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Hybrid PCM—aluminium foams' thermal storages: an experimental study

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Abstract

The latent heat absorption phenomenon associated with melting of a suitable phase change material can be an effective way to improve the thermal energy storage (TES) behaviour in many applications. However, the most suitable materials to be used in heating and refrigeration systems find intrinsic limitations due to their poor heat transfer capabilities. This work experimentally studies the use of aluminium foams as heat transfer medium to improve the overall heat transfer of paraffin waxes that can be possible phase change materials to be implemented in hybrid sensible latent water TESs. The experimental tests were run in a dedicated setup designed, developed and built at the Department of Management and Engineering of the University of Padova. The effects of the use of aluminium foams as enhancing heat transfer medium were studied by comparing the loading and unloading processes of a paraffin wax with melting temperature around 40°C, with and without metal foams, in a water thermal storage unit. The effects of three different foams with 5, 20, and 40 pores per inch (PPI) were investigated.

Keywords: phase change materials; paraffin waxes; aluminium foams; water thermal energy storage

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1 INTRODUCTION

Water thermal energy storage (TES) units can be considered as a simple energy storage and have widely been used all over the world in many domestic and industrial applications for decades. However, sensible TESs require relevant volumes per unit of stored energy according to the acceptable temperature difference. For example, for a 10°C temperature drop, that is common in many heating, ventilation and air conditioning applications such as ambient heating or single-stage absorption cooling, the specific volume required is of the order of 0.1 $m^3\,kWh^{-1}$ (36 $MJ\,m^{-3}$). A reduction in the size of the storage is welcome in building applications. A great improvement can be obtained by using a medium that, at the typical operating temperature of the system, changes from solid to liquid (melting) during the loading period and vice versa (solidification) during the unloading operation. High-latent heat TESs allow to reduce the size of storage systems and/or increase the total amount of energy stored. Values as low as 0.02 $m^3\,kWh^{-1}$ (180 $MJ\,m^{-3}$) can be readily obtained. Hybrid units which combine sensible and latent storage materials can be also applied.

From this standpoint, the identification of suitable phase change materials (PCMs) to be used to improve the energy storage capabilities of the common sensible water TESs becomes crucial. A large number of PCMs (organic, inorganic and eutectic) are available in any required temperature range. As described in many comprehensive reviews [1–3] published in the open literature, PCMs have been widely proposed for thermal storage applications due to their potential of storing and releasing large amounts of energy with a small PCM volume and a relatively low temperature variation. However, the thermal conductivity of these substances is usually very low (in the order of 0.2 $W\,m^{-1}\,K^{-1}$) so that the slow loading or unloading of PCM storages is sometimes the most serious limitation to their use. As such, several researches have been devoted to find out enhancement techniques in order to improve thermal conductivity of the PCMs; Jegadheeswaran and Pohekar [4] and Fan and Khodadadi [5] reviewed most of these efforts. Among the different solutions proposed in the open literature, open-cell metal foams, which consist of a stochastic distribution of interconnected pores almost homogenous in size and shape, seem to be a promising way to enhance the heat transfer performance of the components that use PCMs, because they show high-heat transfer area per unit of volume and high thermal conductivity.

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Metal foams have been demonstrated to be very effective in enhancing the heat transfer during both single-phase and two-phase heat transfer [6–9]. Metal foams have also been proposed to improve the thermal performance of PCMs [10–13]. More recently, Mancin *et al.* [14] have experimentally proved how a metal foam improves heat transfer during solid–liquid phase change process of different paraffin waxes. Besides, Lazzarin *et al.* [15] simulated the use of aluminium foams to improve the heat transfer capabilities of paraffin waxes in hybrid water TESs. The authors demonstrated the suitability of these extended surfaces to enhance both the loading and unloading processes.

This paper presents the experimental results obtained during the phase change process of paraffin waxes with melting temperature around 40°C, with and without aluminium foams, in a hybrid water TES unit. The tested aluminium foams present 5, 20 and 40 pores per linear inch, with porosity higher than 0.9. The experiments investigate the improvements achievable with the use of different aluminium foams in terms of loading and unloading times and overall heat transfer performance.

