Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Numerical Investigation of Hybrid Pin-Finned Heat Sinks filled with Phase Change Material for Optimized Thermal Performance in Mobile Electronics

Sandeep Kumar Sharma.[1], Tushar Choudhary[2*] and Harsh Pandey[3]

[1]Research Scholar, Mechanical Engineering, Dr. C.V Raman University Bilaspur, India
[2*]Assistant Professor, Sustainable Energy Technology Laboratory, Mechanical Engineering Department, PDPM Indian Institute of Information Technology Design and Manufacturing, Jabalpur, India
[3]Associate Professor, Dr. C.V Raman University Bilaspur, India Tushar.choudhary@iiitdmj.ac.in

ARTICLE INFO
Received: 09 Nov 2024
Accepted: 27 Nov 2024

ABSTRACT
A parametric and statistical analysis of a hybrid PCM–pin-finned heat sink under steady heat flux cooling for mobile electronic applications: A numerical study Latent heat storage using paraffin wax as phase change material (PCM) is considered, and heat transfer augmentation is achieved using aluminum circular pin fins. CFD transient analyses are performed with the enthalpy–porosity method to investigate the combined influence of PCM volumetric fraction, pin-fin diameter and applied heat flux density on thermal performances. The results show that the PCM integration decreases the peak temperature by 10–12% and delays the onset of heating by 15–20% in comparison with non-PCM configuration, illustrating efficient thermal buffering. Increasing the heat flux from 1500 W/m² to 3500 W/m² reduces of the order of 35–50% the duration time associated with the absorption of latent heat and surface peaking temperature by up to about 20%, which shows the shift, in strong dependence with FL. Et 12 The pin-fin size has a strong impact on the phase change dynamics—the increase in diameter improves PCM melting rate by 20–22% at mid-melting conditions, since the total heat transfer area increases. Nevertheless, beyond the optimum diameter of about 3 mm, additional thermal resistance is imposed whereby the heat capacity and thermal conductance decrease by 10–12%. Optimized finds can have a maximum heat capacity of about 3.5 kJ/K and increase the thermal conductance by around 30% compared to those with no fin. Analysis indicates convective resistance controlled - An experimental verification of above result shows that thermal enhancement is determined by a balance of the conductive surface increase and convective resistance. The statistically determined results supply design guidelines that can be physically interpreted for manufacturable, high performance PCM-based heat sink for compact and mobile electronics.

Keywords: *Hybrid Heat Sink, Phase Change Material, Heat Transfer, CFD*

Introduction

As the power density continues to increase in mobile electronic devices, advanced thermal management solutions are required for these devices to achieve efficient and reliable operation. Previous heat sinks traditionally use conduction and convection to cool, however, their effectiveness is often limited by increased miniaturization and power demand. Phase Change Materials (PCMs) have become a promising alternative to this, as they store energy in the form of latent heat where thermal buffering and peak load management will be enhanced. Nevertheless, the intrinsically low thermal conductivity of PCMs limits their capacity for heat dissipation, thereby requiring the implementation of high-conductivity structures, like metallic fins. Significant work has been carried out in the direction of improving thermal performance of heat sink through various approaches such extending fins inside PCM, sink orientation, nanofluid for various applications.
Sajid et al. [1] proposed a study of a segmented divides and hybrid channel heat sinks for high concentrator photovoltaic (HCPV) systems. The result of the analysis shows some effects of the heat sink arrangement, the concentration ratio, and Reynolds number in the performance of a high concentration triple-junction solar cell. Compared with a conventional straight channel design, the maximum solar cell temperature of the hybrid

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

channel is reduced by 39.5%, which leads to an increase of 39.5% in the Nusselt number. It also has a high value of performance evaluation criterion and this accompanied by light weight of the heat sink facilitates the use of the device in sun-tracking applications. Fu et al. presents a hybrid heat sink performance improvement optimisation strategy which combines Taguchi method, response surface method (RSM), non-dominated sorting genetic algorithm (NSGA-II) and TOPSIS. This technique reduces thermal resistance, average pressure drop, and temperature non-uniformity. The optimised design enhances coolant flow and heat dissipation, revealing microchannel heat sink design insights.

Abdulsahib et al. [3] focused on the numerical study through COMSOL Multiphysics regarding enhancement of heat transfer in heat sinks in terms of natural convective flow. Two key configuration types are studied: with and without solid fins and how heat transfer performs at increasing Rayleigh number, both of which are found to be improved with the use of porous fins. With an arrangement of half-squares outperforming half-circles, creating the absolute best thermal management possible. Another study indicates that the application of hybrid nanofluids alongside fin structures improves the performance of heat sinks as per their findings. Shahid et al. focused on a hybrid passive solar photovoltaic thermal management system through pin-fin heat sinks and forced convection. For 5 W and 10 W heat production, it decreases the temperature by 43.39% and 61.29%, accordingly. The cross-flow pattern results in 40.80% to 58.45% cooler temperatures than the reverse-flow pattern. You are used to produce reliability and efficiency.

Ghorbani et al. [5] investigate passive thermal management strategies using PCM to transfer 1 MW of electrical energy to commercial vehicles. They research hybrid solid-liquid phase change materials (PCMs) and heat sink topologies for charging heat dissipation. The combination of dissimilar PCMs enhances surface temperature control, particularly in hybrid configurations. An altitude model of instrument thermal performance is demonstrated through nonlinear 1D transient analytical model validation for heating at constant temperature and heat flow. Zhang et al. [6] proposed a hybrid active heat sink based on PCM to regulate transient lumped high heat flux shock electronic devices. The study targeted phase-change temperatures, heat transfer coefficient, heat sink features and porosity of porous metal structure. The findings showed that the hybrid heat sink was very efficient at maintaining temperatures, with a reduction of over 10 K.

S. Mahmoud et al. [7] experimentally studied the thermal behavior of PCM restricted between different arrangements of inserts. It was proposed that having more fins on the heat sink with additional parallel or crossing fins has the potential to increase more heat transfer, which then help in reducing the critical temperature. In addition, work on melting process in PCM with partial fins was carried by different authors. Lacroix and Benmadda [8] performed numerical experiments on PCM filling a rectangular container with horizontal fins heated from left. Increasing wall PCM thickness in the fins proved to increase natural convection effects. Huang et al. [9] they performed a study using both numerical and experimental approaches to investigate the thermal management of solar systems by placing half a horizontal fin. The authors noted improvements in temperature control. But adding fins increases flow restriction of convection process in the melted PCM, which reduces control effectiveness. L. Tan et al. [10] These studies have focused on the process of melting PCM in a finned rectangular container through a numerical investigation. Eight straight fin configurations were compared with four other alternative fin shape configurations (i.e. straight fin, T-shape fin, Y-shape fin, and cross-shape fin). The solution was found to desensitize heat transfer.

Kalbasi et al. optimised fin number in PCM-based heat sinks for thermal properties. The authors verified the optimisation regression model using ANOVA. Their findings show that the appropriate number of fins reduces with fin thickness and heat sink height, yet larger imposed heat fluxes require more fins for thermal management. Shatikian et al. quantitatively studied PCM melting in a finned heat sink with constant base heat flow. Vertical internal fins on a horizontal heated surface held the PCM. Variations in fin height, thickness, PCM layer thickness, and heat flow were used to parametrise the study. Transient simulations using ANSYS Fluent 6 showed that heat flux intensity, PCM thermal capacity, and fin shape greatly affect phase change dynamics. Dimensional analysis was used to demonstrate melt fraction and Nusselt number correlations as functions of Fourier, Stefan, and Rayleigh numbers.

