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CHARACTERISATION OF EDIBLE SUNFLOWER AS A HEAT STORAGE MEDIUM FOR SOLAR COOKING

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ABSTRACT

Charging and discharging experiments to evaluate Sunflower Oil as a heat storage medium for domestic solar cooking applications are presented. An experimental setup to evaluate the thermal performance of Sunflower Oil during charging and discharging cycles is presented. Energy and exergy based experimental thermal performance parameters are evaluated. Energy, exergy, thermal gradient and exergy factor values are evaluated with experimental tests. High temperature charging is found to be the most viable option. This option results in higher energies, higher exergies, higher thermal gradients and higher exergy factors. For the discharging cycles, a high flow-rate results in a fast heat transfer rate. This fast rate of heat transfer destroys thermal stratification earlier but heats up water faster. The lower discharging flow-rate ensures that the discharging cycle can be carried out for a longer period. This is beneficial in utilizing the stored energy and exergy for a longer period, such that it can be used for cooking foods that take a longer time to cook. An optimal discharging flow-rate is also suggested. The optimal flow-rate comprises between fast heat transfer and using the stored energy more effectively. Exergy factor profiles during charging and discharging cycles show characteristic dips which correspond to the time when the thermal gradients begin to decrease. Sunflower Oil is found to be a viable and readily available TES medium which can be used in domestic solar cooking applications.

INTRODUCTION

In the developing world, the rate of deforestation is high due to the cutting of fire-wood for cooking food. An alternative environmentally friendly means of cooking of food is provided by solar cookers. Their use is, however, limited to sunshine hours when the sun is available [1]. Small thermal energy storage (TES) units can be employed to cater for this drawback [2-5]. Two main types of TES units for solar cookers are sensible heat thermal energy storage (SHTES) and latent heat thermal energy storage (LHTES) systems. LHTES systems are more expensive due to their construction complexity, the thermal degradation of phase change material (PCM) and the cost of the PCM itself. Small SHTES systems are thus more appropriate for the use with solar cookers since they are easy to fabricate and maintain.

Water is a cheap and widely available TES medium but its usefulness for TES at high temperatures for cooking of food is limited by its boiling point. This is because it cannot be stored beyond its boiling point without pressurizing it. Pressurizing water adds an additional cost to the storage vessel. Water also does not stratify properly in a simple storage tank [6-8] and this reduces the storage efficiency. Thermal oils can store thermal energy at temperatures greater than the boiling point of water [9-12].

Sunflower Oil is widely used in the cooking industries in South Africa for preparing fast foods like chips and fried foods. Sunflower Oil is locally manufactured in South Africa and reasonably priced at R 300(~USD 30) per 25 litres. Being edible implies that Sunflower Oil cannot contaminate food when it comes in contact with the food in cooking applications. Used Sunflower Oil in South African homes and restaurants is usually disposed of in environmentally non-friendly ways. This used oil could be stored in small TES units to cook food or pre-heat water for cooking thus reducing the demand of electrical energy for cooking. The use of Sunflower Oil as a TES medium for cooking applications is justified by the following reasons; (i) Sunflower Oil is readily available and extracted from Sunflower Oil seeds grown locally in most countries in the world, (ii) Sunflower Oil is edible and does not contaminate foods, (iii) its characteristics are comparable to other thermal oils used for domestic heat storage applications reported in literature [13-14] , (iv) Sunflower Oil is generally non- toxic and its fumes are generally tolerated (v) and its flash point is around 250 ^{o}C, a temperature that is above the cooking temperature of most foods.

In this paper, an experimental setup is presented to test the thermal performance of Sunflower Oil during charging (heat storage) and discharging (heat utilization) cycles.

EXPERIMENTAL SETUP AND PROCEDURE

The schematic diagram of Figure 1 shows the operation of the charging and discharging cycles. In the charging mode, the charging flow direction is represented by the solid arrows in Figure 1.

