Experimental Energetic and Exergetic Performance of a Combined Solar Cooking and Thermal Energy Storage System

Katlego Lentswe, Ashmore Mawire * and Prince Owusu

Physics Department, Material Science, Innovation and Modelling (MaSIM), North-West University, Mmabatho 2745, South Africa
* Correspondence: ashmore.mawire@nwu.ac.za

Abstract: Most solar cookers usually perform a single task of solely cooking food during sunshine hours. Solar cookers coupled with thermal energy storage (TES) material for off-sunshine cooking are usually expensive and require complex engineering designs, and cannot be used for dual purposes, for example, solar water heating and cooking. In this paper, a solar cooker that can perform dual tasks of cooking as well as storing thermal energy to be used during off-sunshine periods is presented. The experimental setup is composed of a parabolic dish, a solar receiver coupled with a flat plate and an oil-circulating copper coil for charging and discharging a storage tank. The objective of the experiment is to evaluate the energy and exergy thermal performance parameters of the dual-purpose system during charging and discharging cycles. The effect of the flow rate and the mass of the load are investigated while using sunflower oil as both the heat transfer fluid and the storage material. Charging and discharging experiments are conducted using four different flow rates (2, 3, 4, 5 mL/s), and with different masses (0.5, 1, 1.5, 2.0 kg) with water and sunflower oil as the test loads. The charging results show that the average energy and exergy rates as well as their corresponding efficiencies increase with an increase in the charging flow rate. On the other hand, the increase in the mass load tends to decrease marginally the average charging energy and exergy rates for water, and their corresponding efficiencies. For sunflower oil, the average charging energy and exergy rates and efficiencies showed a more pronounced decrease with an increase in the mass. Water generally shows higher charging and discharging energy and exergy efficiencies compared to sunflower oil with an increase in the flow rate. For discharging results, the correlations between the energy and exergy thermal performance parameters with respect to the flow rate and the heating load are not well defined possibly due to different initial storage tank temperatures at the onset of discharging and the inefficient discharging process which needs to be optimized in future.

Keywords: combined; energy and exergy analysis; solar cooker; thermal energy storage

1. Introduction

Cooking is a process that is performed daily in all households, and most disadvantaged communities utilize polluting cooking energy resources such as paraffin, wood, cow dung, and coal. These non-clean energy sources emit harmful gases that are lethal to the environment and human beings [1–3]. To reduce harmful gases, an alternative method to cook is to utilize solar cooking. Cooking using the sun is completed by capturing energy from the sun using a solar cooker, and there are several types of solar cookers depending on the temperature range and cooking style [4]. The most common types are (1) solar box cookers, (2) solar panel cookers, and (3) concentrating solar cookers. Each type of solar cooker is designed to accommodate certain types of cooking methods such as frying, boiling, and roasting. One of the major disadvantages of solar cookers is that they cannot operate during non-sunshine periods. A possible solution for this disadvantage is to combine solar cookers with thermal energy storage (TES) systems to utilize the stored heat.
during non-sunshine hours. The most common TES materials that have been studied over the years are sensible heat storage materials [5–11] and phase change materials (PCMs) [12–16]. Researchers have studied the integration of solar cookers with the TES system and evaluated their performances, particularly solar concentrating cookers because of the higher temperatures they achieve which implies a shorter cooking period and the possibility of a wide variety of cooking processes such as frying, baking, and boiling [17].

Thermal energy storage (TES) is the ability of a material to store thermal energy [18]. TES systems combined with solar cookers can be advantageous during non-sunshine periods. In recent years, researchers have extensively investigated solar cookers integrated with TES systems [19–32]. Saxena and Karakilçik evaluated a solar cooker with low-cost storage material [19]. The experimental setup had the objective of evaluating the thermal performance of a solar box cooker with additional reflective mirrors, and low-cost thermal energy storage. Different ratios of a mixture of sand and granular carbon were utilized as the thermal heat storage, and this was placed inside the solar box cooker. Experiments were conducted to determine the optimum ratio of sand and granular carbon. The results obtained showed that the thermal efficiency was seen to be 37%, and it was concluded that the experimental setup was viable to cook during off-sunshine periods. An experiment of a box-type solar cooker with a sensible heat TES medium was performed by Cuç [20]. A comparison of the thermodynamic behavior of two solar box cookers with and without a sensible heat TES medium was presented. Bayburt stone was used as the TES medium. The energy efficiency of the Bayburt stone cooker was found to be in the range of 35.3–21.7%, while the energy efficiency of the conventional cooker was lower ranging between 27.6–16.9%. Vigneswaran et al. [21] presented an evaluation of a solar box cooker assisted with a latent heat energy storage system. The experimental setup was composed of a solar box cooker, a varied number of reflectors, and PCM. The performance of the experimental setup was evaluated by varying the number of reflectors with a latent heat storage medium. Results showed that incorporating the latent heat storage medium in a solar box cooker with an optimum number of four mirrors enabled cooking during off-sunshine periods. Saxena et al. [22] evaluated the performance of a solar box cooker integrated with sensible storage material on the surface of the absorbing plate. Sand and granular carbon were used as sensible heat materials. Cooking experiments were conducted using different food products to establish the performance of sensible heat material during non-sunshine periods. The results obtained showed that there was an improvement in the solar cooking performance when both sensible heat materials were mixed compared to the non-storage case. Milikias et al. [23] evaluated an improved box solar cooker with sensible heat TES. The experimental setup aimed to evaluate the box cookers with and without TES using black stone and concrete as the sensible heat storage materials. Stagnation, test loads (water), and cooking experiments were performed to evaluate the thermal behavior of the two solar box cookers. Experimental results of the evaluation showed that the improved box-type solar cooker took two hours to boil water, whereas the conventional box took three hours.

