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Maximisation of heat transfer in a coil in tank PCM cold storage system

A. Castell [a,*], M. Belusko [b], F. Bruno [b], L.F. Cabeza [a]

[a] GREA Innovació Concurrent, Universitat de Lleida Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain
[b] Institute for Sustainable Systems and Technologies, University of South Australia, Mawson Lakes Boulevard, Mawson Lakes, SA 5095, Australia

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ABSTRACT

Thermal energy storage systems for both heat and cold are necessary for many industrial processes. High energy density and high power capacity are desirable properties of the storage. The use of latent heat increases the energy density of the storage tank with high temperature control close to the melting point. Tube in PCM tank is a very promising system that provides high packing factor. This work presents an experimental study of a PCM tank for cold storage applications. Two different configurations and different flow rates of the heat transfer fluid were studied. The effectiveness of the PCM storage system was defined as that of a heat exchanger. The results showed that the heat exchange effectiveness of the system did not vary with time, decreased with increasing flow rate and increased with increasing heat transfer area. The effectiveness was experimentally determined to only be a function of the ratio $\dot{m}/A$. This equation was found to be adequately be used to design a PCM storage system, and a case study is presented. It was shown that the tube in tank design together with a low temperature PCM is suitable as a thermal storage facility for cold storage.

1. Introduction

Thermal energy storage systems for both heating and cooling are necessary for many industrial processes. High energy density and high power capacity for charging and discharging are desirable properties of the storage system.

To date most storage facilities use a single-phase storage material for that purpose. The use of latent heat through the use of phase change materials (PCM) increases the energy density. These systems have been studied for many years, focussing on PCM stability and improving heat transfer [1–4]. This research has investigated PCM encapsulated in different shapes in order to maximise the storage density, as well as improving the thermal conductivity of the PCM [5]. Due to the packing factor within the PCM tank, the traditional storage of PCM in spheres can result in a reduction of the effective storage density of 50% [6,7]. Other studies used PCM modules inside water tanks with much lower packing factors [8]. Recently Martin et al. developed a tube in PCM tank achieving up to 80% packing factor and good power of heat transfer [9]. This concept was similar to another one studied in Austria and reported in the IEA Solar Heating and Cooling Implementing Agreement [10] as well as been analyzed by Hamada and Fukai [11]. Finally, Mehling et al. have developed a tube in PCM tank arrangement which achieves packing factors of over 90% [12,13].

A completely different concept using direct contact PCM-HTF (heat transfer fluid) has been analyzed [14]. A cold storage using water as HTF and a commercial paraffin with phase change temperature at 7 °C was describes and studied experimentally. Some parameters were determined to be important for the behaviour of such a system and several limitations in its operation were detected.

In another work developed by Medrano et al. different heat exchangers were tested as PCM storage systems [15]. The geometries studied were: (1) double pipe heat exchanger-PCM (DPHX-PCM), (2) double pipe heat exchanger-PCM matrix (DPHX-PCM matrix), (3) double pipe heat exchanger fins-PCM (DPHX fins-PCM), (4) compact heat exchanger (comp-HX-PCM), and (5) plate heat exchanger (Plate-HX-PCM). Results showed that (2) DPHX-PCM matrix was a promising concept, presenting higher average power per unit area and per average temperature gradient. These results highlight the interest in a more in-depth and further study of a complete system based on such a concept.

However, limited research has investigated the use of PCM for cold storage (at temperatures between 0 °C and −40 °C). PCM represent the most ideal solution for off peak storage. Most of the studies related to cold storage have focused on PCM in spheres [16–19]. Consequently a tube in tank design for cold storage application warrants investigation.

To achieve energy savings and to operate an off-peak cooling system efficiently it is necessary to be able to select a PCM which is near the temperature of the heat transfer fluid used in a typical on peak system. The PCM freezing temperature is required to be

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* Corresponding author. Tel.: +34 973 003577; fax: +34 973 003575.
E-mail address: acastell@diei.udl.cat (A. Castell).

