• Title: Enhancing Latent Heat Energy Storage with Heat Pipe-Metal Foam: An Experimental Investigation of the Partial Filling Strategy

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• Abstract

Melting and solidification of a phase change material (PCM) is investigated experimentally by applying a partial filling strategy to the hybrid enhancement of heat pipe-metal foam (HP-MF) in a vertical cylinder. HP-MF enhancement can improve the heat transfer capacity of the PCM system as it combines HP’s efficient heat transfer capacity with MF’s highly effective thermal conductivity capability. The experimental results demonstrate that the partial filling strategy in the melting and solidification of HP-MF PCM can be optimized for effective MF utilization in the HP-MF PCM system. A filling ratio of 83% of MF in HP-MF PCM shows almost identical total melting and solidification along with a temperature distribution to that of an HP-MF PCM (95% porosity, 20 pore density (PPI)). It is plausible to conclude that the removal of 33% or less mass had no significant effect on the overall melting process of HP-MF PCM. It should be noted that the HP-MF PCM system's heat pipe heat transfer efficiency significantly decreased during the melting process when the MF filling ratio was 37.5% and 12.5%.

•Highlights

* A novel approach to implementing the partial filling strategy of MF for HP-MF PCM system
* Experimental investigation on the thermal performance of the HP-MF PCM system during both the melting and solidification processes
* Discussion on impact of conduction and convection on melting and solidification temperature at various fill heights in HP-MF PCM system

• Keywords:Phase change material (PCM)

* Latent heat thermal energy storage (LHTES)
* Heat transfer enhancement
* Heat pipe (HP)
* Metal foam (MF)
* Partial filling strategy

• List of abbreviations including units and nomenclature:

* PCM: phase change material
* LHTES: latent heat thermal energy storage
* HP: heat pipe
* MF: metal foam
* HP-MF: heat pipe – metal foam

1.0 Introduction

2.0 Experimental Design

3.0 Results and Discussion

3.1 Melting Process

3.2 Solidification Process

4.0 Conclusion

1. **INTRODUCTION**

Latent heat thermal energy storage (LHTES), with its high energy density and isothermal phase transitions, shows promise for storing thermal energy in a variety of applications. [1,2]. An obstacle to the development of LHTES commercially is the low thermal conductivity of most phase change materials (PCMs) resulting in low heat transfer effectiveness [3]. Various types of heat transfer enhancement techniques have been studied extensively to address this issue [4,5].

Metal foam (MF) and heat pipe (HP) are the two most widely used enhancement techniques in PCM. MF improves thermal conductivity as well as overall heat transfer in PCM [6,7]. MFs infused in PCM possess the capacity to enhance heat transfer rates owing to the comparatively large interfacial surface area between the MF and PCM. [8]. However, the total amount of PCM was decreased because of the MF's immersion in PCM, and the presence of MF in PCM limits PCM's natural convection [9]. In contrast, HPs efficiently and with little temperature loss transmit heat across long distances [10].

Siahpush et al. [11] noted that the presence of MF led to an increase in the rates of both melting and solidification. Wu and Zhao [12], as well as Libeer et al. [13], observed that MF PCM with lower MF porosities resulted in a reduced mass of PCM, as the MF occupied space within the PCM system. This consequently led to a decrease in the overall thermal energy storage capacity. Wu Zhang et al. [14] concluded that conduction primarily governed heat transfer until the PCM melted, at which point convection became the dominant mode of heat transfer. Mancin et al. [15], through experimental analysis of MF PCM with varying densities, while maintaining a constant porosity, found that this approach reduced the phase change duration and promoted a more uniform temperature distribution. Liu et al. [16] and Qu [17] et al. proposed that the effect of porosity as more significant than pore density. In their work, Wu and Zhao [18] reported a significantly faster heat transfer rate, up to 250%, when employing a bottom heating arrangement compared to a top heating arrangement. In terms of inclination angles, Yang et al. [19] conducted experiments and found that they had an insignificant influence on the melting rate of MF PCM.

