably accurate.

Table 4: Details of the instrumentation

Name	Parameter	Range	Accuracy	Resolution
Eppley pyrheliometer	Direct solar radiation	0-10 mV(0-1250 W/m^2) –Sensitivity 8 µV/(W/m^2)	Single point, ±5 W/m^2, Daily and Hourly Average, ±1 %	1 W/m^2
K-type thermocouple	Temperature	-200-1260 ^{o}C	±2.2 ^{o}C	0.1 ^{o}C
Benetech anemometer	Wind speed	0-30 m/s	±5 %	0.1 m/s
Agilent 34970A Datalogger	K-type of thermocouple	-100-1200 ^{o}C	±1.0 ^{o}C	0.1 ^{o}C
Agilent 34940A Datalogger	Voltage (Pyrheliometer)	0-100 mV	±0.009 %	0.001 mV
Mass balance	Mass	0-5.000 kg	±0.001 kg	±0.001 kg

Figure 5: Experimental testing of the two storage cooking pots with two parabolic dish solar cookers.

For the off-sunshine cooking experiments, the two cooking pots were loaded with the same amount of food as in the solar cooking experiments immediately after solar cooking for maximum utilisation of the stored heat. The repeated use of the stored heat after a storage cooking test was also investigated to find out if extended use of the stored heat was possible. The cooking pots were placed in wonderbag slow cookers which were closed with the top covers, as shown in Figure 6. Draw-strings were tightened once the pots were inside the wonderbags so that the stored heat could effectively cook food. The storage cooking tests were carried out indoors. As with the solar cooking tests, the off-sunshine tests were carried out two times each with water and sunflower oil as the cooking fluids. Each heat retention cooking test was carried out for a minimum duration of one hour deemed to be adequate for cooking food as established by Chaudhary et al., (2013) who performed similar tests with a storage cooking pot. The storage and cooking temperatures were monitored every 10 s from the start to the end of the cooking experiments.

Figure 6: Wonderbag cookers with the storage pots placed inside them during the heat retention off sunshine cooking experiments.

Table 5 shows a summary of the experimental conditions and dates for the solar cooking periods. The first two tests were performed with water, while the last two tests were performed with sunflower oil. The tests with water were carried out with larger food masses as compared to those with sunflower oil. Generally, for the majority of tests, the average solar radiation was above 800 W/m^2. The first test was under very cloudy conditions; thus, the average solar radiation was lower at 642 W/m^2 with a very high standard deviation of around 58 % of the average solar radiation value. This test thus had the longest duration of 6.6 h. The best test conditions were seen during test 4, with the highest average solar radiation and the lowest standard deviation in the average solar radiation. The average ambient temperatures were greater than 26 ^{o}C for all the tests. The average wind speed was less than 2 m/s for all the tests. Test 2 and test 3 had lower average wind speed conditions.

Table 5: A summary of the experimental conditions during the solar cooking periods

Test No and Date	Average solar radiation and standard deviation (W/m^2)	Average wind speed and standard deviation (m/s)	Average ambient temperature and standard deviation (ºC)	Total solar cooking period (h)	Total mass of food cooked (kg)
1-28/02/20	642±377	1.9±0.8	31.9±2.0	6.6	0.9
2-09/03/20	887±198	0.9±0.9	29.2±1.7	4.8	0.9
3-24/03/20	837±252	1.1±0.4	26.6±2.0	3.8	0.5
4-25/03/20	919±66	1.6±0.4	30.3±1.4	4.2	0.5

A summary of the test conditions for the storage cooking periods immediately after the solar cooking tests is presented in Table 6. The same types and amount of food were used as in the solar cooking tests. Test 4, with the best solar cooking conditions, had two consecutive storage cooking periods, and the total cooking period was 2.5 h. As with the solar cooking tests, the experimental tests with water used a larger mass of water and food. Test 1 had the longest cooking period due to the type of food which was cooked.

Table 6: A summary of the experimental test conditions during the storage cooking periods

Test No and Date	Total storage cooking period (h)	Total mass of food cooked (kg)	Cooking fluid	Type of food cooked
1- 28/02/20	1.7	0.9	Water	Potatoes/rice
2-09/03/20	1.5	0.9	Water	Rice/chicken
3-24/03/20	1.0	0.5	Sunflower oil	Chicken/fries
4-25/03/20	1.2, 1.3	0.5, 0.3	Sunflower oil	Chicken/fries/tomatoes, Chicken

2.5. Experimental thermal analysis

The total solar energy incident on the dish aperture area for the solar cooking period can be estimated as (Bhave and Kale, 2020);

$$\boldsymbol{Q_{inc}} = \sum \boldsymbol{I_{av}\, A_c \Delta t} \qquad (\mathbf{2.1})$$

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

$$\boldsymbol{I_{av}} = \sum_{i=1}^{N} \frac{\boldsymbol{I_i}}{\boldsymbol{N}} \qquad (\mathbf{2.2})$$

, where *N* is the number of samples taken during the measurement interval.

The total energy stored during the solar cooking period is estimated as (Bhave and Kale, 2020);

$$\boldsymbol{Q_{ust}} = \sum \boldsymbol{m}\, \boldsymbol{c_S} \Delta \boldsymbol{T} \qquad (\mathbf{2.3})$$

, where m is the mass in the storage pot, $\boldsymbol{c_S}$ is the specific heat capacity of the storage material and $\Delta \boldsymbol{T}$ is the moving average temperature between the next and previous time step interval $\Delta \boldsymbol{t}$. A cumulative moving temperature is evaluated in a similar manner to the solar radiation as;

$$\boldsymbol{T_{av}} = \sum_{i=1}^{N} \frac{\boldsymbol{T_i}}{\boldsymbol{N}} \qquad (\mathbf{2.4})$$

, to account for up and down fluctuations of the temperature due to the variable wind speed and solar radiation conditions.

