Modelling of oil based medium temperature sensible heat thermal energy storage systems during charging

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Abstract

A simulation model for oil based medium temperature sensible heat storage systems for domestic solar cooking applications is developed and validated with experimental results. The simulated and experimental results are simultaneously compared for three sensible heat storage systems during charging. The three systems compared are a Sunflower Oil storage tank, a Sunflower Oil/10.5 mm pebbles packed bed storage tank and a Sunflower Oil/31.9 mm pebbles packed bed storage tank. The packed bed TES systems have void fractions of 0.39 and 0.43, respectively. A forward finite difference model is developed in Matlab to simulate the storage systems. Validation of the thermal energy storage (TES) models is done using a flow-rate of 4 mls^{-1}. A good level of agreement exists between simulated and experimental results with an overall mean percentage error (deviation) of 6 % for the Sunflower Oil/31.9 mm pebbles packed bed storage tank. The effect of the charging flow-rate, inlet charging temperature, thermal oil and solid storage material is investigated with the model. An increase in the flow-rate leads to the faster decrease in the temperature gradients in the TES systems considered. An inlet temperature increase results in faster rises of the storage tank temperatures, and higher maximum temperatures in the storage tanks. Considering the different thermal oils, the best storage performance is seen with Sunflower Oil since it shows better thermal stratification. The best packed bed sensible heat storage material is granite since it shows larger thermal gradients.

Keywords: Charging; Modelling and simulation; Packed bed thermal energy storage; Sunflower Oil

1. Introduction

Energy is essential for the social and economic development of any society (Rehma et al., 2014). Clean energy supply is still limited especially in most developing countries as biomass still serves as the major source of cooking energy. The supply of fossil fuels has also become inadequate for the growing global population which has led to an upward rise in their prices due to their high demand (World Energy Council, 2010). In order to continuously harness and utilize clean and sustainable energy which is not disrupted by low/no sunshine periods, solar thermal energy storage (TES) is essential (Kolb et al., 2011). Thermal energy storage (TES) is an emerging advanced technology for storing thermal energy that can enable more efficient and clean energy utilisation. TES systems developed for domestic applications are practically categorized as latent heat thermal energy storage (LHTES), sensible heat thermal energy storage (SHTES) and thermo-chemical reactions. LHTES is advantageous over SHTES because of its high thermal energy density. Unfortunately, LHTES systems are expensive. LHTES using phase change materials (PCMs) has a challenge of severe degradation with time. PCMs usually have low thermal conductivities and require a longer time to absorb and release the same energy for domestic applications such as cooking. This implies that the larger thermal conductivities of sensible heat materials (SHMs) are important for easy heat transfer in TES systems. Foong et al., (2011) noted that in developing countries where the issue of cost effectiveness and simplicity outweighs the issue of superior thermal performance, SHTES systems are more viable options for small-scale domestic applications like cooking of food. This is because these SHTES systems are cheap to design and easy to fabricate and maintain. Several experimental studies have been conducted on SHTES systems (Bindra et al., 2013). However, scientific work using experiments is expensive and needs a lot of precautions which can be alleviated by developing a simulation model.

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Simulation is used to study in detail the dynamics of using different TES configurations and materials in terms of their thermal performance characteristics (Kumar & Rosen, 2010). The classical analytical solution for the heat transfer between a fluid and solids in a packed bed was developed by Schumann, (1929). He used several assumptions of materials. The assumptions included high thermal conductivity inside the solids, low conductivity between solids in axial direction, constant fluid properties, no wall heat losses and no temperature gradient in the radial direction. Another simplified model which basically follows Schumann's model was proposed by Vortmeyer & Schaefer, (1974). This model does not neglect the axial thermal conductivity. The model is useful for systems where the thermal conductivity of the solid phase is much larger than that of the liquid phase, and it combines the two phase models (solid and liquid) into a single phase model. Chikukwa, (2007) modelled a rock bed storage system using the Schumann model and air as the heat transport fluid. Results from the study indicated that rocks could be used to store high temperature heat. Unfortunately, insulation posed a big challenge. Okello et al., (2009) reported an experimental study on high temperature heat storage using rock beds. They presented simulated temperature profiles in the bed during charging and discharging that were similar to the experimental data. Mawire et al., (2008) carried out simulated performances for an oil/pebble packed TES system using a validated model. They reported that thermal stratification, and the total amount of energy and exergy stored were all important parameters for the thermal performance and evaluation of oil/pebble bed storage systems. Lovseth, (1997) proposed a design of a rock bed for high temperature heat storage using solar concentrating systems. What made the system unique was that it was a small scale concentrating system, easy to fabricate, with heat storage for rural food preparation. The study clearly pointed out that further work was needed to achieve a novel system that could be used for cooking. Van-den-Heetkamp (2002) reported on the practical aspects and preliminary results on a rock bed storage system designed for cooking. This study was based on the initial work conducted by Lovseth, (1997). Experimental work and theoretical analysis of the system showed that the system was realistic since the theoretical results were in good agreement with the experimental data. However, it was observed that much work still needed to be done on the system integration of the packed bed. Markus et al., (2011) developed a heat transfer model for high temperature storage using rock beds and air as the HTF. Unfortunately, this study neglected heat transfer by radiation. According to Parameshwarana et al., (2012), the majority of the existing models are applied for low temperatures. These low temperatures are only suitable for space heating using air and water as the storage materials.

