NUMERICAL PARAMETRIC ANALYSIS OF HYBRID THERMAL ENERGY STORAGE SYSTEM USING PHASE CHANGE MATERIALS (PCMs) UNDER INDIRECT SEQUENTIAL CHARGING AND DISCHARGING

M. Y. Abdelsalam\textsuperscript{1}, J. S. Cotton\textsuperscript{1}, M. F. Lightstone\textsuperscript{1}  
\textsuperscript{1}McMaster University, Hamilton, Ontario, Canada  
abdelsmy@mcmaster.ca, cottonjs@mcmaster.ca, lightsm@mcmaster.ca

ABSTRACT

Modular single-tank hybrid thermal energy storage (HES) system was numerically modeled to study its dynamic performance under indirect sequential charging/discharging cycles. A parametric analysis was conducted to investigate the effect of key parameters on the storage gain of the hybrid system compared to sensible energy storage (SES) system. The HES system was found to outperform the SES system but the storage gain was limited, mainly by the thermal resistance of the PCM. Reducing the thickness of the PCM modules from 60 mm to 10 mm yielded an increase of approximately 6 times in the storage gain. Also, close to 100\% enhancement in the storage gain was obtained by using PCM with thermal conductivity of 2 W/m.K compared to that with 0.2 W/m.K. Systems with broad temperature ranges tended to store more energy as sensible heat in the PCM, which resulted in diminishing the storage gain.

INTRODUCTION

Thermal energy storage (TES) is crucial to the energy conservation in many thermal systems. When carefully designed TES systems can reduce the mismatch between the energy supply during the peak periods and the energy demand during the off-peak periods. Sensible energy storage (SES) systems using water tanks are used in thermal storage applications especially in domestic space and water heating. In order to satisfy the energy demands, bulky tanks (~1000 liters) are commonly used. Such large volumes pose many difficulties in installation, operation and maintenance of the storage system. In addition, they occupy significant footprint of premium real estate. In the early 2000s, many researchers investigated the concept of multi-tank cascaded SES systems where a number of modular water tanks (~200 liters) are connected in series or parallel. Such design offers flexibility for retrofit applications in addition to significant reduction of the footprint of the storage system since the tanks can be stacked vertically to occupy smaller space. However, the cascaded storage performance was found to be sensitive to the characteristics and dynamics of the charging and discharging systems. De-stratification was observed by Cruikshank and Harrison (2011) in a system with three 270-litre tanks connected in series when the charging temperature dropped below the bulk temperature of the tanks. Dickenson et al. (2012) found that charging and discharging the cascaded system of three tanks (270 liters each) connected in series subjected to realistic hot water draw profiles (according to the Canadian Standard Association, CSA-F379.1) resulted in better sequential stratification and higher water temperature sent to the demand as compared to the case of parallel configuration. However, the parallel discharging configuration was found to offer a higher degree of stratification during the off-peak periods of the charging loop. Mather (2000) showed that de-stratification of the cascaded system can be reduced by using indirect charging and discharging of the storage system. Also, Mather carried out a numerical study on the performance of an eight 200-liters tank cascaded SES system charged by a 16.67-m\textsuperscript{2} solar collector and discharging to proposed demand profile. The solar fraction of the cascaded system was found to be comparable to that of a perfectly stratified tank with the same volume. Latent heat storage (LHS) systems using PCMs have found their place in market in the past few decades as excellent candidates for TES applications. PCMs, especially those undergoing solid-liquid transformation such as paraffin wax and hydrated salts, have experienced intensive development in their availability, cost and thermal storage capacities (Abhat, 1983, Zalba et al., 2003). They are characterized by their large energy storage capacity in the form of latent heat of fusion which leads to compact designs. In addition, they
demonstrate passive modulation of the temperature of the storage system since the phase change processes typically take place at a fixed temperature, i.e., melting temperature. The current study was motivated by the advantages of the cascaded modular design studied by Mather (2000) in addition to the benefits offered by PCMs. The concept of cascaded HES system where a series of modular tanks using water and PCM modules as the storage medium, charged and discharged indirectly using heat exchangers, is expected to show promising performance compared to a similar design with only water as the storage medium. Theoretically, the cascaded HES system can offer more than a 2-fold increase of the energy stored in a similar SES system provided that the volume fraction and melting temperature of the PCM inside the tanks were carefully tuned (Sarafraz, 2013). However, the performance of the cascaded HES system under realistic charging and discharging conditions still needs to be investigated. This paper focuses on the study of the performance of a single-tank modular HES system compared to a similar SES system in order to furnish a better understanding of the concept before exploring the cascaded system. The performance of the single-tank hybrid thermal storage system with PCMs has been shown in the literature, (Mehling et al., 2003, Kousksou et al., 2011, Nallusamy et al., 2007, and Reddy et al., 2012) to be influenced by many critical parameters such as: the thermo-physical properties of the PCMs, the size and configuration of the PCM modules, the heat transfer coefficient between the PCM and the heat transfer fluid, in addition to the charging and discharging patterns imposed on the system. However, broader understanding of the vast potential of the hybrid TES system and the significant impact of the key parameters on its dynamic performance was found to be lacking. As such, the current study undertakes a methodical numerical parametric analysis to investigate the effect of the prominent parameters on the thermal dynamics of the HES system. This parametric analysis is meant to highlight the areas of strength of the HES system compared to the conventional SES system.

