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Experimental comparison of heat storage pots containing powdered iron filings and erythritol using parabolic dish solar cookers

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Abstract. Solar cookers cannot be used without heat storage during cloudy periods or at night. Heat storage can be used for cooking during cloudy periods and at night. Two storage cooking pots are thus experimentally evaluated to compare their heat storage performances. A latent heat storage material (erythritol) is compared with a sensible heat storage material (powdered iron filings) during solar cooking periods using parabolic dish solar cookers and during storage cooking periods using wonderbag insulating solar cookers. The powdered iron filings storage pot shows a faster temperature rise during the no-load test, attaining a maximum pot temperature above 200 °C compared to 190 °C for the erythritol due to the higher thermal conductivity of iron filings. However, the storage temperature for erythritol at the end of the no-load test is around 180 °C compared to 140 °C for iron filings. For the storage cooking period, the erythritol storage pot can boil water. In contrast, the iron filings storage pot shows ineffective heat transfer, achieving a maximum temperature of only about 70 °C. For the simultaneous heating and storage test, the iron filings pot shows higher temperatures during the solar cooking period and much lower temperatures during the storage cooking period than the erythritol pot.

Keywords: Erythritol, Heat storage, Iron filings, Solar cooking

1. Introduction

Cooking is a daily activity that humans undertake for survival. Most poor rural communities in low-income countries use carbon-based cooking fuels such as charcoal, firewood and liquified petroleum gas (LPG). Carbon-based fuels have negative impacts on both the environment and human health. Greenhouse gases emitted by burning carbon-based fuels pollute the atmosphere and accelerate global warming [1]. Additionally, inhalation of greenhouse gases causes chronic health conditions such as lung cancer and tuberculosis [2]. Solar cookers offer an alternative environmentally friendly way of cooking food using freely available solar energy [3]. Different designs of solar cookers have been evaluated in recent years to mitigate greenhouse gas emissions from carbon-based fuels [4-7].

Solar cookers have the major disadvantage of being unable to cook food effectively during non-sunshine or low-sunshine periods [8]. Thermal energy storage (TES) can be integrated with



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solar cookers to use solar cookers during low or no sunlight conditions, as reported in recent studies [9-12]. As reported in recent studies, the cheapest way to integrate TES with solar cookers is by embedding the cooking pot with TES materials [13-16]. Thermal energy is stored during sunshine hours using cooking pots and can be utilised during off-sunshine hours. It is also possible to simultaneously cook and store energy using storage cooking pots, as reported in [15-16].

Two types of TES easily integrated into solar cookers are sensible heat TES (SHTES) and latent heat TES (LHTES). SHTES materials, such as rocks, thermal oils and water, are cheaper and readily available but have lower energy storage densities than LHTES materials, which carry more energy per unit volume. LHTES based on phase change materials (PCM) is more expensive and suffers from other disadvantages such as lower thermal conductivity of the storage material and subcooling during the release of the stored latent heat. It is thus essential to compare these two storage systems for implementation with solar cookers to compare the benefits of cost versus better thermal performance. Regarding the cooking and storage speed, the concentrating type of solar cookers is the most viable since higher storage and cooking temperatures can be achieved [18]. In a bid to understand the storage performance of storage cooking pots using SHTES and LHTES, two storage cooking pots containing powdered iron filings (SHTES) and erythritol (LHTES) are compared experimentally using two 1.2 m parabolic dish cookers. Water heating experiments during solar and storage cooking periods are carried out. The experiments compare highly thermally conductive, widely available SHTES (powdered iron filings) and LHTES (erythritol) during solar and storage cooking periods. Erythritol has been widely investigated as a TES material in solar cookers [13, 15-16] whereas little or no reports have been reported on powdered iron filings as TES material in solar cookers. The main novel aspect of the study is comparing erythritol and powdered iron filings in storage cooking pots for solar cooking applications to conclude on the thermal performance before combining SHTES and LHTES materials to reduce the cost of storage.

2. Experimental method

Two small 1.2 m parabolic dish solar cookers reported by Mawire et al. [16] were used in the water heating experimental tests. Figure 1 shows a photograph of the parabolic dish solar cooker reported in more detail by Mawire et al. [16]. The parabolic dish solar cooker has a reflective solar capture area of around 1.13 m², and its focal point diameter is about 60 mm. The dish weighs around 12 kg when unloaded. Manual tracking of the dish was done every 10-15 minutes using the manual tracking mechanism of the dish during experimental tests.