The literature available shows that there is very limited work on both modelling and experimental analysis of TES systems designed for cooking using sensible heat materials in the medium temperature ranges using thermal oils. These materials include granite rock pebbles and Sunflower Oil which are widely available in most countries worldwide. The aim of this study is to model oil based medium temperature sensible heat thermal energy storage systems during charging for use in indirect solar cookers. Experimental results of three sensible heat storage systems are used to validate the model namely; (a) A TES system of 7 l of Sunflower Oil (b) a Sunflower Oil/10.5 mm pebble packed bed TES system with a void fraction 0.39, and (c) a Sunflower Oil/31.9 mm pebble packed bed TES system with a void fraction 0.43. A parametric study will be further performed using the experimentally validated model.

2. Mathematical model

A model for predicting the thermal performance of TES systems at medium to high temperatures (100 ^{o}C to 300 ^{o}C) was developed. The model was based on numerical integration, and was used for the prediction of the thermal profiles in the packed systems for performance optimization. The mathematical model developed using Matlab was used to generate temperatures at each axial node and at new time steps, using an implicit-time matching forward finite difference method. The forward finite difference method was chosen for this study because of the small size of the TES system design where few parameters were considered during simulation. A number of explicit assumptions were made in the formulation of the mathematical model for this study. The assumptions were:

i. radiant heat transfer in the storage was neglected and the governing equation was a one axial dimensional equation;
ii. the overall insulation of the system was considered uniform;

iii. the thermo-physical properties of the pebbles were considered constant and calculated at an average temperature;
iv. the pebbles were assumed to be identical and that there was no internal heat generation within the bed;
v. the pebbles were assumed to have a constant volume; and
vi. the HTF was assumed to be flowing over the rocks with a uniform velocity.

The modified equation from Schumann model (Schumann, 1929) for the heat transfer fluid (HTF) is given as Equation 1;

$$\rho_S c_S A_T L_T \varepsilon \frac{\partial T}{\partial t} = Q - \rho_S c_S A_T L_T \dot{V} \frac{\partial T}{\partial y} - u_S \left[T - T_{amb}\right] \qquad (eq.1)$$

, where Q (W) is the heat energy, ρ_s (kgm^{-3}) is the density of Sunflower Oil, c_s (Jkg^{-1}K^{-1}) is the specific heat capacity of Sunflower Oil, A_T (m^2) is the cross sectional area of the tank, L_T(m) is the height of the storage tank ε (-) is the void fraction, $\dot{V}$ (mls^{-1}) is the volumetric flow rate, u_S (WK^{-1}) is the insulation value of the storage tank, T(K) is the temperature of Sunflower Oil, y(m) is the axial coordinate t(s) is the time and T_{amb} (K) is the temperature of the surroundings. The conduction term was not considered in Equation 1 because its effect was negligible as compared to the convection term. Hence convection dominates when a fluid alone was considered for heat transfer/storage. The modified equation from Schumann model for the oil/pebble bed storage system is given as Equation 2;

$$\left[\rho_S c_S A_T L_T \varepsilon + \rho_r c_r A_T L_T (1-\varepsilon)\right] \frac{\partial T}{\partial t} = Q - \rho_S c_S A_T L_T \dot{V} \frac{\partial T}{\partial y} - u_S \left[T - T_{amb}\right] + k_r A_T \frac{\partial T}{\partial y} + h(T - T_r) \qquad (eq.2)$$

,where ρ_r (kgm^{-3}) is the density and c_r (Jkg^{-1}K^{-1}) is the specific heat capacity of the granite pebbles, u_S (WK^{-1}) is the overall heat loss coefficient from the storage tank, k_r (Wm^{-1}K^{-1})is the thermal conductivity of the granite pebbles and h (WK^{-1}) is the heat transfer coefficient from the oil to the pebbles.

The simulated packed bed used in this study was partitioned into 20 adjacent segments/sections. The new values of temperature of the HTF were obtained at the time step of 0.05 s. The temperatures generated by the model in this study were obtained basing on conditions considered for the experimental TES system. The initial conditions considered during the study are;

$$T(t=0) = T_r(t=0) = T_{amb}.$$

The boundary conditions of the TES systems considered during the study are;

$$T(y=0) = T_{in}, \quad \frac{\partial T(y=H)}{\partial y} = 0, \quad \frac{\partial T_r(y=0)}{\partial y} = \frac{\partial T_r(y=H)}{\partial y} = 0$$

, where y(m) is the axial coordinate and H (m) is the height of the tank. The level of accuracy between the experimental and the simulated results was analysed using percentage errors as; (Boylan & Syntetos, 2006);

$$\%\,\text{error} = \frac{|A_V - E_V|}{E_V} \times 100\%$$

, where A_V is the approximate value and E_V is the exact value.

A number of parameters such as the void fraction, specific heat capacity and density among others were used during validation analysis. The thermo-physical parameters of the materials used for validation purposes are summarized in Tab. 1 and Tab. 2. Tab. 1 present the parameters of the materials used during validation. The density and specific heat capacity of Sunflower Oil in Table 1 varied with temperature (Mawire, 2016).

