EXPERIMENTAL ANALYSIS OF THE MELTING PROCESS IN A PCM/ALUMINUM FOAM COMPOSITE MATERIAL IN HYPERGRAVITY CONDITIONS

Sauro Filippeschi,* Mauro Mameli, & Paolo Di Marco

University of Pisa, DESTEC, Largo Lazzarino 2, 56122 Pisa, Italy

*Address all correspondence to: Sauro Filippeschi, University of Pisa, DESTEC, Largo Lazzarino 2, 56122 Pisa, Italy; Tel.: +39 050 221 7153; Fax: +39 050 221 7160, E-mail: sauro.filippeschi@unipi.it

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Phase change materials [(PCMs), e.g., paraffin waxes, fused silica salts, and polyethylene glycol] can be successfully used for thermal management and heat storage in ground and space applications. Open-cell metal foams embedded in the PCM material increase the overall thermal conductivity and accelerate the melting process. The literature shows that the pore size and relative density strongly affect the melting process performance. Most studies have shown that the high thermal conductivity of the open-cell metal foam dominates the melting process. The natural convection effect usually is attenuated; however, it can be relevant if it occurs. An experimental activity has been designed and carried out under the framework of the European Space Agency student program Spin Your Thesis 2017 to analyze the effect of different hypergravity levels and configurations on the melting performance of a composite aluminum foam (10 pores per inch)/paraffin wax material at two different heat fluxes. The gravity level ranges from 5g up to 20g using a large diameter centrifuge facility. The effect of gravity on the melting process has been investigated by measuring the melting time and the dynamic evolution of the melted area. The experiments show that the hypergravity condition accelerates the melting process: it is 12% faster ranging from 5g to 10g. Infrared visualization allowed us to define the melting front dynamic evolution. A natural convection regime was observed in all of the experiments. The natural convection incipience accelerates the melting process. A critical analysis of the scaling criterion in the literature has been qualitatively done and a modified Rayleigh number is proposed to characterize the melting process.

KEY WORDS: phase change material (PCM), modified Rayleigh numbers, metallic foam, hypergravity, natural convection

1. INTRODUCTION

Thermal systems based on phase change materials (PCMs) have been studied for space applications since the early 1970s by the National Aeronautics and Space Administration (Hale et al., 1971), which has again become a hot research topic for ground applications over the last two decades (Gulfram et al., 2019). The development of innovative passive devices for thermal storage applications is one of the most interesting technological targets in industrial fields. PCMs are particularly attractive because they can store a large amount of energy in compact devices (Nazir et al., 2019). PCMs have already been successfully applied to different fields such as thermal management in low-energy buildings (Khudhair and Farid, 2004), lithium batteries (Malik et al., 2016), aerospace (Mulligan et al., 1996), and smart textiles (Mondal, 2008). Since their energy storing rates are often limited by low thermal conductivity (usually lower than 0.4 W/mK), several methods have been proposed in the literature to enhance their global conductivity, which are mostly based on embedding high-conductivity materials within the PCM (Fan and Khadadadi, 2011). Among them, open-cell metal foams are very promising (Zhao and Wu, 2011) because they have good mechanical properties, ultra-low relative density, and a high heat exchange area.

Several different metal foams and PCM materials have been coupled and investigated in the past. Xiao et al. (2013), Mancin et al. (2014), and Baby and Balaji (2013) showed that the heat transfer capability of paraffin/metal
foam composite materials may be from 3 up to 10 times larger than the case without foam. In these studies, all of the tests were carried out with paraffin waxes (at different melting temperatures) embedded in copper foams with different morphologies, tortuosity, pores per inch (PPI), and relative densities. The experiments showed that the melting process is mostly dominated by heat conduction and the high equivalent thermal conductivity of the composite material.

Siahpush et al. (2008) performed an experimental study to evaluate the enhancement of the heat transfer performance of copper porous foam added to cylindrical solid–liquid phase change thermal energy storage systems. The results showed that copper porous foam has a significant effect in enhancing the heat transfer process, despite the attenuation of natural convection in a PCM due to the flow resistance (viscous forces) of the foam.

The melting process has been numerically simulated in several papers. For instance, Liu et al. (2013) and Srivatsa et al. (2014) developed two-dimensional (2D) and three-dimensional (3D) transport models to simulate the paraffin melting process as it is embedded in a metal foam. The 2D and 3D models both showed that the complex metal foam morphologies, low pore radius, and high viscosity of the PCM usually prevent any convection motion. Similar results were obtained by Chen et al. (2014), who developed and applied a mathematical model to a copper foam/paraffin wax composite material and showed that heat conduction is the dominant regime during the melting process.

