COMPARISON OF ROKI AND SUNFLOWER OILS AS SENSIBLE HEAT STORAGE MATERIALS FOR COOKING APPLICATIONS

BY

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DECLARATION

I FRANK SAYUNI MNDEME do hereby declare that this dissertation has been developed by me under the guidance of my supervisors, and has not been submitted to any University or any academic institution for the purpose of an academic award.

Signature: ……………………………………………

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APPROVAL

This is to certify that the dissertation by Frank Sayuni Mndeme was developed under our close supervision and is hereby approved for submission to Kyambogo University, Physics Departmental Higher Degree Committee for consideration.

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DEDICATION

I dedicate this dissertation to my lovely husband Erick Charles Nkyalu, for his support and encouragement during the study period.

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LIST OF SYMBOLS

DSC	Differential Scanning Calorimeter
TES	Thermal Energy Storage
SHSM	Sensible Heat Storage Material
LHSM	Latent Heat Storage Material
TCHSM	Thermochemical Storage Material
PCM	Phase Change Material

ABREVIATIONS AND ACRONYMS

c	Specific heat capacity	J/kg°C
Eo	Output energy rate during charging	W
Exo	The output exergy rate during charging	W
E_{XF}	Exergy factor	-
m	Mass	kg
Δt	Time interval	s
T	Temperature	℃
T_a	Ambient temperature	℃
i	Initial water temperature	℃
T_f	Final water temperature	℃
Q_{US}	Total energy stored during cooking period	J
Q_{uti}	The total heat utilization	J
V	Volume	m^3
V_{Roki}	Viscosity of Roki	mPa.s
$V_{\text{Sunflower}}$	Viscosity of Sunflower	mPa.s
ρ	Density	kg/m^3
η_{uti}	The heat utilization ecfficiency	-

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ABSTRACT

Sensible heat storage materials are cheaper than latent heat storage materials for small storage volumes. Static experiments to evaluate the thermal performances of two Ugandan locally available edible vegetable cooking oils for medium temperature thermal energy storage are presented. The two vegetable oils evaluated and compared are Sunflower oil and Roki oil (a blend of Palm oil and Sunflower oil). Temperature profiles are used to assess the thermal performances during heating cycles, cool-down cycles, energy, exergy, and heat utilization. The results show that Roki oil attains a higher maximum temperature (~ 170 ℃) compared to the Sunflower oil (~ 160 ℃) during low-temperature heating cycles. Roki oil shows higher temperatures during cooling compared to Sunflower oil, achieving a final temperature (~ 78 ℃) slightly higher than that of Sunflower oil (~ 76 ℃). Roki oil shows a maximum energy rate of 413 W compared to Sunflower oil showing a maximum energy rate of 387 W, this is possibly due to the low thermal mass (mc) of Roki oil compared to Sunflower oil. Roki oil also shows higher maximum exergy rate of ~ 129 W compared to that of Sunflower oil ~ 120 W. This occurs because of the lower thermal mass (mc) of the Roki oil which leads to a quick rise of temperature. The exergy factor of Roki oil (0.31 – 0.62) is slightly higher than Sunflower oil (0.27 – 0.59) within 1 hour and 40 minutes. This is possibly due to the higher difference in temperature of Roki oil compared to Sunflower oil. The heat utilization characteristics of the two heat storage materials are experimentally determined in water heating experiments using 1.0 kg to 3.0 kg water loads. Roki oil shows higher average heat utilization (151 – 350) kJ, and higher average heat utilization efficiency values (0.25 – 0.66) as compared to Sunflower oil (148 – 300) kJ and (0.25 – 0.60), respectively. The average heat utilization and average heat utilization efficiency values increase with the increase in the water load for both Sunflower oil and Roki oil. The best overall performance is shown by Roki oil compared to Sunflower oil. Preliminary results with parabolic dish solar cookers are also presented in this work. The results show that Roki oil performs better than Sunflower oil during heating, cooling/heat retention, and heat utilization.

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

A solar cooker is a cooking device that uses energy from the sun to cook (Mawire et al., 2020). Solar cookers have the advantages of being environmentally friendly, cheap, and the food they cook is healthy. The main types of solar cookers include; the parabolic dish cooker, indirect type cookers, oven cookers, and panel cookers (Aramesh et al., 2019). The parabolic dish solar cooker have raised more attention to scientists due to its low cost in fabrication and good thermal performance (Ahmed et al., 2020).

Cooking forms part of the daily activities of a human being for survival and well-being. There are many ways of cooking food. For example, using firewood, electric cookers, gas cookers, charcoal stoves, and solar cookers. According to the World Health Organization, out of three billion individuals cooking with biomass and coal, 4 million deaths per year occur due to inhaling emissions from these cooking methods (Osei et al., 2021). Apart from the hazards of cooking over an open fire which causes indoor air pollution, deforestation and greenhouse gas emissions are also caused by open fires. Wood, petroleum, and natural gas are the major energy sources for cooking, frying, and baking in Uganda. Deforestation is widespread in developing countries as a result of the chopping of firewood for cooking. Cooking with firewood produces smoke, which is a leading cause of early deaths in most developing countries because of lung-related diseases (Gazdar and Zhou, 2018). The expense of petroleum fuels is likewise growing, and these fuels release harmful pollutants into the atmosphere. As the world grows more complicated, environmentalists are increasingly concerned about deforestation, and the need for renewable energy alternatives to fossil fuels is essential.

Many solar cookers are available in both local and international markets for domestic applications. However, they cannot be used during periods when the sun is unavailable. To continue using solar cookers during periods when the sun is unavailable (when it is cloudy, raining, and at night), or to use electrical cookers during load shedding periods, there is a need to store energy. If solar cookers or electrical cookers are used with a thermal storage unit, then there is a possibility of cooking food during the off-sunshine hours and load shedding periods. Energy storage saves money, but it also saves the environment.

A thermal energy storage system (TES) can be directly combined with a cooking pot, which is the direct storage cooking mode (Lecuona et al., 2013), in a solar cooker as well as in an electric cooker. TES systems can help to save a lot of money, preserve indigenous fossil fuels and reduce total energy consumption (Muthusivagami et al., 2010). The three main types of thermal energy storage systems are; sensible heat storage materials (SHSM), latent heat storage materials (LHSM), and thermochemical storage materials (TCHSM) (Amy et al., 2021). In SHSM, the stored energy is reserved in a liquid or solid medium by transferring heat to that medium (liquid or solid). This process is known as charging, and results in to the temperature increase of the medium. By lowering the temperature, the energy can be obtained from the medium when needed. This process is called energy discharging (Bergan and Greiner, 2014).

The LHSM technique employs the phase change material (PCM) as a storage medium for thermal energy. In this system, the thermal energy is stored when the phase transition process of PCM occurs, melt from solid to liquid phase or solidified from the liquid to solid phase example salt hydrates, paraffin, and organics (Elias and Stathopoulos, 2019). In the TCHSM, the stored energy is typically stored in the form of bond energy of a reversible chemical reaction involving one or more chemical compounds as the storage material (Nithyanandam et al., 2017). Sensible heat storage materials are cheaper than latent heat storage material for small storage volumes (Sarbu and Sebarchievici, 2018). However, for cost-effective and efficient heat storage, understanding the thermal and physical characteristics of sensible heat storage materials is critical (Mishra et al., 2021). Thermal oils (Sunflower, Palm oil etc.), rocks (small pebbles or large pebbles), water, metals, and salts (molten salt) are all good heat storage materials. At medium to high temperatures, the solid particulate matter requires a heat transfer fluid to store thermal energy. Thermal oil is more suitable than water since water has temperature limitation because of its boiling temperature point. Water is an inexpensive and readily accessible TES medium; however, its boiling point limits its usage for food cooking at high temperatures. This is because it cannot be kept without pressurizing it beyond its boiling point. More costs are expected for the storage vessel when water is being pressurized (Mawire, 2016). One of the benefits of thermal oils is that they serve as a means for heat transfer and storage that can be used for domestic applications such as food cooking and generation of steam.

Vegetable oil is used as a food and heat storage material. Vegetable oils have excellent fluid characteristics such as; a high viscosity index, high lubricity, strong insulating properties, low volatility variations in kinematic viscosity caused by temperature fluctuations in fluid temperatures ranging from 40 ℃ to 100 ℃ and they are widely available. In heat storage, vegetable oils can be used as sensible heat storage media (SHSM) after usage in the cooking applications such as home like frying chips, chicken, mandazi, and sweet potatoes. These vegetable oils instead of being thrown away can be used as storage in medium-temperature cooking applications. Vegetable oils can be used as SHSM which are cheaper and economically viable compared to phase change materials. Vegetable oils are produced locally in most countries in Sub- Saharan Africa. Recently, the more applicable thermal oil for domestic applications has been a Sunflower cooking oil

(Lugolole et al., 2018). It has been observed that Sunflower oil has excellent thermal stratification characteristics, as well as high values for energy and exergy (Lugolole et al., 2018). There is another vegetable oil called Roki which is cheaper than Sunflower oil. It is mostly used and locally available in Uganda at affordable prices at 30,000 Ugandan Shillings (~ USD 8.52) per 5 liters compared to Sunflower oil which is 60,000 Ugandan Shillings (~ USD 17.04) per 5 liters. It is a hard oil (it is semi-solid at room temperature) (Omara et al., 2019), and a blend of Palm oil and Sunflower oil (Mukwano, 2021).

1.2 Statement of the problem

Electric and solar cookers are clean and healthy methods of cooking food, but the problem with the electric cooker is that cooking is not possible during load shedding periods, while for the solar cooker, it is impossible to continue cooking when the sun is unavailable. To continue cooking during load shedding periods with electrical cookers, there is a need to store the energy before the load shedding period. To cook with solar cookers during off-sunshine periods, energy needs to be stored during the period when the sun is available. Recently, Sunflower oil was widely applicable as a sensible heat storage material in thermal energy storage (Mawire et al., 2014, Mawire, 2016, Kajumba et al., 2020). However, Sunflower oil is expensive in comparison with locally available cooking oils in the market. Therefore, there is a need to explore the heat storage performances of the different cooking oils which are cheaper than Sunflower oil and easily available in the local market. Roki oil is a suitable example of such oils since it is a blended oil, cheaper than Sunflower oil, and locally available in Uganda.

1.3 Aim of the study

This study aims to compare the thermal performance of Roki oil and Sunflower oil as sensible heat storage materials for domestic applications in storage cooking pots.

1.4 Objectives of the study

To achieve the aim, the objectives of the study are to;

i. Design and fabricate specialized cooking pots that will be filled with Roki oil and Sunflower oil as sensible heat storage materials.

ii. Measure thermophysical properties of Roki oil and Sunflower oil.

iii. Investigate the heat storage performances of Sunflower oil and Roki oil.

1.5 Scope of study

This work is focused on comparing the Roki oil and Sunflower oil thermal performances as heat storage media during heating, cooling, and heat utilization. Roki and Sunflower oils that are used in this study are manufactured by Mukwano Group of Companies, Uganda. Cooking pots made of stainless steel are used to investigate the thermal performance of Sunflower oil and Roki oil. These experiments were conducted at Kyambogo University.

1.6 Significance of the study

The research findings can enable consumers to choose appropriate and relatively cheaper thermal oils for domestic TES. This is an alternative method to reduce energy consumption. The stored energy is useful when the sun is unavailable for solar cooker users, and when there is load shedding for the users of electric cookers.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature review of related studies on thermal energy storage, sensible heat storage material, Sunflower oil, Roki oil (a blend of palm oil and sunflower oil), and specialized cooking pots, and the effect of cooking load.

2.2 Thermal energy storage

Thermal energy storage (TES) is an energy storage technology that uses thermal energy by applying heat on a medium so that the resulted energy stored can further be used for heating applications or for power generation (Irena, 2013). With the prominence on effective use and waste heat conservation, TES in the form of sensible and latent heat has become an essential element of energy management (Demirbas, 2006). TES has come out as a way to trap heat from low temperature as wells as high temperature sources (Mishra et al., 2021). In thermal storage systems, the energy provided to a system of storage to be used at a future time, involving three steps; charging, storing, and discharging. A complete storage cycle is shown in Figure 2.1.

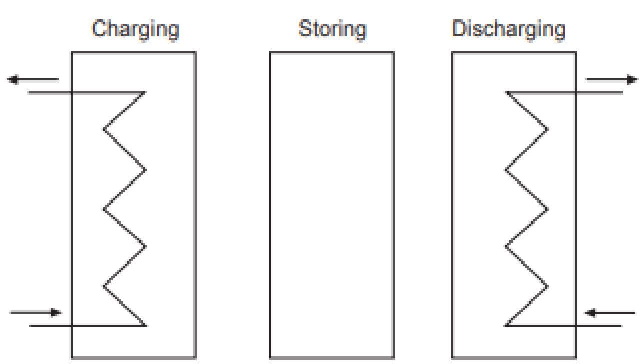

Figure 2.1: Illustration of complete storage cycle.

TCHSM is the least technically mature, and the most complicated form of thermal energy storage (Kimpton, 2021). According to construction complexity and price of the PCM itself, LHS systems are more expensive (Mawire et al., 2015). Other challenges of LHS are their low thermal conductivities, and lower thermal stabilities (i.e. thermal properties change with temperature) (Nithyanandam et al., 2017). SHSM is more appropriate for use since they are cheaper, readily available, and easy to fabricate and maintain (Mawire, 2016).

2.3 Sensible heat storage material

Among all the three means of storing thermal energy, the kind of thermal energy that has been gaining popularity was sensible heat thermal storage (SHSM), since it is the most applicable for domestic scale TES applications (Lugolole et al., 2018). The materials employed in SHSM can store thermal energy without experiencing a phase transition (Mishra et al., 2021).

SHSM is better than latent heat thermal storage in terms of technology and economics. (Dinker et al., 2015). This storage material is commonly used due to its simplicity in terms of design, operation and implementation (Kuravi et al., 2013). The volume, specific heat, density, and temperature differential of the materials are all related to the quantity of heat stored in SHSM (Dekhil et al., 2020). To enable heat transfer during energy charging, the large quantity of thermal conductivity of storage material is required (Lugolole et al., 2018). Sensible heat storage materials include water, sand, pebbles, rocks, steel balls. and thermal oil (Mawire et al., 2014). The use of sensible heat storage materials makes storing wastes from heat and thermal energy to be easy and less expensive, and the degree of storage is determined by the material's thermophysical characteristics (Mishra et al., 2021).

Both water and thermal oil can be used as SHSM (Mawire et al., 2014). For the case of water, its boiling point limit the cooking of food at high (Mawire, 2016). The advantage of thermal oil over water is that it can keep thermal energy at higher temperatures than water (Mawire et al., 2015). SHSM uses the heat capacity as well as the change in temperature of the storage material when there is energy charging or discharging processes. Energy is absorbed when the storage material temperature increases and withdrawn when the temperature decreases.

