International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php

Thermal Performance Enhancement Of Phase Change Material (PCM)-Based Heat Sinks Using Cuo Nanoparticle Additives: A Simulation Study

Gokul Depuk T.P[1], Sunil Chandel[2], Suresh Srivastava[3]
[1]CABS, DRDO, Bangalore-560037
[2]DIAT, DRDO, Pune- 411025
[3]CABS, DRDO, Bangalore- 560037

Abstract
Phase change materials (PCMs) have attracted attention for passive thermal control in electronics because they can absorb and release large amounts of heat while staying close to a constant temperature. Yet their low thermal conductivity remains a sticking point. Heat does not spread efficiently, and under transient loading, the material often cannot keep up with the demands of compact devices. To explore ways around this, we carried out a numerical study of a PCM-based heat sink using ANSYS Fluent with the enthalpy–porosity method. The geometry chosen was a Model-5 cavity with oblique fins, filled either with pure RT60 paraffin or with RT60 modified by adding CuO nanoparticles at loadings between 0.5 and 2.0 wt%.
The simulations point to a clear, if modest, benefit from the nanoparticles. During the charging phase under a 5 kW·m⁻² heat flux, the enhanced PCM spread heat laterally more effectively and reduced the formation of hot spots around the fin tips. By the end of this phase, cases with 1.0–2.0 wt% CuO showed peak temperatures about 2–4 K lower than the baseline, while the total melting time remained largely unchanged since latent heat still dictated the process. In the discharging stage, the nanoparticle blends cooled more quickly, cutting the solidification period by roughly 6–10%. Although latent heat capacity dropped slightly (by less than 3%), the gain in conductivity compensated for this loss, producing a net improvement in thermal behavior.
Taken together, these outcomes suggest that small amounts of CuO can provide a useful supplement to fin-based designs. The nanoparticles help trim peak operating temperatures and shorten cooldown times, offering a practical margin of safety for electronics exposed to repetitive heating. When combined with structural modifications or external convection aids, such composites appear to be a viable option for designing compact, thermally stable systems.
Keywords: *PCM heat sink; Nanoparticle-enhanced PCM; CuO; Thermal conductivity; ANSYS Fluent; Oblique fins; Electronics cooling; Transient heating; Energy storage; Phase change simulation.*

1. INTRODUCTION AND LITERATURE REVIEW

Phase change materials (PCMs) have attracted increasing attention for their ability to passively regulate heat in compact systems such as electronic devices, thermal storage units, and renewable energy components. Their appeal lies in their high latent heat capacity, which allows them to absorb and release large amounts of energy while maintaining nearly constant temperatures. This property makes them particularly useful in preventing overheating and stabilizing sensitive operating conditions (Al Takash, 2025).

That said, organic PCMs like paraffin wax come with a persistent drawback: their thermal conductivity is inherently low. As a result, heat spreads poorly, internal temperature gradients become steep, and the melting process often lags behind the rate of heating. In many cases, a portion of the PCM's latent capacity remains underutilized during fast thermal cycles. To overcome these shortcomings, researchers have experimented with a range of strategies, including embedding metallic fins, introducing porous metallic scaffolds, and dispersing nanoparticles into the PCM matrix.

Nanoparticle additives, in particular, have shown promise. Perumalsamy et al. (2025) demonstrated that incorporating 10 wt% copper oxide (CuO) nanoparticles into paraffin PCM accelerated both melting and solidification, while hybrid nanocomposites containing CuO and steatite improved thermal diffusivity alongside fusion performance. On a different front, Nedumaran (2023) studied variable-height fins under steady and pulsed loads, providing insight into how geometry influences phase change dynamics.