Numerous studies on the use of HP PCM have been conducted in the fields of solar energy, heat exchangers, building cooling, and electronic components [20,21,22]. According to Sharifi et al. [23], melting rates rise when condenser length or HP diameter increases. Tiari et al. [24] concluded that greater temperature accelerates the charging process while increased flow rate has a considerable impact on the charging rate but little impact on the discharging rate. In a related study, Motahar et al. [25] found more evidence that lower temperatures speed up the discharge process.

After reviewing the research on various heat transfer enhancements in the PCM system, Jasim et al. [26] concluded that using HP-MF is potentially one of the most effective enhancement techniques for improving thermal performance overall. The synergy of HP's robust heat transfer capabilities and MF’s efficient thermal conductivity holds substantial promise for augmenting the thermal performance of an HP-MF PCM system. A bibliometric analysis of the literature further reveals a notable increase in interest and research activities in HP-MF PCM investigations during the year 2020, underscoring the significant potential for improvement even though the research on HP-MF enhancements in PCM systems is still in its early stages with a small number of studies. [27].

In one of the earliest studies on HP-MF PCM, Nithyanandam and Pitchumani et al. [28] used numerical analysis to examine the impact of HP arrangement, pore density, and heat transfer fluid (HTF) velocity during both charging and discharging operations. The study found that a larger MF pore density during charging affected heat transfer and that the HP-MF PCM had a higher melting and solidification rate. The effectiveness and impact of inclination angle on a cylindrical LHTES system with HP, HP-foil, and HP-M Fin PCM during melting and solidification were evaluated experimentally by Allen et al. [29,30]. The study found that the porosity had a considerable influence on PCM's melting and solidification rates, but the pore density and inclination angle effect were negligible. Q.Lv [31] demonstrates that HP-MF (Nickel) PCM generates a low melting rate with a consistent temperature gradient but the amount of HP does not correspond with the rate of melting. An experimental investigation on a novel separation type of battery thermal management system (BTMS) with HP-MF (Copper) PCM was done by Zhang et al. [32. By lowering the temperature imbalance within the battery pack, the proposed solution was found to increase reliability and performance over a longer period. According to Tiari et al. [33], the primary factor affecting the thermal performance of the system is the porosity of the MF. reducing the MF porosity leads to a more even distribution of temperature within the phase change material (PCM), resulting in significant enhancements in energy storage and release rates. Additionally, this reduction in MF porosity also reduces the time needed for both charging and discharging processes. In a study conducted by Hayat et al. [34], an experimental investigation was conducted to explore the thermal performance of HP PCM, MF PCM, and HP-MF PCM, under three varying heat conditions, both with and without the use of a cooling fan. The results indicated that the HP-MF PCM, when used in conjunction with a cooling fan, exhibited the most significant reduction in temperature during the charging process and demonstrated exceptional cooling efficiency during the discharging phase. This was attributed to its combination of a low phase change temperature and a high heat storage capacity. Furthermore, the HP-MF high thermal conductivity minimized the occurrence of supercooling.

Recent research has looked at the partial filling technique of MF in PCM to maximize the techno-economic performance of MF. The storage capacity and heat transmission effectiveness of PCM can be profitably increased by employing a partial filling approach. Zhu et al. [35] used filling efficiency to study the height ratio effect between the copper foam and the heat sink. The study showed that higher height ratio values not only enhance the thermal performance of the heat sink but also increase the system's weight and cost. Max filling efficacy performance was demonstrated by the partial filling ratio of 0.67. The impact of filling ratios and porosities on the melting rate of PCM was investigated in a study by Joshi and Rathod [36,37]. The lower portion of the chamber had partially been filled with metal foam, which increased the temperature gradient and, thus, the melting rate. It was observed that MF with a partial filling of 75% melts almost at the same time as MF PCM. According to Xu et al.'s [38,39] numerical analysis of the ideal filling ratio and filling strategy based on the TES rate density criterion, the ideal filling ratio for porous media is 0.7. Based on the limited literature review presented, the ideal filling ratio of metal foam is suggested 0.67 and 0.75 filling ratio for the optimized techno-economic performance of MF.

