EXPERIMENTAL ANALYSIS ON A SINGLE TANK ENERGY STORAGE SYSTEM INTEGRATED WITH A COOKING UNIT FOR SOLAR COOKING

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Abstract

This paper presents the experimental analysis and thermal performance of a single tank energy storage system integrated with a funnel and cooking unit designed, constructed and tested using a funnel system to produce high quality heat front for immediate cooking without mixing thermocline. A prototype was constructed using available suitable materials. It consists of funnel system, heating element, refined sunflower oil and a stainless-steel tank. The funnel was made of metal pipe and a position for a cooking unit to provide immediate cooking. Oil was used as a heat storage medium and a 1.5kW, 220V heater was used to heat it. The heater was switched on during charging and switched off during discharging process. It charged the STESS, fast and effectively to temperatures above 180ºC in 20 minutes highly attributed to system design. There was no mixing of hot and cold oil during the charging and hot heat. An overflow barrier-controlled charging while oil circulated in one way and reversed during the discharge process. The funnel charging energy efficiency was estimated to be 72.5% for the first case of barrier height and 51.9 % in the second barrier level by the funnel technique. About 453.6kJ of energy was consumed in boiling 1.5L of water in 10 minutes while 1.04MJ in boiling 1 kg of dry beans in 2hours. There was 6.23MJ left during charging while cooking and 3.54MJ left after discharging process.

Keywords: Single tank system, Funnel system, Quality heat front, Heat storage.

1. Introduction

Globally, 3 billion people rely on biomass materials for cooking and commercial activities, leading to an estimated four million deaths annually due to household air pollution [1]. While some people use liquid petroleum gas and grid electricity, over 85% of the population in developing countries, particularly in Africa, still rely on biomass energy, causing harmful effects on the environment, health, and climate change [2]. The use of biomass fuels has resulted in significant greenhouse gas emissions, deforestation, conflicts, food shortages, and extreme weather conditions. The cost of LPG fuel and other gasoline has also increased over time. Energy storage systems are most suitable application for indirect solar cooking methods [3-5].

Mawire et al. [6] investigated both vegetable oils (palm oil and refined sunflower) and refined mineral oil (shell thermia B) in South African market as possible heat transfer and thermal energy storage fluids. The study reveals that, refined sunflower had the highest exergy and energy efficiencies followed by palm oil during charging, with values increasing as the thermal gradient increases. Tabu et al. [7] experimentally evaluated the thermal performance of selected oils in Uganda for heat storage system for indirect solar cooking applications. Sunflower oil and Palm oil were selected from the local market and Shell Thermia B, a synthetic oil; energy and exergy analysis were performed to test their suitability as heat transfer and heat storage fluids. Sunflower oil was reported to have higher stratification and stored more

10.18086/swc.2023.03.04 Available at http://proceedings.ises.org

energy. Sunflower, being an edible vegetable oil was then recommended for TES system for cooking and the key properties are summarized on Table 1.

Table 1: Thermophysical properties of refined sunflower oil [7]

Physical quantity	**Dependent variable/Value**	**Unit**
Density	$930.62 - 0.65\,T$	kgm^{-3}
Specific heat capacity	$2115.0 + 3.13\,T$	$Jkg^{-1}K^{-1}$
Thermal conductivity	$0.161 + 0.018e^{(\frac{}{26})}$	$Wm^{-1}K^{-1}$
Flash point temperature	235	℃
Smoke point temperature	350	℃

Mawire et al.[8] experimented the thermal performance of rock pebbles as sensible materials in terms of the axial temperature distribution, total energy stored, the exergy, and the transient charging efficiency. The results indicated that not only the value of the total amount of energy stored is important for the thermal performance of oil-pebble-bed systems but also that the exergy stored and the degree of thermal stratification. The system had no cooking unit integrated. In addition, Kajumba et al. [9] evaluated the performance of TES system integrated with a cooking unit; the cooking unit was made below the heat storage and hot oil from tank was driven by means of gravity for heat extraction. They reported a challenge of depletion of hot oil from the TES tank during cooking since the oil could not be circulated back into the TES tank. Further investigations of designs and technologies were reported by a number of researchers on small scale thermal energy storage system for solar cooking applications by [10]–[13].

