ECONOMIC, ENERGETIC AND EXERGETIC STUDY OF A WATER TANK
INCLUDING PCM MODULES INSIDE

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1. INTRODUCTION

The Research Group in Applied Energy (GREA) started a research work on Phase Change Materials (PCMs) in 1999. Since then we have been working on different aspects of these materials and have carried out a substantial amount of experiments (thickening, corrosion, heat transfer enhancement) in the laboratory with various types of phase change materials: paraffins, salt hydrates and even fatty acids. Selecting the most suitable PCM for the corresponding application is a crucial point for the good performance of the application.

A promising research line with PCM in GREA is the inclusion of PCM modules in the upper part of a water storage tank in order to increase its thermal capacity without breaking the beneficial thermal stratification, and reduce the required tank volume. This proved enhanced performance of the water tanks with PCM on top raised the interest of a local hot water storage manufacturer, who is partially supporting this research as they foresee a potential new product line of smaller tanks with PCM that have a reduced volume and are able to provide the same thermal performance as the standard water tanks.

This work analyses the energy and exergy balances for a charging process in a particular experimental water tank with PCM and the economic viability of manufacturing water tanks with PCM on top, as well. For this economic evaluation a necessary first step is to quantify the percentage of reduction of the water tank in such a way that the new smaller tank with PCM should provide the user the same energy performance as the bigger tank with only water. Once this energy tank equivalence is established for various makeup water temperatures and various water tank volumes, a feasibility study is also developed to evaluate the economic savings of a smaller PCM-water tank with the same thermal energy capacity as the larger reference water tank.

2. ENERGY AND EXERGY ANALYSES

The work presented here is the energy and exergy analyses for the charging process of a Thermal Energy Store (TES) system consisting of a domestic hot water tank (DHW) with PCM inside. Energy and exergy balances were done on both the coil heat exchanger side and the tank side. The data used for the analyses were obtained from the experimental set-up showed in Figure 1 and temperatures in different levels inside the tank, inlet and outlet heat transfer fluid temperature and flow rate as well as PCM temperature inside the modules were measured.

The system studied consists of a 300 L domestic hot water tank with 1.5 L PCM modules inside in such a way that results in a total amount of 4.3 kg of PCM, and an external heater of 2 kW. The fluid circulating is a mix of glycol and water that transfers the energy to the tank through a coil heat exchanger. And the properties of the PCM used (Figure 2) are shown in Table 1.
Table 1: Thermal properties of the selected PCM

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granular compound</td>
<td>90% Sodium Acetate + 10% Graphite</td>
</tr>
<tr>
<td>Density</td>
<td>1,35 – 1,4 kg/L</td>
</tr>
<tr>
<td>Melting point</td>
<td>58ºC</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>2,5 kJ/kg·K</td>
</tr>
<tr>
<td>Enthalpy</td>
<td>180 – 200 kJ/kg</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>2 – 5 W/m·K</td>
</tr>
</tbody>
</table>

Energy analysis

The system considered was the water tank with PCM modules inside and the coil heat exchanger and was treated as an open system in transient state. The general energy balance equation is shown in Equation 1.

\[
E_{in} - E_{out} = \Delta E_{system}
\]

\[
(Q_{in} + W_{in} + \sum m_{in} \theta_{in}) - (Q_{out} + W_{out} + \sum m_{out} \theta_{out}) = \Delta E_{system}
\]

Equation 1

\[
\theta = h + ke + pe
\]

Since the system did not involve any work, and heat transfer interaction with the ambient, kinetic and potential energy were neglected, Equation 2 was obtained for the energy balance of the coil heat exchanger. The term \( m \) corresponds to the total heat transfer fluid mass quantity circulated during all the charge time of the system:

\[
E_{in} - E_{out} = m(h_{in} - h_{out})
\]

\[
E_{in} - E_{out} = H_{in} - H_{out}
\]