Figure 1. A photograph of the 1.2 m parabolic dish solar cooker [16].

The storage cooking pot configuration consisted of a 1-litre small black stainless cooking pot placed inside a larger 5-litre cooking pot. The simple storage cooking configuration using erythritol as the storage material is shown in figure 2. The exact configuration was used with iron filings as the storage material.



Figure 2. A Photograph showing the open inner and outer pots using 2 kg erythritol as the storage material. The same configuration was used with iron filings.

The space between the pots was filled with thermal energy storage (TES) material. 2.0 kg of erythritol was filled in the space between the pots in the first storage cooking pot. In the second storage cooking pot, 2 kg of iron filings were filled in the space between the two pots. Figure 3 shows photographs of the small and large pots with dimensions before adding storage materials. A detailed description of the dimensions of the cooking pots and the thermal properties of the storage materials is shown in table 1. Storage cooking pot 1 was a latent heat cooking pot consisting of erythritol, while pot 2 was a sensible heat storage cooking pot consisting of

powdered iron filings. Storage material and heated water temperatures were measured with two K-type thermocouples (accuracy of ± 2 °C) placed inside the inner and outer pots during solar and storage cooking experiments. The first thermocouple for measuring the storage temperature was placed on the left-hand side inside the larger pot, approximately 2 cm from the top of the storage materials. The second thermocouple was placed flat at the bottom of the inner storage cooking pot. These thermocouples moved slightly while manually tracking the parabolic dish, but it was deemed unnecessary to weld the thermocouples at fixed positions in the cooking pots to reduce the technical complexity of the pots. The main objective of the experiments was to obtain a general overview of the cooking process temperatures inside the storage materials and cooking pots instead of highly accurate readings. Figure 4 shows the photographs of the erythritol and powdered iron filings, the test storage materials.

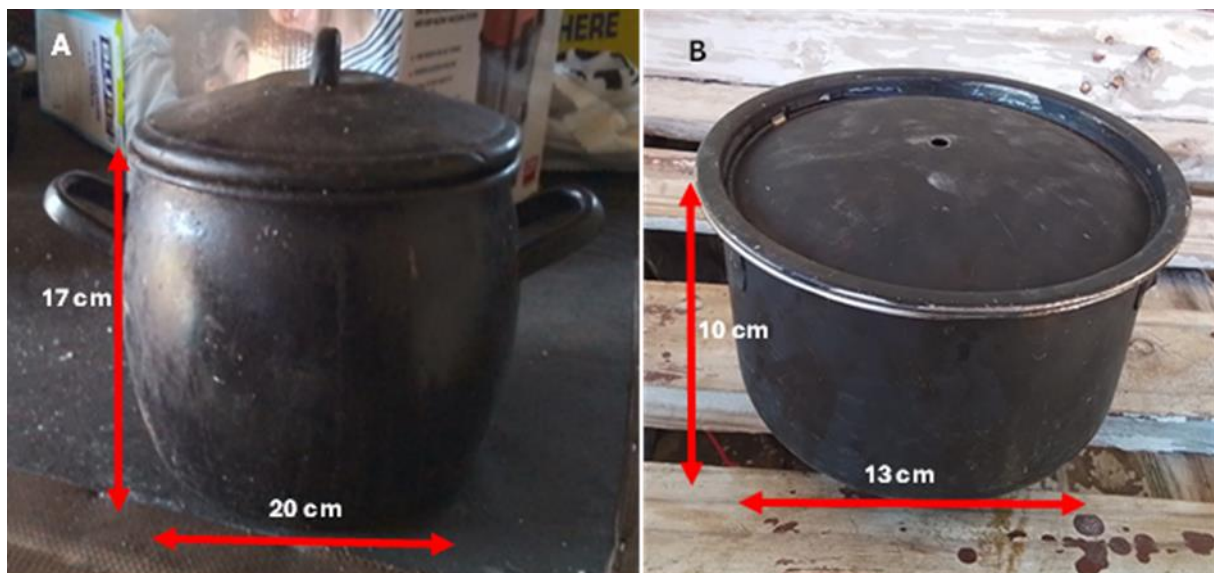


Figure 3. A Photograph showing the open inner and outer pots using 2 kg erythritol as the storage material. The exact configuration was used with iron filings.



Figure 4. Photographs showing (A) powdered iron filings and (B) erythritol.

