Experimental test of a hot water storage system including a macro-encapsulated phase change material (PCM)

L Mongibello¹, M Atrigna¹, N Bianco², M Di Somma¹, G Graditi¹ and N Risi²

¹ ENEA – Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Portici R.C. – P.le E. Fermi, 1, 80055 Portici NA, Italy
² Dipartimento di Ingegneria Industriale (DII) – Università di Napoli Federico II – P.le Tecchio, 80, 80125 Napoli, Italy

Corresponding author e-mail: luigi.mongibello@enea.it

Abstract. Thermal energy storage systems (TESs) are of fundamental importance for many energetic systems, essentially because they permit a certain degree of decoupling between the heat or cold production and the use of the heat or cold produced. In the last years, many works have analysed the addition of a PCM inside a hot water storage tank, as it can allow a reduction of the size of the storage tank due to the possibility of storing thermal energy as latent heat, and as a consequence its cost and encumbrance. The present work focuses on experimental tests realized by means of an indoor facility in order to analyse the dynamic behaviour of a hot water storage tank including PCM modules during a charging phase. A commercial bio-based PCM has been used for the purpose, with a melting temperature of 58°C. The experimental results relative to the hot water tank including the PCM modules are presented in terms of temporal evolution of the axial temperature profile, heat transfer and stored energy, and are compared with the ones obtained by using only water as energy storage material. Interesting insights, relative to the estimation of the percentage of melted PCM at the end of the experimental test, are presented and discussed.

1. Introduction

By definition, thermal energy storage systems permit to accumulate energy for a later use, thus allowing, for example, a better exploitation of distributed poly-generation systems, which thanks to thermal energy storage systems can produce electricity when it is more economically convenient without or with a limited heat dumping [1,2], or a more efficient use of the thermal energy produced by solar thermal panels by accumulating hot water when it is not required by the thermal utilities for a later use [3,4].

Relatively to the thermal energy storage materials, water is the most used one, essentially because it has practically no cost, a high specific heat, and it is not flammable nor toxic. However, in recent years latent heat thermal energy storage (LHTES), that typically relies on the latent heat relative to the isothermal solid-liquid phase transition of PCMs like paraffins, fatty acids and salt hydrates, has gained great attention, as it can provide much higher energy storage density than the sensible thermal energy storage, and as a consequence it can lead to a consistent reduction of weight and volume of thermal energy storage systems [5-9].

This work analyzes experimentally the dynamical behavior of a hot water storage tank including PCM modules consisting in aluminum bottles of 3 liters partially filled with a commercial bio-based PCM having a melting temperature of 58°C.
In the following, the indoor experimental facility and the PCM modules are described first. Successively, the experimental results relative to the hot water tank including the PCM modules are presented in terms of temporal evolution of the axial temperature profile, heat transfer and stored energy, and they are compared with the ones obtained by using only water as thermal energy storage material.

2. Experimental facility
The experimentation of the hot water storage tank with the PCM has been realized by means of an indoor facility, designed and realized to perform experimental validations of analytical models for the numerical simulation of hot water storage systems including PCMs. Figures 1 and 2 show a sketch and a picture of the experimental facility, respectively.

![Figure 1. Layout of the experimental facility.](image1)

![Figure 2. Experimental facility.](image2)
The commercial insulated hot water storage tank has a vertical cylindrical shape, a height of 1.27 m, an internal diameter of 0.65 m, and a total capacity of about 420 liters. It is equipped with a 1” coiled-tube heat exchanger having a total heat exchange area of 1.9 m$^2$, and with 10 type-T thermocouples with the hot junctions equally spaced along the tank axis. Moreover, the hot water tank is connected to an expansion vessel in order to perform tests at different pressure values. The charging of the thermal energy storage tank is realized by means of a fluidic circuit connected to the tank heat exchanger, while the thermal discharging is done by means of an electric modulating valve that allows to regulate the set-point of the water mass flow rate. The heat exchanger inflow and outflow sections are located at about 0.73 m and 0.28 m from the tank bottom, respectively.

Relatively to the charging circuit, the main components are represented by the pump, modulated by an inverter in order to control the mass flow rate through the circuit, and the electric heater providing heating up to 24 kW. A thermoregulator controls the heater in order to regulate the temperature at the tank heat exchanger inflow section. Figures 3 and 4 show the electric heater and the thermoregulator, respectively. The data acquisition and control are made by means of NI modules mounted on NI cRIO-9066 controller. The control panel has been realized by means of the NI software Labview, and all the controlled parameters are regulated using PID controllers.

