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Numerical Analysis of Heat Transfer and Phase Change in a Metal Foam Enhanced Phase Change Materials for Solar Thermal Energy Applications

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A B S T R A C T

Phase change materials (PCMs) are vital in solar energy systems as a result to their capability for thermal energy storage and release via latent heat. However, the fundamentally low thermal conductivity of most PCMs meaningfully obstructs their heat transfer performance. To address this restriction, the combination of high-conductivity structures such as metal foams demonstrating highly effective. This research exhibits a numerical investigation into the impact of embedding metal foams, particularly aluminium and copper, within two types of PCMs (RT42 and RT54HC) to boost their thermal performance in solar thermal applications. The research appraises metal foam porosity levels ranging between 85% to 95%. The results indicate a notable decrease in melting (charging) time as porosity decreases, specifically a 15.4% reduction for aluminium foam and a 10% reduction for copper foam when the porosity ratio drops from 95% to 85%. This highlights the occasion for considerable enhancement of heat transfer performance at lesser porosity levels. While using aluminium foam, RT42 melts faster than RT54, with melting times of 1121 s and 1787 s respectively, indicating a 37% decrease. However, increasing heat flux further reduces melting time, with RT42 in 85% porosity copper foam hitting 870 s at 3000 W/m².

1. Introduction

Phase change materials (PCMs) are lengthily recognised for their practicality in thermal energy

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storage, largely in solar energy implications. The are specifically characterised by its ability to absorb and release large amounts of latent heat throughout phase transitions, which allows for improved thermal regulation and prolonged energy obtainability beyond sunlight hours [1]. This property makes latent heat thermal energy storage (LHTES) tremendously advantageous, conveying high energy density and phase change at an approximately constant temperatures, that outstrips the performance of sensible thermal energy storage or chemical energy storage approaches [2]. Notwithstanding these advantages, a foremost benefit of LHTES systems is the characteristically low thermal conductivity of most PCMs, that would expressively hinder heat transfer performance [3]. To resolute this severe restriction, the researchers were enthusiastically developed various approaches to enhance the thermal conductivity of PCMs. One highly efficient practice comprises integrating PCMs with high-conductivity structures such as metal foams. The combination of metal foams, like copper and aluminium, can improve heat transfer rates and overall system performance, making them highly suitable for a range of solar thermal applications, such as solar dryers, water heaters, and photovoltaic (PV) thermal collectors [4,5]. While many studies improved solar collectors including parabolic troughs and advanced linear Fresnel designs [6-9], overall system efficiency still depends on effective thermal storage. Thus, the current trend of research focuses on enhancing PCM performance using metal foam.

A substantial body of conducted research was motivated on the incorporation of metal foams into PCMs. Zhao et al. [10] investigated experimentally the influence of integrating metal foam into paraffin wax (RT58) for thermal performance enhancement. The results elaborated that the existence of metal foam can upgrade the overall heat transfer rate by a factor of 3 to 10 and mitigate the solidification time by more than 50%.

Xiao et al. [11] further prepared paraffin/nickel foam and paraffin/copper foam composite PCMs for latent thermal energy storage. The researchers reported that vacuum impregnation can enhance the thermal conductivity, with the paraffin/nickel foam elucidating nearly three times the conductivity of pure paraffin. This research also distinguished that surface porosity ranged from 90% to 94%, with minor shifts in phase change temperatures, displaying peak melting deviances of 0.55 °C and 0.40 °C for the respective composites.

Zhu et al. [12] inspected the presentation of embedded paraffin in 90% porous aluminium foam to enhance the thermal energy storage. Utilising the finite volume model, the researchers specified that growing foam pore density, reshaping the cold wall, and employing discrete heat sources can improve the melting and heat transfer. More importantly, the optimised design boosted the overall efficiency to 83.32%, meaningfully outclassing pure paraffin.

Ghahremannezhad et al. [13] directed a numerical research on copper metal foams with gradient porosity to improve the overall heat transfer of paraffin wax. The findings indicated that gradient structures can raise the thermal performance and produced more uniform melting in a comparison to uniform foams. The researchers also specified that the direction of porosity and the heat source location can expressively influence the system's thermal behavior.

Senobar et al. [14] revealed the improvement of thermal conductivity in RT44HC PCM utilising copper oxide Nanoparticles and copper metal foams, both separately and in combination. The associated findings ascertained a growth in heat transfer rate in a comparison to pure PCM: 13%, 17%, and 24% during melting, 24%, 26%, and 65% during solidification, and 7%, 11%, and 12% with constant heat flux.

