USE OF EXTERNAL VERTICAL FINS IN PHASE CHANGE MATERIALS MODULES FOR DOMESTIC HOT WATER TANKS

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ABSTRACT

The effect of using external vertical fins in Phase Change Materials (PCM) modules to improve the natural convection coefficient in water was studied in this paper. The use of PCM in a water tank working with a solar system allows a lot of energy to be stored, but it is necessary to transfer this energy to the water during demand. Heat transfer has been optimized in PCM composites and modules but not in the case of natural convection to the water. External fins increase the heat transfer surface and the heat transfer coefficient changes. An experimental work was designed and carried out to determine natural convection heat transfer coefficients for PCM cylindrical modules with two different external vertical fin geometries. Results were presented as a temperature variation over time of the PCM and the surrounding water, and the heat transfer coefficient as a function of the temperature difference for different fins. The results proved the technical potential of external fins for heat storage systems using PCM.

KEYWORDS: Phase Change Material (PCM), Fins, Natural convection, Thermal Energy Storage (TES), Solar Energy.

1. INTRODUCTION

Efficient and reliable thermal storage systems are an important requirement for many applications due to non-coinciding heat demand and supply or availability. One of the typical examples of such mismatch is solar energy. Among the thermal energy storage concepts, latent heat thermal storage is regarded as a promising technology.

A Phase Change Material (PCM) is any material used for latent heat thermal storage. Their use in Domestic Hot Water (DHW) tanks would keep hot water for a longer time. In such a system, a lot of energy can be stored as latent heat, but it should be able to be transferred from the PCM to the water when needed, therefore heat transfer within the PCM and to the water is of high interest (Cabeza et al., 2005; Ibáñez et al., 2005).

In DHW tanks the PCM is contained in modules to avoid mixing with water. These modules have been optimized in geometry (Nogués et al., 2002) and internal heat transfer (Cabeza et al., 2002). There are several methods to enhance heat transfer in PCM, but the authors have decided to use a PCM-graphite composite material which features both high storage density and large heat flux.

When using these PCM-graphite composites inside metal modules, the heat barrier is the heat transfer from the metal container to the water (Cabeza et al., 2002). To increase this heat transfer in the external part of the module vertical fins can be attached. By using fins the heat transfer area is extended and the coefficient of heat transfer by natural convection changes. This work studies the influence of adding external fins in the PCM modules.

The use of fins inside the PCM has been extendedly studied. These fins can be axial or radial and are usually attached to the tubes. In this case the most important part is the formulation of phase change problems. Several
Theoretical techniques have been developed, such as the enthalpy method by Ockendon and Hodkins, 1975, Eliot and Ockendon, 1982, and Ismail, 1998, 1999, 2001, the Landau transform method associated with the finite volumes method, the interface immobilization method together with the finite volumes approach, or the integral energy method. Ismail, 1998, 1999 presented a comprehensive review of literature on the subject as well as the results of many experimental and numerical studies on phase change heat transfer into and around simple and complex geometries.

Fins geometry is an important parameter when considering the addition of fins on a PCM module. In a vertical module two different fins geometries can be considered: horizontal and vertical fins. There is much more literature for horizontal fins (Karaback, 1992, Campo and Harrison, 1994, Laor and Kalman, 1996, Zubair et al., 1996, Campo and Stuffle, 1996, Mokheimer, 2002), but this geometry interferes with the natural convection in the PCM module in the considered application. On the other hand there is no literature for vertical fins around circular vertical tubes, but this geometry would improve natural convection on the water side of the PCM module. Because of this, in this work external vertical fins have been used to increase the heat transfer from the PCM to the water.

Some examples of the use of fins and natural convection are the study of annular fins with different profiles presented by Mokheimer, 2002, and the effect of radial fins in a horizontal annulus by Rahnama and Farhadi, 2004.

The use of PCM modules in DHW solar systems was proven in previous works (Cabeza et al., 2005; Ibáñez et al., 2005). The experimental set-up of these works was a 146 L tank connected to two solar collectors. Four PCM modules were introduced in the upper part of the tank and the performance of the system was tested. The tank was instrumented to measure inlet and outlet water temperature, and the water stratification in the tank. In this work, the influence of adding external fins to the PCM modules was studied. A mathematical model to simulate the PCM tank performance was developed. An appropriate heat transfer coefficient for the studied geometry was necessary to run this model. As this coefficient was not found in the literature, an ad-hoc experimental work was carried out.