Furthermore, Abedigamba et al. [14] reported on the heat of utilization and efficiency values of two selected oils namely; Sunflower oil and Roki oil in Uganda. The results suggest that Roki oil is a potential heat storage material for domestic applications however, the Sunflower oil indicated better heat of utilization characteristics than Roki oil during the tests. Okello et al.

[15] designed and tested a TES System integrated with a cooking unit where the cooking unit was embedded inside the oil TES tank. They demonstrated boiling of beans during charging. However, cooking during discharge was limited by the fact that the hot oil at the top would mix with the cold oil from the bottom. Hence, the quality of the heat front and thermal stratification in the tank was destroyed during discharge cycle

The paper describes a new design for a Thermal Energy Storage (TES) system that is integrated with a funnel and cooking unit. The funnel system was designed to charge a small volume of oil in it quickly to higher temperatures without mixing hot oil a in the single tank, enabling immediate cooking and quality heat front. This funnel can be adjusted to vary the cooking rate and temperature of oil by raising it up and down manually. This was not possible with earlier designs reported in literatures [15]. The TES cooker consists of a single tank system with a funnel inside it and a position for cooking unit. Heating is done using a grid electricity in the funnel, and a small barrier allows hot oil to overflow into the tank after reaching a certain temperature. The hot oil overflows into the bulk tank while the cold oil from the bottom enters the funnel to be heated and process is repeated. The system ensures that there is no mixing of hot and cold oil, maintaining quality heat front for cooking. This single tank system developed as an alternative cooking technology for solar cooking. Experimental tests were conducted to demonstrate and validate the system's effectiveness for solar cooking application.

2. Materials and Methods

2.1. System Design and Experimental Setup

Figure 1 shows the single tank energy storage system integrated with a funnel and cooking unit. The heating chamber consists of a pipe made metal, and on top made in the form of funnel; this is referred to as a funnel top. A heating element positioned at the centre of the funnel system heat the oil inside the tank. Funnel is made adjustable using long screws attached to the funnel top. Refined sunflower oil was used as heat storage medium. The Table 1 presents the dimension of the cooking system constructed and experimentally tested.

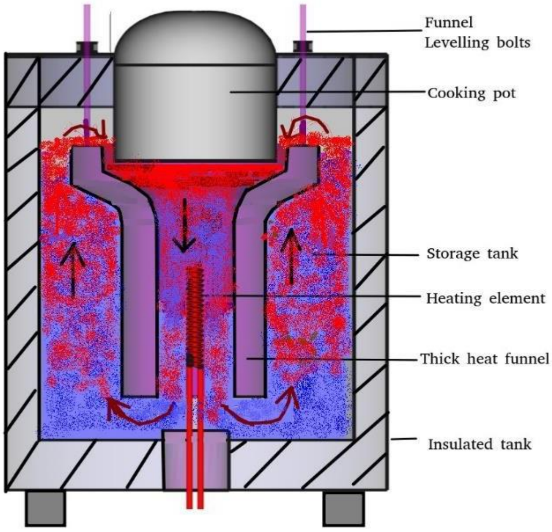

Figure 1(a): Schematic diagram of the system design.

Table 2. The dimensions of the main parts of the single tank heat storage system.

Design components	Internal diameter (m)	Height (m)
Storage tank	0.30	0.40
Cooking pot	0.20	0.10
Funnel top/Cooker	0.20	0.05
Heat funnel	0.07	0.25

Figure 1 shows the schematic diagram of the experimental setup. The heat storage had 18L refined sunflower oil and heat source was supplied by the heating element mounted inside the funnel center. A prototype was constructed and tested on grid; where; during charging; the heating element was switched on to heat the oil meanwhile the heater was switched off during discharging process of the single tank system. A number of thermocouple sensors interfaced with TC 08 data logger and a computer was used to collect data on temperature profile every minute in; the funnel system, heat storage and cooking unit to analyze its performance during charging and cooking -discharge process.

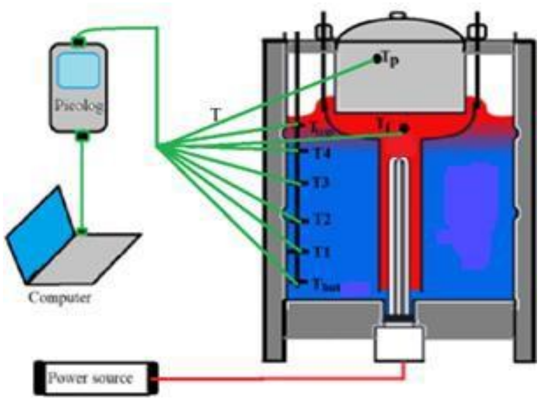

Figure 1(b): Schematic diagram for Experiments and data collection showing the arrangement of thermocouple sensors.

