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Study of the Performance of a Hybrid Thermal Energy Storage System with Cylindrical PCM Encapsulations under Real Solar Conditions

Cristina Bianqui[1], Alberto Egea[1], Alberto García[1], Antonio Viedma[1], José Miguel Paredes-Parra[2], Rubén Soto[2]

[1]Departamento de Ingeniería Térmica y de Fluidos, Universidad Politécnica de Cartagena
Campus Muralla del Mar, C/ Doctor Fleming, s/n, 30202 Cartagena, España
cristina.bianqui@upct.es; alberto.egea@upct.es; alberto.garcia@upct.es; antonio.viedma@upct.es

[2]Centro Tecnológico de la Energía y del Medio Ambiente (CETENMA),
Polígono Industrial Cabezo Beaza, C/ Sofía, 6-13, 30353 Cartagena, España
jmparedes@cetenma.es; ruben.soto@cetenma.es

Abstract - The intermittent nature of solar energy makes the development of thermal energy storage systems essential to ensure a constant and reliable energy supply. In this study, a hybrid accumulator, incorporating both water and phase change material (PCM) contained within encapsulations, has been developed. The accumulator is a cylindrical stainless-steel tank where 85 cylindrical stainless-steel encapsulations are placed. They are arranged in a cascaded packed-bed configuration, as the encapsulations are set in 5 levels and filled with PCMs of different melting points. Three paraffins from the manufacturer Rubitherm are used. Their thermal properties are measured experimentally to obtain accurate values and gain a deeper understanding of their behaviour. Tests are conducted by simulating the heating stored by solar collectors and the energy discharges are performed according to the EN 50440:2015/A1:2020 standard. Tests have been conducted simulating a typical summer day in Cartagena (Spain), yielding optimal results as the requirements specified in the standard have been met. In addition, it is observed that the cascaded configuration enhances the stratification in the tank. This ensures the supply of hot water for consumption.

Keywords**:** encapsulated PCM, thermal energy storage, domestic hot water, solar systems efficiency, solar energy.

1. Introduction

As stated in the Renewables 2024 Global Status Report [1], the residential sector represents approximately one-third of total energy consumption, and about 75% of this is used for water and space heating. These are predominantly low-temperature thermal energy applications, which are suitable for renewable energy sources, particularly solar energy.

The growth of solar domestic hot water systems (SDHWS) is driven by their cost-effectiveness and sustainability when meeting residential energy demands. However, their efficiency is limited by solar energy intermittency, particularly during adverse weather or at night. Therefore, energy storage is essential for integrating renewable sources, as noted by the European Commission in the REPowerEU project [2].

Latent thermal energy storage (LTES) systems have been developed to enhance SDHWS efficiency by using phase change materials (PCM). PCM absorb and release thermal energy when changing phase, which enables them to store and release large amounts of latent heat, between 180 to 540 kJ/kg [3], within a specific temperature range. In recent years, hybrid accumulators, which have water and PCM in encapsulations, have been designed and manufactured. These systems are known for their easy manufacturing, rapid DHW acquisition, suitability for domestic use and cost-effectiveness [4]. Furthermore, using encapsulated PCM enhances the heat transfer area, thereby increasing the heat exchanged between the PCM and the water. Hybrid accumulators commonly incorporate macroencapsulated PCM in a packed-bed configuration as they are easier to incorporate inside it, such as in the studies performed by Yu et al. [5] and Raul et al. [6].

Different authors have studied the impact of replacing the water tank in SDHWS with hybrid packed-bed accumulators. Ding et al. [7] simulated a solar system with a hybrid accumulator and got up to 30% saving in electrical power. Nallusamy et al. [8] experimentally investigated a conventional SDHWS and another incorporating PCM in the accumulator. Tests were conducted under solar conditions and the hybrid system showed a major performance. Abdelsalam et al. [9] reported the reduction of the size of the storage tank up to 40% when using a hybrid accumulator.

A strategy to improve the efficiency of hybrid accumulators integrated into solar systems is the use of encapsulations with PCMs of different phase change temperatures. These are incorporated into the accumulator in different layers to form a cascaded packed-bed system. Various authors [10], [11] concluded that such accumulators have a better performance than those that incorporate only one type of PCM; they enhance the stratification of domestic hot water in the tank, store latent energy from early hours, optimizing the entire solar energy collection cycle, and enable solar collectors to operate at high efficiency.