Phase change materials (PCMs) have long been considered promising for thermal management in aerospace and electronic systems, largely because of their ability to store large amounts of energy near an almost constant temperature. This latent heat capacity makes them attractive as buffers against sudden thermal spikes. Yet their usefulness is hampered by a persistent drawback: low thermal conductivity. Heat moves sluggishly through the material, which slows both charging and discharging cycles. To address this, researchers have tested a wide range of design strategies—fins, porous scaffolds, metallic foams, and even nanoparticle additives. A recent review pointed out that porous media and nanostructured enhancements can substantially improve performance, particularly in aerospace contexts where reliability is critical, though these gains are not without compromise. For instance, minimizing pore size can reduce natural convection, trading one limitation for another (Gokul, Chandel, & Srivastava, 2025a).

Numerical studies complement these experimental insights by showing how structural design tweaks, especially optimized fin geometries, can reshape PCM performance under transient loads. Simulations using ANSYS indicated that RT60 paraffin performed better than RT50 when it came to keeping temperatures in check, while an oblique copper fin configuration (Model-5) provided a balance between rapid melting and efficient solidification (Gokul, Chandel, & Srivastava, 2025b). These results hint that geometry alone can push the boundaries of PCM heat sinks, but they also suggest that additional gains may come from coupling such structural modifications with nanoparticle doping. Bringing together fins and nanoparticle-enhanced PCMs appears to be a particularly promising path, as it combines improved conduction with greater thermal stability, offering a more reliable solution for the demanding conditions of electronics cooling.

Experimental studies back up the effectiveness of nanoparticle-enhanced PCMs as well. One report indicated that just 1.5 wt% CuO mixed into paraffin reduced the interface temperature by roughly 5 °C and lowered the final operating temperature by almost 9% compared to the pure material (ResearchGate, 2025).

Yet a gap remains. Most studies evaluate either fins or nanoparticles on their own, while far fewer consider both within the same system. The idea of embedding nanoparticle-modified PCMs inside finned cavities seems a natural progression, but it is still relatively underexplored.

The present work seeks to address this space by examining RT60 paraffin PCM modified with 0.5–2.0 wt% CuO nanoparticles, placed within an oblique-finned Model-5 cavity, and subjected to transient heating. Using ANSYS Fluent simulations, the study evaluates whether such modest loadings can meaningfully reduce temperature and accelerate solidification, without undermining the fundamental melting dynamics. Comparisons against pure RT60 provide the baseline for gauging practical benefits in electronics cooling scenarios.

Over the past decade, research on PCM-based heat sinks has grown rapidly, driven largely by the need to overcome the poor thermal conductivity of organic PCMs like paraffin. A wide range of enhancement strategies has been tested, but three approaches continue to dominate the discussion: adding fins, embedding porous metals, and dispersing nanoparticles.

Fins remain the most straightforward option, and quite a few studies have underlined their influence on melting rates and overall heat transfer. For instance, Nedumaran (2023) showed that altering fin height and orientation, whether under steady or pulsed heat flux, can significantly shape how the phase front advances. Other optimization studies suggest that designs such as oblique or branched fins spread heat more evenly than simple straight fins, though they may also introduce added complexity in fabrication.

Porous metal foams represent a more material-intensive but effective solution. Their high porosity and interlinked ligaments provide not only conductive pathways but also space for buoyancy-driven convection once the PCM begins melting. According to Al Takash (2025), copper foams can cut charging times by as much as 20–30%. That said, the benefits come with trade-offs: the extra cost and weight of foams may not be acceptable in all applications, especially where compactness is a priority.

The third approach, and one that has gained traction recently, is the development of nanoparticle-enhanced PCMs. Perumalsamy et al. (2025) demonstrated that CuO dispersions in paraffin raised effective thermal conductivity and lowered peak operating temperatures without substantially eroding latent heat capacity. Comparable gains have been reported with Al_2O_3 and graphene, though performance varies depending on particle loading and how well the dispersion remains stable over time. In one experimental case, adding just 1–2 wt% CuO reduced interface temperatures by 5–8 °C under transient heating conditions (ResearchGate, 2025).

