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To cite this article: W Beyne *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **251** 012112

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Experimental investigation of solidification in metal foam enhanced phase change material

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Abstract. A major challenge for the use of phase change materials (PCMs) in thermal energy storage (TES) is overcoming the low thermal conductivity of PCM's. The low conductivity gives rise to limited power during charging and discharging TES. Impregnating metal foam with PCM, however, has been found to enhance the heat transfer. On the other hand, the effect of foam parameters such as porosity, pore size and material type has remained unclear. In this paper, the effect of these foam parameters on the solidification time is investigated. Different samples of PCM-impregnated metal foam were experimentally tested and compared to one without metal foam. The samples varied with respect to choice of material, porosity and pore size. They were placed in a rectangular cavity and cooled from one side using a coolant flowing through a cold plate. The other sides of the rectangular cavity were Polymethyl Methacrylate (PM) walls exposed to ambient. The temperature on the exterior walls of the cavity was monitored as well as the coolant flow rate and its temperature. The metal foam inserts reduced the solidification times by at least 25 %. However, the difference between the best performing and worst performing metal foam is about 28 %. This shows a large potential for future research.

1. Introduction

Temperature-sensitive goods should be kept in a temperature range starting with production until end use. A cold chain must thus be established during transport and storage. For some pharmaceutical cold chain applications, transported goods have to be kept at temperatures between 0 °C and 8 °C to make sure they are not damaged [1]. Other examples of cold chains can be found in food industry [2, 3]. Three major types of solutions exist: active containers [4], passive containers [5] or a mixture of both [6-8]. Active containers include a chiller in addition to the transport container. Passive containers have added thermal mass in the container which is charged prior to usage. Because of the incorporated chillers, active containers are more complicated than passive coolers. Furthermore, frequently switching the chiller on and off can cause compressor failure [4]. Therefore, several authors have added extra thermal mass to active containers to decrease switching of the active cooling [6-8]. Mixed systems are also used to reduce and displace peak power use of the chillers incorporated in the containers [9].

Passive containers require added thermal mass to the passive container. This can be achieved by both sensible and latent heat. However, sensible heat systems have a considerably lower energy density compared to systems operating on latent heat [10]. This is especially the case in cold chain applications in which only low temperature fluctuations are allowed. Therefore, passive cooling is achieved using phase change materials (PCM's) due to the exploitation of their latent heat absorption property. PCM-



based systems primarily use the latent heat of a liquid-solid phase change and they can achieve three to four times the energy density of systems using only sensible heat [10]. By an adequate choice of the PCM melting temperature, temperature can be maintained within the required range during the phase change [11].

Passive containers requires the PCM packages to be chilled and solidified prior to transportation. PCM's however have a low thermal conductivity [12]. This limits the charging speed of the cold storage. To increase the charging speed of PCM systems, enhancement methods can be applied [13, 14]. Examples are using fins, honeycombs, metal foam, rings and graphite inserts [15]. One of the structures showing remarkable potential are open cell metal foams. Du and Ding [16] performed an analytical study based on a one-equation model and the volume averaging technique. They concluded metal foam had a large potential to decrease the charging/discharging time. Zhao and Wu [17] performed an experimental study and came to the same conclusion.

Open cell metal foams are usually characterized by their porosity, pore size and material [18]. The effect of metal foam properties on melting and solidification processes is not entirely understood. Lafdi et al. [19] performed an analytical study on melting of phase change materials. They concluded that the effect of foam porosity and pore density were correlated and needed to be optimized. The effect of foam parameters on the phase change processes is however still unclear [20]. Xiao et al. [21] performed a study on the effective thermal conductivity of open cell copper and nickel foams impregnated with paraffin. They concluded the effective thermal conductivity increased with decreasing porosity. There are conflicting results on the effect of the pore density. Feng et al. [22] experimentally tested unidirectional freezing and concluded the pore density had a negligible effect on the freezing rate. Oya et al. [23] found that pore density had a positive influence on the effective thermal conductivity. Hong and Herling [24] found pore density to have a negative effect on effective thermal conductivity for a paraffin/aluminum foam composite. These conflicting results for different PCM and metal foam parameter combinations hint at strongly correlated effects on different thermal properties of different composites.