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Nomenclature

Δt	time interval (s)
ε	effectiveness (–)
A	heat transfer area (m^2)
C_p	heat capacity of the heat transfer fluid (kJ/kg K)
$\dot{m}$	mass flow rate of the heat transfer fluid (kg/s)
NTU	number of transfer units (–)
PF	packing factor (–)
Q_{act}	energy released from the tank during the phase change (kW h)
Q_{th}	maximum theoretical energy released from the tank during the phase change (kW h)
T_{in}	inlet temperature of the heat transfer fluid to the tank (K)
T_{out}	outlet temperature of the heat transfer fluid of the tank (K)
T_{PCM}	phase change temperature of the PCM (K)
U	thermal transmittance (W/m^2 K)
V_{PCM}	volume of PCM (m^3)
$V_{storage}$	total volume of the storage (m^3)

below this temperature, due to entropy considerations. A PCM freeze temperature near the on peak fluid temperature will ensure that the COP of the refrigeration system is not reduced. To achieve these close temperatures, the thermal resistance through the PCM tank needs to be low.

To design a PCM system with low thermal resistance an effective representation of the PCM system is required. Several numerical models have been developed to simulate the behaviour of PCM tanks [20,21]. However those models have limited application for design purposes. To date little research has focused on developing mathematical characterisations of PCM thermal storage systems readily applicable to design. El-Dessouky and Al-Juwayhel [21] mathematically represented a cylindrical PCM system based on entropy and a function of the thermal resistance to heat flow in both the fluid and PCM. Ismail and Gonçalves [22] represented the PCM by numerically determining the Number of Transfer Units (NTU) which incorporated the thermal resistance. Sari and Kaygusuz [23] experimentally determined the performance of a PCM storage system in terms of heat exchange effectiveness based on the phase change temperature. More recently a new characterisation of a PCM storage system in plates was developed applying the effectiveness – NTU method. The characterisation was based on an experimentally validated model to relate the effectiveness to the phase change fraction and is not time dependant, but readily identifies the heat transfer from a PCM store based on design input data [23]. Consequently it may be possible to develop an experimentally derived characterisation of a PCM tank suitable for design, which can be used to minimise the thermal resistance and maximise the heat transfer.

This work presents an experimental study of a PCM tank for cold storage applications. Two different configurations were studied subject to varying flow rates of the heat transfer fluid (HTF). From the results obtained, an empirical relationship is determined which identifies the effectiveness. Through identifying the effectiveness design parameters can be determined.

2. Experimental set-up

2.1. Tank design

Table 1 presents the specification of the different designs tested. A coil is inserted in the tank and the tank is filled with PCM. The first design has a single coil length, whereas the second design has two coils (high HTS). The coils are looped to be evenly distributed through the PCM (Figs. 1 and 2). Overall, the first design has a higher packing factor (PF) than the second design whereas the second design has a high heat transfer surface area (HTS) (Table 1).

The PCM used was based on a non gelled hydrated salt mixture with a melting point of −27 °C and a latent energy of 145 kJ/kg.

Table 1
Tanks dimensions and parameters.

	High PF design	High HTS design	
PF (–)	0.98	0.95	
Heat transfer surface (m^2)	0.173	0.365	
PCM mass (kg)	30.49	29.55	
Energy storage capacity (kJ)	4390	4255	
Tank diametre (m)	0.29	0.29	
Tank height (m)	0.35	0.35	
Number of HTF passes (–)	14	32	
Circuit 1			5.61
HTF pipes length (m)	5.46	11.62	
Circuit 2			6.01
HTF pipes internal diametre (m)	0.008	0.008	

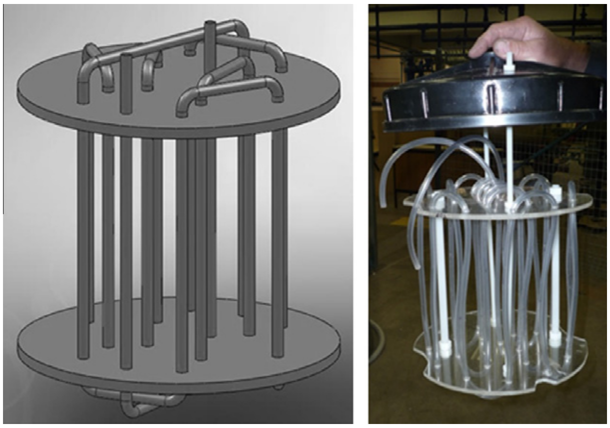

Fig. 1. Schematic and photo of the experimental PCM tank with high PF.

2.2. Experimental procedure

For each configuration different flow rates were tested for the same inlet temperature. The flow rate and the inlet and outlet temperatures were measured for the HTF, while different thermocouples were located inside the tank to register the PCM temperature at different positions (Fig. 3). The inlet and outlet temperature probes were Pt-100 with a maximum error of ±0.05 °C, while the sensors inside the tank were thermocouples with a maximum error of ±0.5 °C. The flow metre was calibrated to an accuracy of 2%.

