Experimental Study of a Latent Storage System using a Vertical-Finned Tube and Shell Heat Exchanger: Early Results

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1. INTRODUCTION

Sources of renewable energy are notable for their extreme time-variance, necessitating an accompanying storage system to reconcile differences in supply and demand. Thermal energy collected from sunlight, for example, may be stored by increasing the sensible heat of water stored in an insulated tank. One limitation of storing heat this way is that the temperature of the storage medium changes according to the state of charge. At high states of charge, the temperature is near the maximum, reducing the rate at which additional heat can be added and increasing the rate of self-discharge. At low states of charge, it is closer to the ambient, resulting in lower quality energy [1]. These limitations can be addressed by the addition of a material with a melting temperature between the supply and demand temperatures. This material, termed phase change material (PCM), undergoes solid-liquid transitions as the thermal storage unit is cycled, storing and releasing energy proportional to its latent heat. The latent heat of a material is generally much greater than its sensible heat, thereby significantly increasing the energy storage density of the system [2]. The phase change process is also nearly isothermal, thus maintaining a consistent quality of energy across different levels of charge.

The primary obstacle facing the integration of PCMs into thermal storage systems is the “rate problem”, where most materials with high latent heat also have relatively low thermal conductivities [3, 4]. One method of addressing the rate problem is to design heat exchangers with parameters tuned to the properties of the PCM and the application to deserve. It is of interest to the designer to obtain the maximum increase in heat transfer from the exchanger for the minimum volume and costs. Heat exchanger design is often done with the assistance of mathematical relationships such as the $\varepsilon$-NTU methods. The $\varepsilon$-NTU method, however, assumes two moving fluids and so must be adjusted for situations involving heat transfer to a stationary material undergoing phase change [5]. In order to develop an $\varepsilon$-NTU method for PCM-based heat exchanger, or possibly an entire new method, additional experimental results obtained on various PCM-based heat exchanger geometries under various conditions must be performed. This paper presents early results of such a parametric study on a specific heat exchanger geometry. Such studies have been performed for packed beds of encapsulated PCM [6, 7] as well as for tubes with annular fins [8]; this study will be adding to this body of knowledge.

2. METHODOLOGY

An experimental parametric study was carried out on a latent heat energy storage system (LHESS), consisting of an array of vertical finned tubes immersed in a rectangular container of dodecanoic acid phase change material (PCM); see Table 1 for its properties. Water was employed as a heat transfer fluid (HTF) to charge and discharge the LHESS. Several system operating conditions were varied to study their effect on the heat transfer rate ($\dot{Q}$) between the HTF and the PCM: HTF temperature (Melting: 65, 60, and 55 °C; Solidification: 21, 26, and 31 °C), parallel or series HTF flow through heat exchanger tubes, and HTF flow rate (Parallel: 8.5 and 6.0 L/min; Series: 1.0 and 0.7 L/min).

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To determine the heat transfer rate between the HTF and PCM, a flow meter (Omega FTB 4605 turbine meter) and thermocouples (T-type) were used to measure the HTF flow rate and change of HTF temperature across the heat exchanger. The rate of heat transfer was calculated using Eq. (1)

\[
\dot{Q} = \dot{m}C_p(T_{out} - T_{in})
\]

where \(\dot{Q}\) is the rate of heat transfer, \(\dot{m}\) is the mass flow rate of the HTF, \(C_p\) is the specific heat capacity of the HTF, and \(T_{out}\) and \(T_{in}\) are the outlet and inlet temperatures of the HTF, respectively. Five thermocouples were also placed in the PCM (Fig. 1b) so that the thermal behaviour of the PCM could be examined during charging and discharging and help explain the temporal and thermal behaviour of the storage system in future studies.

The heat exchanger was assembled from eight copper tubes with vertical aluminium fins. The aluminum fins project 5.5 cm above and below each tube, and run along the entire 20 cm horizontal length (Fig. 1a). The eight finned tubes were spaced along the 30 cm × 30 cm × 15.2 cm storage container, with 3.75 cm between each fin and 1.875 cm between the walls and the edge fins. The fins sat vertically in the PCM by resting on acrylic spacers that covered holes in the container’s lid. Fig. 1b shows the container surrounded by insulating foam and the ends of the eight finned tubes sticking out (the insulation on top of the container was removed for the picture).

The container was filled with 10 kg of PCM, which was then charged and discharged with hot and cold HTF at various temperatures. The HTF temperature was controlled with a model RK-12122-52 15L 230V Cole-Parmer Polystat circulating water bath with an integrated pump. For the series tests, the HTF flowed through each tube in sequence along the heat exchanger (as seen in Fig. 1b). For the parallel ones, the HTF stream was split via a manifold into eight separate streams, one for each tube, before merging again at a second manifold at the heat exchanger outlet. A National Instruments NI-cDAQ 9174 data acquisition system with two NI 9213 modules for thermocouple inputs and a NI 9435 digital input module for flow meter readings was used to read and relay sensor data to a nearby computer.