2.2. Experimental Procedure

The prototype of the STHSS was design and constructed: The experimental schematic diagram in Figure 1(b) was setup and a number of thermocouples sensors arranged in the single tank heat storage, funnel system, and cooking pot were connected to TC-08 data logger to measure and record temperature profile every minute. The system was connected to power source and the system was charged while demonstrating cooking and later heat storage was first charged to average temperature of above 180 oC and then discharged through cooking. Cooking tests were made using water boiling tests and boiling of dry beans. Boiling time and energy consumption during cooking was analysed. Figure 2 shows the experimental setup of the system. Five k-type thermocouples were arranged into the storage tank at a distance of 4.0 cm apart. Thermocouple, $Tpot$ was inserted into the cooking pot while , Tf was on top of the funnel and it registers the same temperature as the sensor,$Ttop$. Inside the tank, more thermocouples,

$T1$, $T2$,$T3$, $T4$ and $Tbot$ were arranged as shown in Figure 4 to. The thermocouples were connected to a TC08 Pico-log data logger interfaced with a computer, and configured to measure and record the average temperatures every minute. The storage tank was filled with 18L of refined sunflower oil. To the heating element rated at 1.5 kW, 220V an AC grid power was connected to provide electricity to heat the oil. Thermocouples were inserted at different points in the system.

Figure 2: A) Showing the picture of the experimental setup of single tank system integrated with a cooking unit B) is the positioning of thermocouples and Pico data logger.

2.3. Experimental Procedure

2.3.1. Charging and discharging of the single tank energy storage system

During the charging process, the power to heater was switched on; this results into heating of the oil in the funnel. The volume of oil in the funnel system was about 2.5 L. The heated oil in the funnel becomes less dense, rises and overflows into the storage tank. The temperature profile in the system was monitored and recorded.

The discharging process involves carrying out cooking tests. After the system was charged to the desired temperature, the heater was switched off during the discharge mode, the hot oil flows from the top of the heat storage tank into the funnel where the cooking pot sits. The cooking pot contained either cold water, rice, or bean's soup. The water or beans was allowed to boil using the energy stored in the system. Boiling of water and beans was repeated several times. In general, the charging and discharging processes were conducted several times during the experiment.

2.3.2. Cooking tests -during charging and discharging

A cooking pot of capacity of 3 L was used to carryout cooking tests. The pot was inserted into top of funnel making good contact with the walls. The bottom of the cooking pot was made in contact with the oil on top of the funnel. Cooking tests were demonstrated during both charging and discharging for boiling 1.5 L of water multiple times and boiling of 1 kg of bean's soup. Beans are common type of sauce consumed by majority of the families in Uganda. It is also the major sauce in schools, eaten by students almost every day. However, beans require a lot of energy before it is ready for consumption with cooking time of over 2 hours [10]. Therefore, it is very important to test if the single tank heat storage unit is able to cook beans. Figure 6 shows pictures of the experimental setup during cooking test that were demonstrated.

Figure 3. A) Picture shows boiling of 1 kg of dry beans in the cooking pot, B) shows the boiling of 1.5 L of water in the pot.

Cooking during charging was started a few minutes after the heater was switched on; due to the fact that the temperature at the top of the funnel rose faster. Cooking was continued as the tank was being charged. On the other hand, cooking during the discharge process was started after the heating element was switched off. While boiling dry beans, more water had to be added into the pot since dry beans take longer time to get cooked. The temperature profile during cooking processes were recorded. A manual valve has been mounted onto the heat storage tank at the lower bottom to occasionally drain the oil from inside the TES tank out in case of servicing and maintenance of the cooker.

2.4. Thermal performance analysis of the single tank heat storage system

2.4.1 Heating power

During charging, a small volume of oil (about 2.5L) was heated in the funnel using the heating element. The temperature of the oil in the funnel would rise faster. The total energy, $Esup$, supplied in heating the oil in time, t, is determined by Equation (1):

$$Esup = Pt \tag{1}$$

where, P is the rated power of the heating element.

