PACKED BED-PCM MATERIAL LATENT HEAT THERMAL ENERGY STORAGE SYSTEM

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ABSTRACT

Packed bed-PCM latent heat thermal energy storage system is presented in this study. The packed bed cylindrical column is filled with spherical capsules of PCM (paraffin wax) that used for solar water heating application. In this study, the physical model is developed to use for analyzing the thermal performance of packed bed-PCM latent heat thermal energy storage. The model depends on energy balance equation that can be applicable only to the sensible heat storage materials and can be converted to enthalpy equation that can be applicable to the PCM storage bed. The governing equations are numerically solved using simple explicit and first order finite difference technique. The results obtained are used for the thermal behavior of both charging and discharging modes. The effects of mass flow rate and inlet heat transfer fluid temperature (Stefan number) on the thermal performance of the PCM capsules of different radii are investigated. The melt/solid fraction distribution of the bed as function of time and axial position during charging and discharging modes is investigated. The results show that higher inlet heat fluid temperature and higher mass flow rate of heat transfer fluid indicates shorter time for complete charging processes. The complete solidification time is too longer compared to the melting time. This is due to the very low heat transfer coefficient during solidification. The charging and discharging rate are significantly higher for the PCM capsule of smaller radius compared those of lager radius. The phase transition temperature range reduces the complete melting time; a difference of 31.7% is observed for the case when the PCM has melting in the temperature range as compared to that for a PCM with at fixed temperature.

KEYWORDS: latent heat, numerical model, packed bed, PCM capsules, thermal energy storage, performance analysis and heat transfer working fluid

1- INTRODUCTION

Latent heat thermal energy storage systems using PCM to store heating or cooling have many applications. Also, the packed bed latent heat thermal energy storage systems are
used for many solar thermal energy applications such as water heating, air conditioning and waste heat recovery system. Felix et al. (2008) present study of heat transfer characteristics of thermal energy storage system using PCM capsule. Such systems have the advantage of large surface to volume ratio of the packed beds and higher storage density for phase change materials compared to conventional bulk storage in tank heat exchangers and sensible heat storage systems. Numerical model for predicting the thermal performance of cylindrical storage tank containing spherical PCM capsules as packed bed latent heat storage system are presented by Ismail and Henriquez (2002). Their model is used to investigate the effect of the working fluid inlet temperature, flow rate of the working fluid and materials of the spherical capsule of 77mm diameter during the solidification process. Kousksou et al. (2005) present dynamic modeling of the thermal storage of an encapsulated ice tank. They took into account the super-cooling phenomena during solidification of water and the effect of coolant flow rate, inlet temperature and the position of the tank on the performance of cold storage. The thermal characteristics of paraffin in a spherical capsule during freezing and melting processes were investigated by Cho and Choi (2000). Numerical analysis of latent heat thermal energy storage system was investigated by Vyshak and Jilani (2007). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications are presented by Zalba et al. (2003).

The main object of this work is to investigate the effect of phase change temperature range on the performance of the packed bed latent heat thermal energy storage system containing spherical capsules for solar water heating applications. The effects of inlet heat transfer fluid temperature (Stefan number), fluid flow rate and the radius of the capsules are discussed for both charging and discharging modes.

2- NUMERICAL ANALYSIS AND GOVERNING EQUATIONS

A thermal energy storage system operates in three modes as: (1) Charging mode which starts with circulation of the heat transfer fluid heated in the collection system at a temperature higher than the PCM melting temperature. This mode occurs during day time when the solar energy collection takes place and terminates with complete melting of the
PCM, charging of the store does not terminate with complete melting of the PCM if the inlet fluid temperature is above the melting temperature, charging of sensible heat continues. (2) Discharging mode which is started by circulation of the cold heat transfer fluid having inlet temperature lower than the PCM melting temperature. The heat transfer fluid exit temperature is time dependent because the rate of solidification of the PCM varies with time. This mode terminates with complete solidification of the PCM. (3) Stand by mode which occurs when there is no further storage of energy occurring because of decreasing heat transfer fluid temperature or the storage tank is completely charged or the energy is directly fed of the utility without using storage and/or no heating from the bed is required. This is the transition period between the charge and discharge modes.

