Performance of a domestic oil storage tank during charging and discharging cycles

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Abstract

The overall experimental thermal performance for complete charging and discharging cycles of a 40 L Sunflower Oil storage tank is presented. Results of two complete charging and discharging cycles are presented. The oil is heated electrically using a copper spiral coil in thermal contact with electrical heaters. A spiral copper coil immersed in a water bath discharges the stored thermal energy. The first complete cycle charges at a low flow-rate of 0.6 L/min and discharges at a high flow-rate of 1.7 L/min. The second cycle charges at a high flow-rate of 1.8 L/min and discharges at a high flow-rate of 1.7 L/min. The charging energy and exergy rates for the first cycle are higher than that of the second cycle, however, the discharging energy and exergy rates are higher for the second cycle. Total stored energy and exergy values for the charging period are higher for the first cycle as compared to the second cycle. The stored energy and exergy are discharged more efficiently in the second cycle. The overall energetic and exergetic efficiencies of the second cycle are higher than those of the first cycle suggesting that a high charging and discharging flow-rate is essential to increase the overall efficiency of the system.

Keywords:Charging; Discharging; Energy; Exergy; Oil Storage Tank

1. Introduction

Two widely adopted thermal energy storage (TES) systems for domestic applications are sensible heat TES (SHTES) and latent heat TES (LHTES) (Dincer and Rosen, 2002). These systems are essential to cater for the mismatch between energy supply and demand especially when intermittent energy resources like solar energy are involved. LHTES has advantages of a high energy storage density and controlled charging and discharging temperatures but it suffers from some disadvantages such as high cost, low thermal conductivity and supercooling in some phase change materials (PCMs), only to mention a few. When issues of cost outweigh the issues of energy storage density and temperature controlled applications, SHTES seems to be the most viable option. Water is the mostly used SHTES for low temperature applications, however, its use is limited to applications below its boiling point so it cannot be used for medium to high temperature applications without pressuring the storage vessel. Thermal oils have been used in recent years for domestic and industrial applications (Mussard and Nydal, 2013; Mussard et al., 2013; Mawire et al. 2009, Bruch et al., 2014; Bruch et al., 2017) . The advantages of these oils are that they can be used for higher temperatures and they exhibit better thermal stratification as compared to water.

Previous studies (Mawire et al., 2014; Mawire, 2016) have focused on the use of Sunflower Oil as a TES medium since it is cheap, it is readily available locally in most countries in the world, it is food grade and environmentally friendly and it has comparable characteristics to commercially available thermal oils. In previous studies smaller storage tanks were used to characterize the performance of Sunflower Oil using separate charging, discharging and heat retention cycles. Energy, exergy and thermal stratification related quantities were evaluated in these separate cycles and the overall thermal performance for a complete charging and discharging cycle was not evaluated which is necessary for a complete understanding of the end user application. Besides this, the previously reported storage tanks were smaller for any real sustainable practical purpose and some initial storage charging conditions were not similar within experimental error limits.

In a bid to understand the overall thermal performance of a domestic oil storage tank during complete charging and discharging cycles, an experimental setup is presented in this paper under two cases and different TES

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parameters are evaluated. The aim is to evaluate the energetic and exergetic performance of the TES system for the two complete charging and discharging cycles. The first complete cycle charges the storage tank at a low flow-rate of 0.6 L/min and discharges it at a high flow-rate of 1.7 L/min. In the second complete cycle, the storage tank charges at a high flow-rate of 1.8 L/min and discharges it at a high flow-rate of 1.7 L/min.

2. Experimental setup and procedure

The experimental setup and procedure for the charging and discharging experiments is shown in Fig. 1 and the main components of the experimental setup are shown in the photograph of Fig. 2. The insulated storage tank (i) is 40 litres and it contains Sunflower Oil. During charging with the electric heater in thermal contact with an oil circulating copper coil, valves (1) and (2) are opened while valves (3), (4), (5), (6) are closed. During discharging, valves (4), and (5) are opened while valves (1), (2), (3) and (6) are closed. The HTF flow rate is controlled by adjusting the frequency of the circulating pump (c) via the VLT microdrive (b). The maximum temperature of the electric heating unit (d) is adjusted by the temperature controller module (e). The flow of the HTF is from the top of the tank to the bottom during both charging and discharging cycles and this is measured with a positive displacement flow meter (f). 5 radial K thermocouples measure the temperature distribution at five different axial positions. Thermocouples T11-T15 measure the temperatures at the top of the storage tank such that an average temperature at the top of the storage is determined. Other average temperatures for levels 2-5 are determined in a similar manner.