Ghalambaz and Zhang [15] investigated a thermal storage system including two horizontal cylinders filled with metal foam and PCM, exposed to an internal pulse heat source and external cooling. Using the finite element method, the researchers perceived faster melting in the upper region as a result to convection, while solidification was slower, lasting approximately 2.5 times longer. The system attained meaningfully greater cooling competence than convection alone, encouraging the researchers to propose using uneven foam distribution design and heating offset for additional improvements.

Li et al. [16] demonstraed a composite material by integrating Nano-encapsulated phase change material (NEPCM) in copper foam to promote thermal energy storage performance. The associated findings indicated that lesser foam porosity can improve the heat transfer, reduce wall temperature by more than 47 °C, and guarateed more constant temperature distribution.

A combination of PCMs with a metal-foam layer was introduced by Shakibi et al. [17] for a PV cooling configuration to boost the heat dissipation at stable PV panel temperature. The researchers were focused on analysing the impacts of PCM thickness, foam material and its porosity on thermal performance and produced electricity. The results showed that increasing PCM thickness and using higher-porosity foam can significantly reduce the PV temperature and improve performance, yielding up to a 2.2% rise in power output. Minimal differences were observed between aluminum and copper foams. Alipour et al. [18] presented a three-dimensional model of a PVT system integrated with PCMs, copper foam, and a nanofluid to improve the heat regulation and overall performance. The researchers evaluated the effect of porosity, nanofluid concentration, and mass flow rate on the temperature distribution. The findings showed that integrating copper foam can increase the thermal efficiency by 25–33% and slightly improve the electrical efficiency by more than 3.9%.

While previous studies have thoroughly investigated the benefits of incorporating metal foams into PCMs to improve the overall performance of for solar thermal energy systems besides highlighting the contribution of specific integrated PCM-foam systems, there is still a necessity to conduct a comprehensive comparative analyses based research across different PCM types and a broad range of metal foam porosities. Furthermore, the previous investigations focused on limited porosity ranges, without systematically exploring the coupled effects on thermal performance. Thus, the current research intendes to fill this gap in the open literature. Specifically, it focuses on analysing the simultaneous impact of both factors (PCM and metal foam) on melting characteristics and overall system efficiency of solar thermal systems. This research attempts to investigate the thermal behavior of copper and aluminium foams at various porosity levels (85%, 90%, and 95%), in combination with two distinct commercial PCMs (RT42 and RT54HC) with different melting temperatures. The inventive perspective of this investigation lies in the comprehensive analysis of how these specific material combination and porosity variation can influence the heat storage and transfer characteristics under consistent solar thermal input conditions. This structured methodology would therefore deliver esteemed perception into optimal PCM-metal foam configurations for improved thermal energy storage systems, sugesting beneficial management for supported design and implication in solar energy systems.

2. Materials and Methodology

2.1 Materials

RT42 and RT54HC are the two selected types of PCMs that characterise by melting temperatures of 42 °C and 54 °C, respectively. The nominated PCMS are suitable for solar thermal energy storage and PV cooling applications. These PCMs are commercial products bought from Rubitherm® Technologies GmbH, a renowned manufacturer specializing in PCM technology. Rubitherm® products are documented for their high-quality, thermal stability, and prolonged consistency, assuring reliable energy system performance.

To upgrade the thermal conductivity of the PCMs, metal foams were integrated into the system. In this aspect, two kinds of foam were used including the aluminum and copper, each assessed at three different porosity levels of 0.85, 0.90, and 0.95. The thickness of the metal foam was maintained constant at 20 mm throughout the study to ensure consistent geometric parameters for comparison. The essential thermal properties of the selected PCMs are summarised in Table 1

Table 1. Thermal properties of PCMs, [19,20]

Parameter	RT42	RT54HC
Melting temperature (°C)	38-43 (41)	53-54 (54)
Heat storage capacity (kJ/kg)	165	200
Specific heat capacity (J/kg K)	2000	2000
Density solid (kg/m³)	880	850
Density liquid (kg/m³)	760	800
Thermal conductivity (W/m K)	0.2	0.2

2.1.1 Effective Thermal Conductivity

The effective thermal conductivity of the PCM-metal foam composite was estimated utilising the Boomsma model. This model is extensively acknowledged to predict the effective thermal conductivity of fluid-saturated metal foams, making an allowance for the thermal features of both the foam matrix and the embedded fluid (PCM in this case). The wide-ranging formulation of the Boomsma model can be conveyed as represented by Boomsma and Poulikakos [21]:

$$k_{eff} = k_f \left[\frac{1-(1-\varepsilon)^{1/3}}{1+\dfrac{1-(1-\varepsilon)^{1/3}}{\dfrac{k_s}{k_f}-1}} + (1-\varepsilon)^{1/3} \right] \quad (1)$$

k_{eff} is the effective thermal conductivity, k_f is the thermal conductivity of PCM, k_s is the thermal conductivity of the solid matrix (metal foam), and epsilon (ε) is the porosity of the metal foam. This model accounts for the complicated pore structure and the variable thermal conductivities of the constituent materials, given that a more precise approximation of the composite's overall thermal performance.