The solar energy storage is thus given by the ratio total energy stored to the total solar incident energy as; (Bhave and Kale, 2020)

$$\boldsymbol{\eta_{storage}} = \frac{\boldsymbol{Q_{us}}}{\boldsymbol{Q_{inc}}}. \qquad (\mathbf{2.5})$$

During the storage cooking period, the total heat utilisation can be estimated by considering the total heat delivered to the cooking fluid and the total heat delivered to each type of food, and it is expressed as (Bhave and Kale, 2020);

$$Q_{uti} = \sum m_l\, c_l \Delta T + \sum m_{f1}\, c_{f1} \Delta T + \sum m_{f2}\, c_{f2} \Delta T + \sum m_{f3}\, c_{f3} \Delta T \qquad (2.6)$$

, where m_l is the mass of the cooking fluid, c_l is the specific heat capacity of the cooking fluid, m_f is the mass of food, c_f is the specific heat capacity of the food. The subscripted value, 1, 2, 3 on the mass and specific heat capacities of the foods indicate the number of food cooked, which in this case is three. For two types of food, the last term in Eq. (2.6) will not appear. 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 (Bhave and Kale, 2020);

$$\eta_{uti} = \frac{Q_{uti}}{Q_{us}}. \qquad (2.7)$$

The specific heat capacity of sunflower oil (one of the storage and cooking fluid) is temperature-dependent, and it can be expressed as (Mawire, 2016);

$$c_{av}\ (J/kgK) = 2115.00 + 3.13T_{av} \qquad (2.8)$$

, where T_{av} is the moving average temperature calculated from the number of samples measured. The other specific heat capacity of the other storage material, erythritol is also temperature-dependent, and it is given as (Gunasekera et al., 2018);

$$c_{av}\ (J/kgK) = 1269 + 4.10T_{av}. \qquad (2.9)$$

The specific heat capacities of the other cooking fluid (water), and foods (rice, potatoes, chicken and tomatoes) are assumed constant. The specific heat capacities are taken to be 4.187, 0.370, 3.430, 3.220 and 3.980 kJ/kg K, respectively, for water, rice, potatoes, chicken and tomatoes as obtained from the online Engineering ToolBox (2020).

To estimate the uncertainties in the mean solar energy incident, mean energy stored, mean heat utilisation, mean storage efficiency and mean storage heat utilisation efficiency for each experimental test, a propagation of error method of the whole solar cooking period is considered according to Eqs. (2.1, 2.3, 2.5, 2.6, 2.7) and propagation of error method was implemented as reported by Mawire et al., (2020c). The uncertainties in the measured variables are obtained from Table 4, and the error in the specific heat capacity is $\delta c_{av} = \pm 21$

kJ/kg K (Mawire et al., (2020c). The percentages errors vary from 1.5 % to 5.5 % of the calculated values, which is deemed acceptable.

3. Results and discussion

Figure 7 shows the results of the cooking experiment performed on an overcast day on 28 February 2020 using the two storage cooking pots (one with erythritol as the PCM, and the other one with sunflower oil). Solar and storage cooking were done with a total cooking mass of 0.9 kg (0.4 kg of potatoes/rice and 0.5 kg of water). The test day was cloudy and windy with the solar radiation and wind speed fluctuating up and down. The solar cooking period was just over 6.5 hrs, and the average solar radiation and wind speed were around 642 W/m^2 and 1.9 m/s, respectively. Even with these poor weather conditions, the temperatures of the storage pots are seen to rise to cooking temperatures above 70 ^oC (Figure 7 (b)). T_{OILST} is the oil storage temperature at the bottom of the pot that is close to the temperature of the food in the oil cooking pot represented by T_{OILF}. Similarly, T_{PCMST} is the PCM storage temperature at the bottom of the PCM pot exposed to the majority of solar radiation, and T_{PCMF} is the food temperature inside the cooking pot. The oil cooking pot shows higher temperatures during the solar cooking period due to its lower thermal mass compared to the erythritol PCM pot. All temperatures in the storage pots fluctuate up and down to maximum values during the solar cooking period due to the variable solar radiation and wind speed conditions. The solar radiation seems to have more influence on the fluctuations as seen by corresponding drops of the temperature profiles during the low solar radiation periods.

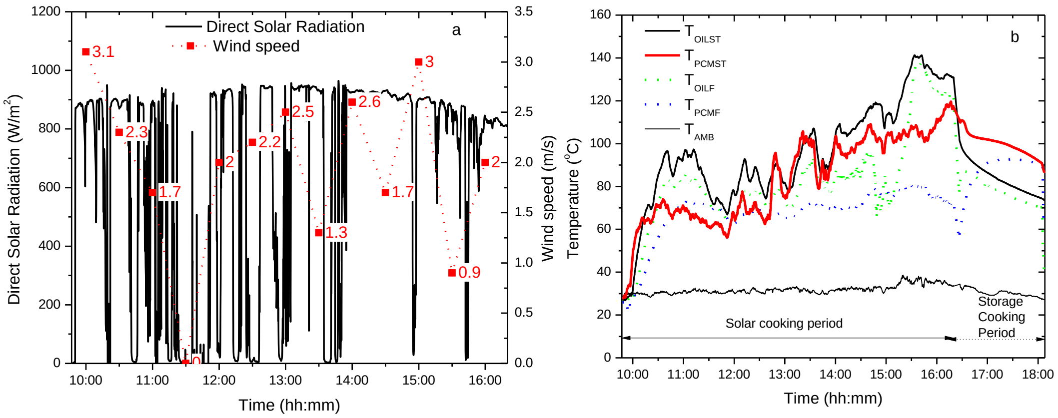

Figure 7: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles of the two storage pots on 28 February 2020.

