

## ENCIT-2018-0065 TEMPERATURE EVOLUTION INSIDE A CAPSULE CONTAINING PHASE CHANGE MATERIAL

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**Abstract.** *Using a simple experimental layout, some tests on the behavior of a phase change material (PCM) were accomplished. To do this, a system using thermal oil as the heat transfer carrier was used and the phase change material being tested was kept inside a steel capsule with 190 mm length, 42 mm internal diameter and 48 mm external diameter. The heat transfer oil transferred heat to the PCM during the energy accumulation step and carried heat away from the PCM during the energy extracting step. The tested PCM was supplied by PCM Products Limited. This PCM, with the commercial name of PlusICE A164 is a sugar alcohol blend and has a fusion temperature of 164 °C. The influence of the mass flow rate of the heat transfer fluid, as well as of its inlet temperature, in the response of the phase change material, was studied. Two layouts of the capsule inside the testing heat exchanger were studied, a vertical and a transversal positioning. Temperature profiles inside the phase change material contained in the capsule were obtained during the experiments.*

**Keywords:** *Thermal Energy Storage, Phase Change Materials, Heat Transfer*

### 1. INTRODUCTION

The present paper reports the experimental work on the study of the temperature evolution inside a carbon steel capsule containing a commercial phase change material (PCM) with a fusion temperature around 164 °C. This PCM was supplied by PCM Products Limited, has the commercial name of PlusICE A164 and is a sugar alcohol blend. Heating and cooling cycles of the PCM containing capsule were carried out in a laboratory scale experimental setup. The main objective of the work was to determine experimental overall heat transfer coefficients from a heat transfer thermal oil towards the PCM and vice-versa in order to evaluate the PCM suitability to be used in an industrial plant that uses solar energy as the heat source. This work has been the continuation of previous studies carried out in the same laboratory (Esteves et al, 2017a; Esteves et al, 2017b; Esteves et al, 2018) for the evaluation of the practical applicability of commercially available PCM's.

### 2. EXPERIMENTAL SET-UP

The PCM heating and cooling experiments were carried out in a laboratory installation where previously heated thermal oil, Therminol 66, transferred heat towards the tested PCM placed inside a capsule. This capsule was located inside a testing heat exchanger and placed either in a vertical or in a horizontal position. Two mass flow rates of the thermal oil were used in the experiments. During the PCM cooling period, the circulating thermal oil was cooled by means of a water cooled shell and tube heat exchanger. Thus a quick reversal of the operating conditions of the laboratory set-up could easily be achieved, and the heating and cooling cycles of the capsule containing the PCM could be implemented in a straightforward manner. Figure 1 presents a global scheme and a picture of the installation.

During the PCM fusion process the thermal oil was heated in the heater A then it was pumped and sent to the test exchanger D. During the PCM solidification step, the thermal oil was cooled in the shell and tube heat exchanger B and then also pumped towards the test heat exchanger D, Figure 1.

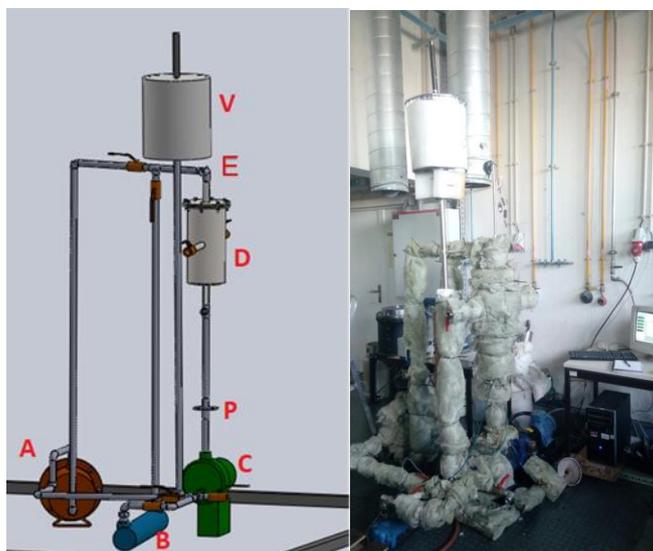


Figure 1. Global 3D scheme and picture of the experimental set-up. A- Thermal oil heater; B- Shell and tube oil cooling heat exchanger; C- Centrifugal pump; D- Testing heat exchanger; E- Air purge, P- Orifice plate, V- Expansion vessel.