The measured effective thermal conductivities for the selected PCMs at various porosity ratios are depicted in Table 2. These values highlight the significant enhancement in thermal conductivity achieved by incorporating metal foams, that directly impacts the heat transfer rates within the composite material.

Table 2. Efficient thermal conductivity of selected PCMs at various porosity ratios

Materials	ε=0.85	ε=0.9	ε=0.95
Thermal conductivity of RT42 with copper metal foam (W/m K)	20.04	13.5	7.3
Thermal conductivity of RT42 with aluminium metal foam (W/m K)	10.3	6.9	3.8

2.2 Numerical Method

The simulation of melting behavior of PCMs improved with metal foams was conducted by developing a one-dimensional transient heat transfer model while considering a simulated solar energy input. A finite difference method was used to solve the developed model that characterised by a C++ program designed to competently handle time-stepping and boundary condition applications. The computational domain was discretized both spatially and temporally to guarantee precise depiction of heat propagation. At the boundary node x=0, a fixed heat flux of 2800 W/m² was assumed following to [22]. Further simulations were achieved with heat flux values of 1000, 2000, and 3000 W/m² to appraise their effect on the overall system efficiency. The opposite boundary at x= n-1 was designed as a convective boundary condition with a heat transfer coefficient of 20 W/m² K [23], while pretending heat loss to the surrounding environment. The initial condition also presumes that the PCM is at a constant temperature below its melting point [24]. This modeling technique, comprising 1D transient heat transfer with PCM improved by metal foam and the applied boundary conditions, is reinforced by recent investigations [25-27]. Figure 1 depicts a schematic diagram of the modal arrangement and associated boundary conditions. Indeed, the designed framework would enable to evaluate the effects of metal foam type, porosity, and selected PCM on the thermal efficiency and energy storage. The current methodology was characterised by the development of 1D model, that simplified the complex heat transfer phenomena, allowing for efficient analysis of the chief heat conduction mechanisms, that are expressively enhanced by the existed metal foam. Additional multi-dimensional investigations could invent convection effects more methodically.

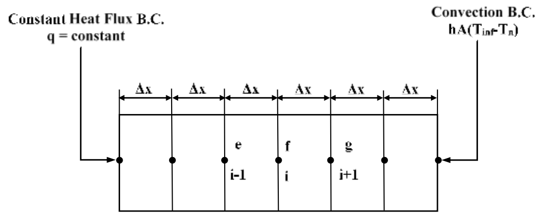

Figure 1. A representation of the one-dimensional heat transfer model with boundary conditions

Figure 2 depicts the overall construction of the numerical program utilised in the current research over a flowchart. The program starts with initializing variables and assigning required arrays, tracked by setting the initial conditions before entering the time loop. Internal values are calculated within this loop, where boundary conditions are employed at the west and east ends. Temperatures are also updated utilising the TDMA solver, and the associated results are written to files, representing the chief computational steps of the developed code.