The food in the oil pot was cooked earlier after physically tasting it in comparison to the PCM pot, and this is shown by the drop of T_{OILF} around 14:45 h where food was removed from it. It took about 5 h to cook food using the oil storage pot because of the very cloudy conditions. After removing food inside the oil storage pot, the temperature inside the pot quickly rose to a peak value of around 140 ^{o}C, which was very close to the oil storage temperature. On the other- hand, the food in the heavier PCM storage pot was cooked about 1h:45 mins later. The maximum storage temperature in the PCM pot was around 120 ^{o}C at the end of the solar cooking period, which was not adequate to induce phase change fully in erythritol. The maximum food temperature in the PCM storage pot was around 80 ^{o}C, and it fluctuated to a lesser extent than the food temperature in the oil cooking pot.

During the storage cooking period, the PCM storage pot shows better thermal performance with a maximum temperature of around 93 ^{o}C that drops marginally to around 89 ^{o}C at the end of the cooking period. On the other hand, even with the higher initial oil storage temperature, the food cooked with the oil cooking pot achieved a maximum temperature of only around 87 ^{o}C, and it dropped to around 69 ^{o}C at the end of the cooking period. This is attributed to the higher thermal conductivity of erythritol both in the liquid and the solid phase combined with its larger thermal mass. Heat conduction from the storage medium to the food is the main form of heat transfer in the wonderbag slow cookers. It is also important to note that even without the phase change process to due lower temperatures achieved in the PCM storage pot, it still outperforms the oil storage pot. The oil storage temperature drops more rapidly when compared to the PCM storage temperature indicating better heat utilisation with the PCM storage pot.

Figure 8 shows photographs of the cooked food on 28 February 2020 after 100 mins using the wonderbags and the storage pots. The potatoes and the rice were well cooked with both pots; however, the heat utilisation of the PCM storage pot was more effective. In principle, both storage cooking pots could be used for off sunshine cooking when combined with the insulated wonder slow cookers.

(a) (b)

Figure 8: Rice and potatoes cooked with water using the wonderbags combined with (a) the oil storage cooking pot and (b) the erythritol storage cooking pot.

Results of another performed on 9 March 2020 on a slightly cloudy day with the two cooking pots are shown in Figure 9. The average solar radiation and wind speed were about 887 W/m^2 and 0.9 m/s, respectively, which were better weather conditions for solar cooking than in the previous test. In this test, also 0.9 kg of food was cooked during the solar and storage cooking periods (0.5 kg of water and 0.4 kg of rice/chicken). As with the other cooking case, the oil pot temperatures are generally higher than the PCM pot temperatures for most of the solar cooking period. The PCM storage temperature shows an accelerated rise from about 14:15 h to around 15:15 h becoming higher than oil storage temperature. This may be attributed to localised heating of the PCM pot at the bottom as manual solar tracking was used in the experiments and it was difficult to achieve perfect uniform heating of the storage material in some instances. However, the oil storage temperature is higher than the PCM storage temperature for most of the duration of solar cooking. Fluctuations of the food temperature due to the external physical conditions are less evident in the PCM storage pot as compared to the oil storage pot. The maximum solar cooking temperature achieved in the oil storage pot is around 95 ^{o}C, whereas in the PCM storage pot it is around 85 ^{o}C. The cooking time (10:40 -14:15 h, 3h:25mins) for the oil storage pot during solar cooking is also shorter than the cooking time using the PCM storage pot (10:40-15:30 h, 4h:50 mins) as with the previous cooking test using water.

However, in this test, water was added after cooking food for the oil storage pot; thus, the temperature inside the pot did not rise drastically.

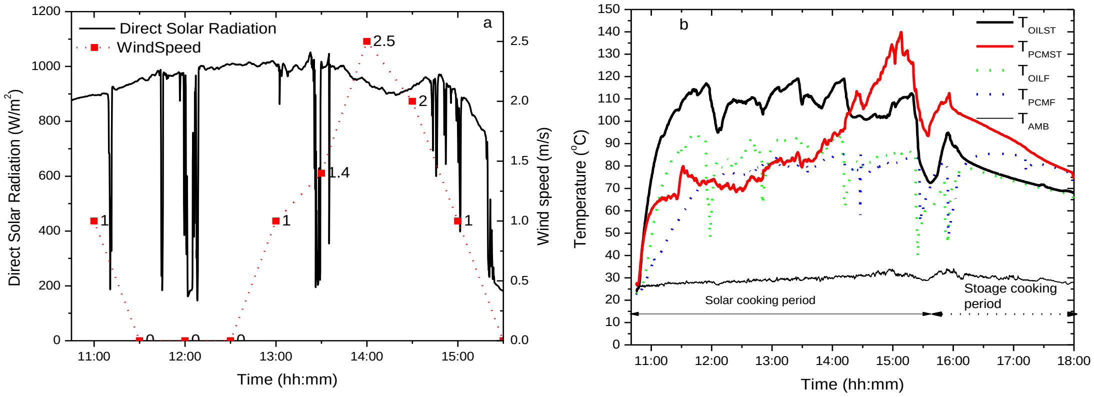

Figure 9: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles of the two storage pots on 9 March 2020.

The storage cooking period shows higher temperatures and more effective heat utilisation was achieved in the PCM storage pot with the maximum food temperature of around 86 ^{o}C, whereas it was 79 ^{o}C for the oil storage pot. The final storage temperatures were around 77 ^{o}C and 68 ^{o}C for the PCM pot and the oil pot, respectively. Food cooked with the oil storage pot was partially cooked as a result of these lower temperatures, whereas the PCM pot cooked the food well during this experimental test in a duration of 1.3 h.