The capsule containing the PCM to be tested was made of a 2 1/2" carbon steel pipe, having welded hemispherical caps, has an overall length of 190 mm and a capacity of 0.233 L, Figure 2. This capsule was installed inside the testing heat exchanger. Figure 2 has the capsule dimensions and shows also its vertical positioning.

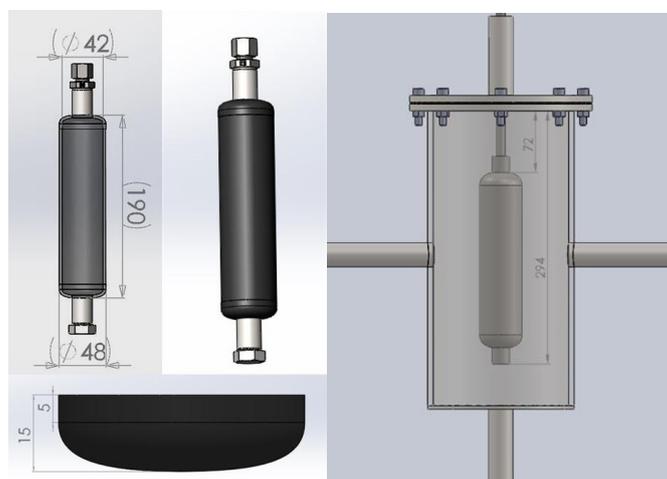


Figure 2. Capsule dimensions and its corresponding vertical set-up

The mass flow rate of the thermal oil was measured through the pressure drop in the orifice plate P, Figure 1. The laboratory installation was equipped with differential pressure transducers and K type thermocouples, as necessary, to follow the operating process. A computer based data acquisition system, composed by two USB connected interface boards from Measurement Computing, received the data collected during the experiments and all this procedure was controlled by the DASYLab software.

Two configurations were used for the capsule. In the simpler one, the capsule was only filled with the PCM. In the second configuration the capsule was equipped with an internal fin system, as depicted in Figure 3.

The PCM that was tested has the commercial designation of Plus ICE A164, and is an alcoholic sugar derived from mannitol ( $C_6H_{14}O_6$ ). The properties supplied by the manufacturer are presented in Table 1. Trhlikova et al. (2015) carried out measurements of the thermal properties of this PCM through a ramp-wise and step-wise transient method, and some of the obtained properties are presented in Table 2, for three temperature values.



Figure 3. Images of the fin system installed in the interior of one of the capsules as well as of the thermocouples positioning.

Table 1. Properties of Plus ICE A164 as supplied by the manufacturer.

Phase change temperature, °C	Density, kg/m <sup>3</sup>	Latent heat, kJ/kg	Specific heat, kJ/(kg K)	Specific energy, MJ/m <sup>3</sup>
164	1500	290	2.42	435

Table 2. Thermal properties of Plus ICE A164 as determined by Trhlikova et al. (2015).

Temperature, °C	Phase	Thermal diffusivity, mm <sup>2</sup> /s	Thermal conductivity, W/(m K)	Specific heat, kJ/(kg K)
30	solid	0.054	0.06	0.68
100	solid	0.049	0.18	2.45
260	liquid	0.078	0,24	2.07

To consider the maximum thermal expansion of 10 % during the PCM fusion step, and also to account for the space required by the fin system introduced into a second capsule, 0.300 kg of PCM were introduced in both capsules to be tested.

### 3. RESULTS FOR THE TEMPERATURE EVOLUTION

Experimental results concerning the time temperature evolution of the thermal oil entering and exiting the test heat exchanger, as well as the time temperature evolution in some particular points inside the capsule containing the PCM, are presented and discussed. Two thermal oil mass flow rates were considered, as well as the two capsule orientations, as previously referred, using a capsule without inner fins and another with inner fins. This lead to a total of eight different experimental situations under analysis.

#### 3.1 Capsule without inner fins

The represented temperature evolution refers to the initial PCM heating step leading to its fusion, followed by the subsequent PCM cooling leading to its solidification. Figure 4 presents the thermal oil temperature simultaneously with the sensible heating of the PCM for the first 8,000 s. Then the phase change occurs and the temperature plateau is quite evident, when the PCM is absorbing heat at an approximately constant temperature of 164 °C. This temperature plateau is longer for the material in the inner core of the capsule, thermocouples T3 and T4. During this almost isothermal period, the temperature difference between the thermal oil and the PCM is around 20 °C.