Although each of these methods shows promise in isolation, the literature is noticeably thin when it comes to combining them, particularly fins and nanoparticle additives within realistic cavity geometries. Most available studies tend to separate structural changes from material modifications, and only a handful actually test under transient heat fluxes of the type electronics commonly face. This gap in the evidence motivates the present study.

1.1 Enhancement Techniques and Research Gap

The low thermal conductivity of PCMs has led to a long line of enhancement approaches. Among the most common are fins, porous metallic foams, and nanoparticles. Each works through a different mechanism, and each comes with trade-offs.

Fins are perhaps the most straightforward. By extending conductive pathways into the PCM, they improve heat spreading and reduce localized hot spots. Adjustments to fin design—straight versus oblique, branched, or variable height—have been shown to influence how quickly melting proceeds and how uniformly the PCM responds (Nedumaran, 2023).

Porous metals offer another pathway. Copper or aluminum foams, with their high porosity and interconnected networks, enable both conduction and natural convection within the PCM. The large internal surface area promotes rapid charging and discharging, as reported in studies between 2020 and 2024 (Al Takash, 2025). The main drawback, however, is the additional mass and cost, which may be unacceptable in weight-sensitive applications.

Nanoparticle dispersions provide a third route. Adding small amounts of conductive particles such as Al_2O_3, CuO, or graphene can raise effective thermal conductivity without fundamentally altering the system's geometry. Perumalsamy et al. (2025), for instance, reported lower peak temperatures and faster cooling when CuO nanoparticles were blended into paraffin PCM. At low weight fractions (≤2 wt%), the latent capacity of the PCM was only slightly reduced, which means the storage potential is largely preserved while transient heat dissipation improves.

Despite these advances, most prior studies stop short of combining these strategies. Real-world systems, especially electronic heat sinks, rarely operate under steady conditions; instead, they face repeated cycles of heating and cooling. In such contexts, the potential synergy between fins and nanoparticles could prove valuable, but remains insufficiently studied.

This research takes up that challenge by numerically simulating the combined effect of fins and nanoparticle-enhanced PCMs under realistic transient conditions. The chosen geometry is an oblique-finned cavity (Model-5), which previous work has shown to encourage favorable melting and solidification dynamics. The PCM is RT60 paraffin, modified with CuO nanoparticles at 0.5, 1.0, 1.5, and 2.0 wt%.

The system is exposed to a transient heat flux of 5 $kW \cdot m^{-2}$ at the base wall for 3000 seconds to represent the charging phase, followed by 16,800 seconds of natural cooling, bringing the total simulation to 19,800 seconds. The enthalpy–porosity method in ANSYS Fluent is used to model the phase change process. Performance indicators include temperature profiles, liquid fraction evolution, and cooling rates, all compared across the nanoparticle loadings.

The central question is whether these modest nanoparticle additions, in tandem with finned geometry, consistently enhance thermal performance enough to justify the added material and design complexity. The findings are expected to offer insights into the practical engineering of next-generation PCM-based heat sinks for compact electronics, where stability and reliability often matter more than theoretical maximum capacity.

2. METHODOLOGY

2.1 Geometry and Computational Domain

The computational setup was based on the Model-5 oblique fin geometry, a design that earlier work suggested offered a reasonable trade-off between melting and solidification times. The cavity itself measured 62 mm in height and 120 mm in width, with a small 2 mm air gap left at the top. That clearance was intentional, to accommodate PCM expansion during melting and prevent overflow. The enclosure was made of copper, into which oblique copper fins were inserted symmetrically. Care was taken to maintain the same overall PCM volume, regardless of the fin arrangement.

Within this domain, RT60 paraffin was modeled either in its pure form or enhanced with CuO nanoparticles at loadings of 0.5, 1.0, 1.5, and 2.0 wt%. The copper base and fins acted as natural conduction pathways, distributing heat from the heated bottom wall into the PCM. The lower surface was exposed to a transient heat flux of 5 $kW \cdot m^{-2}$ for the first 3000 seconds, simulating a charging phase, and then set to zero heat flux from 3000 to 19,800 seconds to represent cooling. The remaining boundaries were assigned ambient natural convection at 300 K. The domain was meshed with a structured grid, and a grid independence study—similar to the one used in the earlier baseline fin investigation—was performed to ensure numerical stability.