Test results using sunflower oil as the cooking fluid for a cooking test performed on 24 March 2010 are shown in Figure 10. In this test, the mass of the food and the cooking fluid was 0.5 kg (0.1 kg of cooking oil and 0.4 kg of chicken/potato chips (fries)). It was generally a slightly cloudy day with three cloudy periods in the duration of the experiment. The average solar radiation and wind speed were around 837 W/m^2 and 1.1 m/s, respectively. These conditions were better than the first experimental test and slightly worse compared to the second test. Generally, higher storage temperatures are achieved using sunflower oil compared to the two previous tests, and the test duration of solar cooking is less. This is as a direct result of using a lower thermal mass of sunflower oil which causes the temperature to rise more. Even though the melting temperature of erythritol is exceeded no clear phase change transition is seen during the temperature rise period. The only sort of phase change phenomenon is seen between 14:15-14:45 h where the PCM shows an almost constant temperature of 110 °C after peaking. This probable phase change temperature is lower than erythritol's stipulated phase change range which is 118-120 °C, possibly due to impurities in the purchased sample or the transformation to a semi-amorphous state. The localised heating of the PCM in the storage pot due to imperfect manual tracking could also explain why the temperature rises very fast during heating with no observed phase change phenomenon. It should also be stated that the parabolic dish solar cooker is quite cheap and it comes with imperfections since it is designed for developing countries. As with the other previous tests, the fluctuations of the food temperature in the PCM storage pot are less as compared to those in the oil storage pot. The solar cooking period for the oil pot is about 1h:45 mins, whereas for the PCM pot it is almost 2 h more (~3h:45 mins). The maximum solar cooking temperature for the oil storage pot (135 °C) is much greater than for the PCM storage pot (95 °C).

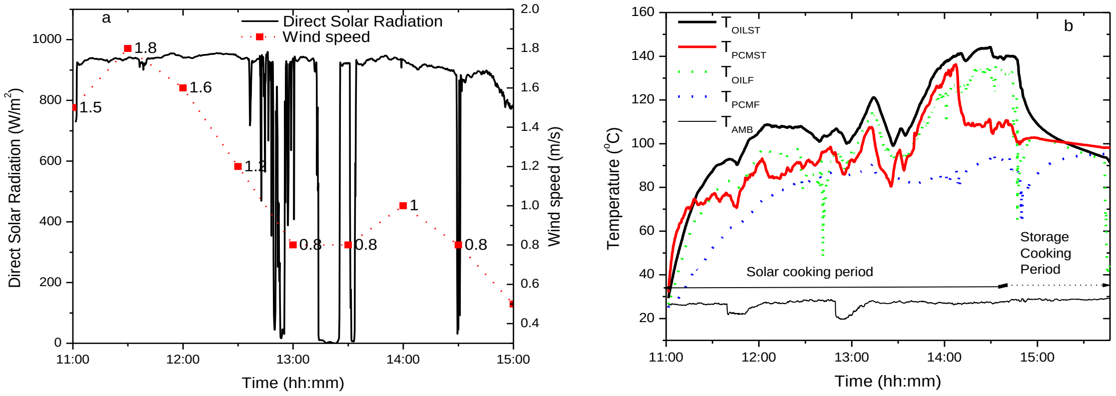

Figure 10: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles in the two storage pots on 24 March 2020.

For the storage cooking period, it is also observed that the oil storage pot shows a more rapid drop in the oil storage temperature compared to the PCM storage pot indicating poor storage heat utilisation. The oil storage temperature drops from around 140 °C to just above 90 °C, while the PCM storage shows a smaller drop from about 105 °C to just below 100 °C. The food temperature in the PCM storage pot rises more steadily, and effective cooking is possible with the stored heat from it, even though lower storage temperatures are attained during solar cooking. Both pots cook the food well using the stored heat; however, more heat is retained after the cooking process in the PCM storage pot.

The results for a cooking test using sunflower oil done on 25 March 2020 are shown in Figure 11. In this test, the solar cooking load was 0.5 kg (0.1 kg of sunflower oil and 0.4 kg of chicken/chips), and two storage cooking loads were used for two consecutive storage cooking periods. The load in first storage period was 0.5 kg (0.1 kg of sunflower oil and 0.4 kg of chicken/chips/tomatoes), while in the second storage period it was 0.3 kg (0.05 kg of sunflower oil and 0.25 kg of chicken). It was a slightly cloudy day, and the average solar radiation was around 919 W/m^{2,} and it was the best average solar radiation in all the tests. This test had the second-highest average wind speed of 1.6 m/s, which reduced the rate of temperature rise due to heat losses.

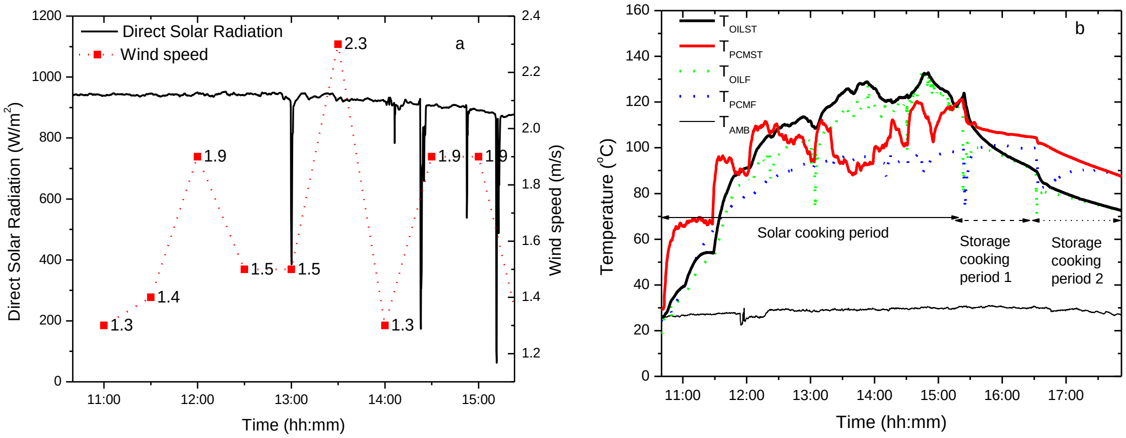

Figure 11: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles in the two storage pots on 25 March 2020.

