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Thermal Performance of Selected Oils in Uganda for Indirect Solar Domestic Cooking Applications

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Abstract

This study experimentally evaluated the thermal performance of selected oils in Uganda for indirect solar domestic cooking applications. The oil samples used were refined sunflower oil, refined palm oil and thermia B. These oils are locally available in Uganda. Thermal stratification, energy and exergy analysis were performed for each oil to determine their suitability for Thermal Energy Storage (TES) using a thermosiphon principle. The results showed that thermal stratification of refined sunflower oil was higher as compared to refined palm oil and thermia B during the first one hour. The stored energy and exergy for refined sunflower oil was generally higher than that of refined palm oil and thermia B. The thermal performance of refined sunflower oil was comparable to that of refined palm oil which was better than that of thermia B.

Keywords: Thermosiphon, thermal stratification, energy, exergy, oil

Introduction

Developing countries largely depend on firewood and charcoal for cooking (Prasanna and Umanand 2011). The dependence of firewood and charcoal for cooking has resulted into loss of biodiversity, health hazard and risks, deforestation, extreme weather changes and low agricultural productivity (Magala 2015). This calls for alternative sources of energy for cooking and solar energy seems to be the best option since it is abundantly received in the region throughout the year. Solar energy can be used for heat production and electricity generation. The heat produced can be used for cooking and drying crops while electricity generated can operate most domestic electrical appliances and satellites (Okello et al. 2014). To improve the usefulness of solar cookers, they should be incorporated with Thermal Energy Storage (TES) systems. The TES systems help to match energy demand to energy supply and cooking can be done at any time of the day (Okello et al. 2014). TES systems are divided into sensible heat, latent and thermochemical systems (Okello et al. 2014). Sensible heat storage system involves heat storage by increase in temperature while in latent heat storage system, heat is stored during the phase change of the storage medium (Liu et al. 2016). Lastly thermochemical heat storage system is a new technology in which heat is stored during chemical reactions. Sensible heat storage system is cheap and effective, and the storage medium can be rock pebbles, water, oils, salt and metals (Mawire et al. 2014).

Numerous studies have been reported on thermal performance of TES media for cooking purposes. Mawire et al. (2014) experimentally evaluated thermal performance of sunflower oil, thermia B, and thermia C during the charging process and found out that sunflower oil had better thermal performance as compared to thermia C and thermia B under high power charging. Nyeinga et al. (2016) presented a computational framework for a dynamic behaviour of a solar concentrating system with rock bed for heat storage based on numerical integration of a set of conservation equations for mass, momentum and energy of heat carrier, rock pebbles, and the wall; the heat carrier was air. They found that initially large temperature gradient existed, but as charging progressed, the temperature gradient between the top and the bottom disappeared. Mussard and Nydal (2013) designed a thermosiphon heat storage system which was coupled with a low-cost small-scale parabolic trough for cooking purposes. The results showed that at temperatures lower than 200 °C, the absorber without insulation was more effective while at temperatures higher than 200 °C, the absorber with glass tube was effective. Okello et al. (2014) compared the thermal behaviour of rock particles and rock particles combined with Phase Change Material (PCM). The results showed that the introduction of PCM cylinders in a bed of rocks increases both energy content of the storage and vertical thermal conductivity. The increase in thermal conductivity was attributed to the use of copper containment. According to the reviewed literature, limited information about the thermal performance of selected oils for TES medium for cooking purposes have been published especially during the charging using thermosiphon principle. Therefore, the study investigated thermal performance of refined sunflower oil, refined palm oil, and thermia B during the charging processes using thermosipon principles. Experiments were done on determination of thermal stratification, energy, and exergy during the charging process.

Materials and Methods

Design and fabrication of thermosiphon charging unit

A storage tank of internal diameter 18 cm and height 40 cm made of mild steel was fabricated. A boiler of internal diameter 18 cm and height 20 cm made of mild steel was fabricated and oriented at 60° to the horizontal. A continuous copper pipe of internal diameter 0.9 cm and total length 151 cm run from the top of the storage tank to the bottom through the boiler. The inlet point to the storage tank was 5 cm from top while the outlet point to the storage tank was 5 cm to the bottom.

Both the outlet and the inlet pipes were oriented at 60° to the storage tank as shown Figure 1. The storage tank was supported by wooden plates screwed on the metal stand and a metallic stand made of mild steel angled bar. The top covers of the stands for both the storage tank and boiler were of size 25 cm by 25 cm. The height of the storage tank stand was 50 cm while for the boiler was 25 cm. The distance of separation between the two top covers of the stand was 78 cm. For easy mobility, the stand was fitted with four rollers. Both tanks were fitted with manual valves from top and bottom using nipples made of mild steel. The manual valves allow replacement of oils during the experiment. A hole of diameter 2 cm was drilled on the top of the storage tank while for the boiler, a hole of 5 cm was drilled on top as shown in Figure 2.