Despite several works showing that for high PPI and low-density levels, viscous forces often inhibit intercellular natural convection, this effect cannot be neglected a priori. The effect of natural convection can be extremely relevant in the melting process. For instance, Sun et al. (2016) reported that in cubic pure paraffin (200 × 200 × 200 mm) melting at 27°C, natural convection shortened the time required for complete melting by 45%. Lafdi et al. (2007) showed how the presence of convective motion enhanced the heat transfer rate in a composite material heated perpendicularly to the direction of gravity. This effect is emphasized in foams with larger pore dimensions (i.e., smaller PPIs). These studies evidence that in some cases natural convection can promote the mass transfer of the melted paraffin among the foam pores; however, this effect has not been systematically studied in pure paraffin waxes (Sun et al., 2016) in terms of melting time.

### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<td>$C$</td>
<td>parameter, Eq. (3)</td>
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<tr>
<td>$c_p$</td>
<td>specific heat (kJ/kg·K)</td>
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<tr>
<td>$D$</td>
<td>diameter (m)</td>
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<td>$\bar{q}$</td>
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<td>$Ra^*$</td>
<td>modified Rayleigh number (-)</td>
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</tr>
<tr>
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<tr>
<td>$Ste$</td>
<td>Stefan number (-)</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (K)</td>
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</tr>
<tr>
<td>$t$</td>
<td>time (s)</td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>distance from the upper side (m)</td>
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### Greek Symbols

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<td>$\epsilon$</td>
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<td>$\gamma$</td>
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<td>$\lambda$</td>
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<td>$\nu$</td>
<td>cinematic viscosity (m²)</td>
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### Subscripts

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<td>metallic foam</td>
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<td>maximum</td>
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<td>min</td>
<td>minimum</td>
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<td>phase change material</td>
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<tr>
<td>Peltier</td>
<td>Peltier element</td>
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<tr>
<td>tr</td>
<td>transition</td>
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<tr>
<td>w</td>
<td>heating wall</td>
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Cheng (1977) analytically studied the natural convection of a viscous fluid from a vertically oriented flat plate in a porous medium. Starting from the analytical solution found by Cheng (1977), Kazmierczak et al. (1986) studied the melting process from an infinite flat plate embedded in a porous medium, with the aim of analyzing the effect of the natural convection flow in the liquid phase in the melting process. Kazmierczak et al. (1986) assumed that the heat conducted to the melting surface was equal to the heat required in the melting process plus the sensible heat required to raise the temperature of the solid to its melting temperature \( T \). In this case, the transient effects in the solid were neglected. This assumption is valid as long as the melting solid is large compared to its thermal boundary-layer thickness. The second assumption was that a Darcy regime was assumed and the melting front was modeled as a flat surface. Starting from the previous works, Jany and Bejan (1988) developed a scaling criterion for a geometrically limited porous medium heated on one side at a constant temperature, which was enclosed by impermeable and adiabatic walls.

The analysis has been focused only on the liquid domain, in which four different regimes occurring during the melting process can be defined, as shown in Fig. 1: the conduction regime (I), transition regime (II), convection regime (III), and variable height regime (IV). In the conduction regime any natural circulation in the domain occupied by the liquid PCM is neglected and the melting front is parallel to the surface at a temperature higher than the melting temperature. The transition regime start as the flow carves its own convection-dominated zone in the upper part of the liquid region, while the lower part remains ruled by conduction. The natural convection regime begins when the upper convection-dominated zone of the transition regime totally fills the height \( H \). The last regime occurs as the melting front reaches the wall opposite the high-temperature side. These four regimes were also recognized by Al-Jethelah et al. (2018) during the melting of a nano-PCM in an enclosed space.

During the conduction regime the heat transfer solution is the same as in the Stefan problem; therefore:

\[
S (Fo) = 2C \sqrt{Fo} \tag{1}
\]

and

\[
Nu = \frac{1}{\pi^{1/2} \text{erf} (C)} \sqrt{Fo} \tag{2}
\]

where \( S \) is the ratio between the distance from the melting front and total height \( H \), and \( C \) is the solution to the following equation:

\[
\frac{C \cdot \text{erf} (C)}{e^{-c^2}} = \frac{\text{Ste}}{\pi^{1/2}} \tag{3}
\]

where \( \text{Ste} \) and \( \text{Fo} \) are the Stefan and Fourier numbers, respectively, which are expressed by the following equations:

\[
\text{Ste} = \frac{c_P (T_w - T_m)}{h_{\text{PCM}}} \tag{4}
\]

\[
\text{Fo} = \frac{\alpha t}{H^2} \tag{5}
\]

**FIG. 1:** Four regimes of the dynamic melting process: (I) conduction regime; (II) transition regime; (III) natural convection regime; (IV) variable height regime (adapted from Jany and Bejan, 1988)
The melting front breaks down its parallel shape as the natural convection becomes relevant in the upper part as Rayleigh number $Ra'$ increases:

$$Ra' = Ra \times Da = \frac{g \beta H^3 (T_w - T_m)}{\nu \alpha} \times \frac{K}{H^2} = \frac{g \beta KH (T_w - T_m)}{\nu \alpha}$$  \hspace{5cm} (6)