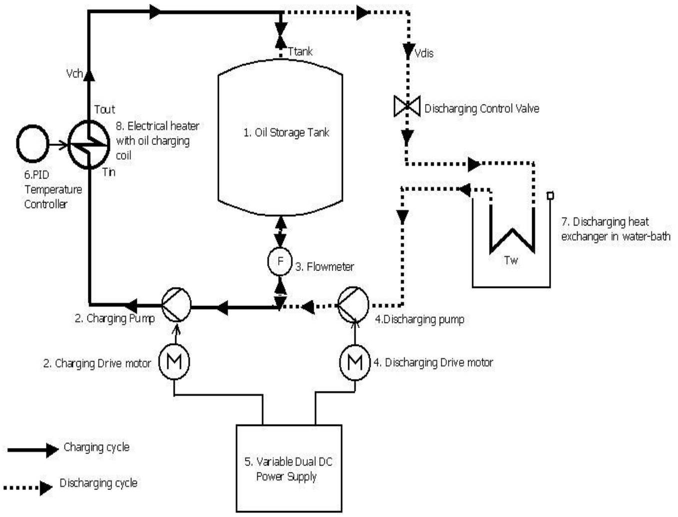

Figure 1 Schematic diagram of experimental setup and operation.

A positive displacement pump (**2**) controlled by a variable DC power supply (**5**) is used to circulate oil through the copper spiral coil that is in thermal contact with two electrical heating elements (**8**). The DC power supply is adjusted manually to vary or maintain the average charging flow-rate, $\dot{V}_{chav}$. An oval gear volumetric flow-meter **(3)** is connected in series between the charging pump and the bottom of a 20 litre insulated thermal oil storage tank (**1**). It thus records the volumetric flow-rate during charging and discharging of the storage tank. The charging pump extracts oil at the bottom of the tank (**1**) and pushes it through electrical heaters with an oil charging coil **(8)**. The oil enters the charging coil at a temperature T_{In} and exits the coil at a temperature T_{Out} after absorbing heat from two electrical heaters controlled by a temperature controller **(6)**. The temperature controller controls temperature of the heating elements by using a PID control mechanism such the temperature of the elements does not exceed the set temperature of the controller by too much. A J-type thermocouple is connected to the centre of the heating elements to monitor the temperature of these elements. The electrical heating elements switch off when their temperature exceeds the set controller temperature by around 2 ^{o}C, and switch on when the temperature is below 2 ^{o}C of the set temperature. The set temperature is set to be below the flash point temperature of the thermal oil to avoid overheating of the oil. The oil enters the top of the storage tank at a temperature higher than that at the bottom of the tank. The charging cycle is repeated until the bottom of the storage tank attains a relatively high temperature.

The discharging cycle flow is represented by the dotted lines in Figure 1. After a discharging cycle, hot oil is extracted from the top of the storage tank at a discharging flow-rate of $\dot{V}_{dis}$ when the discharging control valve is open. This hot oil heats up a 4.5 litres water bath in which a water heating copper spiral coil is immersed and this is represented as (**7**) in Figure 1. A discharging positive displacement pump (**4**) is used to circulate the hot oil through the discharging heat exchanger (copper spiral coil) until the water starts to boil. A J-type thermocouple immersed in the water bath is used to monitor the water temperature.

Fifteen thermocouples (K-type) in three radial positions at five different levels along the height of the storage are used to monitor the temperature distribution along the height of the storage tank during charging and discharging cycles as previously presented by Mawire et al. [10]. The arrangement of the thermocouples is shown in Figure 2 where all the dimensions are in mm. Radial thermocouples are supported with metallic rods at each axial position. Thermocouples at Level 5 (T51, T52, T53) measure the radial temperature distribution at the top of the storage and an average temperature at this axial position is determined using these measurements. Other average temperatures from Levels 4 - 1 are determined in a similar manner.