After the fusion step, the liquid PCM continues to receive thermal energy from the thermal oil and its temperature rapidly increases until reaching thermal equilibrium with the heating oil at around 182 °C. At this point, the thermal oil heating is replaced by its cooling process, and from now on heat is being extracted from the encapsulated PCM. So, from Figure 4 it can be seen that around 12,500 s there is another, albeit shorter, temperature plateau at 164 °C, when the PCM solidifies. The thermal oil cooling rate is stronger than its previous heating rate, and this conditions the rates of heat transfer between the thermal oil and the PCM cooling step. It is a practical limitation of the experimental set-up to avoid any thermal damage of the thermal oil, during the heating process. The PCM cooling process is thus a faster one

with average time duration of 3,600 s. At the end of the heating and cooling cycle there is again thermal equilibrium between the PCM and the thermal oil. In the Figure 5 it is seen another time evolution of the thermal oil and the PCM temperatures, for the same capsule vertical layout, but for a bigger thermal oil mass flow rate.

For both situations shown in Figures 4 and 5, the T1 shows a faster response because this is the point where the PCM temperature closely follows the thermal oil temperature. It is then the first spot inside the capsule where the phase change takes place. The second thermocouple showing temperature changes is T5. The PCM liquefies initially in the bottom of the capsule, then near the mid wall, the formed liquid moves upwards due to convection currents (Esteves et al, 2017a; Esteves et al, 2017b; Esteves et al, 2018) towards the capsule top, thermocouple T5, and finally it liquefies in the central core, thermocouples T2 and T3. The comparison of the temperature time curves of Figures 4 and 5 shows no clear difference among them, meaning that the thermal resistance is inside the capsule, in the PCM.

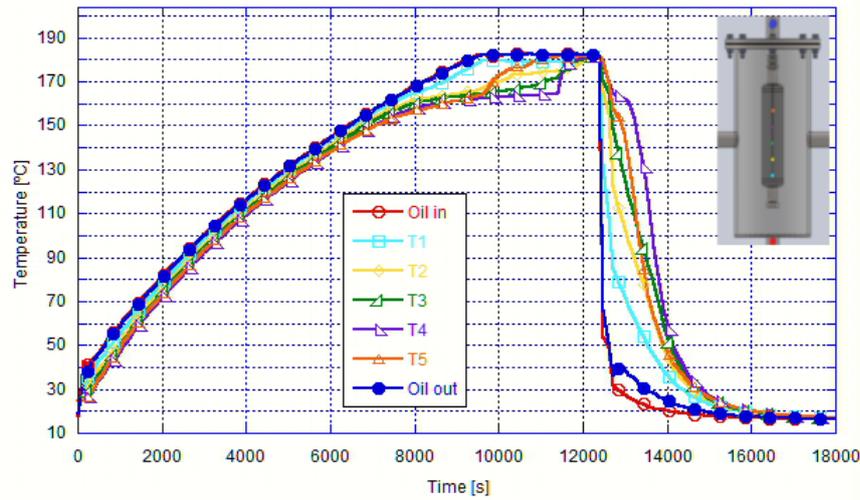


Figure 4. Time evolution of temperature for vertical capsule without fins. Pump at 35 Hz.

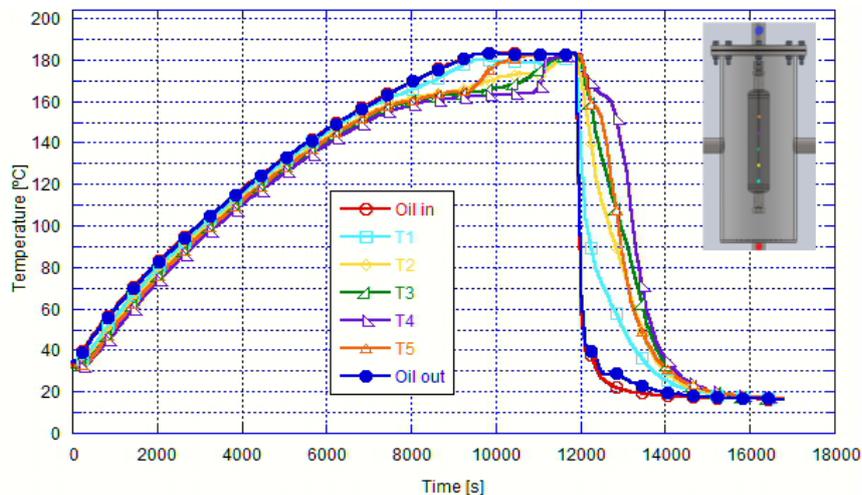


Figure 5. Time evolution of temperature for vertical capsule without fins. Pump at 50 Hz.