According to Jany and Bejan (1988), in the transition regime the convection-dominated zone is in the upper part, while the rest of the melting front remains still parallel to the heating surface. As shown in Fig. 1, $z_t$ is the transition distance from the zone dominated by natural convection, which according to Jany and Bejan (1988) is given by

$$z_t \sim H \cdot Ra' \cdot St \cdot Fo$$  \hspace{5cm} (7)

It is worth noting that the transition regime ends as $z_t$ becomes the same order of $H$; therefore

$$St \cdot Fo \sim Ra'^{1/2}$$  \hspace{5cm} (8)

Jany and Bejan (1988) showed that in this regime the Nusselt number can be given by the following relation:

$$Nu \sim (St \cdot Fo)^{-1/2} + Ra' \cdot (St \cdot Fo)^{1/2}$$  \hspace{5cm} (9)

It is worth noting that the minimum of the Nusselt number has its minimum value at $St \cdot Fo \sim Ra'^{1/2}$ as the natural convection begins to affect the phenomenon. Jany and Bejan (1988) numerically solved Eq. (9) for several $Ra'$ numbers in a square cavity. They found that at $Ra'$ numbers lower than 50, the Nusselt number is approximately equal to $Ra' = 0$ (pure conduction). For $Ra'$ numbers ranging from 50 to 200, the Nusselt function does not show any minimum value. This means that the melting front breaks down the linear shape typically found in the conduction regime (I) (Fig. 1) but remains in the transition regime (II) (Fig. 1). No natural convection regime occurs and the distance from the zone dominated by natural convection ($z_t$) does not reach the same order of $H$. The transition regime (II) (Fig. 1) dominates the melting phenomenon in this enclosure. In conclusion, to have a natural convection regime totally developed according to the Jany–Bejan scaling criterion, a $Ra'$ number higher than 200 must be reached.

Siahpush et al. (2008) applied this approach to a finite cylinder, solving the differential equation in cylindrical coordinates. They compared the scaling model predictions to the experimentally measured radius of fusion values and the results were within 10% of the data measurements in the worst case. The composite material was eicosane and copper foam (98% porosity). The Jany and Bejan (1988) scaling criterion for a square cavity has not yet been experimentally validated.

The present paper deals with the experimental study of an aluminum foam/paraffin wax at different gravity levels. Studying the thermal behavior of a composite material at different gravity levels can, in fact, help to better analyze how natural convection affects the melting process and provide useful data for many different fields of applications (aerospace, automotive, chemical, and biological) where non-standard gravity conditions (apparent gravity vector orientation and level) can dynamically change during normal operations. To date, there are only a few numerical works in the literature that have studied natural convection in PCM composites under non-standard gravity conditions (Asako and Faghri, 1999; Asako et al., 2002; Di Giorgio et al., 2017); however, the studies conducted in these papers were relative to a microgravity environment, where natural convection is essentially absent.

In the literature, no experiments have been conducted to investigate the melting process in a porous material under hypergravity conditions. To fill this lack in the scientific literature, an experimental activity has been designed and carried out under the framework of the European Space Agency (ESA) student program Spin Your Thesis 2017. The main goal of this work is to analyze the effect of different hypergravity levels and configurations on the melting performance of a composite aluminum foam/paraffin wax material at two different heat fluxes. The gravity level ranges from $5g$ up to $20g$ in the large diameter centrifuge (LDC) sites at the ESA European Space Research and Technology Centre (ESTEC) in Noordwijk, Netherlands (Van Loon et al., 2008). The composite material consists of a paraffin wax and aluminum foam (10 PPI). The effect of gravity on the melting process was investigated by measuring the melting time and the dynamic evolution of the melted area. A critical analysis of the scaling criterion in the literature has been qualitatively attempted.
2. EXPERIMENTAL SETUP AND PROCEDURE

The composite material consisted of aluminum foam (50 × 50 × 50 ± 0.5 mm cube, relative density 11.6% and 10 PPI by ERG®) and commercial paraffin wax (Ph EUR, BP, NF CAS 8002-74-2) with a solidification point in the range between 56°C and 58°C. The investigated configurations were the vertical hot surface, where the heat flux direction is perpendicular to the apparent gravity vector direction, and the hot surface down, where the heat flux is parallel to the apparent gravity vector in opposite directions.

2.1 Test Cell and Peripheral Facilities

The experimental rig (Fig. 2) was composed of the composite material and containing box, heating/cooling system, infrared (IR) and grayscale cameras, and an electronic control. The heating/cooling system consisted of a Peltier module (Adaptiva®, ETH-127-14-11-S, 40 × 40 × 5 mm) connected using a highly conductive thermal paste to an aluminum plate on one side, where the foam was brazed, and on the other side to an active cooling system (CoolerMaster®, Masterliquid Pro 280).

