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De-stratification and heat loss comparison of three thermal oils in a small storage tank

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Abstract

An experimental comparison of de-stratification and heat loss characteristics of three different thermal oils in a storage tank is presented in this paper. The three thermal oils evaluated are Sunflower Oil, Shell Thermia C and Shell Thermia B. A small insulated 20 liter storage tank is firstly charged up with the use of an electrical heater in thermal contact with an oil circulating copper spiral coil. After charging, the storage tank is left to cool down for 24 hr cycles. Cool-down experimental thermal cycles are carried out with the three different oils. De-stratification and heat loss parameters are evaluated. The stratification number is evaluated and it signifies the degree of thermal stratification. Stratification numbers are seen to be slightly higher for Sunflower Oil as compared to the other oils at the later stages of cool-down. The heat loss factor for Sunflower Oil is lower when compared to the other thermal oils, suggesting that it is the superior oil in terms of heat retention.

Keywords: *De-stratification, heat loss, thermal oils, storage tank*

1. Introduction

In any domestic heat storage application, the rate of thermal degradation is directly related to the heat losses and the period of useful storage during cool-down thermal cycles. Heat retention or cool-down thermal cycles are essential to obtain a measure of how long the stored heat can be kept without considerable degradation which makes it un-useable. Recent work has been done to study heat losses and stratification in low temperature water storage tanks during cool-down thermal cycles (Cruickshank and Harrison, 2010; Fan and Furbo, 2012; Fernandez-Seara et al., 2011; Oliveski et al., 2003) . Limited studies have been done on heat losses during cool-down cycles using other thermal energy storage (TES) media other than water for higher temperatures (Mawire, 2013; Park et al., 2014; Okello et al., 2014; Oliveski et al., 2005; Suárez et al., 2015). According to our literature review, very little work has been done on experimental heat losses and thermal de-stratification comparisons of different TES media which operate above the boiling point of water. For small domestic scale applications during heat retention periods, it is thus necessary to do this study. In this particular paper, simplified experimental thermal de-stratification and heat loss characteristics of a small domestic oil storage tank using three different thermal oils are presented.

2. Experimental method

The schematic diagram of Fig. 1 shows the operation of the charging cycle before cooling occurs. A positive displacement charging pump (3) controlled by a variable DC power supply (4) is used to circulate oil through a copper spiral coil that is in thermal contact with an electrical heating element (1). The DC power supply is adjusted manually to vary or maintain the average charging flow-rate. An oval gear volumetric flow-meter (5) is at the bottom of a 20 litre thermal oil storage tank (6) such that it records the volumetric flow-rate during charging . The charging pump extracts oil at the bottom of the tank and pushes it through an electrical heater with an oil charging coil (1). The oil enters the charging coil at a temperature T_{in} and exits the coil at a temperature T_{out} after absorbing heat from the electrical heater controlled by a variac (2). The oil enters the top of the storage tank at a hotter temperature as compared to the bottom of the tank. The charging cycle is repeated until the bottom of the storage tank attains a relatively high temperature (~100 ^{o}C).

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For the heat retention tests, the pumps and the electrical heating elements are switched off. The storage tank is then left to cool-down naturally for 24 hrs as temperature data are recorded with a data-logger every 10 s. The storage tank is insulated with 50 cm thick rock wool that this wrapped around its walls. The insulation is placed inside an aluminium thermal shield that surrounds the storage tank.

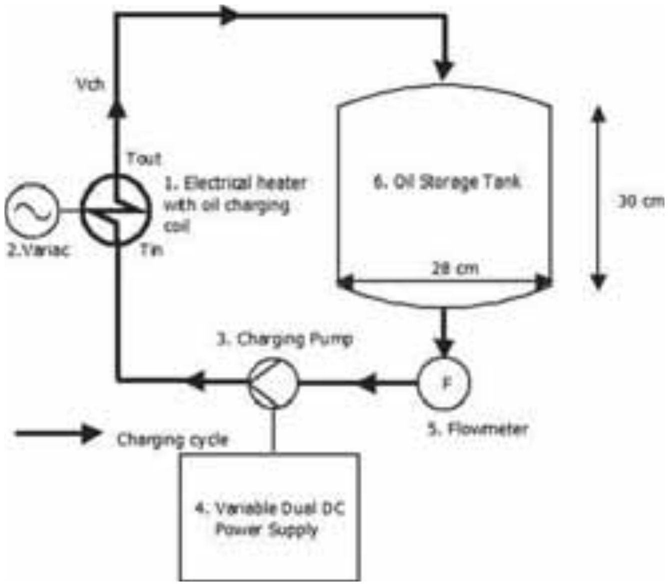

Figure 1: Experimental setup and operation (Mawire and Taole, 2013).

