27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COBEM2023-0740
INFLUENCE OF METAL FOAM ON THE BIO-BASED PCM MELTING PERFORMANCE

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Abstract. *Due to the constant climate changes seen in recent decades and the constant increase in CO_2 emissions, an energy transition must occur through clean energy sources. However, most of these sources are seasonal, which makes it important to store them for later use. Latent thermal energy storage is the most attractive alternative because a large quantity of thermal energy is stored in a small volume. These materials are known as Phase Change Materials (PCMs), and bio-based PCMs can combine high-energy storage with less environmental impact. PCMs have low thermal conductivity, which may restrict their use in some applications. For this reason, it is necessary to use some method to intensify the heat transfer, in which metallic foam is an alternative due to its high surface area. This work aims to experimentally analyze the melting process of palm wax as bio-based PCM encapsulated in a rectangular structure and the influence of inserting a Nickel foam in the thermal process. Different heat fluxes are imposed on the system, which has a constant PCM mass for the different configurations, with and without metallic foam. The results indicate a reduction in total melting time with increased input power. There is an improvement in heat transfer for the configuration of bio-based PCM with metal foam, with a more significant reduction in the total melting time compared to the bio-based PCM configuration without metal foam. Furthermore, increased heat conduction, natural convection reduction, and greater melting fractions were observed with metal foam.*

Keywords: *Phase Change Material (PCM), bioPCM, Metal Foam, Melting process*

1. INTRODUCTION

As the world strives to reduce its reliance on fossil fuels and transition towards renewable energy sources, efficient and cost-effective energy storage systems have emerged as a critical component of sustainable energy infrastructure. One such technology that has gained significant attention is latent thermal heat storage (Mitali et al., 2022).

Latent thermal heat storage offers a promising approach to storing and releasing large amounts of thermal energy, enabling efficient energy management and utilization. Unlike conventional sensible heat storage systems, which rely on the temperature difference between the stored material and its surroundings, latent thermal heat storage utilizes the latent heat of phase change materials (PCMs). This unique property allows for high energy density storage and enhanced energy transfer efficiency, making it an attractive option for various sustainable energy applications (Mehari et al., 2020).

The manufacturing, agriculture, and transportation sectors rely heavily on thermal energy for heating, cooling, and power generation. By incorporating latent thermal heat storage systems into these processes, waste heat can be captured and stored for later use, reducing energy consumption and greenhouse gas emissions. By carefully selecting PCMs with suitable phase change temperatures, it is possible to store thermal energy within a specific temperature range and release it when needed (Ismail et al., 2022). The PCMs can vary depending on their composition (Li et al., 2022a) and can be classified as organic PCMs, such as paraffin or fatty acids; inorganic PCMs, including salt hydrates; eutectic mixtures, which are combinations of two or more substances that melt and solidify at a lower temperature; and, bio-based PCMs derived from renewable biomass sources, such as vegetable oils, fatty acids, or carbohydrates. PCMs generally have high latent heat capacity, low thermal conductivity (Rostami et al., 2020) and small volumetric change between solid and liquid phases (Lone and Jilte, 2021).

The increasing demand for sustainable and environmentally friendly solutions has increased interest in bio-based PCMs (Nazari et al., 2020), as they are materials derived from renewable and natural resources. However, due to their low thermal conductivity, it is crucial to use methodologies that can improve thermal transfer.

In order to overcome this challenge, different alternatives for improving thermal transfer can be used, such as incorporating high thermal conductivity fillers into the PCM matrix (Zhu et al., 2022). These fillers, such as metal fins (Lawag and Ali, 2022), nanoparticle dispersion and metallic foam, can significantly enhance the overall thermal conductivity of the composite material. However, some problems can arise from nanoparticle dispersion; for example, agglomeration and sedimentation in high concentrations may affect thermal uniformity (Dhaidan et al., 2022).