In an experimental study of thermal performance comparison of three SHSM during charging and discharging cycles (Lugolole et al., 2018), it was discovered that the thermal oil storage system has a tendency of charging up fastest. After thermal oil storage, the small pebbles thermal energy storage (TES) followed, and lastly by the large pebbles TES. Thermal oils are commonly use storage systems due to its capability in storing energy than water which has low boiling point and air which has low thermal (Kuravi et al., 2013). Thermal oils can be used in applications that do not require complex heat exchangers small-scale domestic applications (Muthusivagami et al., 2010). The temperature range of the oven is ideal for household cooking. For the storage medium, the temperature should be about 100 °C to 250 °C, while the temperature for water heating is range from 50 °C to 100 °C for domestic application (Muthusivagami et al., 2010). Recent work has shown that Sunflower oil is a good material for domestic thermal energy storage purposes (Mawire et al., 2014, Kajumba et al., 2020, Mawire, 2016).

2.4 Sunflower oil

Sunflower oil can be described as a non-volatile vegetable oil originated from the seeds of the Sunflower. Sunflower seeds grow in most parts of the world (Calero et al., 2014). Experimental investigation of characterization of Sunflower as a heat storage medium for cooking by using sun (Mawire et al., 2015) has been done. The study mentioned the following reasons for using

Sunflower oil as a storage medium for cooking application; Sunflower seeds can be grown in most part of the world and its oil can be locally extracted from Sunflower oil seeds, its edible, non-toxic, it has a flash point of about 250 ℃ (this temperature is above the cooking temperature of most food). The energy charging tests to show the solar cookers thermal performance of three different oils used for thermal energy storage were discussed (Mawire et al., 2014). Results of charging showed higher exergy, higher energy, and higher exergy factor in Sunflower oil compared to Shell Themia B as well as Shell Thermia C. The performance of this oil as a SHSM for home application was done as well (Mawire, 2016). Its thermal performance was observed during the processes of charging, discharging and heat retention. The heat retention that occurred during twenty-four period has showed that the higher temperatures correspond to the increase in heat loss during the cooldown heat retention process.

In the experimental thermal performance oil, which were selected for indirect solar home cooking purposes were refined oil that include Sunflower, Palm, and Thermia B (Chaciga et al., 2019). The outcome of the observation reveals that the thermal performance for refined Sunflower oil was much higher when compared with the others, and has higher energy distribution storage during the charging process. Thermal performance comparison of 3 experimental setups with sensible heat of the thermal energy storage systems during charging cycles experiments was done (Lugolole et al., 2018). It was found out that Sunflower oil has a wide range in terms of temperature and has high specific heat capacity. The study also found that the its viscosity remains low from medium to high temperatures (Mawire et al., 2014). This kind of study was not previously done for Roki oil.

2.5 Roki

Palm oil has been studied recently as a TES material (Frota de Albuquerque et al., 2020). Palm oil is the world's most extensively produced and edible vegetable oil, and it has a wide range of use in the food and non-food sectors (Achaw and Danso-Boateng, 2021). Palm oil has potential for TES based on its thermo-physical and chemical properties such as specific heat capacity, viscosity, and thermal conductivity (Lawer-Yolar et al., 2019). Globally, Palm oil has proved itself as a favorable, low cost, low health risk, and friend to the environmental alternative for passive TES solutions. (Fabiani et al., 2020). The research of two media thermal storage system was performed with Palm oil and paraffin. The results showed that Palm oil which had not been looked at previously in the literature as a TES medium had shown to have high mean efficiency when compared to paraffin, and was a good substitute for paraffin (Ojike and Okonkwo, 2019). A packed bed for solar TES system in the form of sensible heat was observed using a two-phase continuous system (Erregueragui et al., 2016). The model contained Quartzite filler material and for transfer of heat, has Palm oil as the fluid. Using the advanced model, the Palm oil proved as an efficient fluid for transfer of heat when its performance was compared with other synthetic oils for temperature below 300°C. Moreover, Palm oil is edible (Corley, 2009).

There is the availability of a blended edible vegetable cooking oil known as Roki vegetable oil (Mukwano, 2021). It is a hard oil (Omara et al., 2019). Hard oils are semi-solid at room temperature including Palm oil, and soft oils are liquid at room temperature including Sunflower oil. Roki oil is a blend of Palm oil and Sunflower oil. The frying stability of different selected brands of cooking oil in Great Metropolitan Kampala during frying cycles was done by (Omara et al., 2019). Roki oil exhibited the best frying stability. The study recommended that hard oil is preferred to soft oil for deep frying of Irish potatoes and cassava chips, fish, chicken, and dough (mandazi). Roki oil is widely used in restaurants for cooking in Uganda. It is locally manufactured in Uganda, and relatively cheaper than Sunflower, thus its widespread usage in Uganda. The used Roki oil from the restaurant can be re-used in TES for pre-heating water for cooking rice, making hot chocolate, tea, and hot coffee, hence reduce the demand for using electricity for cooking purposes. Presently, no studies have been done on Roki oil as a SHSM.

Since Roki oil is a blend of Palm oil and Sunflower oil, it has potential for TES based upon its thermo-physical and chemical properties. These thermal properties include the viscosity (81.06 $\pm$ 0.6) cP for Palm oil ,and (48.78 $\pm$ 0.9) cP for Sunflower oil, and the slip melting point (32 $\pm$ 0.5) ℃ for Palm oil , and (18 $\pm$ 0.6) ℃ for Sunflower oil (Devi and Khatkar, 2017). The melting enthalpy of 12.30 J/g for Palm oil is higher than 9.24 J/g for Sunflower oil. Melting enthalpy plays a key role in determining the hardness of the oil products (Devi and Khatkar, 2017). Therefore, because Roki oil is a mixture of Palm oil and Sunflower oil, there is a possibility that Roki oil will have a higher TES capacity compared to Sunflower oil.

2.6 Specialized cooking pot

A specialized cooking pot is a special vessel that is designed for cooking food at the same time storing thermal heat/energy. Different specialized cooking pots have been designed and used for sensible heat storage as shown in Figure 2.2.

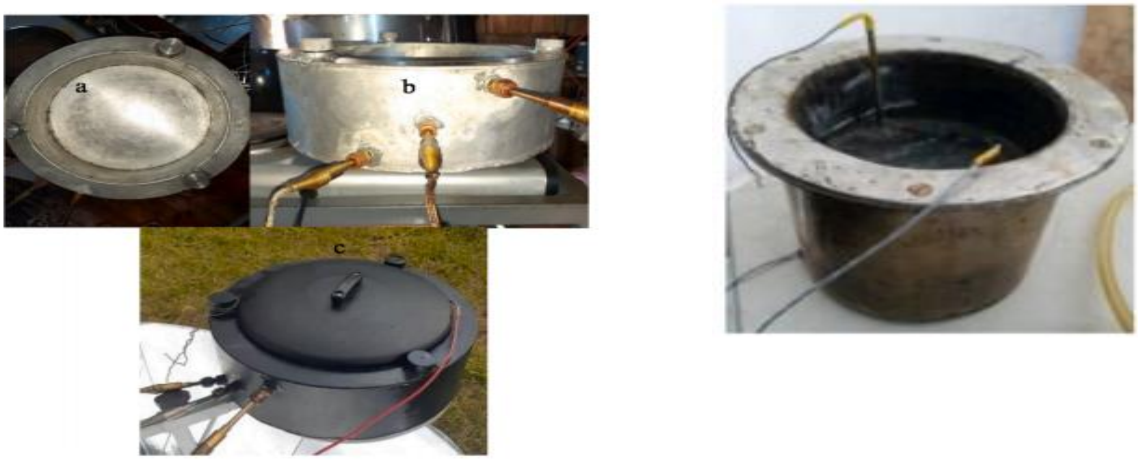

Figure 2.2: Photographs of the storage cooking pots: (1) storage cooking pot (Mawire et al., 2020) and (2) storage cooking pot (Bhave and Kale, 2020).

The problem with the two cooking pots in Figure 2.2 is that they are fixed in such a way that when filled with storage material in the cavity, it is not possible to clean and remove it. For practical domestic applications, one needs a cooking pot that is easy to clean and use. This is because one needs to use it several times. Therefore, there is a need to design and fabricate an alternative specialized cooking pot. This has not yet been done according to the available literature.

2.7 Effect of cooking load

An experiment to show the comparison of the two cooking pots used for storage has been shown during the heat storage and utilization periods for five different quantity of water from 0.5 kg to 2.5 kg (Mawire et al., 2020). Sunflower oil as the SHSM was placed in one pot, while erythritol as the phase change material (PCM) was added in another. The Sunflower oil pot for storage has shown to have a better storage efficiency when compared with erythritol storage pot. With the load increase, both pots have shown to have a reduced storage efficiencies while increase in the heat utilization efficiencies.

Studies were performed on the two different thermal energy storage media (Srivastava et al., 2020). Two storage cooking pots were used, one with Sunflower oil and another one with Mustard oil which were placed in the cooker simultaneously with an equal load of water to compare the performance of both energy storage media. Cooking pots were designed for the storage of heating fluids and cooking food. Load tests were carried out with 0.5 kg and 0.75 kg of water. It was observed that efficiencies increased with an increase in the load. It was also observed that Mustard oil was more efficient as an energy storage medium compared to Sunflower oil as a storage medium.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter explains the research methodology. It presents the research design, fabrication of the specialized cooking pots, and the use of parabolic dish solar cookers and wonderbarg slow cookers. It also presents the experimental tests of Roki and Sunflower oils as SHSM during heating, cooling, and heat utilization. The performance analysis of Roki and Sunflower oils as sensible heat storage materials for domestic low temperature purposes is also presented in this chapter.

3.2 Research design

The study is based on experimental and quantitative analysis. The data obtained from the experiments were analyzed using ORIGIN software. Here, specialized cooking pots were added with sensible heat storage media (Roki and Sunflower oil). Water was used as a test fluid, and different water loads of 1.0 kg to 3.0 kg were used so as to analyze the reaction of load on the thermal performance for both Roki and Sunflower oils.

3.3 Fabrication of cooking pots

Two cooking pots were observed in this work. Sunflower oil as the SHSM in one pot, and the other cooking pot used Roki oil as the materials for sensible heat storage. The cooking pots were of the same size and made up of the same material (stainless steel) with dimensions as shown in Figure 3.1 and Figure 3.2. Stainless steel was preferred because it is durable, does not react with food, provides rapid uniform heating, and is easy to fabricate. To fabricate each of the cooking pots, a stainless-steel sheet metal roll was cut according to the design and dimensions of the different components as shown in Figure 3.1 and Figure 3.2. The welding of the different parts together was done to make a complete functioning cooking pot. These pots were designed in such a way that it is possible to remove the smaller pot inside the bigger one.

Three (3) liters of Sunflower oil and Roki oil were separately heated in different pots. The same amount was used during charging/heating and during discharge/cool down. This amount is reasonable according to the design of the cooking pots that were fabricated. During the cool-down process, the inner pot was placed inside the bigger pot for cooking, and a test load of 1.0 kg water was used during heat utilization.

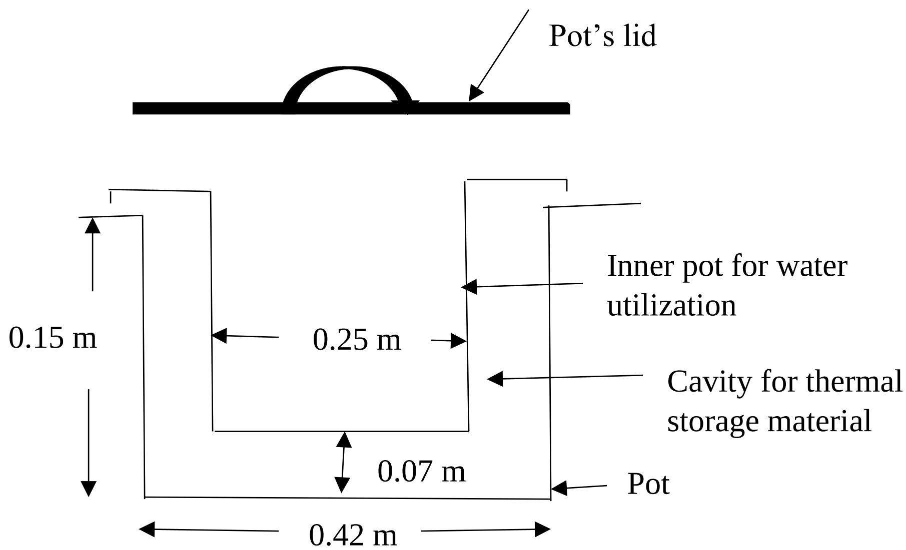

Figure 3.1: Illustration of storage cooking pot.

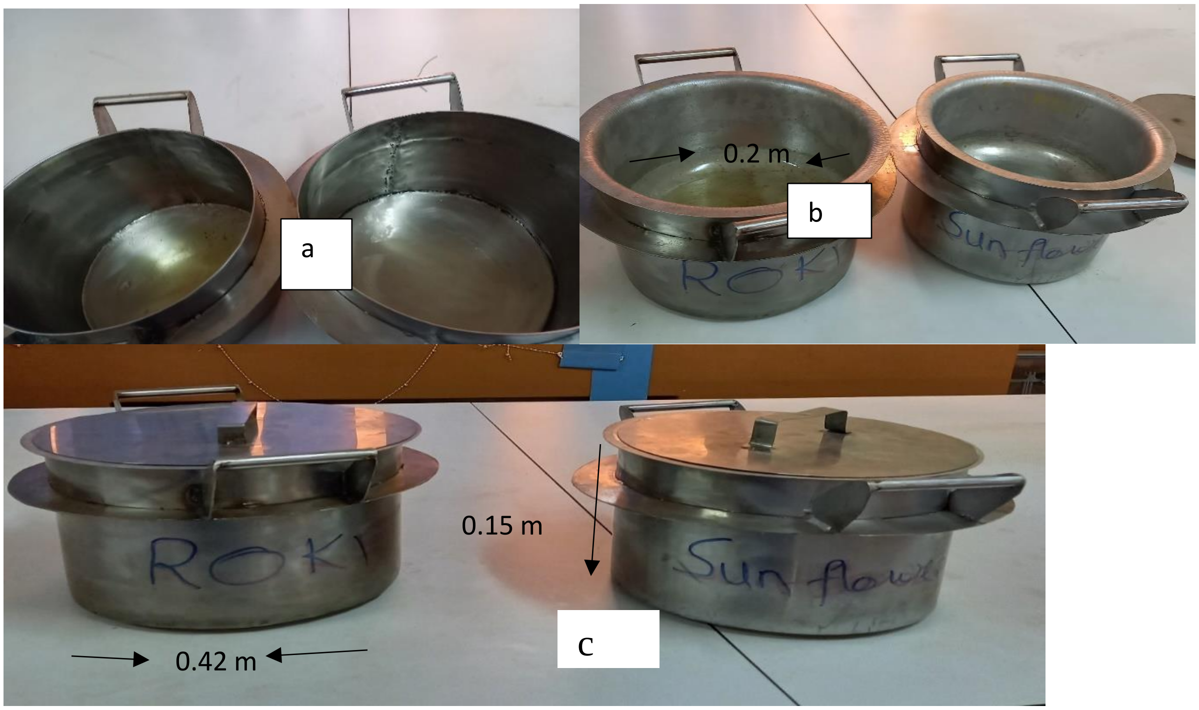

Figure 3.2: Photographs of the cooking pots storage: (a) plan view without the inner pot, (b) plan view with inner pot, and (c) side view of the storage cooking pots with pot lids.