Although spheres are the most common shape, other geometries have been studied. Kumar and Saha [12] developed a mathematical model for a packed-bed system with cylindrical micro-encapsulations since cylinders can optimize the phase change processes due to their higher area-to-volume ratio.

In this study, an analysis of the performance of a hybrid accumulator with cylindrical stainless-steel encapsulations is done. It is a cascaded packed-bed system, with 5 staggered layers of encapsulations filled different PCMs. Three paraffins with different melting points from the manufacturer Rubitherm are selected. An experimental study of their thermal properties is conducted. The accumulator tests are conducted under real solar conditions, simulating the behaviour of a solar collector in a typical summer day in Cartagena (Spain) and with several discharges following the EN 50440:2015/A1:2020 standard.

2. Materials and Methods

2.1. Hybrid Accumulator

The accumulator utilized in this study consists of a stainless-steel tank with an inner diameter of 267.90 mm, a thickness of 2.6 mm, and a height of 460 mm. All its dimensions are shown in Figure 1. Inside the tank, 85 cylindrical encapsulations are arranged in 5 staggered levels, so the water turbulence is enhanced. This configuration is shown in Figure 2. 17 encapsulations are placed in each level. A cascaded disposition is selected, employing PCMs with different melting points, as indicated in Figure 2. These are commercial paraffins supplied by Rubitherm, specifically RT35HC, RT44HC, and RT54HC.

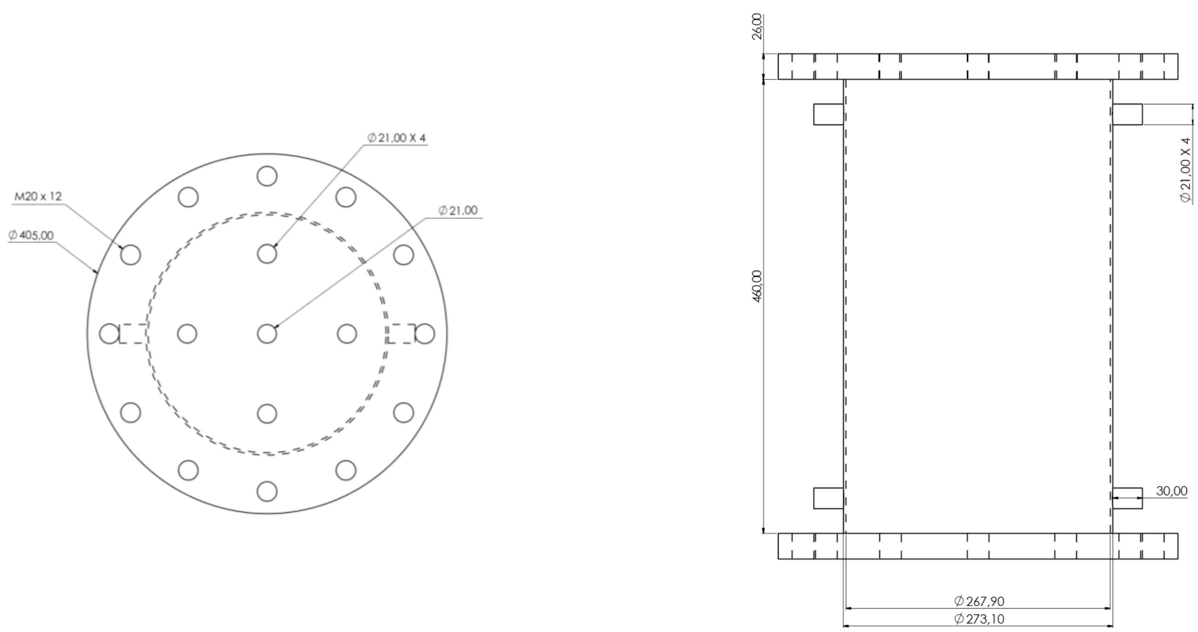

Figure 1: Dimensions of the accumulator: top (left), front (right).

The encapsulations are stainless-steel cylinders with a diameter of 60 mm, a thickness of 1.5 mm and a height of 24.45 mm (Figure 2). In one of the bases, two holes are made. The biggest hole is used to fill the capsule with liquid PCM, using a syringe. The smallest hole allows air to escape during the filling process. Each capsule is filled with PCM to its maximum volume of 40 ml, which corresponds to 80% of its total volume.