METHODOLOGY

A numerical model was developed using FORTRAN 95 to simulate the transient behavior of a single-tank HES system using water and PCM as the storage medium. Also, the performance of a single-tank SES system using water only as a storage medium with the same total volume was simulated to illuminate the advantages of the HES system over conventional SES systems. The design studied by Mather (2000) was adopted in the current study where a modular tank (~200 l) is subjected to indirect charging and discharging by means of two heat exchangers, one is installed at the bottom of the tank for charging and the other at the top of the tank for discharging (Fig. 1). Since the heat transfer mechanism in the proposed system is dominated by natural convection, rectangular PCM modules were chosen for this study because they were believed to offer the highest packing density without compromising the heat transfer characteristics inside the storage tank, in addition to their low price and ease of manufacturing. Other geometric configurations of PCM modules, such as cylindrical and spherical, will be the subject of future investigations.

A square tank with similar dimensions to the cylindrical tank used in Mather’s (2000) studies was numerically modeled. The dimensions of the tank were set to be as shown in Fig. 1. The tank length = 53.34 cm, tank width = 53.34 cm, water height in the tank = 71 cm. The dimensions of the rectangular PCM modules were chosen based on the best utilization of the space between the heat exchangers as well as availability in the market. The module
length = 40 cm, the module thickness = 3 cm and the module height = 50 cm. The tank dimensions as well as the PCM module length and height were kept fixed in this study, whereas the module thickness was varied in the parametric analysis since it directly affects the thermal resistance to the heat transfer through the PCM. The following assumptions were adopted in the numerical model:

1. The storage systems were perfectly thermally insulated.
2. The storage system under study was subjected to sequential charging and discharging cycles with fixed inlet temperatures to the charging and discharging heat exchangers at $T_c$ and $T_d$, respectively. These simple cycles were studied to help understand the performance of the storage system as a component. These results can later be extended to investigate the dynamic performance of the single-tank and multi-tank HES components when integrated into residential/commercial storage systems utilizing solar thermal energy or waste heat recovery.
3. The detailed design of the heat exchanger was not considered and the heat exchangers were modeled using a constant effectiveness value, Eq. (1).
4. The positions of the charging and discharging heat exchangers promote natural convection currents inside the storage tank which act to enhance mixing (Mather, 2000). As such, the water was modeled as a lumped system where the temperature of the water was assumed uniform in space and time variant.
5. Due to the high aspect ratio of the PCM modules ($H_m/t_m \sim 15$), the heat transfer was assumed to be dominant in the direction of the module’s thickness.
6. Heat transfer inside the PCM module was assumed conduction dominated. This will yield a conservative heat transfer solution, since natural convection which enhances heat transfer in the melted PCM is neglected (Bejan, 1988, Viskanta, 1984).
7. As such, the melting and solidification processes were assumed to be one-dimensional in the direction of the module thickness.
8. The PCM was assumed to have single melting point temperature and the thermophysical properties of solid and liquid phases were assumed constant.

