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Experimental analysis of phase change phenomenon of paraffin waxes embedded in copper foams

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ABSTRACT

This paper presents an experimental investigation of the solid–liquid phase change process of three natural paraffin waxes, which show slightly different melting temperature: 53 °C, 57 °C, and 59 °C, at three heat fluxes: 6.25, 12.5, and 18.75 kW m^{-2}. Furthermore, the use of copper foams to improve the phase change process is experimentally studied by employing three different samples with 5, 10, and 40 PPI and constant porosity equal to 0.95. The experimental results clearly show that the presence of the foam matrix improves the heat transfer capabilities of the passive system allowing for lower surface temperature compared to no-foam case, at the same imposed heat flux. A direct video visualization of the process also permitted to show the effects of the porous medium on melting and solidification processes.

1. Introduction

It is well known that the heat transfer associated with a phase change process is much higher than sensible enthalpy change even in forced convection. In particular, the vaporization process has been widely studied because it exploits the highest heat transfer coefficient; this heat transfer mechanism is used in both passive (i.e. heat pipes) and active (i.e. refrigerating machines) cooling devices. However, the solid–liquid phase change process is another interesting possibility to reject even high heat loads, especially when they are intermittent. The term Phase Change Materials (PCMs) commonly refers to those materials, which use the solid–liquid phase change process to adsorb and then release heat loads. In the last decade, the use of PCMs as heat storage in passive heat transfer device has been widely studied both analytically and experimentally. The use of the latent heat absorption phenomenon associated with melting of a suitable PCM can be considered an effective way to delay or modify the temperature rise of a surface subjected to high and intermittent heat fluxes. The intrinsic advantage of the PCM systems is related to their simplicity and reliability; however, the reversible phase change process must be carefully analysed in order to avoid any unmanageable situations during the real operation of these devices.

As described in several comprehensive reviews [1–3] published in the open literature, PCMs have been widely proposed for thermal storage applications due to their capability of storing and releasing large amounts of energy with a small PCM volume and a relatively low temperature variation.

As described by Sharma et al. [2], a large number of phase change materials (organic, inorganic, and eutectic) are available in any required temperature range. An ideal PCM should exhibit a suitable phase-transition temperature, high latent heat of fusion, and high thermal conductivity; it should be characterized by high density associated with a small volume change during the melting process and low vapour pressure in the melt; moreover, it should be chemically stable over a long period of time, non-toxic and non-hazardous, and compatible with the constructional materials. Finally, it should be abundant, available, and cost effective.

Amongst the available PCMs, paraffin waxes have been found to exhibit many desirable characteristics, such as high latent heat, low

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Nomenclature

a_{sv}	surface area per unit of volume [m^{-1}]
c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
HF	heat flux [kW m^{-2}]
l	fibre length [m]
PCM	Phase Change Material [−]
PPI	Pores Per Inch [in^{-1}]
t	fibre thickness [m]
T_{melt}	melting temperature [°C]
Greek symbols	
ε	porosity [−]
λ	thermal conductivity [W m^{-1} K^{-1}]
ρ	density [kg m^{-3}]
ρ_P	relative density [−]

vapour pressure in the melt, chemically inert and stable, non-toxic. However, they also have a very low thermal conductivity and a high volume change during the melting process. In some cases, the paraffin waxes can also be flammable. Thus, heat transfer enhancement techniques are required for their possible implementation in PCM passive cooling devices and thermal storage applications [4]. As such, several researchers have focused their attention to different enhancement techniques proposed to improve the thermal conductivity of the PCMs; Jegadheeswaran and Pohekar [5] and Fan and Khodadadi [6] have reviewed most of these efforts.

Baby and Balaji [7] experimentally investigated different enhancement techniques to improve the performance of PCM heat sinks for electronic equipment cooling; in particular, the authors explored the use of heat sinks with pin fin and plate fin geometries with phase change materials for thermal management of portable electronic devices. The effect of different types of fins at different power levels in enhancing the operating time for different set point temperatures and on the duration of latent heating phase were explored. An enhancement factor of 18 was obtained in the operation time for a pin fin heat sink as compared to that of the heat sink without fins.