Table 1. Dimensions of the storage cooking pots and thermal properties of the storage materials.

Property	Storage Cooking Pot 1	Storage Cooking Pot 2
Diameter of the inner pot (m)	0.130	0.130
Diameter of the outer pot (m)	0.200	0.200
Height of the inner pot (m)	0.100	0.100
Height of the outer pot (m)	0.170	0.170
Volume of the inner pot (m ³)	0.001	0.001
Volume of the outer pot (m ³)	0.005	0.005
Material of inner and outer pots	Stainless steel	Stainless steel
Storage material	Erythritol	Iron filings
Thermal conductivity (W/mK)	0.733 (20 °C), 0.326 (140 °C) [16]	40–50 (25 °C) [17]
Specific heat capacity (kJ/kg K)	1.380 (20 °C), 2.760 (140 °C) [16]	0.460[18]
Latent heat of fusion (kJ/kg)	310.6 [16]	247 [19]
Melting temperature (°C)	118-121[16]	1535 [20]

Solar cooking experiments with the sun and storage cooking using insulated wonderbag cookers used in our previous work [16] were carried out. For storage cooking, cooking pots were placed in insulated wonderbag slow cookers after initially charging the storage cooking pots during cooking experiments using solar energy. The experiments were conducted in Mahikeng in the North-West province of South Africa. The first experimental test involved heating the storage cooking pots for 4 hours without any load using parabolic dish solar cookers, followed by storage cooking for four hours using 1 kg of water with the pots placed in wonderbag cookers. The second experimental test involved heating 1 kg of water while storing heat for 2 hours and loading fresh water (1 kg) after two hours to use the stored when the pots were placed in wonderbags for an additional two hours. This was followed by a similar evaluation for an additional four hours using 0.5 kg of water.

Four K-type thermocouples were used to measure the temperature profiles of the storage cooking pots. The thermocouples were connected to four channels of a 20-channel expansion module of a portable Sefram DAS240BAT datalogger powered by a rechargeable Lithium-Ion battery. A fifth K-type thermocouple connected to one channel of the 20-channel expansion module measured the ambient temperature. The data logger recorded the temperature at time intervals of 10 seconds for the duration of the experiments. The global solar radiation was measured with a Kipp and Zonen CMP11 pyranometer with an accuracy of $\pm 10 \text{ W/m}^2$. It was also connected to one channel of the 20-channel expansion module. No detailed thermal performance evaluations were done since the objective was to compare the thermal profiles of two potential storage materials for solar storage cooking pots. Our previous work presented detailed thermal analyses and solar and storage cooking process results [15-16].

3. Results and discussion

The solar radiation and temperature profiles for the first 4 hr tests are shown in figure 5. The solar radiation varies from around 370 W/m^2 at the start of the experiment to around 20 W/m^2 at the end of the 8-hour experimental period. The maximum solar radiation is around 760 W/m^2 , obtained around 3.5 hrs after the start of the experiment, and the average solar radiation is around 550 W/m^2 . There are also brief instances of small passing clouds shown by the vertical lines dropping downwards, for example, before and after 3 hrs. T_{POTF} and T_{STF} represent the temperatures inside the pot and the storage for the iron filings cooking pot, while T_{POTPCM} and T_{STPCM} are the pot and storage temperatures for the erythritol storage cooking pot. Due to the larger thermal conductivity of iron filings, the pot temperature for iron filings rises very fast to a maximum temperature above $200 \text{ }^\circ\text{C}$ around 1.5 hrs. In contrast to this behaviour, the temperature inside the erythritol pot achieves a maximum temperature of around $190 \text{ }^\circ\text{C}$ just before 4 hrs. Even though the iron filings pot shows higher temperatures inside the pot, the maximum storage temperature achieved is only $140 \text{ }^\circ\text{C}$. This is much lower than the maximum storage temperature of around $180 \text{ }^\circ\text{C}$ for the erythritol storage cooking pot. This is likely due to the high thermal conductivity of iron filings, which increases heat transfer to the walls of the outer pot such that more heat is lost through the walls of the outer compared to the erythritol pot. The results during charging suggest that high thermal conductivity storage materials speed up the storage rate at the expense of storing thermal energy at lower storage temperatures. The fluctuations in the temperature profiles are due to manual tracking of the parabolic solar cookers. Automatic tracking could have been employed, but the cost of the tracking system is more than the cost of the parabolic dish; hence, it is not economically viable to include an automatic tracking system because the emphasis of the design is to lower costs for poor people.