The maximum electrical power supplied to the Peltier cell in the heating mode was 80 W. The aluminum foam was soaked with liquid paraffin wax (filling ratio 95%–97% of the free volume) and located in a Lexan box, which provided thermal insulation from the environment and allowed visualization of the melting and solidification process with a grayscale complementary metal–oxide–semiconductor (CMOS) camera (Ximea® XiQ M2042CG-CM, 2048 × 2048 pixel, 12-bit RGB). The gap between the foam and the polycarbonate wall was lower than 0.5 mm. The other side of the cubic box was equipped with a zinc selenide (ZnSe) window that allowed recording the evolution of the temperatures and melting/solidification front by a low-wave IR camera (FLIR® A65). The aluminum foam surface facing the IR window as well as the temperature sensors visible by the IR camera were painted black (emissivity > 0.95) to increase their emissivity and avoid reflection issues. An external aluminum box contained the polycarbonate box, which was designed to withstand the LDC accelerations and internal pressures originating from the melting of the paraffin wax. A neoprene gasket was used to thermally insulate the aluminum plate from the Lexan box and avoid any paraffin leakage.

The main control unit (MCU), power control unit (PCU) of the Peltier cell, and data acquisition unit (DAU) allowed monitoring the state of the experimental box and peripherals, driving the power supplied to the heater/cooler, and logging the data from the sensors and cameras, respectively, as schematically shown in Fig. 3. The MCU was a PC equipped with serial interfaces, running LabVIEW® 2017. It was connected via USB to the PCU (TEC-1090 by Meerstetter Eng.®), the DAU (Arduino® Due, 32-bit ARM Cortex-M3), and the IR and the CMOS cameras, operating at 1 Hz. The PCU was designed to drive the electric power to a Peltier module since it featured a true bipolar direct current source for cooling or heating. The DAU acquired five temperatures and two heat flux sensors (gSKIN-XM 26 9C by greenTEG®, maximum error ± 0.1 W/cm²). For the temperature measurements, 4-wire platinum resistance Pt-100 sensors were coupled to a MAX31865® RTD-to-Digital Converter (the total maximum error of the temperature

FIG. 2: Experiment schematic representation: (a) the whole test rig; (b) the test cell
measurements was ± 0.2 K): three were located inside the experiment box on the upper side of the composite, in which one was visible by the IR camera (Fig. 2); one was positioned on the target face of the Peltier module; and one acquired the ambient temperature.

To extract the temperature map of the composite material from the thermograms during the experiment, a calibration process was performed in order to evaluate the influence of the ZnSe window and the environment. For every IR frame, the area around the Pt-100 sensor located in the upper part of the IR window was averaged and the resulting mean temperature was used as the calibration reference. The calibration process results are summarized and shown in Fig. 4: the maximum error after calibration was ± 0.8°C. The raw data from the IR camera and Pt-100 sensors were compared in the calibration experiment, the resulting linear regression was computed, and the calibration results of two independent data sets were compared (Fig. 4).

2.2 Experimental Matrix and Procedures

The set of experiments described in the present work took place during a 5-day campaign (September 11–15, 2017) using the LDC facilities at ESA (Van Loon et al., 2008). Table 1 gives a summary of the nine experimental runs and the variable parameters (i.e., heat fluxes, gravity level, and gravity direction with respect to the heat flux). In particular,
Table 1 gives the results for two different heat fluxes: the heat flux directly measured by the heat flux sensors on the Peltier element \(q_{\text{Peltier}}\) and the heat flux at the surface in touch with the PCM material \(q_{\text{PCM}}\), which are linked by the following relation:

\[ q_{\text{PCM}} = q_{\text{Peltier}} \frac{S_{\text{Peltier}}}{S_{\text{PCM}}} \]  

where \(S_{\text{Peltier}}\) and \(S_{\text{PCM}}\) are the surfaces of the Peltier element (40 × 40 mm) and the heating surface in touch with the composite material (50 × 50 mm), respectively. In fact, the conductivity and thickness of the aluminum plate are sufficient to distribute the heat flux uniformly to the PCM surface, as previously verified by finite-element analysis.

Each experiment was carried out using the following procedure: (1) the experimental rig was arranged in either a horizontal configuration (H, hot surface down; \(g\) vector parallel and opposite to the supplied heat) or vertical configuration (V; \(g\) vector perpendicular to the heat flux vector) and then placed inside the LDC; and (2) the LDC was secured and the target gravity profile was set. As the LDC reached the requested gravity level, the test cell was heated at constant heat flux until the paraffin wax melted completely. During this period, the temperature and the heat flux signals, as well as the grayscale and IR images, were recorded.

Finally, the Peltier module electric supply was inverted to cool down the test cell in order to solidify the paraffin as fast as possible and start another experiment. The acquisition lasted for the duration of the entire experiment. Depending on the experimental conditions, the duration of each test ranged from 40 to 60 minutes.

### 2.3 Melted Area Detection

All of the IR and grayscale images were filtered and edited in order to extract the following information: the PCM melting volume evolution, the melting front evolution, and the transient temperature map of the face of the paraffin wax/aluminum foam cubic material. The melting front was evaluated differently in the grayscale and IR images. Figure 5 compares the melting front detection in the grayscale and IR images after 900 s, proving that the heat transfer process is symmetrical with respect to the two faces. A negligible error was measured, as is qualitatively shown in Fig. 5(c).