2. **ANALYTICAL SOLUTION**

The analytical study was based on the following assumptions:

- The fin material is homogeneous and isotropic.
- There are no heat sources in the fin itself.
- The heat flow to or from the fin surface at any point is proportional to the temperature difference between the surface at that point and the surrounding fluid.
- The thermal conductivity of the fin is constant.
- The heat transfer coefficient is the same over the whole fin surface.
- The temperature of the base of the fin is uniform.
- The fin thickness is so small compared to its length and width that the temperature gradient normal to the surface may be neglected.
- The heat transferred through the outermost edge of the fin is negligible compared to that passing through the sides (insulated fin tip).
- The fluid properties are a function of the temperature and are evaluated at the registered temperature.

**Description of the studied system**

The tank studied is 1.250 mm high and 390 mm of diameter with a capacity of 146 L. The introduction of the PCM modules should not interfere with the stratification of the tank, for this reason the study must consider different water temperatures through the tank. Therefore, the tank was divided in six layers at different height, as showed in Fig. 1. Four PCM modules were introduced in the upper part of the tank. The registered data from the solar system experimental set-up (Cabeza et al., 2005; Ibáñez et al., 2005) were:

- Temperature of the water at 0, 30, 60, 90, 110, 120 cm from the bottom of the tank.
- Temperature of the 4 PCM modules.
- Ambient temperature.
- External tank temperature.
PCM modules without fins

In this study, vertical cylindrical modules were used to include the PCM inside the DHW tank. The geometry of the PCM modules was the same as that used in previous experimental work done by the authors (Mehling et al., 2003; Cabeza et al., 2003). These modules were cylindrical, with a diameter of 88 mm and 315 mm high.

To study the behavior of the storage system, an energy balance for water was done. Considering a DHW tank with PCM modules without fins, the governing equation of the system, following the Newton Law, was:

\[ Q_{PCM} = 2 \cdot \pi \cdot r_{PCM} \cdot L_{PCM} \cdot h_{PCM} \cdot \left( T_{s,PCM} - T_{d-60} \right) \]  

(1a)

The defining equation for the heat losses of the DHW tank, following the Newton Law, was:

\[ Q_{losses} = 2 \cdot \pi \cdot r_{ext,d} \cdot L_d \cdot h_{ext,d} \left( T_{s,ext,d} - T_a \right) \]  

(2a)

To evaluate the heat transfer coefficient for natural convection in the equations (1a) and (2a), experimental correlations found in the literature were used.

To determine the increase of water temperature over time the following energy balance equation was used:

\[ Q_{net} = V \cdot \rho_{H_2O} \cdot C_{p,H_2O} \left( \frac{T_{d-100} - T_{d-100t}}{t} \right) \]  

(5a)

where \( T_{d,100} \) and \( T_{d,100t} \) mean the water temperature at 100 cm from the bottom of the tank at a certain time and at the next time step, and \( V \) mean the total volume of the water tank.

Since all the experimental work done in the solar system in our laboratory used four PCM modules inside the DHW tank, the governing equation of the system was:

\[ Q_{net} = 4 \cdot Q_{PCM} - Q_{losses} \]  

(5b)

PCM module with external vertical fins

Fins surface is an important parameter to increase heat transfer to water. To determine the influence of the surface, two different fins were studied, both 310 mm high, but the first one of 20 mm of length, and the second of 40 mm. Each module had eight external fins, providing a 28.45% and 44.28% transfer surface increase respectively, compared to the reference module without fins. Fig. 2 shows the considered configuration.
The governing equations for a storage system using PCM in finned modules were the same used for the system without fins. The main difference in the calculation procedure was the determination of the heat transfer rate from the PCM to the water.

Considering the specific geometry of the PCM container and assuming insulated fin tip, the defining equation was (Çengel, 1998):

\[
Q_{PCM} = N_{fin}^\circ \sqrt{h_{PCM} \cdot Per \cdot k_{fin} \cdot A_c \cdot (T_{s,PCM} - T_d)} \cdot \tanh(a \cdot W_c)
\]  

(6a)

where:

\[
a^2 = \frac{h_{PCM} \cdot Per}{k_{fin} \cdot A_c}
\]  

(6b)

\[
Per = 2 \cdot W_c + 2 \cdot L_{PCM}
\]  

(6c)

\[
A_c = W_c \cdot L_{PCM}
\]  

(6d)

\[
W_c = W_{PCM} + \frac{A}{P}
\]  

(6e)

\[
P = 2 \cdot W_{fin} + 2 \cdot L_{PCM}
\]  

(6f)

\[
A = W_{fin} \cdot L_{PCM}
\]  

(6g)

As no suitable natural convection heat transfer coefficient correlations were available in the literature for the specific geometry of the module, the ad-hoc experimental work presented below was designed and performed.

