An experimental study of a combined solar cooking and thermal energy storage system for domestic applications

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Abstract. In this paper, a combined solar cooker with a Sunflower oil storage tank is presented. The solar cooker consists of a 1.8 m parabolic dish that has an oil circulating copper spiral coil receiver embedded at the bottom of a metallic cooking plate. During sunny periods, cooking and charging of the storage tank take place. 1 L of water is heated up in a cooking pot that is placed on the cooking plate when solar radiation is focused on it, while oil circulating through a spiral coil receiver charges the storage tank. The receiver is connected to a 50 L Sunflower oil storage tank that is used to store heat during charging. A DC pump is used to circulate the oil during charging and discharging. Sunflower oil is the heat transfer fluid during the cooking /charging experiments. Storage tank temperatures above 100 ºC are achieved in the storage tank. During the discharging cycle, the dish is defocused from the sun, and the pump is reversed to extract heat from the storage tank. 1.0 L of water is heated up with the stored heat, however, heat transfer is poor with the heated water only achieving temperatures just above 40 ºC. Preliminary experiments are presented, and the charging process is seen to be more efficient than the discharging process with the charging pump reversed. The average charging and discharging efficiencies are found to be 18 % and 14 %, respectively. The system can be used to cook food as well as provide heat for indirect cooking using insulated bag slow cookers. However, cooking food directly on the cooking plate using the reverse discharging process is not efficient, and heat transfer should be enhanced to make the process more efficient and viable.

Keywords: *Combined solar cooker; Thermal energy storage; Parabolic dish; Sunflower oil*

1. Introduction

Disadvantaged communities and rural areas depend on polluting energy sources such as coal, wood, cow dung and agricultural waste for cooking. Utilizing these harmful energy sources daily increases the chances of health risks, negative environmental impacts, and disrupting the nutritional value of food [1]. To prevent these negative impacts, solar cookers that are affordable and user friendly must be introduced and be promoted to disadvantaged communities that have abundant access to solar energy. Solar cookers are suitable devices that can cook food by converting solar energy to heat energy. They can be used for pasteurization and sterilisation of food. Researchers, scientists and engineers have done extensive work on improving solar cooking systems in recent years [2-13]. Solar cooking is becoming a potential cooking option for disadvantaged communities and rural areas that cannot afford and access traditional cooking methods such as electricity or gas [14-16].

` The advantages of solar cookers are that they have no running costs, they produce nutritious food, they emit no greenhouse gases, and most of them can be homemade (e.g. box solar cookers). There are three common types of solar cookers which are; (1) concentrating solar cookers, (2) box solar cookers, and (3) panel solar cookers. An appealing solar cooker must be user friendly, locally available at an affordable price, and must be able to reach high cooking temperatures in a short period of time. Concentrating solar cookers are appealing because they cook faster, reach higher cooking temperatures and can cook multiple individual meals rapidly as compared to other types of solar cookers [17]. The disadvantage of solar cookers is that they cannot be operated during off-shine periods (e.g. cloudy periods). In order to address this shortcoming, solar cookers must be integrated with thermal energy storage (TES) materials. An ideal thermal energy storage material must be readily available, easy to access and cheap. Sunflower oil is widely used in South Africa for a variety of cooking methods such as frying fast foods like chips. It is locally available in commercial stores, and it is manufactured in South Africa. Although it is mostly utilized for cooking purposes, it can also be used as thermal energy storage (TES) material [18-21].

Limited research has been done on the combination of a concentrating solar cooker and a TES system for the dual purpose of cooking and storing energy [2, 7, 22, 23]. In an attempt to understand the thermal performance of a concentrating solar cooker combined with a TES system, an experimental evaluation of a parabolic dish solar cooker combined with a Sunflower oil storage system is presented in this paper. The novelty of the study is that the concentrating solar cooker coupled with a TES system can cook and store energy simultaneously which is a different design to the other cookers with storage whereby thermal energy has to be stored first before cooking. The stored heat can be used to cook food and other domestic applications during off-shine periods. Combined solar cookers with storage are an important innovation to mitigate greenhouse gas emissions generated by the use of fossil fuels used for cooking in developing countries.