Equation 2

For the tank and the PCM modules, taking into consideration that there was no change in the volume, Equation 3 was obtained. It represents the energy stored in the water and the PCM, and it was calculated as the variation of the energy stored in each subvolume in each time step of the calculations, considering 30 minutes as the time step.
\[ \Delta E_{\text{system}} = \Delta E_{\text{water}} + \Delta E_{\text{PCM}} = \sum (V_i \cdot \rho \cdot \Delta T_i)_{\text{water}} + m_{\text{PCM}} \Delta u_{\text{PCM}} \]

\[ \Delta E_{\text{system}} = \sum (V_i \cdot \rho \cdot c_v \cdot \Delta T_i)_{\text{water}} + \left\{ \begin{array}{l} m_{\text{PCM}} c_{\text{recy}} \Delta T_{\text{PCM}} \rightarrow \text{sensible heat} \\ m_{\text{PCM}} \lambda \rightarrow \text{latent heat} \end{array} \right\} \]

Equation 3

The energetic efficiency was also calculated, defining the efficiency as the ratio between the energy stored in the tank (water and PCM) and the energy supplied by the coil heat exchanger, as it is shown in Equation 4:

\[ \eta = \frac{\Delta E_{\text{system}}}{H_{\text{in}} - H_{\text{out}}} \]

Equation 4

**Exergy analysis**

As in the energy analysis, the exergy analysis started with an exergy balance of the system studied for the charging process (Equation 5).

\[ \Delta E_{\text{tank}} = \Delta E_{\text{coil}} - E_D \]

Equation 5

As it was done in the energy balance, the kinetic and potential exergy were neglected as well as the exergy flows associated to work and heat transfer. Therefore the exergy considered resulted in a balance of the physical and chemical exergy. The decrease of exergy associated to the heat transfer fluid flowing through the coil heat exchanger during the charge process can be written as:

\[ \Delta E_{\text{coil}} = m (e_{\text{ex in}} - e_{\text{ex out}}) = \left[ (e^{PH}_{\text{in}} + e^{CH}_{\text{in}}) - (e^{PH}_{\text{out}} + e^{CH}_{\text{out}}) \right] \]

Equation 6

There was no change in the chemical exergy between the input and output. Thus, the chemical exergy terms are cancelled. The above equation can be written as Equation 7.

\[ \Delta E_{\text{coil}} = m \left[ (h_{\text{in}} - h_0 - T_0 (s_{\text{in}} - s_0)) - (h_{\text{out}} - h_0 - T_0 (s_{\text{out}} - s_0)) \right] = \]

\[ = m \left[ (h_{\text{in}} - h_{\text{out}}) - T_0 (s_{\text{in}} - s_{\text{out}}) \right] \]

Equation 7

Equation 8 shows the calculation for the increase of exergy in the tank. Taking into consideration that there was no change in the volume, and \( \Delta u \) was the thermal energy stored in the tank calculated previously in the energy balance, it resulted in:

\[ \Delta E_{\text{tank}} = V \cdot \rho (\Delta u - T_0 \Delta s)_{\text{water}} + m_{\text{PCM}} (\Delta u - T_0 \Delta s)_{\text{PCM}} \]

Equation 8

As it was done in the energy balance, the efficiency of the exergy balance was calculated as shown in Equation 9, defining the efficiency as the ratio between the increase of exergy available in the tank (water and PCM) and the exergy supplied by the coil heat exchanger.

\[ e = \frac{\Delta E_{\text{tank}}}{\Delta E_{\text{coil}}} \]

Equation 9

3. **ECONOMIC ANALYSIS**

**Energy equivalence**

Before any analysis on the achievable tank reductions, it is necessary to accurately describe the authors’ definition of energy equivalence when the reference water tank and the novel PCM tank are compared.
Figure 3 shows the interpretation of energy equivalence. It can be observed that the reference tank with 300 L at 60ºC is shown on left side. To simplify the mathematical approach a perfectly-mixed tank (no stratification) is considered, thus all the water in the tank is supposed to be at 60ºC. If the tank is completely discharged, the tank is obviously capable of providing the 300 L of water at 60ºC. The tank on the right side is 10% smaller (volume of 270 L) and contains 10 L of PCM in the upper part. To easy the analysis the same tank diameter is assumed in both tanks. The water volume capacity of the new PCM tank is 260 L, as the other 10 L are occupied by the PCM module. For this second tank to have the same energy performance as the reference one, after a total tank discharge of 260 L, the PCM has to be able to transfer his phase change latent heat (assumed at 60ºC) and heat up the additional 40 L to 60ºC. In this case the tank will be also capable of supplying 300 L at 60ºC to the final users. According to the presented equivalence criteria, the PCM tank can be considered equivalent to the reference tank. It is important to note that the makeup water temperature will play a critical role in this definition of thermal equivalence. For that reason a parametric study of the inlet reposition water temperature was included.