The “Enthalpy Formulation Method” (Voller, 1980) was used to simulate the heat transfer inside the PCM module in order to track the melting/solidification fronts during the charging and discharging processes. Detailed description of the numerical model and the solution algorithms are provided in Alexiades (1992). The heat exchangers were modeled using the following equation:

$$Q_{HX} = m \rho C_w (T_{in} - T_{out}) = \varepsilon Q_{HX,max}$$

The maximum heat transfer rate from the heat exchanger takes place when the outlet temperature from the heat exchanger is equal to the temperature of the water in the tank,

$$Q_{HX,max} = m \rho C_w (T_{in} - T_w)$$

Therefore, the effect of the design of the heat exchanger was eliminated from the parametric analysis by assuming a constant value of the effectiveness.

The numerical model was used to undertake a parametric analysis on the dynamic performance and the storage gains of the HES system compared to the SES system. The key parameters that were chosen to be studied in the current study were:

a. PCM modules: volume fraction, $\phi$, module thickness, $t_m$

b. PCM properties: melting temperature, $T_m$, thermal conductivity, $k_{PCM}$

c. Charging and discharging cycles: the inlet temperature to the charging heat exchanger, $T_c$, the inlet temperature to the discharging heat exchanger, $T_d$

In this study, the durations of the charging and discharging cycles, $t_c$ and $t_d$, were assumed equal at eight hours each. Future work will consider variations in the cycle operating temperatures and duration. The parametric analysis was carried out by first defining a base case for comparison, and then each parameter was varied to investigate its effect on the performance of the HES system. Table 1
demonstrates the parametric analysis matrix where the base case values are underlined. The fixed thermophysical properties of water and PCM are shown in Table 2.

Table 1. Parametric analysis matrix

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PCM modules</strong></td>
<td></td>
</tr>
<tr>
<td>Volume fraction, $\phi$ [-]</td>
<td>0.1, 0.2, 0.3</td>
</tr>
<tr>
<td>Module thickness, $t_m$ [mm]</td>
<td>10, 20, 30, 40</td>
</tr>
<tr>
<td><strong>PCM properties</strong></td>
<td></td>
</tr>
<tr>
<td>Melting temperature, $T_m$ [°C]</td>
<td>42, 45, 48</td>
</tr>
<tr>
<td>Thermal conductivity, $k_{PCM}$ [W/m.K]</td>
<td>0.2, 0.4, 1.0, 2.0</td>
</tr>
<tr>
<td><strong>Charging and discharging cycles</strong></td>
<td></td>
</tr>
<tr>
<td>Charging and discharging inlet temperatures, $T_c$ / $T_d$ [°C]</td>
<td>50 / 40, 60 / 30</td>
</tr>
</tbody>
</table>

*Base Case* is underlined

Table 2. Thermophysical properties of PCM and water

<table>
<thead>
<tr>
<th></th>
<th>$\rho$ [kg/m$^3$]</th>
<th>$C$ [kJ/kg.K]</th>
<th>$H_d$ [kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM</td>
<td>850</td>
<td>2.5</td>
<td>200</td>
</tr>
<tr>
<td>Water</td>
<td>1000</td>
<td>4.184</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The dynamic performance of the HES system was evaluated based on the following profiles:

1. The time variation of the water temperature inside the tank, $T_w(t)$.
2. The time variation of the melt (liquid) fraction of the PCM inside the modules, $S(t)$.
3. The time variation of the heat transfer rate from the heat exchangers, $Q_c(t)$, $Q_d(t)$.
4. The time variation of the outlet temperatures of the heat exchangers, $T_{out,c}(t)$, $T_{out,d}(t)$.
5. The accumulated energy stored and recovered, $E_{out}$, as well as the energy accounting in the HES system showing the allocation of the stored energy in different forms: sensible in water, sensible and latent in PCM.
6. The percentage storage gain compared to the theoretical gain representing the ideal limits of the storage systems if given unlimited time for charging and discharging.