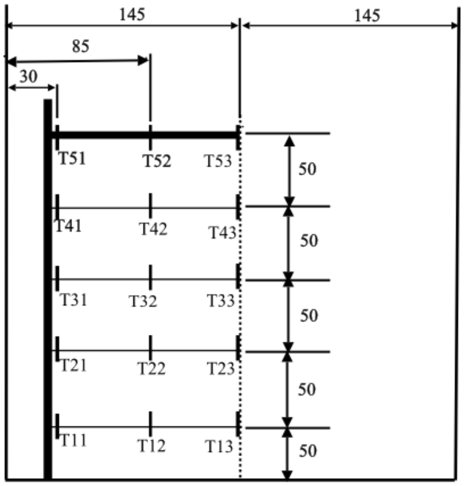

Figure 2 The arrangements of the 15 thermocouples in the storage tank. All dimensions are in mm [10].

The repeatability in measuring the temperature was estimated to be ± 0.1 ^{o}C as determined from the accuracy of the HP 34970A data-logger used for recording the data .The Mcnaught flow-meter used to measure the flow-rate has a basic accuracy of ±1 % as determined from the datasheet of the flow-meter.

EXPERIMENTAL THERMAL ANALYSIS

Experimental thermal parameters to characterize the thermal performance of Sunflower Oil during charging and discharging cycles are presented in this section. During the heat transfer cycles, the total energy in the four segments of the storage tank is given by

$$E_{\mathrm{T}} = \sum_{i=1}^{4} \rho_{\mathrm{av}} c_{\mathrm{av}} V_{\mathrm{vol(i)}} \Delta T_{\mathrm{vol(i)}} \tag{1}$$

where ρ_{av} is the average density of a segment, c_{av} is the average specific heat capacity of a segment, $V_{\mathrm{vol(i)}}$ is the volume of a segment and $\Delta T_{\mathrm{vol(i)}}$ is the temperature difference in a segment of the stratified storage tank. For the top segment 4 (with reference to Figure 2), $\Delta T_{\mathrm{vol(i)}}$ is calculated from the difference of the average temperature of level 5 (T_5) and that of the average temperature of level 4 (T_4). The same formulation is carried for the three remaining segments containing thermocouples from Level 4 to Level 1. The total exergy during charging is expressed as [14]

$$E_{\mathrm{XT}} = \sum_{i=1}^{4} \rho_{\mathrm{av}} c_{\mathrm{av}} V_{\mathrm{vol(i)}} \Delta T_{\mathrm{vol(i)}} - \sum_{i=1}^{4} \rho_{\mathrm{av}} c_{\mathrm{av}} V_{\mathrm{vol(i)}} T_{\mathrm{amb}} \ln\left(\frac{T_{\mathrm{top}}}{T_{\mathrm{bot}}}\right)_{\mathrm{i}} \tag{2}$$

where T_{amb} is the ambient temperature (K), T_{top} is the average temperature at the top of a segment (K) and T_{bot} is the average temperature at the bottom of a segment (K). For segment 4 (with reference to Fig. 2), the temperature at top of the storage T_{top} refers to the average temperature T_5 and T_{bot} refers to the average temperature T_4. The same formulation is applied to the other remaining three segments which cover temperatures T_4 - T_1. The exergy factor which is the ratio of the total exergy to the total energy can be expressed as

$$E_{\mathrm{XF}} = \frac{E_{\mathrm{XT}}}{E_{\mathrm{T}}} = \frac{\sum_{i=1}^{4} \rho_{\mathrm{av}} c_{\mathrm{av}} V_{\mathrm{vol(i)}} \Delta T_{\mathrm{vol(i)}} - \sum_{i=1}^{4} \rho_{\mathrm{av}} c_{\mathrm{av}} V_{\mathrm{vol(i)}} T_{\mathrm{amb}} \ln\left(\frac{T_{\mathrm{top}}}{T_{\mathrm{bot}}}\right)_{\mathrm{i}}}{\sum_{i=1}^{4} \rho_{\mathrm{av}} c_{\mathrm{av}} V_{\mathrm{vol(i)}} \Delta T_{\mathrm{vol(i)}}} . \tag{3}$$

The thermal gradient along the height of the storage tank from T_5 (average temperature at level 5) to T_1 (average temperature at level 1) can be expressed as

$$\frac{dT}{dy} = \frac{T_5 - T_1}{\Delta y} \tag{4}$$

where Δy is axial distance between thermocouples at level 5 and level 1 which is 0.2 m.