Figure 3. Definition of energy equivalence between a reference water tank and smaller PCM tank

It is important to note here that the typical convention in literature to evaluate the increase in energy density for PCM water tanks is somehow different to the defined in this paper. The literature convention generally compares the specific energy released by water for a 1°C temperature change with the PCM latent heat. Under these conditions the increased energy density corresponds to the ratio of the PCM solid-liquid phase change latent heat to the specific heat of 1 kg of water ($\lambda_{\text{H}_2\text{O}}$). For the PCM chosen in this study this ratio achieves a value of about 45. Although this high value is correct using the above definitions, it can be misleading in practical applications and may lead to overestimations of the achievable volume reductions when PCM is included in water tanks. Two are the reasons than lowers the above referred ratio to values below 2. The first one is that the PCM is not replacing the whole water volume, but only a small section of the upper part of the tank (water is still the heat transfer fluid). The second one is that for practical applications, such as central heating or sanitary hot water, temperature differences between supply and return water are much higher than 1°C, in the range of 10-50°C. Besides, it is important to know that there is not a specific methodology to establish the efficiency of a PCM tank and it is a field where the IEA is already working.

Tank reduction

Once the energy equivalence used in this work has been explained, a parametric study of the possible percentages of tank reduction was carried out. The independent variables used as inputs in the calculations, together with their studied ranges and a column of comments which justify the range selection are shown in Table 2.

Once the input variables were defined the calculation procedure was the application of an energy balance that allowed determining the required PCM mass in order to heat up the makeup water from inlet temperature up to 60ºC. Other output parameters derived from the PCM mass were the number of PCM modules of 1.5 L and several useful mass and volume relationships between the upper tank part that was in direct contact with the PCM modules and the total tank.
Three different tank sizes were considered, 300 L, 1500 L and 3000 L. The tanks are made of 2 mm thick stainless steel and have a polyurethane insulation of 0.06 m.

Table 2: Independent variables chosen in the study of PCM tank volume reductions

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Studied range</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of tank reduction</td>
<td>2-25%</td>
<td>This range is reduced in some cases due to physical restrictions.</td>
</tr>
<tr>
<td>Tank volume</td>
<td>300-3000 L</td>
<td>The volume ranges are coincident with the available commercial tank capacities.</td>
</tr>
<tr>
<td>Makeup inlet temperature</td>
<td>5-45ºC</td>
<td>5 and 25ºC simulate sanitary hot water applications and are design conditions for makeup tap water in winter and summer, respectively. 45ºC simulates a central heating case.</td>
</tr>
</tbody>
</table>

4. RESULTS

Energy and exergy results

Figure 4 shows the results of the energy balance of the experimental PCM tank in a charging process. The external electrical heater used to heat up the fluid entering into the tank through the coil has a power of 2 kW. The observed difference between the electrical heater power and the thermal power introduced in the tank are due to the thermal losses existing in the pipes between the electrical heater and the tank inlet. Along the test, the power introduced in the tank decreases because the increased thermal losses between the external heater and the tank. The temperature of the fluid is higher every time step due to the heater and also the difference between this temperature and the ambient temperature increases, therefore the thermal losses also increase.

![Figure 4. Energy balance in the tank and thermal power to the tank.](image)

The energy increase in the tank side is mostly due to the water increase. The PCM contributes only with about a 2% of the increased energy in the tank. It is observed that there is a good agreement between the energy released by the heat exchanger coil and the one gained by the PCM tank. The energetic efficiency has been also calculated obtaining a value of 94%. It means that only a 6% of the energy is lost likely because of the thermal losses through the tank.