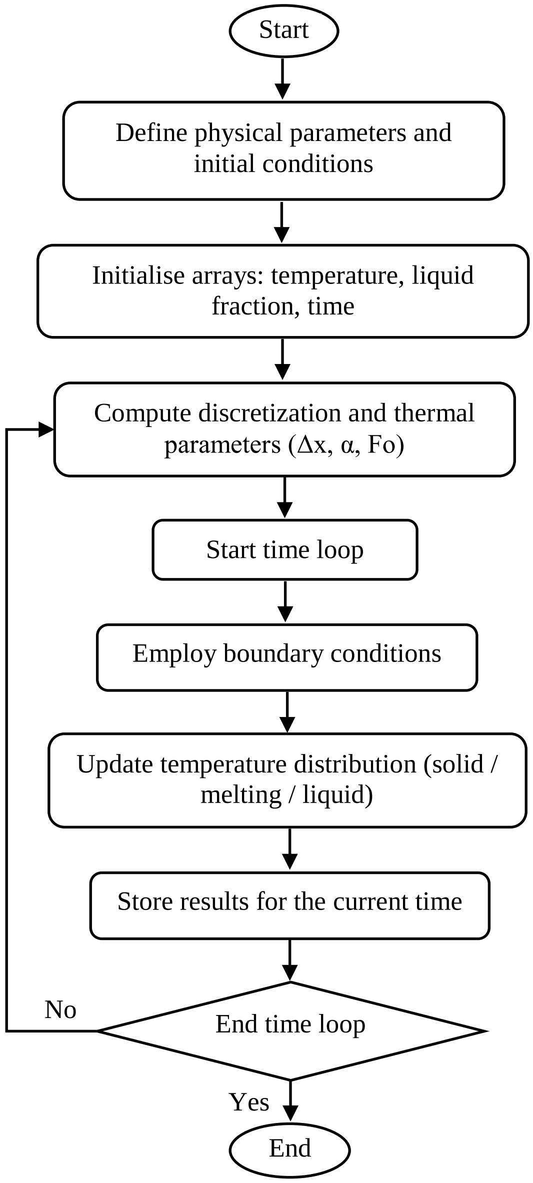

Figure 2. Flowchart of the numerical procedure for transient heat transfer

3. Results and Discussion

The numerical simulations delivered comprehensive visions into the thermal action of metal foam-embedded PCMs under transient heat flux conditions. The current section critically focuses on analysing the effect of metal foam kind, porosity, and PCM selection on melting time and temperature distribution.

Figure 3 shows the changes of temperature for RT-42 embedded with aluminium metal foam at three various porosity ratios of 85%, 90%, and 95%. First of all, all temperature curves depict an on-going growth until hitting the melting point, around at 255 s, after which they remain approximately fixed throughout the phase change process. This plateau specifies the absorption of latent heat by the PCM. Subsequent the accomplishment of melting, the temperature recommences its upward trend, representing the sensible heating of the liquid PCM. A central comment from these curves is the inverse relationship between porosity ratio and melting time for RT-42. Precisely, the recorded melting times are 1121 s, 1230 s, and 1326 s for porosity ratios of 85%, 90%, and 95%, respectively. This action is openly attributable to the improved thermal conductivity of the PCM composite at lesser porosity levels. A decreased porosity infers a greater volume fraction of the highly conductive aluminium foam within the composite, that would meaningfully compensate for the lesser conductivity of the PCM itself. This progressed efficient thermal conductivity enables faster heat transfer throughout the material, thus hastening the melting process. The reduction of 15.4% in melting time from 95% to 85% porosity (1326s to 1121s) can obviously demonstrate the practical benefit of lesser porosity in enhancing the energy storage competence.

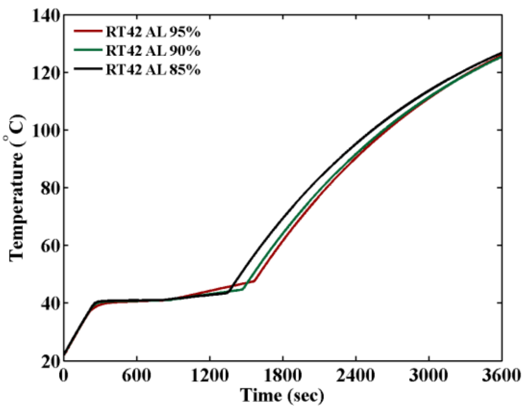

Figure 3. Effect of different porosity ratios of RT-42 with aluminium metal foam on temperature throughout the operational time

Figure 4 reveals the temperature variation over time for RT-54 embedded with aluminium metal foam at two porosity ratios: 85% and 95%. RT-54 has a higher melting temperature of 54 °C compared to RT-42. Similar to RT-42, the melting time for RT-54 embedded with aluminium metal foam at a porosity ratio of 85% is significantly faster than that at 95%. Specifically, the melting time of RT-54 at

85% porosity is around 10% faster than 95% porosity. This considerable decrease would ascertain the reliable trend detected with RT-42, underlining the universal advantage of lesser porosity in enhancing heat transfer rates across various PCM kinds. However, it is vital to realise that PCMs with lesser porosity agree to a lesser latent heat storage capacity as a result to the decreased volume of PCM itself. This demonstrates a critical design trade-off: while lesser porosity improves heat transfer kinetics, it simultaneously reduces the total energy storage capacity of the system. This balance should be cautiously deliberated based on the specific application necessities, where faster charging/discharging can be ordered over maximum energy density.