This paper discusses an experimental investigation of solidification behavior in PCM-metal composite use. Samples with different metal foam parameters are compared.

2. Experimental set-up

2.1. Test set-up

Figure 1 shows the test set up schematic. The heat transfer fluid (HTF) is chilled by the Julabo FL601 chiller. The chiller can deliver a cooling power of 0.33 kW at -10 °C. The HTF can either be routed over a bypass, to charge the chiller, or through a cold plate. Three CP10G16 cold plates from Lytron are placed side by side and connected as shown in Figure 1 a.

The cold plates are submerged in the middle of a rectangular enclosure shown in Figure 1 b. The enclosure consists of glued PM walls. The PM walls on the side perpendicular to the cold plate are 0.25 cm thick. The other Polymethyl Methacrylate (PM) walls have a thickness of 0.5 cm.. On each side of the cold plate, the rectangular enclosure has a size of 2x19x26 cm. The enclosures are filled with metal foam with a height of 16 cm. The metal foam properties are given in Table 1. There are two tests with an aluminum foam of 10 PPI and a porosity of 95.5 %. One sample is pressed against the cold plate, while the other is not. The two samples allow to test the effect of the thermal contact resistance between foam and cold plate. A total of 7 samples are tested. Additionally a case without foam is tested. The enclosure is filled with PCM up to just above the top of the metal foam. Puretemp 1 is used as phase change material. Its properties are shown in Table 1.

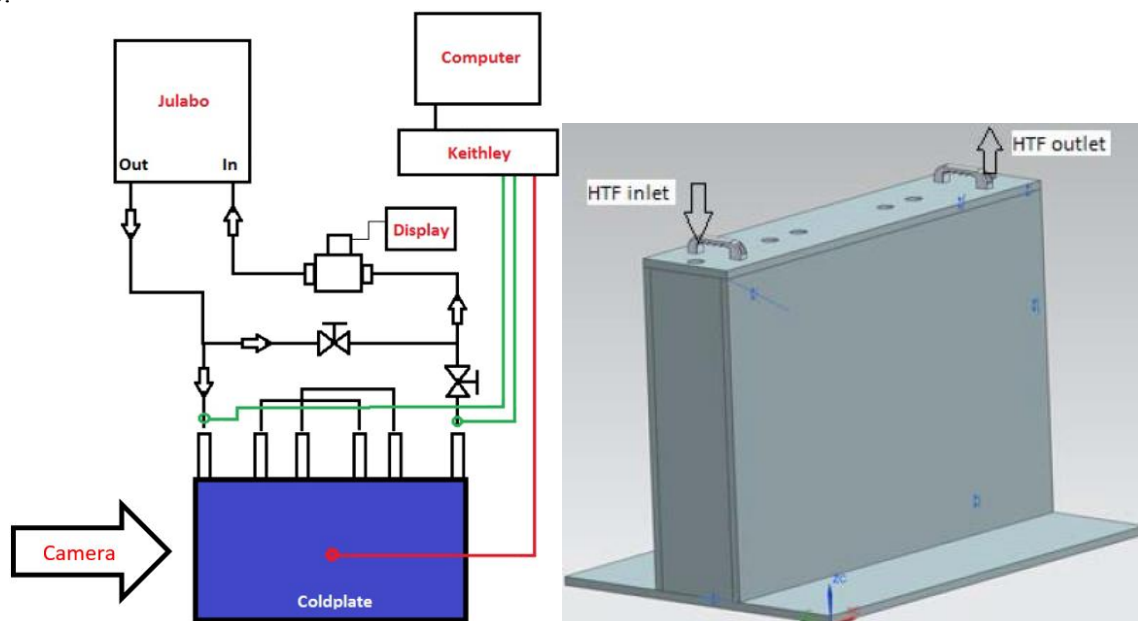
Table 1. Properties of the metal foam samples.