During the solar cooking period, the initial fastest temperature rise is seen with the PCM storage temperature from the start of the experiment to around 12:30 h. This can be explained with the higher initial storage temperature and manual tracking resulting in more localised heating of the PCM storage pot during the initial periods. However, the oil storage cooking pot shows higher storage and food temperatures after this higher initial temperature rise of the PCM storage pot. As with the other cases, the food is cooked faster during solar cooking with the oil storage pot. It takes only 2h:10 mins for the oil cooking pot when compared to around 4h:10 mins for the PCM storage pot, which is almost double the time.

For storage cooking period 1, both the storage and food temperatures for the oil storage pot drop rapidly during the cooking process. Unlike the oil storage pot, the PCM storage temperature drops very slowly, and it seems to be delivering storage latent heat in the temperature range between 105 ^{o}C-110 ^{o}C. The food temperature also rises quickly to 100 ^{o}C, and this temperature is maintained for the whole of storage cooking period 1. The food cooked with the PCM storage cooking pot is slightly more well-cooked as compared to the food cooked with oil storage pot. The second storage cooking also shows better thermal performance with the PCM storage cooking with a maximum food temperature of around 90 ^{o}C compared to 81 ^{o}C for the oil storage cooking pot. The food temperature only drops by 3 ^{o}C at the end of the cooking period for the PCM storage pot indicating the potential for another extra cooking period. In contrast to this, the oil storage pot food temperature drops by around 8 ^{o}C, and cooking food in another storage period is really not possible. The chicken cooked with the PCM storage pot during storage cooking period was well-cooked, while it was partially cooked during the same period using the oil storage cooking pot.

Figure 12 shows the food cooked on 25 March 2020 during the first storage cooking period using the two pots. The food cooked with the PCM storage cooking pot is browner and crispier, indicating that it is better cooked compared to the oil storage cooking pot.

(a) (b)

Figure 12: Chicken, tomatoes and chips (fries) cooked with sunflower oil using the wonderbags combined with (a) the oil storage cooking pot and (b) the erythritol storage cooking pot during the first cooking period.

Figure 13 shows the solar cooking and storage cooking times dependence on the total combined mass of the food cooked. The thermal mass is considered since different foods have different specific heat capacities. It is clear that both the solar and storage cooking times increase with the increase in the thermal mass of the food being cooked. Storage cooking durations were identical for both cooking fluids since the wonderbags were closed and opened at the same time since there was no way of observing the cooking processes once the wonderbags were closed. The storage cooking time is also less for all cases when compared to solar cooking indicating better cooking efficiency. Case 3 (Sunflower oil, chicken, fries) shows the shortest solar and storage cooking since it has the lowest thermal mass, and the longest cooking duration is seen with Case 1 (Water, potatoes, rice) which has the largest thermal mass. The solar cooking times for the sunflower oil storage pot are less than the erythritol storage pot for all foods cooked due to the smaller storage mass of sunflower oil. An almost linear variation in the solar cooking time is observed with an increase in the thermal mass for cases 2, 3 and 4. However, a sharp increase in the solar cooking time is observed from case 2 to case 1 possibly due to the lower average solar radiation conditions for case 1 (642 W/m^2) compared to above 800 W/m^2 for the other three cases as shown in Table 5. The storage cooking time also shows the same variation as depicted by the solar cooking time.

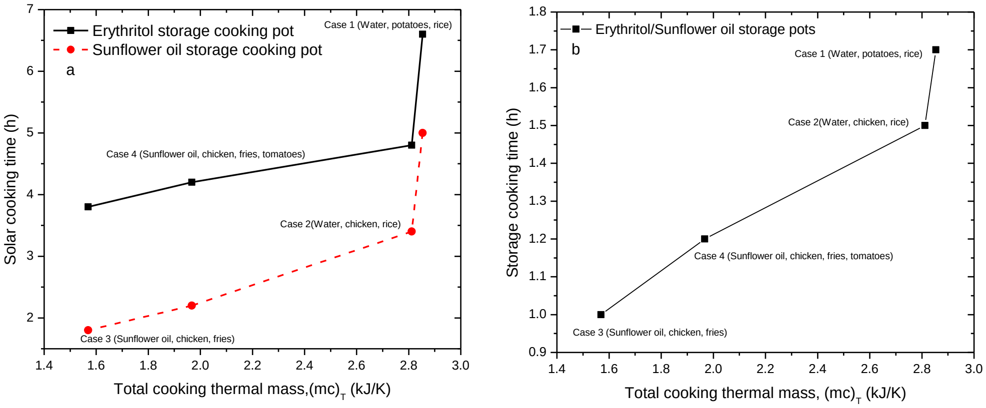

Figure 13: Solar cooking (a) and storage cooking times (b) for different thermal masses of food.