Baby and Balaji tested PCM-based pin-fin heat sink thermal optimisation. Aluminium pin-fin heat sinks with different fin numbers were tried to change the PCM volume proportion of paraffin wax and n-eicosane. A finless PCM heat sink was used for baseline comparisons. The study showed that thermal performance is strongly correlated with PCM volume % and suggested design optimisation. An Artificial Neural Network–Genetic Algorithm (ANN–GA) hybrid technique was used to optimise the n-eicosane-based heat sink's working time. The optimised design worked for paraffin-based PCM systems also. For solar thermal applications, Sathe and Dhoble statistically analysed an inclined PCM-based heat sink with a finned PCM container. The RT42 PCM was used to explore PCM layer thickness, inclination angle, and fin number. Transient simulations

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

examined melting duration, velocity distribution, PCM temperature fields, and heater surface Nusselt number amplification. Extended surfaces lengthen melting duration, and a system sloped at 30° had a maximum Nusselt number boost of 6–9 times, indicating improved convective heat transport.
Bondareva et al. examined how PCM heat sink shape cools electronics. The work statistically evaluated lauric acid melting and solidification in metallic profiles separated into numerous PCM cells using plate fins. The phase transition process was modelled using finite differences. The results showed that adding PCM cells increases the system's effective thermal capacity, enhancing its transient thermal load management. An additively manufactured PCM-based heat sink with a topology-optimized, tree-like interior structure was tested by Ho et al. Combining topology optimisation with sophisticated manufacturing improved thermal performance dramatically. The tree-like heat sink had lower wall temperatures, 13% longer operational duration, and a maximum thermal enhancement ratio of 9.6, making it a promising next-generation electronic cooling solution.
Gado studied electronic heat management using triply periodic minimum surface (TPMS) structures and PCM. TPMS configurations Gyroid, IWP, and Primitive were tested under pulsed power with passive and active cooling. The impact of TPMS relative density (10–30%) was measured. Compared to pure PCM heat sinks, PCM-TPMS heat sinks expedited PCM melting and improved heat transport routes, lowering base temperature. The PCM-Gyroid arrangement performed best. The study also showed that PCM-TPMS topologies reduce heat cycling, enhancing electronic component reliability and durability.Shailesh et al. tested an n-eicosane-based finned PCM heat sink with a heat pipe for electronic cooling. Finless, centrally stemmed, multi-fin, and finless heat sinks were examined. Systematic study examined PCM fill ratio and heat input effects. The best performance was at 99% PCM fill ratio. A sintered heat pipe and three-fin heat sink improved charging and discharging times at all power levels. The finned heat sink with heat pipe performed better overall, proving its practicality for electronic thermal control.
Yang et al. investigated LMPM–based PCM heat sinks using a eutectic Bi–In–Sn alloy experimentally and numerically. The alloy's thermophysical characteristics were characterised and compared to an organic PCM (octadecanol) under different heat fluxes. We examined heat sinks with varying internal cross-fin counts. The LMPM-based heat sink has higher thermal performance, cyclic stability, and no supercooling. Heat sink design and optimisation may be computationally efficient with a reduced three-dimensional conjugate numerical model verified against experimental data.
Final experiments by Jalil et al. examined how PCM integration affects forced convection heat sink cooling. Different input power levels and air flow velocities were tested for heat sinks with and without PCM. Using paraffin wax as the PCM, Al_2O_3 nanoparticles were added for further improvement. PCM integration lowered heat sink temperatures by 18 °C, and adding 2% nanoparticles increased thermal performance, proving nano-enhanced PCM systems work.

Novelty of the present work

Authors	System / Approach	Key Findings	Identified Limitations / Research Gap
Sajid et al. [1]	Hybrid channel heat sink for HCPV systems	Hybrid channel reduced cell temperature by ~39.5% and enhanced Nusselt number; lightweight design suitable for tracking systems	Focused on liquid cooling and HCPV applications; no PCM integration or latent heat utilization; not applicable to compact electronic thermal management
Fu et al. [2]	Microchannel heat sink optimization using Taguchi–RSM–NSGA-II–TOPSIS	Reduced thermal resistance, pressure drop, and temperature non-uniformity	Active liquid cooling only; PCM-based passive thermal buffering not considered
Abdulsahib et al. [3]	Natural convection heat sink with porous fins (COMSOL)	Porous fins enhanced heat transfer at higher Rayleigh numbers	No PCM inclusion; steady natural convection focus; transient thermal storage effects ignored
Shahid et al. [4]	Pin-fin heat sink with forced convection for PV	Temperature reduction up to ~61% under forced flow	Requires external airflow; lacks passive thermal regulation using PCM

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Ghorbani et al. [5]	Hybrid PCM-based passive thermal management for EVs	Hybrid PCMs improved surface temperature control; analytical transient model validated	Large-scale (MW-level) systems; not suitable for compact electronics; limited geometric parametric study
Zhang et al. [6]	Hybrid active PCM heat sink for high heat-flux electronics	Temperature reduced by >10 K during thermal shocks	Relies on active cooling; porous structures increase fabrication complexity
Mahmoud et al. [7]	PCM with multiple fin insert arrangements (experimental)	Increased fin density reduced peak temperature	Lacked optimization of fin geometry and PCM fraction; limited performance metrics
Lacroix & Benmadda [8]	Numerical PCM melting in finned container	Increased PCM thickness enhanced natural convection	Geometry restricted to simple rectangular containers; not linked to electronic heat sinks
Huang et al. [9]	Half-fin PCM system (numerical + experimental)	Improved temperature regulation	Excessive fins restricted natural convection in melted PCM; optimal fin size not defined
Tan et al. [10]	PCM melting with different fin shapes	Fin geometry affects melting behavior	Did not relate fin shape to operational time or thermal conductance
Kalbasi et al. [11]	Fin number optimization in PCM heat sinks (ANOVA)	Optimal fin number decreases with fin thickness and height; increases with heat flux	Focused only on fin number; PCM volume fraction and fin diameter effects not explored
Shatikian et al. [12]	PCM melting with vertical internal fins (ANSYS Fluent)	Melt fraction and Nu correlated with Fo, Ste, Ra	Purely numerical; no assessment of operational time or design optimization
Baby & Balaji [13]	Experimental PCM pin-fin heat sink + ANN–GA	Optimized operating time for n-eicosane PCM	Limited insight into transient heat flux variation and fin diameter effects
Sathe & Dhoble [14]	Inclined finned PCM heat sink (RT42)	Nusselt number enhanced 6–9× at 30° inclination	Application-specific (solar); inclination effects not relevant to electronics
Bondareva et al. [15]	Multi-cell PCM heat sink geometry	Increased effective thermal capacity	Did not evaluate optimal fin size or PCM utilization efficiency
Ho et al. [16]	Topology-optimized PCM heat sink (AM)	13% increase in operational time; high enhancement ratio	Complex geometry; high manufacturing cost; limited parametric transparency
Gado [17]	PCM–TPMS heat sinks	Gyroid TPMS most effective; reduced thermal cycling	Additive manufacturing dependence; scalability and simplicity issues
Shailesh et al. [18]	PCM finned heat sink + heat pipe	Charging/discharging time improved >20%	Hybrid system complexity; difficult isolation of PCM–fin effects
Yang et al. [19]	LMPM-based PCM heat sink	Superior thermal performance; no supercooling	High cost and density of LMPM; limited suitability for mobile electronics
Jalil et al. [20]	PCM + nanofluids under forced convection	Temperature reduced by ~18 °C	Nanoparticle stability and fin–PCM interaction not addressed

This study aims to provide a systematic and interpretable analysis of a hybrid PCM–pin-fin heat sink under realistic heat flux conditions relevant to applications, addressing the identified gaps in the literature. This study simultaneously evaluates the interrelated effects of pin-fin diameter, PCM volume fraction, and applied heat flux density on the transient thermal response of the system, in contrast to earlier works that examined these factors independently. Emphasis is placed on quantifying key performance indicators that are frequently addressed in isolation in the literature, such as melting dynamics, operational time enhancement, effective

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

heat capacity, and thermal conductance. A high-fidelity CFD-based parametric framework implemented in ANSYS is utilised to analyse phase change behaviour and heat transfer mechanisms comprehensively, facilitating the identification of optimal design regimes grounded in physical insight rather than empirical adjustments. The proposed approach maintains geometric simplicity and manufacturability, ensuring practical relevance for compact and mobile electronic thermal management applications. This effectively bridges the gap between advanced PCM-based heat sink concepts and deployable engineering solutions for next-generation electronic sustaining applications.

