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Performance characterization of a PCM storage tank

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Abstract

This paper presents the experimental results of a versatile latent heat storage tank capable of working with organic phase-change materials within a temperature range of -10°C to 100°C. The tank contains a paraffin with a phase-change temperature between 3°C and 8°C. Firstly, this study focuses on explaining the design criteria which were followed to build the tank. Secondly, a full experimental characterization of the performance has been carried out. The enthalpy-temperature curve, the specific heat and density have been measured for the tested paraffin. The performance of the tank has been analyzed in terms of the vertical stratification within the PCM, the effectiveness, the reacted fraction and the total heat transfer of the tank. The results indicate that up to 78% of the maximum capacity is reached within 4h. The performance is mainly controlled by the supply temperature and the effect of the mass flow rate is almost negligible given that all the tests are in laminar flow.

Keywords: latent heat thermal storage, paraffin, experimental, PCM

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NOMENCLATURE

h	Enthalpy, kJ kg^{-1}	T	Temperature, $^{\circ}\text{C}$
\dot{m}	Mass flow rate, kg s^{-1}	C_p	Specific heat, $\text{J kg}^{-1} \text{K}^{-1}$
\dot{Q}	Thermal power, W	Q	Energy, J
L	Position in the coils, m	A	Heat transfer area, m^2
ε	Effectiveness	TES	Thermal Energy Storage
PCM	Phase Change Material	LHTS	Latent Heat Thermal Storage
HTF	Heat Transfer Fluid	SHS	Sensible Heat Storage
HEX	Heat Exchanger	Re	Reynolds number
D	Inner diameter of the coils, m	μ	Dynamic viscosity (N s m^{-2})
f	Phase change fraction		
 <i>Subscripts</i>			
supply	Inlet temperature of the tank	return	Return temperature of the tank
init	Initial conditions		

1. Introduction

In recent years, significant R&D activities are being developed in the field of thermal energy storage (TES). Arce et al.[1] for instance, showed the potential benefits of TES for Europe in terms of energy saving and reductions in the thermal load and CO₂ emissions.

Among the different possibilities for TES, cold storage is attracting an increasing interest for different applications such as in HVAC systems, where cold storage can help shift the peak loads, decrease the operation costs, and reduce the installed capacity [2]. Published work has shown the benefits of cold storage for the HVAC in different buildings [3-6]. In the latter cases, the daily variations of the electricity tariffs are a key point to evaluate the economic benefits [7]. In Spain for instance, depending on the electricity tariff, the cost of the electrical power consumption during off-peak hours at night can be less than half the cost during peak hours [8].

Recently, Oró et al. [9] presented a comprehensive review of solid-liquid phase change materials (PCMs) used in the field of cold storage. Paraffins generally have lower thermal conductivities than hydrated salts. Nevertheless, on a long term, hydrated salts present some drawbacks due to phase-segregation or to the poor compatibility with metal containers [10], whereas paraffins have a more stable behaviour [11] and in some cases, despite having a lower thermal conductivity, depending on the design of the prototype, paraffins have shown a better performance than hydrated salts [12].

Concerning literature on mid-scale to real-scale systems, Lázaro et al. [12], Dolado et al. [13] characterized experimentally the performance of a PCM-air heat exchanger containing 135 kg paraffin in aluminum slabs, and analyzed the effect of important operating parameters such as the flow rates or the difference between the supply temperature and the mean phase-change temperature. Recently, the University of Lleida[14] designed and built two storage tanks containing around 170 kg and 155 kg of hydroquinone respectively, immersed in a shell-and-tube heat exchanger. The experimental results and the analysis of the effectiveness helped design a bigger system with around 4600 kg of hydroquinone which is installed in a solar-cooling installation [15] at the University of Seville (Spain).

Banaszek et al. [16] characterized experimentally a vertical spiral heat exchanger containing 112 kg paraffin. Tay et al. [17] from the University of South Australia have also carried out some extensive work with vertical tube-bundle systems containing up to 179.2 kg of ice/water or hydrated salts. Some interesting results were obtained by comparing the average effectiveness with and without dynamic melting within the PCM.