3.4 Wonderbag cookers

The wonderbag can be described as a self-contained, insulated bag that is primarily intended to minimize the amount of fuel used in food preparation (Mawire et al., 2020). This bag is also non electric. Food is heated to a temperature which is hot enough before being passed on to an insulated wonderbag, rather than being cooked in a pot on an electrical, firewood, charcoal, or biomass burner throughout the cooking period. This process uses the thermal insulation principle, keeping the meal warm without the use of external fire. More heat energy is expected to be saved when the wonderbag is used for cooking. The properties of the wonderbag cookers used in this experiment are shown in Table 3.1. The photographs of the wonderbag cookers are shown in Figure 3.3.

Table 3.1: Properties of the wonderbag cookers.

Property	**Value**
Mass of wonderbag when is empty (kg)	0.870
Capacity ($\boldsymbol{m^3}$)	0.008
External height when there is no pot (m)	0.290
Internal height when there is no pot (m)	0.280
Diameter when is fully opened (m)	0.90
Diameter when there is pot inside (m)	0.500
Base diameter (m)	0.390
Insulation thickness (m)	0.130
Thermal insulation	Polystyrene
Thermal conductivity (W/mK)	0.030

Figure 3.3: A photograph showing the insulating wonderbag used for heat retention cooking experiment.

3.5 Experimental setup and procedure

3.5.1 Electric cooker

The experimental setup and its operation is shown in Figures 3.4 and 3.5. The main components of the experimental setup are the electric cooker, cooking pots, data logger, computer, electrical wires, thermocouples, and power supply. An electrical heating element in contact with the stainless-steel cooking pot was used. The oil inside the cooking pots (D and E) was heated with an electric cooker that was manually controlled with the power controller knob (I and J) as shown in Figures 3.4 and 3.5. The power controller knob was used to control the set power of the heating element as 1, 2, 3, 4, and 5, with 1 being the lowest power, and 5 as the highest power. The data logger for data logging and the computer for data storage and analysis is shown in Figure 3.4. The electrical cables (F, G, and H) from the computer, data-logger, and the electric cooker respectively, were connected to the power supply as shown in Figures 3.4 and 3.5.

As a precaution, the edge of a K-type thermocouple that has a high temperature resistance insulation substance was directed to the center of the heating element in a way that it monitored the temperature of the heating element for control purposes. Also, electrical heater had a thermostat which automatically switched on and off to avoid over-heating of oil as controlled by the power controller knob.

Three K-type thermocouples (A, B, C) in Figure 3.4 were used to monitor the temperature of oil in each cooking pot. Two thermocouples (A and C) were used to monitor the oil temperatures in the separate pots, and the third thermocouple (B) was used to observe the ambient temperature heating (charging) and heat retention (discharging) periods. Three (3) liters of Sunflower oil and Roki oil were separately charged or heated for 120 minutes and the temperature was measured by thermocouples with an accuracy of ± 2.2 ℃ which were recorded at a time interval of 10 s on the data logger (HP 34970) using the Agilent Benchlink computer software for the data to be analyzed and compared.

During cool down, heat utilization experiments were carried out with different water loads of 1.0 to 3.0 kg. The data were saved after 240 minutes of the cool-down heat retention (heat utilization) cycles. The experiment was conducted three times (recurrent), and the average values were used in the final analysis.

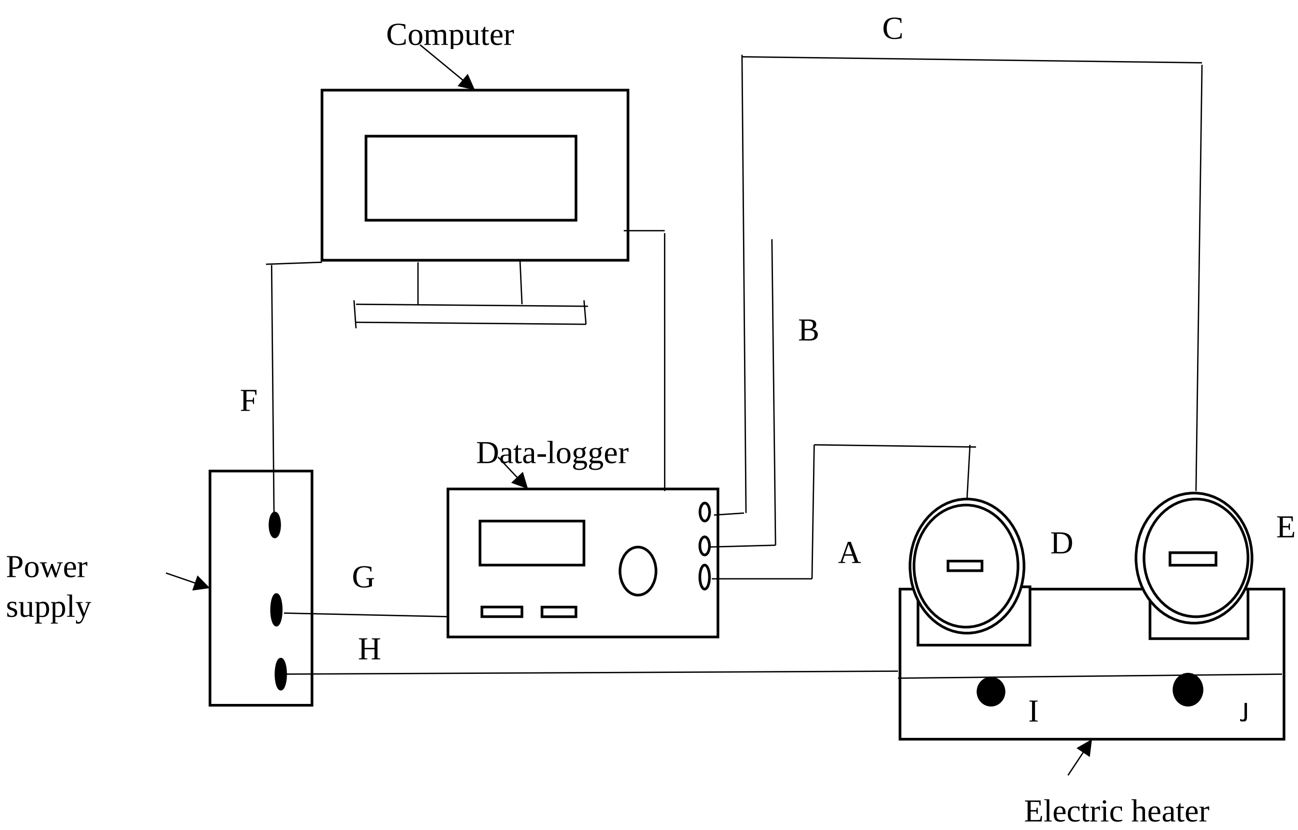

Figure 3.4: Illustration of the experimental setup and operation.

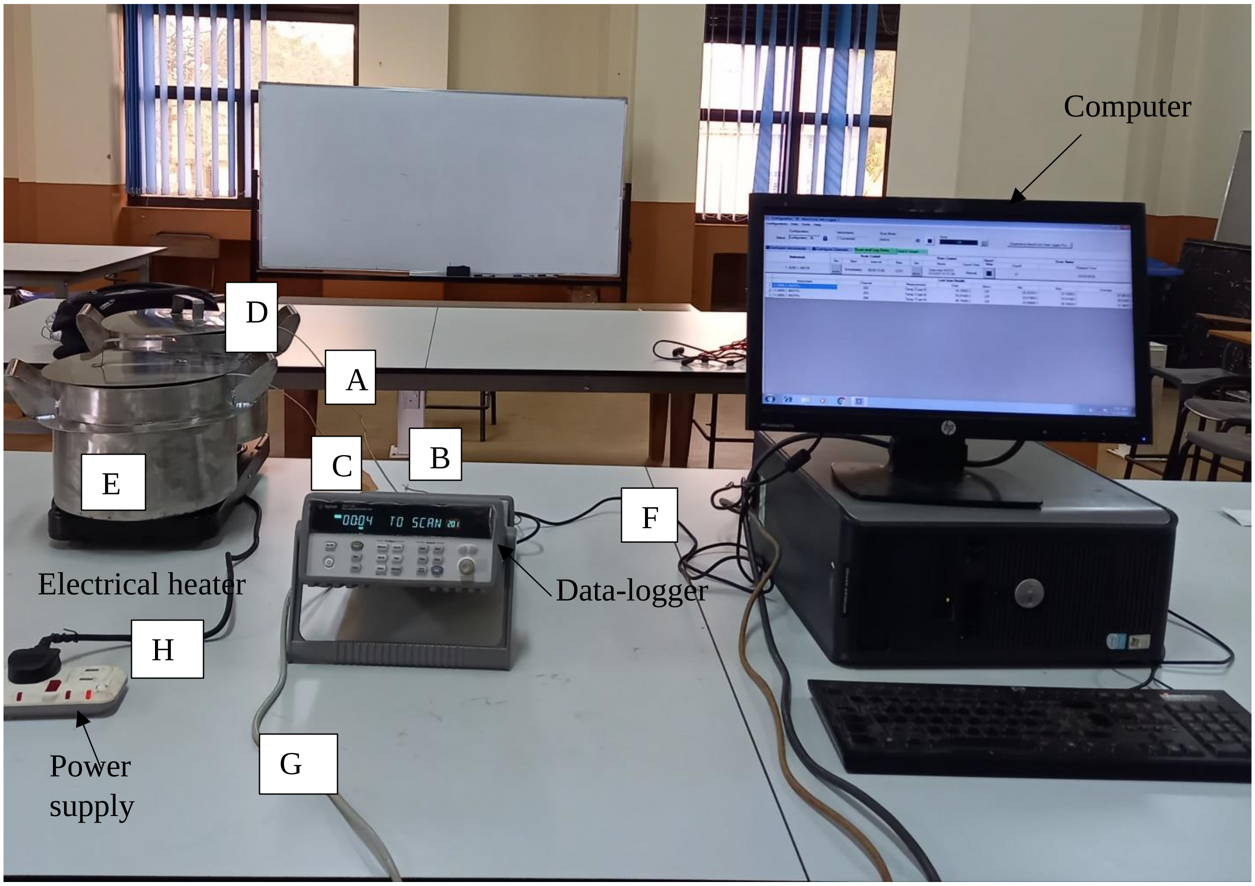

Figure 3.5: A photograph of the main components of the experimental setup.

3.5.2 Parabolic Dish Solar Cooker

The solar cookers using parabolic dish with diameters of 1.5 m were used in this experiment to concentrate the solar radiation and convert it to heat using aluminum foil reflectors. Figure 3.6 demonstrates how the solar cooking experiment of the two storage pots is performed when the parabolic dish solar cookers were used. K-type thermocouples with accuracies of ±2.2 ◦C were used to measure the temperatures of the cooking loads and (Roki and Sunflower) oils as SHSM in the solar heating experiments. Solar radiation was recorded using a pyranometer. This device had an approximately 95% response time within 5 s, and uncertainty of less than ±5 W/m^2 for a measurement of a single point. Apart from the solar cooking experiment, another K-type thermocouple was used to record the ambient temperature in each measurement period. The minimum cooking period of 2 hours was considered to be enough for achieving high temperatures. The solar cookers adapt the manual tracking which was based on pots shading, to obtain the solar radiation incident to the maximum level on the cooking pots with the reduced amount of shading. In this experiment, after every 15 minutes, the solar cookers were adjusted, to achieve highest sun radiation to incident on the cooking pots with minimum shading. These tests were conducted under a similar ambient condition and at the same time. Cooking experiments were performed using 1.0 kg for both Sunflower oil and the cooking fluid with sensible heat storage materials (Roki and Sunflower oils) in the cooking pots to investigate which pot charged up faster. The thermocouples and pyranometer were initially connected to the Agilent 34970 data logger device which recorded the informational data in the interval of 10 s for every cooking observational test. The speed of the wind was scaled manually using a hand-held anemometer to achieve the prevailing wind speed conditions since these conditions affect the solar cookers performance. The measurement interval was conducted after 15 minutes due to the fact that the wind speed measurement was conducted manually and only estimated values were required. The information of the sensors and the instruments used in these experimental tests are presented in Table 3.2. The data logger measured the pyranometer voltage signals, and the K-type thermocouples temperature signals. For the measurement of the speed of the wind, the maximum uncertainty of ± 0.2 m/s was recorded from a hand-held anemometer employing the accuracy of a maximum speed of wind of 2.1 m/s in the tests. Also, mean radiation from a sun recorded in hourly basis was (885.3 $\pm$ 0.6) W/m^2.

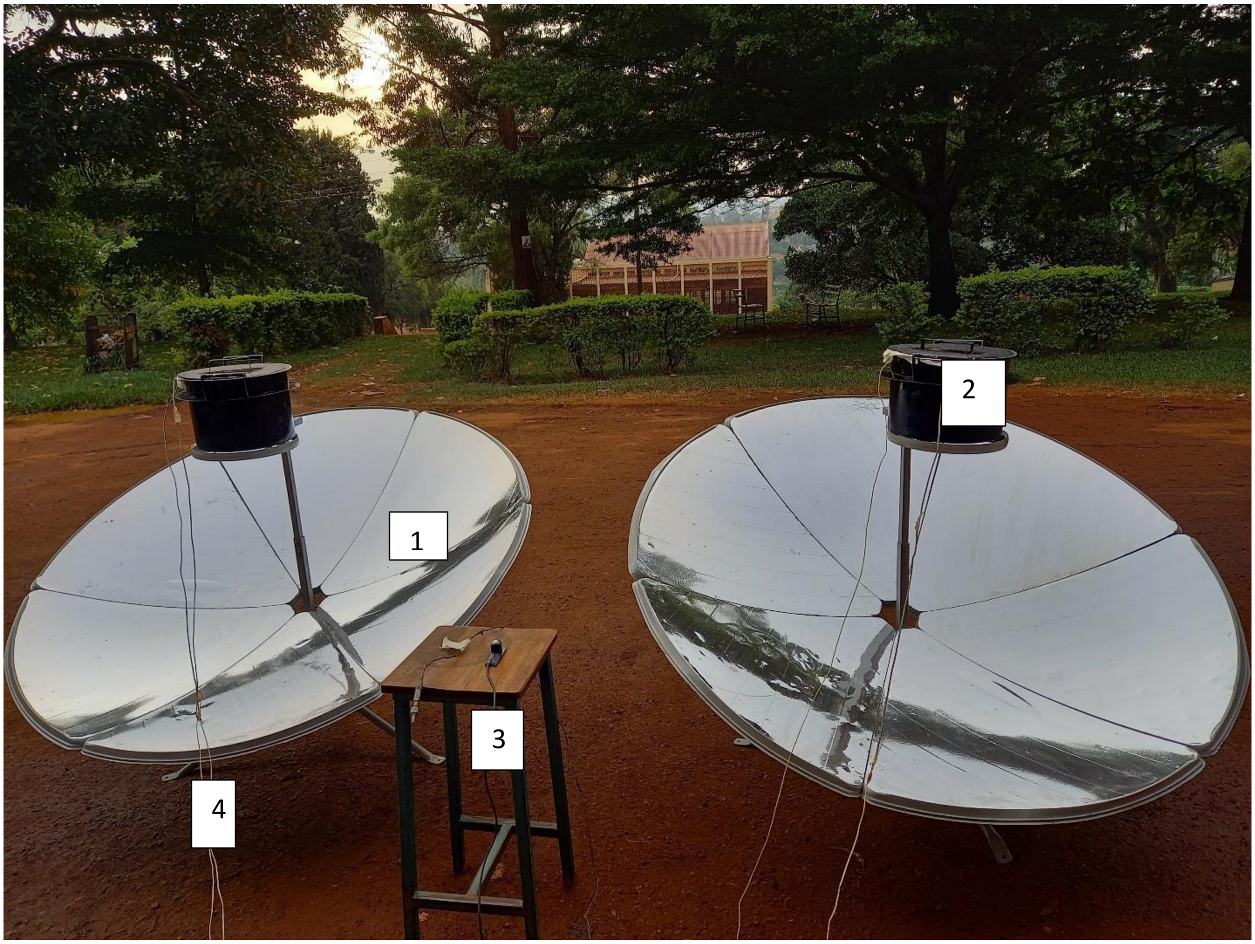

Figure 3.6: Experiment showing two parabolic dish solar cookers with two storage cooking pots. 1. Parabolic dish solar cooker 2. Cooking pot 3. Pyranometer 4. Thermocouple extension.