Experimental procedure

Seven k-type thermocouples each at an interval of 5 cm were placed at the central axis of the storage tank as shown in Figure 3.

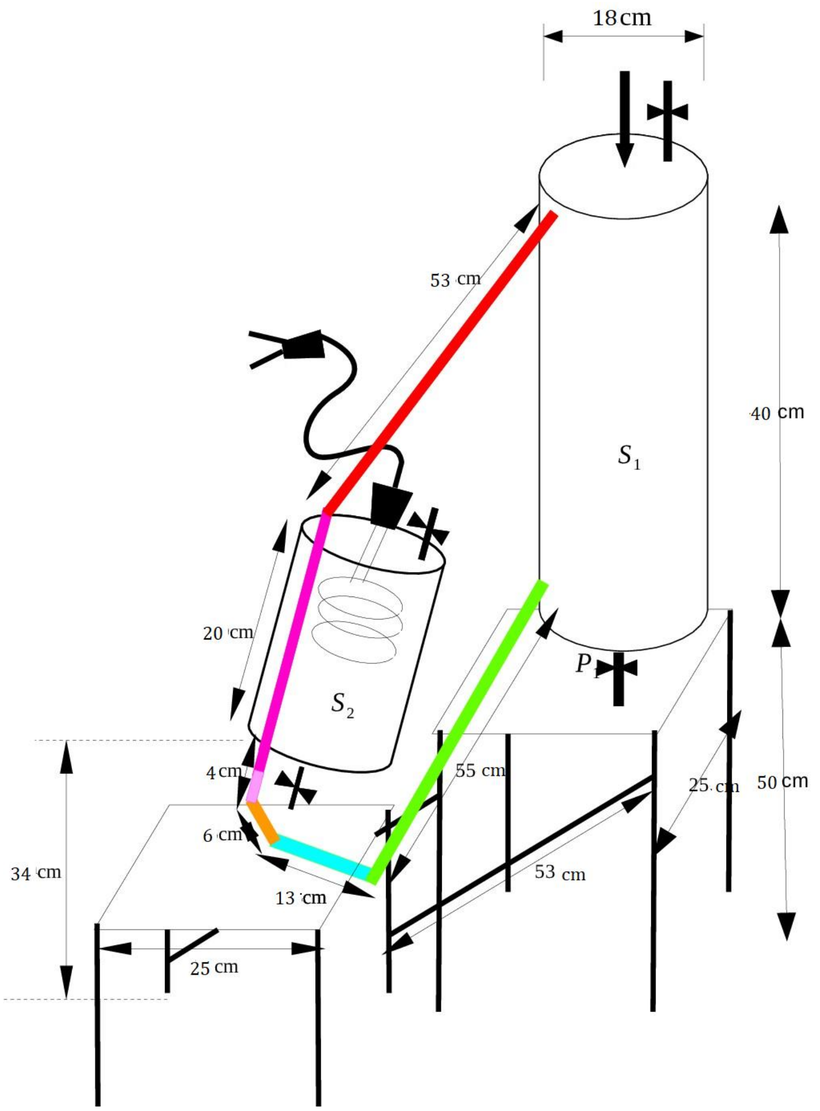

Figure 1: The schematic diagram showing the thermosiphon charging unit consisting of a boiler with a heater inside and a storage tank.

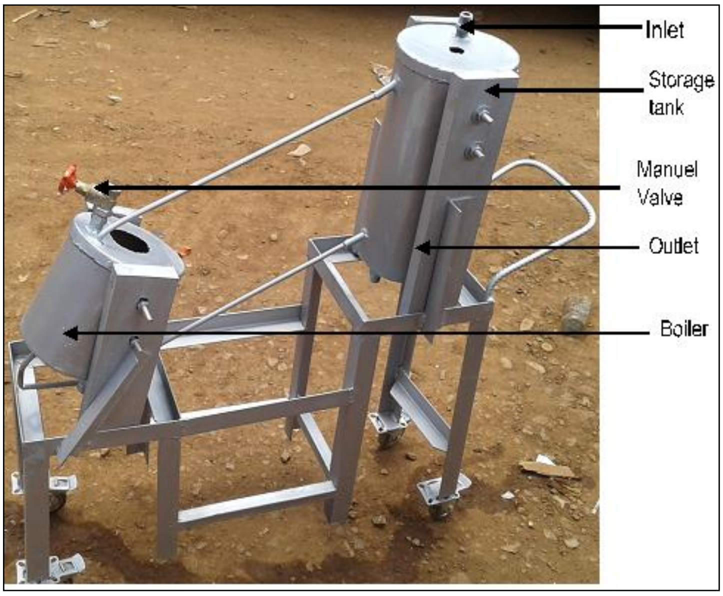

Figure 2: The constructed thermosiphon charging unit.