Tab. 1: Input parameters of materials used to model the TES system

Property	**Value**
Volume of Sunflower Oil, *V*	7.0 ± 0.5 l
Specific heat capacity of pebbles, c_r	798 ± 1 $Jkg^{-1}K^{-1}$
Density of pebbles, ρ_r	2634 ± 2 kgm^{-3}
Thermal conductivity of pebbles, k_r	2.12 ± 0.02 $Wm^{-1}K^{-1}$
Heat transfer coefficient from the oil to the pebbles, h	120 ± 1 WK^{-1}
Insulation value of the storage tank, u_s	5 ± 0.1 WK^{-1}
Average ambient temperature, T_{amb}	23.0 ± 0.2 °C
Void fraction of small pebbles, ϵ	0.39 ± 0.01 (-)
Void fraction of big pebbles, ϵ	0.43 ± 0.01 (-)
Average diameter of small pebbles	10.5 ± 0.5 mm
Average diameter of big pebbles	31.9 ± 0.5 mm
Specific heat capacity of Sunflower Oil, c_s	c_s=2115.003+3.13T $Jkg^{-1}K^{-1}$
Density of Sunflower Oil, ρ_s	ρ_s=930.62-0.65T
Thermal conductivity, k_s	k_s=0.161+0.018 exp(−T/26.142)

Table 2 presents the parameters of the TES tank used in this study.

Tab. 2: Parameters of thermal energy storage system

Property	**Value**
Diameter of the tank	0.123 ± 0.005 m
Insulation thickness	0.056 ± 0.005 m
Height of bed	0.692 ± 0.005 m

3. Results and discussion

3.1. Validation of model

The validation of the models for the Sunflower Oil only storage system, the Sunflower Oil/10.5 mm pebbles storage system and the Sunflower Oil/31.9 mm pebbles storage system at a flow rate of 4 mls^{-1} is shown in Fig. 1. Experimental results presented by Lugolole et al. (2018) have been used for validation purposes. The temperature profiles at the top, middle and bottom sections of the experimental storage tank (Levels A, C, D) have been used for validation of the model. The inlet temperature is not presented since the focus is mainly on the temperature distribution inside the tank Generally, the experimental and simulated temperature profiles are close to each other for the same axial level considered as shown in Fig. 1. However, some discrepancies between the experimental and simulated temperature profiles are observed at different levels of the storage systems as shown in Fig. 1. The experimental temperature profiles Te1 rise faster than the simulated temperature profiles Ts1 at level A of the tank in the first 30 mins for all TES systems in Fig. 1. This is because the temperature of the HTF entering the TES system initially rises faster due to the non-uniform and slightly higher heat flux at the outlet of the heater to the inlet of the storage tank in the experimental system. This makes the experimental temperature profiles Te1 to be higher than the simulated temperature profiles Ts1 at level A in all storages. However, the experimental temperature profiles Te2 and Te3 generally have lower temperature values in the initial stages of charging than the simulated temperature profiles Ts2 and Ts3 at level C and level D for the oil only storage tank. The reason is that the insulation of the storage tank is not uniform at the lower levels of the storage tank which results in more heat losses during the experiments. The model assumes uniform insulation of the storage system throughout the charging cycle. Similarly, the experimental temperature profiles Te2 and Te3 generally remain lower than the simulated temperature profiles Ts2 and Ts3 in the initial stages at level C and D for the small pebbles storage tank. The slower rise of the experimental temperature profiles is caused by the non-uniformity of the surfaces and sizes of the small pebbles. As a result, heat transfer between the small pebbles and oil is not uniform. Further, the void fraction is not uniform due to varying pebble sizes with an average diameter considered in the experiment, whereas the model assumes that all the surfaces and the particle sizes of the small pebbles are uniform. For the larger pebbles in Fig. 1 (c), the experimental and simulated temperature profiles are very close to each other in the initial stages at level C and D due to the large thermal mass of this storage system. Even though there are deviations between experiment and simulation, the total percentage deviation is not greater than 6 %, thus the model may be used with reasonable certainty to predict the behaviour of oil/packed bed systems.