2 PCMS AND METAL FOAMS

An ideal PCM should exhibit a suitable phase transition temperature, high latent heat of fusion and high thermal conductivity; it should be characterized by high density associated with a small volume change during the melting process and low vapour pressure in the melt. Moreover, it should be chemically stable over a long period of time, non-toxic and non-hazardous and compatible with the building materials. Finally, it should be abundant, available and cost-effective [2]. Among the available PCMs, paraffin waxes have been found to exhibit many desirable characteristics, such as high latent heat, low vapour pressure in the melt, chemical inertia and stability, non-toxicity and very low price. However, they also have a very low thermal conductivity and a high volume change during the melting process. Nowadays, these two drawbacks are limiting the potential applications of the paraffin waxes as PCMs in water thermal storage units.

For these reasons, two commercial paraffin waxes with a melting point around 40°C and 45°C, RUBITHERM® RT40 and RT45, were purchased from Rubitherm Technologies GmbH (Germany) to be tested in the experimental apparatus aimed at investigating the thermal performance of different PCMs and their enabling technologies for hybrid water TESs. The present experimental results refer to RT40; Table 1 lists the main thermophysical properties of this paraffin wax.

As described before, metal foams have been identified to be implemented as heat transfer medium to eliminate and/or mitigate the two main limitations of the paraffin waxes when used for energy storage applications. A typical picture of an aluminium foam is reported in Figure 1. Most characteristic parameters are the size of the windows (or pore diameter), which correlates with the pore density (the number of pores per linear inch, PPI), porosity ε (defined as the volume of void divided by the total volume), the relative density ρ^* (defined as the density of the foam divided the density of the metal) and the surface area per unit of volume a_{sv} [16]. Table 2 lists the values of the main characteristics of the aluminium foams.

3 EXPERIMENTAL SETUP AND TEST PROCEDURE

Figure 2 reports a schematic of the experimental test rig designed to study the heat transfer performance of different PCMs with and without aluminium foam as heat transfer medium to be implemented in hybrid water TESs. As it can be noted, the setup consists of a 70-L insulated water tank used to simulate the TES. The hot water coming from the tank passes through a Brazed Plate Heat Exchanger (BPHE) fed with tap water, and then it is pumped into a 9-kW electrical heater driven by a proportional integrative derivative regulator, before entering again into the water tank (there is no stirring in the tank).

By controlling the electrical power and the water flow rate, the temperature of the water contained in the tank can be set and kept at the desired value. As illustrated, the water temperature is measured in several locations throughout the system by means of calibrated T-type thermocouples with an uncertainty estimated to be ±0.05 K.

The setup can run experiments by varying the water temperature from around 15°C up to 75°C, in this way PCMs with different melting temperature can be tested. In order to study the enhancement achievable with a selected technique (aluminium foam-filled tube in Figure 2), the system was designed to run comparative measurements.

In particular, as illustrated in Figure 2, two similar tubes can be tested at the same time, one is empty, while the second one implements the enhanced surface. Both tubes are filled up with a certain amount of PCM and then tested at a constant water temperature to monitor the loading and unloading times, as well as the PCM phase change process by means of T-type thermocouples.

The tests were run to study the effects of aluminium foams on the heat transfer performance during the solid–liquid phase

Table 1. *Main thermophysical properties of the RT40.*

Phase change temperature (range) (°C)	Density (solid) (kg m^{-3})	Density (liquid) (kg m^{-3})	Latent heat capacity (kJ kg^{-1})	Specific heat capacity (solid) (kJ kg^{-1} K^{-1})	Specific heat capacity (liquid) (kJ kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})	Volume expansion (%)
38–43	880	760	165	3.00	2.30	0.21	12.5

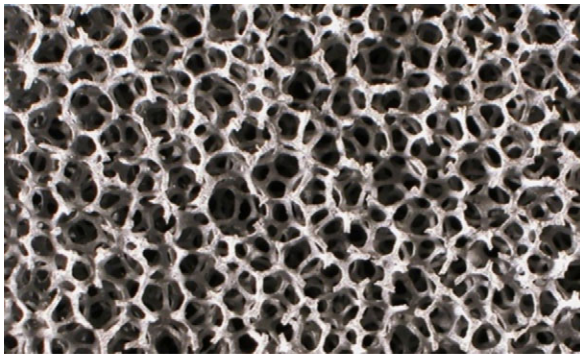

Figure 1. *Picture of a 10 PPI aluminium foam.*

Table 2. *Main geometrical characteristics of the aluminium foam samples.*

Type	PPI (in^{-1})	ε (-)	ρ^* (%)	a_{sv} ($m^2\ m^{-3}$)
Al_5_7.9	5	0.921	7.9	339
Al_10_5.2	10	0.948	5.2	601
Al_10_7.3	10	0.927	7.3	731
Al_10_10.7	10	0.893	10.7	876
Al_20_7.3	20	0.927	7.3	1190
Al_40_8.6	40	0.914	8.6	1834