Thus, literature on experimental systems with a significant capacity is relatively scarce and recent. It is nevertheless essential to continue this work in order to increase the know-how on complex aspects such as the dynamic thermal properties of the PCMs, the buoyancy effect within the PCM and the heat exchange with the heat transfer fluid (HTF).

The present work provides an insight on the design process which was followed to build a versatile LHTS tank. The tank is an experimental prototype and has been designed based on the recent experience with a bigger system [18], but can work on a wider range of temperatures between -10°C and 100°C . The aim of this work is (i) to describe the configuration of the tank and (ii) carry out a detailed analysis of the tank performance.

Some novel aspects are introduced in this work, for instance, the combination of a sensible heat storage (SHS) tank downstream from the LHTS tank, which has helped achieve a fine regulation of the supply temperature during the tests in comparison with published literature in this field. Furthermore, the analysis of the heat transfer fluid temperatures or the phase change fraction are generally not analyzed in such detail. Dimensionless parameters such as the total heat transfer or the effectiveness can be nevertheless very helpful in the design of PCM storage tanks [15],[19].

2. Experimental set-up

2.1. Description of the latent heat thermal storage tank

The LHTS tank has been designed based on the recent experience on a bigger system, a commercial ice storage tank [20,21]. In such applications, the PCM (water) is compatible with plastic and therefore low-cost solutions are generally employed in commercial tanks (e.g. polyethylene tubes).

However, when designing a LHTS tank for other PCMs such as in this study (ice/water and paraffins), a special attention has to be paid to the compatibility between the tank materials and the target PCMs [10]. Furthermore, given the desired temperature range (-10°C to 100°C), the materials also need to withstand such a wide temperature range. Copper was finally chosen for the internal coils and INOX AISI 316L steel was selected for the external wall of the tank. INOX AISI 316L is among the best metallic materials for its compatibility not only with paraffins, but also with salt hydrates [10]. In the case of the internal coils, copper was selected due to its better malleability (the curvature near the vertical collectors is significant) and in order to facilitate the weldings in

the connections. The use of polymer materials for the external structure or the heat exchanger would indeed be less expensive, but they are not compatible with the paraffin on a long term, as indicated by the manufacturer of the PCM [22].

The thermal dilatations of the heat exchanger have also been considered in the design process, as well as the volume changes of the target PCMs. In order to avoid any problems due to the latter aspects, the vertical collectors and the spiral coils are not completely fixed and can move upwards or downwards in order to avoid any fractures due to dilatations of the coils. Actually, during the entire experimental campaign, the heat exchanger geometry has remained unchanged despite the volume variations within the tested paraffin.

Figs. 1 and 2 show the detailed geometry of the experimental prototype. The latter figures should be analyzed in parallel to Table 1 which summarizes the materials which have been used, as well as the main geometric parameters of the tank (e.g. spacing or pitch between tubes, detailed geometry, volume of PCM in each zone of the tank, etc...).. As for bigger tanks for ice-storage [20,21], the present tank consists of spiral-shaped coils which are placed in counter-flow in horizontal planes. Hence, the flow is centrifugal and centripetal in any 2 adjacent coils. In total, the tank consists of 8 coils which have been welded to 4 vertical collectors, two in the center and two in the external part of the tank.

As an indication, Table 2 presents a summary of the costs of the tank for each of the components. The tank is an experimental prototype and the costs should not be considered as a commercial reference, but they can give an indication for readers interested in building similar systems. From the total cost of the tank (4654€), the most expensive parts are the external wall of the tank (steel INOX AISI 316L) and the insulation, which together account for 68.5% of the total cost.

In this work, the tank has been filled with the paraffin RT8 from RUBITHERM [22]. In addition to the tests inside the tank, the enthalpy-temperature curve of the PCM has been obtained at the Universidad de Zaragoza by means of the T-history method. Among the advantages of this approach compared to the conventional analysis technique of DSC, the following points should be highlighted: a) larger amount of sample leading to a better representativity of the sample, b) accuracy of the sample temperature and, c) capability of directly obtaining the enthalpy as a function of temperature and also allowing the analysis of specific phenomena such as subcooling or hysteresis.