Figure 5 illustrates the exergy analyses for each component of the system considered, the tank and the coil heat exchanger. As it was expected due to the exergy balance, the exergy input is given by the coil and it is transferred to
the water with the associated exergy destruction. Therefore, the sum of the increased exergy in the tank and the irreversibilities is equal to the exergy provided by the coil heat exchanger. As it was done in the energy balance, the efficiency of the exergy balance was calculated obtaining a value of 64%. This means that only the 64% of the initial exergy of the heat transfer fluid can be transformed into useful work.

![Figure 5. Exergy analyses of the system considered.](image)

**Economic results: Effect of the PCM tank reduction on the number of PCM modules**

Figure 6 shows the effect of the PCM tank reduction on the number of PCM modules for the three makeup water temperatures in study. The corresponding ratio of PCM volume and total tank volume is included in the right Y axes. For the most favourable case (makeup temperature of 45°C), which corresponds to the return temperature in central heating applications, it was possible to achieve a smaller equivalent PCM tank up to a maximum reduction of 25% (225 L tank). This new tank would need a total PCM volume of 23.8 L. This volume corresponds to 15.9 modules of 1.5 L capacity that would be located in vertical position in the upper quarter of the tank height. Smaller tank reductions (less than 25%) were also possible, which would mean smaller PCM tank overcosts but also smaller economic savings in steel and insulation material.
Results for a makeup water temperature of 25ºC showed that the maximum achievable tank reduction in this case was only of 6% (tank of 282 L). This was an expected finding as more PCM mass was needed to heat up the makeup water from 25 to 60ºC than in the case from 45 to 60ºC. Another view of the same situation is that the previously referred energy equivalent tank of 225 L with 15.9 PCM modules was not equivalent anymore for this new makeup water temperature, since makeup water would be only be heated up to 40ºC instead of the required 60ºC.

For the worst case with a makeup temperature of only 5ºC, the maximum tank reduction is lower than 2%. The 25% smaller equivalent tank for the case of 45ºC makeup water is no longer equivalent as the mass of PCM will only be able to heat up the 98.8 L of additional water up to 20ºC.

**Economic results: Effect of PCM cost on tank savings**

The adopted definition of energy equivalence imposes severe constraints to the range of possible tank volume reductions when makeup water temperature is in the range of typical sanitary hot water applications (5-25ºC). Thus the analysis on economic savings will be focused on the most favourable case of backup water of 45ºC, which corresponds to a typical central heating application. In any case, if the analyses were to be repeated for the cases with lower makeup water temperatures, the resulting economic savings would be always smaller than the ones presented herein.

Table 3 presents the cost of the materials that contribute to the final manufacturing tank cost, together with other physical parameters necessary for the economic evaluation that were not stated previously. All these values were provided by the local tank manufacturer. The cost of the PCM module container was neglected. A cost range is selected for the PCM in order to perform a parametric study on the final tank cost.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel cost</td>
<td>€/kg</td>
<td>4</td>
</tr>
<tr>
<td>Stainless steel density</td>
<td>kg/L</td>
<td>8.05</td>
</tr>
<tr>
<td>Insulation cost</td>
<td>€/kg</td>
<td>2</td>
</tr>
<tr>
<td>Insulation density</td>
<td>kg/L</td>
<td>0.045</td>
</tr>
<tr>
<td>PCM cost</td>
<td>€/kg</td>
<td>0-2</td>
</tr>
</tbody>
</table>
Figure 7: Economic savings per tank versus PCM specific cost for various tank sizes (selected conditions: 25% of volume reduction, makeup temperature 45°C).

Figure 7 presents the effect of the PCM cost on the manufacturing savings (or overcosts) per tank for three different tank volume capacities. Results correspond to an energy equivalent PCM tank 25% smaller for makeup water temperature of 45°C. When PCM costs tend to 0 €, economic savings over 130 €/tank are obtained for the 3000 L tank. These savings are reduced to about 95 and 40 €/tank for 1500 and 300 L tank volumes, respectively.