2.4.2 Thermal energy stored in the tank

The total thermal energy, Est, stored in the stratified tank divided into n-segments after charging for a given time, t, is determined by Equation (2):

$$Est = \sum_{j=1}^{n} \rho av cp,av Vj \Delta Tj \tag{2}$$

where ρav, is the average density of refined sunflower oil in a segment, cp,av, is the average specific heat capacity of oil in a segment, Vj is the volume of oil in the jth segment, and ΔTj is the temperature difference in a segment of the stratified tank.

2.4.3 Rate of energy consumption during cooking

The rate of energy, E_W required to boil water of mass, m_W from an initial temperature, T_{ini}, to final temperature, T_w (the boiling point) in time, t, is given by Equation (3):

$$E_w = \frac{(\rho_w V_w) c_{p,w} (T_w - T_{ini})}{t} \tag{3}$$

where, V_w, is the volume of water, ρ_w the density of water, $c_{p,w}$ the specific heat capacity of water. Heat loss to the environment is ignored.

The rate of energy, E_b required to boil beans of a given mass, m_b, is determined by Equation (4) as:

$$E_b = \frac{(m_b c_{p,b} + m_w c_{p,w})(T_{boil} - T_{amb})}{t_1} + \frac{m_w L_v}{t_2} \tag{4}$$

where m_b is the mass of beans, $c_{p,b}$ is the specific heat capacity of beans, m_w is the mass of water, $c_{p,w}$ is the specific heat capacity of water, T_{boil} is the boiling point of water, T_{amb} is the ambient temperature, t_1 refers to time to reach the boiling point, and t_2 is time when the water is at its boiling point as the beans continues to boil. In case of boiling beans, usually more water is added once the water level drops during cooking, therefore, the new times: t_1 and t_2 have to be determined again. We assume the same mass of water. Table 3 provides thermal properties of beans and water used in the study.

Table 3: Summary of Properties of water and dry beans; properties of beans adapted from [12].

Parameter	Value
Density of water, ρ	1000 kgm^{-3}
Specific heat capacity of water, $C_{p,w}$	42000 $Jkg^{-1}K^{-1}$
Specific heat capacity of dry beans, $c_{p,b}$	1800 $Jkg^{-1}K^{-1}$
Moisture content of dry beans	12% w.b

2.4.4 Thermal charging efficiency

The thermal energy charging efficiency, η_{ch},is determined by Expression 6 as:

$$\eta_{ch} = \frac{E_{sto}}{E_{input}} \times 100\ \% \tag{6}$$

where E_{sto}, is the energy stored in the tank, and E_{input}, is the electrical energy supplied to heat the oil. The charging efficiency was determined for cases where no cooking was done during charging. The heat loss to the environment was ignored in the above computation.

2.4.5 Heat extraction efficiency

The heat extraction is determined during the discharge cycle. It is based on the cooking of food or boiling water using the energy stored in the tank. The heat extraction efficiency, η during cooking is expressed as Equation (7):

$$\eta = \frac{E_{cons.}}{E_{rel.}} \times 100\% \tag{7}$$

where, E_{cons} is the energy consumed by the food in the cooking pot while E_{rel} is the energy supplied to the cooking pot. However, the energy released by the heat storage, is determined by

$$E_{rel} = E_{cons} + E_{loss} \tag{8}$$

where; the energy consumed by food (boiling beans and water) is determined using equation (9)

$$E_{cons} = (m_b c_{p,b} + m_w c_{p,w})(T_{boil} - T_{amb}) \tag{9}$$

While the energy loss during this process is estimated using the expression (10)

$$E_{loss} = (\mathrm{UA})(LMTD) \tag{10}$$

Where; U is the heat transfer coefficient of material of the tank while, A, is the surface area of the system and $LMTD$ is the log mean temperature difference of oil inside the tank in Kelvin**.**

3. Results and Discussions

3.1 Thermal Charging at the first overflow barrier position

The experimental setup in Figure 6 was used to carry out the charging process. The heat storage tank contained 18 L of refined sunflower oil. About 2.5 L of oil was in the heating chamber. The oil level in the funnel was adjusted to be just at the bottom of the funnel barrier. Figure 4 shows the temperature profiles in the system during charging for about 90 minutes.