Mathematical modelling

The analysis is based on the fundamental conservation laws of mass, momentum, and energy, which together describe the fluid flow and heat transfer processes within the hybrid heat sink.

1.1 Mass Conservation (Continuity Equation)

For an incompressible fluid, the continuity equation ensures that mass is conserved throughout the domain:
$\nabla \cdot u = 0$
where u is the velocity vector. In this simulation, the assumption of incompressibility is valid given the relatively low-speed and moderate temperature gradients, which minimizes density variations. For flows where density variations are non-negligible, a compressible form of the continuity equation would be required.

1.2 Momentum Conservation

The momentum conservation equation is given by the Navier–Stokes equations, which account for the inertial, viscous, and pressure forces acting within the fluid:
$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \mu \nabla 2u + F$
Inertial Term: $\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right)$represents the change in momentum.
Pressure Gradient: $-\nabla p$ drives the flow.
Viscous Term: $\mu \nabla^2 \mathbf{u}$ accounts for the internal friction within the fluid.
Body Forces: **F**includes any external forces such as gravity. In the context of PCM phase change, buoyancy forces arising from temperature-dependent density variations may be included via the Boussinesq approximation.
In regions where phase change occurs, especially within the mushy zone, the local structure of the PCM may resist fluid motion. To account for this, a damping term derived from Darcy's law is introduced:

$$\mathbf{S}_{\text{mushy}} = -C\frac{(1-f)^2}{f^3 + \epsilon}\mathbf{u},$$

where $f$is the local liquid fraction, $C$is a mushy zone constant that characterizes the resistance to flow, and $\epsilon$is a small number to avoid division by zero. This term effectively reduces the velocity in regions transitioning from liquid to solid.

1.3 Energy Conservation

The energy equation describes how thermal energy is transported via conduction and convection and is influenced by internal heat sources or sinks:

$$\rho c_p\left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) = \nabla \cdot (k \nabla T) + Q,$$

where:

- $T$is the temperature,
- $c_p$is the specific heat capacity,
- $k$is the thermal conductivity, and
- Qrepresents any volumetric heat generation or absorption.

In the context of PCM phase change, the latent heat effect is not directly visible in the classical energy equation. Instead, it is incorporated through a reformulated enthalpy method (discussed in detail in the Phase Change Modelling section). This reformulation allows the simulation to capture both sensible and latent heat contributions within a unified framework.

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Modelling of Phase change material

Phase change in the PCM (paraffin wax) is modelled using the enthalpy–porosity method. This approach integrates the latent heat effect into the energy equation, allowing the simulation to capture the melting and solidification processes continuously.

2.1 Enthalpy Formulation

The total enthalpy H of the material is defined as the sum of sensible heat and latent heat contributions:

$$H = c_p T + Lf,$$

where:

- $L$is the latent heat of fusion,
- $f$is the liquid fraction, varying from 0 (completely solid) to 1 (completely liquid).

This formulation ensures that the energy absorbed or released during the phase change is accurately represented.

2.2 Liquid Fraction and the Mushy Zone

The liquid fraction $f$is a temperature-dependent variable that models the phase transition over a finite temperature range. It is typically defined as:

$$f(T) = \begin{cases} 0, & T \le T_s, \\ \dfrac{T - T_s}{T_l - T_s}, & T_s < T < T_l, \\ 1, & T \ge T_l, \end{cases}$$

where:

- $T_s$is the solidus temperature,
- $T_l$is the liquidus temperature.

This linear interpolation within the mushy zone allows for a smooth transition between the solid and liquid phases. The mushy zone represents the temperature range in which both solid and liquid phases coexist, and its properties are intermediate between those of the fully solid and fully liquid states.

2.3 Incorporation into the Energy Equation

In practice, the energy equation is reformulated to account for the enthalpy change:

$$\rho \frac{\partial H}{\partial t} + \rho \mathbf{u} \cdot \nabla H = \nabla \cdot (k \nabla T) + Q.$$

This approach implicitly couples the temperature field with the latent heat effect via the enthalpy H, allowing the solver to automatically adjust the energy balance as the PCM undergoes phase change.

2.4 Numerical Treatment of Nonlinearity

The nonlinear relationship between temperature and enthalpy due to the phase change is addressed by:

- Using an implicit time-stepping scheme to enhance stability during rapid transitions.
- Iteratively solving the coupled equations until convergence is achieved.
- Incorporating the mushy zone damping term into the momentum equations to suppress unrealistic fluid motion in partially melted regions.

This numerical strategy ensures that the phase change process is captured accurately and that the transient behavior of the hybrid heat sink is resolved with sufficient detail.

Methodology

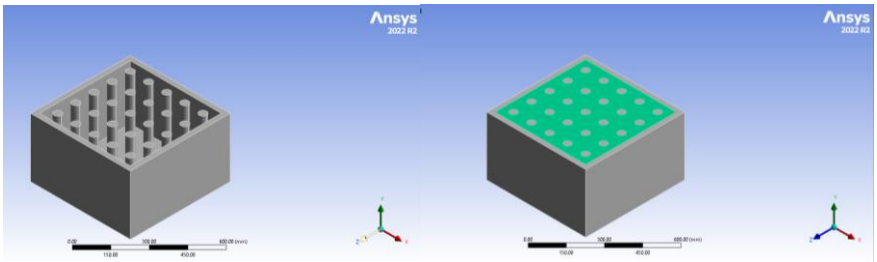
Figures 1 and 2 depict the computational model and meshing process used in the numerical analysis of a hybrid pin-finned heat sink combined with phase change material (PCM) to optimize thermal performance in mobile electronics. Figure 1 displays the heat sink without PCM, in which cylindrical pin fins enhance convective heat dissipation, and in Figure 1b, PCM fills the voids between the fins, enabling latent heat absorption and delaying temperature rise to maintain stable thermal performance. Figure 2 shows the mesh model consisting of over a

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

quarter million elements validated through a grid independence study ensuring computational efficiency and accuracy. A structured hexahedral mesh is applied with refined grids near the fins and PCM region precisely capturing conduction, convection, and phase transition effects. The finite volume method employing the enthalpy-porosity approach models PCM phase change. Boundary conditions include a uniform heat flux at the base, natural convection on exterior surfaces, and an initial temperature of 293 K. A transient simulation uses time steps of 1-5 seconds running 150-200 minutes evaluates PCM charging and discharging cycles. The research aims to demonstrate the hybrid heat sink with PCM improves thermal regulation by significantly reducing peak temperatures and enhancing cooling effectiveness making it suitable for high-powered mobile electronics.



(a) (b)