Metal foams have gained attention as effective thermal conductivity enhancers for PCMs (Aramesh and Shabani, 2022; Tang et al., 2023; Hu et al., 2023). Its high surface area, responsible for increasing the contact area between the fluid and its surface (Shi et al., 2023), and the open-cell structure of metal foams allow for high thermal conductivity by facilitating heat flow through the interconnected metallic network. When infused with PCMs, metal foams create a composite material with improved thermal conductivity. Moreover, metal foams offer advantages such as lightweight construction, high porosity, and compatibility with various PCMs.

Li et al. (2022b) compared the use of metal foam in a thermal storage system to fins. In this study, the authors used different numbers of fins and foams with different pore densities, maintaining the volume of the system constant. Metal foams improved the system's performance, besides increased heat conduction and decreased natural convection.

Ejaz et al. (2022) experimentally studied the use of metal foams in a photovoltaic panel to improve the panel's efficiency by reducing the operating temperature. They used two thicknesses of foam, comparing the results with a reference panel (without metal foam). The results showed an increase in electrical power due to the incorporation of the foams and an increase in conversion efficiency through thicker foam.

Utilizing metal foams with bio-based PCMs offers a sustainable and efficient pathway for enhancing heat transfer capabilities, enabling more effective thermal energy storage and management. Therefore, the current work focuses on the experimental analysis of the melting process of palm wax, a bio-based PCM encapsulated in a rectangular structure. The aim is to investigate the influence of inserting a Nickel foam in the thermal process. The experimental setup allows for examining the melting behavior and thermal performance of the PCM in different conditions. The findings of this study contribute to the design and optimization of PCM-based energy storage systems for applications such as thermal energy management and storage in renewable energy systems.

2. METHODOLOGY

Figure 1 shows the schematic representation of the experiment setup, which consists of a rectangular reservoir, a power supply, a power quality analyzer, a video camera and a portable computer.

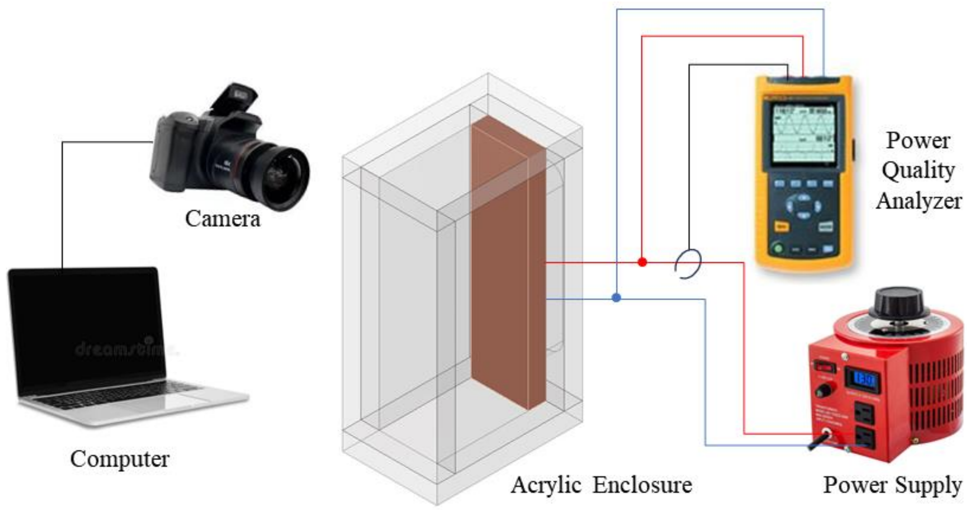

Figure 1 - Experimental setup.