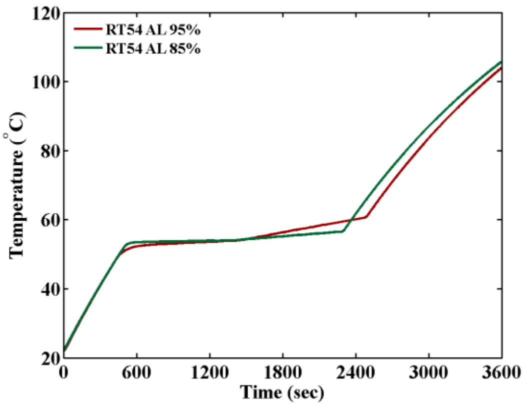

Figure 4. Impact of various porosity ratios of RT-54 of aluminium metal foam on temperature throughout the operational time

Figure 5 demonstrates the deviations of temperature throughout the operational time for RT-42 with copper metal foam at 85% and 95% porosity ratios. The effect of metal foam porosity on the melting time is more distinct with copper foam as a result to its greater thermal conductivity in a comparison to aluminium. The melting time for RT-42 with copper metal foam at 85% porosity is around 17 minutes (1007 seconds), while at 95% porosity, it outspreads to approximately 20 minutes (1170 s). This is an indication of a notable 14% decrease in melting time when using 95% instead of 85% porosity. This considerable variation can be principally ascribed to the greater thermal conductivity of copper, that causes a more effective and fast distribution of heat throughout the PCM. The growth in porosity, on the other hand, dilutes the highly conductive copper matrix, thus mitigating the efficient thermal conductivity and obstructing heat transfer. These outcomes muscularly aid the obtained conclusion that copper foam, particularly at lesser porosity, can deliver greater thermal performance for hastening PCM melting processes.

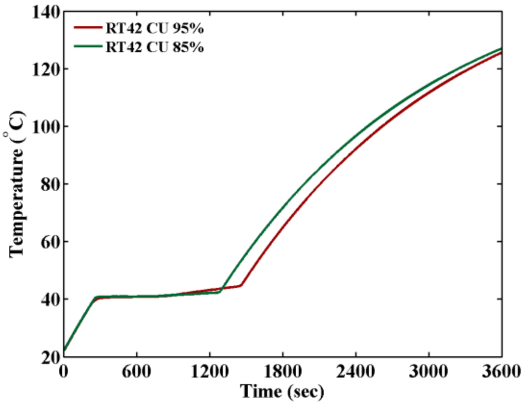

Figure 5. Impact of various porosity ratios of RT-42 of copper metal foam on temperature throughout the operational time

The discrepancy of temperature over the operational time for various PCMs, RT42 and RT54, when integrated to aluminium metal foam is depicted in Figure 6 using a fixed porosity ratio of 85%. The associated curves elucidate parallel thermal actions, categorized by an initial sensible heating phase, tracked by a melting plateau, and then extra sensible heating of the liquid phase. The major difference between the two curves is the melting temperature, that is essential to the type of PCM used (41 °C for RT42 and 54 °C for RT54HC). The obtained results are important as they indicate that while the PCM type dictates the operating temperature range and energy storage capacity (as RT54HC has a greater heat storage capacity of 200 kJ/kg compared to RT42's 165 kJ/kg), the central heat transfer dynamics, predominantly the rate of melting, are mainly impacted by the thermal characteristics of the embedded metal foam and its porosity. Accordingly, the appropriate PCM should be wisely selected for applications necessitating specific melting temperatures. In this aspect, the metal foam kind and porosity value can be optimised to attain favourable heat transfer rate, with the metal foam having a more central impact on the kinetic aspects of thermal performance. Furthermore, the latent heat of the PCM expressively affects the melting time. The melting time of RT42 was around 37% lesser than that of RT54 for the case of aluminium foam.

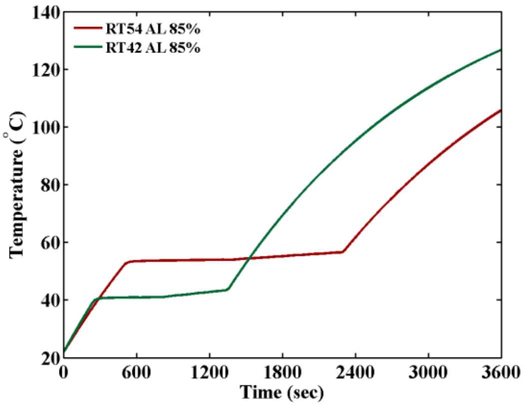

Figure 6. Temperature behaviour of RT-42 and RT-54 of aluminium metal foam against operational time at a constant porosity ratio of 85%