The T-history installation has been described in recent literature [23,24] and the measurements were carried out following the methodology presented by Lázaro et al. [25]. Very recently, a set of round robin tests was also carried out among

European experts in the characterization of PCMs and the methodology was better defined [26].

The heating and cooling curves of the RT8 paraffin have been obtained in the temperature range of -2°C to 15°C and of 15°C to 2°C respectively. As the reference substance used should not change phase, a water-glycol mixture has been used (60%vol. glycol). Previously, the specific heat of the reference solution has been determined by DSC in order to enter this value in the T-history software. This characterization has been carried out by measuring with a 1K/min in heating mode (from -30°C up to 30°C), using sapphire as reference material. The average specific heat in the range of temperatures from -10°C to 15°C is 2.97 J/g.

Figure 3 shows the enthalpy-temperature curves which have been obtained. The paraffin RT8 exhibits a melting temperature range between 3-8°C approximately, instead of an ideal, single melting temperature of 8°C. According to the manufacturer [22], as measured with a 3-layer calorimeter [18], the enthalpy variation in the temperature range 0-15°C is of 176 kJ/kg, but according to the T-history measurements, there is around 26% less capacity, which is not a negligible difference.

As the heat transfer rate is slower in the manufacturer curves, the corresponding heating and cooling curves are almost identical. The manufacturer and the measured enthalpy-temperatures are inevitably different given that the measurement principle, heat transfer rate and sample mass are not the same. In the measured curves a sharp decrease is observed in the cooling process at around 8°C. During the heating process, the main enthalpy gain is reached in the temperature range 3-9°C. From the measured enthalpy-temperature curves, a characteristic temperature of 5.3°C has been obtained for the phase-change.

Figure 3 also shows a polynomial fitting of the enthalpy-temperature curves in order to serve as inputs in future simulations. The correlations are given in Eqs. (1-2) and have been obtained with coefficients of determination (R^2) of at least 9.98.

$$\begin{aligned}
 h_{heating}(-2^{\circ}C \leq T \leq 16^{\circ}C) \\
 = & -9.0800 \cdot 10^{-5} \cdot T^6 + 4.3332 \cdot 10^{-3} \cdot T^5 - 7.0586 \cdot 10^{-2} \cdot T^4 \\
 & + 3.7596 \cdot 10^{-1} \cdot T^3 + 4.6432 \cdot 10^{-1} \cdot T^2 + 5.1456 \cdot T - 1.3059 \cdot 10^2
 \end{aligned}
 \tag{1}$$

$$\begin{aligned}
h_{cooling}(2^{\circ}C \leq T < 8.1^{\circ}C) \\
&= 2.6080 \cdot 10^{-3} \cdot T^6 + 2.7400 \cdot 10^{-2} \cdot T^5 - 1.6791 \cdot T^4 + 1.9583 \cdot 10 \\
&\cdot T^3 - 1.0030 \cdot 10^2 \cdot T^2 + 2.5611 \cdot 10^2 \cdot T - 3.7774 \cdot 10^2 \\
h_{cooling}(8.1^{\circ}C \leq T < 16^{\circ}C) &= 1.6113 \cdot T - 2.2705 \cdot 10
\end{aligned} \tag{2}$$

Table 3 provides other relevant thermal properties of the tested paraffin. The thermal diffusivity has been measured by means of a LFA 457 MicroFlash apparatus. The specific heat has been obtained from a DSC test with a heat transfer rate of 1 K/min. Finally, the density has been measured with a DM40 density meter.