A summary of the temperatures attained using the wonderbags during the storage cooking periods for the two pots is presented in Table 7. It is seen that higher initial cooking temperatures are seen with the oil storage cooking pot due to the higher temperatures attained during solar cooking. The PCM storage cooking pot generally shows higher final storage and cooking temperatures showing that cooking using this pot is more effective during the storage cooking periods. Cases 3 and 4 using sunflower oil as the cooking fluid also show higher cooking temperatures for both cooking pots.

Table 7: A summary of storage cooking temperatures attained using the wonderbag.

Cooking pot	Cooking time (mins)	Initial storage temperature (ºC)	Final storage temperature (ºC)	Maximum food temperature (ºC)	Final food temperature (ºC)
Erythritol					
Case 1	100	117.1	90.1	92.9	89.4
Case 2	90	100.3	77.0	85.6	75.9
Case 3	60	100.7	98.2	95.8	95.7
Case 4	70, 80	121.1, 103.0	103.0, 87.5	101.2, 90.2	93.2, 87.5
Sunflower Oil					
Case 1	100	140.0	74.3	87.1	69.0
Case 2	90	79.5	68.3	79.1	67.1
Case 3	60	137.5	91.0	103.1	69.0
Case 4	70, 80	122.3, 89.2	89.2, 72.6	105.1, 80.6	78.6, 72.3

Table 8 shows a summary of the solar cooking period test results. Generally, food is well cooked using both storage cooking pots except that the cooking periods for the sunflower oil pot are lower than those of the erythritol storage cooking pot. The storage efficiencies are higher for the sunflower oil pot compared to those of the erythritol pot. However, the efficiencies of both pots are quite low possibly due to the low efficiency of the parabolic dish solar cooker which has been recently reported to achieve maximum water and sunflower oil heating efficiencies of 0.15 and 0.22, respectively, when using black non-storage cooking pots (Mawire et al., 2020b). A larger, more efficient dish will improve the storage efficiency as well as an optimised and more efficient storage cooking design as reported recently by Bhave and Kale (2020). The storage efficiencies for frying potatoes and cooking rice as reported by Bhave and Kale (2020) are also reasonably low at 11.34 % and 13.51 % respectively, even with an optimised storage cooking pot and a better solar concentrator resulting in higher operational temperatures. These storage efficiencies are not exceptionally higher than to the ones obtained in this study which range from 2.5 % to 3.7 % for the erythritol storage cooking pot, and from 3.0 % to 7.1 % for the sunflower storage cooking pot. Two efficiencies are shown for the sunflower oil storage pot. These efficiencies signify the efficiency at the end of the solar cooking process for the sunflower oil storage pot, and the efficiency at the end of the experimental test when both pots have cooked the food. The solar cooking period for the sunflower oil pot is shorter compared to the erythritol pot; thus, the first storage efficiencies shown in Table 8 are higher than the second storage efficiencies for sunflower oil. It is also important to state improvements in the efficiency of solar collection and storage results in increased costs which will render the designed product too expensive for use in the developing world with very limited resources. Future work will look at storage pot design improvement.

Table 8: A summary of the solar cooking period experimental results

Cooking pot	Cooked food	Cooked load (kg)	Cooking time (hrs)	Cooking results	Storage efficiency (-)
Erythritol					
Case 1 (Water -0.5 kg)	Potatoes/rice	0.4 (0.2, 0.2)	6.6	Boiled, well cooked	0.037
Case 2 (Water -0.5 kg)	Rice/chicken	0.4 (0.2, 0.2)	4.8	Boil, well cooked	0.025
Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	3.8	Fried and slightly crispy, well cooked	0.032
Case 4 (Sunflower oil-0.1 kg)	Chicken/fries /tomatoes	0.5 (0.2, 0.2, 0.1)	4.2	Fried and slightly crispy, well cooked	0.028
Sunflower oil					
Case 1 (Water-0.5 kg)	Potatoes/rice	0.4 (0.2, 0.2)	5.0	Boiled, well cooked	0.036*(End of solar cooking period) , 0.032 (End of experimental test)
Case 2 (Water-0.5 kg)	Rice/chicken	04 (0.2, 0.2)	3.4	Boiled, well cooked	0.046*, 0.032

Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	1.8	Fried and very crispy, well cooked	0.071*, 0.041
Case 4 (Sunflower oil-0.1 kg)	Chicken/fries/ tomatoes	0.5 (0.2, 0.2, 0.1)	2.2	Fried and very crispy, well cooked	0.042*, 0.030

A summary of storage cooking results is shown in Table 9. The erythritol storage cooking pot uses the stored heat more effectively as all the tests showed that the food are well cooked, and the heat utilisation efficiencies are higher than those for the sunflower oil pot. The erythritol storage cooking pot also shows more effective heat utilisation when cooking foods with higher thermal masses (Cases 1 and 2) as compared to the lower thermal masses (Case 3 and 4). This in agreement with the work by Islam and Sahelin (2014) where larger amounts of food resulted in better thermal performance when wonderbag slow cookers were used. For the sunflower oil storage cooking, there seems to be no clear relationship between the cooking thermal mass and the utilisation efficiency, possibly due to the inefficient heat transfer mechanisms in this pot. As already mentioned, the use of fins and other heat transfer improvements as well as cooking larger amounts of food can improve the efficiency of heat utilisation which varied between 4.8 % to 14.3 % for the erythritol storage cooking pot, and 3.7 % to 6.0 % for the sunflower oil storage cooking pot. A comparison with other related works with optimised finned storage cooking pots achieving higher operating temperatures shows considerably higher heat utilisation efficiencies of 32.38 %, 32.82 % and 30.28 %, respectively (Bhave and Kale, 2020; Bhave and Thakare, 2018). The efficiencies were higher also due to the latent heat contributions considered, and the thermal performance evaluations, which assumed step responses from the initial temperature to the final cooking temperature which is not the case in reality.

