Numerical Analysis of a Thermal Storage System with Inserted Heat Pipes for Medium-High Temperature Range

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ABSTRACT

Three-dimensional transient numerical analysis was conducted to predict the heat transfer characteristics of a thermal energy storage system for medium-high temperature range with inserted heat pipes. The storage tank was filled with a phase-change material (PCM), potassium nitrate in this study, to minimize its volume utilizing the enthalpy change during fusion and solidification. The heat pipes of 1-m long and 25.4-mm diameter penetrated the PCM in the tank and extended between two heat exchanging sections located at the opposite ends of the tank. During a heat charging mode, heat pipes transferred heat from a hotter steam at one side to the PCM. And during a heat discharging mode the heat pipes delivered heat from the PCM to a colder steam at the other side. The steam temperatures during the charging and discharging mode of the thermal storage system were 668 K and 513 K, respectively. The heat transport capability of the heat pipe was represented by a solid structure with very high effective thermal conductance estimated by the experimental data in the medium-high temperature range. Discussion was provided based on the predicted temperature values and the amount of heat transferred. Both cases of heat pipes with and without fins were compared each other.

Keywords: Heat pipe, thermal storage system, phase-change material, medium-high temperature, numerical analysis

1. INTRODUCTION

Among a variety of thermal storage systems, the one utilizing a phase-change material (hereinafter denoted by PCM) may have a typical advantage of the reduced volume of the system for the same amount of required energy storage, compared with the ones using sensible heat storage, (Zalba, 2003). This is due to a large amount of the latent heat during the phase-change process. For a thermal storage system in the solar thermal systems, molten salts have often been used for a medium to high temperature range required for the application. However, the inherently low thermal conductivity of the molten salts caused difficulties in many practical applications, such as very large temperature gradient, and very low heat transfer rate, thus a very long response time.

Significant efforts have been made to alleviate this problem. Previous studies included mixing an additive having a high thermal conductivity with the molten salts (Velraj, 1999). However, the heat transfer enhancement was not satisfactory enough. As can be seen in Trp’s (2005) and Long’s (2008) studies, a heat carrying fluid may be pumped through the piping embedded in the phase change material to store and discharge thermal energy. This method however, requires heavy liquid piping which increases system mass and a pump which is a moving part demanding power and maintenance. A system with heat pipes embedded into the phase change material may enhance heat transfer performance considerably while saving the pumping power and it may have an advantage in maintenance compared to the other methods. This study focused on the heat transfer characteristics of the last method.

A numerical analysis was desired to predict the transient temperature response of a thermal storage system with inserted heat pipes filled with potassium nitrate as a PCM in a high temperature range. A commercial computer code FLUENT was used for this purpose. In FLUENT, the heat pipe can be treated as a solid material with extremely high thermal conductivity, whose value may be estimated based on the experimental data. Furthermore, a novel configuration of the thermal storage system was investigated having a single storage tank in the middle interfaced with high and low temperature sources at the opposite ends through heat pipes. The system exchanged heat with hotter steam during a charging mode, and with colder steam during a discharging mode.
2. MODELING PROCESS

2.1. Description of the Model

Fig. 1 depicts the model consisted of thermal energy storage unit with inserted heat pipe. The heat pipes were configured vertically for maximum utilization of the gravitational force for the liquid return. During a charging (thermal storage) process, highly superheated steam at high temperature (395 °C, 2.7 MPa), flowing through the heat exchanging section below the tank, transfers thermal energy to the heat pipe. Then the thermal energy is carried by the heat pipe to the PCM contained in the tank located in the middle section. The upper heat exchanging part was treated as insulated since there is no flow of steam at a lower temperature (395 °C, 2.7 MPa), flowing through the heat exchanging section below the tank, transfers thermal energy to the heat pipe. Therefore, a performance comparison is desired between the systems with and without fins.

The model in this study was consisted of a single thermal storage module having only one heat pipe embedded in a unit of the PCM tank. An actual system can be constructed with multiples of the module presented in this study depending on the performance requirements. In addition, it may incorporate fins wherever necessary and available. The upper heat exchanging part was treated as insulated since there is no flow of steam at a lower temperature (395 °C, 2.7 MPa), flowing through the heat exchanging section below the tank, transfers thermal energy to the heat pipe. Then the thermal energy is carried by the heat pipe to the PCM contained in the tank located in the middle section. The upper heat exchanging part was treated as insulated since there is no flow of steam at a lower temperature during the thermal storage process. The thermal energy carried by the heat pipe are used initially, in the form of sensible heat, to increase the temperature of the PCM to its melting point, after which additionally transferred heat is used to melt the PCM, in the form of the latent heat. After the PCM in the tank is completely melted, the energy is again used to increase the temperature, in the form of sensible heat. Potassium nitrate (KNO$_3$) was considered as PCM in this study of which the melting point is known to be 334°C (607 K).