3. PCM module
Each PCM module consists in an aluminum bottle of 3 liters partially filled with a commercial bio-based PCM, without any additives and without applying any sophisticated technic for the enhancement of heat transfer inside the PCM. Figure 5 and 6 show the aluminum bottle and the PCM, respectively, while table 1 reports the main characteristics of the PCM.
Table 1. PCM thermo-physical characteristics.

| Property                             | Value                  |
|--------------------------------------|------------------------|
| Melting point                        | 58°C                   |
| Latent heat                          | $225 \times 10^3$ J/kg |
| Thermal conductivity (liquid)        | 0.15 W/m/K             |
| Thermal conductivity (solid)         | 0.25 W/m/K             |
| Density (liquid)                     | 810 kg/m³              |
| Density (solid)                      | 890 kg/m³              |
| Specific heat (liquid)               | 2710 J/kg/K            |
| Specific heat (solid)                | 2470 J/kg/K            |

Each bottle contains about 1.7 kg of PCM. Considering that, with the tank water at ambient temperature, the pressure at the tank bottom is regulated at 1.5 barg, and that the tank discharging can be made within a limited range of water mass flow rate, the above quantity of PCM has been calculated so that the module internal pressure remains lower that the one in the tank during both charging and discharging. In such a way, accidental spillage of liquid PCM from the bottle is avoided.

4. Results

In this section the results of two experimental tests, one realized including 14 PCM modules inside the hot water storage tank, and the other one using only water as heat storage material, are reported and compared. In both the cases, all the experimental measures have been recorded with a sample time of 1 s.

Figure 7 shows a picture of the PCM modules inside the tank, which have been positioned in the upper part of the tank through a flange.

The two different thermal energy storage systems have been tested applying the same initial conditions, and the same boundary conditions over the entire experiments duration. Indeed, in both the experimental tests, the energy storage system has been charged for a period of six and half hours, with a constant water mass flow rate through the serpentine of 0.2 kg/s, and with an increment of the water temperature at the serpentine inflow section of 5°C/(30 min), except for the last thirty minutes, in which the temperature at the serpentine inflow has been kept constant and equal to 85°C. In both the cases, the initial temperature of the water at the serpentine entrance was set to 30°C, and about the same initial water temperature profile along the tank axis was established. Furthermore, in both the cases the indoor ambient temperature has been regulated to 23 °C for the entire experiments duration.
In the following, the results relative to the test with water and PCM will be referred to using (w+PCM), while (w) will be used for the ones relative to the case with only water.

4.1. Temperature axial profiles and accumulated thermal energy

Figure 8 shows the temporal evolution of the measured water temperature profiles along the tank axis, while figure 9 reports the evolution of the total energy transferred from the serpentine to the tank water, and of the total energy accumulated in the water, from the initial state.

![Figure 8. Water temperature profiles along the tank axis: red curves (w); black curves (w+PCM).](image)

The energy transferred from the serpentine to the tank water has been calculated as the product of the sample time and the difference between the enthalpy flow rate at the serpentine inflow section and the outflow one, while the water internal energy increment has been evaluated using the measured temperatures along the tank axis. As concerns the calculation of the internal energy increment, it has been supposed that the measured temperatures represent the average water temperatures relative to the tank horizontal sections passing through the measuring points. This position, of course, leads to approximated results.

For convenience of discussion, both the experimental tests are divided into two parts. The first part goes from the test start to the instant in which the maximum water temperature in the upper part of the tank with water and PCM reaches the PCM melting temperature (58°C), that occurs after about 13,500 s, and the second one from 13,500 s to the end of the test.

Figure 8 shows that in the first period, due to the lower total heat capacity that characterizes the thermal energy storage tank with water and PCM in this period, the case (w+PCM) experiences a more rapid increase of the water maximum and mean temperatures. In particular, considering the profiles reported in figure 8, it can be seen that the difference between the temperature profile in case (w+PCM) and the one in case (w) increases from the test start to 9,000 s, and then decreases slightly from 9,000 s to 12,600 s. By contrast, in the same period, the case (w) presents a higher heat exchange between the water flowing through the serpentine and the one in the tank, and a higher heat storage in the water, as can be noticed in figure 9. This is explained considering that case (w) presents a slightly higher temperature difference between the water temperature in the serpentine and the one in the tank section where the serpentine is located.