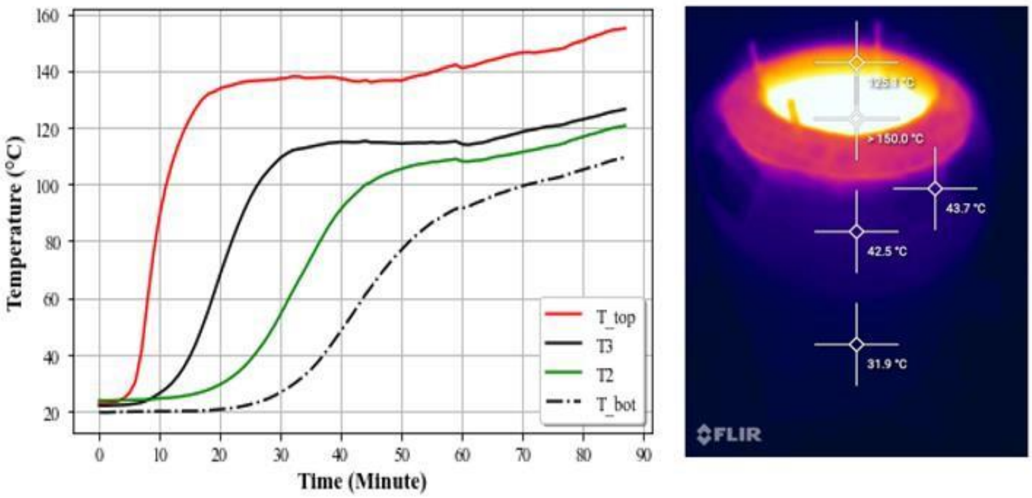

Figure 4. The temperature profile inside the energy storage tank and the funnel; and on the right hand is the thermal image showing heat distribution at the top of the tank and in the cooking unit.

It can be observed from Figure 4 that the temperature at the top of the funnel increased rapidly to about 138 ^{o}C within 20 minutes. Thereafter, the temperature remained fairly constant for the next 30 minutes despite the continuous heating. After about 1 hour, a slight increase in temperature was observed at the top of the funnel; the maximum temperature attained was about 155 ^{o}C at the end of the charging process.

The temperature profiles in the storage tank indicates that in the first 10 minutes, the temperatures were close to ambient temperature. Thereafter, the temperature at the top of the tank started to increase, reaching about 134 ^{o}C in 20 minutes. After additional 10 minutes of charging, the temperature at the top of the tank increased rapidly for the next 20 minutes to about 140 ^{o}C at the top and reached 115 ^{o}C in the middle, and then remained fairly constant for about 30 minutes. Further increase in charging, resulted into slight rise in temperature. On the other hand, the temperatures in the middle and bottom of tank remained close to ambient for the first 20 minutes of charging. Thereafter, the temperatures in the middle and bottom of the tank were observed to increase rapidly for the next 30 minutes reaching 110 ^{o}C and 90 ^{o}C respectively. Further increase in charging did not cause significant rise in temperature in the tank.

The rapid increase in the temperature at top of the heat funnel is attributed to the fact that a small volume of oil (about 2.5L) was heated in the funnel. Therefore, in about 10 minutes, the temperature at the top of the funnel had reached 100 ^{o}C. In addition, there was minimum heat conduction through the sides of the funnel into the storage tank during the start of the charging process. The heated oil in the funnel, becomes less dense and therefore, rises into the funnel top and this is replaced by cold oil flowing from the bottom of the tank into the funnel s observed, natural circulation sets in. As the oil is heated further, it rises above the funnel barrier and overflows into the tank. This is the cause for the rise in temperature of the oil at the top of the tank, while the middle and the bottom of the tank remained at ambient temperatures. Due to the overflow of hot oil into the tank, the temperature at the top of the funnel remained fairly constant. As cold oil is circulated from the bottom of the tank into the funnel for heating, the middle and bottom sections are replaced by hot oil flowing from the top and hence the observed increase in temperatures. However, the flow cold oil from the bottom of the tank into the funnel causes a slight decrease in temperature at the top of the tank as observed by the temperature profile after an hour. Thereafter, as heating continues, we observed an increase in temperature.