The curves for the temperature time evolution for the horizontal positioning of the capsule are shown in Figures 6 and 7, while in Table 3 are presented average values for the thermal oil mass flow rate and velocity for frequencies of pump feeding of 35 and 50 Hz.

Table 3. Thermal oil average mass flow rate and velocity inside the test exchanger.

Capsule position	35 Hz, kg/s	50 Hz, kg/s	35 Hz, m/s	50 Hz, m/s
Vertical	0.41	0.52	0.0075	0.010
Horizontal	0.42	0.55	0.0067	0.0093

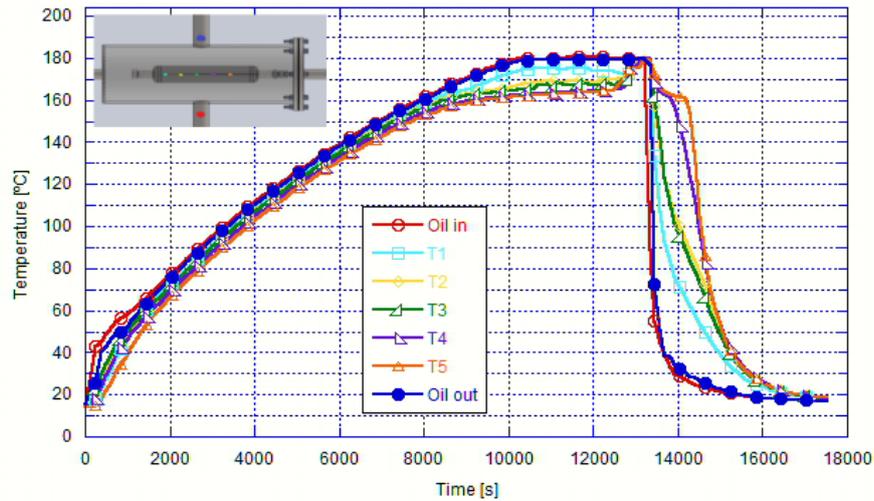


Figure 6. Time evolution of temperature for horizontal capsule without fins. Pump at 35 Hz.

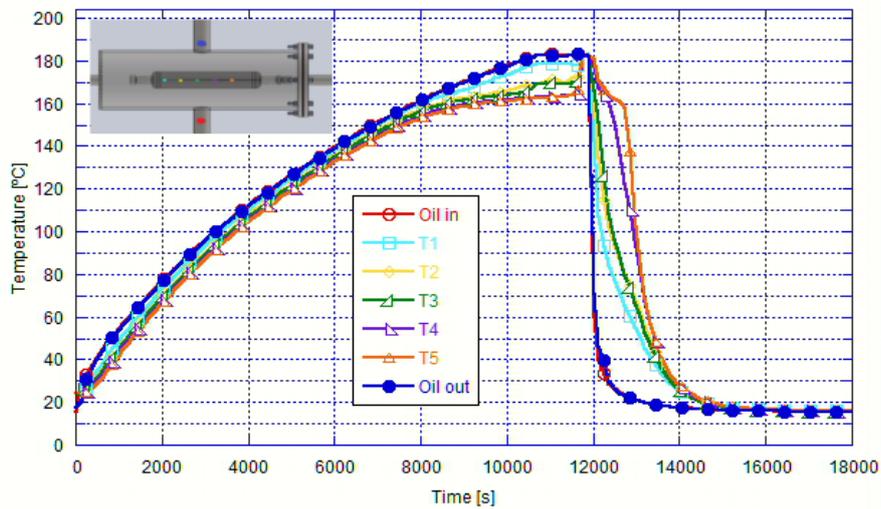


Figure 7. Time evolution of temperature for horizontal capsule without fins. Pump at 50 Hz.

For the horizontal placement of the capsule as the thermocouples are placed along the axis of the capsule they now show a uniform temperature behavior, although thermocouple T1 still presents temperature values closer to the oil temperature, only because it is the one nearest to the capsule wall. Now, the oil mass flow rate interferes on the evolution of the temperature profiles inside the PCM. While for the pump supply frequency of 35 Hz the phase change plateau starts at 10,000 s and ends at 13,000 s, when using the pump supply frequency of 50 Hz, the phase change plateau goes from 10,000 s to 12,000 s.

### 3.2 Capsule with inner fins

Considering now the results for the capsule with an inner fin system, Figures 8 and 9 refer again to the vertical placement of the capsule. Comparing these curves with those for the capsule without inner fins, it is clear a more uniform temperature evolution of the PCM, and now it is thermocouple T5 that reaches earlier the thermal equilibrium during the heating step.