Material	Aluminum	Copper
Thermal conductivity	229 W/m°C	401 W/m°C
Pore density / Porosity	5 PPI / 0.955	10 PPI / 0.967
	10 PPI / 0.955	10 PPI / 0.933
		20 PPI / 0.933
		40 PPI / 0.933

Table 2. PureTemp 1 properties

	PureTemp 1
Melting temperature	1 °C
Melting enthalpy	301 J/g
Thermal conductivity	0.15 W/m°C (liquid)
	0.25 W/m°C (solid)
Specific heat capacity	2.43 J/g°C (liquid)
	2.32 J/g°C (solid)
Density	1.00 kg/l (liquid)
	1.10 kg/l (solid)

The set-up is equipped with four thermocouples and one flowmeter. Firstly the flow rate of the HTF is measured using a Bürkert frequency flow rate sensor. Secondly the temperature of the HTF at the inlet and outlet of the cold plates is measured by two calibrated K-type thermocouples. The cooling power can thus be determined from the product of the HTF flow rate, density, specific heat capacity and temperature difference across the cold plates. Two additional K-type thermocouples measure the temperature outside of the cold plate as well as the PM inside wall temperature. The ambient temperature is measured using a PT100. Finally the melting front is visualized using a camera on the side of the set-up.

**Figure 1.** (a) Test set up schematic; (b) 3D model view of the test set up.

2.2. Measurement procedure

First the HTF reservoir is cooled by the chiller to -16°C . The HTF is then circulated through the cold plate. Every 5 seconds, the temperature and flow measurement readings are recorded using a Keithley data acquisition system and a desktop computer. The measurement is stopped once the PM wall temperature reaches -5°C . The stopping criteria is chosen to ensure the enclosure is fully solidified. The procedure is repeated for the other six metal foam enhanced PCM samples and the PCM alone.

3. Measurement results

3.1. Cooling power

The first measurement result is the cooling power of the Julabo chiller. This power is integrated and divided by the PCM-foam volume to obtain the cooling energy per unit of volume as a function of time. The resulting error on the cooling energy is 17 %. The results for the no-foam and the best performing case with foam are shown in Figure 2. The cooling energy is referenced to the enclosure volume. The metal-foam case outperforms that without foam as the experiment is terminated sooner and the slope of the energy-vs-time curve is steeper. Both curves reach different maximum energy densities. In a case with no heat gains from the ambient, both curves should reach the same required cooling power after correction for the porosity.

Cooling down the PCM volume from $+20^{\circ}\text{C}$ to -5°C requires about 100 kWh/m^3 cooling energy in the no foam case. The required cooling energy is however below this value. The experiment is thus terminated before the sample has fully solidified. Cooling down the foam sample over the same temperature interval requires about 93 kWh/m^3 . The required cooling energy is however $\sim 20\%$ higher. The PM single pane walls do not suffice to reduce the losses to an acceptable level.

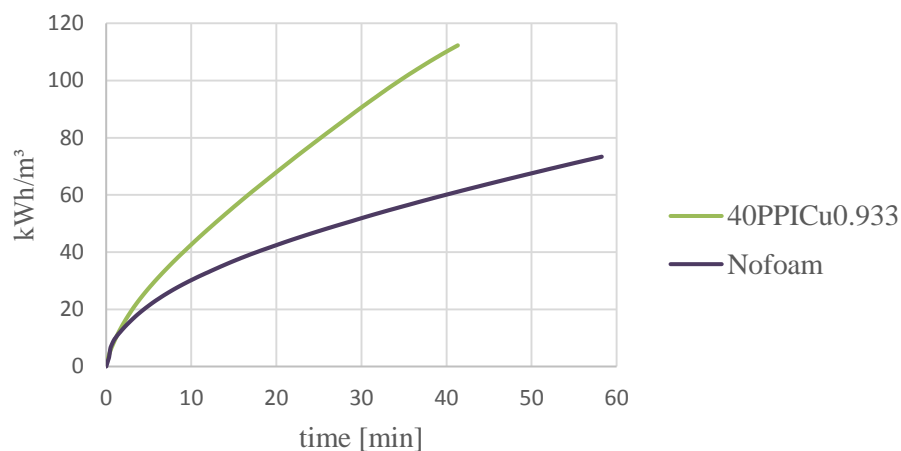


Figure 2. Cooling energy per volume as a function of time.