To ensure that heat gain into the PCM tank was not affecting results, heat gain measurements were conducted of the PCM tank at low temperatures. These tests involved measuring the heat gain in the PCM over time using the internal temperature measurements

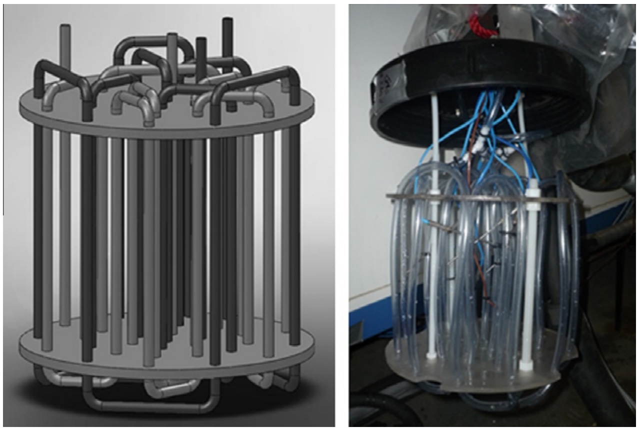

Fig. 2. Schematic and photo of the experimental PCM tank with high heat transfer surface.

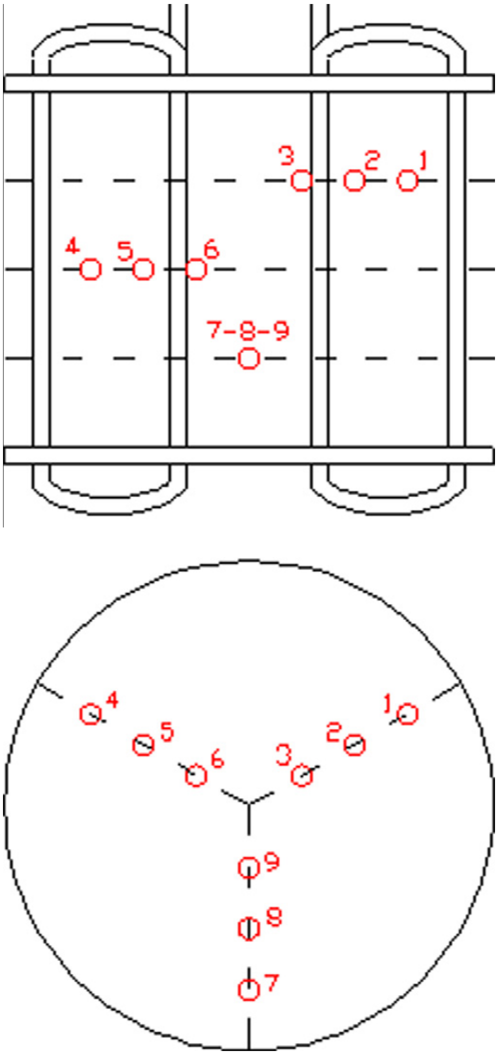

Fig. 3. Schematic of the instrumentation.

of the PCM. This value was found to be 12 W, or 1–3% of the heat transfer.

Experiments were performed for different flow rates, ranging from 0.007 kg/s to 0.106 kg/s, with average power capacities from 0.090 kW to 1.015 kW. Inlet temperature for the discharging experiments was set to 15 °C.

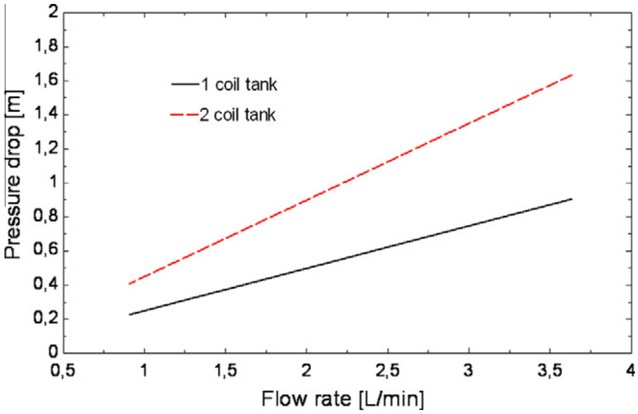

Fig. 4. Pressure drop as function of flow rate for the PCM tanks.