This paper proposes a novel approach to implementing the partial filling strategy of MF for hybrid enhancement of HP-MF in PCM. For effective MF distribution in the system, MF was systematically added at the region of high-temperature gradients at various ratios to PCM fill height, specifically ratios of 0, 0.17, 0.33, 0.5, 0.67, 0.83, and 1.0 to augment the melting process. The experimental investigation focused on assessing the effect of the partial filling strategy on the thermal performance of the HP-MF PCM system during both the melting and solidification processes. To determine the impact of conduction and convection heat transmission on melting and solidification temperature at various fill heights, temperature distribution within the PCM and temperature fluctuations along the HP component are investigated.

**2.0 Experimental Design**

Faghri et al. [23] created an experimental PCM and HP setup to compare the effects of HP, solid rods, and hollow tubes on the melting of PCM at low temperatures. The experimental design suggested by Faghri was modified by Tiari et al. [24] and Motahar et al. [25] in order to perform further HP, MF, and PCM studies. In the current study, experimental setup design and assembly procedure were adapted with reference to Faghri's research (23) to study the effect of the partial filling strategy in HP-MF PCM system.

The main components of the experimental setup are shown as a schematic depiction in Fig. 1. The experimental setup comprises a test rig with a vertical cylindrical container and a heat exchanger enclosure, water bath for Heat Transport Fluid (HTF) circulation, flow meter, and data acquisition system.

The acrylic vertical cylinder was constructed with of inner diameter of 41 mm, wall thickness of 10 mm, and height of 125 mm are filled with MF embedded in the PCM and concentrically located HP. The aluminum enclosure for the heat exchanger has dimensions of 140 mm x 100 mm x 100 mm and a thickness of 10 mm. A copper heat pipe (HP) with a length of 175 mm and a diameter of 8 mm, utilizing water as its working fluid, facilitates heat transfer between the MF PCM inside the cylinder and the HTF in the heat exchanger enclosure. The experimental rig is placed within a polystyrene container to minimize heat loss. Temperature measurements are carried out using K-type thermocouples (TCs), strategically placed in the radial and axial positions indicated in Figure 2.

In this study, an organic PCM, n-octadecane (CH3(CH2)16CH3), obtained from Thermofisher with a purity of 99%, was selected as the PCM and copper foam with 95% porosity and 20 pores per inch (PPI) were selected as MF. This choice was determined by its stable thermophysical characteristics and transparent liquid phase, which allows for the observation of melting and solidification phenomena [40-42]. Relevant thermophysical properties of n-octadecane are compiled in Table 1.

In the melting phase (or solidification phase), the initial temperature of the PCM was set at 24°C (or 31°C) by circulating the HTF (water) via a water bath circulator. Once the system achieved equilibrium at the desired initial temperature (with all TCs in the PCM showing a deviation of no more than 0.2°C), the experimental procedure was initiated by introducing water at a constant temperature of 45°C (or 11°C).

To investigate the melting and solidification behaviors in the HP-MF PCM system associated with the partial filling approach, a series of experiments were carried out. These experiments involved varying the filI height ratio, R of MF to PCM, specifically at the R of 0, 0.17, 0.33, 0.5, 0.67, 0.83, and 1.0 (as detailed in Table 1).

The experimental setup included stacking 6 annular disks of MF through press fit installation around HP. Each annular disc is 12.5mm thick with inner dimensions of 5.9 mm and outer dimensions of 39mm. Initially, 6 stacked of MF configuration resulted in a total height of approximately 75mm, equivalent to a metal R of 1.0 (Case R1).

After completing the melting and solidification experiment at R of 1.0 (corresponding to Case R1), one stack of annular discs was systematically removed, effectively advancing to Case R2, and the melting and solidification experiments were then repeated. This process of removing one stack, corresponding to the subsequent case, was carried out in a stepwise manner, advancing through the cases one at a time. Following the removal of each stack, the PCM was refilled to a level of 75mm. This cycle continued until the R reached zero, designated as Case R7 when all 6 discs had been removed.