2. Experimental setup and procedure

Figure 1 shows a laboratory experimental setup of a solar parabolic dish cooker combined with a TES system. (1) An insulated 50-L cylindrical stainless steel storage tank was filled with Sunflower oil. K-type thermocouples with accuracy of ± 2.2 ^{o}C were fitted at five different axial positions from the top to the bottom of the storage tank. (2) A DC pump was connected to the outlet of the storage tank and was used to circulate Sunflower oil from the bottom of the storage tank to the receiver and back to the top of the storage tank

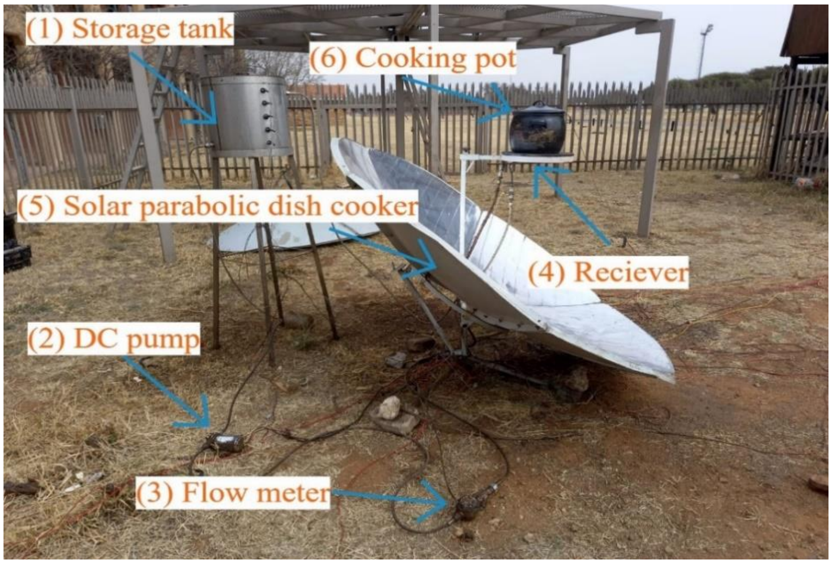
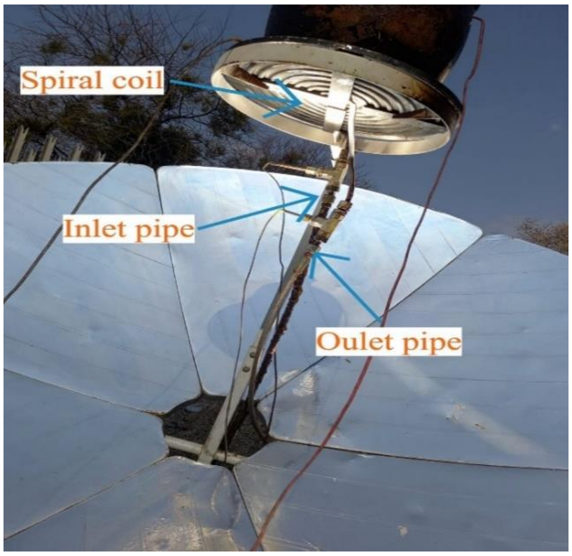
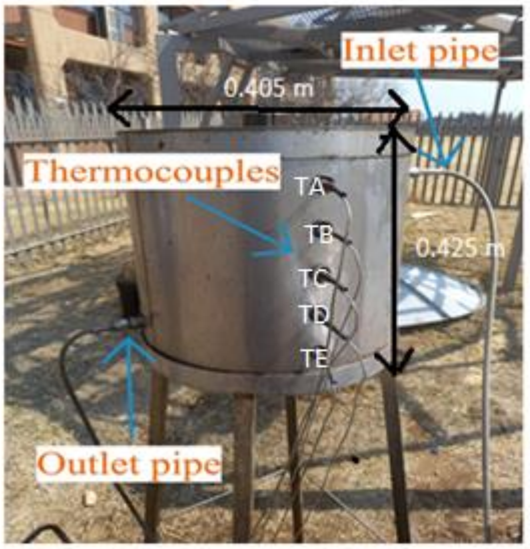