### Table 1 Thermophysical properties of dodecanoic acid [9]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Heat capacity solid at 20°C</td>
<td>1.95 ± 0.03 J g⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Heat capacity liquid at 45°C</td>
<td>2.4 ± 0.2 J g⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Thermal conductivity solid at 30 °C</td>
<td>0.160 ± 0.004 W m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Thermal conductivity liquid at 50 °C</td>
<td>0.150 ± 0.004 W m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Density solid at 22 °C</td>
<td>930 ± 20 kg m⁻³</td>
</tr>
<tr>
<td>Density liquid at 50 °C</td>
<td>885 ± 20 kg m⁻³</td>
</tr>
<tr>
<td>Volume change from 44 °C to 22 °C</td>
<td>6.1%</td>
</tr>
<tr>
<td>Onset of melting temperature</td>
<td>43.3 ± 1.5 °C</td>
</tr>
<tr>
<td>Heat of fusion</td>
<td>184 ± 9 J g⁻¹</td>
</tr>
</tbody>
</table>

Fig. 1: Photograph of: a) One vertical aluminum-finned copper tube b) The container with eight finned tubes.
3. RESULTS AND DISCUSSION

Figures 2 and 3 show $\dot{Q}$ between the HTF and PCM for three HTF inlet temperatures during melting (Figs. 2a and 3a) and three HTF inlet temperatures during solidification (Figs. 2b and 3b). Figure 2 shows results for parallel flow configuration at 8.5 L/min, while Fig. 3 shows results for series flow configuration at 1.0 L/min. In the melting experiments, in both the parallel and series flow configurations, higher HTF temperatures result in higher $\dot{Q}$. This can be explained by the larger $\Delta T$ between the hotter HTF and the PCM; however, because of the higher HTF temperature, higher heat losses to the environment through the plastic piping contributes to a perceived increased in $\dot{Q}$. In the solidification experiments, the impact of the HTF inlet temperature is marginal in $\dot{Q}$.

Owing to the heat losses to the environment and the increased role of natural convection, the melting experiments show higher peak in $\dot{Q}$ than the solidification experiments with the same $\Delta T$ with respect to the PCM melting temperature (~43 °C); e.g., $\Delta T = 22$ °C for both $T_{HTF} = 65$ °C and $T_{HTF} = 21$ °C. However, further studies and analysis must be completed to determine the amount of heat losses to the environment throughout all experiments and understand if natural convection indeed contributes to increase $\dot{Q}$ in the melting experiments. What appears clearly in the results, is that the system presents a clear narrow maximum in $\dot{Q}$ in the first hour of the melting experiments; this could indicate the onset of melting or more specifically the onset of natural convection in the liquid PCM. This narrow peak is not present in the solidification experiments.

![Fig. 2: Parallel flow at 8.5 L/min for (a) melting and (b) solidification.](image)

![Fig. 3: Series flow at 1.0 L/min for (a) melting and (b) solidification.](image)
When comparing the two flow configurations, the parallel flow results in higher $\dot{Q}$ in the beginning of the 10 hour experiments in both melting and solidification. For melting, the larger $\dot{Q}$ can be attributed to the increased heat losses to the environment because of the increased amount of piping in the parallel configuration. The solidification results point to the fact that identical flow in all eight finned-tubes (parallel) leads to faster heat transfer than a longer residence time of the HTF flowing continuously in the eight finned-tubes (series). It appears the difference in $\dot{Q}$ is approximately 125 W between both configurations for both melting and solidification.

The HTF flow rate was also varied (8.5 vs 6.0 L/min for parallel flow and 1.0 vs 0.7 L/min for series flow) which resulted in nearly identical $\dot{Q}$ (results not shown here for lack of space). This point to the fact that for these configurations of heat exchanger, the HTF flow rate has a very minor effect.

4. CONCLUSIONS

In this experimental parametric study of an LHESS using dodecanoic acid as the PCM and a finned tube array and shell as the heat exchanger, the operating conditions of HTF temperature, HTF flow configuration, and HTF flow rate were varied to study their effect on the heat transfer rate between the HTF and the PCM. Higher HTF temperatures led to increased $\dot{Q}$ in the melting experiments, while lower HTF temperatures led to marginal difference in the $\dot{Q}$ in the solidification experiments. Higher $\dot{Q}$ were also achieved in the melting experiments over the solidifications experiments with the same $\Delta T$ between the melting temperature of dodecanoic acid and HTF temperature. Parallel flow proved to be more effective in both melting and solidification of the PCM over series flow across all experimental configurations, while the HTF flow rate had very little effect on the $\dot{Q}$. All observations involving higher $\dot{Q}$ in certain parametric configurations over others had their explanation possibly rooted in the phenomenon of environmental heat loss, the presence of natural convection and the nature of the melt front in the system. Additional work must be performed to determine the heat losses to the environment in the various configurations and study the behaviour of the PCM within the system. By continuing to study the effect of varying common operating conditions of heat exchangers, this study is a first step in developing a heat exchanger design method for PCM-based heat exchangers.

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REFERENCES