The selection of PCM for a solar box cooker integrated with a TES unit using a multi-criteria decision-making technique was performed by Anilkumar et al. [24]. The study aimed to select an optimum PCM for a solar box cooker. Multi-criteria decision-making (MCDM) models were utilized to determine efficient PCMs. Erythritol was found to be the recommended PCM with a mass that was less than 6.06 kg. Saxena et al. [25] designed and investigated the thermal performance of a box cooker with flexible solar collector tubes. The objective of the experiment was to develop a solar box cooker that has a faster response and is uninterrupted during the cooking process. Three TES materials (grain carbon power, paraffin wax, and a mixture of carbon powder and paraffin wax) were inserted in cylindrical copper tubes to determine the thermal parameters of the improved solar box cooker. The results obtained showed that the overall thermal efficiency of the modified solar box cooker was seen to be 53.81% more than that of a conventional solar box cooker. The performance assessment of a box-type solar cooker using Jatropha oil as
a heat storage material was completed by Nébié et al. [26]. Experiments were carried out to evaluate the cooking power and the efficiency of the solar box cooker during off-sunshine periods. The results showed that by integrating the Jatropha oil with a solar box cooker the maximum temperature reached 157.7 °C. Experimental validation of a high-temperature solar box cooker with a solar-salt-based thermal storage unit was completed by Coccia et al. [27]. The objective of the experiment was to characterize the solar box cooker integrated with a PCM solar-salt-mixture TES unit. The results showed that the PCM improved the load thermal stabilization during off-sunshine periods. Palanikumar et al. [28] investigated a solar box-type cooker with nanocomposite PCMs using flexible thermography. The experiment aimed to compare a solar box cooker with PCM, one with nanoparticles PCM, and one without nanoparticles PCM. The results showed that the solar box cooker with nanoparticles PCM was 11% more efficient than the solar box cooker configuration without PCM.

In addition to solar box cookers with TES, recent work has also been completed on solar concentrating cookers with TES. A solar parabolic dish cooker with a porous medium was experimentally evaluated by Lokeswaran and Eswaramoorthy [29]. The experiment aimed to build an affordable and energy-efficient parabolic dish cooker. The experimental test was conducted with and without the porous medium. The scrap material receiver was combined with a cooking vessel, and stagnation and water boiling tests were conducted to determine the thermal performance, heat factor, and cooking power. Results showed that the optical efficiency factor with and without porous medium increased to maximum values of 61% and 57%, respectively. The stagnation temperature for the utensil with a porous medium receiver was about 8 °C more than the stagnation temperature of the utensil with the plain receiver. Wolffe and Hassen [30] presented an experimental evaluation of two solar cookers with storage. In the experiments, two TES cooking pots were heated at the focal regions of the two parabolic dish cookers. The heat storage materials in the pots were rocks and engine oil. Charging and discharging experiments using water as the test load were performed to determine the maximum temperatures that could be achieved. The maximum temperature achieved was 355 K after 40 min, and this was evidence that the TES pot could cook rice.

An analysis of the thermal performance of solid and liquid energy storage materials in a parabolic dish solar cooker was completed by Senthil and Cheralathan [31]. The objective of the experiment is to enhance the thermal performance of a solar cooking pot using different sensible heat storage media. The sensible heat storage media considered were sand, stone pebbles, iron grits, steel balls, coconut oil, sunflower oil, and olive oil. Charging and discharging experiments were performed using the different sensible storage media to determine which storage material was the most efficient. Sunflower oil showed the best thermal performance compared to the other storage media. The performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking was completed by Mawire et al. [32]. The experimental setup was composed of a parabolic dish cooker which was used to reflect the sun rays to the storage pots, and two storage pots that contained sunflower oil and erythritol PCM as the storage materials. Cooking experiments were carried out using different food during sunny periods and off-sunshine to evaluate the performance of the storage pots. During non-sunshine periods, the storage pots were inserted into the wonderbag slow-insulated cookers. The results showed that the sunflower oil storage cooking pot cooked faster and had higher temperatures compared to the erythritol PCM storage cooking pot during solar cooking periods. However, during off-sunshine periods, erythritol performed better than sunflower oil.

As presented in the literature review, there has been a limited amount of recent research that has been focused on dual-purpose/combined solar cookers with TES for cooking simultaneously while storing thermal energy for other domestic purposes such as cooking and water heating. This research gap that has been identified needs to be investigated. In this work, a solar cooking system combined with storage was designed and
developed for domestic applications in rural communities to perform dual tasks of simultaneously cooking and storing solar thermal energy for usage later. The novelty lies in the fact that solar cooking is possible as well as storing energy for usage later for other domestic purposes. The system is envisaged to be more cost-effective and versatile than the current solar cooking systems which only are used for the single purpose of cooking food. This paper aims to evaluate the thermal performance of the combined solar cooking and TES system based on thermal performance evaluators from energetic and exergetic perspectives. The stored energy during the solar cooking periods is used for off-sunshine cooking in this paper, although other applications can be investigated such as solar water heating and solar food drying. The results will be useful for the further development of dual-purpose/combined solar cooking systems with thermal energy storage. Very few of these systems have been developed.

2. Experimental Setup and Procedure

A photograph of an experimental setup of a solar parabolic dish cooker combined with a TES tank is shown in Figure 1.

![Figure 1](image)

An outdoor experimental setup of an SK-14 parabolic dish cooker combined with a TES system. The experimental components that were utilized are (1) a storage tank, (2) DC pump, (3) flow meter, (4) receiver, (5) solar parabolic dish cooker, and (6) a cooking pot.

A 30 L stainless steel storage tank (1) with a diameter of around 0.03 m was filled up with sunflower oil. It was insulated with 0.005 m of rock wool, and it was a cylindrical structure. Sunflower oil was also used as the heat transfer fluid (HTF). Five K-type were attached along the height of the storage to measure the axial temperature distribution (TA-TE) as shown in Figure 2b. Circulation of the heat transfer fluid was induced by a DC pump (2) which was connected to the storage tank via a positive displacement flowmeter (3) with an accuracy of ± 1%. The HTF was heated in a receiver (4) which was connected to the top of the storage to charge it after absorbing concentrated solar thermal energy from the parabolic dish solar cooker (5). A copper spiral coil embedded underneath a black-painted circular plate constituted the receiver as shown in Figure 2a. The receiver placed at the focal point of the parabolic dish absorbed concentrated solar thermal radiation from the parabolic dish. A Kipp & Zonen CHP1 Pyrheliometer measured the direct solar radiation while placed on a Kipp & Zonen SOLYS 2 Solar tracker. Simultaneous heating of the load in a black cooking pot (6), and heating of circulating sunflower in the coil was made possible by absorbing the concentrated solar radiation. Different test loads
of both sunflower oil and water were poured into the pot and used in the experiments. During the discharging period, the solar parabolic dish cooker was defocused, and the DC pump was configured to extract the heated fluid from the top of the storage tank. The hot oil extracted from the top storage tank flowed into the outlet pipe of the receiver to deliver heat to the spiral coil that is attached to a circular cooking plate. A black cooking pot filled with the test load was placed on top of the black plate absorber to heat the load. Sunflower oil flowed from the outlet pipe of the copper spiral coil to the inlet pipe of the storage tank to charge the storage tank.

Figure 2. Photographs of the (a) receiver, (b) storage tank, and (c) a schematic flow diagram of the experimental setup.