The temperatures in the storage tank during cool-down are monitored with 15 K-type of thermocouples placed inside the storage as shown in Fig. 2. The 15 K-type thermocouples are placed at three radial positions at five different levels along the height of the storage tank (5 axial levels). 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. An average storage tank temperature is thus determined from these average temperature measurements. The top thermocouples are placed at a level 50 mm below the top of the storage tank, while the bottom thermocouples (Level 1) are placed at a level 50 mm above the bottom of the storage tank.

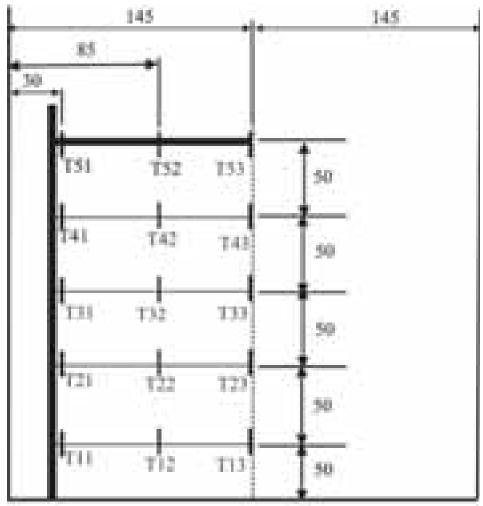

Figure 2: The arrangements of the 15 thermocouples in the storage tank. All dimensions are in mm (Mawire and Taole, 2013).

3. Experimental thermal analysis

During the heat retention thermal cycles, the stratification number is defined by Fernandez-Seara et al. (2007) as the ratio of the mean of the thermal gradients at each time interval to that of the beginning (t = 0) and it is expressed as

$$Str = \frac{\left(\frac{\partial T}{\partial y}\right)_t}{\left(\frac{\partial T}{\partial y}\right)_{t=0}} \quad (1)$$

where

$$\frac{\partial T}{\partial y} = \frac{1}{j-1}\left[\sum_{j=1}^{j}\left(\frac{T_{j+1}-T_j}{\Delta y}\right)\right]. \quad (2)$$

where T is the average temperature at an axial level and $\Delta y = 0.05$ m is the axial distance between two adjacent thermocouple levels.

The energy lost during a 4 hr heat retention process is given as

$$E_L = \rho_{av} c_{av} V_{ST}\left(T_{iniav} - T_{finav}\right) \quad (3)$$

where ρ_{av} is the average density of the storage tank segments, c_{av} is the average specific heat capacity of the storage tank segments, V_{ST} is the total volume of the segments, T_{iniav} is the initial average temperature of the storage tank segments and T_{finav} is the final average temperature of the storage tank segments. The total rate of heat loss (which is inclusive of the insulating material, oil and tank conductivity e.t.c) during heat retention processes can be expressed as (Cruickshank and Harrison, 2010)

$$P_L = \frac{\rho_{av} c_{av} V_{ST}\left(T_{iniav} - T_{finav}\right)}{\Delta t} \quad (4)$$

where Δt is the 4 hr time interval. Heat loss to the surroundings can also be expressed as

$$P_L = U_L^{'}\left(T_{av} - T_{amb}\right) \quad (5)$$

where T_{av} is the average temperature of the segments and $U_L^{'}$ is the heat loss factor given by

$$U_L^{'} = U_L A_{ST}. \quad (6)$$

where U_L is the heat loss coefficient and A_{ST} is the overall area of the storage tank segments where the temperature is measured.

The thermal properties of the oils are temperature dependent and their temperature dependent equations are calculated from their datasheets and research papers published in literature from experimental tests (Shell Thermia B Datasheet, 2014; Shell Thermia C Datasheet, 2014; Esteban et al., 2012; Fasina and Colley, 2008; Turgurt et al., 2008). Table 1 shows the thermal properties of the different oils as a function of the temperature in ^{o}C. Sunflower Oil has the highest temperature dependent density and specific heat capacity. The thermal conductivities are seen to be within the same range. Information regarding the viscosity change with temperature of the oils was not available in literature therefore experiments need to be done.