Figure 1 CAD model of Hybrid Heat sink(a) without PCM (b) with PCM

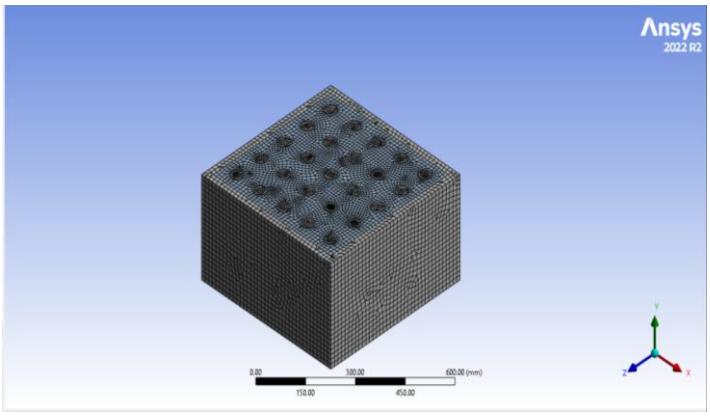


Figure 2 Mesh model

Grid Independence Test

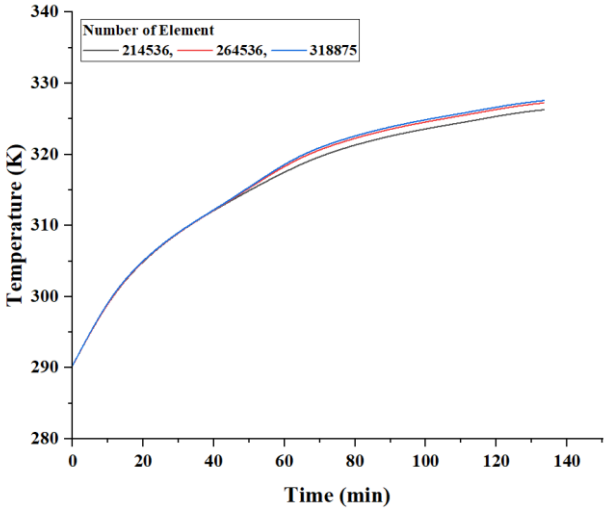


Figure 3 **Grid Independence Test**

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

the tabulated graph shows a grid independence test of temperature response of a hybrid heat sink with varying mesh element counts of 214536 (black), 264536 (red), and 318875 (blue). The temperature profiles remain very similar, indicating that the scheme is numerically stable and converges for different grid sizes.
Statistically significant differences in peak temperature between the 214,536 and 264,536 element cases are <0.5% and <0.3% for the difference between 264,536 and 318,875 elements. This indicates that this further mesh refinement does not significantly change the resultant temperature response with a maximum deviation of 1% across all cases. The results validate that the mesh with 264,536 elements is sufficient to reach accurate results in the simulation while maintaining computational efficiency without sacrificing precision. The results guarantee the credibility of the selected mesh in thermal simulations of hybrid heat sinks, preventing unnecessary computational expenses while preserving fidelity.

Result and Discussion

Influence of volumetric PCM fractions

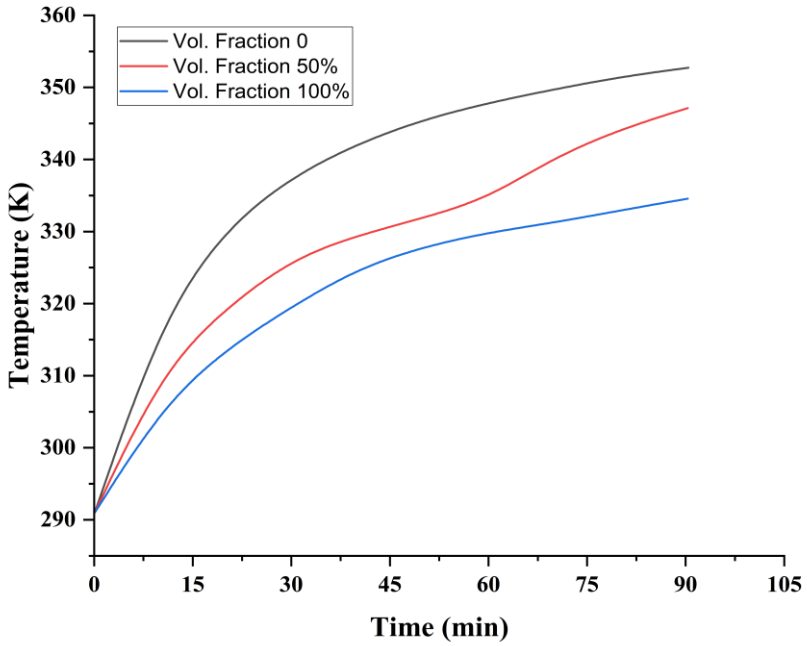


Figure 4 Influence of volumetric PCM fractions on temperature of a hybrid heat sink

Figure 4 shows with time temperature response of a hybrid heat sink for different volumetric fractions of the phase change material (PCM): 0%, 50% and 100%. The curves show the change in the heat sink thermal performance with increasing PCM fraction. The black curve (Vol. Fraction 0%) system that would show the most temperature increase with time. The red curve (Vol. However, the blue curve (Vol. Fraction 50%) shows a controlled temperature drop. Sample S4 (a mixture ratio of PCM to polymer fraction 100%) exhibits the greatest reduction in temperature, suggesting improved thermal regulation with increased PCM incorporation.
With approximately 5–7% temperature decline at 50% PCM volume fraction (through statistical quantification) as compared to the 0% PCM case, it confirms superior thermal buffering. The peak temperature drops by 10–12% with 100% PCM fraction, thus validating a significant improvement in thermal control. The initial temperature rise is also impacted, where temperature increases 15–20% slower in the first 30 minutes for the 100% PCM case than for the 0% PCM case.
This trend highlights the potential of PCM to reduce temperature fluctuation and improve heat sink performance. The elevated PCM fractions were evidenced to enhance thermal management with significant time delay for temperature elevation while maintaining lower operating temperatures. On the other hand, an increase in PCM fraction leads to a decreasing difference in temperature with the increase in PCM fraction beyond a certain limit, which is clearly visible by comparing the 50% with the 100% cases in temperature

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

series. These experiences are relevant to designing hybrid heat sinks for electronics cooling, energy storage, and thermal management applications, particularly due to the critical impact of PCM integration in reducing thermal fluctuations within a system and improving reliability.

Influence of input heat flux densities on temperature profile

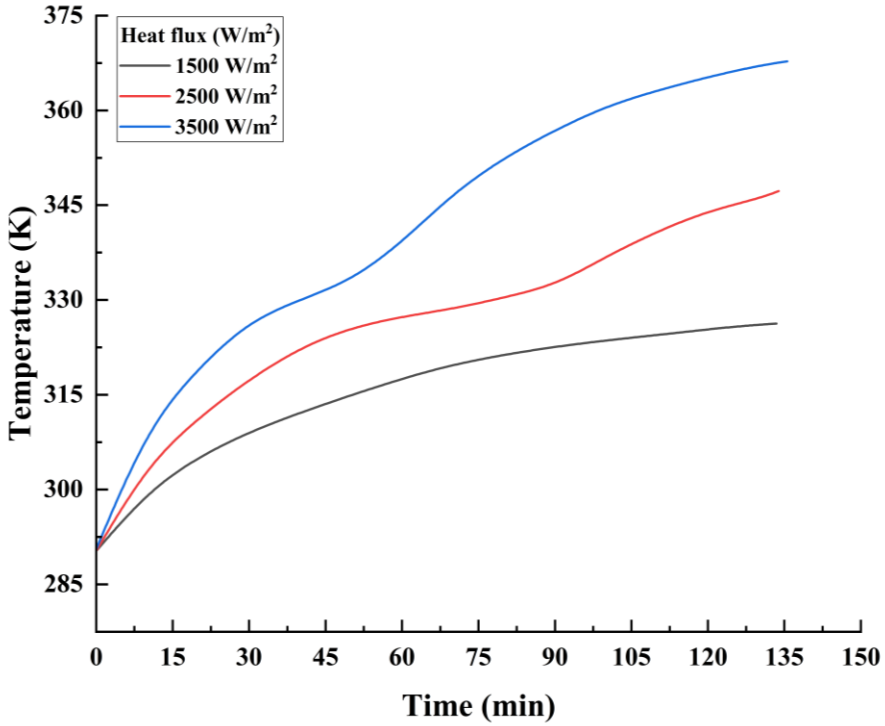


Figure 5 Influence of input heat flux densities on temperature profile

A series of heat fluxes from 1500 W/m² to 3500 W/m² are imposed on the base of the heat sink, and the respective temperature response is outlined in figure 5. The result shows that with an increasing input heat flux, the latent heating phase of the phase change material (PCM) shortens, which stands within reasonable behavior. In particular, the duration of the latent heat of the PCM is about 35–50% shorter in terms of heat flux increasing from 1500 W/m² to 3500 W/m². This is due to the fact that a higher heat flux enhances the heat absorption rate, resulting in a more rapid change from solid to liquid.

Moreover, the peak temperature at 135 minutes enhances by ~12% when considering 1500 W/m² case (~325 K) and 2500 W/m² case (~345 K). A comparable 20% rise of peak temperature can be seen comparing the section 1500 W/m² to 3500 W/m² (~365 K). Similarly, the 3500 W/m² case has a 25–30% steeper increase in temperature in the first 30 minutes in comparison with the 1500 W/m² case.