Photographs of the receiver (a), the storage tank with its dimensions (b), and a schematic diagram of the experimental setup (c) are shown in Figure 2. The receiver at the focal region of the parabolic dish heated circulating sunflower oil to charge the storage tank as well as the load contained in black cooking pot placed on it as shown in Figure 2a. The top of the receiver was a flat circular stainless-steel plate with a diameter of 0.013 m and a thickness of 0.008 m. A copper spiral coil was attached at the bottom of the plate for circulating the HTF to charge the storage tank. The whole receiver was painted black with a specialized high-temperature resistance paint to increase its absorbance of solar radiation.

The dimensions of the storage tank and thermocouples to measure the temperatures at 5 axial levels (TA–TE, TA = 0.080 m, TB = 0.150 m, TC = 0.220 m, TD = 0.290 m and TE = 0.360 m from the top of the storage) are shown in Figure 2b. The storage tank has a height of 0.425 m and a diameter of 0.405 m. A schematic diagram of the experimental setup is shown in Figure 2c. The DC pump circulated cold sunflower oil at the bottom of the storage system to the inlet of the receiver. Circulating sunflower oil absorbed concentrated
solar radiation to come out hot at the outlet of the receiver thus charging up the storage system. A pot placed at the top of the receiver with a heating load was also simultaneously heated up during charging. The flowmeter measured the flow rate during the charging cycle, and a strainer blocked solid residues from entering the flowmeter. During discharging, the pump was reversed to extract heat from the storage system, while the receiver was defocused. The stored thermal energy was used to heat the cooking pot with the test load.

Test loads of 0.5, 1.0, 1.5, and 2.0 kg were used in the black cooking pot during charging and discharging cycles to investigate the effect of the mass on the energy and exergy performance at a flow rate of 2 mL/s. Water and sunflower oil were used as the loads for each test mass. A constant test load of 0.5 kg was used while using 4 different flow rates (2.0, 3.0, 4.0, and 5.0 mL/s) to evaluate the effect of the flow rate on the energetic and exergetic performance. Each test was conducted separately with water and sunflower oil as the heating loads.

3. Thermal Performance Parameters

3.1. Energy Analysis

The energy-based thermal performance parameters during the charging and discharging cycles are presented in this section. The receiver power or energy rate of the circulating fluid is given as [33]:

\[
P_R = \rho_{av} c_{av} \dot{V}_R(T_{out} - T_{in}),
\]

where \(\rho_{av}\) is the average density of sunflower oil circulating through the receiver, \(c_{av}\) is the average specific heat capacity, \(\dot{V}_R\) is the average flow rate of sunflower oil, \(T_{out}\) is the outlet temperature of sunflower oil exiting the receiver, and \(T_{in}\) is the inlet temperature of sunflower oil entering the receiver. The average density and specific heat capacity of sunflower oil are temperature dependent, and vary with temperature \(T\) as [34,35]:

\[
\rho_{av} = 932.37 - 0.66 T,
\]

and

\[
c_{av} = 2115 + 3.13 T.
\]

The parabolic dish solar power \((P_d)\) concentrated at the receiver is expressed as [33]:

\[
P_d = \eta_o A_p G_T,
\]

where \(\eta_o\) is the optical efficiency of the dish, \(A_p\) is the aperture area of the parabolic dish and \(G_T\) is the amount of direct solar radiation from the sun. The average charging energy efficiency \((\eta_{Ech})\) is defined as the ratio of receiver energy rate \((P_R)\) to the solar energy power \((P_d)\), and it is expressed as [33]:

\[
\eta_{Ech} = \frac{P_R}{\eta_o A_p G_T} = \frac{\rho_{av} c_{av} \dot{V}_R(T_{out} - T_{in})}{\eta_o A_p G_T}.
\]

The discharging energy efficiency of the storage tank can be defined as the ratio of the total energy discharged from the storage tank to the total energy stored during charging, and it is expressed as [34]:

\[
\eta_{Edis} = \frac{\sum_{t_d} \rho_{av} c_{av} \dot{V}_R(T_{out} - T_{in}) dt_{(dis)}}{\sum_{t_c} \rho_{av} c_{av} \dot{V}_R(T_{out} - T_{in}) dt_{(ch)}},
\]

where \(t_c\) and \(t_f\) are the initial and final times during charging \((ch)\) and discharging \((dis)\) cycles.

3.2. Exergy Analysis

The charging exergy rate \((E_{CHXR})\) with reference to the ambient temperature is expressed as [33]:
\[ E_{CHNR} = P_R - \rho_{av} c_{av} V_{av} T_{amb} \ln \left( \frac{T_{Rout}}{T_{Rin}} \right), \]  

where the \( T_{amb} \) is the ambient temperature. The quality of energy delivered to the parabolic dish and the receiver is the solar exergy rate expressed by the Petela expression multiplied by the solar power [33,36,37] giving:

\[ E_{XS} = \eta_o G_T A_P \left[ 1 + \frac{1}{3} \left( \frac{T_{amb}}{T_S} \right)^4 - \frac{4T_{amb}}{3T_S} \right], \]  

where \( T_S \) the surface temperature on the sun is around 5778 K. \( \eta_{Exch} \) the exergy efficiency during charging is determined by dividing the charging exergy rate and the solar exergy rate giving the expression [33,37]:

\[ \eta_{Exch} = \frac{P_R - \rho_{av} c_{av} V_{av} T_{amb} \ln \left( \frac{T_{Rout}}{T_{Rin}} \right)}{G_T A_P \left[ 1 + \frac{1}{3} \left( \frac{T_{amb}}{T_S} \right)^4 - \frac{4T_{amb}}{3T_S} \right]}. \]  

The discharging exergy efficiency \( (\eta_{Exdis}) \) is calculated as the ratio of the total discharging exergy \((dis)\) to the total charging exergy \((ch)\), and it is expressed as [34]:

\[ \eta_{Exdis} = \frac{\sum_t \int_{t=1}^{T_R} \rho_{av} c_{av} V_{av} T_{amb} \ln \left( \frac{T_{Rout}}{T_{Rin}} \right) dt_{dis}}{\sum_t \int_{t=1}^{T_R} \rho_{av} c_{av} V_{av} T_{amb} \ln \left( \frac{T_{Rout}}{T_{Rin}} \right) dt_{ch}}. \]  