The most factors and parameters to be considered in the present storage unit containing the PCM include:

1- The configuration of the storage unit.
2- Type of heat transfer fluid.
3- Temperature limits within which the unit is to operate.
4- Thermo-physical properties of the PCM.
5- The storage capacity of the tank.
6- Pressure drop and pump power.
7- Useful heat gain over the solar collector.

The physical model of the thermal energy storage system of packed bed-PCM capsules is shown in Fig. (1).

The following assumptions that involved in the present work are drawn as:

1- The flow in the tank is axially direction and incompressible.
2- The tank is thermally insulated very well.
3- The flow is from the top when charging and is from the bottom when discharging.
4- The thermo-physical properties of the heat transfer fluid are invariant with temperature.
5- Temperature variation is only along the axial direction.
6- Heat transfer between the capsules in the radial direction is negligible.
7- The internal heat generation in the bed is negligible.
8- The porosity of the bed is 0.4 which is defined as the ratio of void volume to the total volume of the bed.

9- The tank length, $L$, was divided into $N$ elements of sufficiently small length $L/N$ so that the element can be assumed to be at a single temperature.

10- The packed bed column is divided into $N$ elements, each containing PCM capsules surrounding by heat transfer fluid.

11- The average fluid temperature and solar energy gain by the solar collector.

In case of the heat losses is negligible, and the energy stored in the heat transfer fluid also negligibly small, the energy balance equation at an instance of time can be written as the following:

$$\frac{\partial T_f}{\partial Z} = -\frac{U_v A}{(m C_p)_f} (T_f - T_b) \quad (1)$$

Where energy balance equation takes on an element of volume $(A \Delta Z)$ is having PCM at a temperature $T_b$ and the heat transfer fluid flowing at the rate of $m_f$ and entering at a temperature $T_f$.

By simplification, the equation (1) becomes as follows:

$$\frac{\partial T_f}{\partial (Z/L)} = -N_{TU} (T_f - T_b) \quad (2)$$

Where $[N_{TU} = \frac{U_v A L}{(m \dot{C}_p)_f}]$ is the number of transfer units

By integrating the above equation (2), integration yields as:

$$\frac{T_{fi} - T_{f i+1}}{T_{bi} - T_{bi}} = 1 - \exp\left(-\frac{N_{TU}}{N}\right) \quad (3)$$

Then, the outlet temperature of the heat transfer fluid for $i^{th}$ element is written as follows:

$$T_{f i+1} = T_{fi} - \left[(T_{fi} - T_{bi})\left(1 - \exp\left(-\frac{N_{TU}}{N}\right)\right)\right] \quad (4)$$

Equation (4) can be expressed for each control volume forming a system of $N$ simultaneous equations. The $N_{TU}$ value and bed temperature of the element ($T_{bi}$) can be
determined by knowing the volumetric heat transfer coefficient and the energy transferred into PCM capsules.

Then, the volumetric heat transfer coefficient for thermal storage system can be written as, Chandra and Willits (1981):

$$U_v = \frac{6U_o (1-\varepsilon)}{D_c}$$  \hspace{1cm} (5)

Where $U_o$ is the outer surface overall heat transfer coefficient of the capsule and is a function of the mode (charging or discharging), the state of the PCM capsule in the control volume (fully solid, fully liquid or phase change processes) and the mechanism of heat transfer (conduction, convection or combined conduction and convection).

$U_o$ can be calculated during the fully liquid or fully solid stages by using thermal resistance concept for each capsule as follows:

$$U_o = \frac{1}{A(R_{ext} + R_c)}$$  \hspace{1cm} (6)

During the phase change process, $U_o$ can be calculated also by using thermal resistance concept for each capsule as follows:

$$U_o = \frac{1}{A(R_{ext} + R_c + R_m(t))}$$  \hspace{1cm} (7)

Where $R_{ext}$ is the thermal resistance between the capsule wall and heat transfer fluid due to convection on the external surface of the capsule and depends on the porosity of the bed, heat transfer fluid properties and Reynolds number of heat transfer fluid flow and can be determined from Nusselt number correlation proposed by Wekaeo et l.(1979) as:

$$Nu_{Dc} = 2.0 + 1.1\left[6(1-\varepsilon)ight]^{0.6} \text{Re}_{Dc}^{0.6} \text{Pr}_f^{1/3}$$  \hspace{1cm} (8)