Such variations are important in thermal energy storage applications, as they illustrate the effect of heat flux on the thermal response and efficiency of the PCM itself. For applications like solar thermal systems, hybrid energy storage, and passive cooling technologies, shorter latent heating phases allow quicker storage and retrieval of heat,which is an advantage. Understanding this statistical variance aids in better heat sink designs, PCM selection and phase change material thermal management.

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Influence of Pin diameter on liquid fraction

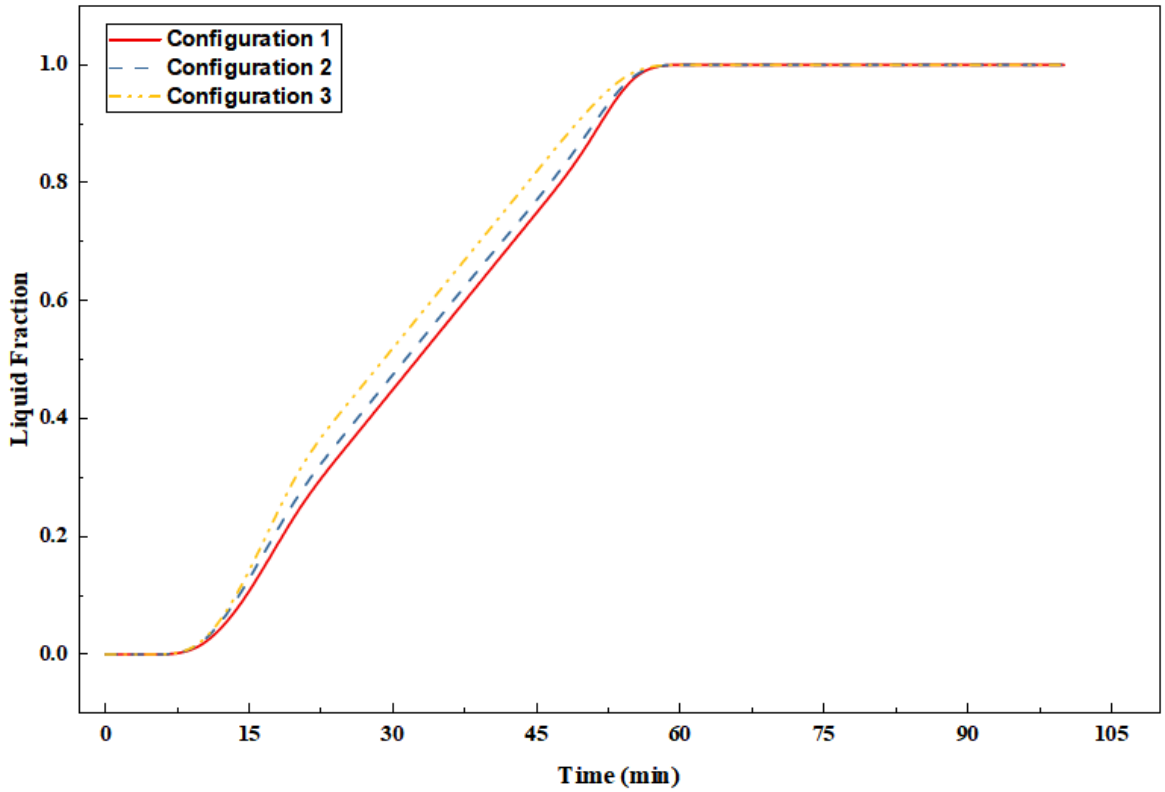


Figure 5 Influence of input heat flux densities on temperature profile

The figure illustrates the time-dependent changes in the PCM liquid fraction across three heat sink configurations, specifically with pin-fin diameters of 2 mm (Configuration 1), 3 mm (Configuration 2), and 4 mm (Configuration 3), all subjected to a constant heat flux of 2500 W/m². The melting process consistently demonstrates a sigmoidal trend. It starts with an initial period of sensible heating, during which the liquid fraction is nearly zero. This is followed by a phase of significant latent heat absorption, where the liquid fraction increases swiftly. Finally, the process reaches a saturation stage, culminating in complete melting and a liquid fraction that approaches unity.

An evident quantitative enhancement in melting performance is noted as the pin-fin diameter increases. In the active phase-change regime, which lasts approximately 15–50 minutes, Configuration 3 consistently exhibits a greater liquid fraction compared to Configurations 2 and 1. At approximately 30 minutes, the liquid fraction for the 4 mm pin-fin configuration is around 0.55, whereas the 3 mm configuration shows about 0.50, and the 2 mm configuration indicates a liquid fraction of 0.45. An enhancement of nearly 10% is observed when the pin diameter is increased from 2 mm to 3 mm, and an approximate increase of 20–22% occurs when the diameter is raised from 2 mm to 4 mm under mid-melting conditions. In a similar manner, the duration needed to achieve full melting decreases with an increase in pin diameter. Configuration 1 attains complete liquefaction in roughly 58–60 minutes, while Configuration 3 reaches this state in about 52–54 minutes, indicating a decrease in total melting time of approximately 8–10% compared to the smallest pin-fin diameter.

The fundamental principles that dictate this behaviour are intricately connected to the enhancement in effective heat transfer surface area that results from larger pin-fin diameters. A larger pin diameter directly improves the solid–PCM interfacial area, thereby enhancing conductive heat transfer from the heated base into the PCM in the initial phases of melting. With an increase in the liquid fraction, the expanded heated surface enhances buoyancy-driven natural convection within the molten PCM, leading to improved heat redistribution and a faster progression of the solid–liquid interface. The integration of conductive and convective processes leads to an increased melting rate and a more pronounced increase in liquid fraction as pin diameters increase. Although there are variations in transient behaviour among the configurations, they all reach a liquid fraction of unity. This suggests that while enhancing surface area can improve the rate of

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

latent heat utilisation by approximately 20%, the total latent heat storage capacity is still determined by the mass of the PCM.