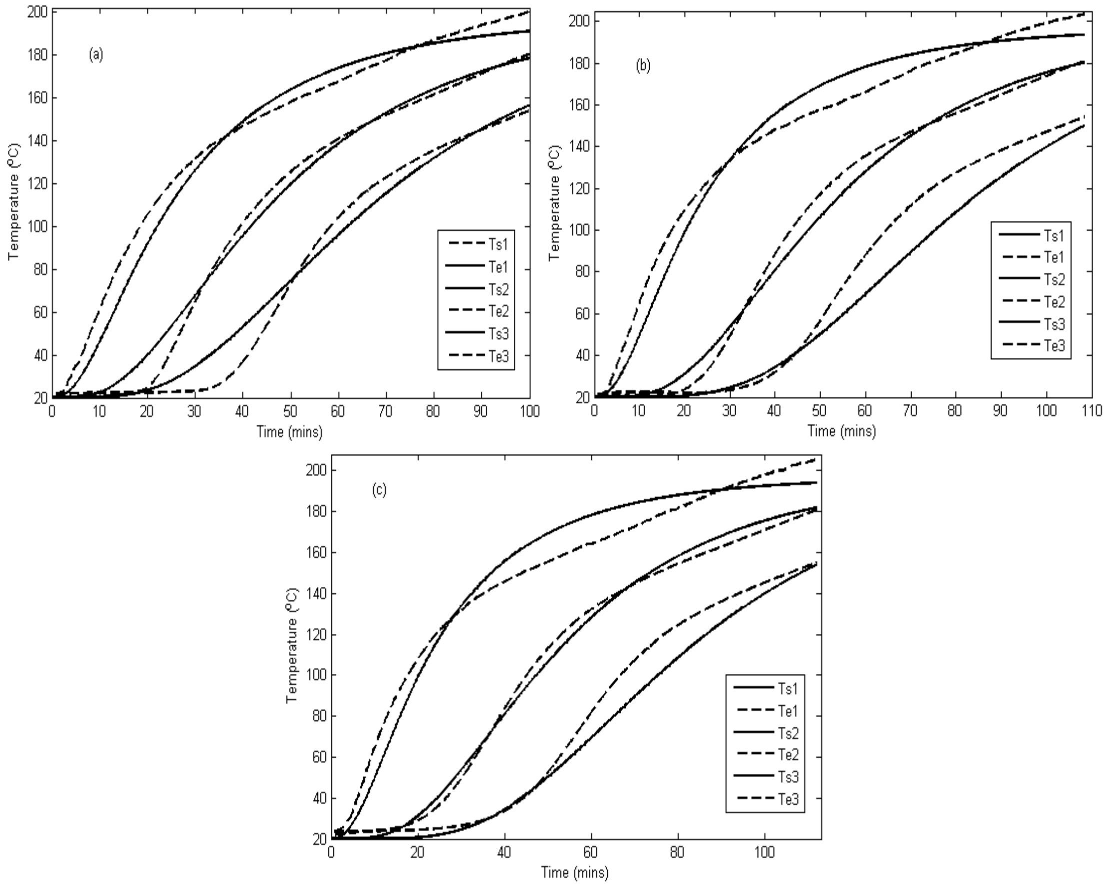

Fig. 1: Validation for the three sensible heat storage systems at a flow rate of 4 mls^{-1}; (a): oil TES, (b): 10.5 mm pebbles TES and (c): 31.9 mm pebbles TES.

3.2. Effect of different flow rates

The simulation study of the Sunflower Oil/31.9 mm pebbles TES system is conducted at four different flow rates of 4 mls^{-1}, 10 mls^{-1}, 16 mls^{-1}and 22 mls^{-1}, respectively, at a control input temperature of 200 ºC, and simulation results are presented in Fig. 2. The temperature profiles of the experimental systems Levels A-D (top, lower top, middle and bottom) are simulated as Ts1-Ts4 as shown in Fig. 2. The Sunflower Oil/31.9 mm pebbles storage is used during simulation because of the larger thermal mass advantage of the larger pebbles. The temperature profile trends in Fig. 2 are observed to be different at the varying flow rates. Temperature profiles rise faster especially at the higher flow rates as compared to the lower flow rates due to the increase in the heat transfer rate. The thermal gradients are highest at the lowest flow rate of 4 mls^{-1} as shown in Fig. 2 (a). The reason is that the heat from the preceding level in the simulation model takes a longer time to reach the next level due to the lower velocity of the HTF. As a result, the rate of temperature rise is low. Therefore, the lowest flow rate creates a high degree of thermal stratification within the TES system. This is in contrast to the profiles with the higher flow rates of 10 mls^{-1} in Fig. 2 (b), 16 mls^{-1} in Fig. 2 (c) and 22 mls^{-1} in Fig. 2 (d) where the thermal gradients progressively decrease with increasing flow rate. The results further show that the decline in the thermal gradients is greater in Fig. 2 (c) and Fig. 2 (d) than with lower flow rates (Fig. 2 (a), (b)). This explains why the highest flow rate undergoes the highest de-stratification as shown in Fig. 2 (d). However, the rate of temperature rise is greatest at the highest flow rate of 22 mls^{-1} (Fig. 2 (d)) as compared to the lowest flow rate of 4 mls^{-1} (Fig. 2 (a)) due to the fastest heat transfer with the highest flow rate. Generally, the flow rate of 4 mls^{-1} is chosen to be used in further simulations because it shows a better stratified distribution for the longest time for the four flow rates considered, which indicates a greater potential of storing more quality energy.