$\text{Re}_{Dc}$ can be obtained from the following relation:

$$\text{Re}_{Dc} = \frac{\rho \tilde{U} D_c}{\mu}$$  \hspace{1cm} (9)

Where $D_c$ and $\tilde{U}$ are the capsule diameter and superficial velocity in the bed, respectively. $R_m(t)$ is the internal resistance of the capsule which depends on the solid-liquid interface and can be calculated by using one-dimension heat conduction model with phase change as
derived by Felix et al. (2006) for solidification and melting for PCM inside cylindrical and spherical capsule.

The bed temperature ($T_b$) can be calculated by using the energy balance between the heat transfer fluid and the bed. Where the energy transferred to the bed equals ($U_V A \Delta Z (T_f - T_b)$), results in raising the bed temperature at rate of $\frac{dT_b}{dt}$ written as follows:

$$U_V A \Delta Z (T_f - T_b) = (1-\varepsilon)\rho_b A \Delta Z C_{p,b} \frac{dT_b}{dt} \quad (10)$$

For simplification of Eq. (10), multiply both sides by $\frac{AL}{(mC_p)_f}$ and it becomes as:

$$U_V (T_f - T_b) \left( \frac{AL}{(mC_p)_f} \right) = (1-\varepsilon)\rho_b C_{p,b} \frac{dT_b}{dt} \left( \frac{AL}{(mC_p)_f} \right) \quad (11)$$

Since $N_{TU} = \frac{U_V AL}{(mC_p)_f}$, the above equation becomes:

$$\left( \frac{(1-\varepsilon) AL \rho_b C_{p,b}}{(mC_p)_f} \right) \left( \frac{dT_b}{dt} \right) = N_{TU} (T_f - T_b) \quad (12)$$

The initial and boundary conditions for the above set equations are:

**For the heat transfer fluid:**

$$T_{f(Z,0)} = T_{\text{initial}} \quad (13)$$

$$T_{f(0,t)} = T_{f_i} \quad (14)$$

$$\frac{\partial T_{f(Z,t)}}{\partial t} = 0 \quad \text{at } Z = L \quad (15)$$

**For PCM capsule and the bed:**

$$T_{b(Z,0)} = T_{\text{initial}} \quad (16)$$

$$T_{b(Z,t)} = T_{\text{final}} \quad \text{at } Z = L \quad (17)$$
\[
\frac{\partial T_b(Z,t)}{\partial t} = 0 \quad \text{at } Z = 0 \quad (18)
\]
\[
T_p(r,0) = T_{\text{initial}} \quad (19)
\]
\[
T_p(r,t) = T_{\text{wall}} \quad \text{at } r = R \quad (20)
\]
\[
\frac{\partial T_{p(r,t)}}{\partial r} = 0 \quad \text{at } r = 0 \quad (21)
\]

Where \( r \) is solid-liquid interface radius of capsule and \( R \) is internal radius of the capsule.

### 3- NUMERICAL PROCEDURE:

Equation (12) can be discretized for \( i^{th} \) element using simple explicit and first order finite difference formulation, Ozisik (1994) and can be expressed as:

\[
\left(1 - \varepsilon\right) A L \rho_b C_{p,b} \left(\frac{T_{bi}^{n+1} - T_{bi}^n}{\Delta t}\right) = \left(m C_p\right)_f \Delta t N_{TU} (T_{ji}^n - T_{bi}^n) \quad (22)
\]

i.e.

\[
(1 - \varepsilon) A L \rho_b C_{p,b} (T_{bi}^{n+1} - T_{bi}^n) = \left(m C_p\right)_f \Delta t N_{TU} (T_{ji}^n - T_{bi}^n) \quad (23)
\]

Equation (23) is the energy balance equation and can be applicable only to the sensible heat storage materials and can be converted to enthalpy equation that can be applied on the PCM storage bed as:

\[
(1 - \varepsilon) A L \rho_b (H_{bi}^{n+1} - H_{bi}^n) = \left(m C_p\right)_f \Delta t N_{TU} (T_{ji}^n - T_{bi}^n) \quad (24)
\]

\[
H_{bi}^{n+1} = \frac{1}{A L \rho_b (1 - \varepsilon)} \left(m C_p\right)_f \Delta t N_{TU} (T_{ji}^n - T_{bi}^n) + H_{bi}^n \quad (25)
\]

The enthalpy of bed in the element at particular time can be determined by using the known enthalpy values in the previous time period. This equation is valid at all elements at a particular time. The PCM used in this study is a technical grade Paraffin wax of congealing point 58–60 °C with a purity of 99%.