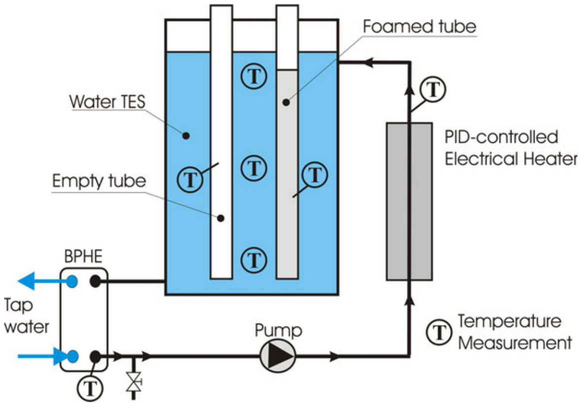

Figure 2. *Schematic of the experimental setup.*

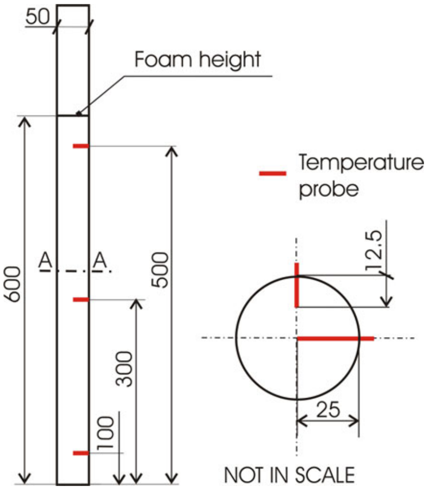

Figure 3. *Location of the temperature probes (in millimetres).*

change of paraffin waxes. The test samples consisted of seven 800-mm-long, 2” outside diameter tubes, closed on one side. One of these tubes was empty and it was filled up with the selected paraffin wax, the other six were manufactured to locate different 600-mm-long Al foam cylinders, which were brazed to the inside tube wall to minimize the contact resistance. Each of these tube contains around 1 kg of paraffin wax. As reported in Figure 3, each tube was equipped with six T-type thermocouples to monitor the phase change process at different tube heights.

The tests involved both the melting and solidification processes. The test procedure was the following: the water contained in the tank was heated up to the set temperature, i.e. 50°C or 60°C, depending on the desired boundary conditions, by means of the electrical heater. When the desired water temperature was reached, the two instrumented tubes filled with paraffin wax were inserted in the water tank and all the data were recorded. Then, when the measured paraffin temperatures read by the installed thermocouples approached, the water one remaining almost constant, the hot water was purged out and the tank reload with tap water to study the solidification, i.e. unloading process. It is worth underlying that, as depicted in Figure 2, also the water temperatures at different heights were monitored. During the tests, the temperature difference between the water temperatures measured at different tank heights was always lower than 0.1 K. Moreover, preliminary tests were run by swapping the tubes’ position to verify the repeatability of the measurements: no noticeable differences either in the charging and discharging times and temperature profiles were noticed. The set operating test conditions are listed in Table 3.

The loading (i.e. melting) process was considered completed once all the central line thermocouples reached steady-state values closed to that of the water tank; consequently, the unloading (i.e. solidification) process was considered concluded when all those temperature readings became constant, close to that of the water tank.

4 EXPERIMENTAL RESULTS

This section presents the experimental results carried out during the loading and unloading processes by setting the water tank temperature at around 50°C and 23°C, respectively. Table 4 lists the loading and unloading times measured for different tubes filled with the same amount of RT40 paraffin wax, with and without metal foams. In this work, three different metal foams having almost the same porosity and different pore densities (5, 20, and 40 PPI) were investigated.