2.2. Instrumentation of the LHTS tank

Fig. 4 shows the instrumentation inside the LHTS tank. A special emphasis has been held to monitor any possible temperature gradients within the PCM, and also within the HTF along the different coils. As shown in Fig. 4, 18 T-type thermocouples have been placed in total, on 3 different rows, and in 6 different columns. The nomenclature for each thermocouple (T_{ij}) stands for the number of the row (subscript i) and for the column (subscript j). The latter thermocouples measure the PCM temperature with an accuracy of ± 0.15 K using functions from the National Institute of Standards and Technology (NIST) for the voltage/temperature conversion following the methodology explained in recent literature [18,27]. The HTF temperatures in different points of the coils have also been measured by means of T-type thermocouples with a same accuracy of ± 0.15 K, following the same experimental procedure by direct contact as in recent work [20,21]. The supply and return temperatures of the LHTS tank are measured with RTD thermal resistances PT100 1/10DINB which have an accuracy of ± 0.03 K [18]. Finally, the mass flow rate of the HTF is measured by means of a SIEMENSCORIOLIS flow meter with an uncertainty of ± 7.3 kg h⁻¹ [18]. All the temperature measurements are monitored with a time recording interval of 1 minute using a datalogger Agilent 34970A.

2.3. Full test rig and measurement campaign

The experimental test rig represented schematically in Fig. 5 has been presented in recent literature [18,20,21] and thus, this paper focuses in the new modifications of the set-up. One significant improvement concerns the regulation of the supply temperature. Due to the temperature difference between the supply temperature and the initial temperature of the tank, at the beginning of any test, the thermal power which is exchanged was very high, and the former regulation, with only one plate-heat exchanger (HEX), could not ensure a perfect regulation of the supply temperature at the initial part of the tests. A sensible heat storage (SHS) tank of 1000l has now been placed downstream of the LHTS tank to avoid this problem and the regulation of the supply temperature in the initial part of the tests has improved significantly.

During the preparation of the tests, the SHS is first prepared at the target temperature. Once the test starts and the heat transfer fluid flows through the LHTS tank, the initial thermal power peak is absorbed by the SHS and afterwards, the heat exchangers provide a more precise tuning of thermal power to guarantee a constant supply temperature.

To prepare the SHS for a solidification test, in a first step (a) the SHS is cooled down to the target supply temperature. In order to avoid a thermal stratification inside the SHS, the colder HTF is injected from the top of the SHS tank until the nominal temperature is reached. Once the test starts, in a second step (b) the hotter HTF is injected from the bottom of the SHS tank. The discharge tests are prepared analogously, doing operation (b) during the preparation test and operation (a) along the test itself.

By means of the disposal of the SHS downstream from the LHTS tank, the target supply temperature is reached within a band of $\pm 0.3\text{K}$. The mass flow rate is ensured $\pm 50\text{ kg/h}$ around the target value. The target mass flow rates are 1000, 1500, 2000 kg/h and the supply temperatures are 3, 1, -1°C for the solidification tests and 9, 11, 13°C for the melting tests. This gives a total of 9 tests for both the solidification and melting processes.

Tables 3 and 4 summarize the experimental campaign which has been carried out. Although a vertical stratification of temperatures of the PCM is unavoidable within the tank, the PCM temperature in all tests has been controlled as best as possible by starting the tests with a same temperature in thermocouple $T_{\text{PCM}23}$ ($13^\circ\text{C} \pm 1\text{K}$ and $-6.5^\circ\text{C} \pm 1\text{K}$ for the solidification and melting tests respectively). This ensures similar initial conditions in all solidification (S) and melting tests (M). Tables 3 and 4 also provide the mean Reynolds number (Re) as calculated by means of Eq. (3).

$$Re = \frac{4\dot{m}}{\pi D \mu} \quad (3)$$

The critical Reynolds number in coils leading to secondary flows is in this case of around 5911. In all the tests the Reynolds number is lower and consequently the flow is laminar in the entire experimental campaign.

3. Results and discussion

3.1. Stratification of temperatures within the PCM

Fig. 6 shows some typical temperature profiles of a charge or solidification test (S5). The temperatures are shown for the third vertical column (T_{PCM3}) which is in the middle of the spiral-shaped coils and for the sixth column (T_{PCM6}) which is in the center of the tank, and is hereafter far from the coils.