### 3.3. Experimental Uncertainty

The uncertainty analysis method [38] based on the propagation of errors was used to estimate the uncertainties in the derived thermal performance parameters such as the energy and exergy rates during charging and discharging. For example, the uncertainty in the receiver energy rate is given as [38]:

\[ \delta P_R = \sqrt{ \frac{\delta P_R}{\partial P_R}^2 \left( \frac{\partial P_R}{\partial \rho_{av}} \right)^2 + \frac{\delta P_R}{\partial c_{av}}^2 \left( \frac{\partial P_R}{\partial c_{av}} \right)^2 + \frac{\delta P_R}{\partial V_{av}}^2 \left( \frac{\partial P_R}{\partial V_{av}} \right)^2 + \frac{\delta P_R}{\partial T_{Rout}}^2 \left( \frac{\partial P_R}{\partial T_{Rout}} \right)^2 + \frac{\delta P_R}{\partial T_{Rin}}^2 \left( \frac{\partial P_R}{\partial T_{Rin}} \right)^2 }, \]  

where \( \delta \rho_{av} = \pm 0.069 \text{ g/cm}^2, \delta c_{av} = \pm 0.069 \text{ J/gK}, \delta V_{av} = \pm 0.1 \text{ mL/s}, \delta T_{Rin} \) and \( \delta T_{Rout} \) are \( \pm 2 \text{ }^\circ \text{C}. \) Other uncertainties in other derived quantities were determined similarly, and these were between \( \pm 1\text{–}5\% \) of the average values which was not too high and acceptable within the limits of the experimental measurement equipment.

### 4. Results

Solar and storage cooking experimental results using 0.5 kg of water and oil utilizing a flow rate of 2 mL/s are shown in Figure 3. The solar and storage cooking periods were both 3h, 11h00–14h00, and 14h00–17h00, respectively.

Solar radiation was only considered for the solar cooking period, and during the storage cooking period, the parabolic dish cooker was defocused because it did not affect heat retention. The plots of Figure 3A1 present wind speed and solar radiation profiles using water as the load charging with a flow rate of 2 mL/s. For most of the duration of charging, the solar radiation is around 850 W/m², while the wind speed shows a maximum value close to 1.7 m/s at 13h30. The wind is seen to also fluctuate up and down during the charging process. Figure 3A2 shows the solar radiation and wind speed behavior, during the solar cooking period when oil was used as a test load. The solar radiation was approximately 770 W/m² from 11h00 to 13h00, and it decreased to around 740 W/m² from 13h00–14h00. For the oil test, the solar radiation was lower as compared to the water test. The wind speed for the oil test also fluctuated up and down as seen with the water test load. However, the wind speed values were greater compared to the water test, with a maximum value of approximately 4.2 m/s being achieved at 11h30.
Figure 3. Experimental results of two test loads (water and sunflower oil) for a load of 0.5 kg utilizing a flow rate of 2.0 mL/s. (A) Direct solar radiation and wind speed (A1—water, A2—sunflower oil), (B) the temperature profiles of the solar receiver (B1—water, B2—sunflower oil), and (C) the temperature profiles of a storage tank (C1—water, C2—sunflower oil). Experimental dates were 10 July 2021 and 13 July 2021 for water and oil tests, respectively.

Figure 3B1,B2 presents the receiver temperature profiles for both test loads (water and sunflower oil) during charging and discharging. The inlet and outlet receiver temperatures are given as \( T_{\text{rin}} \) and \( T_{\text{rou}} \), respectively, while the cooking temperature at the surface of the plate is \( T_{\text{surface}} \). Both the surface and receiver temperatures during the charging process (solar cooking) for both loads fluctuate up and down due to manual tracking of the dish. The use of manual tracking lowered the cost of the system since automatic
Tracking was deemed rather expensive and complicated because of the articulated flexible piping used in the flow loop. Surface plate temperatures were in general lower than the receiver outlet temperatures due to the transfer of heat from the cooking plate to the heated load. For water as a test load, the outlet receiver temperature was around 160 °C, whereas the surface temperature was around 190 °C at the end of charging. This was due to not defocusing the receiver immediately before commencing the discharging process. Water achieved a maximum temperature close to 90 °C at the end of the solar cooking process. The receiver inlet temperature fluctuated up and down to a maximum of around 55 °C except when discharging was about to start where it rose sharply because of not defocusing the receiver. Using oil as the test load, the same fluctuation of the receiver and surface temperatures are seen due to the manual tracking of the parabolic dish solar cooker. However, the maximum receiver inlet and outlet temperatures achieved were comparable to the water test regardless of higher ambient wind speed and lower solar radiation conditions. The higher wind speed conditions for the oil test only marginally reduce the receiver temperatures. Possibly due to the low thermal mass of oil as the cooking load, higher temperatures were seen with oil as compared to water as the load. The oil cooking pot achieved a maximum temperature of around 120 °C. The effect of not immediately defocusing the receiver before discharging is also seen during the heating of oil where the temperatures rose sharply at the end of the charging cycle.

For the discharging cycle, both heating loads show a drop in the receiver temperatures as the stored energy is used to heat the loads. For water, the temperature rises to a maximum of around 35 °C, whereas the oil drops from about 50 °C to just above 30 °C at the end of the discharging period. This shows ineffective heat transfer during the discharging period probably because of the long connecting pipes that were used in the experimental setup since the same charging and discharging flow loop was used to cut down on costs. These long pipes resulted in poor heat transfer due to large exergy losses induced by heat losses to the environment. A more effective way to use the stored heat is directly transferring the stored energy to a storage cooking pot placed in an insulated slow cooker as recently reported by Mawire et al. [32]. Another possibility is to use shorter pipes for the discharging loop and enhance heat transfer at the plate so that acceptable cooking temperatures can be attained.

Storage tank temperature profiles for the whole charging and discharging cycles are shown in Figure 3C1,C2. The two thermal profiles for both heating loads are almost comparable and show similar thermal behavior. Fluctuations such as the receiver outlet temperature are seen with the top storage temperature (T_s) during charging since the top of the storage tank was connected to the outlet of the receiver. Manual tracking seemed to affect the top of the storage tank. Water as a test load achieved a maximum temperature of around 125 °C at the top of the storage tank while sunflower oil achieved a maximum of around 118 °C. This is possibly due to the higher charging solar radiation conditions for the water load. Additionally, slightly higher temperatures are seen in the storage tank for the water load because of the higher solar radiation. The discharging cycle shows higher temperature drops in the storage tank with water compared to oil. This suggests that stored energy is utilized more effectively when using water as the discharging load compared to oil. This is supported by plots B1 and B2 of Figure 3 which show a temperature rise for water as a load compared to a continual temperature drop with oil as the heating load. Stratification is visible at the beginning of the charging and discharging period for both heating loads. The degree of thermal stratification reduces as charging and discharging progress.