**NUMERICAL RESULTS AND DISCUSSION**

1. **Base Case**

In order to remove the dependence on the initial conditions in the tank, simulations were run for a series of charging/discharging cycles until the performance of the storage system became periodic. As expected, the PCM was found to have a significant impact on the temporal behavior of the HES system compared to the SES system. Figure 2 shows the water temperature as a function of time for both the HES and SES systems. The lumped capacitance assumption yielded the typical exponential trends of the water temperature in the SES system during successive charging and discharging. However, in the HES system with the 30% PCM by volume and a melting temperature of 45°C, the temperature of the water was found to increase until the PCM was preheated to its melting point. Then as the PCM was melting, the water temperature flattened around the melting temperature of the PCM.

![Fig. 2. Temporal temperature profiles for water, $T_w$ in SES system (solid black line), and HES system with $\phi = 0.3$ ($T_m = 45 ^\circ C$) operating between $T_c = 50 ^\circ C$ and $T_d = 40 ^\circ C$](image-url)

As expected, the same trend was found during the discharging process. Most PCMs available in the
market are characterized by low thermal conductivity (~0.2 W/mK) which results in high thermal resistance within the modules. This limits the charging and discharging heat transfer rates of the storage systems (Abhat, 1983). Therefore, the limiting case of an idealized PCM with infinite thermal conductivity was also studied. The idealized PCM is treated as a constant temperature lumped system during melting/solidification. It is shown that the water temperature attained a constant value closer to the melting temperature of the PCM shortly after the PCM started melting. Also, all the PCM in the tank were melted completely around 2 hours before the charging cycle ended. The water temperature then increased as the liquid PCM temperature increased, storing heat in the form of sensible energy. As such, reducing the thermal resistance in the storage system led to higher rates of PCM melting and solidification (Fig. 3).

This can be further explained by Figs. 4-5, where the heat transfer rate from both the charging and discharging heat exchangers are plotted versus time. Both figures demonstrate symmetric performance during charging and discharging because the melting temperature of the PCM was chosen at the mean value of operation temperature range: \( T_c = 50 \, ^\circ C \) and \( T_d = 40 \, ^\circ C \). The real gain from using PCM in the HES system manifests itself in the modulation of temperature inside the system in a way that increases the rate of heat transfer from the heat exchangers. That is the PCM forces the system to operate around its melting temperature which helps increase the temperature potential between the heat exchangers and the system, and hence leads to higher heat transfer rates. Such advantage can be utilized to vastly increase the storage capacity of the storage system by tuning the different key parameters to maximize the charging and discharging rates.

For example, using ideal PCM reduces the overall thermal resistance of the system which leads to much higher heat transfer rates. However, the charging/discharging time durations as well as the amount of PCM employed in the HES system limit the gains (which can be presented by the net trapped area between the HES and SES curves). It is shown that after the PCM was fully melted and started
superheating the heat transfer rate from the charging coil started dropping, approaching that of the SES system. It can be then postulated that having more PCM inside the tank or charging for shorter time periods would have led to higher gains. Another perceived advantage of using PCM in HES systems was noticed on the outlet temperature from the heat exchangers. Fig. 6 shows that the outlet temperature from the charging heat exchanger of the HES system is lower than that of the SES system. This is attributed to the effect of PCM on the temperature modulation of the system. This reduction in the outlet temperature is advantageous in the context of a solar thermal collector system since the lower temperature fluid would be sent to the solar collector.

As the outlet temperature of the storage tank decreases, the thermal losses from the collector will decrease and the efficiency of the solar collector will increase leading to higher solar fractions. Similarly, the outlet temperature from the discharging heat exchanger of the HES system is higher than that of the SES system (Fig. 7). This indicates higher temperatures sent to the demand, reducing the need for auxiliary heating systems and leading to higher utilization of the stored energy. However, it is worth mentioning that other parameters of the HES system, such as the PCM volume fraction, melting temperature, thermal conductivity, module thickness as well as the charging and discharging temperature profiles, will play a critical role in minimizing the outlet temperature from the charging heat exchanger and maximizing that from the discharging heat exchanger.

