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Experimental thermal performance comparison of pure and metal foam-loaded PCMs

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Abstract. The thermal performance of latent heat thermal energy storage (LHTES) systems considerably depends on thermal conductivity of adopted phase change materials (PCMs). To increase the low thermal conductivity of these materials, pure PCMs can be loaded with metal foams. In this study, the melting process of pure and metal-foam loaded phase change materials placed in a rectangular shape case is experimentally investigated by imposing a constant heat flux at the top. Two different paraffin waxes with melting point of about 35°C are tested. The results obtained with pure PCM are compared with those achieved from the use of PCM combined with two different porous metals: a 10 PPI aluminum foam with 96% porosity and a 20 PPI copper foam with 95% porosity. The results demonstrate how metal foams lead to a significant improvement of conduction heat transfer reducing significantly the melting time and the temperature difference between the heater and PCM.

1. Introduction

Large heat storage capacity of phase change materials (PCMs) allows to use these materials in order to obtain compact thermal energy storage systems. In fact, their thermo-physical properties guarantee a significant reduction of the thermal storage size, and the linked heat losses, maintaining the same amount of stored energy [1]. The main disadvantage of PCMs is related to their low thermal conductivity (generally about 0.2 W/(mK)), which considerably slows down the melting process and causes a wide temperature gradient within PCM [2]. To solve this problem, the use of metal foams coupled to PCMs has received an increasing attention during the last years and represents a suitable solution to make these materials more attractive for commercial devices. Metal foams, in fact, are characterized by a much higher thermal conductivity if compared to PCMs and can be inserted within the PCM to increase the phase change process velocity, with no penalization on the heat storage capacity [3].

To assess the influence of metal foams features (e.g. porosity, pores density) on the improvement of PCMs' thermal performance, more experimental studies are needed. In this work, the melting process of PCMs combined with aluminum and copper foams is experimentally tested. Moreover, experiments on the melting process of pure PCMs are performed in order to quantify the performance improvement due to the insertion of metal foams.

The main aim of this paper is to demonstrate how the introduction of metal foams significantly increases the average thermal conductivity of the PCM-based system, resulting in an enhancement of the phase change process in terms of reduced time and larger temperature uniformity.

2. Experimental set-up

The experimental set-up used in this study is shown schematically in Figure 1 and Figure 2.

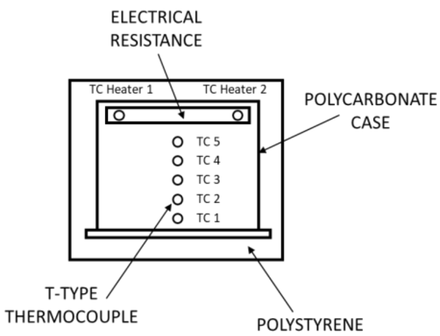

Figure 1. Thermocouples arrangement layout in the case.

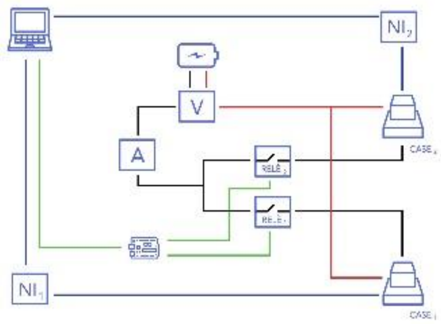

Figure 2. Layout of experimental set-up.

The PCM is poured in a polycarbonate container (thermal conductivity 0.21 W/(mK)) with dimensions 145x90x100 mm. To limit the heat losses, the container is completely insulated by a 60 mm layer of polystyrene (thermal conductivity 0.035 W/mK) and the overall heat exchange coefficient is 0.22 W/(m^{2}K). Five metal bars, on which T-type thermocouples are inserted to record the temperature distribution within the PCM during the heating process, are placed at different heights of the case. Two additional thermocouples are placed directly in contact with the heat source, represented by an electrical resistance (110x70x5 mm, 100 Ω). The heat source is placed on the top of the containers (73 mm from the bottom), in order to have only conductive heat transfer from the top to the bottom of the case. The geometry of the case and the position of the heater are able to guarantee a 1D heat flux, along the vertical axis, without significant boundary effects; a series of video was able to demonstrate how the melting surface was perfectly planar and orthogonal to the case vertical axis. In Figure 1 the layers of the insulated case as well as the position of the heater and thermocouples are shown. The lower thermocouple (TC1) is placed 3 mm far from the bottom, and all the thermocouples are equally spaced by 13 mm. Experimental tests have been carried out powering the electric heater by means of a DC generator imposing a constant voltage of 17.1 V. The case was filled with liquid PCM and the experimental test is started with the activation of the heater when the PCM was completely solid at the ambient temperature. Then, the heater was switched off as soon as the maximum heater temperature of 57°C was reached, to avoid thermal stress on the polycarbonate case.