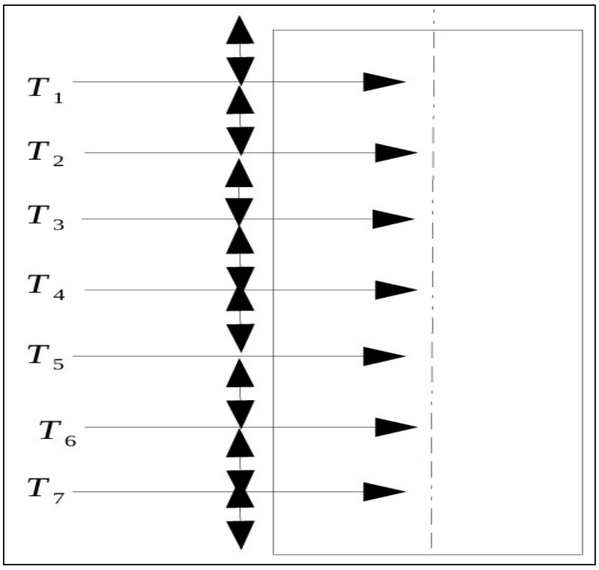

Figure 3: Arrangement of thermocouples in the storage tank at a distance of 5 cm apart.

The thermocouples were tied together using a flexible insulated metallic thread. Another k-type thermocouple was inserted in the boiler to monitor the temperature of the oil. All the eight thermocouples were connected to a TC-08 Data Logger interfaced with a computer. 10 litres of each oil were poured in the storage tank while in the boiler 4 litres of refined sunflower oil were used. An electrical heater of 1.5 kVA was used for heating the oil in the boiler. The temperature of the boiler was maintained in the range of 230 to 240 °C manually, by switching the electrical heater on and off.

The switching on was at temperature of 234 °C and the temperature of the boiler continued decreasing to 230 °C as the result of thermal inertia; while the switching off was at the temperature of 238 °C and the temperature continued rising to 240 °C. The boiler was used for charging the storage tank for 6 hours and the experimental setup is as shown in Figure 4.

Figure 4: The experimental setup showing charging of the storage tank by thermosiphon principle in which eight thermocouples were connected to a TC-08 data logger to monitor the tanks' temperatures.

Thermal analysis

To determine thermal stratification, temperature profiles, temperature distribution along the height of the tank, thermal gradient and stratification numbers were considered. According to Fernández-Seara et al. (2007) the thermal gradient of an oil-only-TES system at any time as, t during charging process is given by:

$$\left(\frac{\Delta T}{\Delta y}\right)_t = \frac{1}{5}\sum_{j=1}^{j=5}\left(\frac{T_{j+1} - T_j}{\Delta y}\right)$$

where j is the node which takes on the values $j = 1,2,3,4,5,6,$ T_j are the nodal temperatures along the height of the storage tank, and Δy is the interval distance between adjacent thermocouples. Fernández-Seara et al. (2007) also expressed the stratification number at any time, *t* during the charging process as:

$$stn = \frac{\left(\frac{\Delta T}{\Delta y}\right)_t}{\left(\frac{\Delta T}{\Delta y}\right)_{t=0}}$$

where $\left(\frac{\Delta T}{\Delta y}\right)_{t=0}$ and $\left(\frac{\Delta T}{\Delta y}\right)_t$ are initial thermal gradient and thermal gradient at any time, respectively.

Mawire et al. (2014) defined the total energy stored, E_t in a tank during the charging process as:

$$E_t = \rho_o c_o \sum_{i=1}^{i=5} v_{o(i)} \Delta T_{(i)}$$

where ρ_o is the density of the oil, c_o is the specific heat capacity of the oil, $v_{o(i)}$ is the volume of oil in the i^{th} segment, and $\Delta T_{(i)}$ is the temperature difference between two adjacent nodes of the i^{th} segment of a stratified tank.

Mawire et al. (2014) expressed the total exergy stored, E_{xt} during the charging process as:

$$E_{xt} = \left(\rho_o c_o \sum_{i=1}^{i=5} v_{o(i)} \Delta T_{(i)}\right) - \left(\rho_o c_o \sum_{i=1}^{i=5} v_{o(i)} T_{amb} ln\left(\frac{T_{top}}{T_{bot}}\right)\right)$$

Where T_{amb}, T_{top}, and T_{bot} are the ambient temperature, temperature at the top of segment, and temperature at the bottom of segment, respectively.

Results and Discussion

Temperature profiles of the boiler

Figures 5a, 5b, and 5c show the temperature profiles of the boiler used for charging refined sunflower oil, refined palm oil, and thermia B, respectively in an oil-only-TES system. The temperature profiles increased rapidly from 24 °C to 238 °C in 30 minutes during the initial heating. The temperature profiles then remained fairly constant during the charging period. The small fluctuation of temperature was due to manual switching on and off of the electrical heater; the electrical heater was switched on when the temperature of the boiler was 234 °C and off when it was 238 °C.