The thermal properties of Sunflower Oil are temperature dependent and the temperature dependent equations are calculated from research papers published in recent literature [15, 16]. Table 1 shows the thermal properties of Sunflower Oil as a function of the temperature in $^{\circ}$C.

Table 1: Temperature dependent thermal properties of Sunflower Oil

ρ (kg/m^3)	c (J/kgK)	k (W/mK)
ρ_S = 930.62-0.65T	c_S = 2115.00+3.13T	k_S = 0.161+0.018exp(-T/26.142)

RESULTS AND DISCUSSION

Charging Results

Figure 3 shows temperature profiles of the storage tank under high temperature and low temperature charging conditions. High temperatures are achieved by using the two heating elements at a low flow-rate of 2.2 ml/s. Low temperature charging is achieved by using one heating element at a high flow-rate of 4.2 ml/s. For low temperature charging, the set temperature of the controller is 200 $^{\circ}$C, while for high temperature charging, the set temperature is 250 $^{\circ}$C.

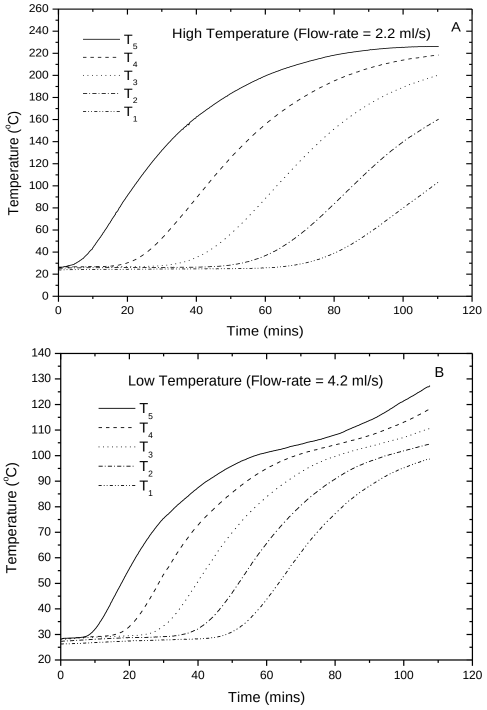

Figure 3 Temperature profiles of Sunflower Oil under high temperature and low temperature charging conditions.

For high temperature charging, the storage tank has the greatest degree of thermal stratification along the height of the storage tank due to the higher temperatures achieved at the top of the storage tank. The temperature at the bottom of the storage tank (T_1) is limited to 100 $^{\circ}$C because the flow-meter connected to the bottom of the storage tank can only operate at temperatures up to 120 $^{\circ}$C. For low temperature charging, the higher flow-rate results in thermal stratification being lost quickly due to the increased rate of fluid mixing. The heat transfer rate for low temperature charging is greatest when the upper level temperatures show characteristic thermal gradient rises after around 90 mins of charging. The low temperature profile shows a characteristic rise of the upper level temperatures at the later part of charging. This is possibly due to a combined effect of the shorter residence time in the storage tank which degrades sensible heat and the lower viscosity of the oil at top of storage such it flows faster and absorbs heat at a faster rate.

Figure 4 shows the energy and exergy profiles for the two different charging conditions. High temperature charging at a low flow-rate shows the greatest values of the energy and exergy stored. This is due to the higher degree of thermal stratification induced by the low flow-rate which results in a larger thermal gradient. The profiles of the energy and exergy are seen to peak as thermal stratification increases and then drop due to the drop in thermal stratification as charging progresses. Exergy values are lower than energy values for the two experimental conditions. The exergy profile for low temperature charging attains a peak value, drops and rises again due to the upper level temperature variations depicted in Figure 3.