Table 3. *Operating test conditions.*

Parameter	Loading	Unloading
Set water temperature	50 ± 0.5°C	23 ± 0.5°C

Table 4. *Loading (melting) and unloading (solidification) times.*

Parameter	Time	
	Loading	Unloading
RT40 in empty tube	More than 2 h	More than 2 h
RT40 with 5 PPI foam	15 min	23 min
RT40 with 20-PPI foam	16 min	19 min
RT40 with 40-PPI foam	14 min	21 min

From the analysis of the data listed in Table 4, it clearly appears that the use of the metal foams strongly reduces the melting (loading) and solidification (unloading) times as compared to the case of the empty tube. In particular, the melting process is speeded up of more than eight times, while the solidification one is reduced more than six times. It is also interesting to point out that the investigated foams behaved similarly, meaning that there is not any appreciable effect of the pore density on the improvement introduced by the porous media. Similar results were also found by Mancin *et al.* [14].

Figure 4 compares the temperature profiles recorded during the melting process of RT40 paraffin wax contained in two different tubes, one filled with a 20-PPI foam, while the second one empty. For the sake of clarity, only the two thermocouples located at 500 mm (TOP) from the bottom for both tubes were plotted. Furthermore, in the bottom right side of the figure, a small window showing the first 14 min of the melting process to better highlight the temperature profiles measured in the tube containing the foam was reported.

Considering the results plotted in the diagram, it can be stated that the melting process, when the foam is used, is very fast and, at this height, it is almost completed in around 10 min, whereas it takes more than 1 h and 20 min without foam. The small window in the bottom right side of Figure 4 permits to highlight that, as reported in Table 1, the melting process occurs from around 38°C to 43°C. Furthermore, the loading process using the foam was completed before the paraffin contained in the empty tube could have started to melt; in fact, at 00:09 the temperature measured by the 12.5-mm TOP thermocouple of the empty tube was still lower than 38°C.

This behaviour can be explained considering how, in the case without foam, the melting process proceeds: when the tube is inserted in the hot water, the wall almost instantly reaches 50°C and a thin layer of solid paraffin wax melts, the liquid has a very low thermal conductivity (0.2 W m^{-1} K^{-1}) and thus it acts as a thermal shield limiting the heat transfer through the solid and the consequent melting process. Moreover, the volume variation implies that the liquid quickly moves towards the top covering the solid; thus, the melting process occurs radially from the tube wall towards the centre and from the bottom and top towards the centre. This means that the last solid which eventually melts will be that located in the middle of the tube. This is confirmed by the temperature measured by the thermocouple located in the centre of the tube at 300 mm from the bottom.

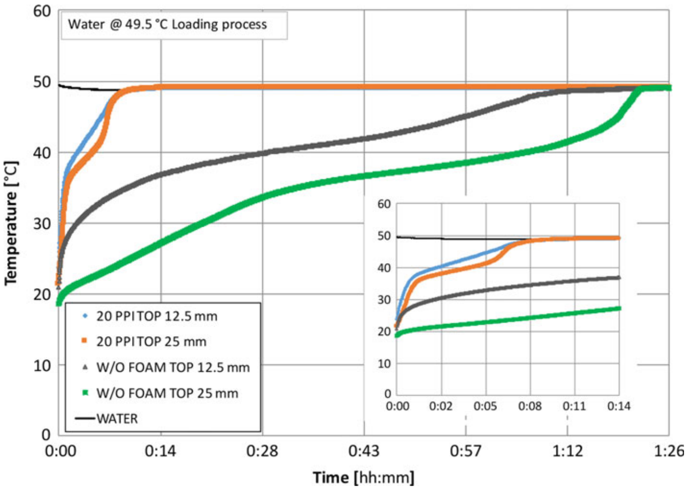

Figure 4. *20-PPI foam vs. empty tube. Loading process at 50°C of water tank temperature.*