Table 9: A summary of the storage cooking period experimental results

Cooking pot	Cooked food	Cooked load (kg)	Cooking time (hrs)	Cooking results	Heat utilisation efficiency (-)
Erythritol					
Case 1 (Water -0.5 kg)	Potatoes/rice	0.4 (0.2, 0.2)	1.7	Well cooked, rice and potatoes soft.	0.143
Case 2 (Water -0.5 kg)	Rice/chicken	0.4 (0.2, 0.2)	1.5	Well cooked, both foods soft.	0.102

Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	1.0	Well cooked, food crispy	0.080
Case 4 (Sunflower oil-0.1 kg, 0.05 kg)	Chicken/fries /tomatoes	0.5 (0.2, 0.2, 0.1), 0.25	1.2. 1.3	Well cooked, food crispy. Chicken well cooked in second test.	0.048*(First test)
Sunflower oil					
Case 1 (Water-0.5 kg)	Potatoes/rice	0.4 (0.2, 0.2)	1.7	Well cooked, rice and potatoes soft.	0.037
Case 2 (Water-0.5 kg)	Rice/chicken	0.4 (0.2, 0.2)	1.5	Partially cooked, rice a bit hard.	0.060
Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	1.0	Well cooked, food less crispier	0.059
Case 4 (Sunflower oil-0.1 kg, 0.05 kg)	Chicken/fries/ tomatoes, Chicken	0.5 (0.20, 0.2, 0.1), 0.25	1.2, 1.3	Well cooked, food less crispy. Chicken partially cooked in second test	0.043*(First test)

Table 10 compares the cooking temperatures achieved with the two storage cooking pots with recent work that has been published on solar cooking storage pots.

Table 10: A comparison of recent work on storage cooking pots

Author	Storage material	Storage mass(kg)	Cooking fluid and combined mass of food (kg)	Maximum temperature achieved in cooking vessel (ºC)	Time taken to achieve the maximum cooking temperature (mins)
Mawire et al., (2020)-Present work	Erythritol	5.438	Water, 0.900	92.9	53
Mawire et al., (2020)-Present work.	Sunflower oil	3.438	Water, 0.900	87.1	13
Mawire et al., (2020)-Present work.	Erythritol	5.438	Sunflower oil , 0.500	95.8	60
Mawire et al., (2020)-Present work.	Sunflower oil	3.438	Sunflower oil, 0.500	103.1	11
Bhave and Kale, (2020)	Solar salt	2.230	Water, 0.325	100.0	20
Bhave and Kale, (2020)	Solar salt	2.230	Ground nut oil, 0.409	180.0	17
Chaudhary et al., (2013)	Acetanilide	2.500	Water, 2.000	84.3	90
Lecuona et al., (2013)	Paraffin wax	5.416	Water, 4.000	90.0	240

Bhave and Thakare, 2018	$MgCl_2 \cdot 6H_2O$, Therm 500	0.480, 0.554	Water, 0.150	100.0	30
Yadav et al., 2017	Acetamide, Stone Pebbles	Not mentioned	Water, 0.400	68.4	120
Yadav et al., 2017	Acetamide, Iron grits	Not mentioned	Water, 0.400	60.1	90

Limited previous work has been reported that clearly evaluates solar cooking storage pots; thus only five authors are used for the comparison. The maximum cooking temperatures and the times for achieving maximum cooking temperatures are slightly better than the work presented by Lecuona et al., (2013), Yadav et al., (2017) and Chaudhary et al., (2013), bearing in mind that some of these authors used larger water thermal masses and different storage materials. Bhave and Kale (2020) and Bhave and Thakare (2018) presented very optimised designs with fins, a better parabolic dish concentrator and one PCM had a higher melting temperature resulting in higher temperatures and faster temperature rises. Their storage cooking masses were also generally lower; however, the intention in the near future is to optimise the design of the cooking pots so that faster solar and storage cooking times can be achieved.

4. Future work

In general, the solar cooking pots showed reasonably good thermal performance considering that they were used with a relatively low efficiency parabolic dish solar cooker and the pots were not of an optimised and efficient design. More future work needs to be done to enhance the heat transfer of the storage material with the use of fins, nanoparticles and an optimised pot design. A better and more efficient parabolic dish solar concentrator needs to be used to achieve higher cooking and storage temperature. A thermal model of the cooking vessel needs to be developed to optimise the design of the pot and also to investigate the integration of the wonderbag. The thermal model will be validated with experimental results presented in this work, and optimisation design changes (shape, fins, materials etc.) to increase the heat transfer efficiency will be performed with a parametric study. The PCM storage material showed good storage cooking characteristics, but the phase change process needs to be improved to shorten the solar cooking period, which was rather too long. Sunflower oil showed good solar cooking characteristics, but its thermal conductivity needs to be enhanced for it to be more useful during the storage cooking period. Future work will also look at combining both PCM and sensible heat storage material in a single cooking pot to enhance the performance of the pot for both solar and storage cooking periods as reported by Yadav et al., (2017). The effect of different loads of water and sunflower oil on the storage and heat utilisation efficiencies also needs to be studied experimentally and numerically in future work. A thermo-economic and payback analysis of the designed system also needs to be investigated to find out if it is affordable for developing countries.