The bed temperature \( T_b \) can be evaluated as a function of \( H_b \), i.e. by employing the enthalpy as the dependent variable and temperature as the independent variable. The
temperature distribution of all the elements in the bed is predicted at an instant of time by knowing the enthalpy values in each element.

Temperature distribution of the bed as function of location of the storage tank and time can indicate the amount of energy stored as well as the stratification in the bed. The melt/solidified fraction of an element can be calculated based on the temperature of bed at a particular time.

The total melt fraction or solidified fraction in a storage tank represented by integrating the melt/solidified fraction distribution in all the elements in the bed using the following equation:

$$F_t = \sum_{i=1}^{N} \frac{F_i}{N}$$  \hspace{1cm} (26)

Where $F_t$ is the total melt or solidified fraction of the bed, $F_i$ is the melt or solidified fraction of an element $i$ and $N$ is the total number of elements in the bed.

The total energy stored in the ‘$i^{th}$’ element can then be expressed as the sum of the heat storage of PCM capsules and the heat transfer fluid as follows:

$$q_{total,i} = q_{PCM,i} + q_{HTF,i}$$  \hspace{1cm} (27)

Where:

$$q_{PCM,i} = \int_{T_{winl}}^{T_{ps}} m C_p s dT + \int_{T_{ps}}^{T_{pl}} m C_p L dT + \int_{T_{pl}}^{T_{ps}} m C_{P_{om L}} + m L_s + m L_{mL}$$  \hspace{1cm} (28)

$$q_{HTF,i} = m_f C_{p,f} (T_{initial} - T_{final})$$  \hspace{1cm} (29)

The energy storage in bed of $N$ elements can be expressed as:

$$Q_{storage} = \sum_{i=1}^{N} q_{total,i}$$  \hspace{1cm} (30)

Alternatively, the stored energy of the system while charging, $Q_{ch}$ may be computed using the molten fraction of the PCM, temperature of the PCM and that of the heat transfer fluid inside the tank. Similarly the discharged energy of the system $Q_{dis}$ may be computed using the solidified fraction of the PCM, temperature of PCM and that of the heat transfer fluid.

These quantities can be written respectively, as:
\[ Q_{ch} = F_{ml} \cdot L_{ml} + m \cdot C_{ps} \cdot (T_{ml} - T_{initial}) \cdot m \cdot C_{ps} \cdot (T_c - T_{ml}) + m \cdot C_{pf} \cdot (T_f - T_{initial}) \]  
\[ Q_{dis} = F_s \cdot L_s + m \cdot C_{ps} \cdot (T_{final} - T_{ml}) \cdot m \cdot C_{ps} \cdot (T_c - T_{final}) + m \cdot C_{pf} \cdot (T_{final} - T_c) \]  

Direct solar energy gains by solar collector:

\[ Q_U = A_p \cdot F' \cdot [I_t \cdot (\alpha \tau)_{average} - U_l \cdot (T_f - T_a)] \]  
\[ \eta_C \% = \frac{Q_U}{A_p \cdot I_t} \]  

Where \( A_p \) is absorber plate of the solar collector, \( F' \) is the collector efficiency factor =0.895, \( I_t \) is the total solar insolation, \((\alpha \tau)_{average}\) is average collector plate absorptivity/transmissivity =0.642, \( U_l \) is overall loss coefficient, \( T_f \) and \( T_a \) are fluid, ambient temperature, respectively and \( \eta_C \) is the solar collector efficiency. The performance of the present flat plate collector over the day (June, Cairo site) as case study is shown in Table (1).