Evolution of Temperature Profiles in PCM during charging and discharging

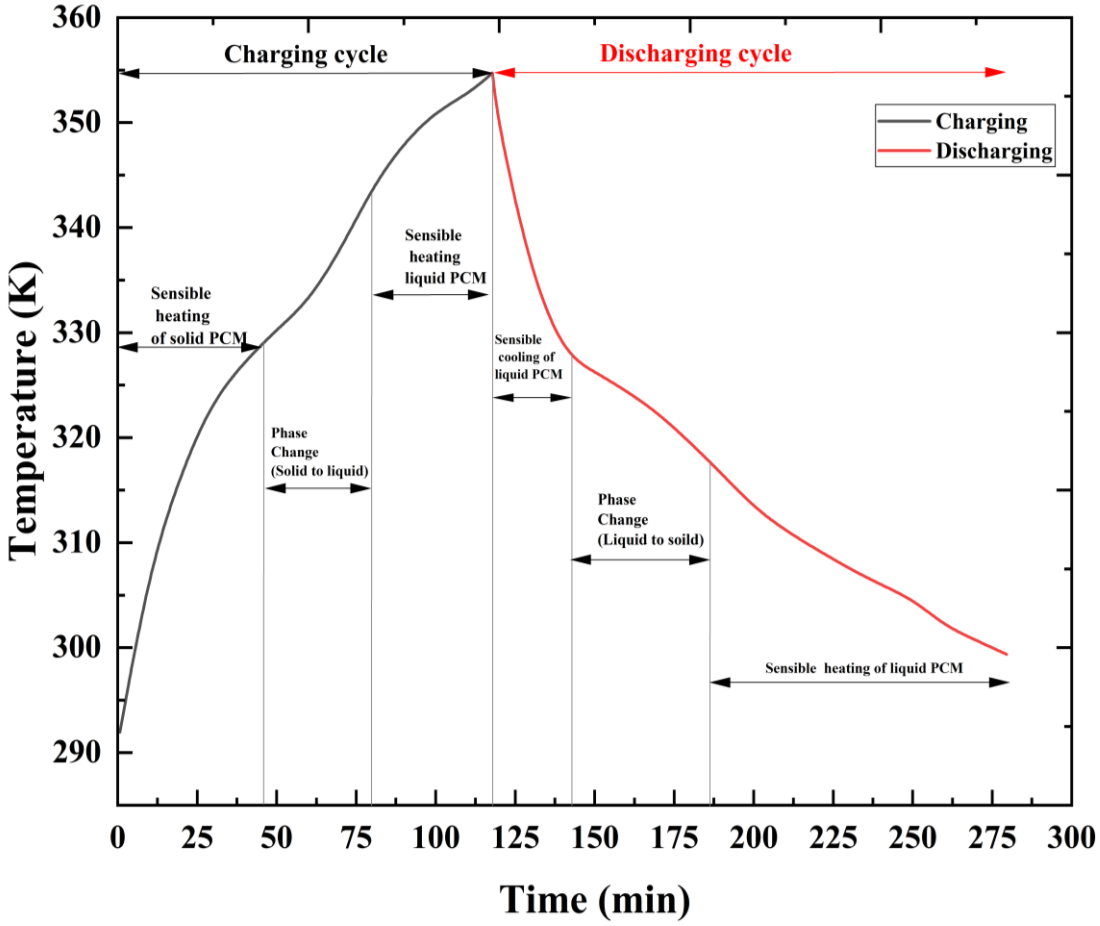


Figure 6 Evolution of Temperature Profiles in PCM during charging and discharging

This figure 6 presents the charging and discharging cycles of hybrid heat sink, where the phase change material (PCM) temperature as a function of time is presented under a heating power of 2500 W/m². The charge cycle (black curve) corresponds to the heating process, while the discharge cycle (red curve) corresponds to the cooling process.

First, sensible heating is observed of solid PCM in the charging phase, occurring where in the first 50 mins the temperature increases by 15% (from 295 K to 330 K). The solid-to-liquid phase change has a duration of approximately 30–40 min, during which the temperature is kept almost constant due to the absorption of latent heat. Then, the sensible heating of the liquid PCM occurs where the temperature rises by an additional 6–8% (from 335 K to 355 K) in the next 50 min, attaining the peak temperature. During the discharging cycle, the sensible cooling of the liquid PCM reduces the temperature by 5% (355 K to 340 K) within the first 25 min. It is followed by a liquid-to-solid phase change for about 50–60 min, having wider latent heat release period than the charging phase. Finally, sensible cooling of the solid PCM takes place, resulting in a gradual temperature decline of 12–15% (from 320 K down to 295 K) over the course of approximately 100 min.

The charging and discharging cycles have a significant asymmetry with 20–30% longer discharging times (supercooling effects, thermal resistance and heat loss mechanisms). A comparative performance analysis of minutes and hours would be beneficial for hybrid heat sink applications, as the heat flux, phase transition duration and heat ex- change carrier rate greatly affects PCM performance. To improve the energy efficiency and operational stability of thermal energy storage (TES) systems, electronic cooling devices and hybrid solar thermal applications, it is crucial to understand these variations.

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Influence of pin diameter & input heat flux densities on operational time enhancement

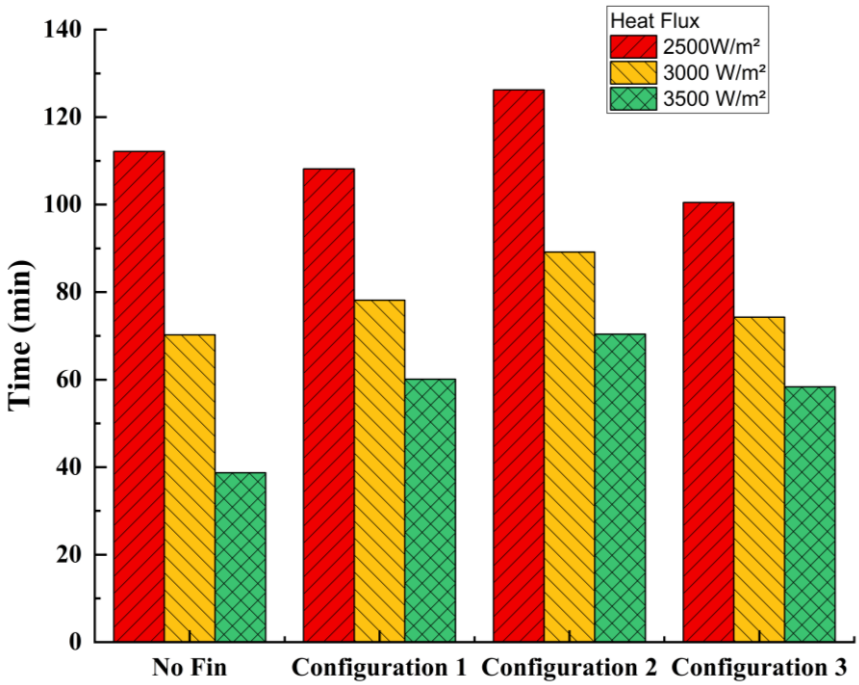


Figure 7 Influence of pin diameter & input heat flux densities on operational time enhancement

Figure 7 presents the duration (in minutes) required for the phase change material (PCM) to finalise its thermal cycle across different heat sink assemblies (No Fin, configuration 1, 2, and 3) at three distinct levels of heat flux (2500 W/m², 3000 W/m², and 3500 W/m²). The results highlight the influence of heat flux and fin configuration on the duration of the thermal response period.

At 2500 W/m2, the No Fin configuration necessitates around 110 minutes, whereas configuration 1, featuring 2mm diameter pins, slightly decreases this duration to 105 minutes, representing a 5% reduction. Configuration 2, which utilises 3mm diameter pins, demonstrates optimal performance, requiring 125 minutes—a 13.6% increase compared to No Fin—indicating improved heat dissipation and storage capabilities. Design 3, which employs 4mm diameter pins, demonstrates a minor reduction in functionality, reflected in a cycle time of 100 minutes, approximately 9% lower than that of configuration 2.

With an increase in heat flux to 3000 W/m², there is a noticeable reduction in the thermal cycle duration for all assemblies. The No Fin configuration reduces to 70 minutes, reflecting a 36% decrease from 2500 W/m². Design 1 adjusts to 75 minutes, indicating a 28.6% decrease. Configuration 2 is set at 85 minutes, showing a 32% decrease, while configuration 3 is at 72 minutes, marking a 28% decrease. At 3500 W/m2, there is a noticeable reduction in the cycle time. The No Fin configuration results in a duration of 40 minutes, reflecting a 64% reduction from 2500 W/m². Configuration 1 achieves 60 minutes, indicating a 42.9% reduction. Configuration 2 extends to 68 minutes, corresponding to a 45.6% reduction, while configuration 3 attains 55 minutes, which represents a 45% reduction.

Configuration 2, which utilises 3mm diameter pins, consistently exhibits the longest phase change period, indicating efficient heat absorption and storage. In contrast, configuration 3, featuring 4mm diameter pins, shows a minor reduction in performance, presumably due to heightened thermal resistance. The data indicates that a rise in heat flux significantly reduces PCM cycle time, achieving up to a 64% decrease at 3500 W/m² compared to 2500 W/m². This highlights the importance of selecting the optimal pin diameter for effective thermal energy storage applications.