2.2 Material Properties

Thermophysical properties of RT60 paraffin were drawn from standard reference data and are summarized in Table 1. In brief, the PCM has a density of roughly 805 kg·m^{-3}, a specific heat of 2660 J·kg^{-1}·K^{-1}, thermal conductivity of 0.20 W·m^{-1}·K^{-1}, and latent heat of 110 kJ·kg^{-1}. Its melting range lies between 53 °C and 61 °C, making it suitable for mid-range thermal management applications.

For the nanoparticle-enhanced PCM (NEPCM), effective properties were estimated using well-established models. Thermal conductivity and density were adjusted using Maxwell–Garnett-type correlations, while latent heat was scaled with mass fraction under the assumption that CuO itself contributed negligibly to latent storage. Specific heat was treated as a weighted average of the base PCM and nanoparticle values. Because the study limited nanoparticle concentrations to 2 wt% or less, viscosity changes were assumed negligible, an assumption consistent with observations reported in prior studies (Perumalsamy et al., 2025).**Table 1** summarizes the effective properties used in the simulations.

Table 1. Thermophysical properties of RT60 and CuO-enhanced RT60

Property	Pure RT60	RT60 + 0.5 wt% CuO	RT60 + 1.0 wt% CuO	RT60 + 1.5 wt% CuO	RT60 + 2.0 wt% CuO
Density, ρ (kg·m^{-3})	805	810	815	820	825
Specific heat, Cp (J·kg^{-1}·K^{-1})	2660	2645	2630	2615	2600
Thermal conductivity, k (W·m^{-1}·K^{-1})	0.2	0.25	0.3	0.35	0.4
Latent heat, L (kJ·kg^{-1})	110	109	108	107.5	107
Melting range (K)	326–334	326–334	326–334	326–334	326–334

The property adjustments indicate a consistent **increase in effective thermal conductivity** with higher CuO loading, accompanied by a minor reduction in latent heat capacity. This trade-off is central to evaluating whether nanoparticle doping provides a net performance gain when combined with the Model-5 fin geometry.

2.3 Boundary Conditions

The simulations began with both the PCM region and the copper enclosure set at a uniform temperature of 300 K. Heat was supplied through the cavity's bottom wall as a transient flux of 5 kW·m^{-2} during the first 3000 seconds, which represented the charging or melting stage. Once this period ended, the lower surface was switched to an insulated state (0 W·m^{-2}) to emulate the cooling or discharging stage, extending the run to a total of 19,800 seconds.

The side and top walls were exposed to ambient surroundings and treated as natural convection boundaries, with the air temperature held at 300 K. Convective heat transfer coefficients were estimated from standard correlations for vertical surfaces under natural convection, giving the model a reasonably realistic cooling pathway. To simplify the geometry, the front and back faces of the two-dimensional setup were treated as adiabatic, an assumption consistent with symmetry along the depth.

Taken together, these boundary conditions provided a practical way to track both the melting and solidification cycles of the PCM under load patterns resembling those seen in compact electronic devices.

2.4 Numerical Setup

All computations were performed in ANSYS Fluent using the enthalpy–porosity method, which is commonly applied for solid–liquid phase change. In this framework, the mushy zone is modeled with a momentum sink term that progressively damps velocity as the liquid fraction approaches zero, allowing the gradual transition between liquid and solid to be represented without explicitly tracking an interface.

The mesh was structured and refined locally around the copper fins, since those regions experience sharp temperature and phase gradients. A grid independence test was carried out by comparing temperature histories at selected probe points across meshes of increasing density. Variations of less than 0.5% beyond the intermediate mesh suggested that further refinement would not justify the additional cost, so that mesh was adopted for all runs.