Regarding to the aforementioned findings, it is fair to admit that incorporating metal foams can meaningfully improve the heat transfer performance of PCMs, causing a generous decrease in melting time. This advantage is inversely relevant to the porosity ratio. Indeed, lesser porosity (greater metal content) can result in a faster melting. Copper foam reliably outpaces aluminium foam as a result to its greater thermal conductivity, delivering more radical decrease in melting time. However, lower porosity values can improve heat transfer kinetics, and then decreases the total latent heat storage capacity as a result to less PCM volume. The selection of PCM chiefly dictates the operating temperature range and overall energy storage, whereas the metal foam largely governs the rate of heat transfer within the composite system.

Figures 7 to 10 elaborate the consequence of heat flux on the melting time of PCM embedded with metal foams. Clearly, it can be stated that increasing the heat flux can lead to a reduction in the melting time. Three heat fluxes were investigated: 1000, 2000, and 3000 W/m^2. The criteria applied to choose these values were as follows: firstly, 1000 W/m^2 corresponds to the values of solar radiation, and the other two values (2000 and 3000 W/m^2) correspond to the values of solar radiation for concentrated solar systems. Figure 7 shows the effect of increasing heat flux on the melting time for RT42 with aluminium foam. The highest melting time occurs at 1000 W/m^2, which exceeds 2800 s. At a heat flux of 2000 W/m^2, the melting time is 1683 seconds. The lower value of melting time ١٠٢٢ s can be obtained at 3000 W/m^2. Figure 8 presents the RT54 with copper metal foam at three different heat fluxes. It can be observed that the melting time is higher than that of RT42 due to the high latent heat of RT54 if compared to that of RT42. The melting time is 2740 and 1600 s at 2000 and 3000 W/m^2, respectively. Furthermore, the heat flux of 1000 W/m^2 is out of the simulation ranging time of 3600 s for all the tested cases. The melting time of RT42 (٨٧٠ s) and RT54 (1553 s) with copper foam is lower than that of an aluminium foam as depicted in Figures 9 and 10 for RT42 and RT54, respectively.

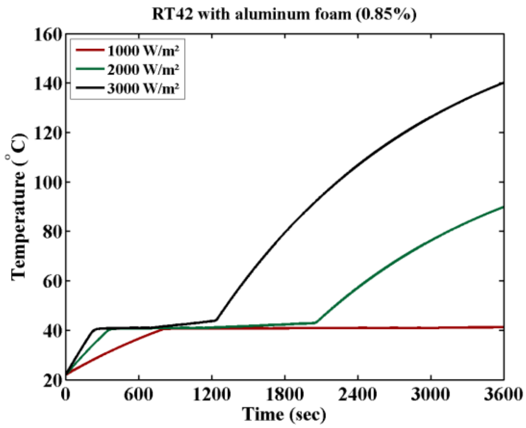

Figure 7. Temperature variation of RT42 against operational time with aluminium foam (85% porosity) under three heat flux levels

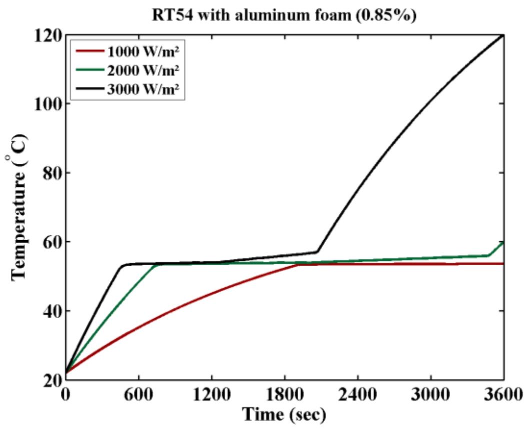

Figure 8. Temperature variation of RT54 against operational time with aluminium foam (85% porosity) under three heat flux levels

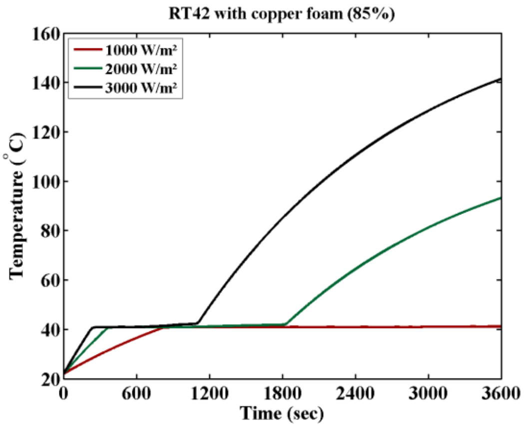

Figure 9. Temperature variation of RT42 against operational time with copper foam (85% porosity) under three heat flux levels