Data from the TCs were connected and recorded by data capture equipment (Graphtec, midi logger GL840) at intervals of 2 minutes for analysis during each experimental session.

*z(mm)*

|  |  |  |
| --- | --- | --- |
| TC | r |  |
|  | 10 | 105 |
|  | 18 | 105 |
|  | 15 | 120 |
|  | 10 | 143 |
|  | 18 | 143 |
|  | 4 | 25 |
|  | 4 | 55 |
|  | 4 | 165 |

Cylinder

MF+PCM

T8

T2, T1

T5, T4

T3

HP

Heat Exchanger

T7

*r(mm)*

T6

1. (b)

**Fig. 1. (a) Schematic diagram experimental rig ; (b) TC position point.**

Data Acquisition System

Water bath

Flow meter

Valve

Test Rig

**Fig. 2. Schematic diagram of the experimental system**

|  |  |  |
| --- | --- | --- |
|  | PCM | Metal Foam |
| Material | n-octadecane | Copper |
| Melting point, *T*m/K | 301 |  |
| Latent heat of fusion, *h*sl/kJ kg−1 | 243.5 |  |
| Density, *ρ*/kg m−3 | 800 | 8954 |
| Specific heat *c*p/J kg−1 K−1 | 1912 | 383 |
| Thermal expansion, *β*/1 K−1 |  |  |
| Thermal conductivity,  *λ*/W m−1 K−1 | 0.358 | 400 |

**Table 1 n-octadecane and copper thermophysical properties**

|  |  |  |
| --- | --- | --- |
| Case | MF filling height | Fill height ratio, |
| R1 |  |  |
| R2 |  |  |
| R3 |  |  |
| R4 |  |  |
| R5 |  |  |
| R6 |  |  |
| R7 |  | 0 |

**Table 2: Summary of partial filling strategy for copper foams.**

A close up of a device

Description automatically generated**A glass tube with wires and screws

Description automatically generatedA close-up of a snake

Description automatically generated**A close-up of a device

Description automatically generatedA close-up of a glass tube with liquid and wires

Description automatically generatedA close-up of a wire

Description automatically generated

A close-up of a machine

Description automatically generated

R3

R1 (Tm

R7

R6

R5

R4

R2

**(a)**

A close-up of a piece of ice

Description automatically generatedA transparent tube with wires and wires

Description automatically generated**A close-up of a glass container

Description automatically generated**A glass tube with wires and screws

Description automatically generatedA glass tube with red and green wires

Description automatically generatedA close-up of a machine

Description automatically generatedA close-up of a machine

Description automatically generatedV

R5

R6

R4

R3

R7

R2

R1

**(b)**

**Fig 3 Test Sample (a)Melting process for case R1-R7 (b) Solidification process for case R1-R7**

**3.0 Results and Discussion**

This investigation aimed to study the effect of the partial filling strategy during the melting and solidification process. Fig. 3 shows the melting and solidification for Case R1 to Case R7. The analysis comprised examining the temperature distribution and temperature variations along the HP component to study the effect of conduction and/or convection heat transfer during melting and solidification processes. Notably, the partial filling technique applied to the HP-MF PCM configuration introduces a novel consolidation of convection and conduction effects, the indication of which varies by the degree of PCM filling. Melting and solidification occurrences were inferred from the recorded temperature data. By tracking the propagation of melting or solidification patterns between TCs, it was possible to discern the prevailing mode of heat transfer.

Efficient heat transfer from the high-performance HP component to the MF PCM is demonstrated by a notable reduction in temperature along the HP, aligning the HP temperature closer to Tm (melting temperature). Based on the readings at the TC points depicted in Fig. 1, the following calculation is made to determine the NHP (temperature drop of the HP):

(1)

**3.1 Melting Process**

1. (b)
2. (d)
3. (d)

(e) (f)

(g)

**Fig.4. Temperatures measured during melting by thermocouples for Case (a)R1, (b)R2, (c)R3, (d)R4, (e)R5, (f)R6, and (g)R7.**

|  |  |  |  |  |  |  |
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**A close-up of a light bulb