The same amount of cooking fluid was poured in to two cooking pots during off-sunshine cooking experiment for maximum utilization of the heat stored. Afterwards, the cooking pots were transferred into the insulating bag which were covered at the upper part, as illustrated in Figure 3.7. The storage of the cooking observational tests was conducted indoors. For this work, the sunflower oil as a cooking fluid was used during the off-sunshine tests as used in the solar cooking tests. Heat retention cooking tests were conducted for a minimum duration of 6 hours. During the cooking tests, the temperatures for both storage and cooking were continuously monitored and recorded after every 10 s.

Figure 3.7: The storage cooking pots inside the wonderbag cookers during off sunshine cooking test.

Table 3.2: Instrumentation information

Name	**Parameter**	**Accuracy**	**Resolution**
Pyranometer	solar radiation	Single point, ±5 W/m^2	1 W/m^2
K-type thermocouple	Temperature	±1%	0.1 ºC
Benetech anemometer	Wind speed	±5%	0.1 m/s
Mass balance	Mass	±0.001 kg	±0.001 kg

3.6 Data logger and multiplexer

A data logger is an electronic device which track and document automatically the environmental variables with time. The data logger was connected to sensors to receive the data, and a computer chip to keep the information. The data from the data logger was then transmitted to a computer for further studies. In this experiment, the data logger was fabricated by Agilent technologies (HP 34970) and has 3 apertures for putting the information logging multiplexer cards. It was directed to a computer that control Benchlink, an information logging software created by Agilent technologies. The data logger used the Agilent Benchlink computer software for the data to be analyzed and compared as shown in Figure 3.8. The data logger contains a multiplexer with 20 channels as shown in Figure 3.8. A circuit or device known as a multiplexer selects and combines several input signals into a single output device. In Figure 3.8, thermocouples were connected to the multiplexer that transferred all input signals to a microprocessor, that receives and evaluate the information and transmitting that processed information to the output devices for control purposes.

Figure 3.8: The 20-channel multiplexer and the data logger.

3.7 Measurement of the thermal properties

Analysis of the sample of the SHSM was carried out to find out the thermo-physical properties such as density, viscosity, specific heat capacity, and heat flow. These properties were useful in calculating important parameters such as output energy rate, exergy rate, exergy factor, energy stored, heat utilization, and heat utilization efficiency.

3.7.1 Measurement of the density

A digital balance shown in Figure 3.9 was used to record the mass of the oil. Firstly, the mass of the empty measuring cylinder (m_1) was determined, then filling it with Roki oil, and the mass (m_2) was measured again using the digital balance. To get the mass of Roki oil, the mass of the empty measuring cylinder was subtracted from the mass of Roki oil in the measuring cylinder. The same procedures were repeated for Sunflower oil. Equation (1) was used to get the density of Roki and Sunflower oil, respectively.

$$\rho = \frac{m_2 - m_1}{v} \tag{1}$$

m_1 m_2

Figure 3.9 (a): Digital balance. **Figure 3.9 (b):** Measuring cylinder.

3.7.2 Measurement of viscosity

In measuring the viscosity of both Roki oil and Sunflower oil, a digital viscometer was used as shown in Figure 3.10. A viscometer is a device used for measuring of fluid viscosity and the properties of the flow of fluids. Viscosity is the measure of the resistance of the fluid to flow, it defines the internal friction of fluid movement (Wright, 2013). In liquids, the viscosity is mainly due to intermolecular cohesion, the intermolecular cohesive force decreases as the temperature increase. Hence with the increase in temperature the viscosity of a liquid decreases. The oil samples were heated up to 190 ℃ using an electric heater. Then, the viscosity of both oils was measured using the digital viscometer at different temperatures from 180 ℃ to 35 ℃, and this was recorded by the data logger.

The oil was heated up to 190 ℃ using an electric heater (E), and then quickly transferred to a calorimeter (D). The digital viscometer (B) was inserted to the heated oil which was in the calorimeter. One K-type thermocouple (F) was used to track the temperature of oil inside the calorimeter. The thermocouple (F) monitored the oil temperatures from180 ℃ to 35 ℃ which were recorded by the data logger (HP 34970**).** The temperature was recorded at the interval of 15 ℃ and 20 ℃. These experiments assisted in comparing the properties of Roki and Sunflower oil.

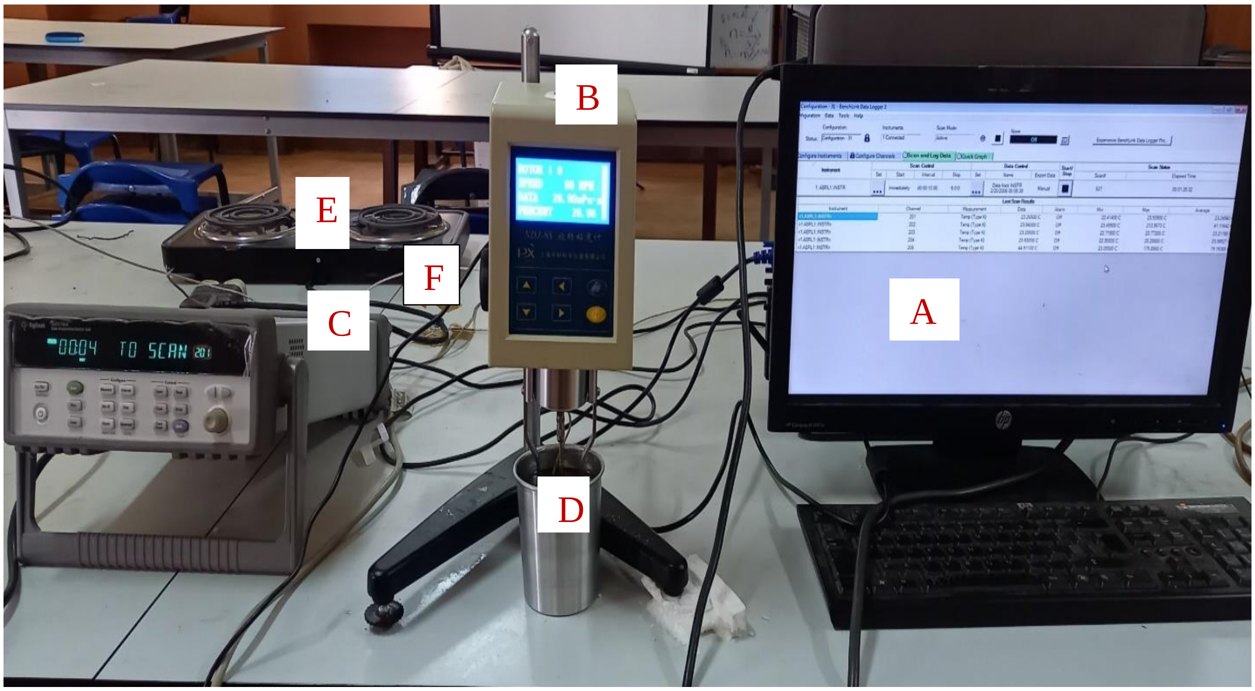

Figure 3.10: Measuring viscosity using a digital viscometer. A. Computer, B. Digital viscometer, C. Data logger, D. Calorimeter, E. Electrical heater and F. Thermocouple.

3.7.3 Measurement of heat flow and specific heat capacity

In measuring the heat flow variation with temperature, a differential scanning calorimeter - DSC (PerkinElmer Simultaneously Thermal Analyzer – STA 600) (2) was connected to the computer (1), a temperature controller (3), and nitrogen gas (4) as shown in Figure 3.11. About 63.154 mg of both oils were placed in hermetically sealed aluminum pans. An empty aluminum pan was used as a reference. DSC is a thermo-analytical method that evaluates the difference in the quantity of heat required to raise the sample temperature and its reference. In the DSC cell nitrogen gas provides excellent sensitivity, as its low thermal conductivity does not interfere with heat measurement. Nitrogen gas used to purge the instrument to avoid reactions with the atmosphere. The energy transferred to or from a sample undergoing a physical or chemical change is measured using differential scanning calorimetry. DSC runs were conducted from 20 ℃ to 200 ℃ at a scan rate of 20 $℃/min$. The data obtained from DSC were the heat flow data (mW) variation with temperature (℃).

Figure 3.11: A photograph showing measurement of the heat flow in variation with temperature. 1. Computer, 2. PerkinElmer Simultaneously Thermal Analyzer – STA 600) 3. Poly science temperature controller 4. Nitrogen gas.

3.8 Performance analysis of Sunflower and Roki oil

Analysis for characterization of the thermal performance of Sunflower oil and Roki oil when heating and heat retention in this section were presented. The parameters are output energy rate (E_0), exergy rate (E_{Xo}), exergy factor (E_{XF}), total energy stored (Q_{us}), the total heat utilization

(Q_{uti}) and heat utilization efficiency (η_{uti}). The different calculations were be done using Eq. (2) – (7), respectively.

The final temperature (T_f), initial temperature (T_i), ambient temperature (T_a) and the time interval (Δt) were obtained from the data logger for the duration of the experiment. Discharging/cooling results were plotted as a function of time during the cool-down periods after the experiments. The analysis was done for Sunflower oil as well as Roki oil. ORIGIN software was used to plot the graphs

(i) The output energy rate during charging was calculated using equation (2) (Mawire et al., 2021, Cuce and Cuce, 2013);

$$E_0 = \frac{mc\,(T_f - T_i)}{\Delta t} \quad (2)$$

,where m is the mass of the oil, c is specific heat capacity of the oil, T_f is the final temperature of the oil measured at each time interval and, T_i is the initial temperature of the oil inside each cooker.

(ii) The output exergy rate during charging was determined using equation (3) (Mawire et al., 2021, Cuce and Cuce, 2013);

$$E_{Xo} = \frac{mc\,(T_f - T_i) - mcT_a \ln\left(\frac{T_f}{T_i}\right)}{\Delta t} \quad (3)$$

, where T_a is the ambient temperature.

(iii) The exergy factor E_{XF}, which is the ratio of the total exergy to total energy expressed as;

$$E_{XF} = \frac{E_{Xo}}{E_o} = \frac{mc\,(T_f - T_i) - mcT_a \ln\left(\frac{T_f}{T_i}\right)}{mc\,(T_f - T_i)} \quad (4)$$

(iv) Total energy stored Q_{us} during the cooking period was calculated from equation (5) (Mawire et al., 2020, Bhave and Kale, 2020);

$$Q_{us} = \sum mc\Delta T \quad (5)$$

, where m is the mass of the oil, c is the specific heat capacity of the oil and ΔT is the moving average temperature between the next and the previous time step at the interval of Δt.

(v) The total heat utilization during the storage cooking period was determined from equation (6) (Mawire et al., 2020, Bhave and Kale, 2020);

$$Q_{uti} = \sum m_w c_w \Delta T \quad (6)$$

, where m_w is the mass of water, c_w is the specific heat capacity of water.

(vi) The heat utilization efficiency was estimated from the ratio of total heat utilization to the total energy stored, and expressed as;

$$\eta_{uti} = \frac{Q_{uti}}{Q_{us}} \quad (7)$$

The thermal performance parameters in Eq. (2) – (7) were plotted in a form of graphs, and their average values were quantified and tabulated in a form of tables as shown and discussed in chapter four.

3.9 Experimental uncertainty

An experimental measurement has an uncertainty associated with it. The thermocouple was set to $\pm$ 2.2 ℃ accuracy which was used to obtain the temperature uncertainty measurements. The accuracy set of the digital balance was used in measuring the mass of the water. $\pm$ 5 g of this accuracy was used to estimate the mass of the water uncertainty. In this experiment, data logger was set to measure the maximum error of about $\pm$ 0.5 s after every 10 s interval. Also, in terms of the maximum percentage errors, the calculated values were estimated by 5 %. The uncertainty in the computed quantities of energy and exergy were determined using propagation of error approach proposed by (Moffat, 1988).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents results obtained from measurements for Roki oil and Sunflower oil as sensible heat storage materials for thermal energy storage. The results of the thermophysical properties of Roki oil and Sunflower oil are presented in the chapter. Also, the thermal performance evaluations for Roki oil and Sunflower oil for charging, discharging, heat utilization, energy, and exergy variation, and the effect of cooking load are presented in this chapter. Preliminary results with parabolic solar cookers are also presented.