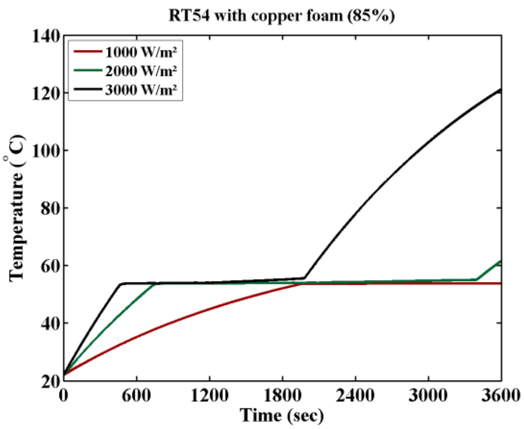

Figure 10. Temperature variation of RT42 against operational time with copper foam (85% porosity) under three heat flux levels

Figure 11 shows the comparison of melting time for RT42 at three porosity ratios (85%, 90%, and 95%) with aluminium and copper metal foams. At all porosity ratios, the copper metal foam exhibits a lower melting time if compared to the aluminium. The higher difference can be obtained at a porosity ratio of 90% at 214 s. Figure 12 represents the comparison of the melting time for RT54 at three porosity ratios. Specifically, the copper metal foam exhibits a lower melting time if compared to the aluminium metal foam but in less degree. The change in melting time between the two metal foams is less in the case of RT54 and it records the greatest difference at a porosity of 95%, where the melting time difference is 107 s between copper and aluminium metal foam at a porosity of 95%.

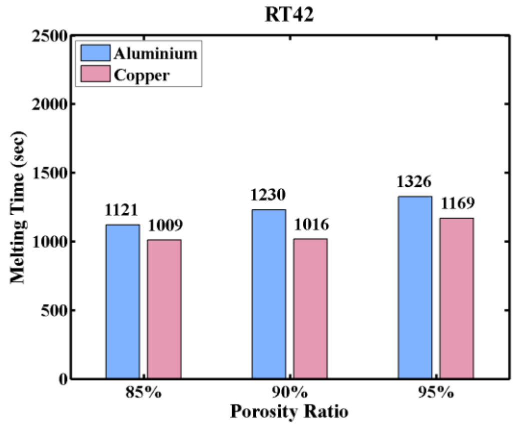

Figure 11. Comparison of the melting time of RT42 at three porosity levels (85%, 90%, 95%) with aluminium and copper metal foam

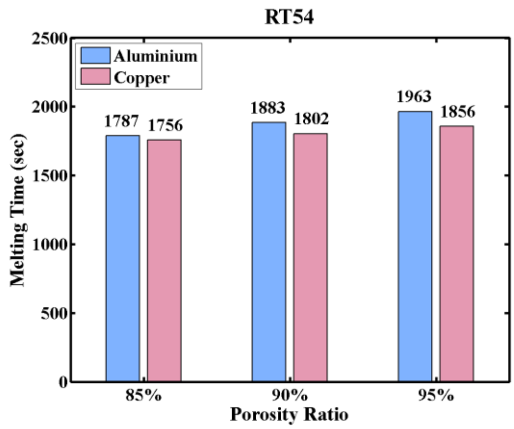

Figure 12. Comparison of the melting time of RT54 at three porosity levels (85%, 90%, 95%) with aluminium and copper metal foam

The results of the current study are compared in this section against those of previous similar studies with various values of heat flux, employing either copper or aluminium metal foam, as shown in Table 3. Although a direct comparison cannot be made directly due to the different boundary conditions, but this comparison can provide insight into the behavior of the PCM melting process. It observes agreement between the current study and previous studies in that increasing heat flux can lead to a shorter melting time. Similarly, the melting time is shorter when using phase-change materials containing copper than when using aluminium foams. Furthermore, the melting time of RT42 was shorter than that of RT54 when using the same metal foam type and at the same heat flux. This is attributed to the effect of latent heat; as the latent heat increases, the melting time also increases.