Inside the accumulator, pre-calibrated type-T thermocouples (accuracy of 0.1 ºC) are placed on the 1st, 3rd and 5th level to measure the water temperature at different heights, as shown in Figure 3. Additionally, a thermocouple is placed in one of the encapsulations of these levels to control its temperature. The thermocouple is inserted into one of the screws, which was previously drilled.

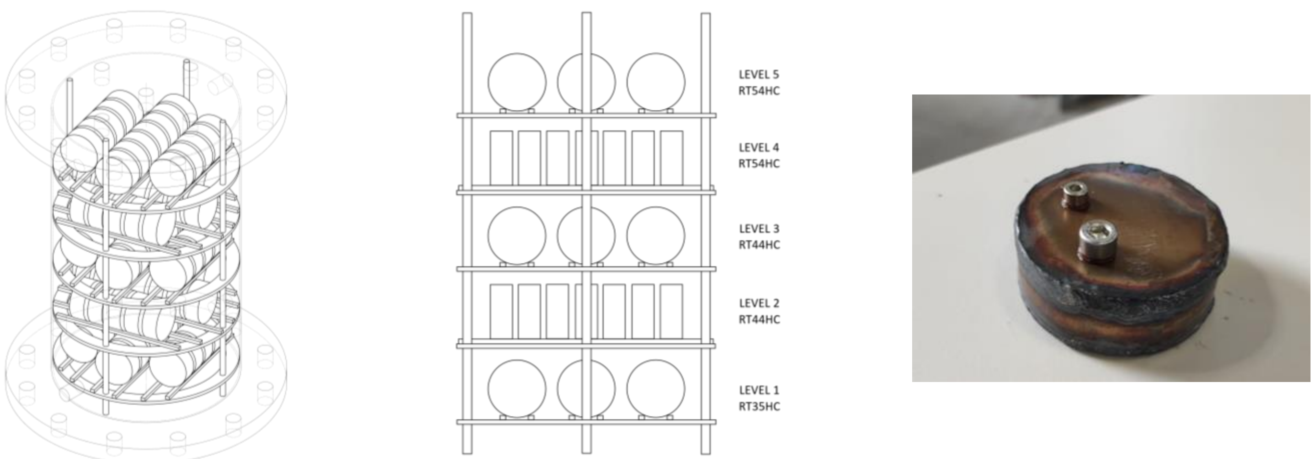

Figure 2: Encapsulation arrangement (left), PCM distribution in each level (centre) and encapsulation (right).

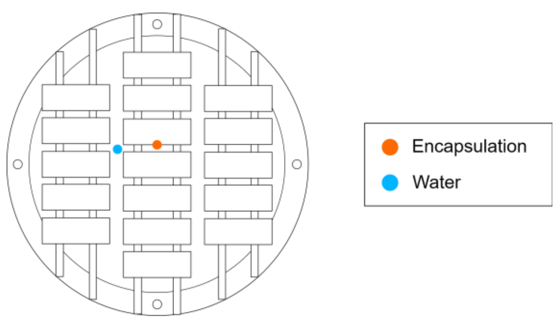

Figure 3: Encapsulations thermocouples arrangement in a level.

2.2. PCM Thermal Properties

The thermal properties of the three paraffins used in this study, RT35HC, RT44HC and RT54HC, are measured experimentally. The objective was to obtain more accurate values that those provided by the manufacturer. The results are shown in Table 1.

The melting and solidification temperature ranges and heat storage capacity are obtained by using DSC (Differential Scanning Calorimetry) analysis, with a Mettler Toledo equipment, model DSC882e. Specific heat measurements ae obtained as well with this method. Both solid and liquid phase thermal conductivities are measured with the MTPS (Modified Transient Plane Source) method, using a TCi thermal conductivity analyser, from C-Therm manufacturer. The solid density is obtained with a helium stereopycnometer, using the SPY-D160-E equipment from Quantachrome Instruments. The liquid density is calculated by measuring the mass and volume of a melted paraffin sample taken with a heated syringe.