The second period is characterized by the solid-to-liquid phase transition of the PCM, or of part of it. Although the quantity of PCM used is relatively low, the effects of the PCM melting are clear if the differences between the temperature profiles in the two cases from 16,200 s to 21,600 s are considered. Indeed, figure 8 shows that at 16,200 s the two profiles are nearly coincident, and that there is a more rapid increase of the temperatures in the case (w) from 16,200 s to 19,800 s, and also...
that from 19,800 s to 21,600 s the difference between the profiles remains practically the same. These results are due to the PCM melting, and can be analysed in more detail considering the same arguments used to analyse the first period.

![Figure 9](image)

**Figure 9.** Heat transferred through the serpentine wall, and energy accumulated as sensible heat in the water.

4.2. Evaluation of the PCM melted fraction

The most challenging and at the same time intriguing task of the present experimental work has been the estimation of the percentage of melted PCM at the end of the experimental test, namely after six and half hours of charging, using only the above reported experimental data, and without implementing any analytical model for the numerical simulation of the melted fraction of PCM inside the modules. This task has been faced by using two different approaches.

The first one is a qualitative approach, and it is based on the analysis of the temperature profiles in the second period, and, in particular, of the ones at the end of the experimental test. The analysis of the evolution of the temperature profiles in the second period reported before, and the fact that the temperatures profile relative to the case (w+PCM) approaches the one relative to case (w) at 23,400 s suggest that at the end of the experimental test relative to the tank with water and PCM, the energy is accumulated essentially as sensible heat, implying that the PCM is all melted, or most likely, almost all melted. In fact, due to the very low thermal conductivity of the PCM, the characteristic time relative to conduction heat transfer inside the PCM, evaluated using the aluminum bottle radius as characteristic length, is very high and equal to about 11.5 h. So, even if the PCM melting is also influenced by natural convection mechanisms, it is highly probable that the PCM was not completely melted at the end of the test. However, this approach is only qualitative and doesn’t allow to calculate the value of the PCM melted fraction.

The second one is an approximated quantitative approach, based on the results reported in figures 8 and 9. Considering the results relative to case (w) in figure 9, namely the two red curves, at each time instant the difference between the continuous curve and the dashed one represents the sum between the heat accumulated in the tank components (walls, insulation, etc.), and the heat losses through the tank external walls. Considering the black curves, which refers to case (w+PCM), at each time instant of the first period the difference between the continuous curve and the dashed one represents the sum between the energy accumulated in the tank components, the heat losses, and the heat accumulated in the PCM modules as sensible heat. In the second period, the difference between the black continuous curve and dashed one also includes the heat accumulated in the PCM as latent heat. Considering that the temporal evolution of the tank water temperature field is very similar in the two cases, as can be seen in figure 8, it has been assumed that, at the end of the tests, the heat
accumulated in the tank components and the heat losses in the two cases are equal. So, the sum between heat losses and heat accumulated in the tank components at the end of the tests has been calculated using the last points of the red curves, and then it has been subtracted to the difference between the last points of the black curves. The result represents the sum between the sensible heat accumulated in the solid PCM, the heat accumulated in the PCM as latent heat, and the sensible heat accumulated in the liquid PCM. Finally, neglecting the sensible heat accumulated in the liquid PCM, after calculating the sensible heat accumulated in the solid PCM considering between the initial temperature in the tank and the melting temperature (58°C), it has been possible to calculate the heat accumulated as latent heat, that resulted to be equal to 1.1 kWh. So, since the latent heat relative to all the PCM melted is equal to about 1.5 kWh, the second approach is in good agreement with the first one, suggesting that at the end of the test the PCM was not completely melted.

5. Conclusion
This work reports the results of the experimental analysis of a hot water storage tank including PCM modules consisting in aluminum bottles of 3 liters partially filled with a commercial bio-based PCM having a melting temperature of 58°C. The experimental results relative to the hot water tank including the PCM modules are compared with the ones obtained by using only water as heat storage material. The two different heat storage systems have been charged for a period of six and half hours, applying the same initial conditions, and the same boundary conditions over the entire experiments duration. Results of the present application evidence the effects of the presence of the PCM, and indicate that, at the end of the heat charging, not all the PCM has undergone melting.

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