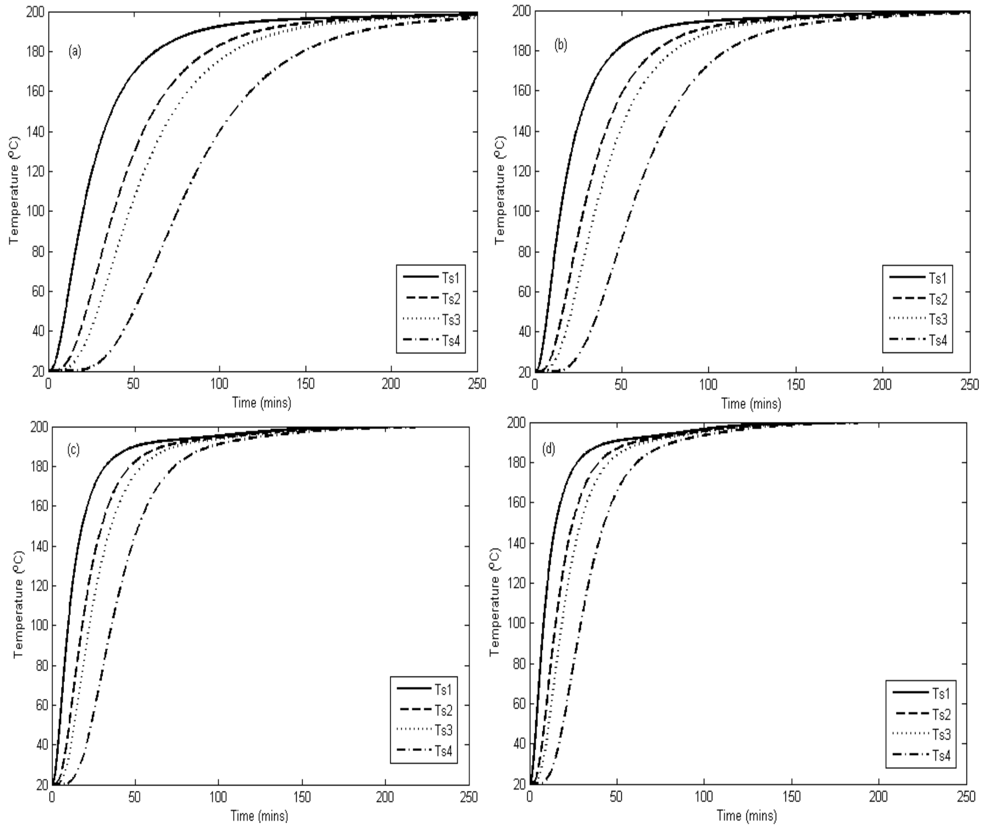

Fig. 2: Simulated TES temperature profiles for the Sunflower Oil/31.9 mm pebbles TES system at varying flow rates during charging; (a): 4 mls^{-1}, (b): 10 mls^{-1}, (c): 16 mls^{-1} and (d): 22 mls^{-1}

3.3 Effect of varying TES input temperatures

Fig. 3 shows the simulated temperature profiles for the Sunflower Oil/31.9 mm pebbles packed bed at varying input temperatures during charging. The control heating input temperatures of 140 ºC, 170 ºC, 200 ºC and 230 ºC at the flow rate of 4 mls^{-1} are considered in the simulation. The selected medium range temperatures favour most cooking applications. Higher temperatures are not considered since they are not compatible to most pumps available in the markets as the pumps can be damaged due to high temperature heat. Consequently, replacement of pumps in the TES systems can make the technology expensive for cooking. Fig. 4 shows that the temperature profiles of all TES systems follow similar trends from the initial temperature of 20 °C to the highest temperature during charging. However, the difference is only observed in the highest temperature reached at the different control input temperatures. Fig. 3 (a) has the lowest maximum temperature of 140 °C due to the lowest control input temperature of 140 °C. A small amount of heat is dissipated to the TES system which makes the TES system to have the lowest rate of temperature rise at the control heating temperature of 140 °C. Lower temperatures are obtained within the period of 250 mins at the lowest input temperature. However, more energy is released to the TES system as the control input temperature increases as shown in plots (b), (c) and (d). The rate of temperature rise for plot (a) at the lowest input temperature is followed by plots (b, c, d) at the higher input temperatures respectively.