It is not possible to accurately calculate the gains from the measurement data. After all, the heat gains from the ambient can both lead to lower and higher required cooling energy. The total heat losses are thus not equal to the difference in measured cooling power and required cooling power for full solidification. The losses could be determined from the PM wall temperature measurements, the ambient temperature and an estimate of the thermal resistance between both. The experiment is however not 1D, therefore a single PM wall temperature measurement does not facilitate the extraction of PM wall temperature profile.

Because of the high heat gains from the ambient, the measurement of the cooling power is only useful for qualitative interpretation. Visual verification for numerical models is a common method in literature [19, 25]. The insulation is therefore often limited to single pane walls. To obtain quantitative results in future studies, heat gains should be reduced. To this aim, insulation can be added to the test set up or

the temperature difference between ambient and phase change temperature should be smaller. In the following subsection the temperature of the PM wall are analyzed and compared.

3.2. Polymethyl methacrylate wall temperatures

Figure 3 shows the PM wall temperature as a function of time. Initially the samples are at room temperature. For the foam samples, the wall temperature quickly drops to the solidification temperature. The temperature is then sustained in a small temperature interval, signifying the PCM is solidifying. After the PCM is solidified, the temperature drops until -5°C at which point the experiment is terminated.

The profile of the best performing metal foam (copper, 40 PPI, porosity of 93.3 %) is compared to the no-foam case. There are three apparent stages in the solidification of the foam sample. Firstly the metal foam and PCM are cooled until the PM wall reaches the solidification temperature. At this moment, solidification has started in between the centre of the cold plate and the PM wall. Due to heat gains from the environment, the experiment deviated from a 2D case and therefore solidification had not started near the corners of the enclosure. Before solidification starts at the PM wall, locations closer to the cold plate will already start solidification. Therefore, the slope of the temperature changes as the temperature drops. The phase change temperature is maintained quite constantly throughout the solidification. Soon after the solidification is completed between the cold and the PM wall, the temperature drops to -5°C . Due to the heat gains from the environment, the sample is not completely frozen at this point.

The profile in the no-foam case is different. Because the effective conductivity is now very low, PCM at the cold wall is already solidifying when PCM at the PM wall is still above 6°C . A solidification front forms gradually growing until it reaches the surrounding of the wall thermocouple. Once most of the PCM in this vicinity is solidified, the temperature quickly drops to -5°C .

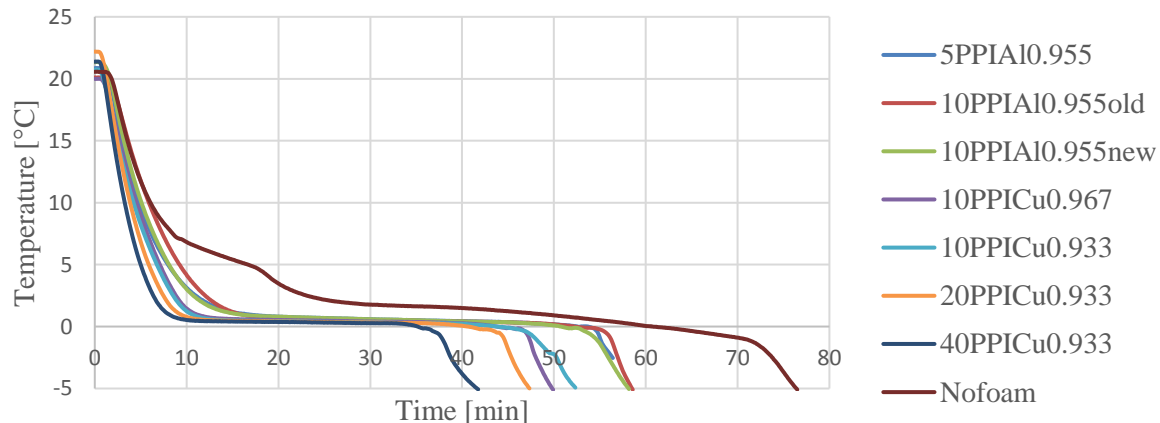


Figure 3. Polymethyl methacrylate wall temperature.