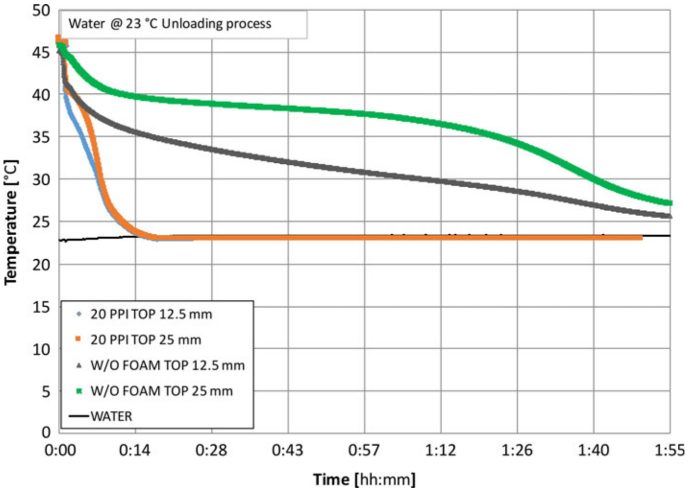

Figure 5. *20-PPI foam vs. empty tube. Unloading process at 23°C of water tank temperature.*

The unloading process of the RT40 paraffin wax recorded by the same top thermocouples of both the empty and the 20-PPI foam-filled tube is reported in Figure 5. The results highlight the interesting capabilities of the aluminium foam in ensuring a fast, efficient and complete unload process. As it was shown before for the loading process, also in the case of the unloading one, the solidification of the paraffin contained in the empty tube starts when the process in the foam-filled one is already

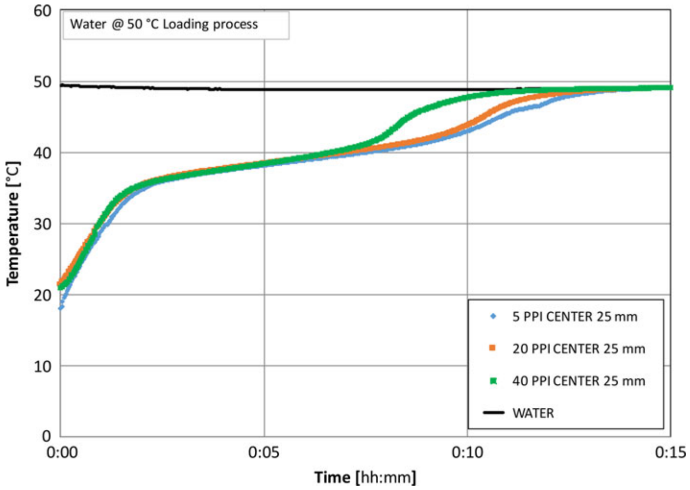

Figure 6. *Pore density effect on the loading process at 50°C of water tank temperature.*

finished. This means that, in the case of the empty tube, it is rather impossible to extract in an efficient and consistent way the heat loaded in the paraffin. This is mainly due to fact that once a thin solid layer is formed at the cold wall, it acts as an insulator layer, limiting the heat transferred from the hot liquid to the cold water. Since the solidification process in the empty tube proceeds from the wall towards the centre and this liquid–solid phase change implies a reduction of the specific volume of the paraffin, a non-uniform solidification occurs and a void volume is generated at the centre of the tube, which also remains after the end of the solidification of the paraffin wax. This represents an additional drawback, that is completely eliminated when the aluminium foams are used.

Figure 6 presents the effect of the pore density on the melting process by plotting the temperature profiles recorded by the thermocouples located in the middle of the three foam-filled tested tubes (centre). From the analysis of the diagram, it appears that the differences between the temperature profiles are almost negligible; in fact, the 5- and 20-PPI aluminium foam-filled tubes showed almost the same results, whereas the 40-PPI foam-filled tube reduced the loading time of around 2 min, as already reported in Table 4.

5 CONCLUSIONS

This paper experimentally investigates the possible use of the aluminium metal foams to improve the solid–liquid phase change process of the paraffin waxes. A test rig was designed and built to simulate a hybrid water TES. A paraffin wax with a nominal melting temperature of 40°C was studied during both the melting (loading) and solidification (unloading) processes. Four different tubes were filled with the same amount of paraffin wax: three of them also contained aluminium foams as heat transfer medium, while the fourth one was empty and taken as a reference. The results highlighted that without any heat transfer medium the phase change process during both the loading and unloading processes took more than 2 h to be completed while when the aluminium foams were used, the loading and unloading times were reduced of around eight and six times, respectively. Furthermore, the aluminium foams also permitted to eliminate the issue related to the void volume generation during the solidification process, which usually occurs in the empty tube because of the specific volume change in the liquid–solid phase change. Finally, it can be concluded that the use of the metal foams represents a viable option to enable the effective use of the paraffin waxes in hybrid water TESs.

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