In order to quantify the benefits of using the HES system over the SES system, energy accounting analysis was developed to compare the total energy stored and recovered in both systems after reaching a pseudo-steady state operation. Also, the total energy stored in the HES system can be divided into three types: (1) energy stored in water, (2) energy stored in PCM as latent heat and (3) energy stored in PCM as sensible heat. These energies can be calculated using the following equations:

\[ E_w = m_w C_w (T_{w,f} - T_{w,i}) \]  
\[ E_{PCM} = \int Q_{HX,c} \, dt - m_w C_w (T_{w,f} - T_{w,i}) \]  
\[ E_{PCM,latent} = m_{PCM} H_f (S_f - S_i) \]  
\[ E_{PCM,sensible} = E_{PCM} - E_{PCM,latent} \]

Subscripts “i” and “f” refer to the initial and final states of the charging cycle. Fig. 8 illustrates the energy accounting in both storage systems including that for an ideal HES system with the PCM treated as lumped system. Fig. 9 shows the percentage storage gain of the HES system compared to the SES system, calculated from the following equation:

\[ \% \text{Storage Gain} = \left( \frac{E_{HES}}{E_{SES}} - 1.0 \right) \times 100\% \]
In the limiting case when the storage system is given enough time to charge to the maximum temperature, \( T_c \), and discharge to the minimum temperature, \( T_d \), a theoretical percentage storage gain can be calculated by:

\[
\text{Theoretical Storage Gain} \% = \left( \frac{\rho_{\text{PCM}}}{\rho_w} \phi \left( \frac{H_{\text{sl}}}{C_w \Delta T_{\text{op}}} + \frac{C_{\text{PCM}}}{C_w} - 1.0 \right) \right) \times 100.0
\]  

(8)

Fig. 8 and Fig. 9 show that ~50% storage gain can be achieved in the HES system with the assumed parameters, whereas ~100% storage gain can be obtained in the HES system with ideal PCM (high thermal conductivity).

It is worth noting that the maximum realizable gain is ~106%. This means that improving the PCM properties leads to higher storage gains approaching the theoretical limits. However, this comes on the expense of more energy stored as sensible heat in both water (+25%) and PCM (+240%), as shown in Fig. 7. This increase in the sensible heat content of the hybrid system reflects less potential for the system to store more heat due to the decrease of the heat transfer rate from the heat exchanger in addition to the negative impact on the system side of the storage component where the return temperature to the energy supply (eg. solar collector) increases and the temperature supplied to the demand decreases. Such interesting conclusions raise the question:

“What is the best combination of parameters used in the HES system that leads to high storage gains compared to the SES system without sacrificing the overall system efficiency?”

The following parametric analysis attempts answering this question through investigating the isolated effect of each parameter on the performance of the HES system.

### 2. Parametric Analysis

#### a. Effect of the PCM volume fraction, \( \phi \)

The effect of increasing the PCM volume fraction \( \phi \) is shown in Fig. 10. For the given dimensions of the PCM modules, higher volume fraction indicated a higher number of modules inside the storage tank, which also implies a higher surface area for heat transfer between the water and the PCM modules. Using CFD simulations, Sarafraz (2013) showed that the heat transfer coefficient between the water and the PCM modules inside the hybrid tank operating under similar conditions to the current study did not change given that the gap spacing between the modules was adjusted above ~10 mm. This was found to be the minimum distance after which the thermal boundary layers on the modules interfere and the heat transfer coefficient began to drop. To isolate such effects, the gap spacing between the modules was fixed for all cases to be 10 mm and the heat transfer coefficient was assumed constant at 150 W/m²K. Therefore, increasing the PCM volume
fraction from $\phi = 0.1$ (3 modules) to $\phi = 0.2$ (7 modules) and $\phi = 0.3$ (10 modules) will lead to a linear increase of the surface area of the PCM modules and hence a linear decrease of the thermal resistance between the water and the surface of the PCM modules. Fig. 10 summarizes the effect of the PCM volume fraction on the dynamic performance of the HES system compared to the SES system. The lower thermal resistance associated with the larger surface area of the PCM modules causes the HES system to operate at a temperature level closer to the melting temperature of the PCM. This yields higher heat transfer rates and better temperature modulation of the system.