The no-foam case thus shows the temperature profile of a single phase front process. The metal foam cases do not. To qualitatively understand the solidification in the metal foam, two extreme heat transfer mechanisms are considered. In the first mechanism, the metal foam is treated as a fin with fin efficiency 1. The first stage of the phase change is the metal foam cooling down to the cold plate temperature. Once the metal has cooled down below the solidification temperature, the PCM starts to solidify not only on the cold wall, but throughout the rectangular enclosure. Each pore thus has its own melting front: pore front solidification. The resulting temperature profile drops quickly to the phase change temperature and stays within the melting range until solidification is completed. **Figure 4 b** gives a schematic representation of pore front solidification.

The second mechanism is depicted schematically on **Figure 4 a**. The metal foam is close to local thermodynamic equilibrium with the PCM. The phase change front moves along the normal of the cold

wall. The result is a single phase change front as opposed to a phase change front in each individual pore. In this case, the wall temperature would gradually drop as the solidification front gets closer to the PM wall. If the enclosure is modelled using the volume averaging technique [18], the first mechanism corresponds to a two-equation model [26] while the second mechanism to a single-equation one [22, 27]. Both models are applied in literature for metal-foam-PCM combinations. The solidification mechanism in metal foam is thus a combination of both extreme cases with the relative contribution of each mechanism depending on foam and PCM properties. Qualitatively this can be shown from the obtained temperature curves.

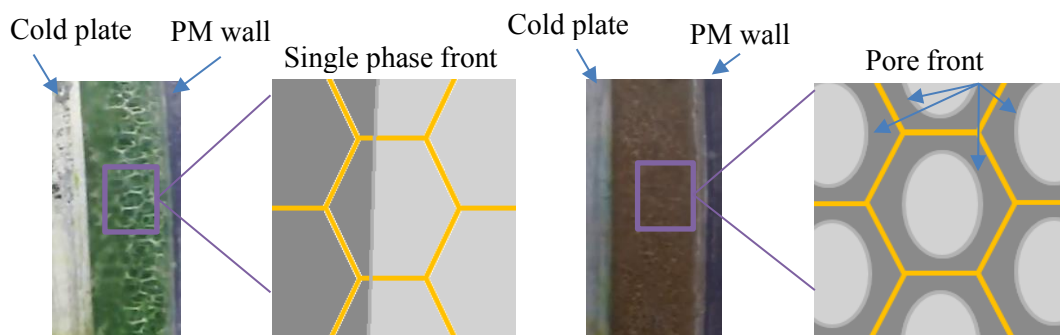


Figure 4. Phase change front mechanisms in metal foam enhanced phase change material; (a) single phase front ; (b) pure phase front.

The temperature curves can be subdivided in three parts: initial drop, solidification, final drop to -5°C . The solidification phase in the absence of foam however exhibits a larger temperature drop. The no foam case is the extreme example of the single phase front solidification mechanism. The lower the temperature drop in the solidification phase, the more uniform the temperature in the PCM-foam composite. A uniform temperature throughout the sample complies to the pore-front solidification.