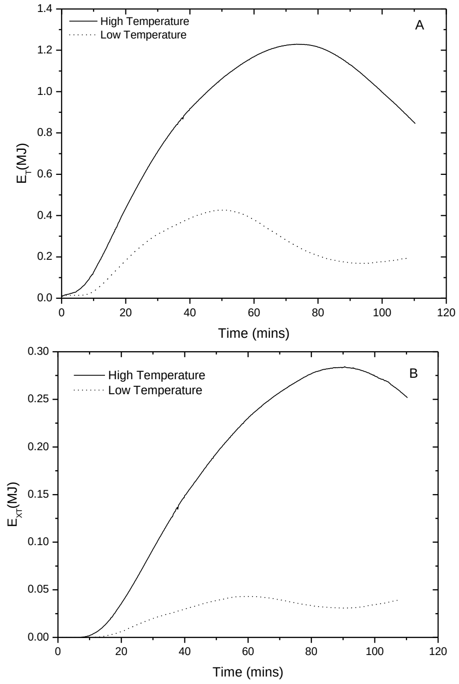

Figure 4 Energy and exergy profiles of Sunflower Oil under high temperature and low temperature charging conditions.

For low temperature charging at the higher flow-rate, the energy and exergy values are low as expected, since this flow-rate promotes a higher loss in thermal stratification. As a result of the increased heat transfer under low temperature charging, the peak values of the stored energy and exergy are attained earlier with a high charging flow-rate. The steepened temperature profiles at the top of the storage tank for low temperature charging cause the energy and exergy profiles to rise slightly after 90 mins of charging. It is also important to note that exergy profiles start to rise at later times. This is due to the fact that it takes some time for the storage tank temperatures to rise above the ambient temperature to enable useful energy to be stored. High temperature charging at a low flow-rate is the ideal charging scenario and these temperatures can be achieved with small solar concentrating systems.

Figure 5 shows profiles of the thermal gradient and the exergy factor (ratio of the quality of energy to the quantity of energy) for the two experimental conditions. The higher temperature charging condition results in the higher thermal gradient. The profiles of the energy and exergy are similar to the thermal gradient profiles however the peaks occur at different times with the peak exergy stored being attained at later times when the storage tank temperatures have increased appreciably. Exergy factors rise at times that are later than those of the thermal gradients as a result of the initial temperatures of the storage tank being close to the ambient conditions.

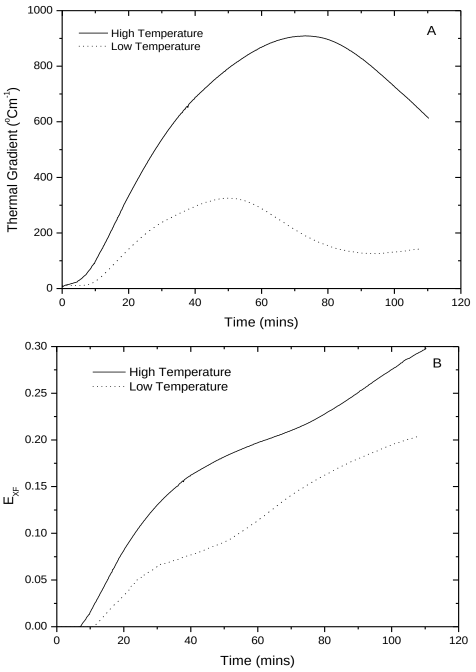

Figure 5 Thermal gradient and exergy factor profiles of Sunflower Oil under high temperature and low temperature charging conditions.