The abnormal high pikes were due to overheating of the oils as the results of delay in switching off the electrical heater, whereas the abnormal low pikes were due to overcooling as the results of delays in switching on the electrical heater. The pronounced fluctuation of the temperature profile during the initial heating of boiler for charging refined sunflower oil was due to external disturbance of the thermocouple inserted in the boiler.

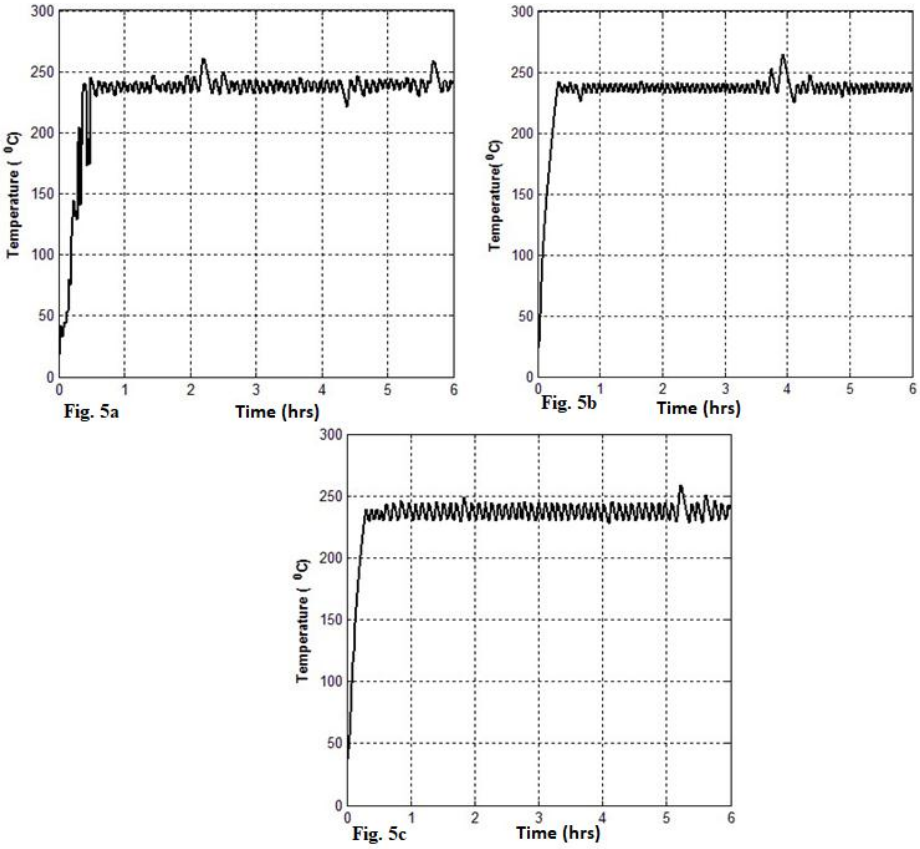

Figure 5: Temperature profiles of the boiler used for charging refined sunflower oil, refined palm oil, and thermia B in an oil-only-TES tank for 6 hours.

Temperature profiles during the charging of an oil–only–TES system

Figures 6a, 6b, and 6c show the temperature profiles for refined sunflower oil, refined palm oil, and thermia B during charging process for 6 hours. T1 and T6 were the inlet and outlet temperatures of the storage tank, respectively. Only 6 temperature points taken along the height of the storage tank were considered because the third thermocouple from top malfunctioned.