Figure 4A1,A2 shows direct solar radiation and wind speed profiles for experiments performed on 3 July 2021 and 4 July 2021 using a flow rate of 4.0 mL/s using 0.5 kg of water and oil as the heating loads, respectively. The average solar radiation for both tests was comparable. The average solar radiation conditions for the water and oil loads of around 840 W/m² and 830 W/m², respectively, were comparable. The wind speeds were significantly different during the experimental tests. For oil as the load, 5.8 m/s was the
highest wind speed compared to 2.0 m/s for water as the test load. Lower wind speed conditions were seen with water as the heating load directly implied lower heat losses for the water test. These ambient wind conditions cannot be controlled since they change daily as already presented in Figure 3A1, A2.

Figure 4. Experimental results of two test loads (water and sunflower oil) for a load of 0.5 kg utilizing a flow rate of 4.0 mL/s. (A) Direct solar radiation and wind speed (A1—water, A2—sunflower oil), (B) the temperature profiles of the solar receiver (B1—water, B2—sunflower oil), and (C) the temperature profiles of a storage tank (C1—water, C2—sunflower oil). Experimental dates were 3 July 2021 and 4 July 2021 for water and oil tests, respectively.
Figure 4B1,B2 shows receiver temperature profiles which show the same trend as with the lower flow rate in Figure 3B1,B2. Higher receiver temperatures are observed with water load as the heating load Figure 3B1 due to lower heat losses because of the lower ambient wind speed conditions since the average solar radiation is comparable. The maximum receiver outlet temperature attained for the water test is 165 °C compared to around 140 °C; however, the temperature differences between the outlet and inlet temperatures are comparable implying similar charging power conditions. The higher flow rate of 4 mL/s induces a faster rise in the load temperature compared to the lower flow rate of 2 mL/s due to the increased heat transfer rates. The maximum temperature of around 97 °C with a higher flow rate, for around 45 min is suitable for cooking most foods such as meat, rice, and potatoes. It is higher than 90 °C for the lower flow rate (2 mL/s) attained at the end of the charging process. As with the lower flow rate, the temperature of sunflower oil rose faster compared to the water load due to the lower thermal mass of oil, and sunflower oil attained a higher temperature of about 130 °C when charging ended. During the discharging cycle, the temperature of the water rose faster compared with the lower flow rate achieving a maximum cooking temperature of around 57 °C compared to 35 °C for the lower flow rate. A similar oil load temperature profile was observed during discharging for the higher flow rate; however, the temperature drops were from around 50 °C to 27 °C with the higher flow rate due to the increased heat transfer rate. As with the lower flow rate, the water temperature rose steadily before dropping compared to the oil temperature, which showed a continual drop for the duration of discharging cycle except for a very insignificant rise at the start of discharge.

Figure 4C1,C2 presents storage tank thermal profiles for the whole charging and discharging periods utilizing a higher flow rate of 4 mL/s for the two test fluids. Thermal stratification in the storage tank is reduced for both test loads. The reduction in the adjacent axial temperature differences provides evidence of the reduced thermal stratification. The maximum temperatures achieved for the top of the storage tank were 138 °C and 115 °C, respectively, for the water and sunflower oil heating loads during the charging cycles. The prevailing higher ambient wind conditions for the oil heating test have the effect of reducing the outlet temperature from the charging coil. Storage tank temperatures rise faster with the higher charging flow rate. There is layering in thermal profiles at a constant temperature just below 100 °C that is observed from around 11h30 to 13h00. The layering commences from the top of the tank and progresses to the bottom like a phase change process in a cylindrical geometry heated from the top to the bottom as the one reported in this paper. This behavior can possibly be explained by the decrease in thermal conductivity with higher temperatures for the higher flow rate particularly as 100 °C is approached at the top of the storage. This decrease in thermal conductivity at higher temperatures outweighs the heat transfer increase due to the higher flow rate. Phase change cannot explain the layering observed since sunflower oil is a sensible heat storage material. Mawire et al. [35] and Mawire [38] observed a similar phenomenon when evaluating the charging process of a sunflower oil storage tank with a high charging flow rate of 4.2 mL/s under controlled laboratory conditions with very little or no wind in the tests. Thermal layering is also observed to a lesser extent above 100 °C for both storage tanks after 13h00. This layering behavior is not seen with the lower flow rate. During the discharging process, thermal stratification in the storage is lost more rapidly compared to the lower flow rate due to the increased heat transfer rate. The water load with higher charging temperatures achieved in the storage tank showed better initial thermal stratification between 14h00–15h30 compared to the sunflower oil load as a direct result of the larger initial temperature difference along with the height of the storage tank at the onset of discharging. This larger temperature difference results in higher water temperatures being achieved compared to the oil temperatures in the pot during discharging. However, after 15h30, the stratification in the storage tank is severely reduced for both cooking loads unlike with the lower flow rate where stratification is maintained for the duration of the discharging process.
Figure 5 shows test results using 1 kg of water and oil at a flow rate of 2 mL/s performed on 17 July 2021 and 20 July 2021, respectively. Generally, the solar radiation for the duration of the experiment was almost constant as with the other tests (Figures 1 and 2). The average solar radiation was seen to be roughly around 850 W/m² and 750 W/m², respectively, for the sunflower oil and water loads. The wind speeds were generally comparable for the water (0–2.0 m/s) and sunflower oil test loads (0–2.5 m/s).

Figure 5. Experimental results of two test loads (water and sunflower oil) for a load of 1.0 kg utilizing a flow rate of 2.0 mL/s. (A) Direct solar radiation and wind speed (A1—water, A2—sunflower oil), (B) the temperature profiles of the solar receiver (B1—water, B2—sunflower oil), and (C) the
temperature profiles of a storage tank (C1—water, C2—sunflower oil). Experimental dates were 17
July 2021 and 20 July 2021 for water and oil tests, respectively.

Figure 5B1,B2 shows the temperature profiles of the receiver which show similar
trends to the previous tests. Generally, for both tests, the rise of the load temperatures was
lower compared to other experimental tests. This was due to the larger thermal mass of
the test load (1 kg). The highest temperature achieved at the end of the solar cooking pe-
riod was ~82 °C for water and ~80 °C for sunflower oil. When comparing the two tests
with 1 kg, a faster rise was seen with water possibly due to slightly lower initial ambient
temperatures for the oil heating test. This shows that the initial ambient temperature con-
ditions have an influence on the temperature even with higher incident solar radiation for
the sunflower oil test. The ambient conditions of the temperature and the wind speed
cannot be controlled; thus, identical ideal test conditions for experimental tests are very
difficult to achieve. The temperatures achieved in the loads are suitable for the slow cook-
ing of some foods. During the discharging process, the effect of the larger thermal mass is
very evident with the water as the test load as it only attains a maximum temperature of
around 30 °C whereas sunflower oil achieves a maximum temperature of around 36 °C.
These temperatures are lower compared to the experimental tests.