5. Conclusion

Two similar solar cooking storage pots were compared experimentally during solar and storage cooking periods. One storage pot had sunflower oil as the sensible heat storage material, while the other one had erythritol as the phase change material. To test their thermal performance during off-sunshine periods, the two pots were placed in insulated wonderbag slow cookers. The major conclusions of the study were;

1. The sunflower oil storage cooking pot showed faster cooking times (1.8-5.0 h) and higher maximum storage temperatures (124-145 ^{o}C), compared to 3.8-6.6 h and 118 - 140 ^{o}C, respectively, for the erythritol PCM pot during the solar cooking period due to its smaller thermal mass. The storage efficiencies for the sunflower oil pot (3.0 - 7.1 %) were higher compared to the erythritol pot during the solar cooking period (2.5 - 3.7 %). For both cooking pots, the cooking period increased with an increase in the total combined thermal mass of cooked food.
2. The erythritol PCM storage pot outperformed the oil storage pot during off-sunshine periods by achieving lower temperature drops during the storage cooking periods even though it had lower initial storage temperatures. The temperature drops from the maximum cooking temperatures ranged from 0.1 ^{o}C to 9.7 ^{o}C for the PCM storage pot, while those of the sunflower oil pot were significantly higher, ranging between 8.3 ^{o}C to 34 ^{o}C. This was due to its larger thermal storage mass, the release of stored latent heat and higher thermal conductivity during the storage cooking period. The heat utilisation efficiencies of the erythritol pot (4.8 -14.3 %) were greater than those of the sunflower pot (3.7 - 6.0 %). The heat utilisation efficiencies of the erythritol storage

pot were generally greater for larger thermal masses as previously investigated by Islam and Salehin (2014).

3. The use of sunflower oil as a cooking fluid instead of water shortened the solar cooking period, and higher temperatures were obtained. The effectiveness of storage cooking was also improved using sunflower oil as higher maximum storage cooking temperatures ranging from 95.8 °C to 105.1 °C were obtained, compared to 79.1 °C to 92.9 °C for water.
4. The performance of the storage cooking pots during the heat utilisation processes was comparable or slightly better than most of the previously reported works (Chaudhary et al., (2013), Lecuona et al., (2013), Yadav et al., 2017) although optimised storage cooking pot designs by Bhave and Thakare (2018) and Bhave and Kale (2020) showed better heat utilisation characteristics.

Appendix A

Table A1: A summary of solar storage heating experiments using a water load of 2 kg

Cooking pot	Average solar radiation and standard deviation (W/m^2)	Average ambient temperature and standard deviation (°C)	Average wind speed and standard deviation (m/s)	Cooking time (hrs)	Storage efficiency (-)
Erythritol					
Case 1 (13/02/2020)	607±286	27.0±1.3	1.3±0.6	6.8	0.021
Case 2 (04/03/2020)	509±348	26.9±1.5	2.0±0.7	5.6	0.038
Case 3 (19/03/2020)	716±352	28.4±1.7	1.4±0.5	5.6	0.038
Case 4 (20/03/2020)	657±331	29.7±1.2	1.7±0.7	4.0	0.029
Sunflower oil					
Case 1 (13/02/2020)	607±286	27.0±1.3	1.3±0.6	6.8	0.027
Case 2 (04/03/2020)	509±348	26.9±1.5	2.0±0.7	5.6	0.049
Case 3 (19/03/2020)	716±352	28.4±1.7	1.4±0.5	5.6	0.044
Case 4 (20/03/2020)	657±331	29.7±1.2	1.7±0.7	4.0	0.048

Table A1 shows the experimental tests for solar water heating with a water load of 2.0 kg to store heat to be used for cooking. The average solar radiation varies between 509 - 716 W/m^2 in the experimental tests; the average wind speeds vary between 1.3 - 1.7 m/s and the average ambient temperatures between 26.9 - 29.7 ^{o}C. The solar water heating periods range between 4.0 - 6.8 hrs, and it observed that storage efficiencies are slightly lower for the PCM storage pot. Although the efficiencies are lower for the PCM pot, they are comparable to sunflower oil pot. The variable cloudy conditions with high standard deviations in the average solar radiation induce different solar water heating periods to attain high temperatures suitable for storage cooking purposes.

Table A2 shows the storage cooking results after heating water loads of 2.0 kg. Food cooked with the PCM storage pot is well cooked in all cases, whereas the food cooked using water for the oil storage pot is partially cooked. The heat utilisation efficiencies for the PCM storage pot are very high when using water (24.2 % - 28. 1 %) as the cooking fluid compared to when using sunflower oil (4.9 - 7.1 %). On the other hand, the sunflower oil pot shows comparable efficiencies for both cooking fluids (10.4 - 16.7 %). This suggests that larger loads should be used for PCM storage pot whereas it makes no significant difference to increase the load in the oil storage pot. Solar heating with larger loads also assists in achieving higher heat utilisation efficiencies in both pots.

Table A2: A summary of storage cooking experiments after solar storage heating with a water load of 2 kg

Cooking pot	Cooked food	Cooked load (kg)	Cooking time (hrs)	Cooking results	Heat utilisation efficiency (-)
Erythritol					
Case 1 (Water -0.5 kg)	Potatoes	0.5	2.2	Well cooked potatoes soft.	0.242
Case 2 (Water -0.5 kg)	Rice/potatoes	0.5(0.1, 0.4)	2.0	Well cooked, both foods soft.	0.281
Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	2.0	Well cooked, food crispy	0.049
Case 4 (Sunflower oil-0.1 kg)	Chicken	0.5	0.8	Well cooked, chicken slightly crispy.	0.071
Sunflower oil					
Case 1 (Water-0.5 kg)	Potatoes	0.5	2.2	Partially cooked, potatoes not too soft.	0.166
Case 2 (Water-0.5 kg)	Rice/potatoes	0.5 (0.1, 0.4)	2.0	Reasonably well cooked, rice and potatoes not too hard.	0.149

Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	2.0	Well cooked, food crispy	0.104
Case 4 (Sunflower oil-0.1 kg)	Chicken	0.4	0.8	Well cooked, chicken slightly crispy.	0.167

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