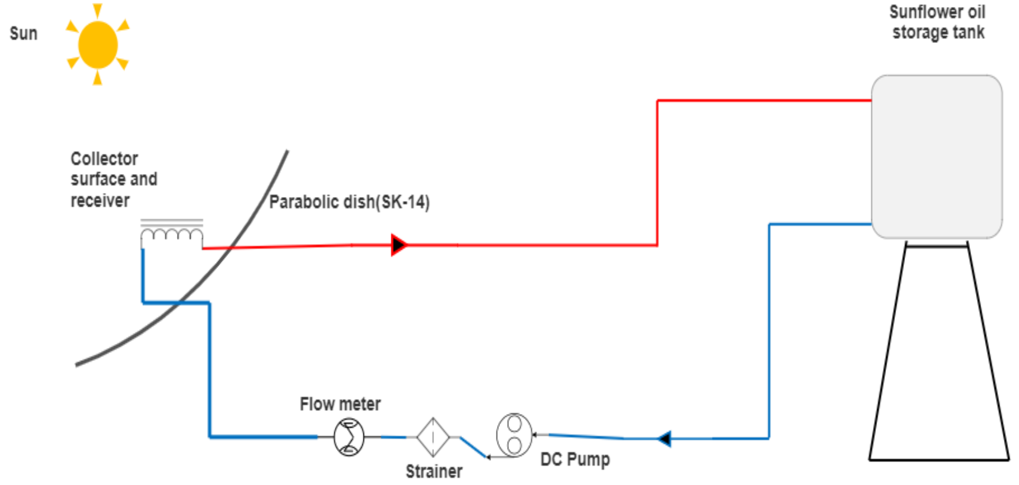
Figure 1: Experimental setup of a solar parabolic dish cooker combined with a TES system. (1) Storage tank, (2) DC pump, (3) Flow meter, (4) Receiver, (5) Solar parabolic dish cooker and (6) Cooking pot.

The flow rate of the Sunflower oil was measured with a pulse-type positive displacement flow meter (3) with an accuracy of ±1 %. The inlet and outlet pipes of the receiver (4) were coupled with thermocouples to measure the inlet and outlet receiver temperatures. The receiver which was a copper spiral coil was placed at the focal region of the solar parabolic dish (SK-14) cooker (5) to allow the heat transfer fluid to be heated thus charging the storage tank. A black cooking pot (6) filled with different test loads (water and sunflower oil of different masses) was placed on top of the receiver during experimental periods.





(a) (b)



(c)

Figure 2: (a) Magnified photographs of the receiver, the (b) storage tank and, (c) schematic diagram of the experimental setup.

Figure 2 shows magnified photographs of the receiver, the storage tank and schematic diagram of the experimental setup. The receiver was composed of a black painted flat stainless steel plate, and a copper spiral coil which was connected with the inlet and outlet pipes to the storage tank. The diameter of the cooking plate was 0.310 m. The receiver was placed at the focal region of the solar parabolic dish cooker and solar radiation was reflected to it as shown in fig. 2 (a). During experiments, Sunflower oil flowed from the bottom of the storage to the inlet pipe of the receiver which was integrated with a thermocouple. Heat was absorbed from the spiral coil by Sunflower oil, and exited through the outlet pipe to the top of the storage tank thus charging the storage tank. The storage tank was a cylindrical stainless steel fitted with 5 thermocouples (T_A-T_E) to measure the axial thermal distribution (fig. 2(b and c)). The storage tank had a diameter of 0.405 m and a height of 0.425 m. Thermocouples were placed at axial distances of 0.083 m (T_A), 0.150 m (T_B), 0.220 m (T_C), 0285 m (T_D), and 0.355 m (T_E), respectively from the top of the storage tank. The outlet pipe of the tank was connected to a DC pump, and the inlet was connected to the receiver. The insulation of the storage tank was glass wool fitted between the inner vessel and the outer vessel of the storage tank. When conducting experiments, 50 L of Sunflower oil was filled to a level just above the top thermocouple (T_A).

3. Thermal analysis

The receiver power from the circulating oil in receiver coil to the storage tank is calculated as:

$$Pr = \rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin}) \tag{1}$$

,where ρ_{av} is the average density, C_{av} is the average specific capacity, $\dot{V}$ is the flowrate of the oil during the circulating period, T_{Rout} is the outlet of the receiver and T_{Rin} is the inlet of the receiver. The average density is calculated as:

$$\rho_{av} = 932.37 - 0.66T \tag{2}$$

, and the average specific capacity is:

$$c_{av} = 2115 + 3.13T. \tag{3}$$

The charging efficiency is calculated by the ratio of the receiver power to the solar collecting power, and it is expressed as:

$$\eta_{ch} = \frac{\rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin})}{A_{ap} G} \tag{4}$$

, where the aperture area of the parabolic dish is A_{ap}, and G is the direct solar radiation that falls on the parabolic dish collector (SK-14). The discharging efficiency can be calculated from the ratio of total energy discharged to the total energy stored from the initial (t_i) to the final time (t_f), and this is expressed as:

$$\eta_{dis} = \frac{\sum_{ti}^{tf} \rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin}) dt_{(dis)}}{\sum_{ti}^{tf} \rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin}) dt_{(ch)}}. \tag{5}$$