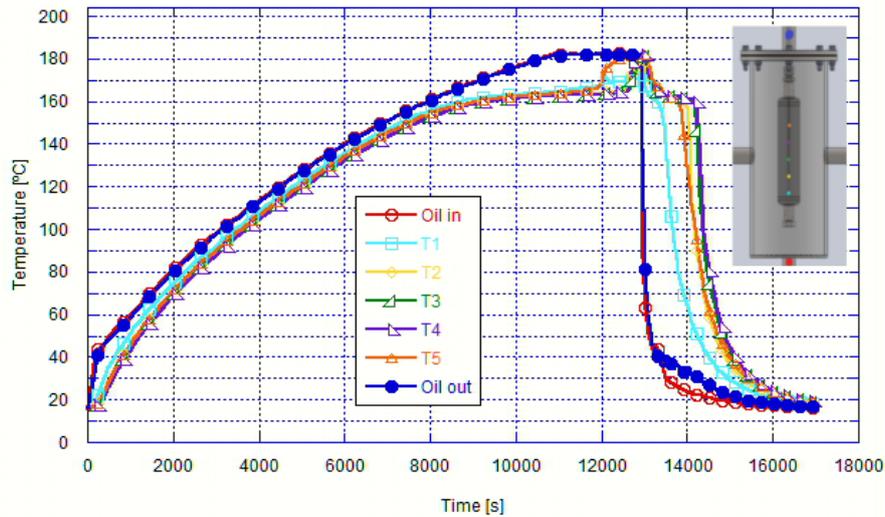


Figure 8. Time evolution of temperature for vertical capsule with fins. Pump at 35 Hz.

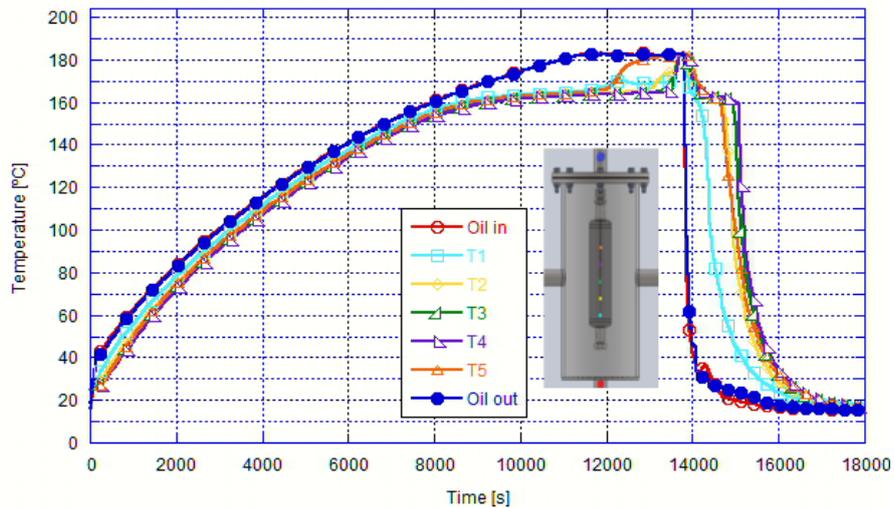


Figure 9. Time evolution of temperature for vertical capsule with fins. Pump at 50 Hz.

For the experiment shown in Figure 8, that refers to a test for a pump frequency of 35 Hz and a vertical capsule with inner fin system, the phase change starts around 12,000 s and ends around 13,000 s, whereas for the same experimental conditions, but with a pump frequency of 50 Hz, the phase change starts at 12,000 s and ends before 14,000 s. The phase change plateau has a slight widening, with the increase of pump feeding frequency, but as a whole the duration of the phase change plateau is smaller than for the equivalent experiments without inner fins. The introduction of the fin system leads to a more homogeneous temperature field inside the PCM, and this can explain the apparent widening of the phase change plateau with the increase of the thermal oil mass flow rate, as the thermocouple readings are more reliable than without fins. In the tests without inner fin system there might be PCM zones inside the capsule that had not yet changed their phase, but due to limitations in the number and positioning of the thermocouples such was not detected.

For the horizontal capsule layout with the internal fin system, results are shown in Figures 10 and 11.