The exergy factor at the end of charging is greater for high temperature charging suggesting that more high quality energy is stored at higher temperatures. The exergy factors at the end of the charging processes are ~0.30 and ~ 0.20 for high temperature and low temperature charging respectively. These results imply that only 30 % and 20 % of quality energy is stored by the storage tank at the end of the respective charging periods. Characteristics dips are evident in the profiles of the exergy factors at ~80 mins *for* high temperature charging and at ~50 mins for low temperature and these correspond to the time when the thermal gradient begins to fall. These characteristic dips can be used to infer qualitatively the time when the thermal gradient begins to fall.

Discharging Results

Figure 6 shows temperature profiles under high flow-rate (8.0 ml/s and low flow-rate (4.2 ml/s) discharging conditions after high temperature charging. The higher flow-rate (8.0 ml/s) shows the higher rate of rise in the water temperature to the boiling point (~ 18 mins) due to the larger rate of heat transfer from the discharging heat exchanger to the water. For the 4.2 ml/s flow-rate, the discharging time for boiling water is ~35 mins due to the lower heat transfer rates. For the lower discharging flow-rate, the discharging test is carried out for 60 mins due to the lower rate of heat transfer.

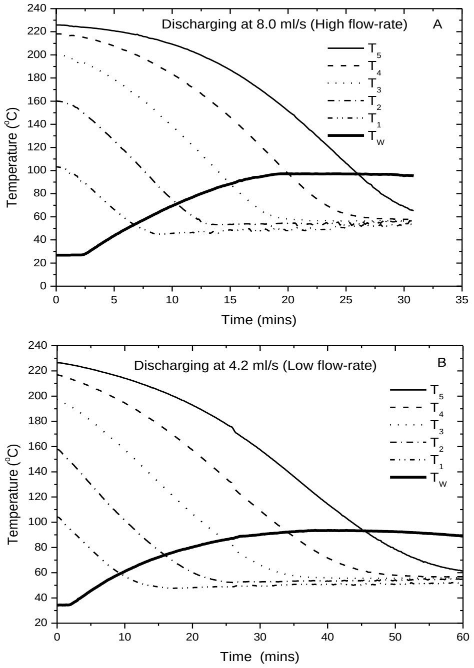

Figure 6 Temperature profiles of Sunflower Oil under high flow-rate and low flow-rate discharging cycles after high temperature charging cycles.

It is important to note that higher flow-rate is useful for fast cooking at the expense of reducing the stored energy rapidly due to mixing caused by the high flow-rate that reduces thermal stratification. At the end of the discharging process, for the high flow-rate, the top of the storage tank is at 65 °C while the bottom is at around 50 °C. This a temperature difference of only 15 °C. The temperature at the top and the bottom of for the lower discharging flow-rate the temperatures are ~160°C and 50 °C (a temperature difference of 110 °C) after 30 mins of discharging. The lower flow-rate extends the discharging period and maintains thermal stratification for a longer period which is desirable when cooking foods that take longer times to cook. It is essential to comment that a relatively large volume of water of around 4.5 litres has been used in the experiments. By using a smaller volume of water and an optimized design for the discharging heat exchanger, the time taken to cook may be significantly reduced as pointed out by Mussard et al. [3].

The energy and exergy profiles under high flow-rate and low flow-rate discharging cycles are shown in Figure 7.

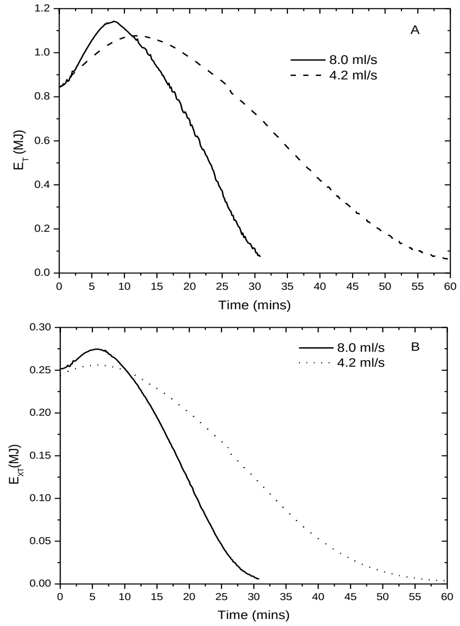

Figure 7 Energy and exergy profiles of Sunflower Oil under high flow-rate and low flow-rate discharging cycles after high temperature charging cycles.