In the solidification test S5, the SHS tank temperature was first prepared at the nominal temperature (1°C) during around 70 minutes, and after this time, the LHTS tank was filled with the cold HTF at 1°C . From this point onwards, the PCM temperatures decrease progressively towards the supply temperature. Nevertheless, the PCM in the center of the tank stays in the latent heat transfer region at around 8.5°C which corresponds to the point where the cooling curves of the T-history measurements decrease sharply. Given the significant distance with respect to the coils, this central zone does not have a sufficient heat transfer area and thus a full phase-change cannot be reached, as happened with a tank with a very similar geometry [18]. It should also be noted that the hotter PCM is always in the upper region of the tank due to the buoyancy forces.

In Fig. 7 the same temperature profiles of the PCM have been plotted for the solidification test with a lower supply temperature and higher mass flow rate (S9). The temperature profile is very similar to test S5 (Fig. 6) although in this case the paraffin temperature is lowered down to around -1°C . Given that the difference between the supply temperature and the phase-change temperature is rather low (2-6K) even at the end of the test the paraffin is still in the latent heat transfer region.

In Fig. 8 a typical discharge or melting test is shown. More precisely, Fig. 8 represents the same thermocouple positions as Figs. 6-7 but for the melting test M6 which has a nominal mass flow rate of 1500 kg/h and a supply temperature of 13°C . The preparation of the SHS tank lasts around 50 minutes and at this point the melting test starts. With this strategy the supply temperature is well regulated and kept almost constant all along the test.

In Fig. 8, the PCM temperatures increase progressively towards the supply temperature. The slope of the curves decreases at the beginning of the latent heat transfer region, which corresponds to the peak of the specific heat and can be therefore explained by the enthalpy-temperature curve of the paraffin (Fig. 3). The paraffin melts gradually and the solid layers detach from the coils. Between 150 min and 230 min approximately, solid paraffin tends to sink towards the bottom of the tank and this movement induces a second decrease in the slope of the PCM temperatures. This aspect can be observed later on in Fig. 15.

In the latent heat transfer region, although the temperatures in column T_{i3} are higher than 8°C , a solid-liquid mixture co-exists. After the latent heat transfer region, the paraffin is fully liquid and due to the buoyancy effect, the hottest paraffin (lower density) is accumulated at the top of the tank. This is the reason why the temperatures in column 3 are inversed at the end of the latent heat transfer region.

As may also be inferred from Fig. 8, it is hardly possible to control the temperature in the center of the tank given the small heat transfer between the PCM and the coils. This is the reason why this region only melts at the very end of the test (after around 270 minutes).

3.2. HTF profile along the coils

As mentioned in section 2.1, the coils have a total length of 13.3m. The supply and return temperatures ($L=0$ m; $L=13.3$ m) are measured with the RTD thermo-resistances. As shown in Fig. 4, the thermocouples which are attached to the coils allow the measurement of the HTF temperatures at $L=4.4$ m and $L=10.6$ m. Thus, the HTF temperatures are measured in 4 different points along the coils of the upper and lower region of the tank.

Figs. 9-10 show the profile of the HTF temperatures for both a solidification test (S5) and a melting test (M6) respectively. The temperatures have been plotted for three characteristic points of the tests, namely the initial sensible heat transfer region, the middle of the latent heat transfer region and the final sensible heat transfer region.

As can be expected, in Fig. 9 the highest temperature difference between the supply and return temperatures is reached in the initial part of the test, the sensible heat transfer region. This temperature difference, or similarly the thermal power, reduces progressively throughout the tests. While the paraffin is in liquid phase, the paraffin can move freely due to the buoyancy effect and subsequently the vertical stratification (“down” and “up”) is higher than in the

latent heat transfer phase and the final sensible heat transfer phase. The upper part of the tank is warmer (as shown in Fig. 6) and hence the HTF heats up more than in the lower part of the tank.

The HTF temperature profile has been represented in Fig. 10 for the melting test M6. As for Fig. 10, the highest temperature differences between the upper and the lower coils correspond to the liquid phase, for instance after the end of the latent heat transfer period in Fig. 8 there is a higher vertical stratification in the PCM due to the buoyancy forces.