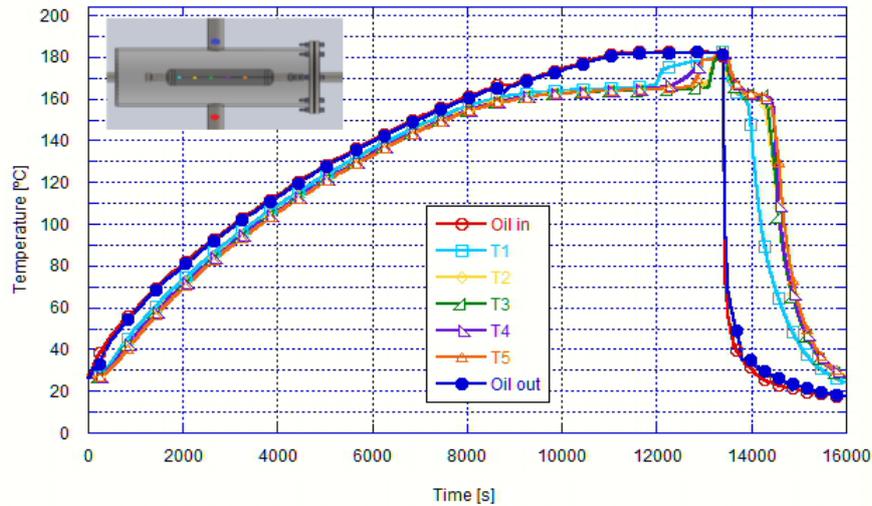


Figure 10. Time evolution of temperature for horizontal capsule with fins. Pump at 35 Hz.

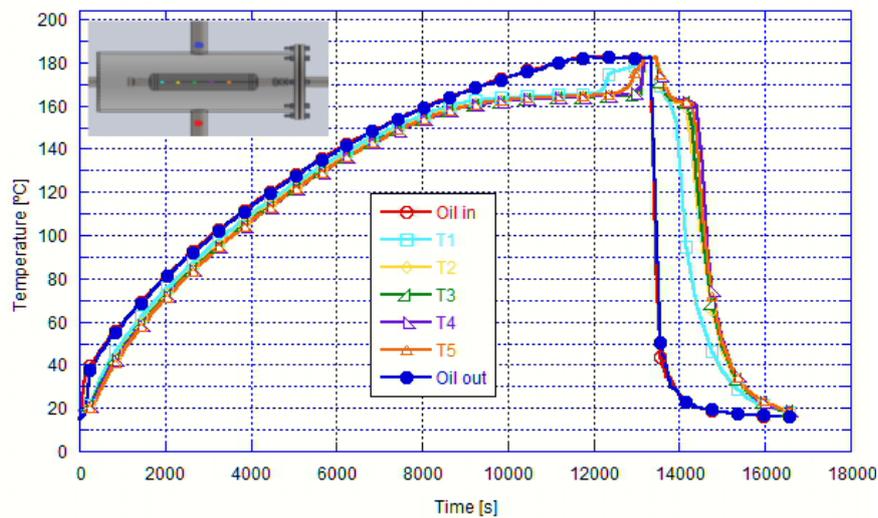


Figure 11. Time evolution of temperature for horizontal capsule with fins. Pump at 50 Hz.

Once again, in overall terms, the phase change plateau is now shorter than for the capsule without inner fin system. The thermocouple T1 is again the one with shorter response time due to its closeness to the capsule surface. For both pump feeding frequencies, the temperature profiles are very similar.

#### 4. OVERHALL HEAT TRANSFER COEFFICIENTS

From the mathematical treatment adjusted to the experimental configurations used in the experiments, that can be found elsewhere (Esteves et al, 2018), the following equations where the base for the determination of the overall heat transfer coefficient  $U$  from the thermal oil towards the PCM inside the capsules,

$$U = \frac{\dot{Q}}{A \Delta T_{ml}} = \frac{\dot{m}_{if} c_{if} (T_{if-in} - T_{if-out})}{A \Delta T_{ml}} \quad (1)$$

with  $\Delta T_{ml}$  given by,

$$\Delta T_{ml} = \frac{(T_{if-out} - T_M) - (T_{if-in} - T_M)}{\ln \left( \frac{T_{if-out} - T_M}{T_{if-in} - T_M} \right)} \quad (2)$$

being  $A$  the heat transfer surface area of the capsule,  $c_{if}$  the thermal oil specific heat,  $\dot{Q}$  the thermal power exchanged between the thermal oil and the PCM.  $T_{if-in}$  and  $T_{if-out}$  are respectively the thermal oil inlet and outlet temperatures, and  $T_M$  is the average temperature of the PCM.