A 9.5 mm thick copper plate of size 120 x 31.5 mm^2 was used as the spreader, and three other surfaces were made of acrylic and had internal dimensions of 120 mm in height, 50 mm in width and 31.5 mm in thickness. The external surfaces were thermally insulated with 20 mm thick Styrofoam, and glass wool was used on one of the four vertical surfaces. The front face insulation was removed for 15 s every 10 min to allow the direct visualization of the phase change process using the video camera. The walls and the base (also made of acrylic) were jointed using silicone. A PTC-type resistor (4 kΩ) was fixed on the rear side of the copper plate. To ensure a uniform heat distribution, a highly conductive silicon-based paste was used to reduce the thermal contact resistance between the copper plate and the heater. The input power was controlled by an AC power supply, where the voltage and electric current were measured through the energy quality analyzer (Fluke, model 43B); thus, the uniform heat flux can be estimated based on the plate surface and the input power.

In the current work, different cases were analyzed: Case A, corresponding to metal foam incorporated into the bio-based PCM and Case B, corresponding to bio-based PCM only. Moreover, in order to analyze the influence of heat flux on melting behavior, two different input powers were used in Case A: 126 W, corresponding to $q_1^{"}$ = 33 kW m^{-2}, and 120 W, corresponding to $q_2^{"}$ = 31 kW m^{-2}. For Case B, the tests were run with only the lowest input power.

The foam-bioPCM module is obtained by filling the foam matrix with liquid palm wax. In this case, the matrix is cooled down uniformly, and the composite foam-bioPCM solid did not present any void volume. Thus, to compare the melting behavior between the different cases, the same mass of bioPCM was used (140 g).

Palm wax was selected as the bio-based PCM; it is white in the solid state and colorless in the liquid state. The phase change temperatures and the latent heat were obtained through the differential scanning calorimeter (DSC), Perkin Elmer model STA 8000. Figure 2 shows the DSC thermogram, where the phase change range is 56.64 - 63.54 °C, and the latent heat capacity is 110,014 kJ/kg. The open cell Nickel-metal foam was selected for the current study; according to the manufacturer, its porosity is higher than 90%, and its pore density is 20 PPI (porous per inch). In Case A, the Nickel-foam is 100 mm high, 50 mm wide and 31.5 mm thick.

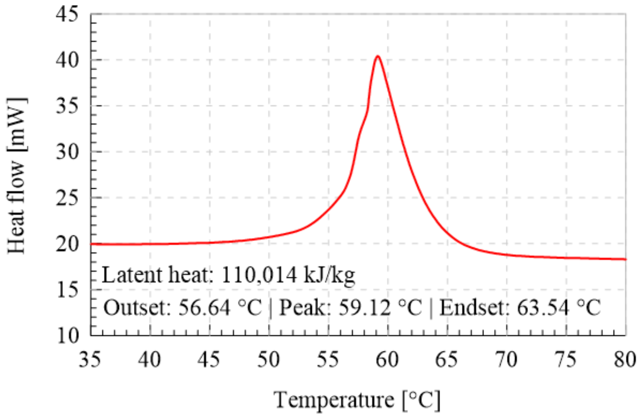

Figure 2 – DSC curve showing the melting process for the bio-based PCM (palm wax).

3. RESULTS AND DISCUSSION

Figure 3 shows the melt fraction (β) variation over time, with and without metal foam, for Case A and B, respectively. The input power is the same (120 W). Melt fraction values vary from 0 to 1, where 0 corresponds to bio-based PCM completely in solid state and 1 completely in liquid state.