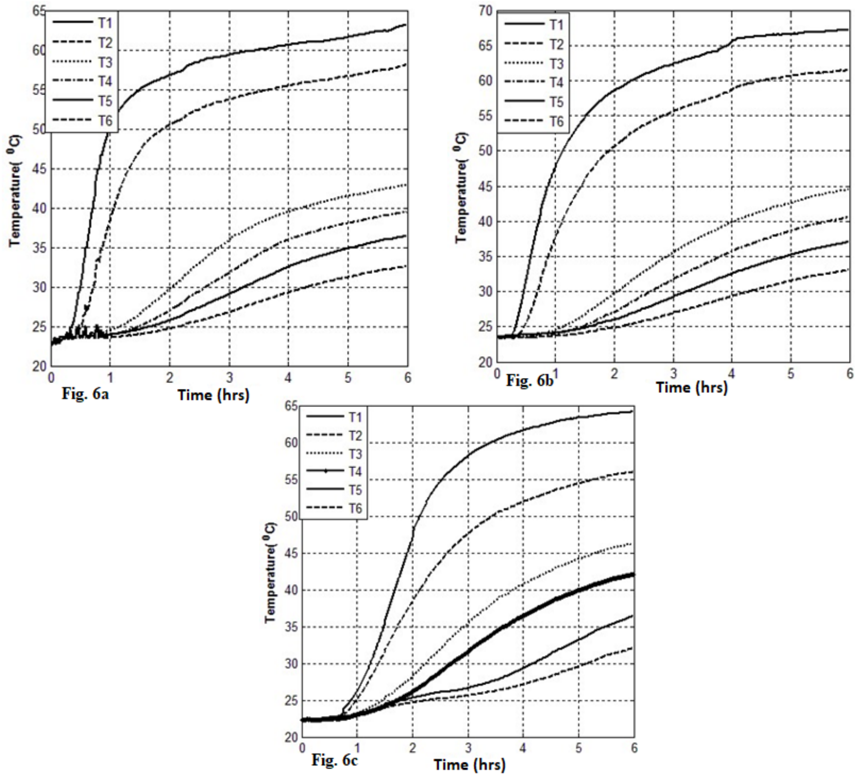

Figure 6: Temperature profiles during charging refined sunflower oil, refined palm oil, and thermia B in an oil-only-TES tank for 6 hours.

Initially, the ambient temperature of the storage tank was about 24 °C for all the three oils. This implies that the initial thermal stratification for the three oils was ignorable since the temperature difference between the top and bottom was very small. The temperature of thermia B took some time to rise because of its low density and specific heat capacity.

At the end of the charging process, the difference in the temperature between the top and bottom for the three oils was insignificant. This means that at the end of the charging process, the three oils had comparably the same thermal stratification. However, if observed in the first one hour, there was a huge difference in the temperature between the top and bottom for the three oils. The high temperature difference between the top and bottom for refined sunflower oil was attributed to its high density and specific heat capacity. This means that refined sunflower oils get charged faster than refined palm oil and thermia B.

Thermal gradients during the charging

The thermal gradients for the three oils are presented in Figure 7. The thermal gradient for refined sunflower oil attained a maximum value of 109.6 °C m^{-1} in 2 hours and 24 minutes while that of refined palm oil was 107.9 °C m^{-1} attained within 4 hours and 6 minutes. Finally the thermal gradient of thermia B attained a maximum value of 116.1 °C m^{-1} in 4 hours and 18 minutes. This rapid increase is attributed to increased temperature at the top of the storage tank and low temperature at the bottom as the hot oil entered the storage tank from top. As charging progresses, the hot oil from the top of the storage tank keeps flowing downwards, hence increasing the temperature of the oil at the bottom. This reduces the difference in temperature between the top and the bottom of the storage tank, hence reduction in thermal gradient.

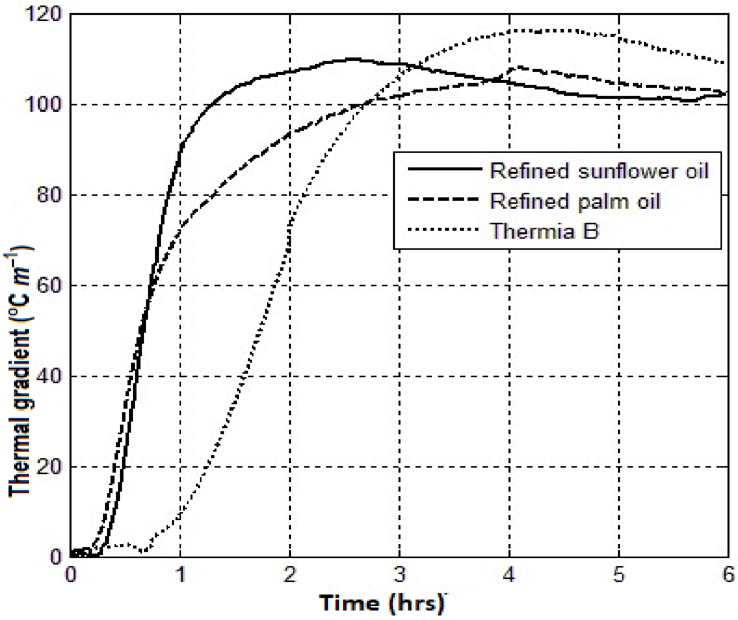

Figure 7: Thermal gradients for refined sunflower oil, refined palm oil and thermia B in an oil-only-TES tank during the charging for 6 hours.