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Influence of pin diameter on heat capacity

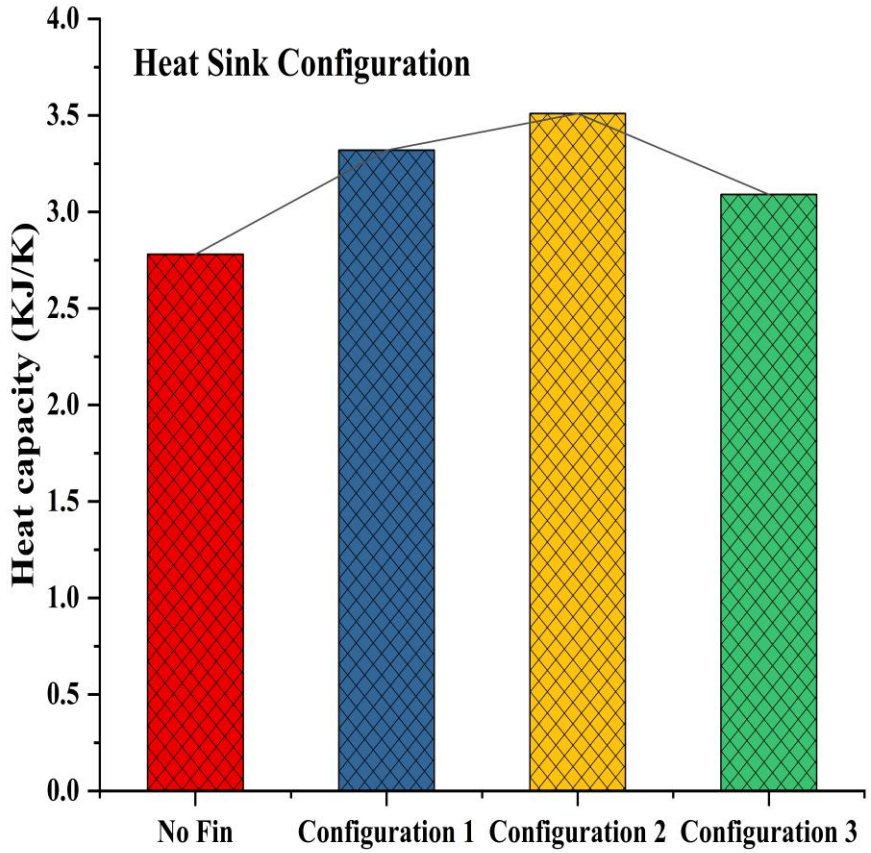


Figure 8 Influence of pin diameter on heat capacity

Heat capacity (KJ/K) of various heat sink configurations, i.e., No Fin, Config 1 (pin diameter=2mm), Config 2(pin diameter=3mm) and Config 3(pin diameter =4mm) are shown in figure-8. The quantity of heat that can be stored in a system depends on its heat capacity, an important factor to consider for the assessment of the thermal storage capabilities of a system and it determines also directly its performance during heating (charging) and cooling processes (discharging).

The No Fin case has the lowest heat capacity of all models (2.7 KJ/K) and is used as a reference baseline. In OP 1 (2 mm diameter pin), an improvement is seen, with a heat capacity of around 3.2 KJ/K – this reflects an increase in heat capacity by ~ 18.5% relative to the No Fin configuration. The Configuration 2 (3mm pin diameter) has the biggest heat capacity of all, around 3.5 KJ/K, which is increased by 29.6% and 9.4% compared with No Fin case and Configuration1 respectively. A comparatively smaller heat capacity (about 3.1 KJ/K) is shown by configuration 3 having pin diameter of 4mm, which value is slightly higher than that for the No Fin but lower to about 11.4% with respect to configuration 2.

This tendency may imply that the heat storage performance is promoted by finning of which shows efficient heat absorption and conductive heat transfer in the system. However, surpassing an optimum of 3 mm maximum pin-fin diameter brings to higher thermal resistance as the solid mass impairs the fluid flow and degrades convective heat transfer, thus diminishing integral effective capacity. These results demonstrate the paramount significance of designing heat sink geometry to maximize the specific heat in applications including

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

but not limited to thermal energy storage, electronic cooling, and hybrid heat sink design as this will provide a better performance in terms of thermal efficiency improvement, operational stability enhancement and system reliability increase.

Influence of heat sink configurations on Thermal conductance

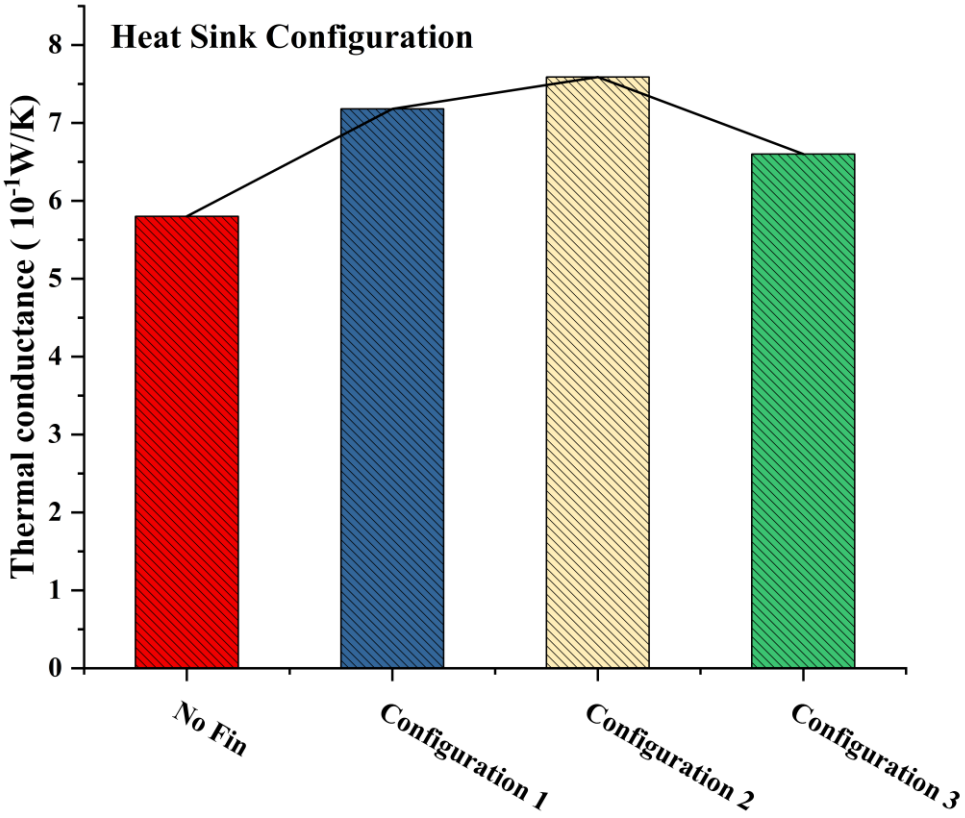


Figure 9 Influence of heat sink configurations on Thermal conductance

The thermal conductance verses number of fins are shown in for three different orientations along with a No Fin configuration in Fig. 9. Configurations 1, 2 and 3 show the pin diameters of 2 mm, 3 mm, and 4 mm respectively. Thermal conductance, as a crucial performance measure in judging the good heat dissipation of heat sinks.

Lowest thermal conductance is obtained for no fin configuration G th ≈ 6.0 × 10^{-1} W/K, taken as a reference for other comparisons. The configuration 1 with the pin size of 2mm achieves remarkable enhancements around 7.2 ×10^-1 W/K, this is about 20% higher than that of no Fin. It can be seen that Configuration 2 achieves the highest thermal conductance of ~7.8 × 10^-1 W/K, which is enhanced by approximately 30% with respect to the No Fin configuration and ~8% compared to Configuration 1 (by a pin diameter equal to d =3 mm). When the pin diameter reaches 4mm in Configuration 3, thermal conductance is further decreased at about 7.0 × 10^-1 W/K, which is still higher than the No Fin case by a factor of approximately 16%, but lower than that of Configuration 2 by about 10%. The trend reveals that a higher pin diameter will result in an initial enhancement of the cooling effectiveness because of the larger conduction and convective area. However, once size exceeds a critical value (3mm in particular), the added thermal resistance due to higher thermal mass and reduced air movement leads instead to lower conductance. It shows that one must choose a proper pin diameter in hybrid heat sinks to improve the performance of electronic coolers, optimize thermal management of power systems and create innovative energy storage devices.