As heating was continued, the temperatures in the middle and bottom sections are seen to rise although the middle section rises faster. This is attributed to the fact that more hot oil from the funnel overflows into the tank, and the dense and cold oil at the bottom of the tank flows into the funnel. This process is repeated resulting into increase in temperatures in the middle and bottom sections of the tank while at the top of the tank, the temperature tends to flatten. In general, there is high heat distribution at the top of the tank as shown by the thermal image. After 90 minutes of charging, about 4.60 MJ of energy was stored in the storage tank in this case using equation 2.

3.2 Thermal charging – effect of increasing height of the funnel

The temperature of the hot oil at the top of the funnel was about 140 ^oC when it started to overflow into the tank. To achieve higher temperatures in the funnel, the levelling screws were used to raise the funnel by 2 cm. This means the height of the barrier for hot oil to overflow into the storage tank was raised by 2 cm above the initial position. The same experimental setup in Figure 2 was used, and Figure 5 shows the temperature profiles in the funnel and tank.

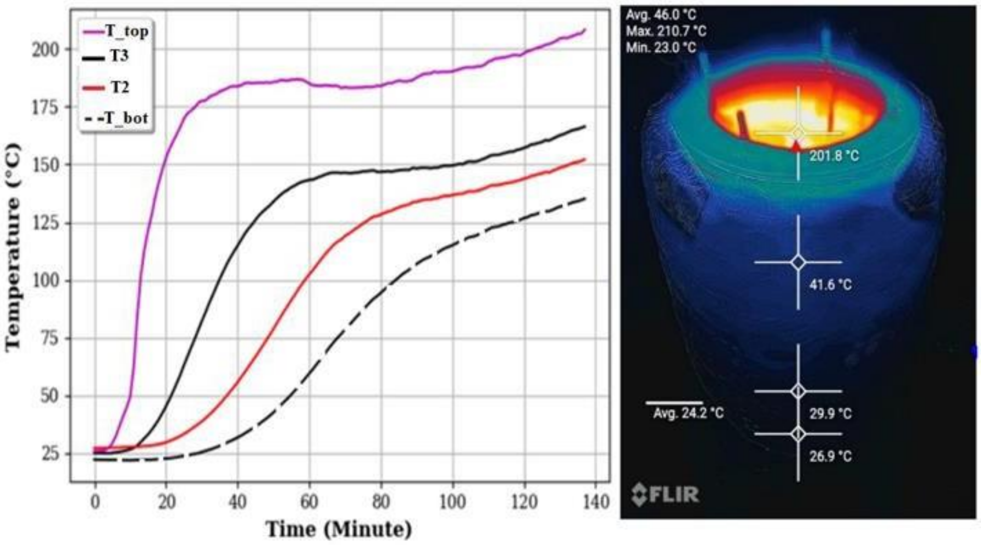

Figure 5. Temperature profiles in the funnel and tank; on the right is the thermal image of the heat distribution in the system. Highest temperature achieved at the top of funnel was above 200 ^oC after 2 hours of charging.

It can be observed from Figure 5 that the temperature profiles depict the same trend as shown in Figure 4. As noted, before, there was a rapid increase in temperature at the top of the funnel because of heating a small volume of oil. However, in this experiment, higher temperatures are attained compared to those in Figure 4. A temperature of about 155 oC was attained at the top of the funnel within 20 minutes compared to 135 oC in Figure 4. The highest temperature at the top of the funnel achieved was about 200 oC after 2 hours of charging.

As explained previously, the temperature at the top of the funnel remained fairly constant when the hot oil began to overflow into the storage tank. At this point, the dense, cold oil at the bottom of the tank flows into the funnel where it is heated. The oil becomes less dense and would rise, and overflow into the tank. This process is repeated as heating continuous. The temperature at the top of the tank reached a maximum of about 150 oC and remained fairly constant; while in the middle and the bottom temperatures of about 125 oC and 100 oC were attained.

The observed high temperatures in Figure 5 compared to Figure 4 are due to the raising of the funnel. The increase in the height of the funnel by 2.0 cm resulted into increasing the barrier height before the hot oil could start to overflow into the tank. This means, the oil is heated longer and hence attaining higher temperatures before starting to overflow into the tank. In general, the heating of small volume of oil causes a sharp rise in temperature in short time leading to overflow of hot oil into the tank. Thermal stratification is established in the tank with a sharp thermocline.