Storage tank temperature profiles utilizing 1 kg water and sunflower oil at a flow rate
of 2 mL/s are shown in plots (C1 and C2) of Figure 5. For both experimental setups, the
maximum temperatures achieved in the storage tank were both just above 120 °C. The rise
of all axial levels for water was slower compared to sunflower oil due to the larger thermal
mass of the water test load. The peaking and fall of the upper-level storage temperatures
(TA and TS) between 12h15–12h30 for water as the test load can be attributed to the rise
and fall of the inlet temperature during that same period. Manual tracking can be attri-
buted to this behavior as well as convective heat losses. Compared to other temperature
profiles (Figures 3 and 4) of the storage tank which were almost identical for water and
sunflower oil, the storage tank profiles for water as the load showed the largest tempera-
ture difference between the top and the bottom of the storage tank at the end of charging
(60 °C). This explains why the stored energy for the water test load is not able to induce a
high-temperature rise in the discharging process due to the lower bottom-level storage
temperatures. The highest storage tank temperatures were seen with the highest flow rate
(4 mL/s—Figure 4) because of increased heat transfer.

5. Discussion of the Results
5.1. Charging Energetic and Exergetic Performance with Different Flow Rates and Heating
Loads

Table 1 shows the effect of the flow rate on the average energetic and exergetic ther-
mal performance parameters with the associated standard deviations during charging.
The water and sunflower oil loads were kept constant at 0.5 kg, while the flow rate was
varied from 2–5 mL/s in steps of 1 mL/s. The average solar radiation varied between 756–
846 W/m² for the water tests. The lowest average solar radiation for the water heating tests
was seen with the highest charging flow rate (5 mL/s). On the other hand, for the sun-
flower oil tests, the average solar radiation varied between 757–848 W/m² in the experi-
mental tests which are comparable to the water heating tests. Higher average wind speeds
(1.19–3.62 m/s) are seen with sunflower oil heating tests compared to the water tests (0.66–
2.49 m/s). Generally, the increase in the oil and water loads increases both the average
energy and exergy rates for both test loads. However, the water showed higher values of
energy and exergy rates compared to sunflower oil, possibly due to the lower tempera-
tures achieved with water as a test load which reduces heat losses. For the water heating
load using 5.0 mL/s, the thermal performance parameters are lower compared to 4.0 mL/s
due to lower average solar radiation conditions. The average energy and exergy efficien-
cies for water and sunflower generally increase with the flow rate except for the 5 mL/s
case with the least average solar radiation. The energy and exergy efficiency values are
generally greater for water as a test load compared to sunflower oil. The change in the windspeed shows no correlation with energy and exergy efficiencies values since the efficiencies increase even with drastic changes in the average wind speed. As an example, the sunflower oil tests for a change in the flow rate from 3.0–4.0 mL/s the average windspeed changes by a factor of 3 (1.19–3.62 m/s) but an expected corresponding decrease in the average energy and exergy efficiencies is not seen. Instead, the average energy and exergy efficiencies increase from 0.16–0.22 and 0.15–0.17, respectively.

Table 1. Effect of the flow rate on the energetic and exergetic parameters for water and sunflower oil loads during charging cycles with a load of 0.5 kg.

<table>
<thead>
<tr>
<th>Flow Rate (mL/s)</th>
<th>Water</th>
<th>Sunflower Oil *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Solar Radiation (W/m²)</td>
<td>Average Wind Speed (m/s)</td>
</tr>
<tr>
<td>2.0</td>
<td>842 ± 10</td>
<td>1.11 ± 0.76</td>
</tr>
<tr>
<td></td>
<td>757 ± 15</td>
<td>*</td>
</tr>
<tr>
<td>3.0</td>
<td>846 ± 10</td>
<td>1.05 ± 0.51</td>
</tr>
<tr>
<td></td>
<td>848 ± 11</td>
<td>*</td>
</tr>
<tr>
<td>4.0</td>
<td>832 ± 14</td>
<td>0.66 ± 0.63</td>
</tr>
<tr>
<td></td>
<td>831 ± 10</td>
<td>*</td>
</tr>
<tr>
<td>5.0</td>
<td>756 ± 7</td>
<td>2.49 ± 0.72</td>
</tr>
<tr>
<td></td>
<td>760 ± 6</td>
<td>*</td>
</tr>
</tbody>
</table>

Sunflower Oil values are represented by *.

Table 2 shows the effect of the load on the energetic and exergetic thermal parameters while charging with a constant flow rate of 2.0 mL/s for water and sunflower oil loads. The load was varied from 0.5–2.0 kg in steps of 0.5 kg. The average solar radiation is between 795–846 W/m² for the water tests which is comparable to the sunflower oil tests of 757–833 W/m². Generally higher (1.11–2.67 m/s) but comparable wind speeds were seen in the sunflower oil heating tests in comparison to the water heat tests (1.08–1.17 m/s).

Table 2. Effect of the mass on the energetic and exergetic parameters for water and sunflower oil loads during charging cycles with 2.0 mL/s.

<table>
<thead>
<tr>
<th>Mass Load (kg)</th>
<th>Water</th>
<th>Sunflower Oil *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Solar Radiation (W/m²)</td>
<td>Average Wind Speed (m/s)</td>
</tr>
<tr>
<td>0.5</td>
<td>842 ± 10</td>
<td>1.11 ± 0.76</td>
</tr>
<tr>
<td></td>
<td>756 ± 15</td>
<td>*</td>
</tr>
<tr>
<td>1.0</td>
<td>846 ± 17</td>
<td>1.10 ± 0.81</td>
</tr>
<tr>
<td></td>
<td>803 ± 10</td>
<td>*</td>
</tr>
<tr>
<td>1.5</td>
<td>840 ± 10</td>
<td>1.08 ± 0.64</td>
</tr>
<tr>
<td></td>
<td>833 ± 15</td>
<td>*</td>
</tr>
<tr>
<td>2.0</td>
<td>795 ± 9</td>
<td>1.17 ± 0.68</td>
</tr>
<tr>
<td></td>
<td>828 ± 7</td>
<td>*</td>
</tr>
</tbody>
</table>

Sunflower Oil values are represented by *.