Table (1): Performance of the present flat plate collector over the day (June, Cairo site)

<table>
<thead>
<tr>
<th>Day hour</th>
<th>8:00</th>
<th>9:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:00</th>
<th>13:00</th>
<th>14:00</th>
<th>15:00</th>
<th>16:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_t ), W/m²</td>
<td>370</td>
<td>369</td>
<td>522</td>
<td>670</td>
<td>755</td>
<td>843</td>
<td>885</td>
<td>785</td>
<td>692</td>
</tr>
<tr>
<td>( T_{av} ), °C</td>
<td>23.9</td>
<td>24.4</td>
<td>26.5</td>
<td>28.4</td>
<td>29.9</td>
<td>31.3</td>
<td>32.7</td>
<td>33.5</td>
<td>33.8</td>
</tr>
<tr>
<td>( T_{f} ), °C</td>
<td>60.6</td>
<td>63.3</td>
<td>65.4</td>
<td>67.8</td>
<td>67.7</td>
<td>66.6</td>
<td>64.8</td>
<td>63.7</td>
<td>60.4</td>
</tr>
<tr>
<td>( U_l ), W/m²K</td>
<td>3.55</td>
<td>3.62</td>
<td>3.66</td>
<td>3.72</td>
<td>3.74</td>
<td>3.8</td>
<td>3.81</td>
<td>3.82</td>
<td>3.82</td>
</tr>
<tr>
<td>( Q_{av} ), W</td>
<td>37.1</td>
<td>252.5</td>
<td>427.3</td>
<td>560.1</td>
<td>619.6</td>
<td>613.5</td>
<td>524.6</td>
<td>378.2</td>
<td>209.9</td>
</tr>
<tr>
<td>( \eta_C ) %</td>
<td>7.7</td>
<td>31.4</td>
<td>40.0</td>
<td>43.8</td>
<td>45.2</td>
<td>45.0</td>
<td>42.9</td>
<td>38.3</td>
<td>29.0</td>
</tr>
</tbody>
</table>

The thermodynamic properties PCM (Paraffin wax) are shown in Table (2) and the range of the operating parameters is given in Table (3), respectively.
Table (2): Thermodynamic properties PCM (Paraffin wax), Hisham et al. (2006)

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Solid</th>
<th>Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature, °C</td>
<td>52</td>
<td>-</td>
</tr>
<tr>
<td>Latent heat of melting, kJ/kg</td>
<td>210</td>
<td>-</td>
</tr>
<tr>
<td>Latent heat of Phase change, kJ/kg</td>
<td>158.3</td>
<td>-</td>
</tr>
<tr>
<td>Density, ρ, kg/m³</td>
<td>860</td>
<td>780</td>
</tr>
<tr>
<td>Specific heat, C_p, kJ/kg °C</td>
<td>2.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Thermal conductivity, k, W/m °C</td>
<td>0.24</td>
<td>0.15</td>
</tr>
<tr>
<td>Viscosity, μ, kg/m s</td>
<td>-</td>
<td>0.205</td>
</tr>
</tbody>
</table>

Table (3): Range of the operating parameters

<table>
<thead>
<tr>
<th>Phase</th>
<th>Initial temperature, °C</th>
<th>Stefan number, Ste (T_HTF °C)</th>
<th>Mass flow rate, m, kg/s</th>
<th>Capsule radii, mm</th>
<th>Phase change temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting</td>
<td>50</td>
<td>0.1134-0.21 (70-82 °C)</td>
<td>0.0398-0.16</td>
<td>20-60</td>
<td>0-8.7</td>
</tr>
<tr>
<td>Solidification</td>
<td>70</td>
<td>0.1042-0.262 (50-35 °C)</td>
<td>0.0398-0.16</td>
<td>20-60</td>
<td>0-8.7</td>
</tr>
</tbody>
</table>

Where Stefan number: \[ Stef .N = \frac{C_p L_f (T_f - T_m)}{L_m} \]