Fig. 10. Temporal temperature profiles for water, $T_{\text{in}}$ in SES system (solid black line), and HES system with $\phi = 0.1$ (solid red line), $\phi = 0.2$ (solid blue line) and $\phi = 0.3$ (solid purple line) operating between $T_c = 50 ^\circ \text{C}$ and $T_d = 40 ^\circ \text{C}$.

Fig. 11. Energy accounting for SES system and HES system with PCM volume fraction $\phi = 0.1, 0.2$ and 0.3.

Fig. 12. This is attributed to the inherent thermal resistance inside the PCM modules. It is expected that in the limit of ideal PCM, the increase in gain will be a linear function of the surface area of PCM modules as manifested by the theoretical gain trend.

b. Effect of the PCM melting temperature, $T_m$

Tuning the melting temperature ($T_m$) of the PCM inside the HES tank is critical to the performance of the storage system. A parametric study was conducted where $T_m$ was changed between 42, 45 and 48 °C. The inlet temperatures to the charging and discharging heat exchangers of the tank were kept fixed at 50 and 40 °C, respectively. Fig. 13 illustrates that the operation of the HES system is quite sensitive to the melting temperature of the PCM.

Fig. 13. Temporal PCM melt fraction, $S$ profiles for HES system with $\phi = 0.3$ melting at $T_m = 42, 45$ and 48 °C. As the melting temperature deviated from the mean temperature between $T_c$ and $T_d$, the system made less utilization of the PCM since only smaller portions of...
the PCM was involved in the storage process. For the system with $T_m = 42 \, ^\circ C$ (closer to $T_d$), all the modules melted completely after the charging cycle but only ~40% of the PCM solidified by the end of the discharging process. The opposite takes place when $T_m = 48 \, ^\circ C$ (closer to $T_c$). The best operation condition was found when $T_m = 48 \, ^\circ C$, where the discharging process was most efficient. Furthermore, only ~40% of the PCM modules were found to be solidified by the end of the discharging cycle. The opposite takes place when $T_m = 48 \, ^\circ C$ (closer to $T_c$). The best operation condition was found when $T_m = 48 \, ^\circ C$, where the discharging process was most efficient. However, only ~40% of the PCM modules were found to be solidified by the end of the discharging process. Such conclusions are also reflected on the energy accounting plots shown in Figs. 14-15, where the storage gains of the HES system were achieved in the HES system by careful tuning of the PCM melting temperature with respect to the operation temperatures of the charging and discharging cycles.

such conclusions are also reflected on the energy accounting plots shown in Figs. 14-15, where high energy and better temperature modulation can be achieved in the HES system by careful tuning of the PCM melting temperature with respect to the operation temperatures of the charging and discharging cycles. Such conclusions are also reflected on the energy accounting plots shown in Figs. 14-15, where high energy and better temperature modulation can be achieved in the HES system by careful tuning of the PCM melting temperature with respect to the operation temperatures of the charging and discharging cycles. Such conclusions are also reflected on the energy accounting plots shown in Figs. 14-15, where high energy and better temperature modulation can be achieved in the HES system by careful tuning of the PCM melting temperature with respect to the operation temperatures of the charging and discharging cycles.

**Fig. 14.** Energy accounting for SES system and HES system with $\phi = 0.3$ melting at $T_m = 42, 45$ and $48 \, ^\circ C$, operating between $T_c = 50 \, ^\circ C$ and $T_d = 40 \, ^\circ C$.