The effect of the flow rate on the pressure drop was studied. Fig. 4 shows the relation between pressure drop and flow rate for the present designs. Although the pressure drop increases when increasing the flow rate, this issue is not critical for the tested flow rates and the present application.

3. Results and discussion

In this section results from the experimental work performed are analyzed and discussed. Even only discharging experiments are studied, a similar behaviour was obtained for the charging experiments. Therefore, an analogous characterisation can be applied for the charging process.

3.1. Temperature evolution

Three examples of the inlet and outlet temperatures for the different experiments are presented from Figs. 5–7 . Consistently, across all tests the outlet temperature increases rapidly initially, achieves a constant temperature for a long period and then begins to increase at the end of the process towards the inlet temperature. This graph is a typical temperature–time curve of a melting process. The initial period represents the sensible heating of the PCM as a solid, the flat section represents the melting process, and the final stage represents the sensible heating of the PCM as a liquid. These measurements were consistent with the internal temperature measurements taken throughout the PCM tank (Fig. 8).

All figures (from Figs. 5–8) show a near constant outlet temperature during the melting process, which shows constant heat transfer in the PCM, throughout the melting process. The thermal resistance to heat transfer as presented in [21] is a function of the resistance due to convection in the HTF and the resistance due to conduction in the PCM. During the melting process the phase change interface moves away from the wall of the tube, and therefore the thermal resistance due to conduction can be expected to increase. This increase has been observed in PCM in spheres [6], in which the melting of the PCM in the sphere increased the conduction resistance between the HTF and the remaining solid PCM in the sphere. This increasing resistance results in an increasing outlet temperature during the melting process. This change in resistance in the PCM is small in the tests conducted, although a slight temperature gradient is observed. The increase in resistance in the PCM may be mitigated by an increase in natural convection. This data suggests that the thermal resistance and subsequently the NTU, and therefore effectiveness does not vary with time.

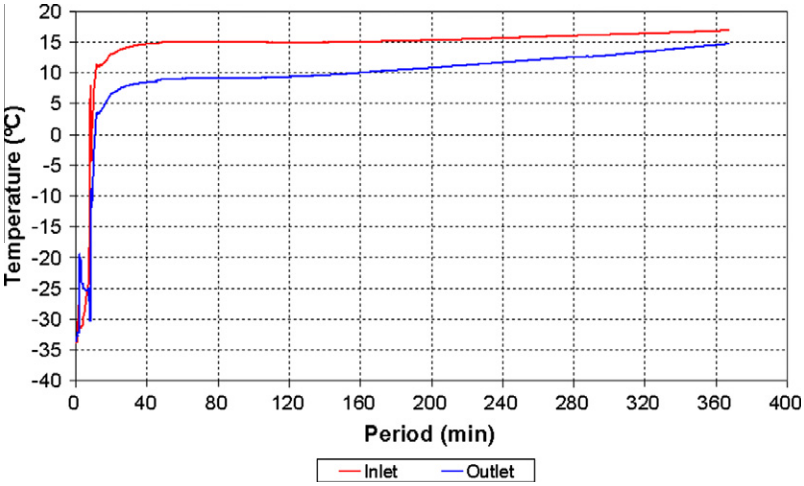

Fig. 5. Inlet and outlet temperatures for the high PF design for a flow rate of 0.026 kg/s.

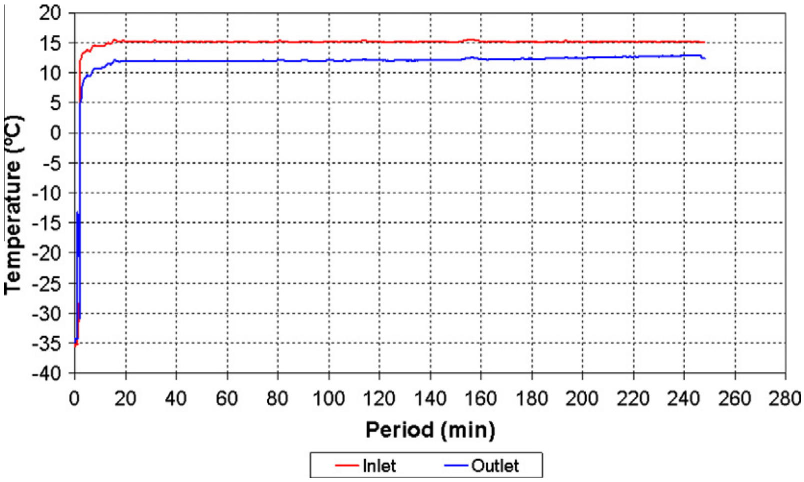

Fig. 6. Inlet and outlet temperatures for the high PF design for a flow rate of 0.047 kg/s.