4.2 Measurement of the thermophysical properties of the two-storage material

Thermophysical properties such as density, viscosity and specific heat capacity also presented in this section as shown in Table 4.1. Thermophysical properties of Roki and Sunflower oil are essential in determining and calculating the thermal parameters such as the output energy rate (E_0), exergy rate (E_{Xo}), exergy factor (E_{XF}), and the total energy stored (Q_{us}). Figure 4.1 show the effect of temperature on the viscosity of Roki oil and Sunflower oil in the temperature range between 35 ℃ and 180 ℃ as suggested by Fasina and Colley (2008). Results for Roki oil shown in Figure 4.1 are new results, which have not been reported in the literature. The viscosity of both Roki oil and Sunflower oil decreases exponentially with increasing temperature as shown in Figure 4.1. The results show that Roki oil is more viscous than Sunflower oil from 35 ℃ to ~100 ℃. As the temperature increases, the viscosity of Roki oil and Sunflower oil are approximately similar from 100 ℃ to 180 ℃. The molecules become more mobile when the temperature rises due to an increase in thermal energy. Because the attractive binding energy is reduced, the viscosity is also reduced. Thermal physical characteristics of the 2 materials for storage, Roki oil and Sunflower oil as shown in Table 4.1. The same volumes of 3 L Sunflower oil, and Roki oil were added into the chambers. In this work, it was decided to use the same volumes rather than the same masses in order to achieve temperature measurement in the storage chamber more precisely. Sunflower oil has a large specific heat capacity of 2.3 kJ/kgK compared to Roki oil 2.2 kJ/kgK. The storage mass of Sunflower oil 2.720 kg was higher than 2.697 kg of the Roki oil. This makes the thermal mass (mc) of Roki oil to be small compared to that of Sunflower oil. This causes Roki oil to attain higher temperatures than Sunflower oil due to its lower thermal mass. The variations of viscosity with temperature for Roki oil and Sunflower oil are $V_{Roki} = 4.43 + 203\ e^{-T/25.94}$ and $V_{Sunflower} = 4.04 + 126\ e^{-T/28.47}$ respectively as shown in Table 4.1. This shows that Roki oil is more viscous than Sunflower oil.

Table 4.1: Thermophysical properties of the Roki oil and Sunflower oil.

Property	**Roki oil**	**Sunflower oil**
Specific heat capacity (kJ/kgK)	2.2 (this work)	2.3 (Mawire et al., 2020)
Density (kg/ m^3)	899 (this work)	907 (this work)
Viscosity (mPa.s)	$V_{Roki} = 4.43 + 203e^{-T/25.94}$(this work)	$V_{Sunflower} = 4.04 + 126\ e^{-T/28.47}$ (Fasina and Colley, 2008)
Volume of the storage material (liters)	3	3
Mass of the storage material in a pot (kg)	2.697	2.720

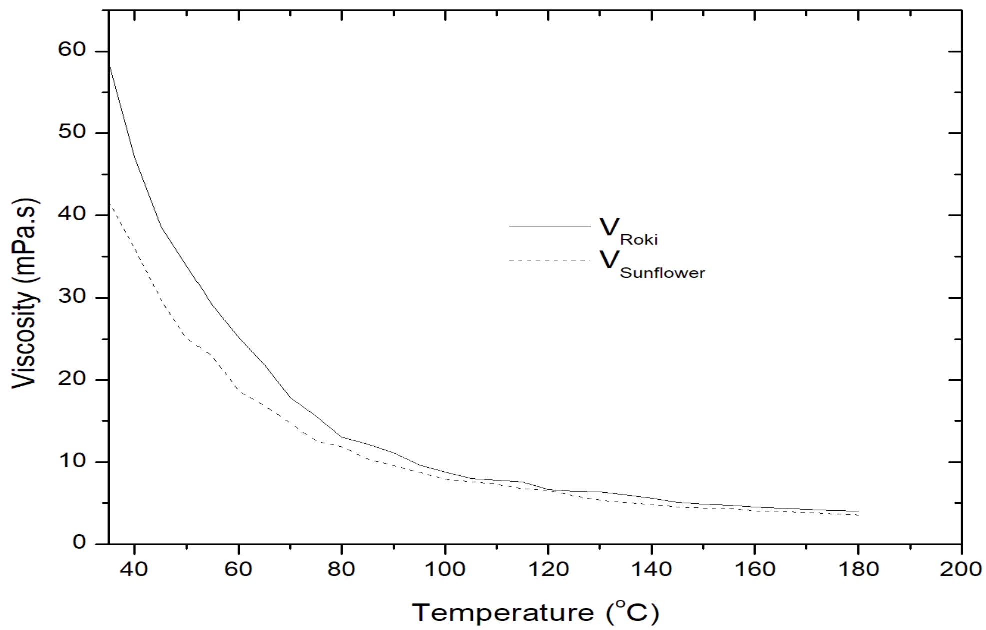

Figure 4.1: Viscosity of Roki oil and Sunflower oil variation with temperature.

4.3 Charging results

The results are presented for low charging power. Low charging power is preferred to high charging power because it is comparable to solar cooking or cooking with the sun in terms of the input power/energy. The charging results are presented for the two vegetable oils (Roki oil and Sunflower oil) in terms of the temperature profiles. Figure 4.2 shows the charging results for 3 L of the oils as SHMS in two separate cooking pots. The greater temperature rise is seen in Roki oil, and it approaches 170 ℃. Both temperature profiles show a characteristic dip of the temperature at a temperature above 55 ℃. This is contributed to lower viscosity when the charging cycles in both oils as heat is being absorbed faster by the heating vessels. However, still above 55 ℃, Roki oil charges faster than Sunflower oil. This is probably because Roki oil has a lower thermal mass compared to sunflower oil. At about 55 ℃, the temperatures of Sunflower oil and Roki oil are equal. The reason most likely is that, Sunflower and Roki oil might have the same thermal mass at that temperature. Sunflower oil approaches a temperature of about 160 ℃. The greater temperature rise is seen in Sunflower oil below 55 ℃. This is likely due to the initial temperature of Sunflower oil being slightly higher than that of Roki oil. In addition, Roki oil is more viscous than Sunflower oil below 55 ℃ . Since Roki oil is a blend of Palm oil and Sunflower oil, and Palm oil is more viscous below 40 ℃ (Esteban et al., 2012), probably justifying the greater temperature rise seen in Sunflower oil. The optimal temperatures achieved during charging are ~ 170 ℃ and 160 ℃ for Roki oil and Sunflower oil, respectively. These are enough to pre-heat water for cooking rice, making hot chocolate, tea, and hot coffee.

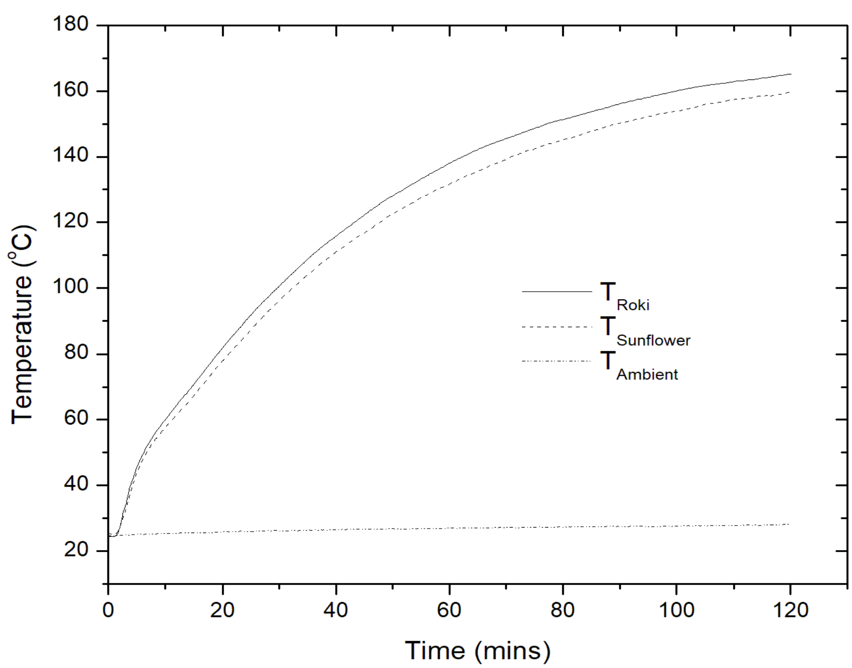

Figure 4.2: Charging/heating graph for Roki oil and Sunflower oil.

Figure 4.3 shows heat flow as a function of temperature for both Roki and Sunflower oil. Roki oil charges faster than Sunflower oil. This is probably because Roki oil has a lower thermal mass compared to Sunflower oil. At a temperature of 190 ℃, sunflower oil slightly overtakes Roki oil. This is because as temperature increases, Sunflower oil and Roki oil become less viscous, and their viscosities become approximately similar as shown in Figure 4.1.

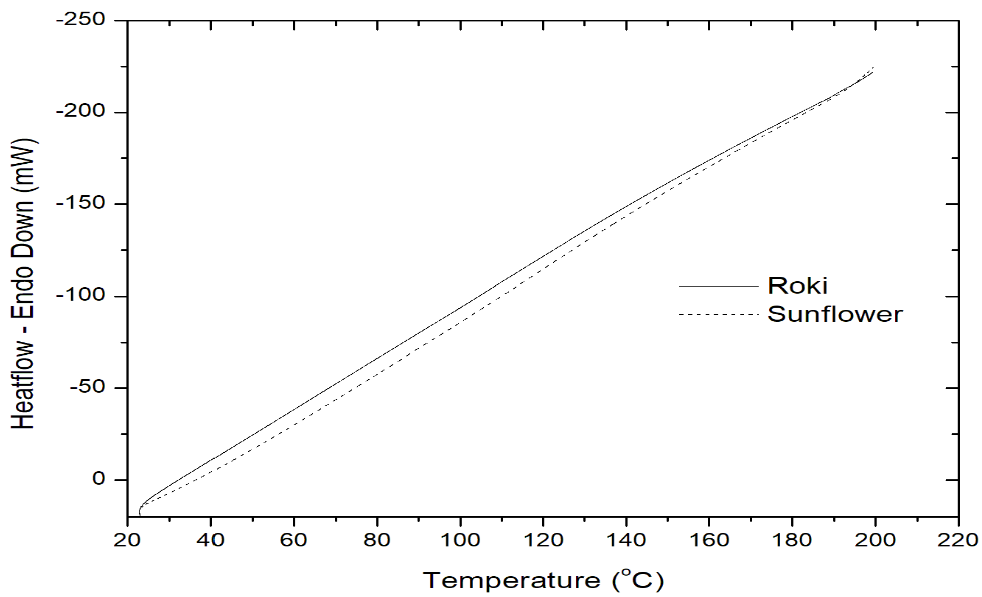

Figure 4.3: Heat flow variation with temperature.

4.4 Discharging results

Experimental results for 60 minutes of heat retention processes are presented in this section after low charging power. The temperature profiles result for the oils are shown in Figure 4.4. The cooling of each thermal oil is done by natural convection. Due to the time lag between switching off the electric heater and adding 1.0 kg water test load for heat utilization, the initial temperatures recorded for Roki oil and Sunflower oil are not the same as the final temperatures achieved during charging. Sunflower oil shows a high decrease in temperature in 60 minutes for the cool-down period. Roki oil temperature drops from 158 ℃ to 78 ℃, a temperature drops of 80 ℃. Sunflower oil temperature drops from 147 ℃ to 77 ℃, a temperature drops of 70 ℃. Higher temperatures are seen for Roki oil during the heat retention cycle although it shows a greater temperature drop. The identical cooking pots/vessels were not insulated at all during cooling down period. It is possible to reduce the heat losses in the two cases by using insulating materials such as a wonderbag during cool-down heat retention periods as was done recently (Mawire et al., 2020). At the end of the 60 minutes (1 h) cool-down heat retention process, the temperatures obtained are enough to warm water for bathing, and to warm cold food. After about 20 minutes of the heat retention process for Roki oil, the temperature achieved is enough to cook food. This is applicable/useful during the period when electrical heating is not possible. For example, when there is scheduled load-shedding for a short duration.

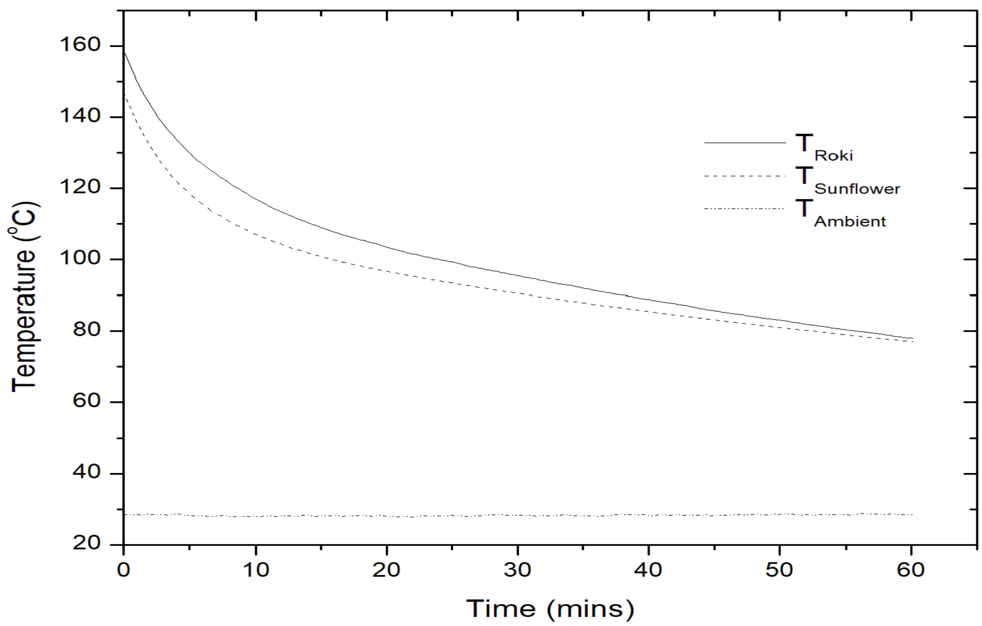

Figure 4.4: Cooling/heat retention graph for Roki oil and Sunflower oil.

4.5 Heat utilization results

Figure 4.5 shows the heat utilization with 1.0 kg water as a test load. In 10 minutes of the cool down/heat utilization, the heat stored in Roki oil is enough to heat 1.0 kg water up to about 97 ℃ which is very close to the boiling point of water. This heat is enough to boil water for cooking. For the case of Sunflower oil, only about 92 ℃ is achieved in 10 minutes of heat utilization due to the lower TES temperature attained. This is slightly lower than the water temperature achieved with heat utilization for Roki oil. The heat utilization performance of Roki oil continues to outperform that of Sunflower oil up to about 40 minutes. After 1 hour, the heat stored in both Roki oil and Sunflower oil are sufficient to warm water (~75 ℃) for bathing.

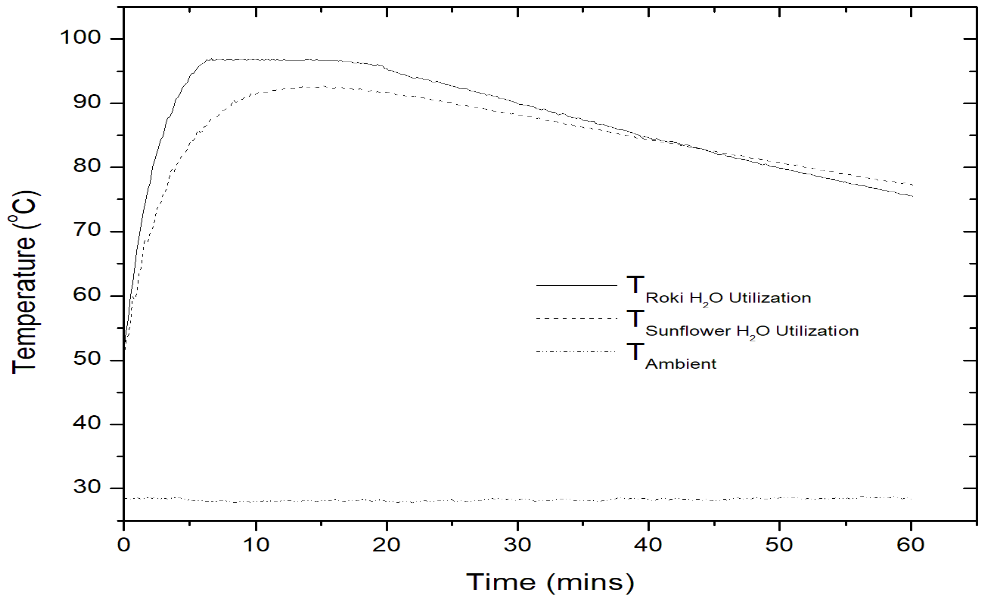

Figure 4.5: Heat utilization graph for Roki oil and Sunflower oil with 1.0 kg water load.