Description automatically generated**

Heat pipe

Liquid PCM

Solid PCM

Metal Foam + PCM

1. (b)

**Fig.5. Recirculation in Case R5 and R6 (a) Top view photo (b) Schematic side view**

In the HP-MF PCM system with partial filling, two primary melting regimes are evident. In the lower enclosure, where MF PCM is filled, simultaneous conduction and convection drive the melting process, while the melting in the upper enclosure which is filled with PCM is dominated by natural convection. However, the presence of MF suppresses convection in MF PCM. Temperature profiles reveal a radial increase indicative of convection driven heat transfer and an axial increase indicative of conduction-driven effects.

In Case R1 (Fig. 4a), the temperature distribution during melting follows a pattern of T4, T1, T3, T5, and T2, with a total melting time of 70 minutes. While the solid-liquid transition mainly advances radially due to conduction in MF. A slight effect from simultaneous conduction and convection in MF PCM is evident, as higher points exhibit slightly elevated temperatures and experience melting before the regions closer to lower TCs. Nevertheless, T2 and T5 reach the melting point almost simultaneously, affirming the dominance of conduction in the process. The temperature distribution remains uniform throughout the melting process. The NHP dropped from 4°C to 1.5°C which is attributed to its higher melting rate due to efficient HP conduction.

In Case R1 (Fig. 4a), the temperature distribution during melting has a pattern of T4, T1, T3, T5, and T2, with a total melting time of 70 minutes. Melting mainly progresses radially due to MF conduction, with slight influence from simultaneous conduction and convection in MF PCM. The HP undergoes a significant temperature drop due to efficient HP conduction.

The temperature distribution pattern and melting time of Case R2 are almost identical to R1 as shown in Fig. 4b. The MF inserted in the PCM are located in the 5/6 th of the lower portion of the as shown in Fig.3. The solid PCM melted significantly more quickly until it was nearly equal to the rate of heat conduction in the MF PCM composite due to the limited amount of PCM on top and heat transfer from both HP and MF PCM. The NHP is nearly isothermal with a temperature drop of about 5°C due to heat transfer throughout the melting period.

During the phase change process in Case R3 as shown in Fig. 4c, the melting time remains only slightly lower than MF PCM with almost uniform temperature distribution indicating relatively low thermal resistance in the strategy involving a 67% filling ratio of MF in HP-MF PCM system. A mild thermal stratification is present in the liquid PCM region during melting due to natural convective transport. The low NHP observed along the HP indicates effective HP heat conduction in R3.

In Case R4 (Fig. 4d), the melting sequence follows the pattern of T4, T5, T3, T1, and T2. Both PCM and MF PCM are evenly distributed at 50%, as depicted in Fig. 3d. Initially, conduction dominates in the lower portion during the first 60 minutes of melting, resulting in higher temperatures for T1, T3, and T2 compared to T4 and T5. However, after the initial 60 minutes, a sharp temperature increase is observed in T4 and T5, surpassing the temperatures in T1, T3, and T2 due to convection.

Cases R6 and R5 involve 12.5% to 25% filling of MF in the lower enclosure, as shown in Fig. 4e and f. Initially, conduction is dominant in the lower enclosure but is quickly replaced by a rapid increase in convection in the upper enclosure around 40 minutes in both cases. The synergy between bottom-based heat transfer from MF PCM and HP on PCM at the molten PCM contact surface drives a convection mechanism of heat transfer, resulting in recirculation inside the melted PCM, as depicted in Fig. 5. The PCM located in the middle of the enclosure remains solid until the later stages of the melting. It is observed that the thermal stratification phenomenon increases with a reduction in MF fill height and buoyancy from R5 to R6. The temperature pattern constricts at the end of the melting process.

For the HP PCM (Case R7) as shown in Fig. 4g, the melting progression unfolds in the order of T4, T5, T3, T1, and T2. Conduction is the primary mode of heat transfer up to the melting point of PCM (Tm=28°C). In the subsequent stages of melting, the PCM temperature measured by these TCs increases at a rate that is almost independent of the axial location. As the PCM melts, its temperature increases rapidly once buoyancy becomes stronger. A strong thermal stratification is observed in the liquid PCM region during the melting process which finally constricts towards the end of the melting process. The NHP remains nearly isothermal, with a temperature drop of about 5°C, owing to its high effective thermal conductivity.