3.3. Overall performance

From an general point of view, the thermal power which is exchanged with the HTF, the effectiveness and the stored energy are key aspects for any application.

The thermal power which is exchanged with the HTF can be expressed as in Eq. (4) based on the internal energy variation of the HTF. Absolute values have been taken for the temperature difference between the supply and the return given that this difference is positive in the melting tests, and negative in the solidification tests.

$$\bar{Q}_{LHTS} = \dot{m}_{HTF} \cdot C_{p,HTF} \cdot |T_{supply} - T_{return}| \quad (4)$$

Figs. 11 and 12 show the effect of the supply temperature on the thermal power. For both the solidification tests (Fig. 11) and the melting tests (Fig. 12) the effect of the mass flow rate is negligible and almost identical thermal powers are obtained. This is due to the fact that all the tests are in laminar flow, where the Nusselt number is constant and therefore the internal heat transfer coefficient is similar.

As in all heat exchanger equipment, the supply temperature has a relevant effect on the thermal power. The higher the temperature difference between the PCM and the supply temperature is, the higher the thermal power. The supply temperature is the main driving force given its effect on the limiting thermal resistances (conduction within the PCM for the solidification tests, conduction and convection in the melting tests).

The average effectiveness provides useful information on the heat transfer between the PCM and the HTF. Tay et al. [17,19,29-31] and the University of Lleida [14,32] have often used this approach, which is based on considering the PCM as a constant temperature heat sink or source, as happens, for instance in an evaporator or a condenser. This hypothesis can be applied in the latent heat transfer region of the tests where the PCM temperature is relatively constant. Furthermore, the sensible heat storage capacity can be neglected in comparison with the latent heat storage capacity.

The effectiveness can be expressed as the ratio between the actual heat which is exchanged by the HTF and the theoretical or maximum heat which could be exchanged if the heat exchanger had an infinite area and the outlet temperature were equal to the PCM temperature:

$$\bar{\epsilon}_{t_1 \rightarrow t_2} = \int_{t_1}^{t_2} \frac{T_{supply} - T_{return}(t)}{T_{supply} - \bar{T}_{PCM}(t)} dt \quad (5)$$

The effectiveness has been evaluated in the latent heat transfer region ($t_1 \rightarrow t_2$) and it is represented in Fig. 13 for the solidification tests (a) and for the melting tests (b). Although there is a slight effect of the supply temperature, it is almost negligible in the tested range of conditions and thus a simple correlation has been developed depending on only the mass flow rate. The mean square deviation between the experimental and the correlation has been minimized, hereby obtaining correlations (6) and (7), in a similar approach than in recent literature [14,29]. The mean deviation is 3.8% for the solidification tests and 5.6% for the melting tests. In Eqs. (6-8), A is the external surface of the coils in contact with the PCM ($A=5.75 \text{ m}^2$).

$$\bar{\epsilon}_{solidification} = 1 - \exp \left\{ -0.0168 \cdot \left(\frac{A}{\dot{m}} \right) \right\} \quad (6)$$

$$\bar{\epsilon}_{melting} = 1 - \exp \left\{ -0.0146 \cdot \left(\frac{A}{\dot{m}} \right) \right\} \quad (7)$$

Another key issue in any storage tank is the storage capacity. Two relevant dimensionless parameters are the phase change fraction (f) and the total accumulative heat transfer $Q_{LHTS}/Q_{LHTS,max.}$, as expressed in Eqs. (8-9). The phase change fraction relates the enthalpy variation in the PCM with respect to the maximum enthalpy variation which can be reached. The total heat transfer is often used in transient heat conduction and is defined by the relation between the internal energy variation of the HTF until a given time t and the maximum energy variation that can occur if the entire PCM temperature changes from the initial temperature to the supply temperature.