Figure 4.6 shows the heat utilization with 1.5 kg water as a test load. In 15 minutes of the cool heat utilization, the heat stored in Roki oil is enough to heat 1.5 kg water up to about 82 ℃ which is around the same as the boiling point of water. For the case of Sunflower oil, only about 65 ℃ is achieved in 15 minutes of cool down/heat utilization due to the lower TES temperature attained. Heat utilization for 1.0 kg shows a maximum higher temperature than 1.5 kg, it is because of a higher thermal mass.

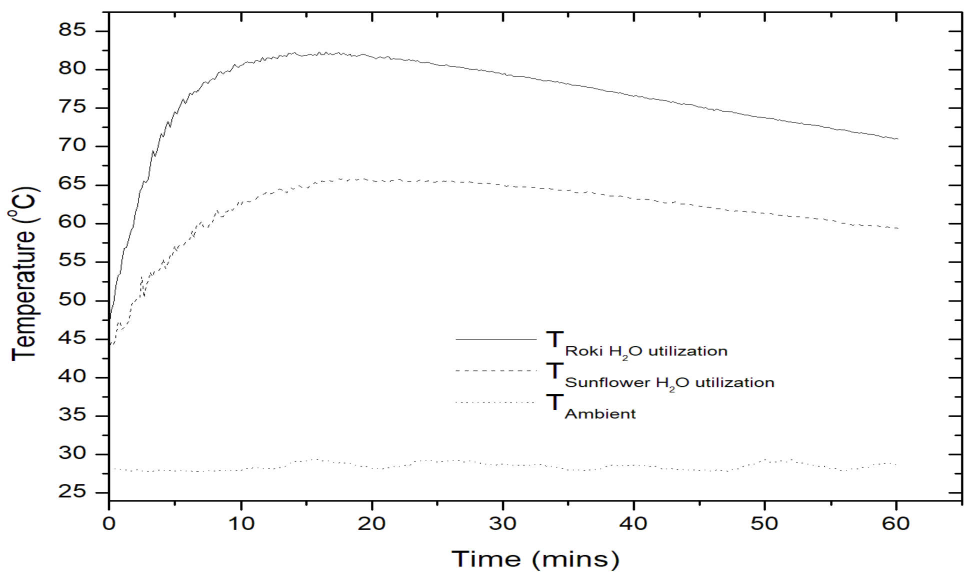

Figure 4.6: Heat utilization graph for Roki oil and Sunflower oil with 1.5 kg water load.

Figure 4.7 shows the heat utilization with 2.0 kg water as a test load. In 20 minutes of the heat utilization, the heat stored in Roki oil is enough to heat 2.0 kg water up to about 75 ℃ , and for the case of Sunflower oil, only about 63 ℃ is achieved in 20 minutes of heat utilization due to the lower TES temperature attained during charging.

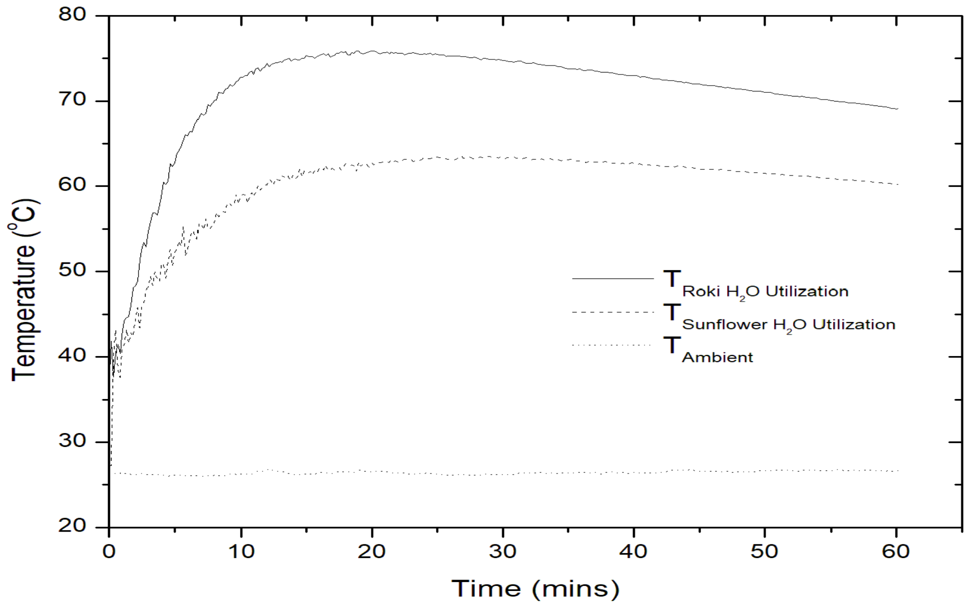

Figure 4.7: Heat utilization graph for Roki oil and Sunflower oil with 2.0 kg water load.

Fig. 4.8 shows the heat utilization with 2.5 kg water as a test load. In 30 minutes of the cool down/heat utilization, the heat stored in Roki oil is enough to heat 2.5 kg water up to about 69 ℃ and for the case of Sunflower oil, only about 56 ℃ is achieved in 30 minutes of heat utilization due to the lower TES temperature attained during charging.

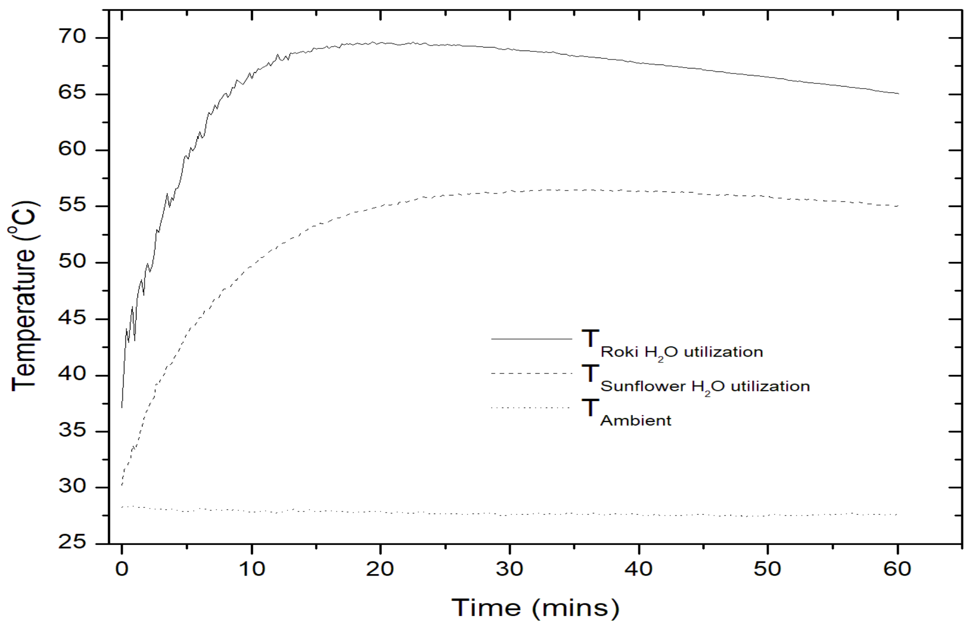

Figure 4.8: Heat utilization graph for Roki oil and Sunflower oil with 2.5 kg water load.

Figure 4.9 shows the heat utilization with 3.0 kg water as a test load. In 37 minutes of the cool down/heat utilization, the heat stored in Roki oil is enough to heat 3.0 kg water up to about 66 ℃ , and for the case of Sunflower oil, only about 55 ℃ is achieved in 37 minutes of heat utilization also due to the lower TES temperature attained for Sunflower oil during charging.

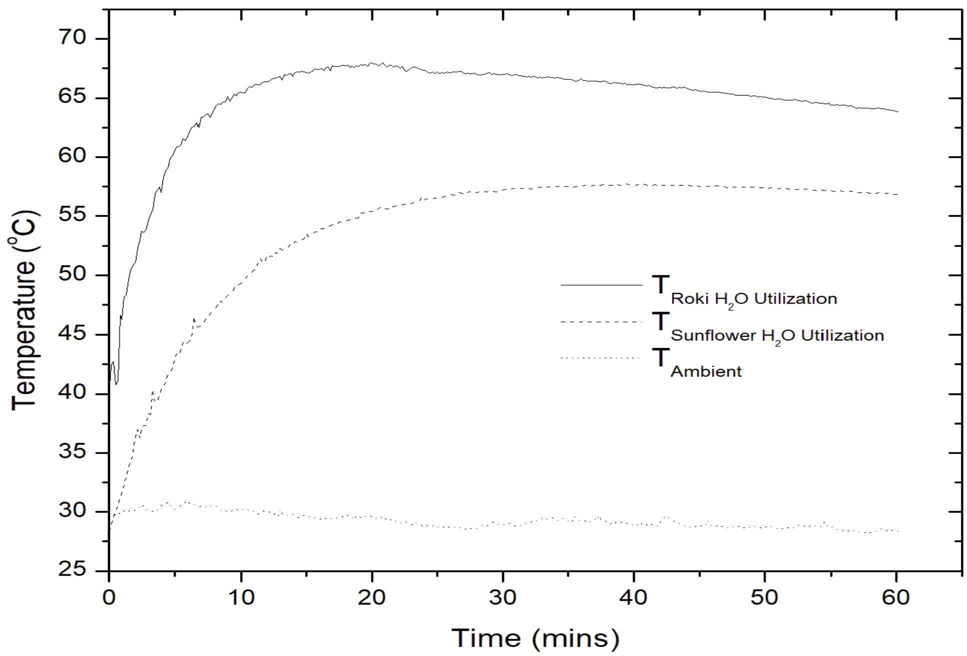

Figure 4.9: Heat utilization graph for Roki oil and Sunflower oil with 3.0 kg water load.

Generally, from Figure 4.5 to Figure 4.9, the results shows that the maximum temperature for cooking food decreases for both Roki oil and Sunflower oil as the cook load increases. Roki oil performed better because it attained maximum temperatures slightly higher than Sunflower oil.

4.6 Energy and exergy variation for Roki and Sunflower oil as sensible heat storage materials

Figure 4.10 shows energy rate profiles for Roki oil and Sunflower oil. Roki oil shows slightly higher energy rate values compared to Sunflower oil because of the slightly higher temperature difference during charging.

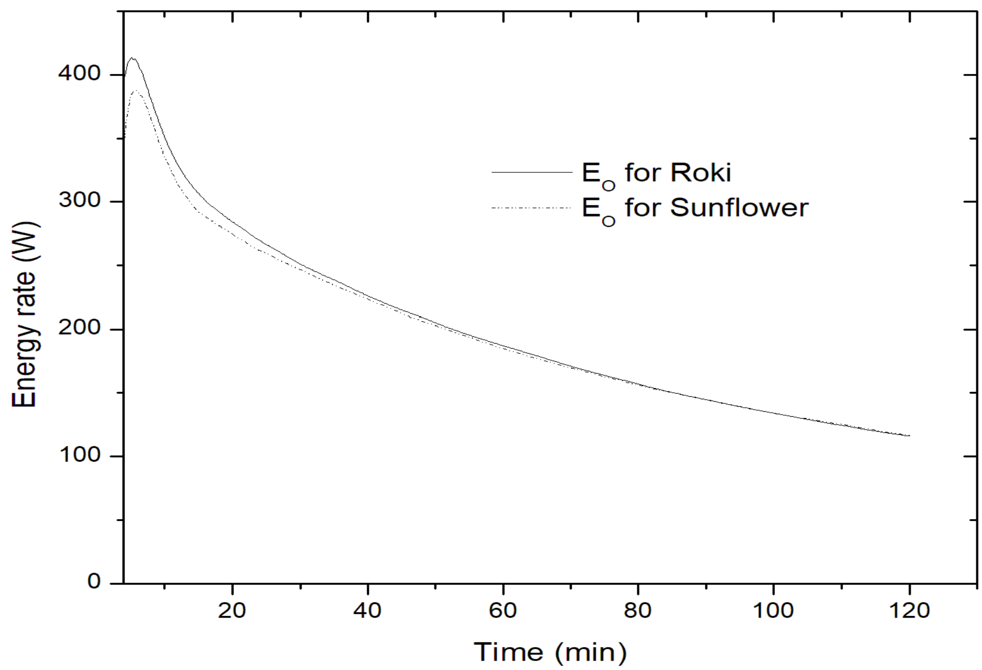

Figure 4.10: Output energy rate during charging for Roki oil and Sunflower oil.

Roki oil shows a maximum higher energy rate of 413 W compared to Sunflower oil showing a maximum energy rate of 387 W. It is possibly because of a low thermal mass of Roki oil (mc) which induces a faster and higher temperature rise compared to Sunflower oil. The output energy rate between (100-140) W for both Roki oil and Sunflower oil became almost the same and this is due to the effect of viscosity as temperature increases as shown in Figure 4.10.

The exergy analysis, which was based on the second law of thermodynamics, can provide the direction for optimizing the TES system by determining the quality of energy stored/recovered during the storage process (Li, 2015). Exergy rate plots of Roki and Sunflower oil are shown in Figure 4.11. In general, the charging exergy rates increases to maximum levels as charging continues. Roki oil shows higher maximum exergy rate of ~ 129 W compared to that of Sunflower oil ~ 120 W, this is possibly because of the higher temperature difference during charging.