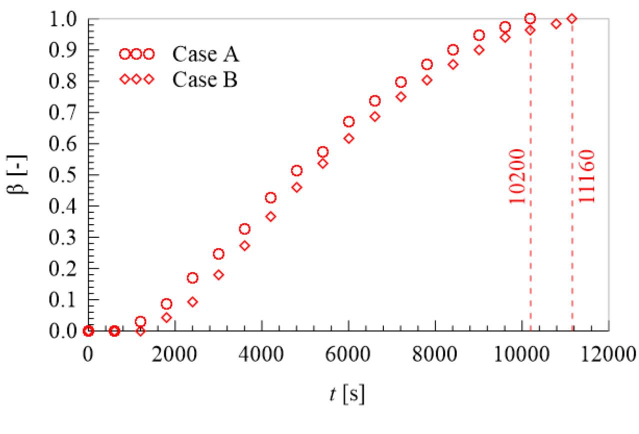

Figure 3 - Melt fraction (β) as a function of time for Case A and Case B

One may observe that, by incorporating Nickel-foam, there is an improvement in the thermal processes, making the melting process occur in a shorter time compared to the case with only bio-based PCM. For Case B, the total melting process occurred in 11160 s, while for Case A, it occurred in 10200 s, corresponding to a quantitative difference of 960 s or 8.6%. Compared to pure palm wax, palm wax/Nickel foam composite showed a better heat transfer performance.

Figure 4 shows pictures taken from the melting process, for Case A and Case B, at different moments. One may observe that the onset of melting occurs parallel to the copper plate in both cases (t = 1800 s). This behavior suggests heat transfer occurs through heat conduction in the initial instants. Furthermore, the melting front exhibits a convex shape, leaning towards the top-right direction. This suggests that heat transfer is more pronounced on the top than on the bottom due to the buoyant force's prevalence and the influential role of natural convection in facilitating heat transfer. Case A has greater intensification in the melting front's lower region than Case B. This behavior can be better visualized from 2400 s on, where the melting front quickly moves away from the copper plate. Such a behavior indicates that heat transfer is dominated by heat conduction through the foam.