3. EXPERIMENTAL WORK

Experiments done

To determine the effect of adding vertical fins to the external part of the module, some experiments were conducted. The PCM-graphite composite used was sodium acetate trihydrate with graphite (90:10 vol.%). This product has a melting point of 58°C, a melting enthalpy between 180 and 200 kJ/kg, a density between 1,35 and 1,4 kg/L, a heat capacity of 2,5 kJ/kg·K, and a thermal conductivity between 2 and 5 W/m·K. <Question: any nucleating agent added to the mixture, or the graphite filled this function as well?>

Three different modules were used: one without fins, another one with small fins (20 mm length) and the last one with big fins (40 mm length).

The experimental work reproduced the behaviour of the PCM modules in a DHW tank. The dimensions of the tank used were: 440 mm of diameter and 450 mm of height. Five type-K thermocouples and a data-logger instrumented the experimental set-up. Two thermocouples were located inside the PCM module (one in the centre and the other at half distance between the first one and the metal container). The other ones were situated inside the water, outside
the PCM module, one of them in contact with the external surface of it. The distance between the inside water thermocouples was 50 mm, and all thermocouples were at 135 mm distance from the top of the tank. Fig. 3 illustrates the instrumentation of the experiments.

Fig. 3 Experimental set-up.

The experimental work consisted on introducing the module containing melted PCM at 70°C into the cold water tank to evaluate the heat transfer phenomenon. The experiment was stopped when PCM and water temperatures were the same.

Natural convection heat transfer coefficient

Once the experimental work was done, heat transfer coefficient by natural convection for this specific geometry could be calculated. The following procedure was used:

1. Calculation of the heat transfer rate.
   The PCM (sodium acetate trihydrate) was mixed with graphite in a composite. Therefore, during all the experimental processes the mixture was not melted inside the PCM module, remaining in solid phase; only the sodium acetate trihydrate went through the melting/solidifying process, but not affecting the solid structure of the composite. Therefore, the heat transfer rate inside the PCM module could be determined using conduction equations (Fourier law).

\[
q = \frac{k_{PCM} \cdot A_{cond}}{d_T} \left( T_{PCM, \frac{\sqrt{2}}{4}} - T_{PCM, \frac{\sqrt{2}}{4}} \right)
\]

where:

\[
A_{cond} = 2 \cdot \pi \cdot \left( \frac{r_{PCM, \frac{\sqrt{2}}{4}}}{2} \right) \cdot L_{PCM}
\]

2. Calculation of the natural convection heat transfer coefficient.
   Once the heat transfer rate was calculated, the natural convection heat transfer coefficient could be determined using Newton law.

\[
h_{PCM} = \frac{q}{A_{transfer} \cdot (T_{surface} - T_{close})}
\]

where:

\[
A_{transfer} = 2 \cdot \pi \cdot r_{PCM} \cdot L_{PCM}
\]

for the module without fins, and

\[
A_{transfer} = 2 \cdot \pi \cdot r_{PCM} \cdot L_{PCM} + 2 \cdot N_{fin} \cdot W_{fin} \cdot L_{PCM}
\]
for the modules with vertical fins.

4. RESULTS

The experimental results showed an increase in the heat transfer rate when using PCM modules with vertical fins. This effect can be measured by the time needed by the modules to heat the water. Fig. 4a shows the time needed to heat the water due to the PCM phase change. To cool down the PCM from 60°C to 45°C (which assures a complete solidification of the PCM) using a PCM module without fins the time needed was about 17 minutes.

When using 20 mm fins, to achieve the same temperature decrease as in the experiments without fins, the time necessary was about 13 minutes (a reduction of 23.53%). Fig. 4b showed the heating and cooling down processes of the water and the PCM respectively.

Finally, PCM modules with 40 mm fins reduced the cooling down time to 7 minutes for the same temperature decrease (a reduction of 58.82%). Fig. 4c showed the heating and cooling down process for these experiments.