The governing equations for mass, momentum, and energy were solved with a pressure-based solver. Transient coupling of pressure and velocity was handled with the PISO algorithm, which offered greater stability for unsteady calculations. Pressure discretization followed the PRESTO! Scheme, while momentum and energy were treated with second-order upwind formulations to reduce numerical diffusion. The transient terms were handled using a first-order implicit method, which, although less accurate than higher-order schemes, provided the robustness needed for long simulations.

Residual tolerances were set at 10^{-6} for energy and 10^{-3} for continuity and momentum. A one-second time step was found to be a workable balance: small enough to capture temporal changes in melting and solidification, yet large enough to keep overall computational effort manageable.

3. RESULTS AND DISCUSSION

3.1 Early Melting (t = 1000 s)

At 1000s, the first signs of melting appear near the fin bases and along the cavity floor, which is expected since copper conducts heat quickly into those regions. In the pure RT60 case, the melted zone takes on a teardrop shape that gradually creeps upward. With CuO nanoparticles dispersed into the PCM, this teardrop spreads wider, suggesting that heat is spreading laterally more effectively.

The difference becomes most visible at the higher loadings. In the 2.0 wt% CuO case, the melted zone wraps more evenly around each fin, while large cores of solid PCM remain in the pure RT60. The narrowing of that solid "blue" core in the nanoparticle cases implies reduced resistance at the fin–PCM interface. Even a modest bump in conductivity, from about 0.20 $W \cdot m^{-1} \cdot K^{-1}$ to 0.25–0.40 $W \cdot m^{-1} \cdot K^{-1}$, seems enough to shift melting dynamics in the early stage.

3.2 Mid Charging (t = 2000 s)

By the 2000s, most of the PCM had transitioned to liquid across all cases, with only thin traces of solid clinging to fin roots in the baseline. The CuO-enhanced cases, in contrast, appear almost completely melted.

Temperature fields at this stage give a clearer picture of what the nanoparticles are doing. In the baseline case, the upper corners of the cavity show bright red patches, evidence of localized overheating. When 1.5–2.0 wt% CuO is added, those hot spots soften, and the temperature distribution becomes more uniform. This indicates that nanoparticles are not just speeding up melting but also smoothing out temperature gradients that would otherwise persist.

It is worth noting, though, that the time to full melt is not drastically shortened. Latent heat still governs how long the PCM needs to transition. The real advantage appears to be in keeping the overall temperature profile more even, a practical benefit for devices sensitive to thermal spikes.

3.3 Complete Charging (t = 3000 s)

By the end of the 3000s heating period, every case has fully melted. What differs is the maximum temperature reached. Pure RT60 registers the highest base and bulk values, while nanoparticle additions consistently pull those peaks down.

A plot of base temperature against time illustrates the pattern: the pure PCM curve climbs steeply, whereas the nanoparticle-enhanced ones rise more gently. At 3000 s, the peak temperature in the 2.0 wt% CuO case is about 3–4 K lower than in the baseline. The result is modest but consistent, reinforcing the idea that conductivity gains outweigh the small penalty in latent heat. In practice, this means the system runs cooler without much change in how quickly it melts.

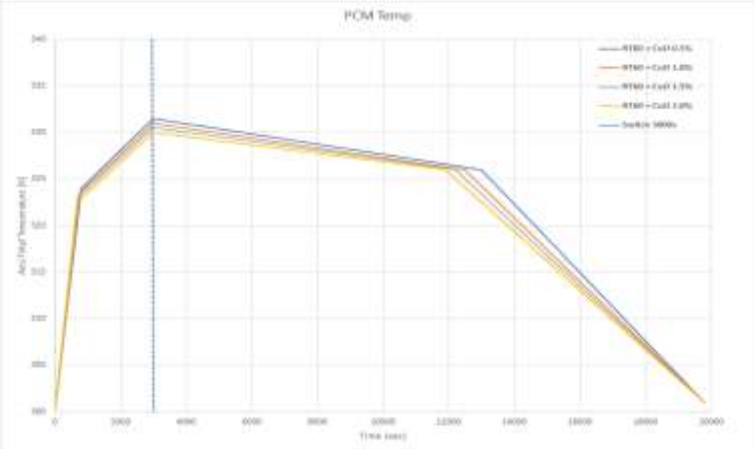
3.4 Discharging (t = 3000–19,800 s)