Next, we describe the procedure to calculate the melting front shape over time. From the preliminary analysis, it was noted that both cameras were able to capture the liquid zone with its melting front. In the grayscale images the liquid paraffin was transparent, while the solid phase was opaque. The aluminum foam added one-third brighter tone, which made automatic analysis of the melting front too complex. For this reason, no automatic procedure could be defined to elaborate all of the grayscale images and the analysis was done using only the IR images.

It is well known in the literature that a PCM melts in the transition temperature range (Wang et al., 2016a), even if the melting process of the PCMs is theoretically considered to be isothermal or nearly isothermal. PCMs with a narrow

### TABLE 1: Experimental matrix resume

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<tr>
<th>Experiment Run Number</th>
<th>Heat Flux (W/cm²)</th>
<th>(g) Level (× 9815 m/s²)</th>
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<td></td>
<td>(q_{\text{Peltier}})</td>
<td>(q_{\text{PCM}})</td>
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<tr>
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<tr>
<td>9</td>
<td>3</td>
<td>1.9</td>
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†V = vertical, H = horizontal, hot surface down.
melting temperature range have better thermal performance. Usually, the melting range is conventionally measured by a dynamic calorimeter (Wang et al., 2016b). In this study, the transition temperature range was experimentally measured from the analysis of the PCM temperature evolution over time during the solidification process. Since the solidification process is slower than the melting process, the former was used to evaluate the melting temperature range calculation. A typical temperature trend of paraffin wax solidification is shown in Fig. 6, where the temperature of the liquid material shows two changes in slope as it passes from the liquid to the solid state. The temperature slope variation occurs in a narrow temperature range (57°C–56.25°C), which was considered to be the actual temperature transition range (rather than the broader one indicated in the paraffin data sheet). This procedure was repeated at different heat fluxes, metal foam porosities, and PPIs, and good repeatability was observed. The melting temperature range was approximately 1°C around an average temperature of 56.5°C ± 0.5°C. This definition of the temperature range allows the melting front thickness to be detected and the melting profile position to be located at different times. Unfortunately, the melting front location can be affected by some relevant local temperature uncertainties close to the boundaries of the sample. For this reason, a smoothing procedure was applied to the melting profile by using second-order polynomial interpolation. After the melting front was calculated each time, the melted area was easily assessed as the area between the front and heating surfaces. An example of the melting area measurement over time, together with the measurement uncertainties, is shown in Fig. 7. Figure 7 shows that the uncertainties in the melted area assessment are lower than 7%. The maximum error is relative to the end of the melting process, where the paraffin wax is almost completely melted (25 × 10^{-4} m^2). The maximum error is lower than 3% since the melted area is lower than 20 × 10^{-4} m^2.
3. RESULTS AND DISCUSSION

3.1 Effect of the Gravity Level on the Melting Performance

It was expected that since natural convection is directly related to the acceleration magnitude higher gravity levels would induce a faster paraffin melting process. The time required to melt all of the paraffin wax was measured in each experiment at the same heat flux and configuration. The diagrams in Figs. 8–11 show the evolution over time of the composite material temperature at three different locations (Fig. 3). Note that the starting time of the melting process (dashed line) detected by IR analysis is not simultaneous with the time at which the temperature probe (Temperature 1) enters the melting transition range (the semitransparent band). In fact, the onset of melting usually occurs at the middle of the heating surface, while the temperature probe (Temperature 1) is located on the side of the heating surface. At this time, the temperature detected by the probe (Temperature 1) could be out of the melting range, as shown in Fig. 12. The melting process ends as the third Pt-100 sensor (Temperature 3) exceeds the melting range. The secondary y-axis on the right-hand side of the plots shows the heat flux directly measured on the Peltier heating element on the PCM side.

Experiments 3 and 6 were conducted with the same heat flux ($1.5 \times 10^{-4}$ W/m$^2$) and different gravity levels ($5g$–$10g$). Experiment 4 was conducted at a heat flux of $1.9 \times 10^{-4}$ W/m$^2$ and two different gravity levels. Experiment 7
FIG. 9: Experiment 6 (2.5 W/cm², 10g), horizontal orientation; evolution of the composite material over time and melting starting time (dashed line)

FIG. 10: Experiment 4 (3 W/cm², 5g), horizontal orientation; evolution of the composite material over time and melting starting time (dashed line)

FIG. 11: Experiment 7 (3 W/cm², 10g), horizontal orientation; evolution of the composite material over time and melting starting time (dashed line)
PCM/Composite Melting Process in Hypergravity Conditions

was conducted at a heat flux of $1.9 \times 10^{-4}$ W/m$^2$ and the same gravity levels. All of the figures show that the gravity and the heat flux affect the duration of the melting process and do not affect the maximum temperature at the heating surface (Temperature 1), which is always lower than 65°C and is only raised negligibly even when all of the paraffin close to the surface is melted and the heating surface is wetted by the liquid. The duration of the melting process and the onset of the natural convection regime strongly affect the dynamic evolution of the melting process in terms of melted area versus time, as shown in Figs. 13 and 14 at two different heat fluxes supplied to the PCM, 1.5 and $1.9 \times 10^{-4}$ W/m$^2$, respectively. To better understand these plots, it is useful to remember that the total melting area was 25 cm$^2$.