#### 4.1 Capsule without inner fins

Figure 12 presents the evolution of the overall heat transfer coefficient for two thermal oil mass flow rates, corresponding to the two feeding frequencies of the pump of 35 and 50 Hz, for the vertical placement of the capsule, whereas Figure 13 presents the  $U$  values for the horizontal placement of the capsule.

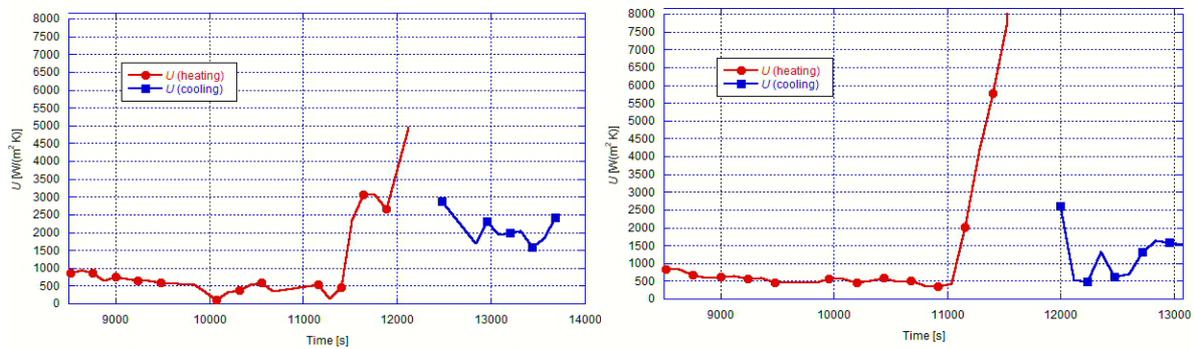


Figure 12. Time evolution of  $U$  for vertical capsule without fins. Left 35 Hz, right 50 Hz.

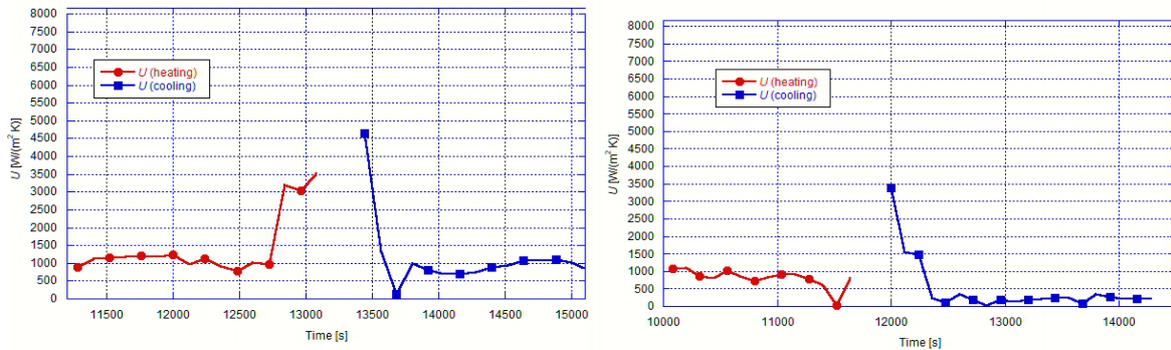


Figure 13. Time evolution of  $U$  for horizontal capsule without fins. Left 35 Hz, right 50 Hz.

The overall heat transfer coefficient in the solid phase and beginning of the phase change (red lines) is for the vertical position of the capsule around  $500 W/(m^2 K)$ , whereas for the horizontal position of the capsule it evolves around  $1000 W/(m^2 K)$ . The sudden jumps motivated by the increase of convection currents, associated to the appearance of the liquid phase, are quite clear in both situations, the vertical and the horizontal placement of the capsule. The evolution of  $U$  during the PCM cooling process is more stable but the values for 50 HZ seem too low, however. The initial fast descent of  $U$  (blue lines) is concerned with the disappearance of the liquid phase, and when the solid phase dominates the overall heat transfer values are lower.

#### 4.2 Capsule with inner fins

The next two figures present the evolution of the overall heat transfer coefficient, when the capsule has the inner fin system, either for the vertical positioning, Figure 14, or for the horizontal positioning, Figure 15.