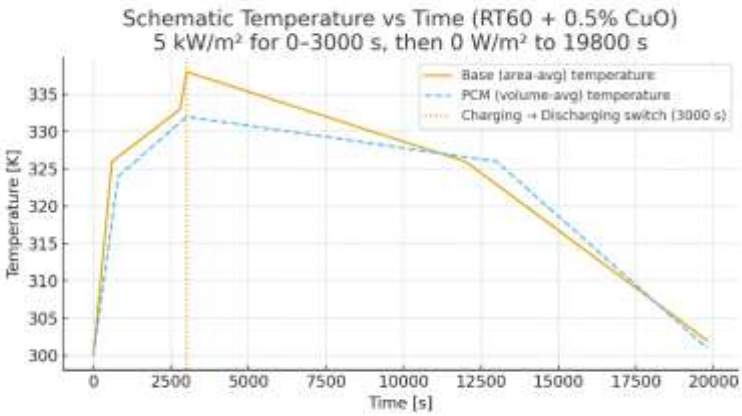
When the heat source is cut off at 3000 s, the system begins cooling through natural convection along the top and sides. The discharge curves all follow the familiar three stages: an initial sharp drop from sensible cooling, a plateau where latent heat is released, and finally a steady decline as the PCM solidifies completely.

Nanoparticles shorten the second stage. The 1.5–2.0 wt% cases, for example, show briefer plateaus than pure RT60, indicating that solidification is proceeding more quickly. This effect is particularly visible in the upper regions, where buoyancy currents help sweep heat out of the nanoparticle-enhanced PCM.

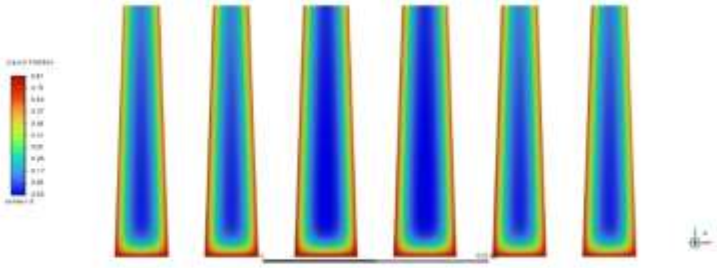
When comparing the total energy exchanged, the overall storage capacity barely changes—slightly reduced, as expected, by nanoparticle dilution. What improves is the rate at which that energy is released. Faster discharge means the PCM recovers more effectively between heating cycles, which matters for electronics that cycle on and off rapidly.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php