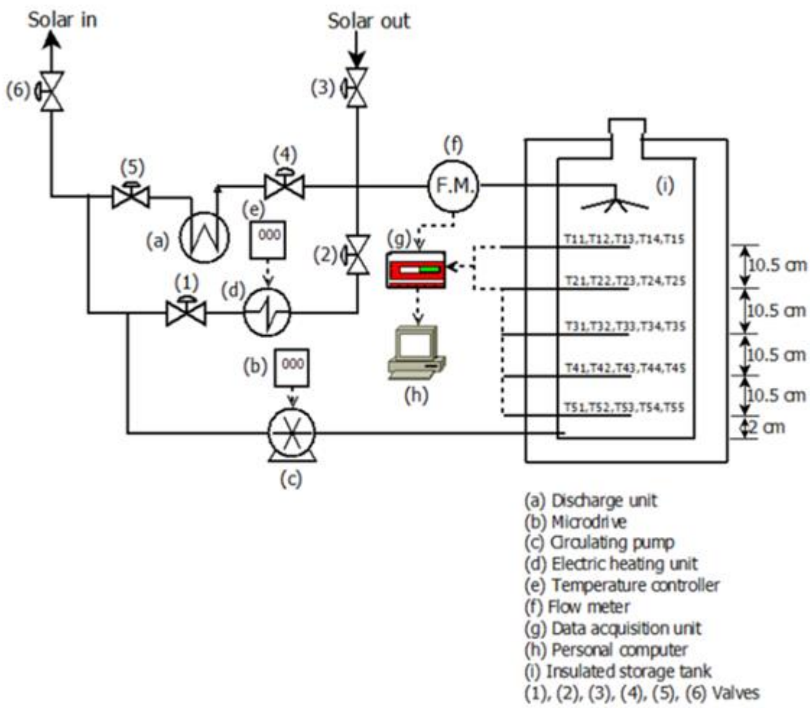

Figure 1: Experimental setup

Firstly it was ensured that the average temperature of the storage tank was around 40 ^{o}C by slightly charging it if it was below this temperature, or discharging it if it was above this temperature. Charging was performed by opening valves (1) and (2) in Fig. 1, while the other valves were left closed. For discharging, valves (5) and (4) were opened while the other valves were closed. During each charging cycle, the temperature controller for the electrical heater was set to 250 ^{o}C and the flow-rate was set to a desired value by adjusting the frequency of the microdrive. Charging was continued until the top of the storage tank attained an average temperature of just above 190 ^{o}C. After this, discharging was immediately done by opening valves (5) and (4) and the discharging cycle was stopped when the temperature of the water bath (which contained 3 liters of waters) fell to just below 100 ^{o}C.

Figure 2: Photograph of experimental setup showing the main components. (1) Insulated storage tank (2) Electrical heater with copper spiral coil (3) Control valves (4) PID temperature controller (5) Discharging coil (6) Datalogger

3. Thermal performance parameters

The charging energy rate depends on the inlet and outlet charging temperatures of the storage tank and is expressed as

$$\dot{E}_{ch} = \rho_{av} c_{av} \dot{v}_{ch} (T_{chin} - T_{chout}) \quad (1)$$

where ρ_{av} is the temperature dependent average density of the oil at the start and end of charging, c_{av} is the temperature dependent average density of the oil at the start and end of charging, $\dot{v}_{ch}$ is the volumetric charging flow-rate, T_{chin} is the inlet charging temperature at the top of the storage tank and T_{chout} is the outlet charging temperature at the bottom of the storage tank. The total energy stored in stored tank can be estimated by integrating Eq. (1) from the start of charging to the end of charging for each small temperature measurement interval and this can be expressed as (Alam; 2015; Jegadheeswaran et al., 2010)