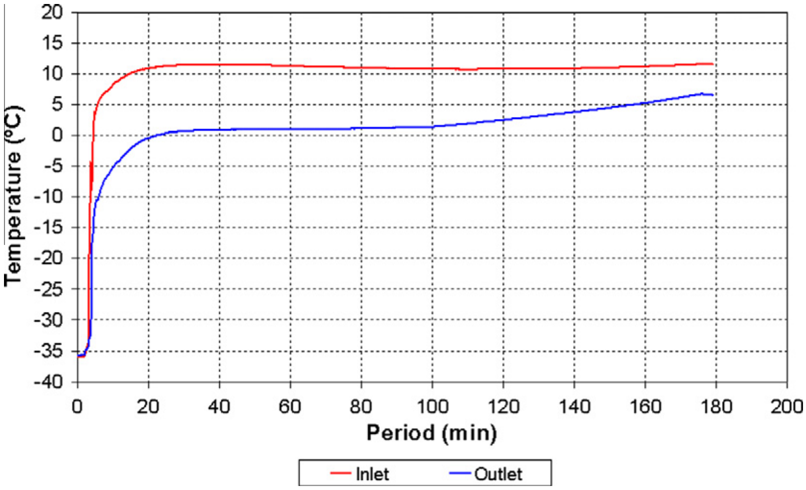

Fig. 7. Inlet and outlet temperatures for the high HTS design for a flow rate of 0.024 kg/s.

With increasing flow rate the temperature difference between the inlet and outlet temperature decreased. This result shows that as the flow rate increases the fluid has less time to achieve lower temperatures and therefore heat transfer is less effective. Given that the inlet temperature is essentially the same in all experiments, the lower the outlet temperature the more effective is the

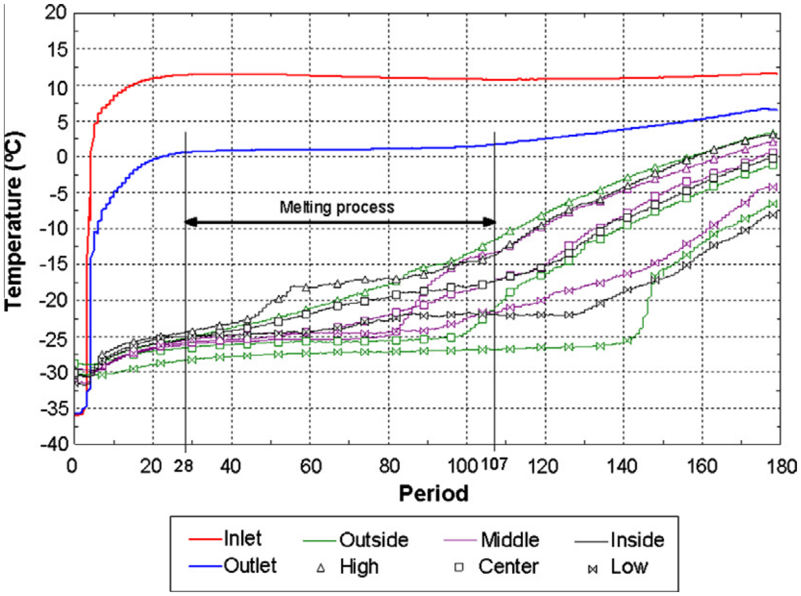

Fig. 8. PCM temperature inside the coil in tank for the high HTS design for a flow rate of 0.024 kg/s.