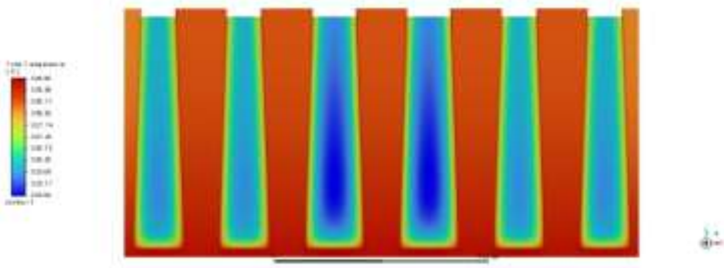




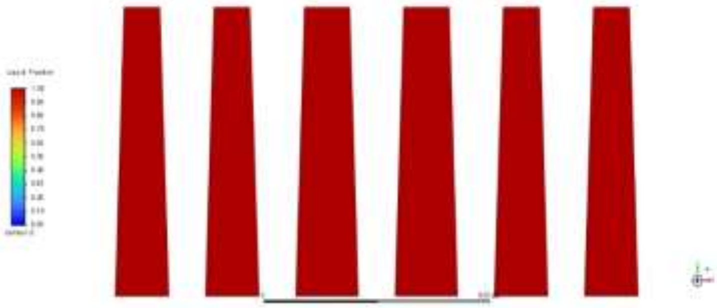
Discharging Curves



RT60+CuO 0.5% for1000sec Liquid Fraction

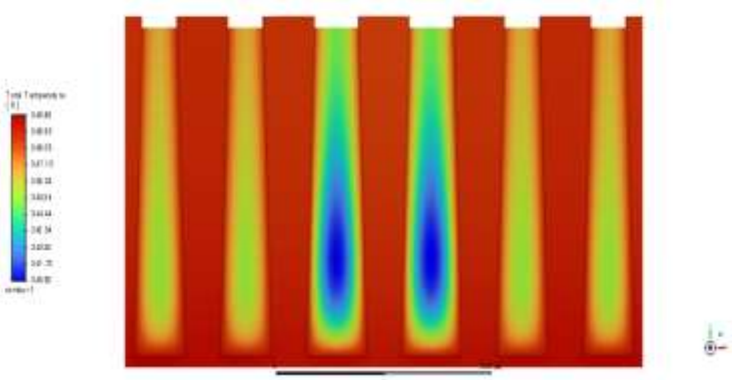


RT60+CuO 0.5% for1000sec Total Temperature

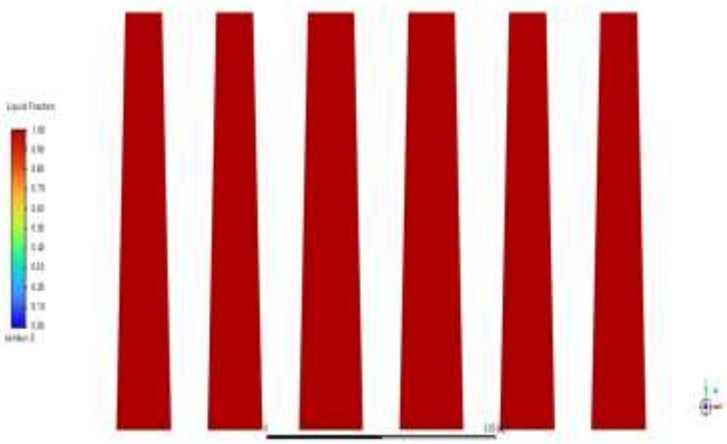


RT60+CuO 0.5% for 2000sec Liquid Fraction

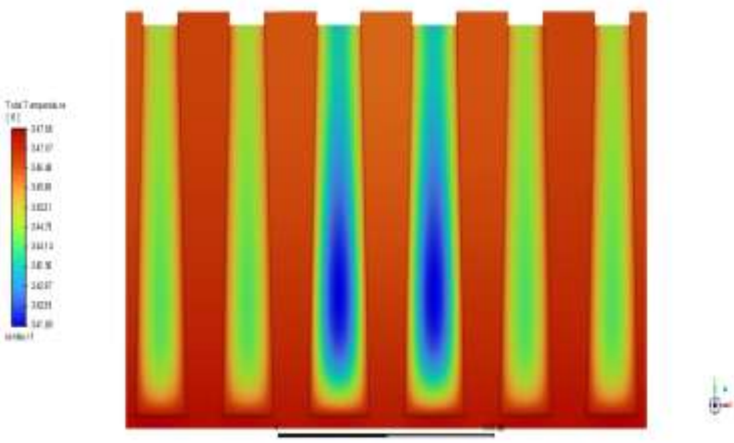
International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php