The average energy and exergy rates for water as a test load decrease marginally with the increase in the load whereas a larger decrease with the load is seen with sunflower oil. Higher energy and exergy rate values of water are due to the larger specific heat capacity of water compared to sunflower oil as well as the lower temperatures attained using water which resulted in lower heat losses. The decrease in the average energy and exergy rates with respect to the mass is due to the lower receiver temperatures obtained with the larger
heating load. The average energy efficiency values for both water and sunflower oil decrease very marginally with load, and it seems the average energy efficiency is independent of the load. The average energy efficiencies are comparable for both loads. The average exergy efficiency for water is independent of the load since it shows very little variation with an increase in the load. On the other hand, the exergy efficiency of sunflower oil as the test load decreases with an increase in the load (0.14–0.05). The exergy efficiency values for sunflower decrease with the load and are lower than those for water due to the lower receiver temperatures attained for water which has a direct influence on the heat losses.

Generally, water as a test load is seen to be more effective in terms of energy and exergy delivered while charging the storage tank. The flow rate has a more significant effect on the energetic and exergetic performance of the combined system than the heating load.

5.2. Discharging Energetic and Exergetic Performance with Different Flow Rates and Heating Loads

Table 3 shows the effect of the flow rate of the discharging energetic and exergetic performance. The average initial storage tank temperatures of water as the load (94–125 °C) were slightly higher but comparable to those of sunflower oil (97–104 °C *). The differences in the initial storage tank temperatures are unavoidable due to different ambient conditions such as the different ambient temperatures and different wind speeds. There is no general trend in variation of the average energy and exergy rates with respect to the flow rate for both water and sunflower oil heating loads due to the varying initial storage tank temperatures which cannot be controllable under real-life conditions. However, high average energy and exergy rates (49–95 W; 23–55 W) are seen with water compared to sunflower oil (34–68 W *; 15–34 W *) possibly due to the large heating thermal mass of water. The energy and exergy efficiencies also show no variation trend with the flow rate. The energy and exergy efficiencies for water (0.06–0.14; 0.05–0.12) are slightly higher than those of sunflower oil (0.06–0.12 *; 0.04–0.08) suggesting water has a slightly better heating load during discharging.

Table 3. Effect of the flow rate on the energetic and exergetic of water and sunflower oil loads during discharging cycles with a load of 0.5 kg.

<table>
<thead>
<tr>
<th>Flow Rate (mL/s)</th>
<th>Water Average Initial Storage Temperature (°C)</th>
<th>Average Wind Speed (m/s)</th>
<th>Average Energy Rate (W)</th>
<th>Average Exergy Rate (W)</th>
<th>Energy Efficiency (%)</th>
<th>Exergy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>106 ± 6</td>
<td>0.91 ± 0.89</td>
<td>59 ± 4</td>
<td>41 ± 2</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>97 ± 6 *</td>
<td>2.93 ± 1.00 *</td>
<td>51 ± 2 *</td>
<td>26 ± 1 *</td>
<td>0.12 *</td>
<td>0.08 *</td>
</tr>
<tr>
<td>3.0</td>
<td>109 ± 8</td>
<td>0.77 ± 0.60</td>
<td>57 ± 3</td>
<td>35 ± 3</td>
<td>0.11</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>99 ± 7 *</td>
<td>0.67 ± 0.98 *</td>
<td>58 ± 2 *</td>
<td>34 ± 2 *</td>
<td>0.09 *</td>
<td>0.08 *</td>
</tr>
<tr>
<td>4.0</td>
<td>125 ± 7</td>
<td>0.24 ± 0.45</td>
<td>95 ± 1</td>
<td>55 ± 2</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>104 ± 4 *</td>
<td>1.61 ± 1.44 *</td>
<td>34 ± 2 *</td>
<td>15 ± 2 *</td>
<td>0.06 *</td>
<td>0.04 *</td>
</tr>
<tr>
<td>5.0</td>
<td>94 ± 4</td>
<td>1.61 ± 1.08</td>
<td>49 ± 2</td>
<td>23 ± 2</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>100 ± 3 *</td>
<td>2.59 ± 0.78 *</td>
<td>68 ± 2 *</td>
<td>31 ± 2 *</td>
<td>0.11 *</td>
<td>0.07 *</td>
</tr>
</tbody>
</table>

Sunflower Oil values are represented by *.

Table 4 shows the effect of the mass of the discharging thermal performance parameters using a constant discharging flow rate of 2 mL/s. The average initial storage tank temperatures for water (97–114 °C) are slightly greater compared to those of sunflower oil (95–100 °C *). The average wind speed conditions for the water tests (1.10–1.17 m/s) are lower compared to the sunflower oil tests (1.11–2.67 m/s *). As with the effect of the flow rate tests, there is no general trend of the variation of the average energy and exergy rates
with the load. In some cases, sunflower oil shows higher average energy and exergy rate values compared to water so no general conclusive evidence can be drawn up of which fluid performs better than the other with different mass loads. The variation of the discharging energy and exergy efficiencies also show no correlation with the heating load for both fluids, and no generalized conclusion can be drawn up. For the larger loads (1.5–2.0 kg), the energy and exergy efficiency values for sunflower oil are greater than those of water suggesting the better performance of sunflower oil with the larger loads when using similar discharging flow rates. It is suggested that future experiments should be carried out in an environmentally controlled location or laboratory where the initial and final temperatures can be controlled to understand more fully the discharging characteristics. However, in real-life situations, the environmental variations cannot be controlled, and the most important issue is whether the system performs its specified tasks regardless of varying environmental conditions.

**Table 4.** Effect of the mass on the energetic and exergetic parameters for water and sunflower oil loads during discharging cycles with 2 mL/s.