4- RESULTS AND DISCUSSIONS

The results obtained from the heat transfer analysis of packed bed-PCM capsules are presented and discussed below under initial and boundary conditions, numerical values of performance of the solar collector, thermo-dynamic properties of PCM (Paraffin wax) and operating parameters range shown as in Table (1), Table (2), Table (3) respectively. The effective parameters of the present analysis are the mass flow rate, heat transfer fluid inlet temperature, the radius of the capsule and phase change temperature range. In the present work a cylindrical storage tank of 1 m diameter and 1.5 m length i.e. length to diameter
ratio 1.5, completely filled with PCM spherical capsules has been considered for the storage of solar energy that is intercepted by a solar collector system for a period of 9 hours per day. Obviously, the temperature of the water at outlet collector depends on the solar insolation of Cairo site, (June as case study). The storage system contains paraffin wax as phase change material in High Density Polyethylene (HDPE) spherical capsule, having density of 0.93 gm/cm$^3$, the storage capacity of 85.5 MJ of thermal energy when considering only the latent heat of the storage material. The total storage capacity of the tank increases to 143.7 MJ when considering the latent heat and sensible heat of the paraffin wax along with the sensible heat of the heat transfer fluid (water) over the temperature range of 20 °C. Numerical calculations were made with various element and time step sizes and it was found that the results are independent of element and time step size below respective sizes of 1 mm and 1 s.

4-1 Effect of Stefan number (heat transfer fluid temperature)

The total melt fraction of the PCM in the bed for various values of Stefan number (heat transfer fluid temperatures) is shown in Fig. (2). The time to reach the complete melting of bed (melt fraction of 100%) decreases as the inlet temperature of heat transfer fluid is increased. For the Stefan number of 0.2501 ($T_{in}$ = 82 °C), the time was shorter by about 42% to reach the melt fraction of 100% than that for the Stefan number of 0.1143 ($T_{in}$ =70 °C). This shows the melt fraction and the complete charging time are strongly affected by the inlet temperature of heat transfer fluid (Stefan number). Higher Stefan number (i.e. higher inlet heat transfer fluid temperature) means the shorter of the time interval for complete charging.

4-2 Effect of capsule radius

The total melt fraction of PCM as a function of capsule radius and time indicating the complete charging time of the bed is 480, 510, 540, 570, 600 and 630 min for 20, 25, 30, 40, 50 and 60 mm capsule radii, respectively; is shown in Fig. (3) It was noticed that the bed with smaller capsules taking less time for charging. It can be seen that at the end of 6
hours of charging, the total melt fraction for 20 mm capsule is 80.2% and for 60 mm capsule is 73%. For the capsule of 20 mm radius it took shorter time by 24% to reach the melt fraction of 100% than that for the 60 mm capsule during the melting process.

The total solidified fraction of PCM as a function of capsule radii is shown in Fig. (4). It can be observed that at the end of 6 h of discharging process the solidified fraction for 20 mm capsule is 51% while for 60 mm capsule is 26%; a reduction in solidification fraction of about 49%. For melting process, the effect of radius of capsule is much weaker, for example there is reduction of only 9% as the capsule radius changes from 60 mm to 20 mm. It means it is better to select a capsule of smaller radius to get higher storage rate in the bed.

4-3 Effect of mass flow rate of heat transfer fluid

The variation of total melt fraction of PCM as a function of time for different heat transfer fluid mass flow rates is illustrated in Fig. (5), the curves rise to the complete melting position early with the increase in the mass flow rate. Higher the mass flow rate, the shorter the time interval needed for complete charging.

4-4 Effect of melting temperature range on the performance of the present system

The temperature distribution in the storage tank for the melting of PCM at constant temperature process \((T_m = 59.9 \degree C)\) is shown in Fig. (6). In the beginning, the PCM in the capsules near the entrance is heated and melted but the PCM in the capsules near the exit remains unaffected and the temperature is equal to the initial bed temperature. It requires a large amount of energy in terms of latent heat at a particular temperature for phase change process. The temperature of the bed is equal to the melting temperature of the PCM for longer period in this ideal case. A very high gradient of temperature distribution is observed near the melting temperature \((T_m=59.9 \degree C)\) when melting is complete again a very high gradient of temperature occurs near the inlet temperature of heat transfer fluid line. The charging of the capsule takes place by sensible heating of the solid and sensible heating of the liquid in the stage 1 and stage 2, respectively. For example, at Z/L of 0.5, the bed takes 50 min to
reach the melting temperature (solid heating), the bed is at the same temperature till 400 min during this period of 350 min the melting takes place at the melting temperature and finally the bed took 100 min to reach the temperature of 70 °C (liquid heating).