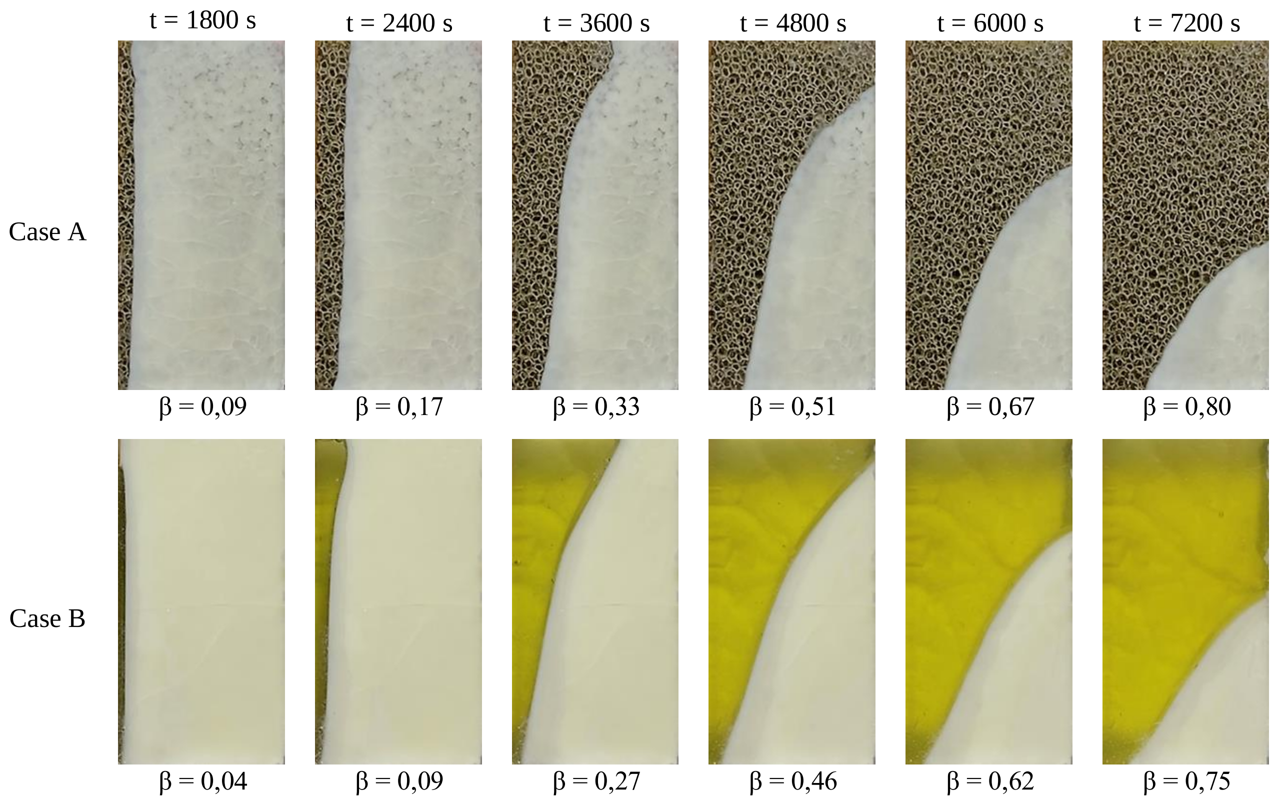

Figure 4 - Melting front behavior for Case A (metal foam incorporated in the bio-based PCM) and Case B (pure bio-based PCM).

Figure 5 presents the influence of input power on the melt fraction variation for Case A. By increasing the heat flux, the melting process occurs earlier. For 126 W, the total melting process occurs in 9720 s, while for 120 W, it occurs in 10200 s, representing a quantitative difference of 480 s or 4.7%. Higher input power promotes faster melting, enhancing heat transfer efficiency.

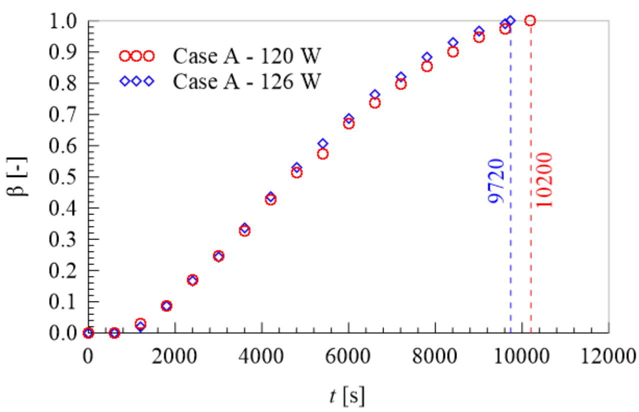

Figure 4 - Influence of input power on the liquid fraction (β) for Case A.

Figure 6 shows the melting front behavior for Case A for different input power at different instants of time. The melting front tends to advance more rapidly through the bio-based PCM, indicating an accelerated melting process as the input power increases. The porous structure of Nickel foam facilitates enhanced heat transfer through increased surface area and convective heat transfer mechanisms.