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Journal of Information Systems Engineering and Management
2024, 9(3)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Comparative Performance Evaluation of the Present Hybrid PCM–Pin-Finned Heat Sink

Performance Parameter	**Baseline Case**	**Optimal Configuration (Present Work)**	**Quantitative Improvement / Change**
PCM Volume Fraction	0% (No PCM)	100% PCM	Peak temperature reduced by **10–12%**
Initial Temperature Rise (first 30 min)	No PCM	PCM-filled heat sink	Temperature rise delayed by **15–20%**
Applied Heat Flux Range	1500 W/m²	3500 W/m²	Latent heat duration reduced by **35–50%** with increasing heat flux
Pin-Fin Diameter	2 mm	**3 mm (Optimal)**	PCM melting rate enhanced by **~20–22%**
Time to Complete PCM Melting	~58–60 min (2 mm pins)	~52–54 min (3 mm pins)	Melting time reduced by **8–10%**
Operational Time Enhancement	No Fin: ~110 min (2500 W/m²)	3 mm pins: ~125 min	Operational time increased by **~13.6%**
Heat Capacity	No Fin: ~2.7 kJ/K	3 mm pins: ~3.5 kJ/K	Heat capacity increased by **~29.6%**
Thermal Conductance	No Fin: ~6.0 × 10^{-1} W/K	3 mm pins: ~7.8 × 10^{-1} W/K	Thermal conductance enhanced by **~30%**
Excessive Pin Diameter Effect	4 mm pins	—	Heat capacity reduced by **~11–12%** vs. optimal case
Overall Thermal Stability	Conventional finned sink	Hybrid PCM–pin-fin sink	Improved thermal buffering and delayed peak temperature

Conclusion

An in-depth numerical investigation of a PCM–pin-finned heat sink for enhancing the transient thermal response of compact and portable electronics was carried out in this work. A high-order CFD methodology based on the enthalpy–porosity model was used to insightfully investigate the correlated effects of PCM volume fraction, heat flux density and pin-fin diameter aiming at developing physically realistic design chart. The results illustrate that thermal control is greatly improved when the PCM replaces a pin-finned heat sink. When volume fraction of PCM was increased from 0% to 100%, it caused peak temperatures to lower by 10–12% and the initial time for which the temperature starts increasing also deferred by (15–20%) thus confirming considerable thermal buffering capacity of latent heat storage. Beyond a certain point, PCM sub-fractions was subject to the law of diminishing returns. This indicates that there may be an optimal PCM content in terms of practical design.

The input heat flux density is the most influential to how well phase change materials (PCM) perform. The absorption time of latent heat reduced by 35–50%, with the increase of heat flux from 1500 W/m² to 3500 W/m², at the same time, increasing the peak temperatures up to ~20%. The results indicate that PCM heat sinks only perform well for intermediate heat fluxes for which they have enough time to utilize the latent effect. This work provides a complete understanding of the effect of pin-fin diameter on phase-change dynamics and thermal performance. Increasing the pin diameter allowed faster PCM to melt by enlarging the solid-PCM contact area and by accelerating conduction and buoyancy-driven convection. At mid-melting condition a liquid fraction increased by 20–22% with increasing pin size from 2 mm to 4 mm. Exceeding the optimum diameter adds mass to the fin; this has the effect of increasing thermal resistance (and limiting flow) and is a negative in terms of performance. In all cases, a 3 mm pin-fin diameter configuration presented the best performance. It had the longest operation time, highest thermal capacity (ca 3.5 kJ/K), and maximum thermal conductance, which was about 30% higher than that for the no-fin case.

Studies of charge and discharge showed an inherent PCM cycle assymetry where the discharging time was 20–30% longer than charging, which are explained by thermal resistance and heat loss mechanisms. This behavior has significant implications for real-world electronic duty cycles where there must be a constant cooling presence regardless of whether power is off or the load is minimal. The results show that thermal performance

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

no longer continues to increase with increasing fin size, and reaches the maximum due to a compromise between enhanced heat transfer area and increased thermal resistance. This analysis provides the optimal hybrid configuration which is simple in geometric construction and for easy fabrication with good thermal performance as a competitive cooling technique for future mobiles and compact electronic cooling technology.

References

[1] Abdulsahib, Ahmed Dhafer, Dhirgham Alkhafaji, and Ibrahim M. Albayati. "Optimizing Heat Sink Performance by Replacing Fins from Solid to Porous inside Various Enclosures Filled with a Hybrid Nanofluid." *Frontiers in Heat and Mass Transfer* 22, no. 6 (2024): 1777-1804.
[2] Ghorbani, Mahdi, Hailei Wang, and Nicholas Roberts. "Analytical and numerical modeling of phase change material and hybrid PCM-heat sinks for high-power wireless EV charging." *International Communications in Heat and Mass Transfer* 154 (2024): 107460.
[3] Zhang, De-Xin, Chuan-Yong Zhu, Xin-Yue Duan, Bing-Huan Huang, Liang Gong, Kui Li, and Ming-Hai Xu. "Transient temperature control performance evaluation of a novel hybrid PCM-based active heat sink." *e-Prime-Advances in Electrical Engineering, Electronics and Energy* 5 (2023): 100230.
[4] Mahmoud, Saad, Aaron Tang, Chin Toh, AL-Dadah Raya, and Sein Leung Soo. "Experimental investigation of inserts configurations and PCM type on the thermal performance of PCM based heat sinks." *Applied Energy* 112 (2013): 1349-1356.
[5] Lacroix, M., and M. Benmadda. "Numerical simulation of natural convection-dominated melting and solidification from a finned vertical wall." *Numerical Heat Transfer, Part A Applications* 31, no. 1 (1997): 71-86.
[6] Huang, M. J., P. C. Eames, and B. Norton. "Thermal regulation of building-integrated photovoltaics using phase change materials." *International Journal of heat and mass transfer* 47, no. 12-13 (2004): 2715-2733.
[7] Tan, Lippong, Yuenting Kwok, Ahbijit Date, and Aliakbar Akbarzadeh. "Numerical analysis of natural convection effects in latent heat storage using different fin shapes." *Int J Energy Sci* 1 (2011): 162-8.
[8] Kalbasi, Rasool, Masoud Afrand, Jalal Alsarraf, and Minh-Duc Tran. "Studies on optimum fins number in PCM-based heat sinks." *Energy* 171 (2019): 1088-1099.
[9] Shatikian, V., G. Ziskind, and R. Letan. "Numerical investigation of a PCM-based heat sink with internal fins: constant heat flux." *International Journal of Heat and Mass Transfer* 51, no. 5-6 (2008): 1488-1493.
[10] Baby, Rajesh, and C. Balaji. "Thermal optimization of PCM based pin fin heat sinks: an experimental study." *Applied Thermal Engineering* 54, no. 1 (2013): 65-77.
[11] Sathe, Tushar, and A. S. Dhoble. "Thermal analysis of an inclined heat sink with finned PCM container for solar applications." *International Journal of Heat and Mass Transfer* 144 (2019): 118679.
[12] Bondareva, Nadezhda S., and Mikhail A. Sheremet. "Influence of PCM heat sink shape on cooling of heat-generating elements in electronics." *Applied Thermal Engineering* 213 (2022): 118695.
[13] Ho, Jin Yao, Yu Seon See, Kin Chong Leong, and Teck Neng Wong. "An experimental investigation of a PCM-based heat sink enhanced with a topology-optimized tree-like structure." *Energy conversion and management* 245 (2021): 114608.
[14] Shailesh, K., Y. Naresh, and J. Banerjee. "Heat transfer performance of a novel PCM based heat sink coupled with heat pipe: An experimental study." *Applied Thermal Engineering* 229 (2023): 120552.
[15] Yang, X.H., Tan, S.C., Ding, Y.J., Wang, L., Liu, J. and Zhou, Y.X., 2017. Experimental and numerical investigation of low melting point metal based PCM heat sink with internal fins. *International Communications in Heat and Mass Transfer*, *87*, pp.118-124.
[16] Jalil, Jalal M., Hussein S. Mahdi, and Asim S. Allawy. "Cooling performance investigation of PCM integrated into heat sink with nano particles addition." *Journal of Energy Storage* 55 (2022): 105466.

Copyright © 2024 by Author/s and Licensed by JISEM. This is an open access article distributed under the Creative Commons Attribution License which permitsunrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.