The thermal gradients for both refined sunflower oil and refined palm oil were comparatively the same in the first 30 minutes of the charging process because their densities are very close and hence the amounts of heat transferred to the storage tank were almost the same. The thermal gradient of refined sunflower oil increased sharply within the first one hour due to its high density and specific heat capacity; it therefore absorbs large amount of heat faster. Thereafter, the thermal gradient for refined sunflower oil increased more than that of refined palm oil during the rest of the charging process. This result agreed with the observations of Mawire et al. (2014) in which they found that the thermal gradient of sunflower oil was higher than that of thermia B during the first two hours of the charging process when the oil flow rate was 2.2 ml/s. They also reported the initial rapid increase in thermal gradient up to maximum and thereafter it decreased gradually. The results show that the thermal gradient of refined sunflower oil was generally higher for more than 4 hours as compared to that of refined palm oil and thermia B. This means that refined sunflower oil has a better thermal stratification and for a longer period of time. Hence refined sunflower oil can be used for longer hours before losing its thermal stratification.

Temperature distribution along the height of the storage tank

Figures 8a, 8b, and 8c show the temperature distribution along the height of the storage tank during charging at time interval of 1 hour for refined sunflower oil, refined palm oil, and thermia B. At the start of the charging process, the temperature was equal to the ambient temperature.

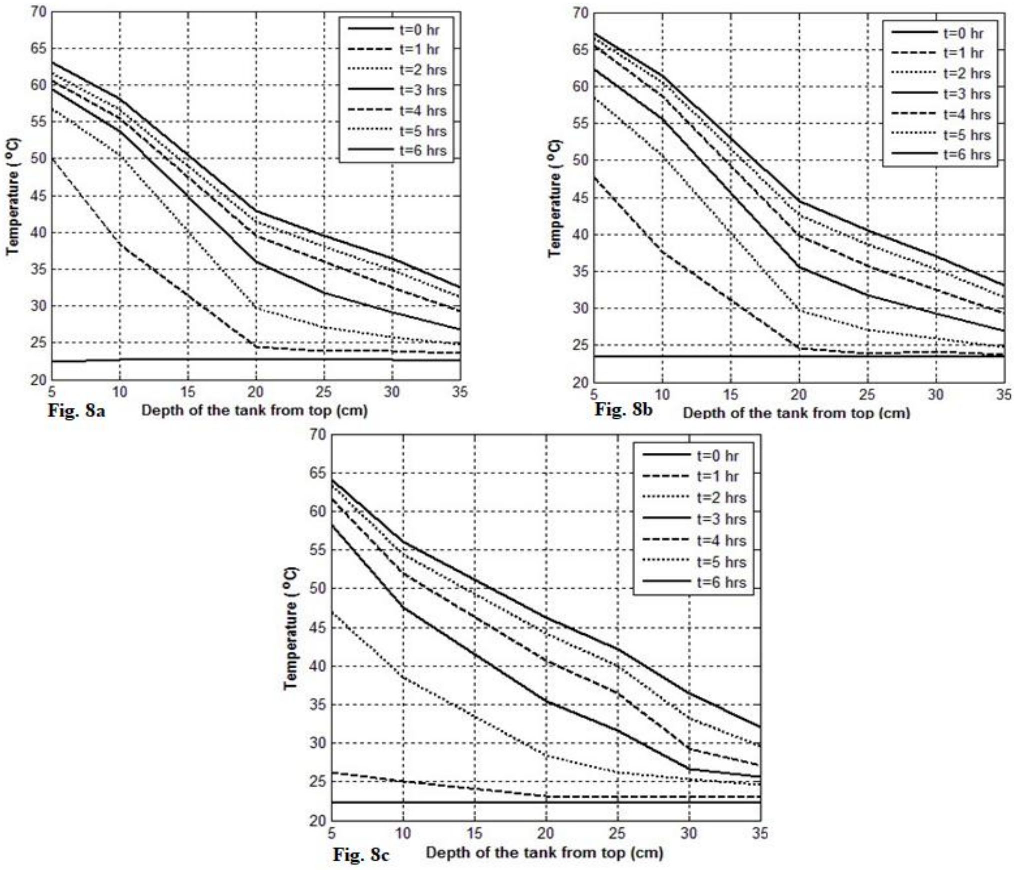

Figure 8: Temperature distribution for refined sunflower oil, refined palm oil, and thermia B along the height of the storage tank at time interval of 1 hour during the charging of an oil-only-TES for 6 hours.

As charging progresses, hot oil enters the top of the storage tank and loses heat and the cold oil from the bottom of the storage tank goes into the boiler for further heating. The temperature along the storage tank increases from the top to the bottom; so there is a clear thermal stratification between the top and the bottom of the bed and this agrees with Nyeinga et al. (2016).

In the first one hour, both refined sunflower oil and refined palm oil had high temperatures at the top (≈ 50 °C) and low temperatures at the bottom (≈ 24 °C) which implies high thermal stratification while thermia B had a temperature of ≈ 27 °C at the top of the tank and a temperature of 23 °C at the bottom of the tank and this means low thermal stratification due to its low density and specific heat capacity.

After 6 hours, the temperature differences between the bottom and the top of the storage tank for the three oils were similar and this implies that the difference in their thermal stratification was insignificant. This is probably attributed to steady state thermosiphon flow rate of the charging oils.