**3.2 Solidification Process**

(a) (b)

(c) (d)

(c) (d)

(e) (f)

(g)

Fig.6. Temperatures measured during solidification by thermocouples for case (a)R1, (b)R2, (c)R3, (d)R4, (e)R5, (f)R6, and (g)R7.

Natural convection has a minimal impact during the solidification phase, making each case (R1-R7) primarily conduction driven. In all the Cases PCM solidification progresses rapidly until it reaches its solidification temperature (~28°C) due to sensible heat in liquid PCM. After the sensible heat is extracted from molten PCM, the temperature profiles contract as isothermal solidification of the PCM occurs.

In MF PCM (Case R1) and HP PCM (Case R7), the solid-liquid interface progresses uniformly in the radial direction, following the sequence of T4, T1, T3, T2, and T5 as shown in Fig. 6 a,g. In the case of MF, PCM solidification occurs more quickly and uniformly than in PCM due to its higher thermal conductivity of MF.

Case R2, with limited MF in the upper enclosure and in contact with both HP and MF PCM, experiences a significantly faster solidification rate at the point of contact, nearly equivalent to the heat conduction in the MF PCM composite, as shown in Fig. 6b. The solidification rate progresses uniformly in the radial direction, resulting in a similar temperature distribution and solidification time to that of MF PCM.

In Case R3 (Fig. 6c), solidification times are lower than MF PCM, with a slightly faster solidification rate in the lower enclosure than the upper enclosure. This suggests that the amount of PCM at the upper enclosure is significant enough that the heat transfer in MF PCM surpasses that due to HP for the strategy involving a 67% filling ratio of MF.

For other partially filled HP-MF PCM cases (Case R4-R6), faster solidification occurs at the lower portion of the enclosure in the radial direction before the upper enclosure due to higher conductivity of MF, leading to non-uniform temperature distribution across all configurations in the early phase of solidification. However, once layers of PCM have formed on the surface of MF PCM and HP in all three circumstances, the entire solidification time is almost the same in R5 and R6 due to higher thermal resistance in solid PCM.

In Case R7, as solidification continues after isothermal solidification, layers of PCM solidify on the surface of HP, increasing the temperature gradient in the radial direction. Significant thermal resistance in conduction due to the low thermal conductivity within the PCM slows down the solidification rate of PCM.

During solidification, the NHP remains nearly isothermal with a temperature drop of less than 10°C for all cases, owing to relatively effective thermal conductivity in solidification than melting process.

1. **Conclusion:**

The study examined the melting and solidification characteristics of HP-MF PCM hybrid enhancements across different metal fill height ratios: 0, 0.17, 0.33, 0.5, 0.67, 0.83, and 1.0. The melting process in the partially filled HP-MF PCM system was influenced by convection and conduction, whereas solidification is dominated by conduction heat transfer.

The total time required for the melting and solidification processes in an HP-MF PCM system with an 83% MF filling ratio is nearly equal to that seen in an HP-MF PCM system. It is plausible to conclude that the removal of 33% or less mass had no significant effect on the overall melting process of HP-MF PCM. It should be noted that the HP-MF PCM system's heat pipe heat transfer efficiency significantly decreased during the melting process when the MF filling ratio was 37.5% and 12.5%.

The nearly equal solidification times for the HP-MF PCM system from 37.5% to 50% and 12.5% to 25% MF filling ratios demonstrate that the solidification in the partial filling strategy may also be optimized and is not dependent on the filling ratio.

This work suggests that a partially filled HP-MF PCM system with optimized conduction and convection processes has a promising future. As temperature distribution may be homogenized with partial filling ratios, such a system has the potential to considerably improve heat transfer efficiency, cost-effectiveness, weight reduction, storage capacity expansion, and system stability.

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