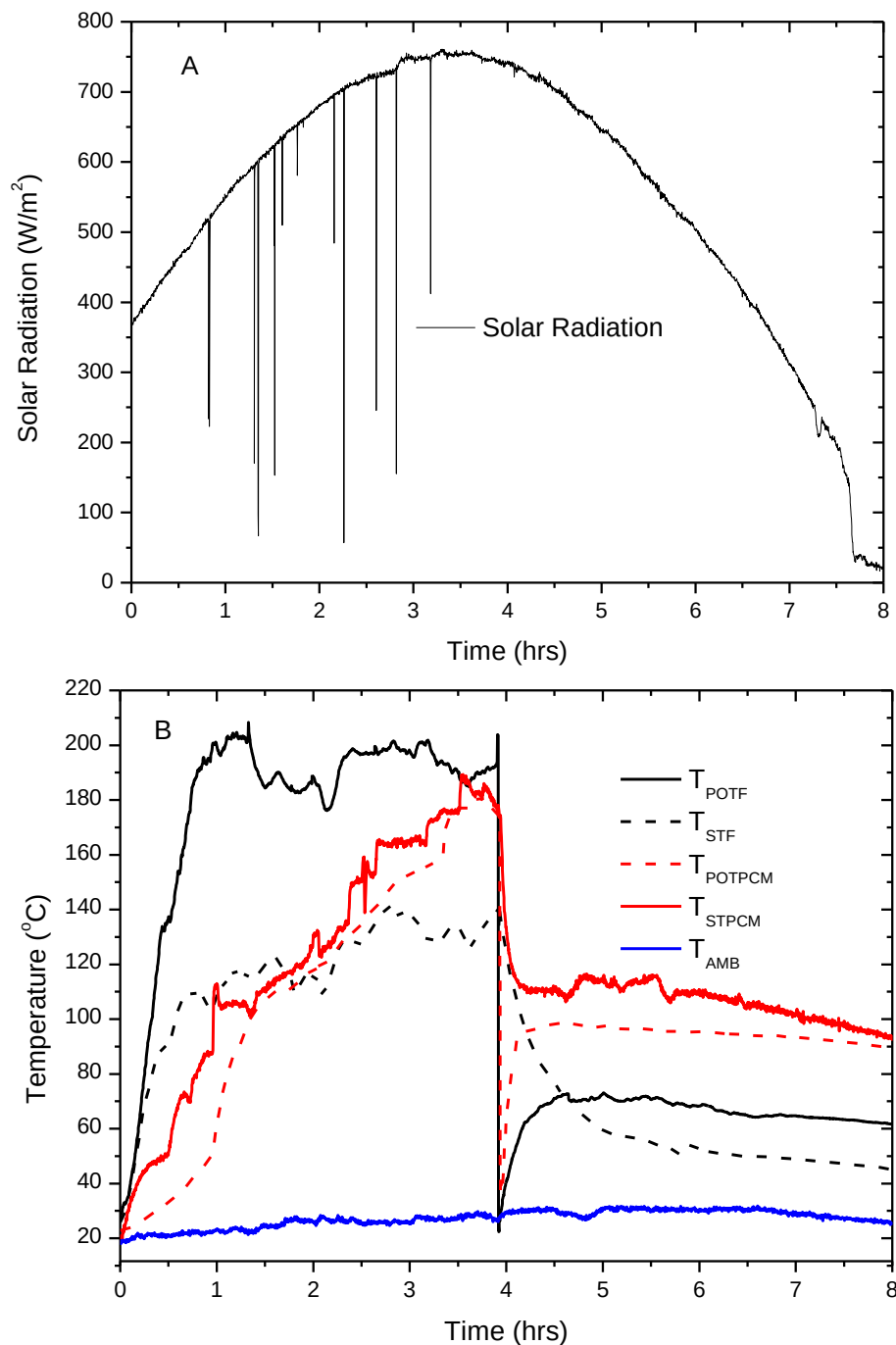


Figure 5. (A) Solar radiation profiles and (B) thermal profiles of the storage cooking pots for the experiment performed on 18 May 2024 from 10:00-18:00 hrs.