The conduction regime lasted for 1050 s (dotted line in Fig. 13) when the melting front was located at 17 mm from the heating surface. As illustrated in Fig. 13, the test at the higher gravity level (the red curve) shows a higher

FIG. 12: Melting front evolution at different times and corresponding Rayleigh numbers: (a) Experiment 1 (1.5 W/cm$^2$, 5g); (b) Experiment 2 (1.5 W/cm$^2$, 10g)

FIG. 13: Melted area measured in Experiments 3 and 6
melted area with respect to the case at lower gravity acceleration (the blue line). At $t = 1700$ s after the melting starting time the total melted areas are $21.20$ and $24.03 \times 10^{-4}$ W/m$^2$, respectively, for the two gravity level cases. The total duration of the melting process is 12.3% lower in the case of $10g$. This is related to the earlier instauration of the convective flow motions, which improve the heat transfer.

Figure 14 shows the melted area temporal evolution in the paraffin wax/aluminum foam material at the heat flux of $1.9 \times 10^{-4}$ W/m$^2$ for three different gravity levels: $5g$, $10g$, and $20g$. The duration of the heat conduction regime is negligible, and the increase in the gravity level accelerates the melting process immediately after the melting process begins. As the gravity level increases, the melting process is faster: 800 s after the melting starting time the ratios between the melted area and the total area are 52%, 61%, and 79% for $5g$, $10g$, and $20g$, respectively. The comparison of the evolution of the melted area shows that the gravity can amplify the role of the heat flux in the melting mechanisms. At low heat flux, the gravity begins to improve the melting performance at 1000 s after the melting process is started. Indeed, at high heat flux, gravity accelerates the melting and affects the phenomenon after only 200 s. Figures 13 and 14 show that the effect of the heat flux is relevant from $1.5$ to $1.9 \times 10^{-4}$ W/m$^2$. For instance, after $t = 800$ s the melted area is 2 times larger at $5g$, 2.3 times larger at $10g$, and 3 times larger at $20g$. This is due to the incipience of natural convection as described in the following section.

3.2 Critical Scale Analysis

In order to better understand the role of natural convection, the IR images were analyzed under different conditions because the visualization of the melting front shapes supported the detection of the incipience of natural convection. The relevant role played by natural convection in the melting process of porous material must be linked to the different parameters of the metal foam.

In order to understand if the Jany–Bejan scaling criterion can be applied to predict the incipience of natural convection, $Ra'$ numbers were calculated in Experiments 1 and 2 (vertical orientation) at different Ste–Fo numbers. The analysis was limited to the vertical orientation according to the Jany–Bejan approach.

The main difference between the Jany–Bejan theory and the present experiments deals with the boundary condition: the Jany and Bejan (1988) theory was limited to a heating surface kept at a constant temperature. Instead, the present experiments were conducted at constant heat flux. Despite the different boundary conditions, Figs. 8–11 show that the temperature of the heating surface (Temperature 1) shows small variations during the melting process. In this way, the assumption of constant temperature can be considered almost verified and the $Ra'$ numbers experimentally determined can be indicative of the evolution of the process.

The modified $Ra'$ number given by Eq. (6) is, therefore, calculated using Temperature 1 as the temperature of the wall and 56.5°C as the melting temperature. The effective thermal conductivity of the composite material was
calculated using the Wang et al. (2016) correlation, here reported as
\[
\lambda_e = \sqrt{\lambda_{\text{max}}^2 \cos^2 \gamma + \lambda_{\text{min}}^2 \sin^2 \gamma}
\] (11)
where angle \( \gamma \) depends on the tortuosity and is calculated by the following equation:
\[
\tan^2 \gamma = \frac{16 (1 - \varepsilon)}{\varepsilon^2 \ln \left( \frac{\lambda_{\text{foam}}/\lambda_{\text{PCM}}}{1 - \varepsilon} \right)}
\] (12)

The effective thermal conductivity of Eq. (11) is based on the assessment of the minimum and maximum conductivity given by
\[
\lambda_{\text{min}} = \frac{\lambda_{\text{foam}} \lambda_{\text{PCM}}}{\lambda_{\text{PCM}} (1 - \varepsilon) + \lambda_{\text{foam}} \varepsilon}
\] (13)
\[
\lambda_{\text{max}} = \lambda_{\text{foam}} (1 - \varepsilon) + \lambda_{\text{PCM}} \varepsilon
\] (14)

Equation (11) was verified with the experimental data by measuring the heat flux and temperature gradient along the X direction in the composite material. The temperature gradient at the wall was estimated using the temperature profiles measured with the IR camera during the heat conduction period, when no melting phenomenon had started. During the heat conduction regime, the profile was assumed to be linear and a least-squares method was used with the temperature of the first 100 pixels close to the heating surface taken along a line perpendicular to the surface located at the centerline of the square. The effective thermal conductivity calculated with Eq. (6) was compared with the thermal conductivity given by the following relation:
\[
\lambda_{\text{exp}} = \frac{q_{\text{PCM}}}{(\Delta T/\Delta x)_{x=0}}
\] (15)

The relative error in the effective heat flux evaluated with Eq. (6) was ±2.5%. The paraffin wax viscosity was also measured within the temperature range of 58°C–83°C through a concentric cylindrical rheometer. All of the properties of the composite material are reported in Table 2.