To compare the different samples, two metrics will be used. Firstly the total solidification time. The shortest solidification time is achieved by the 40 PPI 93.3 % copper foam. It is also closest to pore front solidification since the temperature drop in the solidification stage is the smallest of all tested samples. Comparing the aluminium foam samples with the copper foam samples show a clear influence of metal foam material. The effect of pore density on the total solidification time depends on the foam material. For aluminium foam, the influence of pore density is trumped by that of thermal contact resistance between cold plate and metal foam. For copper foam, pore density has a strong influence, shortening solidification times by 20 %. The porosity seems to have a minor influence for copper foam. Finally, all foam parameters reduce solidification times by at least 25 %. The difference between the best performing foam (40 PPI, 93.3 %, copper foam) and the worst performing foam (10 PPI, 95.5 %, aluminium foam) is however about 28 %.

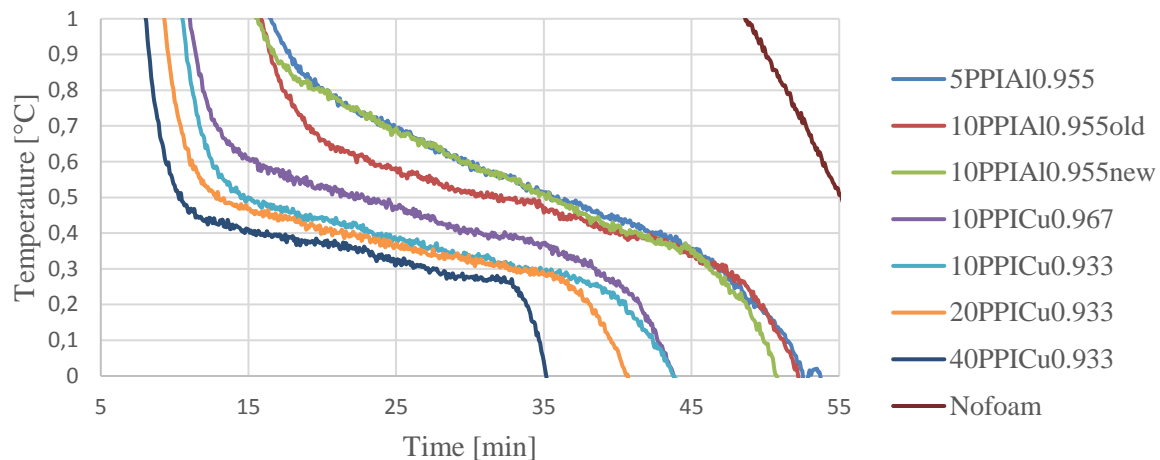


Figure 5. Polymethyl methacrylate wall temperature, detail during PCM solidification.

The slope of the PM wall temperature in the solidification region is a second metric for the metal foam enhanced PCM performance. **Figure 5** shows the temperature profiles of the metal foam enhanced PCM during the solidification phase. Linear regression is performed during the solidification phase. There is a significant difference between the slopes of aluminium-copper foams and between foams of different porosities. The three copper foam samples with a porosity of 93.3% do not have a significantly different slope, nor do the 5PPI and 10 PPI (new) 95.5% aluminium samples. The main effect influencing the balance between pore front and single front solidification are thus material and porosity, not pore density.

4. Conclusion

Phase change materials can provide a safe, reliable solution to maintain temperatures in challenging cold chains. They however have low thermal conductivities, which inhibit fast cooling of the PCM packages. Therefore, metal foam can be inserted in PCM to increase effective thermal conductivity and decrease cooling time. Open cell metal foam is often characterized by material, porosity and pore density. The effect of these characteristics on metal-foam-PCM composites is however still unclear. In the present study, 7 different metal foams are impregnated with PCM and compared to the case without metal foam. Solidification in foam samples goes by two main mechanisms: pore front and single phase front solidification. All samples outperform the sample without foam by at least 25 %. However, the difference between the best- and the worst-performing metal foam inserts is 28 %, signaling a large potential for future research. The presented conclusions in this article are however only qualitative because of significant heat gains from the environment. Future research should include an estimate of heat gains as well as an effort to reduce them. Furthermore, further tests on the effect of metal foam parameters are necessary to determine optimal PCM enhancement methods.

Acknowledgements

This study has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement N° 657466 (INPATH-TES).

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