<table>
<thead>
<tr>
<th>Mass Load (kg)</th>
<th>Water Sunflower Oil *</th>
<th>Average Initial Storage Temperature (°C)</th>
<th>Average Wind Speed (m/s)</th>
<th>Average Energy Rate (W)</th>
<th>Average Exergy Rate (W)</th>
<th>Energy Efficiency (-)</th>
<th>Exergy Efficiency (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>107 ± 6</td>
<td>1.11 ± 0.76</td>
<td>59 ± 4</td>
<td>41 ± 2</td>
<td>0.14</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>97 ± 6 *</td>
<td>2.67 ± 1.70</td>
<td>51 ± 2 *</td>
<td>26 ± 2 *</td>
<td>0.12 *</td>
<td>0.08 *</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>110 ± 10</td>
<td>1.10 ± 0.81</td>
<td>42 ± 3</td>
<td>21 ± 1</td>
<td>0.14</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95 ± 7 *</td>
<td>1.11 ± 0.76</td>
<td>90 ± 6 *</td>
<td>34 ± 2 *</td>
<td>0.11 *</td>
<td>0.08 *</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>97 ± 5</td>
<td>1.08 ± 0.64</td>
<td>41 ± 3</td>
<td>26 ± 0.5</td>
<td>0.09</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95 ± 9 *</td>
<td>1.84 ± 0.95</td>
<td>46 ± 2 *</td>
<td>15 ± 0.2 *</td>
<td>0.13 *</td>
<td>0.10 *</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>114 ± 7</td>
<td>1.17 ± 0.68</td>
<td>28 ± 0.5</td>
<td>23 ± 0.5</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ± 7 *</td>
<td>2.46 ± 0.73</td>
<td>43 ± 3 *</td>
<td>31 ± 2 *</td>
<td>0.09 *</td>
<td>0.06 *</td>
<td></td>
</tr>
</tbody>
</table>

Sunflower Oil values are represented by *.

### 5.3. Comparison of Results with Other Researchers and Cost

Table 5 presents a comparison of the current presented work and previous work by other authors. It is important to state that our reported system is different from other reported systems since our system has a cooking plate as well as an oil-circulating coil to heat the storage tank. The other systems only circulated fluids to heat the storage tanks. The reported system shows generally better or comparable energy rate, exergy rate and efficiencies compared to other reported systems irrespective of performing the dual purpose of cooking as well storing solar thermal energy. The proposed system seems to be a practical system for implementation in decentralized communities because of the higher or comparable energy and exergy rates to other systems reported in Table 5.

**Table 5.** A comparison of the present work with previous work completed by other researchers.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Heat Transfer Fluid</th>
<th>Test Load</th>
<th>Optimum Flow Rate (ml/s)</th>
<th>Energy Rate (W)</th>
<th>Energy Efficiency (-)</th>
<th>Exergy Rate (W)</th>
<th>Exergy Efficiency (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mawire et al. [34]</td>
<td>2020</td>
<td>Sunflower oil</td>
<td>Water</td>
<td>6.0</td>
<td>1000</td>
<td>0.325</td>
<td>200</td>
<td>0.112</td>
</tr>
<tr>
<td>Asmelash et al. [39]</td>
<td>2014</td>
<td>Soya bean oil</td>
<td>Water</td>
<td>-</td>
<td>200</td>
<td>0.06</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Farooqui [40]</td>
<td>2013</td>
<td>Thermal fluids</td>
<td>(vegetable oil and sunflower oil)</td>
<td>-</td>
<td>203</td>
<td>0.300</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Table 6. Estimated total cost of the combined solar cooking and TES system.

<table>
<thead>
<tr>
<th>Component No</th>
<th>Component Description</th>
<th>Cost R(USD *)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Parabolic Dish</td>
<td>2500(136 *)</td>
</tr>
<tr>
<td>2</td>
<td>Storage Tank</td>
<td>800(44 *)</td>
</tr>
<tr>
<td>3</td>
<td>Receiver</td>
<td>500(27 *)</td>
</tr>
<tr>
<td>4</td>
<td>Pipes</td>
<td>500(27 *)</td>
</tr>
<tr>
<td>5</td>
<td>Pump</td>
<td>2000(109 *)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>6300(343 *)</strong></td>
</tr>
</tbody>
</table>

USD values are represented by *. The USD values in brackets correspond to South African Rand amount R.

### 6. Conclusions

A dual-purpose solar cooker for cooking and storing thermal energy simultaneously that can be used during off-sunshine periods was presented. The experimental setup comprised a parabolic dish, a solar receiver coupled with a flat-plate and an oil-circulating copper coil for charging a storage tank. Energy and exergy thermal performance parameters of the dual-purpose system during charging and discharging cycles were presented. The effect of the flow rate and the mass of the load were investigated using sunflower oil as both the heat transfer fluid and the storage material. Charging and discharging experiments are conducted using four different flow rates (2, 3, 4, 5 mL/s), and with different masses (0.5, 1, 1.5, 2.0 kg) with water and sunflower oil as the test loads. In summary, the following conclusions were drawn up from the study:

a. Charging results showed that the average energy and exergy rates as well as their corresponding efficiencies increased with an increase in the charging flow rate. Water showed higher average charging energy and exergy efficiencies compared to sunflower oil.

b. The increase in the mass load decreased marginally the average charging energy and exergy rates for water, and their corresponding efficiencies. For sunflower oil, the average charging energy and exergy rates and efficiencies showed a more pronounced decrease with an increase in the mass, and sunflower oil showed lower values compared to water.

c. For the discharging results, the correlations between the energy and exergy thermal performance parameters with respect to the flow rate and the heating load were not well defined for both heating loads possibly due to different initial storage tank temperatures at the onset of discharging and the inefficient discharging process which needs to be optimized in future. However, the discharging average energy and
exergy rates and their corresponding efficiencies were higher for water compared to sunflower oil when using different discharging flow rates.

d The proposed dual-purpose system is cheaper than less versatile single-purpose commercial domestic solar hot water heating systems hence it is viable to commercialize it for decentralized rural communities.

Future work will investigate the proposed system under laboratory-controlled conditions using artificial sunlight to eliminate the variable and uncontrolled ambient conditions during charging and discharging. This might be, however, very expensive for moderately equipped laboratories in the developing world thus collaborating with researchers in the developed world seems to be the best option. In the future, we intend to also test the system with water for a dual-purpose solar cooking and water heating system. The proposed system regardless of its low efficiency during discharging seems to add to the body of knowledge of new proposed dual-purpose systems which can cook as well as store thermal energy for later usage. These systems are more economically viable and can be used in the developing world as sustainable solar energy solutions for domestic purposes in decentralized communities.

Author Contributions: Conceptualization, K.L. and A.M.; Data curation, K.L. and P.O.; Formal analysis, K.L. and A.M.; Investigation, K.L. and P.O.; Methodology, K.L., A.M. and P.O.; Project administration, A.M.; Supervision, A.M.; Visualization, A.M.; Writing—original draft, K.L., A.M. and P.O.; Writing—review & editing, K.L., A.M. and P.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data will be available by contacting the corresponding author.

Acknowledgments: We thank the Instruments Making Department of the North-West University for fabricating the experimental system, especially the head of department, Thys Taljaard. The first author (Katlego Lentswe) wishes to acknowledge SOLTRAIN (Southern African Solar Thermal Training and Demonstration Initiative) for a bursary to carry out the research reported in this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References