The PCMs used as working materials in these tests are RT 35 (*Rubitherm (D)*, thermal conductivity 0.2 W/mK, heat storage capacity 160 kJ/kg @ 29 – 36°C) and RT 35 HC (*Rubitherm (D)*, thermal conductivity 0.2 W/mK, heat storage capacity 240 kJ/kg @ 34 – 36°C). For each test, 660 g of PCM have been poured in the container.

To improve the thermal conductivity of PCM, aluminum (*Recemat bv (NL)*, porosity 96%, pores density 10 PPI, thermal conductivity 237 W/mK) and copper (*Porometal (CN)*, porosity 95%, pores density 20 PPI, thermal conductivity equal to 390 W/mK) metal foams have been used.

The T-type thermocouples (range 0-100°C, uncertainty ±0.5 K) are collected by NI DAQ modules (NI 9213) and shared with a PC by means of LabView.

Three tests have been performed for each PCM: the first one, considered as a reference, with the pure PCM, the second and the third ones with PCM loaded with copper and aluminum foam, respectively. Moreover, each experiment has been repeated three times, to confirm the repeatability of the experimental measures.

3. Results and discussion

The temperature trends measured by the thermocouples for pure RT 35 and for RT 35 loaded with aluminum metal foam are shown in Figure 3 and Figure 4, respectively. In these figures the heater temperature (TC Heater) indicates the arithmetic mean of the values recorded by the two thermocouples placed below the electric resistance. The initial temperature is different (between 17 °C and 22 °C) in some of the tests because the ambient temperature in the laboratory was not always the same.

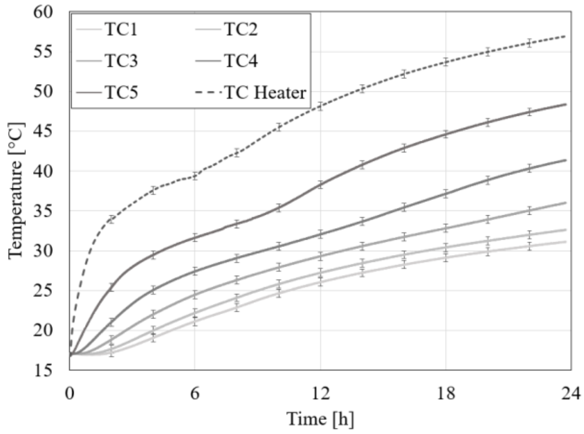

Figure 3. Temperature trends for pure RT 35.

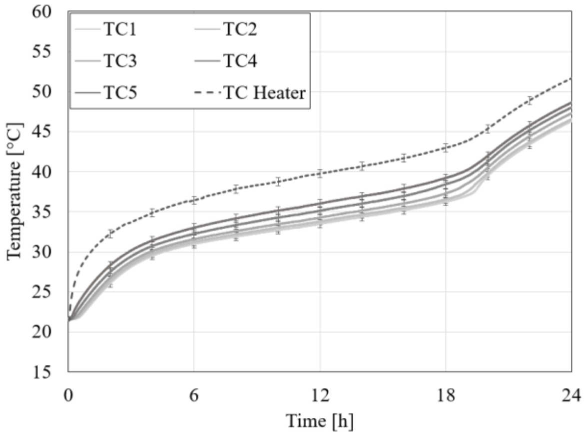

Figure 4. Temperature trends for RT 35 loaded with aluminum foams.

Focusing on Figure 3, it is evident how in presence of pure PCM heat conduction is very poor: a large temperature difference among the thermocouples is evidenced for a fixed imposed heat flux at the top. In particular, when the heater maximum temperature is reached (i.e. 57°C), the PCM temperature in the lower part of the case (TC1) is equal to 31°C and the phase change is not still started. Moreover, there is a significant temperature difference, equal to 10 K, between the heater and the PCM in the upper part of the case (TC5) due to the large thermal resistance of the pure PCM.

After 24 h, only the first two thermocouples, closer to the heater, evidenced a complete PCM melting process (T>36°C). On the contrary, the lower layers of PCM (TC2, TC1) have barely started the melting process at the end of the test after 24 hours.