Table 1. PCMs thermal properties

Thermal properties [units]	RT35HC	RT44HC	RT54HC
Melting temperature [ºC]	32-38	41-47	53-58
Solidification temperature [ºC]	35-27	37-43	48-51
Melting heat storage capacity [J/ kg]	233700	253000	196000
Solidification heat storage capacity [J/ kg]	237500	260000	201500
Specific heat capacity [J/ (kg ºC)]	1900	1950	2000
Solid phase thermal conductivity [W/ (m ºC)]	0.155	0.152	0.158
Liquid phase thermal conductivity [W/ (m ºC)]	0.148	0.148	0.153
Solid density [kg/ m^3]	880	930	1020
Liquid density [kg/ m^3]	790	790	880

2.3. Experimental Setup

In Figure 4, the experimental setup used in these tests is shown. The recirculation system, located on the left of the diagram, simulates the heating provided by solar collectors by using an electric resistance. In this way, hot water enters the system from the top, corresponding to the charging process. During discharge, water for consumption is drawn from the top of the accumulator and supply water enters the bottom of the accumulator. PT100 sensors measure water temperature at the different inlets and outlets.

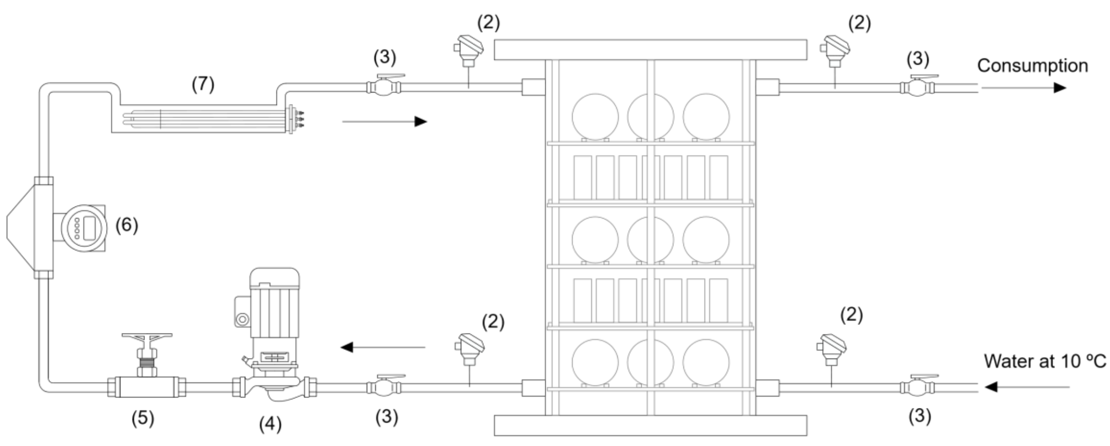

Figure 4: Experimental setup. (1) Hybrid accumulator, (2) Temperature sensors, (3) Control valves, (4) Pump, (5) Regulation valve, (6) Flowmeter, (7) Electric resistance

2.4. Experimental Procedure

To assess the performance of the hybrid accumulator, the EN 50440:2015/A1:2020 standard is applied. This standard defines the test procedure to assess the performance of electric heaters used for domestic hot water production. The testing process spans a full day, and water discharges are performed at specific times of the day. These times are detailed in Table 2, for a small size accumulator, along with the requirements specified in the standard. E is the useful energy to be achieved during water discharge, f represents the minimum flow rate, T_m is the temperature at which useful energy starts to be measured and T_p is the minimum temperature to be reached during the discharge. The cold-water temperature entering the accumulator must be 10 ± 2 °C. Once the required amount of useful energy is achieved in each specified hour, discharge is stopped.

Table 2. Requirements for the discharges according to EN 50440:2015/A1:2020 standard

$Time$ (h)	E (kWh)	f (l/min)	T_m (ºC)	T_p (ºC)
7.00	0.105	3	25	-
7.30	0.105	3	25	-
8.30	0.105	3	25	-
9.30	0.105	3	25	-
11.30	0.105	3	25	-
11.45	0.105	3	25	-
12.45	0.315	4	10	55
18.00	0.105	3	25	-
18.15	0.105	3	40	-
20.30	0.420	4	10	55
21.30	0.525	5	45	-

A test simulating a typical summer day in the city of Cartagena (Spain) using 2 m^2 of solar collectors is conducted. The test lasts 24 hours and starts at 12 a.m. The initial system temperature is set at 70 °C and the supply water enters the system at 10 ºC.