Stratification number

Stratification numbers for the refined sunflower oil, refined palm oil, and thermia B during the charging process are presented in Figure 9. The stratification numbers for the three oils increased rapidly within the first two hours of the charging period. After which, the stratification remained relatively constant and slightly decreasing at the end of the charging process. In all the cases, there existed peak values and this was consistent with Oró et al. (2013) in which they analyzed the thermal stratification of packed bed TES system during the charging process and found that stratification number increased to a certain peak value and thereafter decreased.

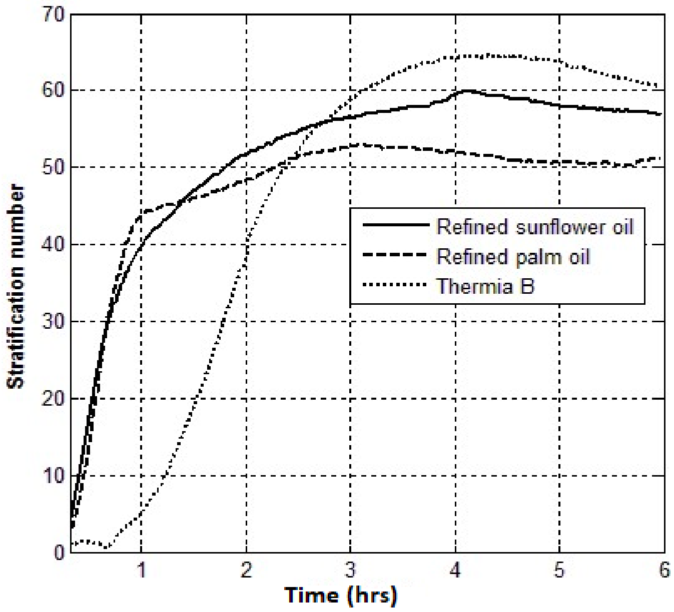

Figure 9: Stratification numbers of refined sunflower oil, refined palm oil, and thermia B during the charging of an oil-only-TES tank for 6 hours.

The initial rapid rise in stratification number was due to absorption of large amount of heat in the boiler by circulating oil resulting into large thermal gradient. The rapid increase in the stratification number implies rapid increase in thermal stratification. The stratification number of thermia B was distinctively the lowest in the first two hours of charging process due to its low density which reduces the amount of heat absorbed from the boiler resulting into low thermal gradient. The stratification numbers for both refined sunflower oil and refined palm oil were comparatively the same during the first one hour of the charging process and thereafter, the stratification number for refined sunflower oil dropped to values lower than that of refined palm oil. The sharp increase in the stratification number of refined sunflower oil at the first hour of charging was due to an equivalent increase in thermal gradient. The variation in the stratification number was due to initial thermal gradient, density and specific heat capacity. Hence, both refined sunflower oil and refined palm oil absorbed large amounts of heat energy during the first two hours of the charging process; refined palm oil had lower initial thermal gradient. Thermia B had the highest stratification at the end of the charging period due to low initial thermal gradient. These results show that both refined sunflower oil and refined palm oil retain their thermal stratification for longer time as compared to thermia B since stratification number described extensively thermal stratification.

Thermal energy profiles during the charging of an oil-only-TES system

The energy profiles of refined sunflower oil, refined palm oil and thermia B during the charging process are presented in Figure 10. The energy profiles for both the refined sunflower oil and refined palm oil increased rapidly in the first one hour until their peak values were attained; the maximum energy for refined sunflower oil was 0.13 MJ attained in 1 hour and 42 minutes while for refined palm oil was 0.12 MJ attained in 2 hours and 18 minutes. The energy profile for thermia B increased gradually until it attained a peak value of 0.10 MJ in 2 hours and 54 minutes. The energy profile for refined sunflower oil was very close to that of refined palm oil in the first 45 minutes after which it increased more rapidly up to its maximum value. Meanwhile, the energy profile for thermia B was quite lower than that of refined sunflower oil and refined palm oil because thermia B has lower specific heat capacity and low density. The high energy profile for refined sunflower oil was attributed to its high specific heat capacity and density.