The effect of phase change temperature range on the charging process is shown in Fig. (7) where the bed temperature profile at the end of 3rd and 6th hours of melting is shown for the case of PCM melting at fixed temperature of 59.9 °C and that melting in the temperature range $T_{m1}$ to $T_{m2}$. Higher stratification is observed for the PCM melting in the range of phase change (i.e. 8.7 °C) compared to that melting at a fixed temperature. This is because of higher heat transfer rate, since the PCM starts to melt at 52 °C which is much lower temperature as compared to 59.9 °C.

Even though the heat transfer coefficient is the same in both the cases, the varying temperature difference between the PCM and heat transfer fluid, a different heat transfer rate is obtained. As a result, the bed having PCM melting in a temperature range reaches the complete melting earlier than the PCM with fixed melting temperature as observed in Fig. (8), which shows the total melt fraction as function of time for these cases. A difference of 31.6% in the complete melting time for PCM with fixed phase change temperature and that with phase change in a temperature range $(\Delta T)_m = 8.7$ °C is observed.

4-5 Bed temperature distribution

The temperature distribution of the packed bed was predicted with various values of Stefan number, mass flow rate, capsule diameter and PCM melting temperature range both for melting and solidification process. Typical temperature distribution of bed at different axial positions for various values of instant of time from start of the charging mode of 40 mm capsules is shown in Fig. (9). The flow rate is 0.0796 kg/s, and the initial temperature of the storage and the inlet temperature of heat transfer fluid are 50 °C and 70 °C respectively.

During initial heating period, the capsules near the entrance are charged while those near the exit are very close to the initial bed temperature. As time elapses the bed temperature rises. During the melting process there are three stages namely; solid heating, phase change and liquid heating as depicted in Fig. (9). From this figure, the paraffin wax used in this
work is characterized by melting in a range of temperature; the melting starts at a temperature of 52.9 °C ($T_{m1}$) and is completed at 61.6 °C ($T_{m2}$). The solid heating takes place up to the temperature $T_{m1}$ (stage 1), the phase change is between the range $T_{m1}$ to $T_{m2}$ (stage 2) and the liquid heating takes place above the temperature $T_{m3}$ (stage 3).

Temperature distribution during solidification mode for a 40 mm capsule is shown in Fig. (10). These distributions also show characteristics similar to those of melting, i.e. liquid cooling, (stage 1), solid cooling (stage 3), and solidification (stage 2), respectively. It can be observed that the bed is not completely solidified even at the end of 10 hours where the entire bed is melted in a much shorter period. This is due to the very low heat transfer coefficient during solidification process as compared to that of the melting process. It is because of high resistance of solidified layer formed in the inner wall of the capsule during solidification process, which reduces the heat transfer rate between the bed and the heat transfer fluid where as during melting process, the melted layer formed near the inner wall of the capsule increases the heat transfer rate by natural convection mode.

**4-6 Distribution of melt/solid fraction in the bed**

The melt fraction distribution of the bed as function of time and axial position during the charging mode of 40 mm capsules is shown in Fig. (11). It is observed high energy transfer in the inlet region leads to higher melt fraction there and the heat transfer fluid leaving the bed almost at the initial bed temperature leading to almost zero melt fraction. The solid fraction distribution of the bed during the discharging mode is shown in Fig. (12).

**5- CONCLUSIONS**

From the obtained theoretical results of the model for a packed bed latent heat thermal energy storage system using PCM spherical capsules is developed in the present study to predict the thermal behavior of the system. The effects of mass flow rate, heat transfer fluid inlet temperature (Stefan number), phase change temperature range and the radius of the capsule on the dynamic response of a packed bed latent heat thermal energy storage system using PCM spherical capsules for both charging and discharging modes are investigated. The following conclusions can be drawn:
1. The charging and discharging rate are significantly higher for the capsule of smaller radius compared those of larger radius.

2. Higher the Stefan number (i.e. higher inlet heat transfer fluid temperature) means the shorter time for complete charging. Similarly for higher the mass flow rate of heat transfer fluid means shorter time for complete charging.

3. The complete solidification time is longer compared to the melting time. This is due to the very low heat transfer coefficient during solidification.

