Simulation of a heat tank with Phase Change Materials (PCM)

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Abstract
Solar energy is the greatest energy source we have but unfortunately it is only available during daytime. In an attempt to overcome this obstacle a way to store the sun’s energy for later use is proposed. In this study the charging phase of a latent heat storage tank (LHST) is simulated. The PCM can store energy in the form of latent heat which can later be used during the nighttime. Na\textsubscript{2}HPO\textsubscript{4}-12H\textsubscript{2}O is used as PCM. This type of PCM is applied for the temperature range it can operate, which is relatively low, and this also explains why solar collectors are selected to provide the required heat. A series of tank formations with one, two, three and five heat transfer tubes will be examined to determine how the charging time is affected by the tank’s dimensions and the number of heat transfer tubes. The phase change heat transfer was implemented using the effective heat capacity method.

Keywords:
Phase change materials (PCM), Latent heat storage, Heat tank, COMSOL

1. Introduction
Solar energy is by all means the largest energy source we have but unfortunately it is only available during daytime [1,2]. Trying to overcome this problem, a way to store the sun’s energy for later use, is needed [3]. This can be achieved by using latent heat storage tanks. The solar energy is used to heat up water which then is circulated by pipes through the tank. The tank is filled with a Phase Change Material (PCM) which turns from solid state into liquid by storing energy in the process in the form of latent and sensible heat [4]. There are several problems which must be taken into account when designing and building a heat tank. The available time we have to charge the tank and store the energy is when we have sunshine (daytime). It serves no point to build a heat tank which cannot be fully charged during the available time as this would consist a waste of material and money. In the effort to design and build Latent Heat tanks the use of a computer simulation software can be very helpful so as to determine the correct material of choice and the optimal tank dimensions. The effect of heat flux, dimensions and number of fluid pipes and the dimensions of the heat tank are numerically simulated using COMSOL Multiphysics. Na\textsubscript{2}HPO\textsubscript{4}-12H\textsubscript{2}O is used as PCM. This type of PCM is selected because it has the desired temperature range which is 35-45 °C. This required temperature range can be provided by solar collectors. The capacity of the system with a medium PCM is given by Eq.(1) and Eq.(2) [5]
\[
Q = \int_{T_i}^{T_m} m C_p \, dT + m a_m \Delta h + \int_{T_m}^{T_f} m C_p \, dT
\]  
(1)

\[
Q = m [C_{sp}(T_m-T_i)+a_m \Delta h_m+C_{lp}(T_f-T_m)]
\]  
(2)

where Q is the quantity of the heat stored, m is the mass of PCM, \(C_{sp}\) is the average specific heat between \(T_i\) and \(T_m\), \(T_m\) is the melting temperature \(T_i\) is the initial temperature \(a_m\) is the fraction melted, \(\Delta h\) is the heat of fusion per unit mass , \(C_{lp}\) is the average heat capacity between \(T_m\) and \(T_f\) and \(T_f\) is the final temperature.

PCM stores 4 to 12 times more heat per unit volume than sensible heat storage materials such as water, masonry and rock [3]. In addition, PCM absorbs and releases heat at a nearly constant temperature.

The number of heat pipes inside the tank can play a major role in the time needed to charge the tank, a small number can lead to inability to achieve full charge while a large number can lead to unnecessarily increased production costs, complexity of manufacture and heat losses.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature</td>
<td>35-45 °C</td>
</tr>
<tr>
<td>Fusion heat</td>
<td>280 (kJ/kg)</td>
</tr>
<tr>
<td>Density</td>
<td>1,582 (kg/m³)</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>1,69 (kJ/kg*k)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0,514 (W/m*k)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1,522 (kg/m³)</td>
</tr>
<tr>
<td>Fusion heat</td>
<td>265 (kJ/kg)</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>1,94 (kJ/kg*k)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0,476 (W/m*k)</td>
</tr>
</tbody>
</table>