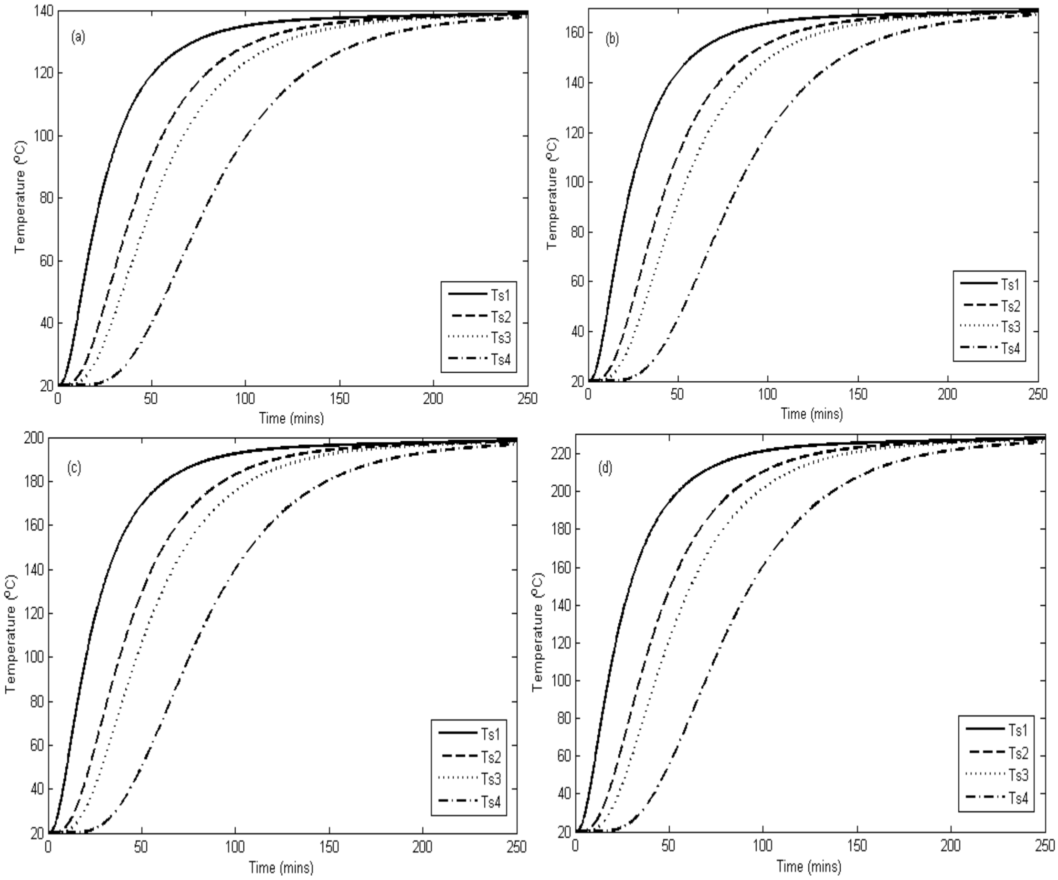

Fig. 3: Simulated TES temperature profiles for Sunflower Oil/31.9 mm pebbles TES at varying input temperatures: maximum (a) 140 °C, (b): 170 °C (c): 200 °C and (d): 230 °C control charging temperatures.

For example, the temperature achieved in plot (d) for the temperature profile *Ts*1 at 100 mins is 220 °C which is greater than the temperature of 135 °C achieved in plot (a) in the same time. This explains why the highest maximum temperature of 230 °C is achieved with the highest set temperature (plot (d)) in 250 mins. Although the input temperature of 230 °C achieves the highest temperature as shown in Fig. 3, the input temperature used in the consequent simulations is 200 °C. This temperature conserves the thermal properties of the thermal oils which are used as the HTFs, and it is suitable for most domestic cooking applications.

3.4 Effect of different thermal oils (HTFs)

Fig. 4 shows the simulated temperature profiles for different thermal oils at the flow rate of 4 mls^{-1} and at a control heating temperature of 200 ºC. The four thermal oils considered are Sunflower Oil, Canola Oil, Olive Oil and Palm Oil. Each thermal oil used is assumed to have a volume of 7.0 l in the TES system. The volume of 7.0 l is selected since this is the volume of Sunflower Oil that was used during the experiments. Different thermal oils are studied to find out the effect of varying the densities and specific heat capacity values on the thermal performance of the TES system developed for this study. The simulation results are used to establish the thermal oil (HTF) with better thermal properties for the TES system. The density, specific heat capacity and thermal conductivity of each of the thermal oils are given in Table 3.

Tab. 3: Properties of thermal oils

Thermal oil	Density (kgm^{-3})	Specific Heat Capacity ($Jkg^{-1}K^{-1}$)	Thermal conductivity ($Wm^{-1}K^{-1}$)
Sunflower Oil	930	2115	0.161
Canola Oil	914	1910	0.188
Olive Oil	915	2300	0.170
Palm Oil	912	2400	0.172

Out of the four storages in Fig. 4, Sunflower Oil TES (a) shows slightly larger thermal gradients up to the end of the charging cycle as compared to the other thermal oils. The explanation is that Sunflower Oil has the highest density among these four thermal oils considered. Similarly, the higher thermal capacity of Sunflower Oil also attributes to the slower temperature rise at all the axial sections of the storage tank such that the equilibrium temperature is achieved at a later time in comparison with the other thermal oils. As a result, the equilibrium temperature of 200 ºC of the Sunflower Oil TES (a) is reached in the longest duration of 250 mins. Similar results of the Sunflower Oil TES were also found out in the study by Mawire *et al*., (2014). Fig. 4 (b) shows the fastest temperature rise such that the equilibrium temperature is reached at 200 mins before the other three storages. This is attributed to the lowest specific heat capacity value of 1910 $Jkg^{-1}K^{-1}$ of Canola Oil used in TES (b). The thermal responses in Fig. 4 (c) and Fig. 4 (d) are comparable. This is because the specific heat capacity of the Olive Oil TES system (c) and the Palm Oil TES system (d) are within the same range. The specific heat capacity of Olive Oil is 2300 $Jkg^{-1}K^{-1}$ while that of Palm Oil is 2400 $Jkg^{-1}K^{-1}$. Hence, the equilibrium temperature is reached around 230 mins for both TES (c) and TES (d). Generally, Sunflower Oil has better thermal stratification characteristics compared to the other thermal oils in this study and can be used as a suitable HTF for medium temperature packed bed TES systems. This is because Sunflower Oil TES maintains the biggest thermal gradients for the entire charging period of 300 mins as compared to the other three thermal oils considered. When the charging time is to be reduced, Canola Oil should be used since it shows the fastest rise to the thermal equilibrium. The densities of these two thermal oils are also almost identical making their thermal masses to be nearly the same.