Figure 4 and Figure 5. shows the charging of the oil by using the funnel technique and the impact 0f adjusting the funnel barrier height varies the temperature at which hot oil begins to overflow into the tank. The energy stored in the tanks under the above cases were estimated from Figure 4 and Figure 5 where About 4.6 MJ of energy was stored during the first charging and about 5.9 MJ in the second case after raising the funnel height by 2 cm.

3.3 Charging the system while boiling 1 kg beans

The heating element was switched on and as well demonstration of boiling tests was performed on the heat storage. The temperature profile recorded and plot

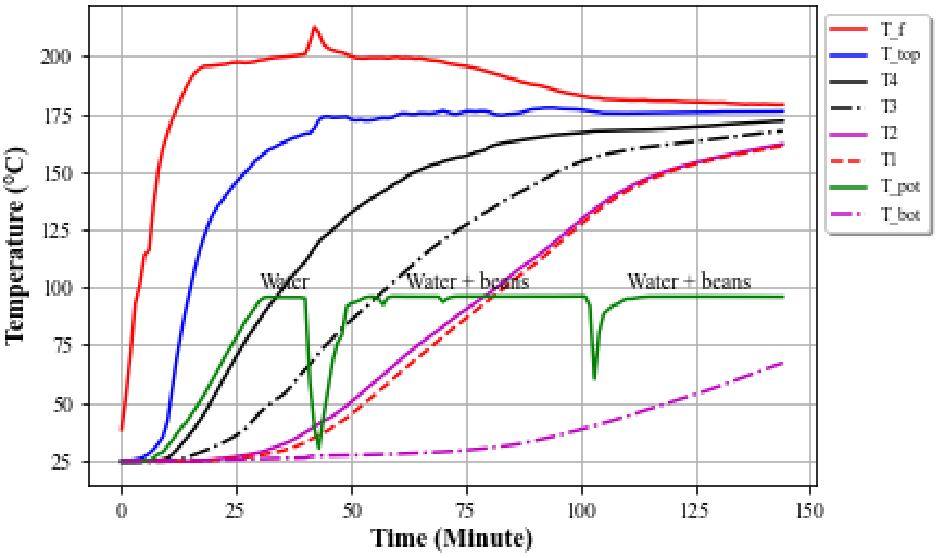

Figure 6. Shows the temperature profile during charging of the system while cooking; boiling of 1.5 litres of water and then boiling 1 kg of beans soup. The beans boiled in about 2 hours and boiling was repeated several times.

Figure 6 shows that the initial 1.5 L of water at 25oC, reached boiling temperature in less than 20 minutes; and boiling was prolonged for further 20 minutes. This is shown by the temperature

$Tpot$ remaining constant, then 1 kg of dry beans was added into the cooking pot. This resulted into the first drop in temperature of the cooking pot after about 40 minutes.

Thereafter, the temperature of cooking pot rose quickly reaching the boiling point in less than 20 minutes. The beans continued to boil at constant temperature T_{pot}. The small drops in temperature of the cooking pot observed between the 50th and 75th minute are associated with opening the lid of the cooking pot to check the status of beans as it boils. After about one hour of boiling beans, a drop in temperature is observed at the cooking pot. This is due to addition of 0.5L of water at room temperature. The temperature of the cooking pot reached to boiling point very fast since a small volume of water was added. The beans boiled for further 40 minutes and it became soft and cooking was stopped. In total it took about 2 hours to boil the dry beans.

The total energy used in boiling of the beans was calculated using Equation (7-9) and it was found to be 3.89MJ. Therefore, the power used in boiling beans within 2 hours is about 3.0 kWh by using equation 3-5. This is a comparable amount of energy consumed in boiling of 1 kg beans when using improved firewood stove reported to be 2.61kWh [14]. The value obtained was slightly higher than that of energy consumed by firewood stove probably due to the calorific energy value in firewood and energy losses. In addition, Kajumba et al. [8] also reported that, it took 2½ hours to boil only ½ kg of dry beans on heat storage. This means that, the current study of single tank system had better performance compared to the previous work reported in literature.

3.4 Discharging process – through Boiling water

in the Figure 7, the cooker was tested by boiling 1.5 L of water obtained at room temperature during the discharge process. The heat storage tank was first charged to about 200 o C, and then, the heater was switched off. Then the first 1.5 L of water was added into the pot and allowed to boil. After boiling of the water, another (1.5L) of water at room temperature was replaced in the pot and the process was repeated several times. Figure 13 shows the temperature during charging and discharge process.