By literature, there are two types of numerical methods usually used to solve the phase change problem; the enthalpy method and the effective heat capacity method [6]. In this study, the phase change problem is solved using the effective heat capacity method. The effective heat capacity of the PCM during phase change is given by Eq. (3) [7].
\[ C_{\text{eff}} = \frac{L}{T_1 - T_2} + C_p \] (3)

where \( L \) is the latent heat of fusion, \( T_1 \) is the onset temperature of phase transition and \( T_2 \) is the end temperature of phase transition

\[
C_p = \begin{cases} 
1.69 & \text{T} < 35 \, ^\circ C \\
4.34 & 35 \, ^\circ C < T < 45 \, ^\circ C \\
1.94 & 45 \, ^\circ C < T 
\end{cases} \quad \text{(kJ/kg*}^\circ \text{C)} \quad (4)
\]

The discontinuity of heat capacity as shown in Eq.(4) was done in COMSOL Multiphysics by using a logic function. The simulations of the latent heat tank storage unit were carried out using a 3D model, which is chosen to solve the problem by using a time dependent solver [4].

Several tank configurations have been considered:

a) Normal diameter tank with one centrally positioned Heat Transfer Fluid (HTF) pipe.

b) Normal diameter tank with three centrally positioned HTF pipes.

c) Normal diameter tank with five centrally positioned in array HTF pipes.

![Heat tank configurations](image_url)

**Fig.1 Heat tank configurations.**

**Table 3** Dimensions and data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Diameter ( D_1 ) (m)</td>
<td>0.4</td>
</tr>
<tr>
<td>External Diameter ( D_2 ) (m)</td>
<td>2</td>
</tr>
<tr>
<td>Tank Height ( H ) (m)</td>
<td>1</td>
</tr>
<tr>
<td>HTF Inlet Temperature ( T_{in} ) (^\circ \text{C)</td>
<td>85</td>
</tr>
<tr>
<td>Mass flow rate/tube ( M_in ) (kg/m(^3))</td>
<td>0.03</td>
</tr>
<tr>
<td>Ambient temperature ( T_a ) (^\circ \text{C))</td>
<td>25(^\circ )</td>
</tr>
</tbody>
</table>
Grid Construction

In order to simulate the phenomenon and track the temperature profiles inside the tank during the charging phase, HTF and PCM space were divided into elements [8-10]. A 3D fine quality grid was formed consisting of 7692 elements - free tetrahedrals on which the calculations were performed. The number of elements serves to our need for high quality grid independent results which will accurately track the phase change process. A greater number of elements would increase the computational time while a smaller number of elements would reduce the time needed for the computations but less accurate results would be deduced [8].

Results

The time step selected is 1 minute. Referring to a normal diameter tank with one centrally positioned HTF the following diagrams are created. In the first temperature profile (a) we can see that the PCM is at ambient temperature 25 °C which is indicated by the dark blue color. At the beginning of the charging phase (t=1 min) the HTF is at 85 °C and this is indicated with dark red. In profile (b) at t=12 min it depicts a temperature rise in the PCM which is indicated by the light blue color as sensible heat starts spreading inside the material.

![3D Temperature profiles Na₂HPO₄-12H₂O with one HTF pipe](image)

At t=35 min the temperature in the PCM has risen significantly and this is indicated by the light green and yellow colour at 40 °C. The material has started to melt around the HTF pipe. In the last temperature profile at t=3.5 hours it is obvious that the PCM has melted totally and it is at a high temperature. The red color of PCM refers to 80 °C but yet the HTF has not reached the temperature of 85 °C.

![3D Temperature profile Na₂HPO₄-12H₂O with one HTF pipe](image)
Moving to the simulation of a normal diameter with three centrally positioned HTF pipes the following outputs are derived. In the first temperature profile (a) we can see that the PCM is at ambient temperature, which is indicated by the dark blue color, at the beginning of the charging phase (t=1 min) while the HTF is at 85°C as it can be seen with the red shades. At t=12 min (b) a temperature increase in the PCM has taken place indicated by light blue as sensible heat starts spreading inside the material. The yellow color indicates that the PCM starts melting.

Later on, at t=35 min, temperature in the PCM has risen significantly and this is indicated by the light green and yellow color at 40 °C. The material has started to melt. In the last temperature profile it can be seen that all the PCM has melted and it is at the high temperature of 80 °C (red color). The center PCM and HTF are at 85 °C.