The experimental Ra’ numbers have been, therefore, used to better understand the melting process of a vertically orientated heated plate in a hypergravity environment. Figure 12 shows the melting front at different Ra’ numbers calculated from Experiments 1 and 2. The visualization of the evolution of the melting process and the analysis of the melting front shape confirm that all four regimes described by Jany and Bejan (1988) can be observed in this composite material. When the wall temperature reaches the paraffin melting transition range, the solid paraffin close to heating surface starts to melt and the linear melting front is fairly parallel to the heating surface. Figure 12 shows the melting front after 240 s at 5g and 10g. In both cases, the indicative Ra’ number is approximately 50, a value corresponding to a conduction regime according to Jany and Bejan (1988). Thus, in reference to Experiment 1 (5g), the transition regime at 5g is evident from the IR image because the linearity in the breakdown of melting front appears only in the upper part of the sample. After 600 s, the natural convection is totally developed in both the experimental and the transitional regime and is extinguished according to the Jany and Bejan (1988) phenomenological description.

Figure 15 shows the temperature map and melting front at approximately the same time for three different experiments in the case of the horizontal configuration. In particular, Experiments 3 and 5 show the results for the same time \( t = 960 \) s after the onset of melting at the 5g and 10g levels, respectively. The results for Experiment 8 refer to a higher gravity level (20g) and higher heat flux, and the data are shown at an earlier time \( t = 600 \) s. Figure 15 shows that as the gravity level increase the dynamic evolution of the melting front is faster. The shape of the melting

<table>
<thead>
<tr>
<th>( B_{\text{PCM}} ) (K(^{-1}))</th>
<th>( \lambda_e ) (W/mK)</th>
<th>( \rho_{\text{PCM}} ) (kg/m(^3))</th>
<th>( c_{p,\text{PCM}} ) (J/kg K)</th>
<th>( \gamma_{\text{PCM}} ) (m(^2)/s)</th>
<th>( K ) (m(^2))</th>
<th>( D_{\text{foam-cell}} ) (m)</th>
<th>( g ) (m/s(^2))</th>
<th>( T_m ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.78 \times 10^{-4}</td>
<td>26.5</td>
<td>850</td>
<td>2490</td>
<td>4.9 \times 10^{-6}</td>
<td>2.24 \times 10^{-7}</td>
<td>0.0022</td>
<td>49.07, 98.15</td>
<td>56.5</td>
</tr>
</tbody>
</table>

TABLE 2: Parameters used for the Darcy–Rayleigh number calculation

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FIG. 15: Melting front evolution in the case of horizontal orientation: (a) Experiment 3 (5g, $1.5 \times 10^{-4}$ W/cm$^2$); (b) Experiment 6 (10g, $1.5 \times 10^{-4}$ W/m$^2$·K); (c) Experiment 8 (20g, $1.9 \times 10^{-4}$ W/cm$^2$)

The melting front is different from the theoretically expected melting front shape, which should be almost linear or present a wavy front. However, it is not easy to detect the incipience of natural convection for the horizontal orientation.

By limiting the qualitative analysis to the vertical orientation, it is possible to conclude that the scaling criterion proposed by Jany and Bejan (1988) is able to qualitatively define all of the melting regimes. It is important to note that at similar Ra$'$ numbers the melting front shapes are even quite similar (Fig. 12). When the Ra$'$ number is higher than 50, the natural convection regime is experimentally observed; however, from the scaling criterion (Jany and Bejan, 1988) this was expected to be above 200. This discrepancy is probably due to the different boundary conditions; therefore, the results cannot be used to quantitatively predict the onset of the natural convection regime in the case of a vertically oriented flat plate heated by a constant heat flux.

The experimental results show that the gravity and heat flux affect the melting process by shortening the melting duration. The Ra$'$ number from Eq. (6) is not influenced by the heat flux and depends only on the temperature of the heating wall. The experiments show that the heat flux does not affect the temperature of the wall. Therefore, the Ra$'$ number from Eq. (6) cannot properly predict the melting process because it cannot take into account the heat flux effect or explain why the variations in the onset of natural convection decrease as the heat flux increases. The different boundary conditions between the theory and experiments are probably the cause for this difference, and could be further investigated by introducing another version of the modified Ra$^*$ number:

$$
Ra^* = \frac{g \beta K \bar{q} H^2}{\nu \alpha \lambda_e}
$$

where $\bar{q}$ is the heat flux imposed at the heating surface. This modified number was proposed by Cheng (1977) for the natural convection heat transfer in porous media with a constant heat flux boundary condition on the vertical heating plate. The modified Ra$^*$ number was calculated for each experiment conducted in the horizontal mode and the results are reported in Table 3. The Ra$^*$ number linearly increases with the gravity level and heat flux, even if the difference between the heating surface and melting temperature is almost constant.