The profiles show an initial slight rise in the stored energy since the top temperature is much higher than the bottom temperature of the storage tank. It takes a finite duration of time for heat from the top to be circulated effectively to the water in the pot where the discharging heat exchanger is placed. For the higher flow-rate having a faster rate of heat transfer, the drop from the peak energy and exergy values is more rapid and the stored energy and exergy is used up to heat up the water quickly. Energy and exergy is utilized more effectively with the lower flow-rate since the rates of the drops of the energy and exergy profiles are slower and occur for longer periods compared to the higher flow-rate. Low flow-rates thus encourage cooking processes which take longer times.

Thermal gradient and exergy factor profiles for the two discharging experimental tests are shown in Figure 8. The faster rate of drop in the thermal gradient is seen with the higher flow-rate due to the greater rate of heat utilization. The lower flow-rate has a lower rate of drop in the thermal gradient at the expense of heating water slower. The exergy factor profiles also show characteristic dips which signify the time when the maximum thermal gradients begin to fall; this was also depicted in the charging exergy factor profiles. The exergy factor values at the end of the discharging cycles are higher for the higher flow-rate suggesting that the quality of the energy stored degrades to lesser values for prolonged low flow-rate charging. However, at the same instant of time, (~30 mins), low flow-rate discharging shows higher values of the exergy factor. There is need to investigate on an optimal discharging flow-rate which is a compromise between obtaining a high rate of heat transfer and obtaining heat utilization for a longer period of time.

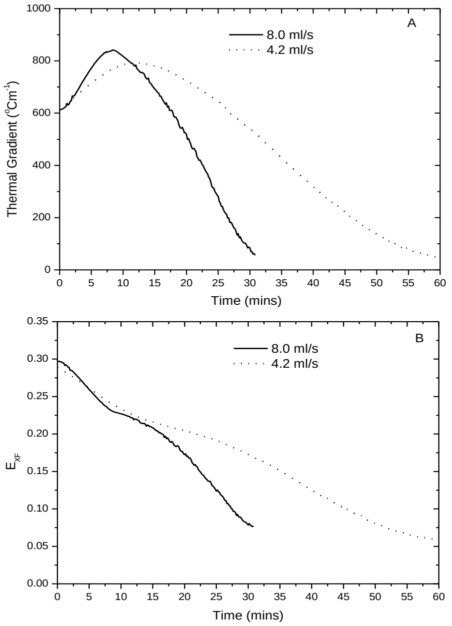

Figure 8 Thermal gradient and exergy factor profiles of Sunflower Oil under high flow-rate and low flow-rate discharging cycles after high temperature charging cycles

CONCLUSION

An experimental setup to characterize edible Sunflower Oil as a heat storage medium for domestic solar cooking was presented. Charging and discharging experiments were performed to evaluate Sunflower Oil experimentally. The thermal performance of the oil was evaluated in terms of energy and exergy based thermal parameters. Four parameters were evaluated namely; energy, exergy, thermal gradient and the exergy factor during charging and discharging cycles.

High temperature charging was found to be the most viable option which resulted in higher energies, higher exergies, higher thermal gradients and higher exergy factors. For the discharging cycles, the higher flow-rate resulted in a fast heat transfer rate which destroyed thermal stratification earlier but heated up water faster. The lower discharging flow-rate ensured that the discharging cycle could be carried out for a longer period. This was beneficial in utilizing the stored energy and exergy for a longer period so that it could be used for cooking foods that take longer times to cook. There is a need to investigate on an optimal flow-rate for better heat transfer and for using the stored energy more effectively. Exergy factor profiles during charging and discharging cycles showed characteristic dips, which corresponded to the time when the thermal gradients started to decrease.

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