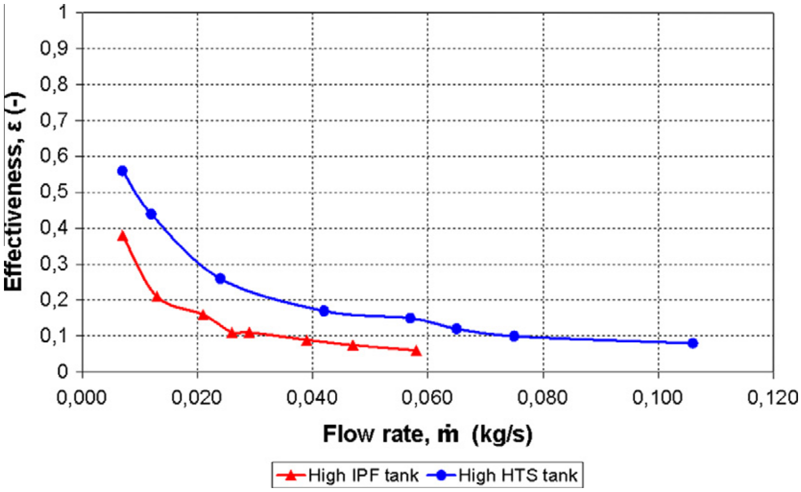

Fig. 9. Effectiveness of the PCM storage tank over the operating mass flow rate.

heat transfer. Increasing the flow rate decreases the outlet temperature, however, Fig. 6 shows the results from the high HTS design, where for the same flow rate the outlet temperature is lower than for the high PF design (Fig. 5). This demonstrates how the increased surface area improves the heat transfer effectiveness in the PCM tank.

3.2. Effectiveness – NTU

A PCM storage tank can be seen and analyzed as a heat exchanger between one fluid and a constant temperature heat sink/source at the phase change interface in the PCM. Therefore, the effectiveness of the PCM storage system can be defined as that of a heat exchanger (Eq. (1)) [24]. The effectiveness is described as a ratio of the actual heat discharged over the theoretical maximum heat that can be discharged. In using a PCM most of the energy is stored as latent heat around the phase change temperature, and so the sensible energy storage component is ignored.

Eq. (1) represents the average effectiveness over the phase change period. However, as shown from Figs. 4–6 since the temperature difference between the inlet and outlet are constant, effectiveness is constant over the phase change period.

$$\varepsilon = \frac{Q_{act}}{Q_{th}} = \frac{\sum \dot{m} \cdot C_p \cdot (T_{in} - T_{out}) \cdot \Delta t}{\sum \dot{m} \cdot C_p \cdot (T_{in} - T_{\mathrm{PCM}}) \cdot \Delta t} = \frac{(\bar{T}_{in} - \bar{T}_{out})}{(\bar{T}_{in} - \bar{T}_{\mathrm{PCM}})} \quad (1)$$

where Q_{act} is the actual energy released from the tank during the phase change (kW h); Q_{th} is the maximum theoretical energy released from the tank during the phase change (kW h); $\dot{m}$ is the mass flow rate of the HTF (kg/s); C_p is the heat capacity of the HTF (kJ/kg K); T_{in} is the inlet temperature of the HTF to the tank (K); T_{out} is the outlet temperature of the HTF of the tank (K); T_{PCM} is the phase change temperature of the PCM (K); and·Δt is the time interval (s).

Since the effectivenesses are based on a constant outlet temperature, this effectiveness gives information about the temperature achieved at the outlet of the storage tank. This temperature is usually a design parameter since it must fulfil the technical requirements of the application. Effectiveness can be represented as a

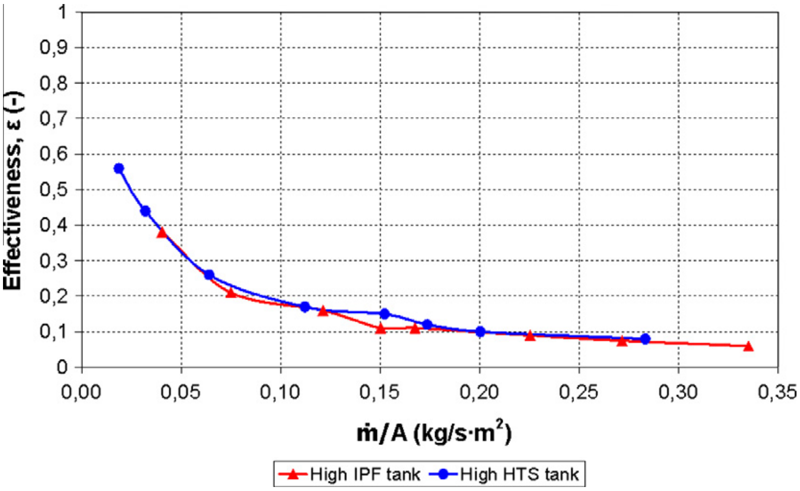

Fig. 10. Effectiveness of the PCM storage tank over the ratio $\dot{m}/A$.