Table 3. Comparison of the results of the present study with the results of the previous studies

Study	PCMs	Metal foam	Heat flux (kW/m^2)	Melting time (s)
Diani and Rossetto [28]	RT42	Copper Foams	10	940
			15	705
			20	558
	RT55	Copper Foams	10	1332
			20	927
			30	728
Khan and Diani [29]	RT55	Aluminum Foams	6.25	4229
			12.50	1592
			18.75	1222
Present study	RT42	Aluminum Foams	1	N/A
			2	1683
			3	1022
		Copper Foams	1	N/A
			2	1470
			3	867
	RT54	Aluminum Foams	1	N/A
			2	2740
			3	1600
	RT54	Copper Foams	1	N/A
			2	2600
			3	1510

4. Conclusions

This research presented a theoretical investigation into enhancing the thermal performance of PCMs used in solar energy storage systems through the strategic incorporation of metal foams. The primary objective was to overcome the inherent low thermal conductivity limitation of PCMs by embedding aluminium and copper metal foams with variable porosities (85%, 90%, and 95%) and evaluating their influence when integrated to two commercial PCMs, RT42 and RT54HC.

The chief findings from this current analysis decorated the sense of integrated metal foams for amplified thermal energy storage. These findings can be summarised in the following:

- The melting (charging) and solidification (discharging) processes are specifically accelerated via the use of metal foams as they have a direct role in elevating thermal conductivity and improving energy discharge and recharge rates within PCM systems. This esteemed concept was translated to more efficient and responsive solar thermal applications.
- Comparing to aluminium foam, copper foam presented remarkable thermal performance as result to its greater thermal conductivity that allows faster heat distribution within the PCM composite, and therefore endorsing speedier phase change kinetics. However, aluminium foam ascertained a practical and cost-effective alternative with accepted efficiency, introducing it suitable for applications where cost is a major concern.
- The porosity ratio of the metal foam was recognised as a serious influential factor. The 85% porosity layout consistently generated greater heat transfer features as a result to its superior metal content, thus forming more vigorous and effective conduction ways throughout the PCM matrix. On the other hand, the 95% porosity, while permitting for a higher volume of PCM, occasioned in decreased thermal performance, supposing a direct trade-off between energy density and heat transfer kinetics.
- The decrease in melting time when reducing the porosity ratio from 95% to 85% was considerable (15.4% for aluminium metal foams and 10% for copper metal foams). This pointed the exponential effect of greater thermal conductivity and lesser porosity on system competence.
- The selection of PCM can play a clear role to achieve optimal performance. RT42, with its lesser melting point, established quicker response to heat, proposing it as a perfect candidate for passive PV panel cooling and moderate-temperature solar applications where rapid thermal regulation is favourite. However, RT54HC, possessing a greater melting point, is better suitable for thermal storage in greater-temperature systems, such as solar water heaters or concentrated solar power applications.
- Notwithstanding their various melting temperatures and energy storage capacities, both PCMs displayed similar essential thermal behaviors. They specifically similarly interacted with the metal foams, ascertaining that the main determinant of heat transfer rate is the metal foam's properties and porosity. However, the PCM manages the operational temperature range and overall energy stored.
- The highest performance of melting rate and thermal behavior were demonstrated for the RT42 integrated copper foam at

85% porosity, highlighting the prosperity for greatly efficient solar thermal energy storage systems.

The current research paid the efforts to analyse the capability of metal foam-PCM composites to afford valued tactics to attain the optimal design and process operation while assuring upgraded thermal energy storage systems. The outcomes signified the importance of structural design and material selection to overwhelmed the basic constraints of PCMs. Development of three-dimensional models can be a prosperous pathway for future investigation to precisely detect the complicated convection effects within the melted PCM. Furthermore, it is advantageous to assess the practical application and economic viability of the composite materials while constructing large-scale solar thermal applications. Investigating the stability of prolonged thermal cycling and material degradation of these composites under operational conditions is of utmost benefit. Furthermore, the potential of functionally graded metal foams or innovative foam structures can be investigated via optimising thermal performance and energy storage density.

Nomenclature

A	Area (m^2)
Fo	Fourier Number
h	Convection heat transfer coefficient ($W/m^2\,K$)
k_{eff}	Effective thermal conductivity (W/m K)
k_f	Thermal conductivity of PCM (W/m K)
k_s	Thermal conductivity of the solid matrix (W/m K)
LHTES	latent heat thermal energy storage
NEPCM	Nano-encapsulated phase change material
PCMs	Phase change materials
PV	Photovoltaic
q	Heat flux (W/m^2)
T_{inf}	Ambient temperature (°C)
α	Thermal Diffusivity (m^2/s)
Δx	Spatial step size (m)
ε	Porosity ratio (%)

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