$$E_{ST} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{v}_{ch} (T_{chin} - T_{chout}) dt \quad (2)$$

and the charging exergy rate is given as (Jegadheeswaran et al., 2010)

$$\dot{E}_{xch} = \rho_{av} c_{av} \dot{v}_{ch} \left[(T_{chin} - T_{chout}) - \left(T_{amb} \ln \frac{T_{chin}}{T_{chout}} \right) \right] \quad (3)$$

where T_{amb} is the ambient temperature. The total charging exergy is also evaluated by integrating Eq. (3) and it is expressed as

$$E_{XCHT} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{v}_{ch} \left[(T_{chin} - T_{chout}) - \left(T_{amb} \ln \frac{T_{chin}}{T_{chout}} \right) \right] dt. \quad (4)$$

The discharging energy rate can be expressed as

$$\dot{E}_{dis} = \rho_{av} c_{av} \dot{v}_{dis} (T_{disin} - T_{disout}) \quad (5)$$

where $\dot{v}_{dis}$ is the discharging volumetric flow-rate, T_{disin} is the discharging inlet temperature from the storage tank to the discharging coil and T_{disout} is the discharging outlet temperature from the discharging coil to the storage tank. The total energy discharged from the stored tank can be estimated by integrating Eq. (5) from the start of discharging to the end of discharging for each small temperature measurement interval and this can be expressed as (Alam, 2015, Jegadheeswaran et al., 2010)

$$E_{DIST} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{v}_{dis} (T_{disin} - T_{disout}) dt. \quad (6)$$

The discharging exergy rate is expressed as (Alam; 2015; Jegadheeswaran et al., 2010)

$$\dot{E}_{xdis} = \rho_{av} c_{av} \dot{v}_{dis} \left[(T_{disin} - T_{disout}) - \left(T_{amb} \ln \frac{T_{disin}}{T_{disout}} \right) \right]. \quad (7)$$

The total exergy discharged is obtained by integrating Eq. (7) and this is expressed as

$$E_{XDIST} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{v}_{dis} \left[(T_{disin} - T_{disout}) - \left(T_{amb} \ln \frac{T_{disin}}{T_{disout}} \right) \right] dt \quad . \tag{8}$$

The overall energy efficiency can be expressed by the ratio of the total energy discharged to the total energy stored and this is expressed as (Alam, 2015; Jegadheeswaran et al., 2010)

$$\eta_e = \frac{E_{DIST}}{E_{ST}}. \tag{9}$$

The overall exergy efficiency can also be expressed as the ratio of the total exergy discharged to the total charging exergy and this is given as

$$\eta_{ex} = \frac{E_{XDIST}}{E_{XCHT}}. \tag{10}$$

The exergy factor (Mawire and Taole, 2014) can be expressed as the ratio of the exergy charging/discharging rate to the ratio of the energy charging/discharging rate and it is given as

$$E_{XF} = \frac{\dot{E}_{xch}}{\dot{E}_{ch}} \quad \text{or} \quad E_{XF} = \frac{\dot{E}_{xdis}}{\dot{E}_{dis}}. \tag{11}$$

The variation of the density and the specific heat capacity with temperature is given as (Mawire, 2016; Mawire et al., 2014)

$$\rho_s = 930.62 - 0.65T \tag{12}$$

and

$$c_s = 2115.0 + 3.13T. \tag{13}$$

4. Results and discussion

Fig. 3 shows two experimental charging plots using the same flow-rate of 0.6 L/min with almost the same initial conditions to test the repeatability of the experimental results. The plots for the two tests are almost identical for the charging temperatures at the top and the bottom of the tank (T_{chin} and T_{chout}), for the top level of the storage tank (T_1) and for the middle of the storage tank (T_3). Small deviations between the two tests are due slightly different initial conditions and the measurement errors due to the accuracies of the thermocouples used in the measurements. It can thus be concluded that the experimental results are reproducible and reliable within the experimental error limits.