For the second part of the experiment, 1 litre of water was added, and the pots were put in wonder bag cookers. Due to the higher storage temperatures of the erythritol storage cooking pot, the water inside the pot boils within 30 minutes. It is also possible that the latent heat stored in

erythritol has been transferred into water. Conversely, iron filings that achieve lower storage temperatures with no phase change show lower water temperatures below the boiling point. The maximum water temperature is only 70 °C for the iron filings storage cooking pot. There is a significant, pronounced temperature drop from around 140 to 55 °C for the iron filings storage during the 4 hrs of heat utilisation. In contrast to this behaviour, at the end of the 4-hr heat utilisation period, the erythritol storage pot still shows storage temperatures above 90 °C, implying that heating energy is still available.

Experimental test results while loading with water during charging and discharging are shown in figure 6. The first two hours involve water heating experiments with a load of 1 litre followed by heat utilisation (storage heating) for two hours using 1 litre of water and the wonder bag cookers with no solar energy. This is followed by solar energy heating using 0.5 litres of water. The last two hours of the experiments involve storage heating using 0.5 litres of water with no solar energy. The maximum solar radiation achieved in the experiment is around 730 W/m², and the average solar radiation for the experimental period is around 487 W/m². The storage temperature for iron filings initially shows a faster rate of rise compared to erythritol during the first 30 minutes of charging. However, as time progresses, it fluctuates up and down, possibly due to heat loss through the walls and manual tracking, achieving a maximum temperature close to 120 °C. For the erythritol, the storage temperature rises steadily with fewer fluctuations achieving a maximum temperature of around 140 °C. Regardless of the lower storage temperatures achieved by iron filings, water is superheated in a pot, achieving temperatures above 120 °C between 1-2 hours of the experiment. This superheating phenomenon is most likely caused by the high thermal conductivity of iron filings since it does not appear for erythritol. Erythritol shows lower water heating temperatures during the first two hours of the experiment, only boiling at around 92 °C after 1.5 hours.

For the storage water heating period between 3-4 hrs, the erythritol storage cooking pot shows superior performance achieving temperatures close to 75 °C compared to 45 °C. Erythritol is thus more effective in transferring stored heat to water than iron filings. This result agrees with the result of Figure 5 (B). For the next solar water heating period, the erythritol storage temperature rises much faster and higher than iron filings due to a higher initial temperature of around 75 °C compared to around 45 °C for iron filings. The same superheating phenomenon observed in the first solar water heating period is also observed for iron filings in the second solar heating period. For the second solar water heating period using a lower heating load (0.5 litres), erythritol achieves the boiling point of water earlier than iron filings, which experience superheating of water. It is essential to state that two other portable temperature sensors connected to multimeters were also used to confirm the result of superheated water. This was not an experimental measurement error. As with the case of the first experimental test case, erythritol showed more effective storage heating than iron filings in the second period of storage water heating. 0.5 litres of water was heated to around 90 °C for the erythritol pot compared to only about 70 °C for iron filings. At the end of period 2 of storage water heating, the storage temperature for erythritol is still above 90 °C compared to iron filings which show a storage temperature below 50 °C. The release of stored latent heat of fusion and the higher specific heat capacity of erythritol in the liquid phase could contribute to better storage performance. The results suggest combining erythritol and iron filings will enable good solar and storage cooking performance since iron filings performed better during the solar cooking period, and erythritol performed better during the storage cooking period.