During a discharging (thermal dissipation) process, on the other hand, saturated steam at a lower temperature (224°C, 2.5 MPa), flowing through the heat exchanging section above the tank, receives heat from the PCM via the heat pipe. For this process, the heat exchanging section in the lower part was assumed to be insulated since there is no flow of superheated steam.

The heat pipe had a total length of 1 m and a diameter of 25.4 mm. The heat exchanging sections located below and above the tank were both 200 mm long. The lower and the upper sections were the evaporator and condenser of the heat pipe since they were interfaced with the higher and the lower temperature steams, respectively. The storage tank was made of stainless steel 316L and had a dimension of 104 mm(width) × 104 mm(depth) × 500 mm(height). The storage tank was made of stainless steel 316L and had a dimension of 104 mm(width) × 104 mm(depth) × 500 mm(height) with the internal volume of 4.9 × 10$^3$ m$^3$. The height of the storage tank was imaginarily divided into four even parts in the longitudinal direction and the three locations among them were labeled top(t), middle(m), bottom(b) to denote heat pipe temperature values. Three radial positions at each of these heights were labeled 1, 2, and 3 to denote temperature values in the phase change material.

Table 1 summarizes thermal properties of the PCM (Janz, 1980), the container material, and the heat pipe. Thermal conductivity and other properties of the heat pipe are effective values based on experimental data of a Dowtherm-A heat pipe operating in the same temperature range.
Adiabatic conditions were applied to the outer walls of the model except the heat pipe. The simulation of a charging mode started with an initial condition of 298 K and lasted until the PCM was melted completely. On the other hand, the initial condition for the simulation of the discharging was assumed to be the melting point of the PCM and lasted for about 2 hours.

2.2. Numerical Models

Computational domain was a quarter of the cross-section of the thermal energy storage unit in Fig. 1 considering the symmetry. FLUENT version 6.3 was used for a numerical study and GAMBIT was used to generate the mesh configuration as presented in Fig. 3. Case (a) represents the model without any fins on heat pipe surface, and case (b) represents the model with fins in the storage tank. The numbers of structured meshes generated were 851,214 for the case (a) and 750,375 for the case (b) using hexahedron/wedge element.

![Figure 2. Schematic of the finned tube in the storage system](image)

Table 1. Thermal properties of the materials at 300 K, 1 atm

<table>
<thead>
<tr>
<th>Items</th>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Specific heat (J/kg K)</th>
<th>Thermal conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM</td>
<td>KNO₃</td>
<td>2090</td>
<td>924.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Heat pipe</td>
<td>STS-Dowtherm-A</td>
<td>7725</td>
<td>522.1</td>
<td>5311</td>
</tr>
<tr>
<td>Container</td>
<td>STS 316L</td>
<td>8238</td>
<td>468.0</td>
<td>13.4</td>
</tr>
</tbody>
</table>

![Figure 3. Mesh configurations of the numerical model: (a) no fins, (b) with fins in storage tank](image)

Convergence check was performed by comparing temperatures at 12 different points for spacing intervals of 1.5 to 3 in the charging mode. Relative errors with reference to spacing interval of 1.5 reduced down to 0.4% for interval spacing 2 or less. With the melting point of the PCM of 607 K, the liquid and solid dominant phases were assumed to be two degrees above and below the melting point. The contact resistances among heat pipe, fins and PCM were ignored in this study.

3. RESULTS AND DISCUSSION

3.1. Charging Mode without Fins

A constant-temperature boundary condition of 668 K was applied to the evaporator surface of the heat pipe during the charging mode. Fig. 4 shows temperature contours on the central plane in the vertical direction of the model at specified times. Fig. 5 summarizes temperature variation at specified locations in the model according to elapsed time up to 4 hours. It is shown that the conducted heat from heat pipe wall diffused through PCM gradually starting from upper part of storage tank. The rate of temperature rise in the upper part of PCM was faster than that in the...
lower part. In one hour, the temperature differences were 29 K and 20 K between t-2 and m-2, and m-2 and b-2, respectively. It was obvious that the heat transfer rate to PCM was very poor considering the temperature differences in the radial direction were 132 K and 185 K between hp-t and t-1, and hp-b and b-1, respectively. Due to a very low thermal conductivity of KNO$_3$, the desired temperature in storage tank did not reach the melting point after four hours except near t-1 point near heat pipe wall. Thus the whole input thermal energy was presumed to have been accumulated in PCM in the form of sensible heat. The amount of accumulated sensible heat was estimated 3,668 kJ. However, this value is relatively large since the process started at the room temperature of 298 K. It is projected that the amount of sensible heat accumulated would be much less in the actual operation since the initial temperature of the storage tank would be between the melting point (607 K) and the temperature of the heat-receiving steam (513 K).