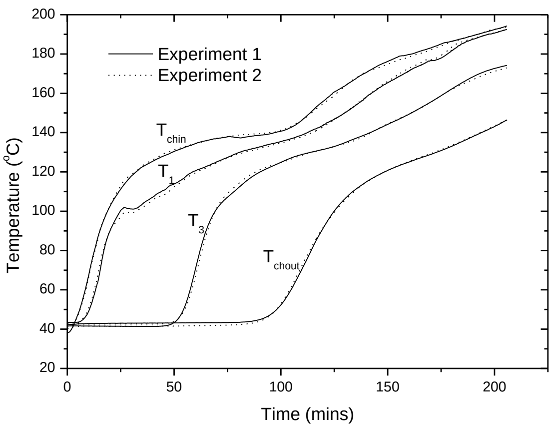

Figure 3: Repeatability charging experiments with a flow-rate of 0.6 L/min.

Fig. 4 shows the temperature profiles along the height of the storage tank for the two complete charging and discharging cycles. For case 1, the temperature profiles show evident layering of the storage tank levels due to the lower charging flow-rate which promotes a larger degree of thermal stratification. The higher flow-rate shows lower temperature differences between adjacent levels due to the larger flow-rate which promotes a higher degree of heat transfer during charging and thus a loss of thermal stratification. Case 2 is charged for a longer period because of the higher flow-rate that causes the upper limit charging temperature of about 190 °C at the top of the storage to be achieved later. The temperature variations for case 1 during charging show a characteristic flattening of the profiles particularly at the top possibly due to heat losses and radial thermal conductivity, thus slowing down the rate of axial heat transfer. Discharging temperature profiles are almost identical for both cases although case 1 has a more thermally stratified distribution at the onset of discharging. Slightly higher TES temperatures are obtained at the end of discharging for case 1 as compared case 2 possibly due to the more thermally stratified distribution

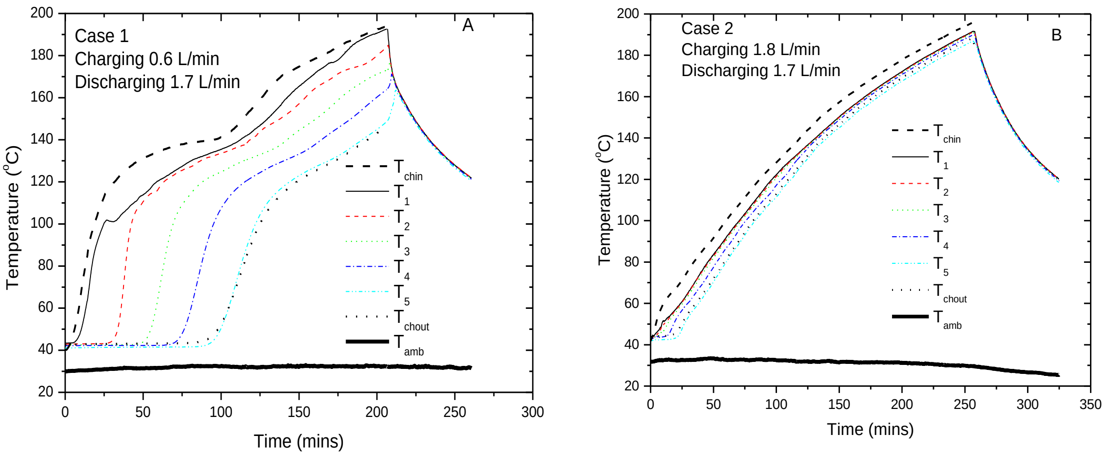

Figure 4: Temperature profiles along the height of the storage tank for experimental charging and discharging cycles case 1 (A) and case 2(B).