The heat transfer coefficient for natural convection for each PCM module geometry was compared in Fig. 5 as a function of temperature difference $\Delta T$. When using 20 mm fins, the temperature difference $\Delta T$ necessary to achieve the maximum heat transfer coefficient ($h=152$ W/m$^2$K with no fins; $h=166$ W/m$^2$K with 20 mm fins) experienced a threefold decrease ($\Delta T=3.5$ ºC with no fins; $\Delta T=1.1$ ºC with 20 mm fins). On the other hand, using 40 mm fins the temperature difference had a fourfold decrease ($\Delta T=0.8$ ºC), but the maximum heat transfer coefficient reduced too ($h=109$ W/m$^2$K).

<Kind of confusing to group together Figs 4a-c and Fig 5 in a square. Howabout instead putting all these result figures on one page, 3 in each column, and then call them Figs 4-9?>
Fig. 6a and Fig. 6b represent the natural convection heat transfer coefficient as a function of the temperature difference $\Delta T = T_{surface} - T_{close}$, for 20 mm and 40 mm fins, respectively. The experimental correlations were divided in three parts to achieve the best fit with the experimental data. The valid range of temperature differences was from 0,7 to 9,2 °C for 20 mm fins geometry, and from 0,2 to 10,2 °C for 40 mm fins.

For 20 mm fins, the experimental correlation is:

\[
\begin{align*}
&h_{PCM} = 369 \cdot \Delta T - 254 & 0,7 \leq \Delta T \leq 1,1 \\
&h_{PCM} = -85 \cdot \Delta T + 267 & 1,1 < \Delta T \leq 3,1 \\
&h_{PCM} = -1 \cdot \Delta T^2 + 13,4 \cdot \Delta T - 35,5 & 3,7 \leq \Delta T \leq 9,2 
\end{align*}
\]  

(9a)

For 40 mm fins, the experimental correlation is:

\[
\begin{align*}
&h_{PCM} = 52,2 \cdot \ln(\Delta T) + 104,4 & 0,2 \leq \Delta T \leq 0,9 \\
&h_{PCM} = -41 \cdot \Delta T + 124 & 0,9 < \Delta T < 3 \\
&h_{PCM} = -0,26 \cdot \Delta T^2 + 3,3 \cdot \Delta T - 6,14 & 3 < \Delta T \leq 10,2
\end{align*}
\]  

(9b)

In the first region the heat transfer coefficient increased with $\Delta T$. The maximum value for the coefficient was achieved at the intersection point between first and second region. For higher values of temperature difference the heat transfer coefficient decreased to values lower than 10. Finally, in the third region the coefficient described a parabolic behaviour not reaching values higher than 10 W/m²K.

There were some differences in the correlations for 20 mm or 40 mm fins. In the first region, the behaviour of the heat transfer coefficient when using 20 mm fins was approached with a linear regression. When using 40 mm fins, a logarithmic regression was used. In the second region both cases were approached with a linear regression. In the third region a polynomial regression was used.

5. DISCUSSIONS

The increase of the heat transfer rate was a result of the increase of the heat transfer area and the lower temperature difference necessary to achieve the same heat transfer coefficient for natural convection.

Using vertical fins did not increase the heat transfer coefficient. When using small fins, a lower temperature difference was necessary to achieve the same heat transfer coefficient as with no fins. Therefore, the needed time to solidify the PCM decreased. The increase of the heat transfer area resulted in an increase of the heat transfer rate.
When using big fins, the heat transfer coefficient was lower. The increase of the fins width interfered the natural convection. In spite of this, the needed time to solidify the PCM was also reduced because of the increase of the heat transfer area.

The increase of the heat transfer rate obtained by using vertical fins could be very useful for applications of PCM modules inside water tanks. These PCM modules are used to store energy in a reduced volume. Using modules with vertical fins the storage systems with PCM would have a faster availability of the stored energy.

In conclusion, the use of external fins in PCM modules reduced the time necessary for the heat transfer to the surrounding water. The temperature difference necessary to achieve a certain value of the heat transfer coefficient by natural convection was also reduced. The bigger the fins were, the faster was the heat transfer process, but the heat transfer coefficient was reduced when compared to the reference case with no fins. The increase of the heat transfer rate resulted in a higher availability of the stored energy in the PCM modules.

REFERENCES