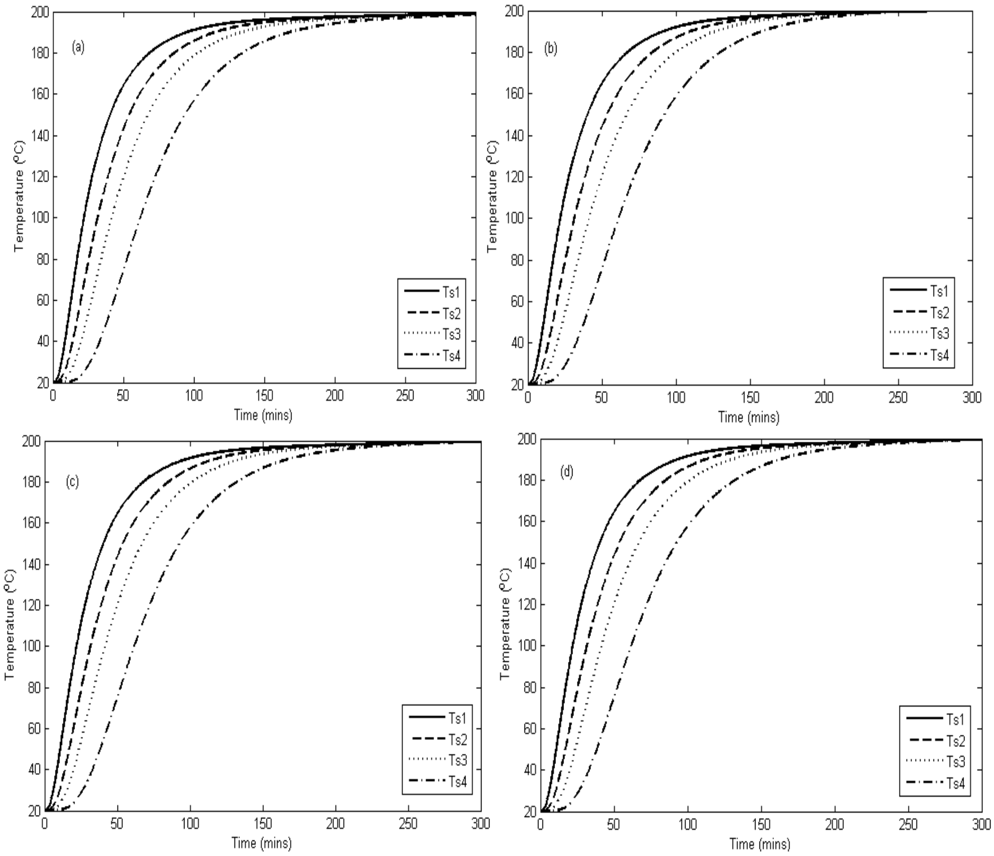

Fig. 4: Simulated TES temperature profiles for different thermal oils; (a): Sunflower Oil, (b): Canola Oil, (c): Olive Oil and (d): Palm Oil.

3.5 Effect of different solid packed bed TES materials

Fig. 5 shows the temperature profiles of four sensible heat solid energy storage materials at a flow rate of 4 mls^{-1} and at a control input heating temperature of 200 ºC. The sensible heat materials are granite pebbles, iron pebbles, alumina and sandstone pebbles. The selected solid thermal storage materials are assumed to have a spherical shape with an average diameter of 31.9 mm having a void fraction of 0.43 in the storage tank. Sunflower Oil is used as the HTF in the storage systems. The density, specific heat capacity and the thermal conductivity of solid packed bed TES materials are given in Table 4.

Table 4: Properties of solid packed bed TES materials

Material	Density (kgm^{-3})	Specific Heat Capacity (Jkg^{-1}K^{-1})	Thermal conductivity (Wm^{-1}K^{-1})
Granite	2634	798	2.12
Iron	7860	462	79
Alumina	3905	765	30
Sandstone	2323	740	2.091

The results in Fig. 5 show that the Sunflower Oil/31.9 mm granite pebbles TES in Fig. 5(a) has the largest thermal gradients followed by the Sunflower Oil/sandstone pebbles TES in Fig. 5(d). This is because the granite pebbles and the sandstone pebbles have lower thermal conductivity values of about 2 Wm^{-1}K^{-1} which causes the higher stratification. The Sunflower Oil/31.9 mm granite pebbles TES (a) has larger thermal gradients than the Sunflower Oil/sandstone pebbles TES (d) because the density of the granite pebbles is slightly higher than the density of sandstone pebbles. As a result, TES (a) has the slowest rise in temperature such that the equilibrium temperature is reached at 300 mins followed by TES (d) whose thermal equilibrium is observed at 250 mins.