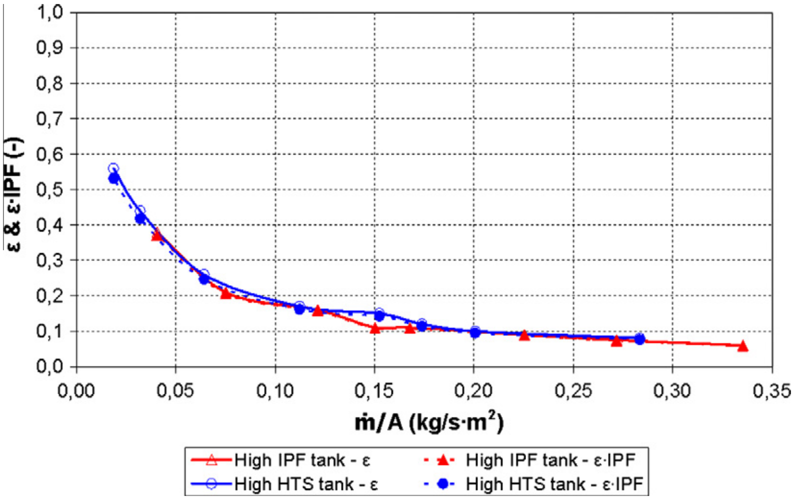

Fig. 11. Comparison between ε and ε·PF.

function of the operating flow rate to characterize the storage system (Fig. 9).

As expected, the effectiveness for both tank designs clearly shows an increasing effectiveness for decreasing flow rates. Since the main thermal resistance of the system is in the PCM itself, low flow rates result in longer circulating time of the HTF throughout the tank, making the heat transfer process more effective despite the lower heat transfer coefficient caused by the laminar flow rate inside the pipes.

Effectiveness defines the working conditions of the storage system and is a key parameters for the tank design since it represents the technical specifications of the application (required temperature output). However, the description of the system presented in Fig. 9 is specific to the coil design used.

A general representation of the behaviour of the storage system independently of the tank configuration is presented in Fig. 10. As shown in Eq. (2), effectiveness is a function of the NTU which is a function of the ratio $\dot{m}/A$. Fig. 10 shows the effectiveness as a function of this parameter and the test results for both tank designs coincide. This curve provides a characteristic design curve independent of the tank design

$$\varepsilon = f(\mathrm{NTU}) = f\left(\frac{A \cdot U}{\dot{m} \cdot C_p}\right) \tag{2}$$

Eq. (3) shows the experimentally derived effectiveness of the tube/tank design for the PCM tested. Both the design and operating conditions are integrated in a single parameter to represent the effectiveness of the storage.

$$\varepsilon = 0.830477 - 17.2411 \cdot \dot{m}/A + 184.522 \cdot (\dot{m}/A)^2 - 1038.48 \cdot (\dot{m}/A)^3 + 3022.2 \cdot (\dot{m}/A)^4 - 4065.01 \cdot (\dot{m}/A)^5 + 1717.23 \cdot (\dot{m}/A)^6 \tag{3}$$

Eq. (3) was developed on a small prototype and its applicability to larger systems is dependant on the amount of natural convection that can be expected in the PCM tank. With larger tanks, increased amounts of natural convection can be expected which will increase the heat transfer in the PCM during the phase change process, and reduce the thermal resistance in the PCM. Eq. (3) will not include this increase.

Another parameter that affects the design is the packing factor (PF). This parameter relates the total volume of PCM with the total

Table 2
Technical requirements for the application.

Temperature level required, T_{out}	−5 °C
Inlet temperature to the storage, T_{in}	10 °C
Phase change temperature of the PCM, T_{PCM}	−27 °C

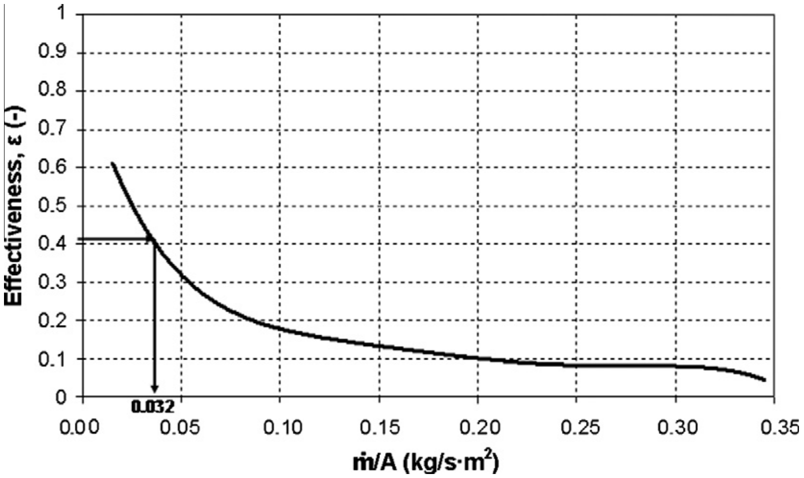

Fig. 12. Determined ratio $\dot{m}/A$ for the case study.