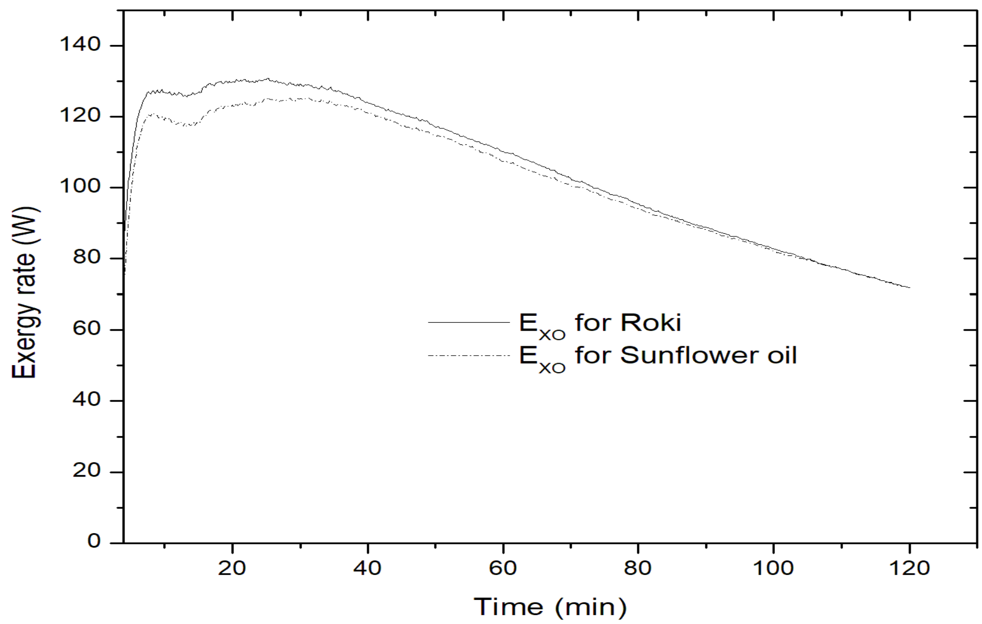

Figure 4.11: Output exergy rates during charging for Roki oil and Sunflower oil.

Figure 4.11 shows higher exergy rate within first 100 minutes of an experiment in Roki oil compared to Sunflower oil. This is possibly due to the higher temperatures achieved as the result of lower thermal mass (mc) in Roki oil compared to Sunflower oil. At 110 minutes, the two oils show the same exergy rates of around 85 W possibly due to the effect of the viscosity as temperature increases as shown in Figure 4.11.

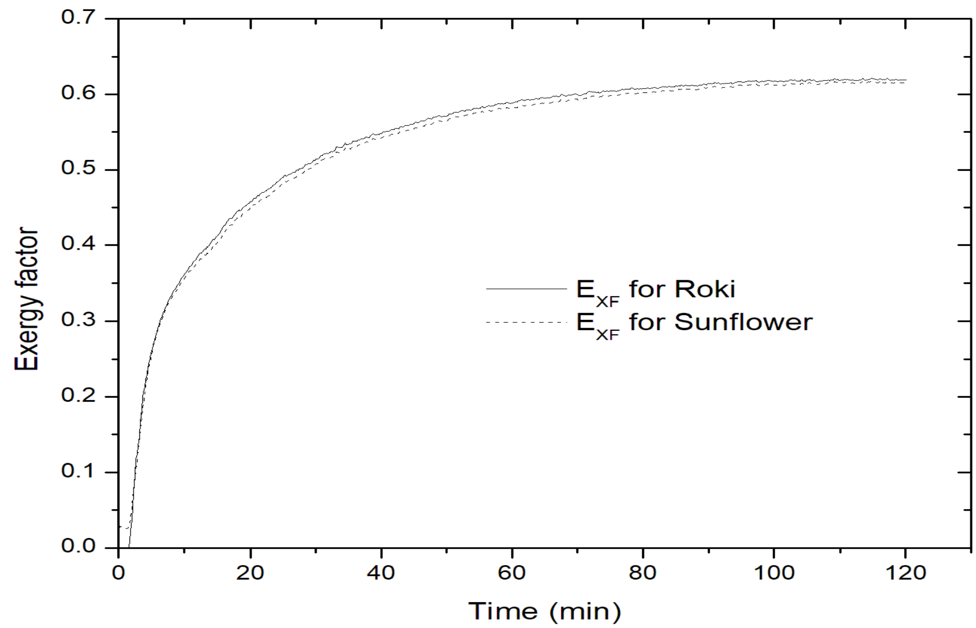

Figure 4.12: Exergy factors for Roki oil and Sunflower oil.

The stored exergy and exergy increase as storage temperatures rise and the stored exergy stored to energy ratio is depicted as the exergy factor in Figure 4.12. Exergy factors of (0.31 - 0.62) for Roki oil are slightly higher than Sunflower oil (0.27 – 0.59) within 1 hour and 40 minutes. This is possibly due to the higher temperature difference of Roki oil compared to Sunflower oil. At the end of charging process, exergy factor values for both Roki and Sun flower oils retain approximately the same values (~0.6). This shows that for low-power charging, the quantity ratio of exergy stored to energy stored for the two storage oils is identical at the end of charging.

4.7 Effect of the load on heat utilization and heat utilization efficiency

An experimental comparison of Roki oil and Sunflower oil is presented during storage and heat utilization using five different water loads of 1.0 kg to 3.0 kg, and it is presented in Table 4.2.

Average energy stored for Roki oil is higher than average energy stored in Sunflower oil by a difference of 4.707 kJ for 1.0 kg of water as shown in Table 4.2. This implies that Roki oil can store more energy than Sunflower oil. Average heat utilization and average heat utilization efficiency for Roki oil and Sunflower oil increases when the water load also increase. This explains that heating water fluid is more efficient if it is larger than when it is small water. The increase in the average heat utilization and heat utilization efficiency for Roki oil was higher than that of Sunflower oil.

Table 4.2: Thermal performance variables of Roki oil and Sunflower oil with electric cooker.

Cooking pot	Heated load (kg)	Average energy stored (kJ)	Average heat utilization (kJ)	Average heat utilization efficiency (-)
Roki oil				
Case 1	1.0	595.458	150.759	0.253
Case 2	1.5	530.043	226.012	0.426
Case 3	2.0	529.281	289.996	0.547
Case 4	2.5	523.638	304.237	0.574
Case 5	3.0	523.638	349.609	0.659
Sunflower oil				
Case 1	1.0	590.751	148.032	0.251
Case 2	1.5	497.474	156.322	0.314
Case 3	2.0	457.356	192.329	0.421
Case 4	2.5	437.048	241.198	0.485
Case 5	3.0	437.048	299.537	0.602

4.7.1 Effect of water load on energy stored

In TES systems, the energy stored is commonly used to study the thermal behavior of the storage material. For 1.0 kg of water new oil was used for both Roki oil and Sunflower oil. There was small difference in energy stored between the two oils. The average energy stored for both oils decrease with an increase in load as shown in Figure 4.13, but the difference in average energy stored for Roki from one cooking load to another is slightly smaller than that of Sunflower oil for 1.5 kg to 3.0 kg. This is possibly due to frying stability Roki oil (Omara et al., 2019). Also this is because Roki oil is more viscous than Sunflower oil, for highly viscous liquid higher energy is needed to deform highly viscous fluid, while lower energy is required for deforming less viscous fluid. Therefore Roki oil is thermally stable than Sunflower oil this makes the average values for Roki oil almost constant from 1.5 kg to 3.0 kg. This is possibly due to the intermolecular forces for Roki oil which are strongly bonded together, causing strong cohesive forces between them.

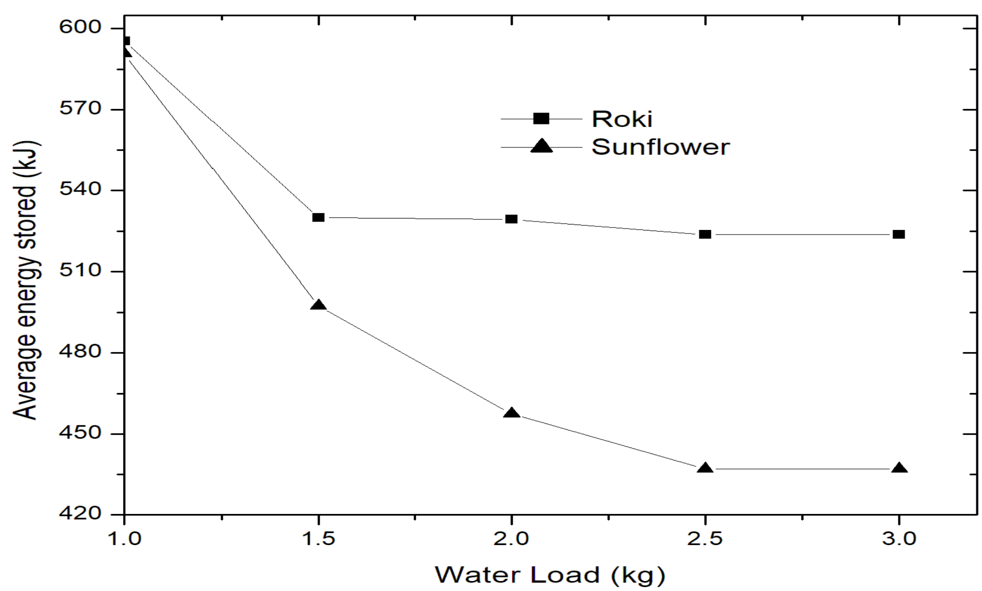

Figure 4.13: Average stored energy with increasing water load for Roki oil and Sunflower oil.

4.7.2 Water load effect on heat utilization and heat utilization efficiency

The variation of average heat utilization and heat utilization efficiency as a function of water load for the two sensible heat storage materials are shown in Figure 4.14 and Figure 4.15, respectively. Average heat utilization and heat utilization efficiency increase with an increase in the water cooking load, possibly due to an increase in thermal masses (mc). Suggesting that greater heat utilization and heat utilization efficiency are obtained when the water cooking loads are increased.

Roki storage cooking pot shows more effective average heat utilization than Sunflower cooking pot. Figure 4.14 shows higher average heat utilization with Roki oil of 188 kJ to 350 kJ compared to Sunflower oil of 116 kJ to 299 kJ for a load increase from 1.5 kg to 3.0 kg. This is possibly due to the higher temperature difference (ΔT) of water load in the Roki storage cooking pot. In addition, this could be due to the higher maximum cooking temperature attained by Roki oil during charging than Sunflower oil as shown in Figure 4.2. Since heat utilization depends on temperature difference (ΔT), this makes the average heat utilization to be higher for Roki oil than for Sunflower oil.

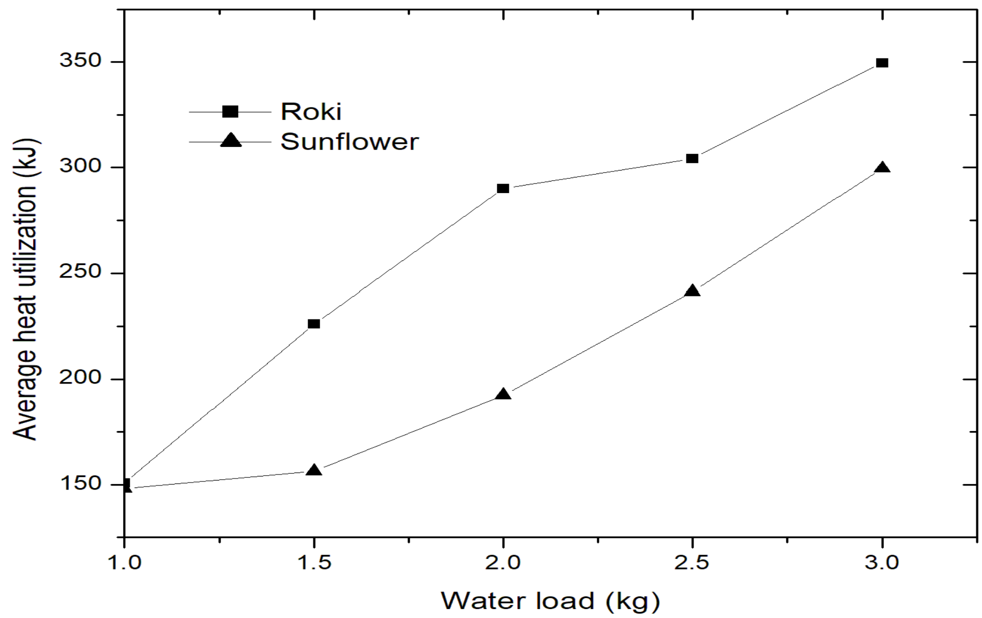

Figure 4.14: Variation of average heat utilization with increasing load for Roki oil and Sunflower oil.

Figure 4.15 shows that the heat utilization efficiency increases when the cooking load increases. This indicating that the water heating load has an impact on the average heat utilization efficiency when the experimental tests was ongoing. In fact, for a water increase from 1.0 kg to 3.0 kg, the average heat utilization efficiencies for Roki storage cooking pot are higher (25.3% to around 65.9%) compared to Sunflower oil (25.1% to around 60.2%). Since heat utilization efficiency depends on average heat utilization and total energy stored which are shown to be higher in Roki oil than in Sunflower oil, hence this makes heat utilization efficiency to be higher in Roki oil than in Sunflower oil.

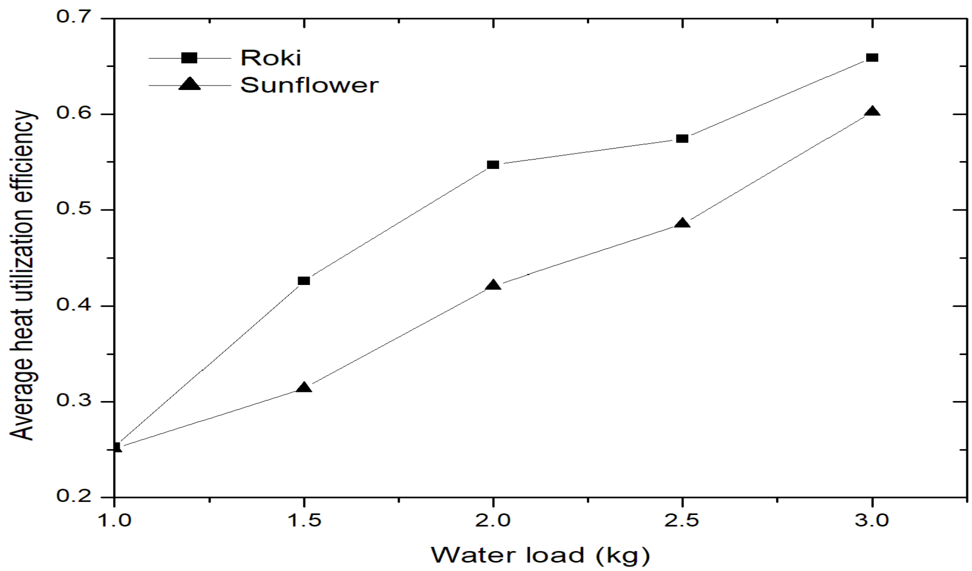

Figure 4.15: Average heat utilization efficiency variation with increasing water load for Roki oil and Sunflower oil.

For the case of a 1.0 kg water load, there is a slight difference in the average heat utilization efficiency values for Roki oil and Sunflower oil. This is attributed to the heating cycles of the oil. The 1.0 kg load was used for the first heating cycle of the oils (brand new oils). Only a difference of 0.2% is obtained when the average heat utilization efficiency values of Roki oil and Sunflower oil are compared. For the case of 1.5 kg to 3.0 kg water load experiments, considerable differences in the average heat utilization efficiency values for Roki oil and Sunflower oil are noticeable. Possibly because the experiments were performed after more than one heating cycle of the oils. This means that the used oil from restaurants which are normally heated many times (many heating cycles) for frying chips, mandazi, chicken, instead of being thrown away can be used for thermal energy storage. After many heating cycles (8 cycles), Roki oil seems to have higher thermal stability (it can be heated for a long time without degrading easily). Therefore, it can store more thermal energy than Sunflower oil.