Table 3 reports the results of the Ra$^*$ numbers and the time when the melted area is at 50% of total melting. Table 3 shows that the Ra$^*$ number is capable of detecting the performance of the melting process because as it

<table>
<thead>
<tr>
<th>Experiment Run Number</th>
<th>Heat Flux (W/cm$^2$)</th>
<th>$g$ ($\times 9815$ m/s$^2$)</th>
<th>$t_{50%}$ (s)</th>
<th>Ra$^*$(-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.5</td>
<td>5</td>
<td>1412</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>1.9</td>
<td>5</td>
<td>800</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>10</td>
<td>1200</td>
<td>130</td>
</tr>
<tr>
<td>7</td>
<td>1.9</td>
<td>10</td>
<td>750</td>
<td>158</td>
</tr>
<tr>
<td>8</td>
<td>1.9</td>
<td>20</td>
<td>600</td>
<td>316</td>
</tr>
</tbody>
</table>
increases the melting process becomes faster. The only discrepancy is given by the $Ra^*$ number in Experiment 6, which presents a melting time higher than Experiment 4 even when the $Ra^*$ number is lower. The $Ra^*$ number seems to match the melting phenomena better than the Rayleigh number given by Eq. (6); however, this small data set is not sufficient to develop a correlation for predicting the onset of natural convection and to perform a scaling criterion.

These experiments were conducted at $Ra^*$ numbers higher than those used in most of experiments presented in the literature, where the low gravity and heat flux yield values of the $Ra^*$ number were lower than 50. Indeed, there is evidence in the literature that natural convection may occur at low heat fluxes when the test cell dimension increases (Sun et al., 2016), and complementarily natural convection may occur for small cells at high heat fluxes (Laffii et al., 2007). At low $Ra^*$ numbers the natural convection is attenuated. A further experimental investigation at $Ra^*$ numbers ranging from 50 to 300 must be carried out in order to assess a scaling criterion that will predict the incipience of natural convection and the melting time duration.

4. CONCLUSIONS

An aluminum foam/paraffin wax composite was experimentally investigated under hypergravity conditions on the LDC at ESA-ESTEC. The composite material consisted of aluminum foam (88% density and 10 PPI) and paraffin wax melting at 56.5°C. The temporal trends of the temperatures in different locations and the melting front evolution recorded by cameras in IR and visible ranges showed that the composite thermal behavior is strongly influenced by the variation of the gravity field.

The experiments showed that the hypergravity condition accelerates the melting process: it is 12% faster ranging from $5g$ to $10g$ at a heat flux of $1.5 \, \text{W/cm}^2$. At low heat flux, the gravity difference enhances the melting performance 1000 s after the melting process is started. Before this time, conduction dominates the heat transfer in the melted region. Indeed, at high heat flux, the gravity accelerates the melting process and influences the phenomenon after only 200 s. The effect of the heat flux is relevant passing from 1.5 to $1.9 \times 10^{-4} \, \text{W/m}^2$. For instance, at low heat flux the melted area after $t = 800 \, \text{s}$ was $6 \, \text{cm}^2$ at both gravity levels; in the case of high heat flux the melted area was 2 times larger at $5g$, 2.3 times larger at $10g$, and 3 times larger at $20g$ for the same time period. This is due to the incipience of natural convection, as observed in the IR image visualizations. Indeed, the IR visualization allowed the definition of the melting front dynamic evolution. Based on the melting front evolution, the incipience of natural convection was detected in all of the cases, and a critical analysis of the scaling criterion proposed by Jany and Bejan (1988) for the melting process of porous media in an enclosure was presented.

By limiting the qualitative analysis to the vertical orientation, it is possible to conclude that the scaling criterion proposed by Jany and Bejan (1988) is able to qualitatively define all of the melting regimes, and as the melting process evolves over time the $Ra^*$ number increases. At similar Rayleigh numbers the melting front shapes are even quite similar. Since the Rayleigh number was higher than 50 the natural convection regime was experimentally observed; however, from the theory this was expected to be above 200. The effect of a different modified Rayleigh number based on the heat flux supplied to the PCM at the heating surface was taken into account. This modified Rayleigh number seems to match the melting phenomena better than the Rayleigh number proposed by Jany and Bejan (1988); however, this small data set is not sufficient to develop a correlation for predicting the onset of natural convection and to perform a scaling criterion. Further experimental investigations at modified Rayleigh numbers ranging from 50 to 300 must be done in order to perform a scaling criterion to predict the incipience of natural convection.

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