Table 1: Temperature dependent thermal properties of the heat transfer oils

Thermal Oil	Density (kg/m^3)	Specific Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)
Sunflower Oil	ρ_S = 930.62-0.65T	c_S = 2115.00+3.13T	k_S = 0.161+0.018exp(-T/26.142)
Shell Thermia C	ρ_C = 893.00-0.67T	c_C = 1798.00+3.58T	k_C = 0.121+0.132exp(-T/18.659)
Shell Thermia B	β_B = 876.00-0.65T	c_B = 1809.00+3.50T	k_S = 0.118+0.018exp(-T/168.660)

4. Results and discussion

Dimensionless thermal profiles are presented in Fig. 3, since the initial TES temperatures were slightly different for the three thermal oils due to slightly different initial charging conditions. Dimensionless temperature profiles ($T' = \frac{T}{T_{ini}}$) enable a fairer comparison of the thermal distributions during heat retention since the temperature distributions are relative to the initial conditions. The heat retention process is started when the bottom of the storage tank has reached a limiting temperature of approximately 100 ^oC during the charging process. This limit was set because the flow-meter could with-stand temperatures of only up to 120 ^oC.

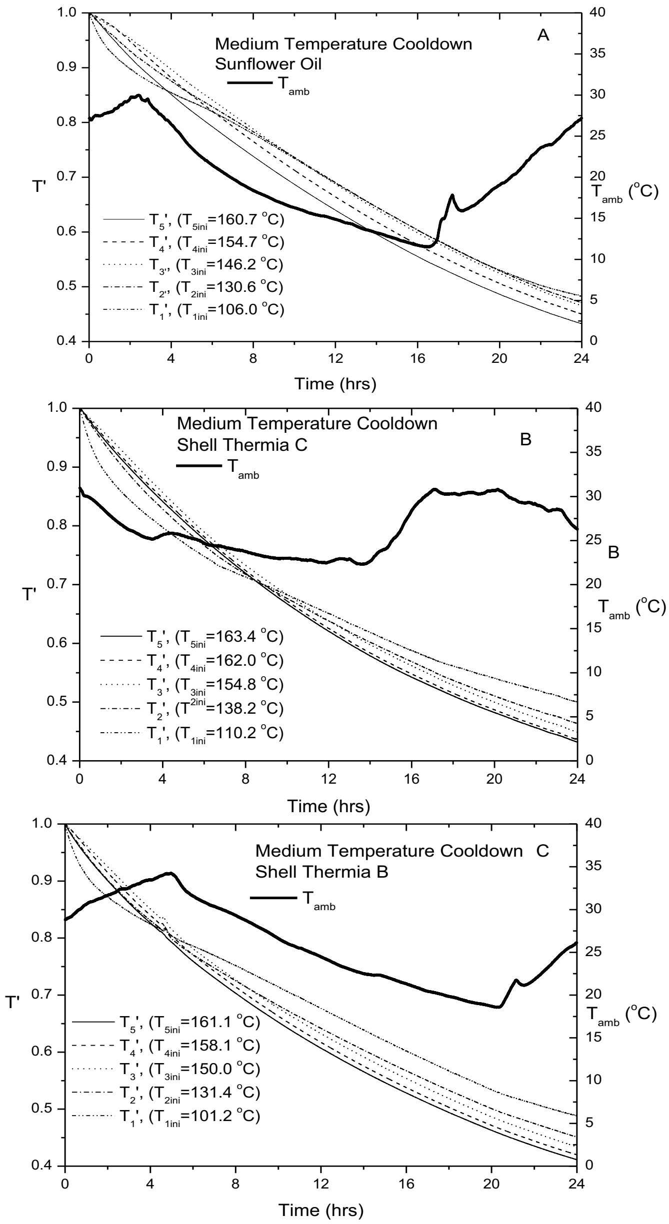

Figure 3: Dimensionless thermal profiles during 24 hr cool-down cycles for the three thermal oils.

Fig. 3 shows a general trend of similar drops in initial temperatures at a faster rate at T_5 (at the top of the storage tank) for the three thermal oils, thus implying more heat losses. T_1 has a slow rate of drop at the later stages of heat retention when compared to T_5 for all the three thermal oils. This is because the density at the bottom of the storage tank becomes appreciably larger than at the top as time progresses because of the lower temperature at the bottom. This implies a larger thermal mass at the bottom of the storage tank at the later stages which results in a low rate of drop in the temperature. The slower rate of drop at T_1 relative to T_5 for Shell Thermia C occurs at a later time due to the higher storage temperatures. Sunflower Oil attains larger average temperatures at the end of 24 hrs suggesting that this the best oil in terms of heat retention even though its initial top storage tank temperatures are less than that of the other two oils. This suggests that the thermal mass effect is more pronounced for Sunflower Oil, the oil with the greatest density. The variations of the ambient temperatures are in accordance to the time of day when the experiments were carried out and these do not any effect on the heat loss process since the storage tank is insulated with a heat loss factor value of around 0.11 W/K.