4. The phase transition temperature range reduces the complete melting time; a difference of 31.6% is observed for the case when the PCM has melting in the temperature range as compared to that for a PCM with melting at fixed temperature.

**Nomenclature**

- A: surface area of capsule, m\(^2\)
- \(C_p\): specific heat, J/kg K
- D: diameter of the bed, m
- \(D_c\): diameter of the capsule, m
- \(F_{mL}\): melt fraction of the bed, %
- \(F_S\): solid fraction of the bed, %
- \(F_t\): total melt or solidified fraction of the bed, %
- \(H\): specific enthalpy, J/kg
- h: outer convective heat transfer coefficient, W/m\(^2\) K
- k: thermal conductivity of PCM, W/mK
- \(k_c\): thermal conductivity of capsule material, W/mK
- \(L_{mL}\): latent heat of melting, J/kg
- \(L_s\): latent heat of solid-liquid phase change, J/kg
- L: length of the bed, m
- \(L_p\): latent heat of solid–solid phase change, J/kg
- m: mass of PCM, kg
- \(m_f\): mass flow rate of heat transfer fluid, kg/s
- \(m_{fT}\): total mass of heat transfer fluid in the bed, kg
- N: number of elements in the bed
- Nu: Nusselt number
- \(Q_{ch}\): charged energy of the tank, kJ
- \(Q_{dis}\): discharged energy of the tank, kJ
- \(Q_{total}\): total energy storage capacity of the tank, kJ
- Re: Reynolds number
- \(R_{ext}\): thermal resistance due to convection on the external surface of the capsule shell
- \(R_c\): thermal resistance due to conduction through the capsule wall
- \(R_{int}\): resistance due to the solidified/melt PCM layer inside the capsule
Stefan number

Tₜₜ bed temperature, °C

Tᵇ average temperature of the bed, °C

Tᶜ average temperature of capsules in the bed, °C

Tᶠ heat transfer fluid temperature, °C

Tᶠᵇ average heat transfer fluid temperature of the bed, °C

Tᵐ melting temperature, °C

Tᵖ solid–solid phase change temperature, °C

Tₖ capsule wall temperature, °C

Tₚₐₙ₉ final temperature of the bed, °C

Tᵢₜᵢₐ₉ initial temperature of the bed, °C

Tᵩₑᵦᵣᵢᵠ environment temperature, °C

t time, s

(ΔT)ₘ solid–liquid phase change range, °C

(ΔT)ₚₙ solid–solid phase change range, °C

Uₒ overall heat transfer coefficient of capsule, W/m² K

Uᵥ overall volumetric heat transfer coefficient, W/m³ K

U supercritical velocity in the bed, m/s

ΔZ element thickness, m

Greek letters

μ viscosity, kg/m s

ρᵇ density of bed, kg/m³

ρᶠ density of heat transfer fluid, kg/m³

ε porosity

Subscripts

b bed

f heat transfer fluid

i inner

L liquid PCM

o outer

S solid PCM

REFERENCES


Fig. (1): The physical model of the thermal energy storage system of packed bed-PCM capsules

Fig. (2): Effect of heat transfer fluid temperatures (Stefan number) on melt fraction of the bed.
Fig. (3): Melt fraction of the spherical capsule bed for various capsule radii.

Fig. (4): Solid fraction of the spherical capsule bed for various capsule radii.
Fig. (5): Melt fraction with the time for various mass flow rate.

Fig. (6): Temperature distribution of melting of spherical capsule bed (melting at constant phase change temperature, $T_m=59.9 \, ^\circ \text{C}$).
Fig. (7): Bed temperature profile at the end of 3\textsuperscript{rd} and 6\textsuperscript{th} hours of melting of spherical capsule at phase change temperature ranges of 0 and 8.7 °C ($T_m = 59.9$ °C)

Fig. (8): Effect of phase change temperature range on melt fraction of the spherical capsule bed.
Fig. (9): Temperature profiles of melting of spherical capsules in the bed.

Fig. (10): Temperature profiles of solidification of spherical capsules in the bed.
Fig. (11): Melt fraction distribution of the spherical capsule bed as function of time during charging mode.

Fig. (12): Solid fraction distribution of the spherical capsule bed as a function of time during discharging mode.