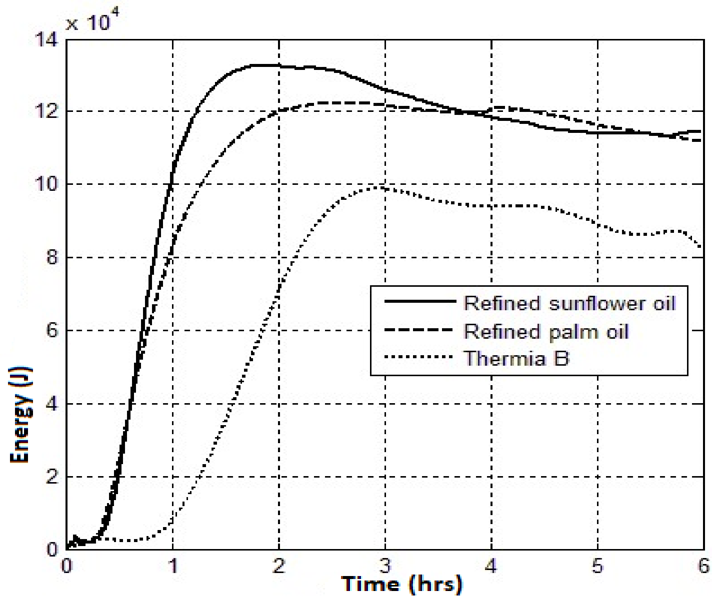

Figure 10: Thermal energy profiles for refined sunflower, refined palm oil and thermia B during the charging for 6 hours.

The rapid initial increase in energy profiles was attributed to high heat absorption in the boiler and probably due to thermosiphon flow which resulted to rapid high energy transfer in the storage tank. The drop in energy after 2 hours and 30 minutes can be attributed to the fact that the density and specific heat capacity for oil decreases and increases, respectively with increasing temperature; but the decrease in density overrides the increase in specific heat capacity as cited by Esteban et al. (2012). Therefore at high temperatures, after 2 hours and 30 minutes, the energy of the three oils slightly decreases.

Thermal exergy profiles during the charging of an oil-only-TES system

The exergy storage profiles for refined sunflower oil, refined palm oil and thermia B during the charging process were plotted and presented in Figure 11. The stored exergy for the three oils generally increased during the first three hours of the charging process and thereafter it remained fairly constant. This was due to rapid increase in thermal gradient of the storage tank during the first three hours of the charging. However, just at the beginning of the charging, the exergy took sometimes to rise when the temperature of the storage tank was significantly higher than the ambient temperature. This was because the exergy depends on the ambient temperature. The exergy for thermia B took much longer time to rise because its initial temperature was much lower than the ambient temperature so that appreciably large time span was required for its temperature to go above the ambient temperature.

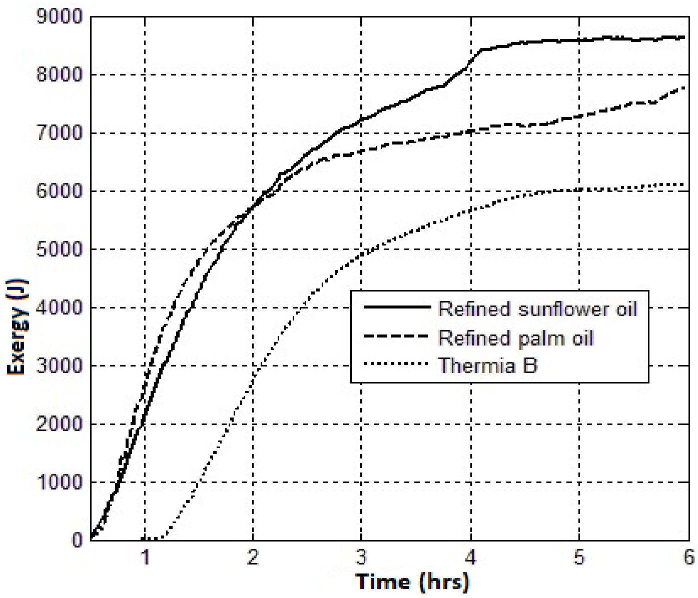

Figure 11: Thermal exergy profiles for refined sunflower oil, refined palm oil and thermia B during the charging of an oil-only-TES tank for 6 hours.

The maximum exergy stored for refined sunflower oil, refined palm oil and thermia B were 8.6 kJ, 7.8 kJ and 6.1 kJ, respectively and all these peaks values were attained at the end of the charging process. The high exergy profile of refined sunflower oil is attributed to high density and high specific heat capacity. The stored exergy profiles for the three oils were generally lower than that of stored energy profiles. The difference in stored energy and exergy was due to contribution of ambient temperature in the computation of exergy.

Conclusion

The thermal performance of refined sunflower oil, refined palm oil and thermia B were evaluated experimentally. The results show that the thermal gradient for refined sunflower oil was higher than that of refined palm oil and thermia B in the first one hour. This means that refined sunflower oil has a better thermal stratification within the first one hour. The stored energy distribution during the charging process for refined sunflower oil was generally higher than that of refined palm oil and thermia B. In conclusion, both refined palm oil and refined sunflower oil can be used as TES media for solar domestic cooking applications; however refined sunflower oil is preferred because it absorbs heat faster which is more suitable since the duration of solar insolation is short. Further studies should be carried out on the TES system size suitable for domestic cooking and heat retention with refined sunflower oil in an insulated TES system.

Acknowledgements

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