**Fig. 15.** Percentage storage gain for HES system with $\phi = 0.3$ melting at $T_m = 42, 45$ and $48 \, ^\circ C$, operating between $T_c = 50 \, ^\circ C$ and $T_d = 40 \, ^\circ C$ (dark grey: Actual - light grey: Theoretical).

c. **Effect of the thickness of PCM module, $t_m$**

The thickness of the PCM modules ($t_m$) is expected to be a key parameter that influences the dynamic performance and the storage gains of the HES system. Reducing the thickness of the modules for fixed volume fraction requires a larger number of modules inside the tank which leads to larger surface area and hence smaller thermal resistance between the water and the PCM modules. Also, smaller module thickness leads to a considerable reduction of the thermal resistance inside the PCM module itself. It was found from Fig. 16 that reducing the PCM module thickness resulted in better temperature modulation around the melting temperature of the PCM, which in turn led to higher heat transfer rates and faster melting/solidification of the PCM. For fixed charging and discharging time periods, this came at the expense of storing more energy in the form of sensible heat.

**Fig. 16.** Temporal temperature profiles for water, $T_w$ in SES system (black line), and HES system with $\phi = 0.3$ using different module thickness, $t_m = 10 \, mm$ (red line), $t_m = 20 \, mm$ (blue line), $t_m = 30 \, mm$ (purple line) and $t_m = 40 \, mm$ (green line).

**Fig. 17.** Energy accounting for SES system and HES system with $\phi = 0.3$ melting at $T_m = 45 \, ^\circ C$, using different module thickness, $t_m = 10 \, mm$, $t_m = 20 \, mm$, $t_m = 30 \, mm$ and $t_m = 60 \, mm$.

The penalty for using smaller $t_m$ in the case of long charging and discharging cycles is illustrated in Fig. 17, where it is seen that the energy stored as sensible heat in water reached a minimum at $t_m = 20 \, mm$ then...
increased by ~37% for \( t_m = 10 \) mm. For \( t_m < 20 \) mm, the latent heat of the PCM is completely utilized where all the PCM in the tank is involved in the phase-change process. Fig. 18 shows that the HES system with 10-mm thick PCM module can store 2 times the energy stored in the SES system with the same volume. This conclusion highlights the potential of the HES system to reduce the total volume required per unit stored energy which can yield significant space savings.

A full system simulation including realistic charging and discharging cycles is still required to fully understand the optimum module thickness for the HES system. Comparing \( t_m = 10 \) mm to 20 mm shows that in terms of total energy stored, the former offers ~2 times the SES system while the latter offers ~1.8 times. However, the outlet temperature from the charging (discharging) heat exchanger of the former is ~ 1 K higher (lower) than that of the latter. As such, the overall efficiency of the system is expected to be lower in case of the 10 mm-thick modules.

d. **Effect of the thermal conductivity of PCM, \( k_{PCM} \)**

Enhancing the thermal properties of PCMs, especially the thermal conductivity \( (k_{PCM}) \), has been thoroughly investigated by researchers to improve their storage capacities (Agyenim et al., 2010). Higher thermal conductivity of the PCM means lower thermal resistance and hence higher charging and discharging rates of the storage system. A parametric study was carried out to investigate the effect of increasing \( k_{PCM} \) up to 10 times (ranging from 0.2 to 2.0 W/mK). The values were chosen to agree with those found in literature for common PCMs (Abhat, 1983). Figs. 19-20 show similar trends of the effect of the PCM module thickness.

e. **Effect of the inlet temperatures to the charging and discharging heat exchangers, \( T_c \) and \( T_d \)**

For the HES system with a PCM melting temperature of 45°C, the effect of the operation temperature range, \( \Delta T_{op} \), defined by \( T_c \) and \( T_d \) needs to be explored. A study was conducted to investigate the
effect of increasing the $\Delta T_{op}$ from 10 K ($T_c = 50^\circ C$ and $T_d = 40^\circ C$) to 30 K ($T_c = 60^\circ C$ and $T_d = 30^\circ C$) on the dynamic performance of the HES system. Fig. 21 shows that the system with narrower $\Delta T_{op}$ provides better temperature control on the storage system. On the other hand, the system with larger $\Delta T_{op}$ offers closer temperature levels to those found in the SES system. Fig. 22 illustrates that storage systems operating under larger temperature ranges have a higher potential to store more thermal energy. However, if the PCM volume fraction is limited, the thermal energy is mostly stored as sensible heat in both water and the PCM.