4. Results and discussion

Figure 3 shows the solar radiation, temperature profiles of the receiver, and storage tank temperatures on 17 May 2021 using 1.0 L of water as the load at a flow rate of 2 ml/s. The solar radiation (fig. 3(a)) during the solar cooking period (11:00-14:00 h) is seen to be around 840 W/m^2 for the duration of the experiment except for brief cloudy periods around 13: 00 h, 13:15 h and 13:45 h., respectively. The inlet and outlet (T_{Rout}, T_{Rin}) temperatures (fig. 3(b)) of the receiver fluctuate up and down during the solar cooking period due to manual tracking of the receiver. T_{Rout} achieves maximum temperatures close to 160 ºC, and T_{Rin} achieves maximum temperatures close to 70 ºC during the solar cooking period. The temperature of the water in the pot reaches a maximum stagnation temperature of around 75 ºC from about 12:30 h- 14:00 h during the solar cooking period thus supporting the idea of dual solar cooking and storage of thermal energy. The surface temperature at the cooking plate shows lower temperatures than the receiver outlet temperature since heat is being extracted by the fluid to charge the storage tank. Fig 3 (c) shows that the top of the storage tank (T_A) achieves maximum temperatures above 120 ºC during the solar cooking period with the bottom (T_E) achieving a maximum temperature close to 80 ºC. A clear stratified distribution of the thermal profiles in the storage tank is seen during charging.