3.2. Charging Mode of the Model with Fins

Fig. 6 represents temperature contours on the central vertical plane of the model at typical time steps during the charging mode when fins were attached to the heat pipe wall in the storage tank. Fig. 7 summarizes the time variation of the temperature at specified locations. In general, the temperature uniformity was enhanced noticeably, both in longitudinal and radial directions, compared with the case without fin (see Figs. 4 and 5) at the same elapsed time. This was considered due to enhanced heat transfer through the extended surfaces. It is obvious that the rate of temperature rise in the storage tank has also been increased remarkably. After one hour of the mode start, for example, the minimum temperature was predicted 385 K at point b-3 for the case without fins (Fig. 4-(a)), but the same was 473 K at point t-3 for the case with fins. It was observed that the whole region of PCM between the fins reached the melting point after 2.8 hours. However, some portion of PCM in the region between the tip of the fin and the corner of container remained slightly below the melting point. The enhanced heat transfer through the fins also lowered the heat pipe temperature at the same elapsed time.

3.3. Discharging Mode without Fins

Fig. 8 shows the temperature variation for the system without fins at typical elapsed times during the discharging mode. The initial condition was assumed 609 K for the whole region of the model where the PCM was in liquid state. The extended heat pipes section above the storage tank was exposed to convection cooling with lower temperature fluid while the extended heat pipe section below the tank was assumed insulated. In this mode therefore, the heat pipe section above the tank worked as a condenser, while the heat pipe section inside the storage tank functioned as an evaporator. For simplification of the modeling, the heat pipe condenser wall temperature was set constant at 513 K, assuming a vigorous heat exchange between the heat pipe wall and the coolant (e.g., saturated or slightly superheated steam) with controlled temperature. It was noticeable that the cooling in the PCM begins from the bottom part in the storage tank, although the temperature variation in the tank was not
Figure 5. Temperature variation for the model without fins and the during the charging mode significant. At the elapsed time of 2 h, the average temperature of the PCM in the storage tank was 602 K, which is only 5 K below the melting point. Therefore, the majority of the thermal energy transfer from the storage tank to the external fluid occurred due to the phase-change (solidification, in this mode) latent heat of the PCM.

3.4. Discharging Mode of the Model with Fins

Fig. 9 represents time variation of temperature for the case with fins during the discharging mode. It is obvious that the cooling rate of PCM is noticeably faster, while that of the heat pipe is slower, than the case without fins (see Fig. 8). After one hour of the discharging mode start, the average temperature of the PCM was 602 K, which was only 5 K below the melting point. At the elapsed time of two hours, the average temperature of the PCM was 587 K, which is 21 K below the initial temperature. Initial cooling rate of the PCM was very slow before the solidification process was completed where the latent heat dominated sensible heat. The cooling rate became faster once the majority of the PCM was solidified.

4. CONCLUSIONS

Based on a series of numerical analyses in this study, the followings can be stated.

1. During the charging mode of the system without fins, the heat pipe rapidly transferred thermal energy from the external heat source and remained isothermal at a high temperature. The PCM temperature rise occurred from the top portion in the tank, so did melting of PCM, and it propagated toward the bottom as time progressed. The radial temperature gradient was always very large almost any vertical locations. For the case with fins, the temperature rise and melting of the PCM occurred from the bottom region of the tank due to the enhanced heat transfer between the heat pipe. As a result, the heat pipe became less isothermal during the process although the temperature difference is not significant. The radial temperature gradient reduced greatly as time elapsed.

2. During the discharging mode of the system without fins, the temperature decrease, and thus the solidification, of the PCM began near the bottom region of the storage tank. The solidification progressed relatively slow due to lower initial temperature difference. For the case with fins, temperature decrease and solidification began almost uniformly along the vertical location, but much rapidly than the case without fins.

Figure 6. Temperature contours on the central vertical plane of the model with fins attached during a charging mode: (a) 1 h, (b) 2 h, (c) 3 h, and (d) 4 h, elapsed time.
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