However, if the PCM specific cost is for example of 2 €/kg, the PCM equivalent tank production would result in an overcost of 20, 230 and 520 €/tank for tank capacities of 300, 1500 and 3000 L, respectively. Trade-off prices which lead to zero savings are about 1.3, 0.6 and 0.4 €/kg of PCM for tank sizes of 300, 1500 and 300 L, respectively.

**Economic results: Effect of the fraction of volume reduction on economic savings**

Any tank volume reduction thanks to the inclusion of PCM brings two opposite effects with regard to the final economic costs of the tank production. On the one hand savings are achieved as the mass of stainless steel and insulation materials are reduced. On the other the overcost associated to the PCM grows since any reduction in tank volume implies an increase of PCM mass to meet the required energy equivalence with the reference water tank. Therefore, the effect of increasing volume reductions can be either a gradual increase in savings or an increasing overcost.

Figure 8 shows that when the combination of PCM, steel and polyurethane costs result in economic savings per tank, further volume reductions (within the permitted ranges previously identified) contribute to more savings. Nevertheless, the opposite behaviour is observed when the PCM cost cannot compensate the steel and insulation savings, i.e. further tank reductions result in more overcosts per tank.
The cost of the PCM in large quantities (more than 1000 kg) provided by the supplier is 6-7 €/kg. It is obvious that a considerable price reduction is necessary for the studied application to be cost-effective. With the current PCM cost the overcost for a 300 L energy equivalent PCM tank is of 150 € (not shown). For larger tanks this overcost value would be even higher. Despite the current tank production overcost, launching a new production line with PCM tanks might still be attractive. The increase PCM water tank production cost could be passed to the final user by announcing the enhanced performance of this novel technology of thermal energy storage. Some of the advantages of this new product line include:

- Small sizes for the same stored energy
- Hot water at a more constant temperature
- Possibility of water reheating when solar energy is not available without consuming fossil fuel or electricity.

The increased market penetration of these PCM tanks may also lead to an increasing competition among PCM manufacturers and to cheaper PCM costs. All the above factors may accelerate the commercial adoption of hot water PCM tanks in a near future.

5. CONCLUSIONS

Energy, exergy and economic analyses were done for a domestic hot water tank with PCM modules inside. The energy and exergy analysis consisted in energy and exergy balances for the charging process of an experimental PCM tank. The energy balance showed an efficiency of 94%, while the exergetic efficiency was of 64%.

The economic study investigated the potential economic benefits of a new production line of hot water storage tanks that include a series of PCM modules in the upper part. The selected PCM is sodium acetate trihydrate with graphite. First, an energy equivalence was established between the reference hot water tank and the new smaller PCM tank and the range of possible tank size reductions was studied for various make up water temperatures. Then potential economic savings were analysed as a function of the PCM cost and the tank volume. Results show that for the application of central heating the inclusion of PCM allows a volume reduction of the PCM tank up to 25%. This reduction could lead to significant economic savings in the tank production cost provided that the PCM specific cost is under 0.4 €/kg. Higher costs up to 1.3 €/kg are still cost-effective for the smaller 300 L tanks. For the limit case of PCM tending to zero €/kg, the economic savings are about 130, 95 and 40 €/tank for tanks of 3000, 1500 and 300 L, respectively. The current PCM cost (6-7 €/kg) is still high for these novel PCM tanks to be cost-effective, but future developments and competition could bring the PCM cost down.

Figure 8: Savings per tank as a function of volume reduction fraction of the energy equivalent PCM tank for various PCM specific costs (selected conditions: 25% of volume reduction, makeup temperature 45 °C).
Despite the current tank production overcost, launching a new production line with PCM tanks might still be attractive. The increase PCM water tank production cost could be passed to the final user by announcing the enhanced performance of this novel technology of thermal energy storage. Some of the advantages of this new product line include:

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ACKNOWLEDGMENTS

The authors would like to acknowledge the companies Lapesa S.A. and SGL Technologies for their collaboration in this research. The work was partially funded with the project ENE2005-08256-C02-01/ALT.

Marc Medrano would like to thank the Spanish Ministry of Education and Science for his Ramon y Cajal research appointment.

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