The same authors [8] conducted an experimental optimization of different PCM based pin fin aluminium heat sinks; paraffin wax and n-eicosane were used as PCMs. Using n-eicosane embedded in a 72 pin fins heat sink, the authors found a 24-fold heat transfer enhancement compared with no-fin case. According to those authors, a large number of uniformly distributed fins are largely responsible for this enhancement in heat transfer.

In a subsequent study, Baby and Balaji [9] have experimentally investigated the effect of heat transfer performance of a PCM based plate fin heat sink matrix under constant and intermittent heat loads. Furthermore, the necessity to quantitatively characterize the behaviour of such heat sinks under intermittent operation was highlighted as a design based on continuous heat duty might lead to oversized, more expensive and sub-optimal heat sinks.

Fan et al. [10] investigated the effects of melting temperature and the presence of internal fins on the performance of a PCM based heat sink for thermal management of electronics. The comparisons were made between two PCMs with similar thermophysical properties but different melting temperatures at various intensive pulsed heat loads. N-eicosane with a nominal melting temperature of 37 °C and 1-hexadecanol with a nominal melting temperature of 49 °C were studied. According to those authors, the use of a PCM with a rationally high melting temperature, limited by the temperature of the cooling target, could extend a longer time of protection from overheating. The use of internal fins can improve the performance of the PCM-based heat sink. In the studied cases, the maximum temperature rise was lowered by up to 10 °C for the finned heat sink.

Mahmoud et al. [11] studied the effects of PCM material, heat sink designs and power levels on PCM based heat sinks performance for cooling electronic devices. Six PCMs were used including paraffin wax, two materials based on mixture of inorganic hydrated salts, two materials based on mixture of organic substances and one material based on a mixture of both organic and inorganic material. Results showed that increasing the number of fins can enhance heat distribution to PCM leading to lower heat sinks peak temperatures. Furthermore, it was reported that the material with the lowest melting temperature showed the best performance in terms of lowest operating temperature and longest duration of low heat sink temperatures.

Kozak et al. [12] experimentally and numerically investigated a hybrid PCM-air heat sink using eicosane as PCM. The experiments were conducted at room and elevated ambient temperatures. A simplified numerical model was developed and successfully compared with the experimental results.

Heat transfer enhancement of PCM-based heat sinks can also be obtained using porous matrix as the thermal conductivity enhancer instead of fins. Many studies considered the enhancement of heat transfer through PCM using porous media. Among these works, Hong and Herling [13] experimentally analysed the effects of geometric parameters of open-cell aluminium foams on the performance of aluminium foam-PCM heat sinks. The authors used a paraffin wax as PCM. For the aluminium foam specimens filled with the PCM, both the heating and cooling times were significantly larger than those with the aluminium foam specimens without the PCM.

The use of carbon foam matrices saturated with paraffin wax for thermal protection purposes was studied by Mesalhy et al. [14]. The effects of the porosity and thermal properties of a porous medium filled with PCM were studied numerically and experimentally. The results showed that the porosity and thermal conductivity of the matrix play important roles in the thermal performance of the system.

Zhao et al. [15] used paraffin wax RT58 as PCM, in which metal foams are embedded to enhance the heat transfer. The test samples were electrically heated on the bottom surface with a constant heat flux. The authors found that the addition of metal foam can increase the overall heat transfer rate by 3–10 times (depending on the metal foam structures and materials) during the melting process and the pure liquid zone.

Tian and Zhao [16] performed numerical investigations of heat transfer in PCMs kept in porous metals. Significantly higher conduction heat transfer rates were reported with the use of metal foams as a consequence of their higher thermal conductivities. On the other hand, higher flow resistance posed by foams suppresses natural convection. All in all, it was noted that enhancement of heat conduction offsets the natural convection loss and, overall, a better heat transfer performance was achieved.

Zhoua and Zhao [17] experimentally investigated the heat transfer characteristics of two different PCMs (RT 27 paraffin wax and calcium chloride hexahydrate) embedded in open-cell metal foams and expanded graphite. The results indicated that the use of porous materials, either open-cell metal foams or expanded graphite, can enhance the heat transfer rate of PCMs. Furthermore, metal foams can provide better heat transfer performance than expanded graphite due to their continuous interconnected structures.

Cui [18] compared the charging performance of paraffin wax with and without copper foam. The results indicated that the foam