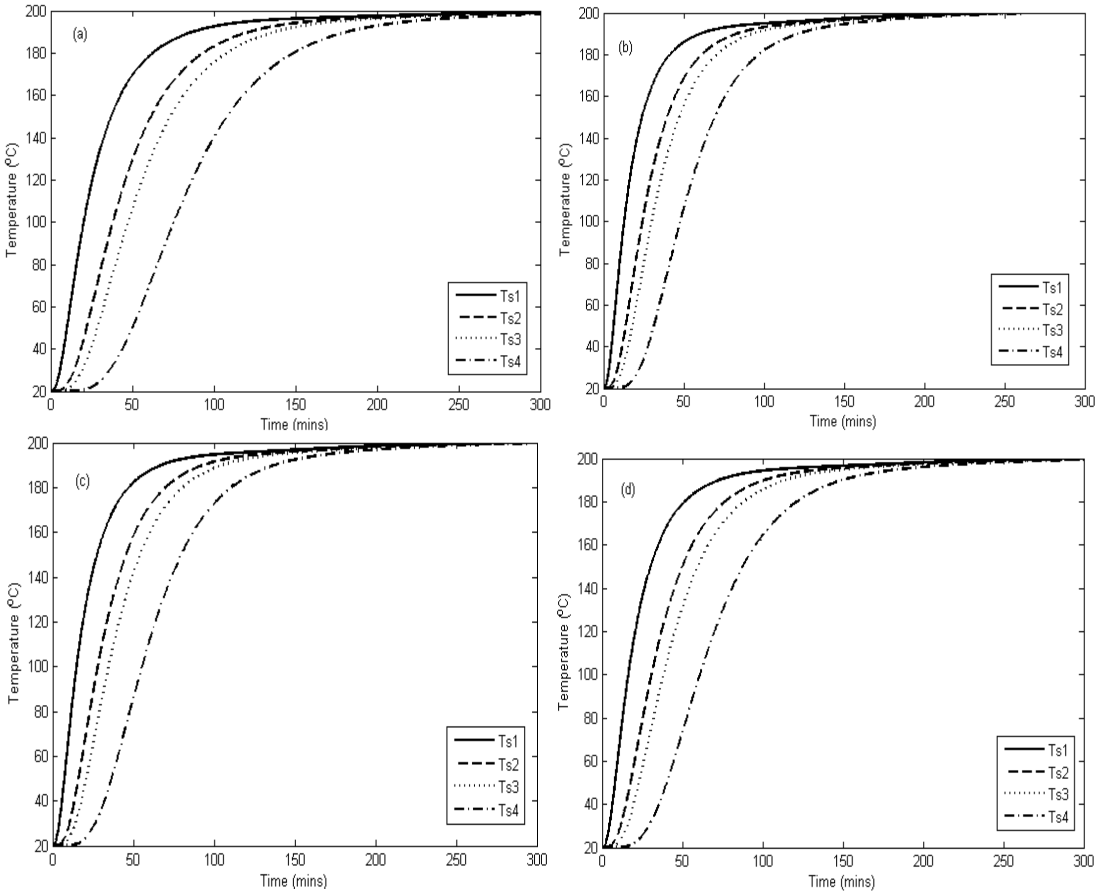

Fig. 5: Simulated temperature profiles for different sensible heat solid energy storage materials; (a): 31.9 mm granite pebbles, (b): iron pebbles, (c): alumina pebbles and (d): sandstone pebbles.

Fig. 5(b) consisting of Sunflower Oil/iron pebbles shows the fastest rise in temperature and the smallest thermal gradients amongst the four storages. This is because the iron pebbles used in TES (b) have the highest thermal conductivity value of 79 $Wm^{-1}K^{-1}$. As a result, the Sunflower Oil/iron pebbles TES (b) attains the equilibrium temperature value at 200 mins earlier than the other TES systems. The temperature rise of the Sunflower Oil/iron pebbles TES in Fig. 5(b) is followed by the Sunflower Oil/alumina TES in Fig. 5(c). The Sunflower Oil/alumina TES (c) has a faster temperature rise as compared to the Sunflower Oil/granite pebbles TES and the Sunflower Oil/sandstone pebbles TES. This is because alumina has a thermal conductivity value of 30 $Wm^{-1}K^{-1}$ which is much greater as compared to the granite pebbles in Fig. 5(a), and the sandstone pebbles in Fig. 5(d) whose thermal conductivity values are very small (about 2 $Wm^{-1}K^{-1}$). This makes the Sunflower Oil/alumina TES to achieve the thermal equilibrium around 230 mins which is much earlier than TES (a) and TES (d). These results are similar to the study conducted by Mawire *et al.*, (2009) where the alumina storage system showed faster axial temperature rise than the fused silica storage because alumina has higher thermal conductivity compared to fused silica. Generally, the Sunflower Oil/granite pebbles TES in Fig. 5(a) has better thermal stratification characteristics than the other thermal storage materials. This is because this TES system has larger thermal gradients which imply less thermal mixing effects and lesser magnitudes of heat losses to the surroundings. Granite pebbles have other advantages of being readily available in most parts of the world. However, for faster charging of a packed bed TES system, higher thermal conductivity pebbles should be utilized.

4. Conclusion

A finite difference model for an oil/packed bed TES system was developed, and validated with experimental results. The results of simulation showed good agreement with the experimental results with an overall mean percentage error (deviation) of 6 % when using a flow rate of 4 mls^{-1}. This overall mean percentage error shows good agreement between the experimental and simulated results. The model was further used to simulate the effect of different flow rates, varying input temperatures, different thermal oils and different sensible heat solid energy storage materials. An increase in the flow-rate led to the faster decrease in the temperature gradients in the TES systems considered. An inlet temperature increase resulted in faster rises of the storage tank temperatures, and higher maximum temperatures in the storage tanks. Considering the different thermal oils, the best storage performance was seen with Sunflower Oil since it showed better thermal stratification. The best packed bed sensible heat storage material was granite since it showed larger thermal gradients. The simulation study thus proved to be a useful tool in evaluating the thermal performance of different storage materials and should be used to complement rather than to completely substitute detailed experimentation. The simulation results can also be used by designers of solid-liquid TES systems to appropriately choose solid pebble bed materials based on their thermal performance. TES systems should be cheap if they are to be commercially viable (Herrmann & Kearney, 2002). For example, the price of Sunflower Oil is 1.20 USD per litre whereas gas costs 1.23 USD per litre. In terms of cooking applications, Sunflower Oil can be recycled (Lugolole *et al*., 2018) whereas gas cannot (Dilip *et al*., 2014). Hence, using a Sunflower Oil packed bed TES is a cheaper means of cooking in comparison with the other existing options (gas and electricity). The TES system modelled in this study is a cheap renewable energy resource for cooking purposes in homes.

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