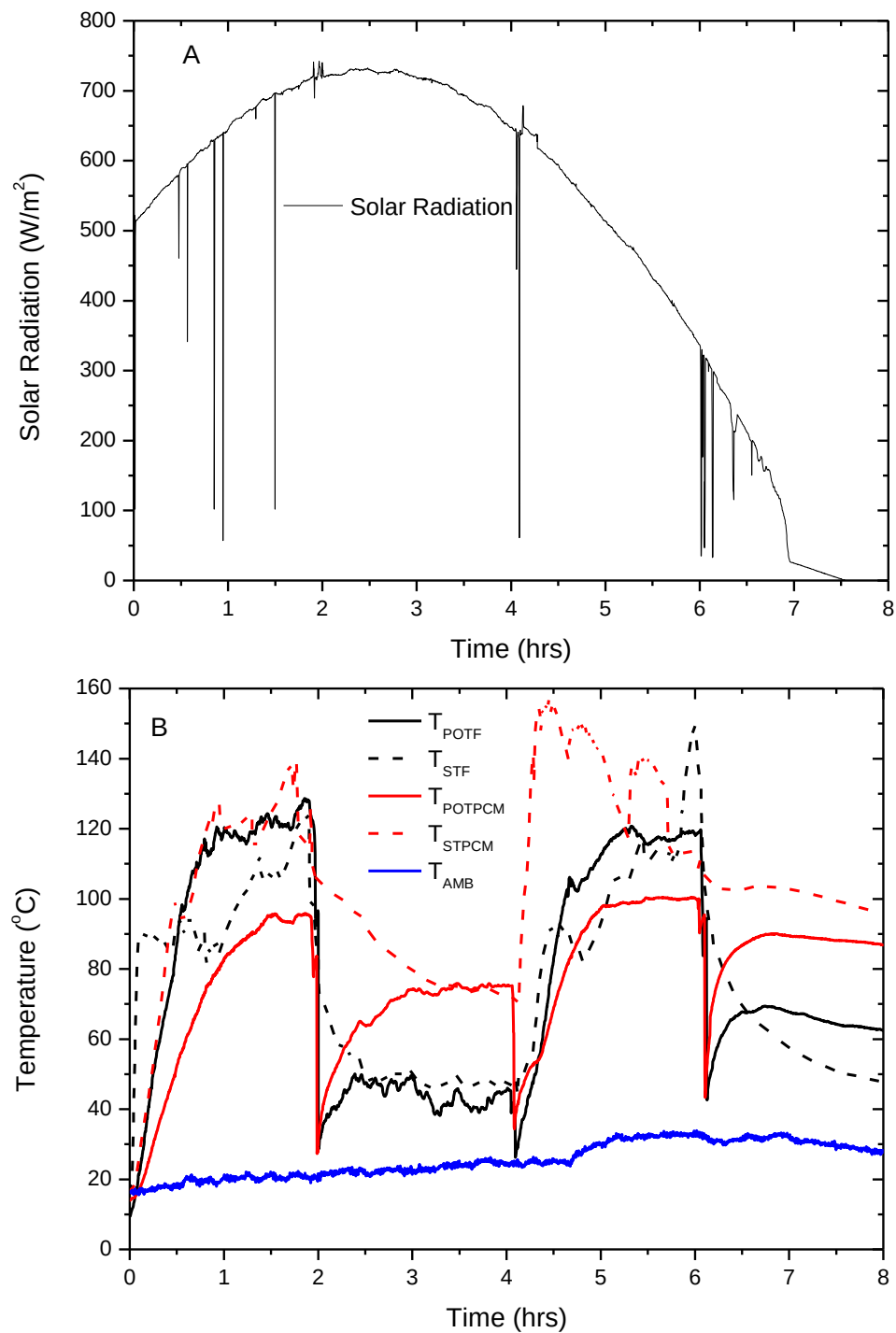


Figure 6. (A) Solar radiation and (B) thermal profiles of the storage cooking pots for the experiment performed on 21 May 2024 from 10:00-18:00 hrs.

4. Conclusion

A latent heat storage material (erythritol) was compared with a sensible heat storage material (powdered iron filings) during solar cooking periods using parabolic dish solar cookers and

during storage cooking periods using wonder bag insulating solar cookers. The iron filings storage pot showed a faster temperature rise during the no-load test, attaining a maximum pot temperature above 200 °C compared to 190 °C for the erythritol due to the higher thermal conductivity of iron filings. This suggests that metallic sensible heat storage materials are more efficient when storage cooking pots are not loaded. For the storage cooking period after the no load heating test, the erythritol pot boiled water, whereas the iron filings storage pot showed ineffective heat transfer, achieving a maximum temperature of only about 70 °C. This suggests that latent heat storage is more efficient than metallic sensible heat storage during heat utilization. The results suggest combining organic phase change material (erythritol) and metallic sensible heat storage (iron filings) will enable good solar and storage cooking performance since the metallic sensible heat performed better during the solar cooking period, and the organic phase change material performed better during the storage cooking period. Other types of medium temperature organic phase change materials such as xylitol and metallic sensible heat storage materials such as aluminium and cast iron need to be compared experimentally and numerically in solar cooking storage pots in future studies. Future work will also investigate a combined or composite storage cooking pot consisting of organic latent heat storage and metallic sensible heat storage to improve the thermal conductivity of the organic phase material during the solar cooking period. The performance of different storage ratios of organic phase materials and metallic sensible heat storage will also be experimentally investigated.

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