Solar conditions are reproduced using the electrical resistance of the facility. The solar curve is modelled using equation 1.

$$G = I_{max} \cdot \left(1 - cos\left(\frac{\pi \cdot t}{27000}\right)\right) \quad (1)$$

Where t is the time in seconds and I_{max} is the maximum irradiance in W/m^2. For a summer day, it is 960 W/m^2. The flat solar collector performance for a mass flow rate of 144 kg/h is given by equation 2.

$$\eta = 0{,}797 - 5{,}9647 \cdot T_e^* \quad (2)$$

Where η is the instantaneous performance of the collector and T_e^* is the reduced inlet temperature, which is calculated according to equation 3.

$$T_e^* = (T_{in} - T_{amb})/G \quad (3)$$

Where T_{in} is the inlet temperature and T_{amb} is the ambient temperature. To evaluate the real stored heat at each time instant, equation 4 is used.

$$Q_{real} = \dot{m}\, c\, (T_{out} - T_{in}) \tag{4}$$

Where $\dot{m}$ is the mass flow rate of the heat transfer fluid (HTF) (water), c is the specific heat of the HTF and T_{in} and T_{out} are the HTF temperatures at the accumulator inlet and outlet.

3. Results and Discussion

In Figure 5, the results of the test are shown. Ideal heat is represented, which corresponds to the maximum power that can be absorbed at each time instant, whereas the real heat is the thermal power stored in the accumulator, calculated with equation 4. Then, the consumption water temperature is represented. It is observed that the system can maintain the consumption water at high temperatures throughout the day.

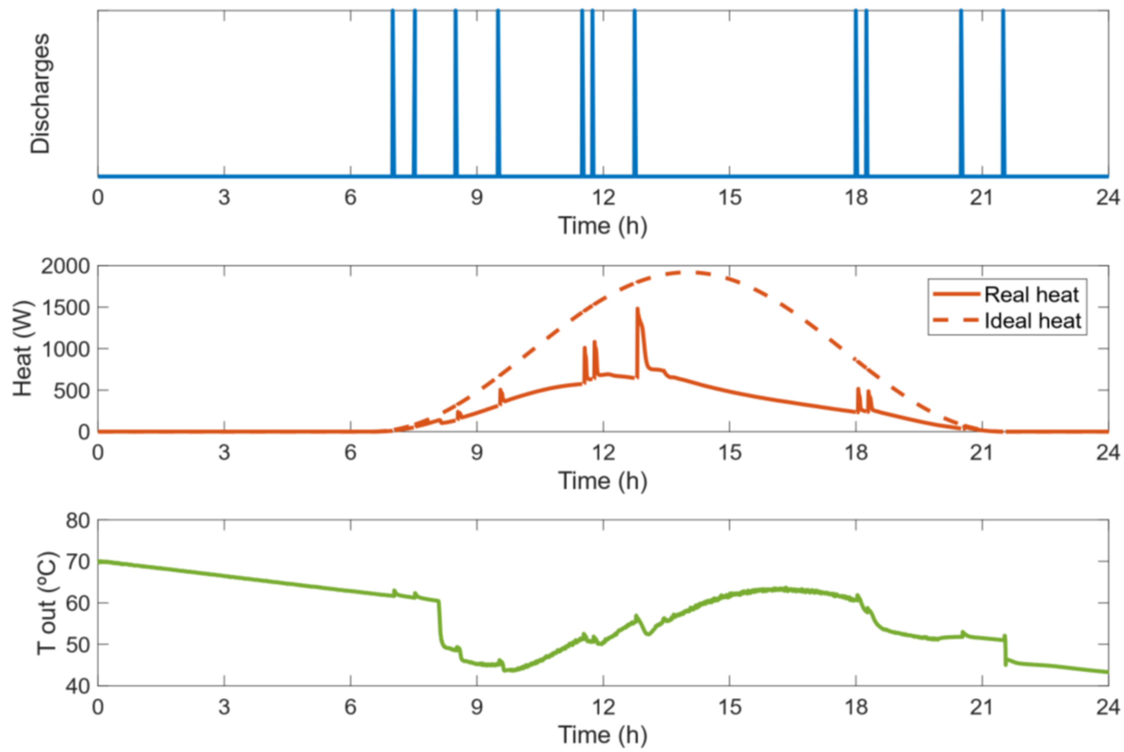

Figure 5: Discharges (up), ideal and real heat (centre) and consumption water temperature (down)

Figure 6 shows the water temperature at the different levels of the accumulator. During most of the test, the water temperature remains between 50 and 60 ºC, but after 8 p.m., a clear temperature stratification is observed. This is due to the lack of heat source. However, the consumption water temperature keeps warm since the PCM situated at the top has the phase change at around 50 ºC. In this way, this cascaded configuration ensures that the consumption water is at the required temperature.

The temperature evolution shows that the rise or drop in water temperature, when there is a charge or discharge, respectively, becomes smoother around the phase change temperatures. This is especially evident around 12 p.m. and 6 p.m., when the slope of the water temperature clearly changes.