$$f(t) = \left| \frac{\Delta h(T_{init} \rightarrow T_{PCM23}(t))}{\Delta h(T_{init} \rightarrow T_{supply}(t))} \right| \quad (8)$$

$$\frac{Q_{LHTS}(t)}{Q_{LHTS,max}} = \frac{\int_{t_1}^{t_2} \bar{Q}_{LHTS} \cdot dt}{M_{total,PCM} \cdot \Delta h_{T_{init} \rightarrow T_{supply}}} \quad (9)$$

In Fig. 14, the phase change fraction has been represented for the tests with an intermediate mass flow rate of 1500 kg/h. In the melting tests (dashed lines) a same trend is observed. The higher the supply temperature, the higher the phase change fraction. This aspect is logical given that higher temperatures enhance the heat transfer within the paraffin. In the solidification tests, the lower phase change fractions are nevertheless achieved for the lowest supply temperature (-1°C) because of the low thermal conductivity of the paraffin.

Fig. 15 shows a top view of the tank for different phase change fractions. The solidification process is progressive, and even for a phase change fraction of around 75% the appearance of the paraffin is still a mushy phase which contains liquid in the middle between adjacent coils.

The melting process can be observed in Fig. 15 by the appearance of liquid and transparent paraffin which is accumulated in the top of the tank. For phase change fractions between 50 and 75%, the solid and coldest paraffin tends to detach from the coils and drops towards the bottom.

In Fig. 16, the total heat transfer of the tank has been calculated after 2h, 3h and 4h for a same mass flow rate of 1500 kg/h. Each test is therefore defined by its supply temperature, or by the difference between the supply temperature and the phase-change temperature (5.3°C). The results indicate that only 9% to 78% of the total capacity is reached within this time. In fact, as shown in Table 1, only 176 L of paraffin are close to the coils, and the remaining 25% paraffinis practically a dead mass. The tested prototype's performance could be hereby enhanced by placing additional coils such as a vertical tube bundle in the central region in order to reach a higher contact surface between the coils and the PCM. A similar problem was encountered in a recent publication from A. Gil et al. [15], who had 24% of dead mass with their LHTS tank.

The tendencies of the curves in Fig. 16 are different depending on the type of process, as also shown in Fig. 14. In the solidification tests, the lowest total heat transfer is reached for the coldest supply temperatures. This point can seem surprising on a first stage, but in fact if the supply temperature is lowered, given that it is very close to the phase-change temperature, within short tests (less than 4h) the enthalpy variation $\Delta h_{T_{init} \rightarrow T_{supply}}$ in the denominator of Eq. (9) increases substantially in comparison with the additional increase in the energy gain (numerator).

For a same temperature difference between the supply temperature and the phase-change temperature, the melting tests are intrinsically faster given that they are controlled by conductive and convective heat transfer, whereas in the solidification tests the process is limited by the low thermal conductivity of the paraffin [18]. In the melting tests, higher supply temperatures enhance the heat transfer within the PCM, whereas in the solidification tests they hardly have any effect on the thermal conductivity.

For this reason, in the melting tests, the total heat transfer increases with both the supply temperature and the melting duration. In fact, for a same duration, the increase of the supply temperature increases the exchanged energy (numerator of Eq. (9)) more than the maximum achievable energy (denominator).

4. Conclusion

This paper presents the design criteria of a LHTS tank and a full experimental characterization of the performance using a paraffin for cold storage.

The incorporation of a SHS tank downstream of the LHTS has enabled to reach a fine regulation of the target supply temperature ($\pm 0.3\text{K}$) throughout the entire tests. A vertical stratification within the PCM is clearly observed (the hotter PCM at the top of the tank), particularly within the liquid phase. This aspect has been deduced not only from PCM measurements but also from the HTF measurements.

Given that the tested mass flow rates are all in laminar flow, the most relevant effect of the operation conditions has been the supply temperature. The average effectiveness has been calculated, as well as the phase change fraction and the total heat transfer. The results have shown that up to 78% of the maximum capacity can be reached within 4h, and that the stored energy is more sensitive to supply temperature variations in the melting tests. With the tested coil design, for solidification tests with 6K less than the phase-change temperature, a full phase-change cannot be reached.

This work is currently under continuation by developing and validating an enthalpy model with the present experimental campaign.

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