volume of the storage (Eq. (4)), estimating the energy density of the system

$$\mathrm{PF} = \frac{V_{\mathrm{PCM}}}{V_{\mathrm{storage}}} \qquad (4)$$

where V_{PCM} is the volume of PCM (m^3); and V_{storage} is the total volume of the storage (m^3).

The PF can be combined with the effectiveness of the storage to provide the aggregate effectiveness on releasing energy from a certain storage configuration. This new parameter can be very usefull to compare different designs that involve encapsulated PCM (plates, spheres, cylinders, etc.) and to compare different configurations (coil in tank, encapsulated PCM, etc.). However, for coil in tank designs with a PF higher than 90% its effect in the comparison of different designs is negligible (Fig. 11).

4. Design of an off-peak tes refrigeration system

A simple method to characterize a thermal energy storage refrigeration system using PCM has been explained in this paper. A hypothetical design study is presented in order to show how to use the methodology for a design/selection purpose.

Some technical requirements must be specified depending on the application. The most important ones are the temperature required for the application (outlet temperature of the storage), and the inlet temperature to the storage tank. Also the phase change temperature of the PCM must be defined. Table 2 presents the data for the case study.

The minimum effectiveness required to fulfil the specifications can be calculated with Eq. (1), resulting in this case in $\varepsilon = 0.405$. Using Eq. (3) and this value the maximum $\dot{m}/A$ to meet the requirements can be found, which in this case was 0.032 kg/s m^2 (Fig. 12).

Once the ratio $\dot{m}/A$ is determined it is valid for any design, and individual parameters can be specified depending on the working conditions. Varying the heat transfer surface will modify the maximum flow rate to meet the requirements for the application. In this case study, three different designs have been considered with different heat transfer surface areas. Table 3 shows the maximum flow rate which can achieve the desired temperature from which the maximum discharge capacity is determined. Therefore the dimensions of the tank can be determined which deliver the required capacity at the required temperature output. The amount of PCM needed can then be determined based on the operational time required, in this example 10 h, and the effectiveness, using Eq. (1).

Table 3
Design parameters to meet the technical requirements based on a D/A of 0.032 kg/s m^2.

Heat transfer surface, A (m^2)	Flow rate, $\dot{m}$ (kg/s)	Discharged power, Q_{dls} (kW)	Amount of PCM, M_{PCM} (kg)
0.173	5.54×10^{-3}	0.234	143.7
0.365	0.012	0.508	311.2
0.800	0.026	1.100	674.2

5. Conclusions

A PCM tank for cooling applications with coil in tank configuration has been studied. The storage tank was analyzed as a heat exchanger between one fluid and a constant temperature heat sink/source at the phase change interface in the PCM. Two different designs were tested in order to characterize their behaviour and determine the main parameters for its design and optimization.

It was also demonstrated that coil in tank designs are effective at delivering a constant outlet temperature and effective heat transfer with large surface areas, with a high PF. The constant inlet and outlet temperatures during the phase change process demonstrate that the effectiveness is constant over the phase change period.

This effectiveness describes an important design specification of the storage such as the temperature level achieved at the outlet and increases with lower flow rates. The representation of the effectiveness as a function of the ratio of the mass flow rate over the heat transfer surface results in a new parameter that considers both the working conditions and the design of the tank. A single equation was obtained for this new representation, which is useful for design. However the equation will underestimate the performance for larger tanks where the effect of natural convection is higher.

Finally, the influence of the packing factor (PF) was analyzed. For different tank configurations (such as encapsulated PCM) the combination of the PF with the effectiveness can give useful information. However, for coil in tank designs with a PF higher than 90% its effect in the comparison of different designs is negligible

In a future work the authors will develop a comprehensive design methodology for PCM tanks. More experiments will be done for such a purpose, testing different designs, sizes, and temperature levels.

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