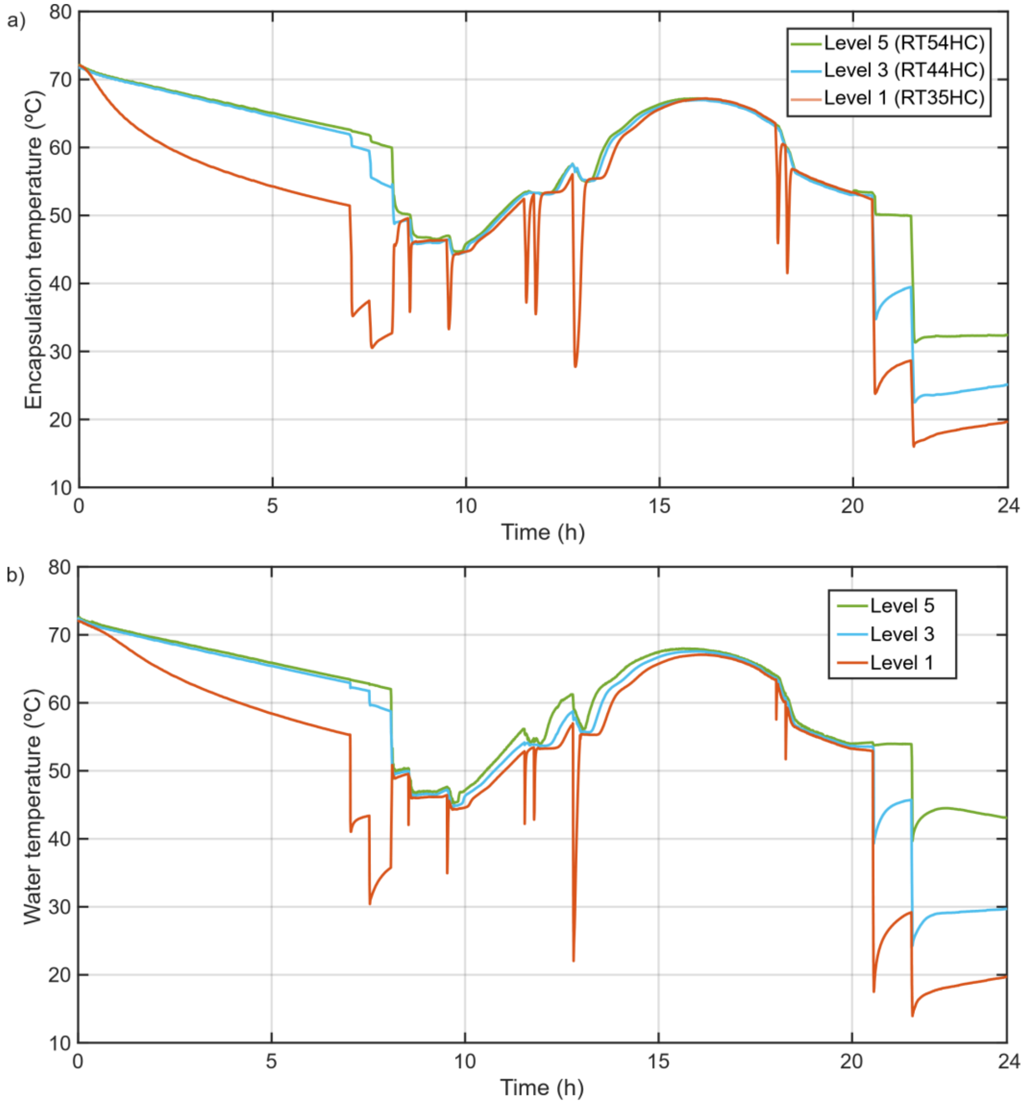

Figure 6: Encapsulation temperature (top) and water temperature (bottom) during the test

4. Conclusion

In this study, the performance of a hybrid thermal energy storage system has been assessed. Cylindrical stainless-steel encapsulations have been placed inside it in a cascaded packed-bed arrangement. Three paraffins with different melting temperatures have been used. Their thermal properties have been measured with suitable experimental methods. Tests under real solar conditions of a summer day have been conducted, following the EN 50440:2015/A1:2020 standard. It is concluded that the system has been capable of keeping high consumption water temperatures and the requirements specified in the standard have been met.

Acknowledgements

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