Table 1: Thermal performance parameters for the two cases

Parameter	**Case 1**	**Case 2**
Charging flow-rate (L/min)	0.6	1.8
Initial average storage temperature, T_{iniav} (°C)	42.4	43.1
T_{1av} at the end of charging (°C)	193.0	191.5
Average charging ambient temperature, $T_{ambchav}$	31.9	31.8
Average discharging ambient temperature, $T_{ambdisav}$	32.0	27.2
Charging time (mins)	206	258
Discharging time (mins)	54	60
Total energy stored, E_{ST} (MJ)	17.28	12.69
Total exergy stored, E_{CHXT} (MJ)	3.41	2.67
Discharging flow-rate(L/min)	1.7	1.7
Maximum charging energy rate (W)	2920	560
Maximum charging exergy rate (W)	490	180
Maximum charging exergy factor (-)	0.31	0.35
Maximum discharging energy rate (W)	3000	3800
Maximum discharging exergy rate (W)	550	950
Maximum discharging exergy factor (-)	0.18	0.25
Total energy discharged , E_{DIST}(MJ)	3.70	4.69
Total exergy discharged, E_{XDIST} (MJ)	0.88	1.25
Overall energy efficiency, η_e(-)	0.21	0.37
Overall exergy efficiency, η_{ex}(-)	0.26	0.47

Table 1 shows the thermal performance parameters for the two cases The total energy and exergy values stored during the charging period for case 1 are higher as compared to case 2 due to the larger degree of thermal stratification in case 1. It is clear that the higher charging flow-rate results in low values of the total energy and exergy stored due to a loss in thermal stratification. Due to a smaller temperature difference between the top and the bottom of the storage tank for the higher charging flow-rate, the maximum charging energy and exergy rates for case 2 are lower as compared to case 1. Even though, the energy and exergy rates for case 1 are higher than that of case 2, the maximum exergy factor for case 2 is larger than that of case 1 due the higher average thermal energy storage temperatures for case 2. This suggests that more quality energy stored is at a higher flow-rate due the increase in the heat transfer rate. For the discharging period, case 2 with the higher temperatures induced by the higher charging flow-rate shows higher values of the total discharged energy and exergy. The overall energy and exergy efficiencies for case 2 are higher as compared to case 1, suggesting that the storage tank should be charged with a high flow-rate which increases the rate of heat transfer thus enabling high TES temperatures to be obtained. These higher temperatures ensure that the energy and exergy is discharged more efficiently with a high discharging flow-rate. Charging with a high flow-rate, however, comes at an expense of increasing the charging time with the currently imposed charging conditions. The overall energy efficiencies increase from 0.21 to 0.37 for case 1 to case 2 and the corresponding exergy efficiencies increase from 0.26 and 0.47 respectively. The exergy efficiencies are seen to be higher than the energy efficiencies which also agrees with previous simulated studies (Mawire et al., 2010) done on an oil/packed bed TES system. Although thermal stratification is important in storing maximum energy and exergy, it seems to be outweighed by the maximum temperature (due to high rate of heat transfer) that can be achieved which improves the overall storage efficiency.

5. Conclusion

An experimental study on the overall experimental thermal performance for two complete charging and discharging cycles of a 40 L Sunflower Oil storage tank has been presented. The oil was heated electrically using a copper spiral coil in thermal contact with electrical heaters. A spiral copper coil immersed in a water bath discharged the stored thermal energy. The first complete cycle charged at a low flow-rate of 0.6 L/min and discharged at a high flow-rate of 1.7 L/min. The second cycle charged at a high flow-rate of 1.8 L/min and discharged at a high flow-rate of 1.7 L/min. The charging energy and exergy rates for the first cycle were higher than that of the second cycle due to the larger degree of thermal stratification induced by the lower flow-rate. The discharging energy and exergy rates were higher for the second cycle due to the higher heat transfer rates which resulted in higher storage tank temperatures. Total stored energy and exergy values for the charging period were higher for the first cycle as compared to the second cycle due to the higher degree of thermal stratification in the first cycle. The stored energy and exergy was discharged more efficiently in the second cycle. The overall energetic and exergetic efficiencies of the second cycle were higher than those of the first cycle suggesting that a high charging and discharging flow-rate is essential to increase the overall efficiency of the system. Although thermal stratification was important in storing maximum energy and exergy, it seemed to be outweighed by the maximum temperature (due to high rate of heat transfer) that could be achieved which improved the overall storage efficiency..

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