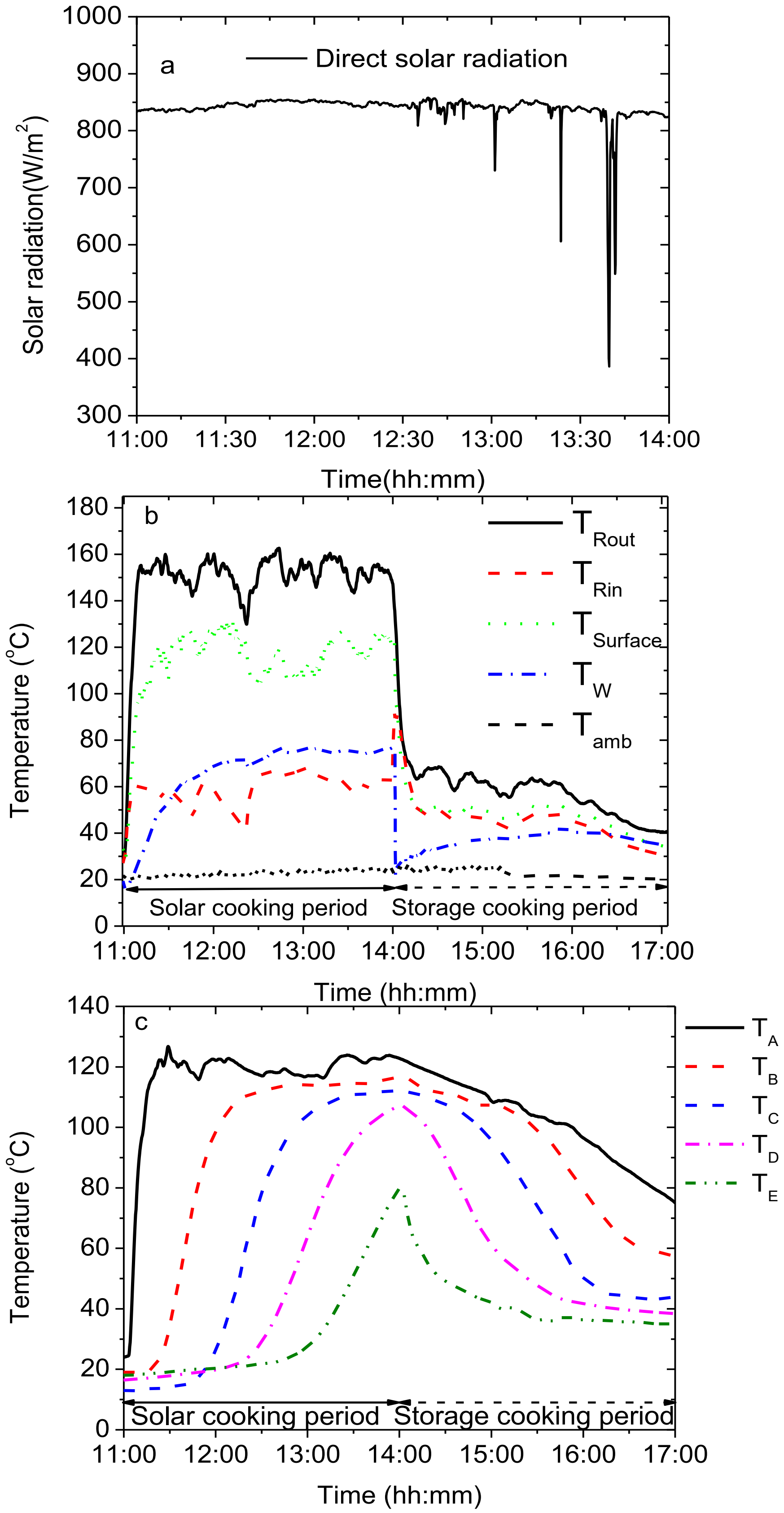


Figure 3: (a) Direct solar radiation, (b) temperature profiles of the receiver, and (c) temperature profiles of the storage tank using 1 kg of water as the test load performed on 17 May 2021 using a flow-rate of 2 ml/s.

During the storage cooking, the stored heat in the tank (fig. 3(c)) is used to heat up 1 L of water by reversing the direction of the pump and defocusing the solar receiver from the sun. During the 3 h discharging period, the maximum temperature achieved by water in a pot is around 41 ºC at 16:00 which is not sufficient to cook food but enough to warm food. This is because of the long flow pipes which induced heat losses during discharging since the same charging loop was used for discharging. Introducing shorter discharging loop pipes will definitely improve the heat transfer rate during discharging. Another improvement will be an optimized receiver to extract and discharge heat efficiently. However, the stored heat can be used indirectly to cook food using slow insulated wonderbag cookers as recently reported in [3]. The storage tank temperature (fig. 3(c)) drops from around 120 ºC at the top of the storage tank (T_A) to around 70 ºC during the discharging the 3 h discharging period. On the other hand, the bottom storage tank temperature drops from around 80 ºC to 35 ºC at the end of the discharging period. As already mentioned, this discharging process can be optimized to improve the thermal performance.

Table 1 shows a summary of receiver energy efficiencies on different days (17 and 18 May 2021) using a water heating load of 1 kg. During the charging cycle, the average charging efficiencies were approximately 18 % and 17 %, which represents an average receiver power of around 367 W at a collector power of around 2100 W. This lower receiver power is excepted since some of the solar energy heats up water used for cooking. This is evidence that receiver can harness energy that can cook light meals such rice, noodles and chicken. During the discharging cycle, the average discharging efficiency was found to be 14 % and 13 %, respectively, indicating poor heat transfer from the storage tank during discharging possibly due to the long connecting pipes. This shows that during the discharging cycle, the stored heat was not suitable for cooking purposes but the stored heat can be used indirectly in storage cooking pots as reported in [3]. Although the performance during discharging is unsatisfactorily, heat transfer mechanisms can be employed to make it more economically viable such it can be scaled up to cook food for at least 10 people. In addition to this, future work intends to replace Sunflower oil with water so that the system can cook as well as provide hot water for a variety of domestic applications such as bathing, cooking and washing dishes.

Table 1. A comparison of receiver charging and discharging efficiencies on different days using 1.0 kg of water

Date	Average charging efficiency (%)	Average discharging efficiency (%)
17 May 2021	18	14
18 May 2021	17	13

5. Conclusion

A combined solar cooker with a Sunflower oil storage tank was investigated experimentally. The solar cooker consisted of a 1.8 m parabolic dish that had an oil circulating copper spiral coil receiver embedded to a metallic cooking plate to charge a 50 L Sunflower oil storage tank. During charging, 1.0 L of water was heated up to around 75 ºC in a cooking pot with storage tank temperatures above 100 ºC being achieved. During discharging, the heat transfer was poor with the heated water only achieving temperatures just above 40 ºC. Preliminary experiments showed that the charging process was more efficient than the discharging process with the charging pump reversed. The system can be used to cook food for a minimum of 3 people in the solar cooking period as well as provide heat for indirect cooking using insulated bag slow cookers. However, cooking food directly on the cooking plate using the reverse discharging process was not efficient, and heat transfer should be enhanced to make the process more efficient and viable.

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