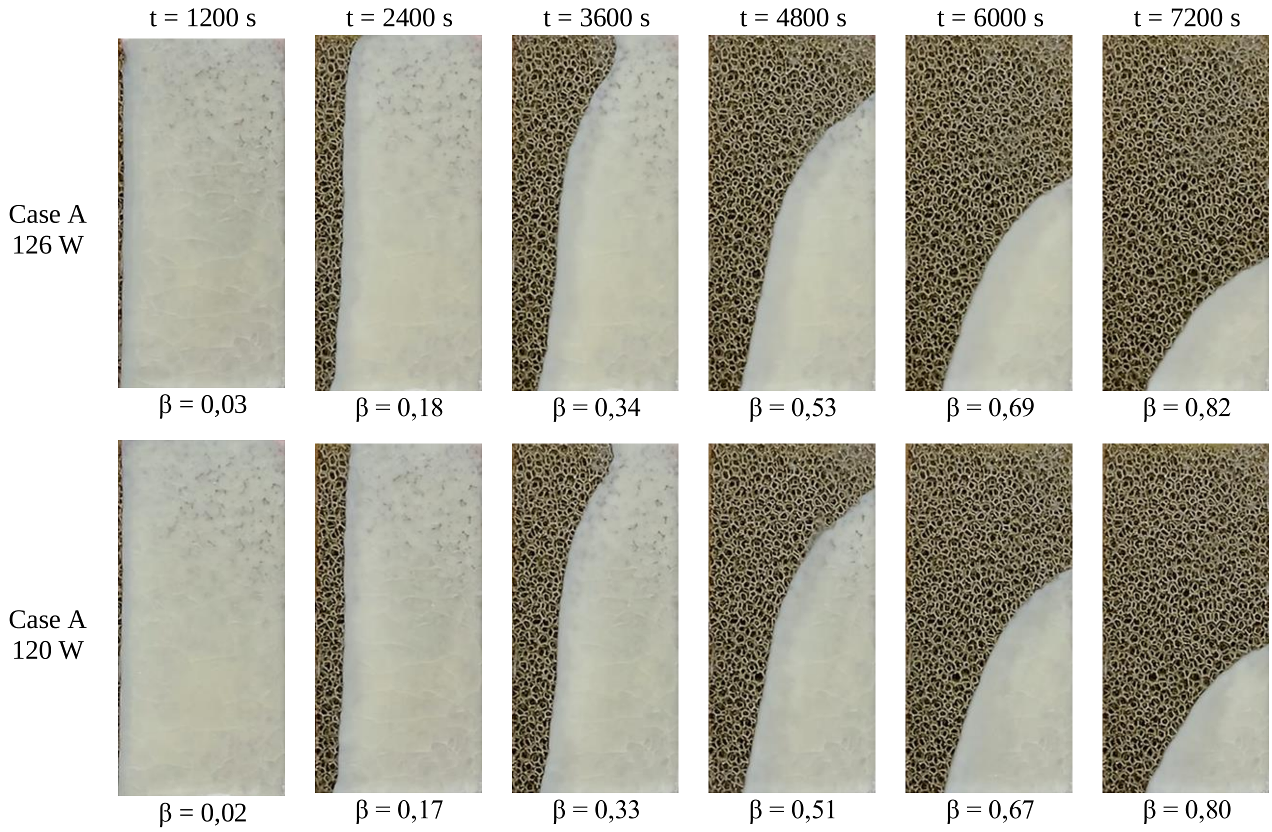

Figure 6 - Melting front behavior as a function of input power for Case A.

Therefore, metal foams with higher porosities, such as the one analyzed in the current work, demonstrate enhanced convective heat transfer, facilitating a faster propagation of the melting front. Likewise, metal foams characterized by higher thermal conductivities contribute to improved heat dissipation, thereby influencing the melting front's shape and speed.

4. CONCLUSION

In this study, the bio-based PCM melting process was experimentally analyzed using a rectangular reservoir through tests carried out with and without the presence of metal foam incorporated in the PCM matrix. The objective of incorporating the Nickel foam in the palm wax (the bio-based PCM chosen for this study) was to increase the thermal properties. The melting fraction was analyzed using images captured during the tests, while examining the melting front in the recorded images allowed us to analyze the dominant heat transfer process. Therefore, the following conclusions can be drawn:

- ✓ Incorporating metal foam accelerates the melting process of the bio-based PCM, which may lead to an increase in heat transfer performance. The metal foam porous structure increases the surface area for heat exchange, facilitating enhanced convective heat transfer. Besides, the high thermal conductivity of metal foam promotes heat transfer.
- ✓ As the input power increases, the melting process accelerates; such behavior is indicated by the tendency of the melting front to advance more rapidly through the bio-based PCM.
- ✓ The increase in heat flux causes greater intensification of thermal processes, and consequently, less time is required for the complete melting of the bio-based PCM.

These improvements have wide-ranging implications for thermal energy storage systems, such as solar thermal storage, building insulation, and thermal management of electronics. Further research is warranted to optimize the design and performance of metal foam-enhanced bio-based PCM composites and explore their potential in real-world applications.

5. ACKNOWLEDGEMENTS

The authors would like to thank UNISINOS and UNESP for the financial support, CAPES, CNPq (458702/2014-5 and 309848/2020-2) and FAPESP (2013/15431-7, 2019/02566-8 and 2022/03946-1).

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