This leads to the loss of the temperature modulation feature of the hybrid storage tank and hence lower overall system efficiency. This result can also be seen in Fig. 23 where the theoretical storage gain decreased as $\Delta T_{op}$ increased, indicating that a higher percentage of the energy was stored in the form of sensible heat. Conversely, systems tuned to operate under a narrower $\Delta T_{op}$ are expected to offer higher storage gains since the stored energy is steered towards the latent heat of the PCM. In fact, this comes at the expense of the diminished heat transfer rates into the storage system which resulted in lower total energy stored per unit cycle of operation.

As a result, it is seen that large operation temperature ranges are necessary in order to maximize the storage capacity of the system, whereas narrow temperature ranges yield higher storage gains as compared to the SES system. This conclusion sheds light on the prospective gains that can be achieved by applying the concept of the cascaded HES using different PCM in each tank. Hypothetically, if the volume fraction and the melting temperature of the PCM are tuned in each tank so that each tank operates under a narrow temperature range, both the storage capacity and gains can be maximized simultaneously.

**CONCLUSIONS**

The effect of different key parameters on the dynamic performance of a single-tank modular HES system was numerically studied. Both the storage capacity and the percentage of storage gain were used to study the effectiveness of the HES system as compared to the conventional SES system. The parametric analysis showed that for the applied range of parameters the storage capacity of the HES system...
can be increased by decreasing the thermal resistance of the PCM modules, i.e. increasing the thermal conductivity and decreasing the thickness of modules. Also, systems operating under larger temperature ranges store more energy over the given time period. However, using the same PCM volume fraction, storing more energy will result in more energy stored in the form of sensible heat of the PCM. This will in turn yield lower storage gains compared to SES system since most of the PCMs have lower specific heat capacities compared to water. In addition, the HES system loses the advantages of the temperature modulation feature of the PCM when the system operates under larger temperature ranges. This is expected to have an adverse effect on the overall system efficiency when the storage component is integrated into realistic applications such as solar thermal systems. The melting temperature of the PCM was also found to be very critical to the performance of the HES system. Three degrees offset from the average of the charging and discharging temperatures cost the HES system around 2.5 times reduction of the storage gain.

ACKNOWLEDGEMENTS

This study was supported by NSERC SNEBRN (Smart Net-Zero Energy Building Strategic Research Network).

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>specific heat capacity [J/kg.K]</td>
</tr>
<tr>
<td>E</td>
<td>energy stored/recovered [J]</td>
</tr>
<tr>
<td>H_f</td>
<td>latent heat of fusion [J/kg]</td>
</tr>
<tr>
<td>m</td>
<td>mass flow rate [kg/s]</td>
</tr>
<tr>
<td>m</td>
<td>Mass [kg]</td>
</tr>
<tr>
<td>Q</td>
<td>heat transfer rate [W]</td>
</tr>
<tr>
<td>S</td>
<td>melt fraction of PCM, the ratio of the liquid PCM to the total volume of PCM</td>
</tr>
<tr>
<td>T</td>
<td>Temperature [°C]</td>
</tr>
<tr>
<td>T_m</td>
<td>melting temperature of PCM [°C]</td>
</tr>
<tr>
<td>t_m</td>
<td>thickness of PCM module [mm]</td>
</tr>
<tr>
<td>ε</td>
<td>heat exchanger effectiveness</td>
</tr>
<tr>
<td>ΔT_op</td>
<td>operation temperature range, T_c – T_d[K]</td>
</tr>
<tr>
<td>ϕ</td>
<td>volume fraction of PCM</td>
</tr>
<tr>
<td>ρ</td>
<td>Density [kg/m^3]</td>
</tr>
</tbody>
</table>

Subscripts

c | charging |
d | discharging |
w | water |

REFERENCES