Finally the simulation of a normal diameter tank. In the first temperature profile (a) with five HTF pipes we can see that the PCM is at an ambient temperature, here illustrated with the dark blue
shades, at the beginning of the charging phase (t=1 min) while the HTF is at 85°C - red has been used to show the results. In 12 min (b), we can see an increase at PCM temperature which is rapidly heated by the five pipes and starts melting around them by storing latent heat.

Fig. 6 3D Temperature profile Na₂HPO₄-12H₂O

Fig. 7 3D Temperature profile Na₂HPO₄-12H₂O with five HTF pipes
As time progresses, at t=35 min the temperature in the PCM has risen significantly which is indicated by the orange color and the material has melted. It is now storing sensible heat by raising its temperature. In the last temperature profile at t=1.5 hours, it can be seen that all the PCM has melted and is at high temperature. The dark red color represents the 85 °C of the HTF. The heat tank is at this point fully charged.

During the operation of the heat tank, the weather may vary, so sunshine may not be available [9]. In this case the Heat Transfer Fluid temperature may not reach 85 °C. In an attempt to estimate the effect of a cloudy day a simulation was done with HTF inlet temperature at 60 °C so as to compensate for the weak sunshine. In the first temperature profile (a) t=1min charging starts with a slower rate and this leads to lower temperature, which is indicated by blue color.

At t=12 min, profile (b), the PCM remains at low temperature and is still in blue color.

Proceeding, at t=35 min, the temperature in PCM has risen and it is indicated by the light blue color. The material has melted and is now storing sensible heat by raising its temperature. In the last temperature profile, at t=3 hours, it can be seen that the PCM has melted totally, is at a higher temperature and this is indicated with a light green shade but has not reached the HTF’s temperature. As a result the heat tank at this point is not fully charged.
Conclusions

Heat storage in the form of Latent heat is feasible using PCM materials and can help cover the thermal energy needs of a building when the sun is down. The different pipe formations affect the optimum charging time of the tank. This is the time when the tank achieves a full charged status. As shown by the diagrams heat conduction and convection is favoured by the number of HTF pipes. Five HTF pipes make it easier for the PCM to raise its temperature, melt and allow heat to be transferred by convection. By examining the temperature diagrams at a radius 0.5m and height 0.5m we can see that at t=12 min in the normal diameter tank with one HTF pipe is at 31.4°C which is below the melting point and at t=35 mins at 8.5°C higher which means the PCM has started to melt. In the tank with three HTF pipes at t=12 mins the PCM has raised its temperature at 39.5°C which is above the melting point and 23 mins later (t=35 mins) its temperature is at 9.5°C above that. The PCM in the tank with five HTF pipes at the same time is at 48.8°C it has already melted and at t=35 mins has reached 57.5°C by storing sensible heat.

The time needed, for a point at a radius of 1m and height 0.5m at the outer wall of the tank to reach temperatures of 85°C for the normal diameter tank with five HTF pipes is 1 hour 30 mins, for a normal diameter tank with three HTF pipes the time is up to 2 hours 30 mins and for a normal diameter tank with one HTF pipe it is 3 hours and 30 mins. Lower inlet temperatures lead to larger charging times. The energy is stored in the form of sensible as well as latent heat for later use. The HTF flow reverses during the night and returns the stored heat to the user. It is clear that with a large number of tubes placed in array inside the material, the charging time can be cut down significantly. The large pipe number allows better heat transfer between HTF and PCM and so the phase change material can melt and start storing energy much faster. Also a great factor in the charging process of the tank is the available sunshine, as shown in the last simulation during a cloudy or partially cloudy day, the HTF inlet temperature will not be as high as 85°C but more likely at 60°C or even lower. At this temperature the time needed the PCM to melt and heat up takes longer and the tank cannot store energy efficiently. A mistake in designing the tank can lead to its inability to achieve the fully charged status and increase unnecessarily the production costs, the complexity of manufacture and the heat losses. For future works, a variety of PCM materials will be simulated.
References