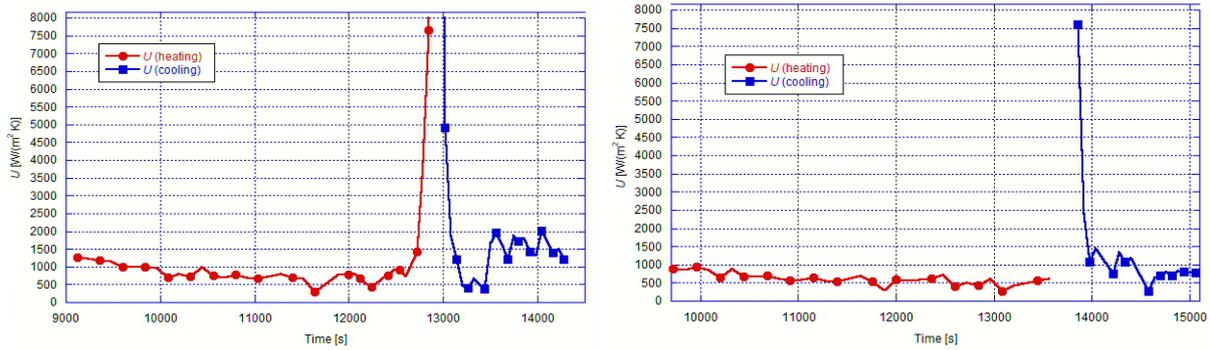


Figure 14. Time evolution of  $U$  for vertical capsule with fins. Left 35 Hz, right 50 Hz.

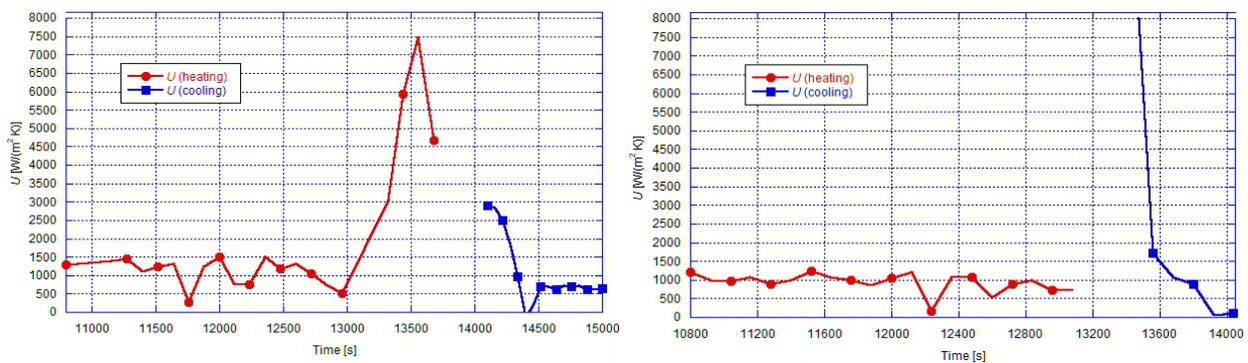


Figure 15. Time evolution of  $U$  for horizontal capsule with fins. Left 35 Hz, right 50 Hz

Now the overall heat transfer coefficients with the fin system are higher, especially for the horizontal capsule. In fact, for the capsule vertical positioning,  $U$  average values are roughly in the 500 to 1000  $W/(m^2 K)$  range, whereas for the capsule horizontal positioning the  $U$  values are slightly above 1000  $W/(m^2 K)$ . These higher values, compared with the no fins situation, Figures 13 and 14, clearly demonstrate that the heat transfer inside the PCM is the dominating heat transfer mechanism.

## 5. CONCLUSIONS

The thermal performance of a carbon steel capsule inside which was introduced a PCM, an alcoholic sugar derived from mannitol ( $C_6H_{14}O_6$ ) and commercially named PlusICE A164, was evaluated in cycles composed by a heating and a cooling phase. The material changed phase around 164 °C. Some typical PCM temperature time evolution plots were presented, for vertical and horizontal positioning of the capsule. One capsule only contained the PCM while the other, besides the PCM, was equipped with an inner fin system.

Thermal oil, was used as the thermal energy conveying fluid, and overall values for the overall heat transfer from the thermal oil towards the PCM, during the PCM heating step, and from the PCM towards the thermal oil, during the PCM cooling step were determined. Plots of the time evolution of this global heat transfer coefficient  $U$  were also presented. The main heat transfer resistance takes place in the PCM material and the range of  $U$  values during heating and the subsequent solid to liquid phase change period was from 500 to 1000  $W/(m^2 K)$ .

## 6. ACKNOWLEDGEMENTS

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## 8. RESPONSIBILITY NOTICE

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