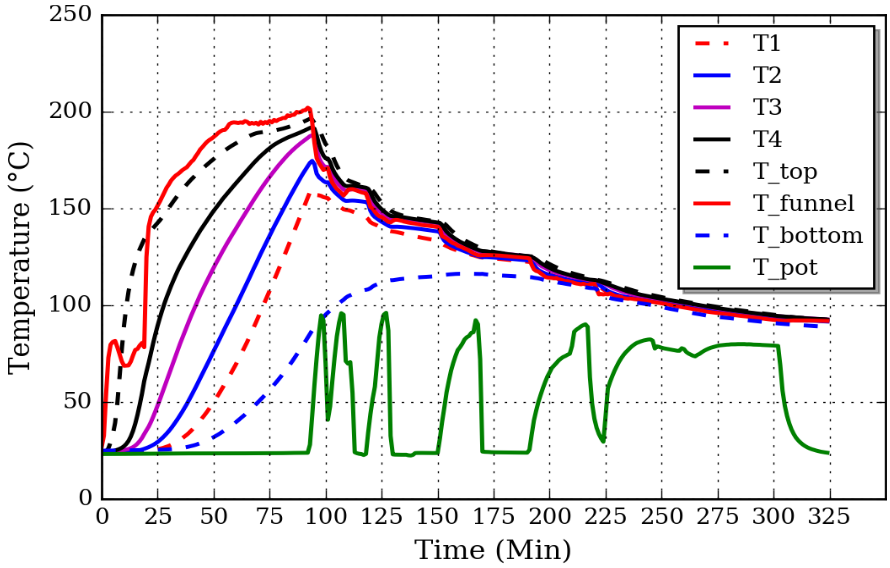

Figure 7. The temperature profiles during charging and discharging cycles of the system; by boiling of 1.5L of water multiple times.

Charging was done for about 80 minutes and the temperatures at the top of the funnel and heat storage tank reached about 200 ºC as observed in Figure 7. Then 1.5L of water at room temperature (25 ºC) was put into the cooking pot. It took about 8 minutes for the water to boil during the first test and consuming about 447.3kJ by equation 4. The green temperature profile recorded by T_{pot} represents different boiling tests. The second boiling test was done immediately; it took about 10 minutes for the water to boil. The drop in cooking temperature profile in the pot happened when the pot was removed and water at room temperature was added. After the first two tests, there was a delay of about 10 minutes before putting more 1.5L of water to boil. After the third cooking test; boiling of water was done after 30 minutes interval for the next two tests. During this time interval, the temperature for the cooking pot remained constant at about 25 ºC. During the final boiling test, the water was left to continue boiling after it had reached its boiling point in 20 minutes. The slight drop in temperature observed during the boiling process was when the top cover on cooking pot was remove. However, the funnel charging energy efficiency was estimated to be 72.5% for the first case of barrier height and 51.9 % in the second barrier level by the funnel technique using equation 6. About 453.6kJ of energy was consumed in boiling 1.5L of water in 10minutes while 1.04MJ in boiling 1 kg of dry beans in 2hours. There was 6.23MJ left during charging while cooking and 3.54MJ left after discharging.

4. Conclusions

The single tank system with funnel charging mechanism was developed tested successfully to charge the energy storage tank to high temperature in a short period without mixing hot oil in the heat storage attributed to the funnel designed. Immediate cooking on the cooker was possible and cooking tests (boiling water and cooking beans) were demonstrated both during charging and discharge process successfully. The funnel maintained quality heat front at both during charging and discharge process. Therefore, an off-grid solar PV system is recommended and suitable to supply power to charge the small volume of oil in this funnel technique for solar cooking.

Data Availability Statement

The data presented in this study are available on request from the author**.**

5. Acknowledgments

The authors are grateful to the Norwegian Agency for Development Cooperation for financial support through NORHED II Project – Energy Technology Network (EnergyNET). EnergyNET is a research collaboration between the Norwegian University of Science and Technology, Makerere University, and African Universities.

The authors appreciate the International Solar Energy Society (ISES, SWC2023) 30th October -4th November Conference 2023, for the invitation and organising the Scientific Event in New Delhi, India.

Conflicts of Interest:

The authors declare no conflict of interest in undertaking this research work and publication.

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