4.8 Preliminary results with parabolic dish solar cookers

The storage cooking pots of the same properties are observed and compared when cooking under the sun and storage for off-sunshine cooking periods. Thermal performance evaluations for Roki oil and Sunflower oil for charging using the parabolic dish cooker and discharging using the wonderbag cooker are presented.

4.8.1 Charging results

During the test day, the sky was clear and wind speed ranges from 1.0 m/s to 1.7 m/s. The solar cooking period was 2 hours, and the average radiation from the sun and speed of the wind were around 885 W/m^2 and 1.2 m/s, respectively as presented in Figure 4.16. Figure 4.17 shows the charging results of the cooking experiment performed from the two storage cooking pots, 3 L of Roki oil in one cooking pot and 3 L of Sunflower oil in the other cooking pot as sensible heat storage materials. Each pot contains an inner pot with 1.0 kg of Sunflower oil used as a cooking fluid. During the charging period, as cooking was taking place, heat energy was also being stored to be used during off sunshine hours. The weather conditions (solar radiation and wind speed) seem to have more influence on cooking with the parabolic dish solar cooker. According to the prevailing weather conditions, the temperatures of the storage pots achieved at the end of charging were above 200 ℃ .

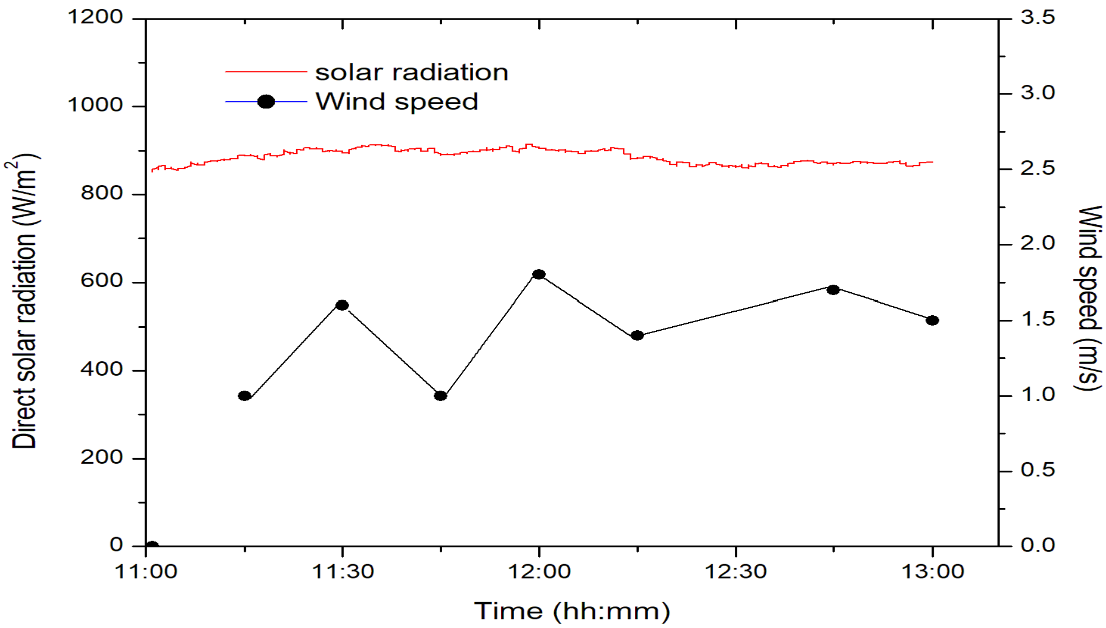

Figure 4:16: Direct solar radiation and wind speed profiles.

The maximum temperatures of the storage cooking pots achieved were ~ 233 °C for Roki oil, and ~ 210 °C for Sunflower oil, respectively. The maximum temperatures for the cooking load were ~ 231 °C for the Roki oil pot. and ~ 201 °C for Sunflower oil pot. When compared Roki oil cooking pot observed to have higher temperatures than the sunflower oil pot during the cooking under the sun. This happened because Roki oil cooking pot has low thermal mass than the Sunflower oil cooking pot. This makes Roki oil to charge up faster and attain maximum higher storage temperatures compared to that Sunflower oil. These temperatures are high enough to cook different types of food like rice, spaghetti, potatoes, fried chicken, and fish because they are above the boiling point of water.

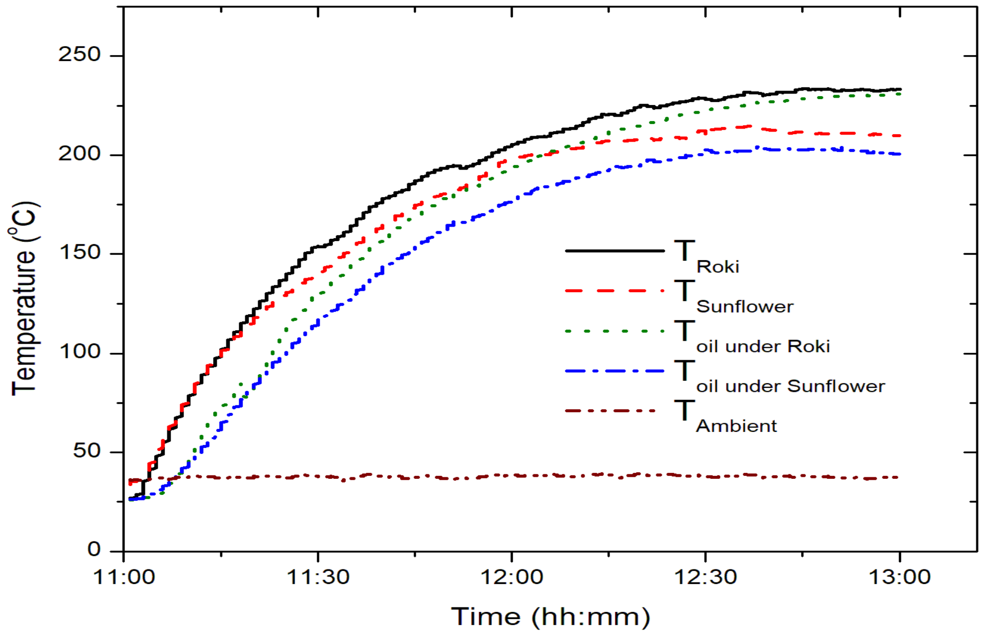

Figure 4.17: Charging/heating graph for Roki oil and Sunflower oil.

4.8.2 Discharging results

During the off-sunshine storage cooking period, the stored heat in both Roki and Sunflower oil pots was utilized to heat up 1.0 kg of Sunflower oil placed in each pot. Roki oil showed better thermal performance with an initial maximum temperature of ~ 223 ℃ compared to ~193 ℃ for Sunflower oil. These temperatures were able to heat the cooking load to up to maximum temperatures of ~ 156 ℃ for the Roki oil pot, and ~ 137 ℃ for the Sunflower oil pot within 30 minutes. During cooling/heat retention for 6 hours, these temperatures dropped from ~ 223 ℃ to ~ 71℃ for Roki oil, and from ~193 ℃ to ~67 ℃ for Sunflower oil as shown in Figure 4.18. Roki oil was able to cook the load faster than Sunflower oil because of its lower thermal mass (mc) compared to that of Sunflower oil. After 6 hours of cooling/heat retention, the remaining stored heat could still be used to warm food, tea/coffee, and water for bathing. Figure 4.18 also shows that after the cooking loads attained their maximum temperatures, their temperatures became higher than those of storage materials (cooling curve). This happens because the bigger pots which were inside the wonderbags were more exposed to the surroundings compared to the inner ones which contained the cooking loads. Therefore, there were more heat losses in the bigger pots which contained sensible heat storage material while the inner pots were gaining heat instead of losing it.

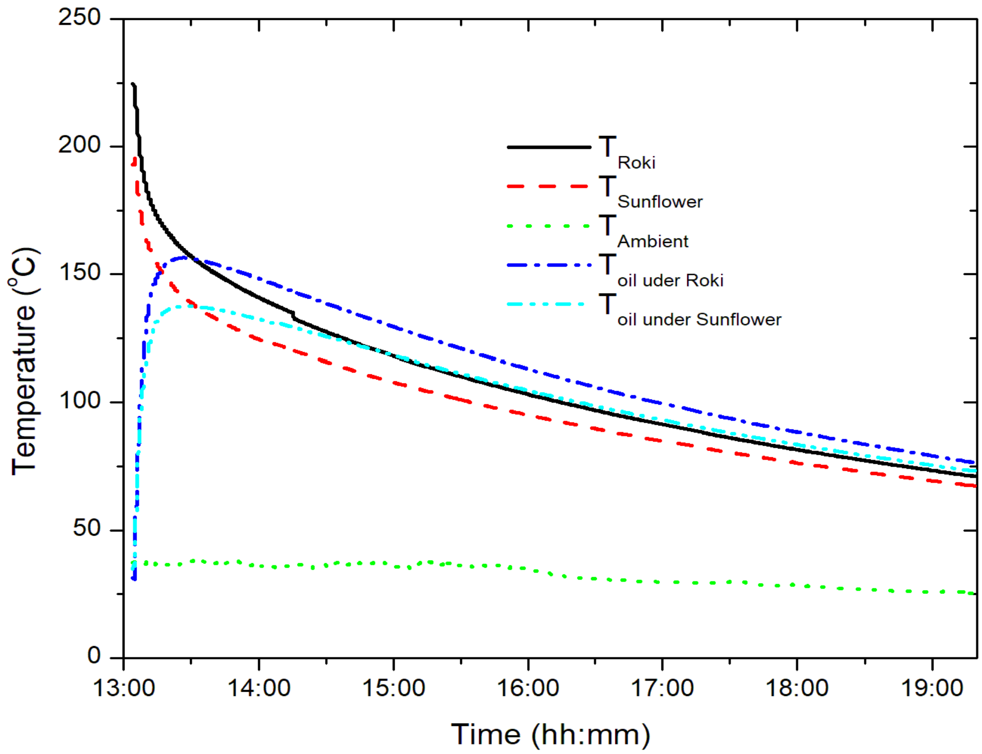

Figure 14.18: Cooling/heat retention graph for Roki oil and Sunflower oil.

4.8.3 Average energy stored, heat utilization and heat utilization efficiency

Roki oil had a higher average stored energy of 927.806 kJ compared to Sunflower oil which had 860.399 kJ as shown in Table 4.3. This is because of the higher temperatures achieved thus the temperature difference is more which results in more energy to be stored. The average energy stored for Roki oil was higher than that stored in Sunflower oil by 67.407 kJ as shown in Table 4.3. This implies that Roki oil can store more energy than Sunflower oil.

Table 4.3: A summary of thermal performance parameter of Roki oil and Sunflower oil with parabolic dish solar cookers.

Cooking pot	Average energy stored (kJ)	Heated load- Sunflower oil (kg)	Average heat utilization (kJ)	Average heat utilization efficiency (-)
Roki oil	927.806	1.0	264.134	0.285
Sunflower oil	860.399	1.0	218.141	0.254

The average heat utilization and heat utilization efficiency for Roki oil were higher than those of Sunflower oil (45.993 kJ and 3.1% higher). Roki oil showed slightly better thermal performance compared to Sunflower oil using the same amount of cooking load (1.0 kg of Sunflower oil). The Roki oil storage cooking pot as a SHSM can be a feasible cooking solution for most countries due to its environmentally friendly.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

An experimental demonstration to compare the performances of the Roki oil and the Sunflower oil as SHSM for home applications was shown. Roki oil and Sunflower oil were experimentally compared using charging and discharging tests. The thermal comparison was made based on their temperature profiles during the processes of charging and discharging cycles, and heat utilization. The thermal performance of the oils was observed in terms of energy, exergy, exergy factor, heat utilization, and heat utilization efficiency. The water fluid that was used in the experiment were from 1.0 kg to 3.0 kg. The main conclusions drawn were:

1. Specialized cooking pots were designed and fabricated. The pots were used in experimental setup and performance comparison of two SHSM (Roki and Sunflower oils).
2. Thermophysical properties such as specific heat capacity and viscosity variation with temperature of Roki oil and Sunflower oil were measured. It was found that Roki oil was more viscous compared to Sunflower oil. It was also found that the thermal mass (mc) of Roki oil was lower than that of Sunflower oil.
3. (i) During charging, the results showed that Roki oil attained a higher maximum temperature (~ 170 ℃) compared to the Sunflower oil (~ 160 ℃) during low power heating cycles.

   (ii) Roki oil showed higher temperatures during cooling compared to Sunflower oil achieving a final temperature (~ 78 ℃) slightly higher than that of Sunflower oil (~ 76 ℃). It was established in this work that during cool-down heat retention for Roki oil, the temperature achieved was high enough to cook food.

(iii) The average heat utilization and average heat utilization efficiency values are dependent on the water heating load. Roki oil showed higher average heat utilization (151 – 350) kJ, and higher average heat utilization efficiency values (0.25 – 0.66) as compared to Sunflower oil (148 – 300) kJ and (0.25 – 0.60), respectively. Heat utilization and heat utilization efficiencies of Roki oil was higher than that of Sunflower oil as water cooking load increased.

4. (i) The result showed energy rate, exergy rate, and exergy factor profiles for Roki oil were higher than Sunflower oil. This might be due to the fact that the low thermal mass (mc) of Roki oil increase to higher temperature compared to Sunflower oil. Also, perhaps due to higher temperature difference of Roki oil compared to Sunflower oil during charging.

   (ii) Average energy stored reduced for both cooking pots when the load was increased, while heat utilization and heat utilization efficiencies increased. The results suggested that Roki oil which is relatively cheaper than Sunflower oil is a potential thermal energy storage material that can be used in place of Sunflower oil.

5. (i) Preliminary results with the solar cooker were presented as well. Roki oil as a SHSM showed better performance with a higher maximum storage temperature of ∼ 223 ℃, compared to Sunflower oil which had a maximum temperature of ∼193 ℃.

   (ii) The final storage temperatures were ∼ 71 ℃ for Roki oil and ∼ 67 ℃ for Sunflower after 6 hours of the off-sunshine storage cooking period.

   (iii) The average storage energy, average heat utilization, and average heat utilization efficiency for Roki oil were higher compared to those of Sunflower oil during cooking under sun and storage cooking periods.

5.2 Recommendations for future work

1. The physiochemical parameters of Roki oil such as the smoke point and flash point are not currently fully understood to explain its behavior. Future work will look at these mentioned parameters.

2. The use of nano-particles in Roki oil to improve its thermal conductivity should be explored in future studies.

3. More experimental tests should be performed with parabolic dish solar cookers using different loads, and also experimental exergy thermal performance evaluations should be done.

4. Parametric studies on the efficiency of cooking should be done in future studies.

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