The data of Figure 4 are obtained by using RT 35 loaded with aluminum metal foams. Comparing the temperature trend of Figure 3 and Figure 4 it is evident the beneficial effect of the presence of the metal foam. A strong reduction of the temperature difference among thermocouples is observed with respect to the case of pure PCM. In particular, the temperature difference between consecutive thermocouples is lower than 1 K, whereas between the heater and TC5 this difference is about 3 K. Moreover, for the same heat flux imposed at the top, the maximum temperature reached by the PCM is lower than that obtained with pure PCM of 9 K. This is confirmed by observing how, after 24 h, the whole volume of PCM was able to complete the phase change process.

In Figure 5 and 6 the results obtained by testing RT 35 and RT 35 HC loaded with copper foams are shown, respectively. It is evident that the main difference between the two cases is the different duration of the melting process (20 hours for RT 35 and 26 hours for RT 35 HC, namely +30%). The longest time required by RT 35 HC for having a complete melting process it is due to its larger latent heat of fusion. Another meaningful consideration can be made comparing Figures 4 and 5, where the temperature trends obtained for RT 35 loaded with aluminum and copper foams are reported, respectively. It is evident how only slight differences are observed by replacing aluminum with copper foams: the difference in temperature distribution is low and within the thermocouple uncertainty.

The positive effect of metal foams is evidenced by the temperature differences recorded among the thermocouples at the end of the tests and reported in Table 1 and 2, respectively for RT 35 and for RT 35 HC. The temperature difference between consecutive thermocouples is lower than 1 K in presence of metal foams but it becomes larger than 3 K for pure RT35.

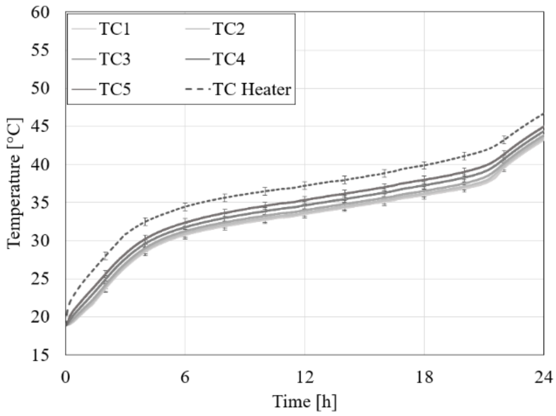

Figure 5. Temperature trends for RT 35 loaded with copper foams.

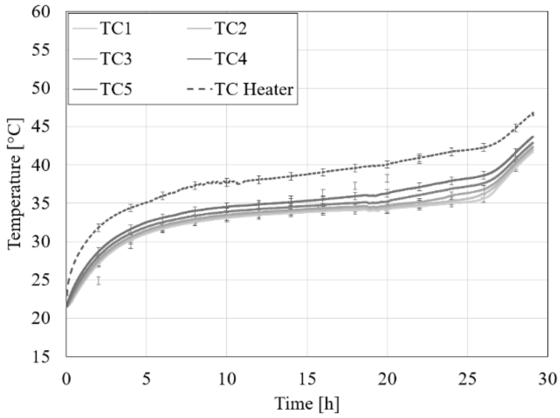

Figure 6. Temperature trends for RT 35 HC loaded with copper foams.

Table 1. Temperature difference [K] among thermocouples for RT 35 after 24 h with a power of 1.6 W.

	Pure PCM	PCM + aluminum foams	PCM + copper foams
Δ(TH- TC5)	8.56	3.19	2.24
Δ(TC5-TC4)	7.00	0.63	0.58
Δ(TC4-TC3)	5.36	0.73	0.47
Δ(TC3-TC2)	3.40	0.64	0.36

Table 2. Temperature difference [K] among thermocouples for RT 35 HC after 30 h with a power of 1.6 W.

	Pure PCM	PCM + aluminum foams	PCM + copper foams
Δ(TH- TC5)	10.50	3.93	1.36
Δ(TC5-TC4)	8.47	0.96	0.89
Δ(TC4-TC3)	4.35	0.64	0.59
Δ(TC3-TC2)	1.32	0.36	0.38

4. Conclusions

In this study, the heat transfer enhancement achievable coupling metal foams with paraffin wax (RT 35, RT 35 HC) during a pure conductive melting process has been investigated. PCM is heated from the top thanks to an electrical heater. The metal foams used in the experiments are aluminum and copper foams with different values of PPI and porosity. The experimental results show that the use of metal foams significantly improves the PCM melting, making the temperature distribution within the PCM more uniform and the complete melting faster, reducing the melting time up to 75%. At the same time, for the same imposed heat flux at the top, the maximum temperature reached at the end of the test to melt completely the material can be decreased up to 10 K in presence of metal foams.

Acknowledgments

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