Fig. 4 shows stratification number profiles for the three thermal oils during 24 hr heat retention cycles. The stratification number profiles decrease with time due to heat losses induced by natural convection. Shell Thermia C shows a delayed drop in stratification number as compared to the other thermal oils. This is because of the higher initial temperatures which promote a higher degree of thermal stratification. The stratification number profiles for Shell Thermia B and Sunflower Oil are almost identical during the first 4.5 hrs of cool-down possibly due to similar temperature profiles. After 4.5 hrs, Sunflower Oil shows greater values of the stratification number. This is because of the larger thermal mass due to the larger density of Sunflower Oil at the later stages. This larger thermal mass results in lower heat losses. The thermal mass effect is also evident after around 13 hrs where the stratification number profile for Sunflower Oil becomes larger than that of Shell Thermia C.

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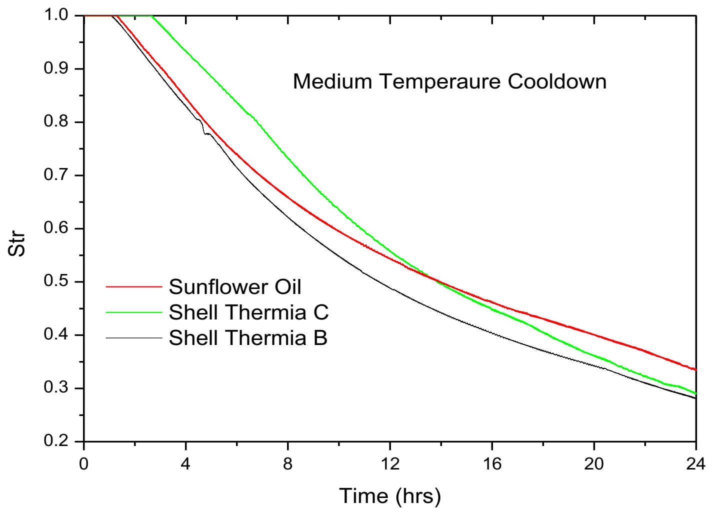

Figure 4. Stratification number profiles during 24 hr cool-down cycles for the three thermal oils.

Fig. 5 shows heat loss factors for the three thermal oils indicated by the slopes of the linear fits. Sunflower Oil is seen to have the least heat loss factor (lower gradient) as compared to the other thermal oils due to its larger thermal mass. Shell Thermia B shows the greatest heat loss factor due to its lower thermal mass. This result suggests that Sunflower Oil has better heat retention as compared to the other thermal oils.

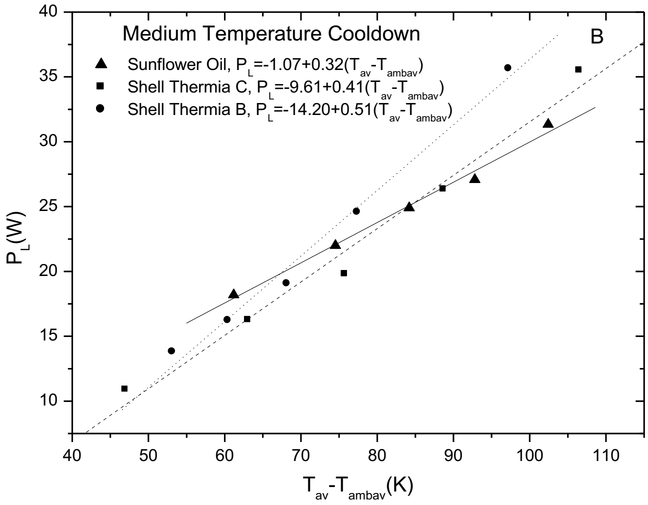

Figure 5. Heat loss factors for the three thermal oils.

5. Conclusion

Experimental results for the comparison of de-stratification and heat loss characteristics of three different thermal oils in a small storage tank were presented in this paper. The three thermal oils evaluated were Sunflower Oil (an edible oil), Shell Thermia C and Shell Thermia B. De-stratification and heat loss parameters were evaluated from cool-down thermal profiles. The stratification number was evaluated and it signified the degree of thermal stratification. Stratification numbers were seen to be slightly higher for Sunflower Oil when compared to the other oils at the later stages of cool-down due its larger thermal mass. The heat loss factor for Sunflower Oil was lower as compared to the other thermal oils, suggesting that it was the superior oil in terms of heat retention.

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