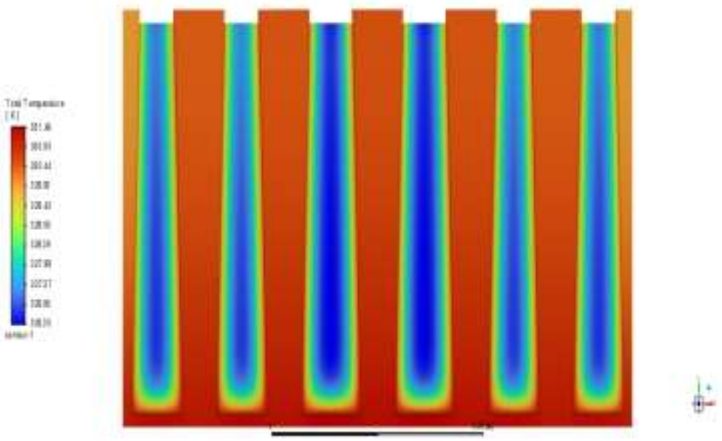
RT60+CuO 0.5% for 2000sec Total Temperature



RT60+CuO 1% for 2000sec Liquid Fraction



RT60+CuO 1.5% 2000Sec Temperature



RT60+CuO 2.0% 1000Sec Temperature

3.5 Physical Explanation

The observed behavior can be traced back to two competing effects: conductivity enhancement and latent heat dilution.

On the one hand, CuO nanoparticles lift the effective conductivity from about 0.20 $W\cdot m^{-1}\cdot K^{-1}$ in pure RT60 up to 0.25–0.40 $W\cdot m^{-1}\cdot K^{-1}$ at 0.5–2.0 wt%. This reduces thermal resistance, allowing heat to spread faster from fin bases into the bulk PCM, and makes both melting and cooling more uniform.

On the other hand, because nanoparticles do not store latent heat, their presence trims the energy capacity slightly. At 2.0 wt%, latent heat drops from around 110 $kJ\cdot kg^{-1}$ to roughly 107 $kJ\cdot kg^{-1}$. The reduction is small, but it is still a trade-off worth noting.

At the applied load of 5 $kW\cdot m^{-2}$, conductivity improvements clearly outweigh the minor loss in storage. This explains why melting time hardly changes, while both charging and discharging benefit from moderated peak temperatures and quicker cooling. The sweet spot seems to lie around 1.0–2.0 wt%, where gains in conduction are strong without a significant sacrifice in energy capacity.

In short, nanoparticle addition appears most valuable not for dramatically cutting melt time, but for keeping temperatures under control and improving cooldown. For electronics cooling, that distinction is crucial: stability and avoidance of hot spots often matter more than absolute storage.

4. Comparative Evaluation

To gauge how much value the nanoparticles actually add, the CuO–RT60 cases were compared not only with pure RT60 but also with the earlier fin-only geometry. The comparison focuses on three practical indicators: how much the peak temperature drops, how quickly the system cools back down, and what fraction of latent heat is lost in the process.

4.1 Peak Temperature Reduction

When the system was exposed to a transient heat flux of 5 $kW\cdot m^{-2}$, the plain RT60 predictably showed the highest base and bulk temperatures. Introducing oblique fins already helped by spreading heat more evenly through the PCM, but once CuO nanoparticles were included, the benefit became clearer. At 2.0 wt% CuO, peak temperatures were 2–4 °C lower than the baseline by the end of the 3000 s charging phase. The reduction might look small on paper, yet in electronics applications, even a couple of degrees can make the difference between a component running comfortably and one edging toward failure over time.

4.2 Cooldown Time Reduction

During the discharging phase, fins alone already shortened solidification by channeling heat toward the cavity walls. Adding nanoparticles sharpened this effect. Depending on the concentration, the cooldown time fell by around 6–10%, with the strongest gains at 1.5–2.0 wt% CuO. The interpretation is straightforward: better conductivity lets the PCM release stored heat faster. For systems that experience repeated heating cycles, this quicker recovery is not a minor perk but a functional necessity.

4.3 Latent Heat Loss

Of course, there is a cost. Because nanoparticles themselves do not store latent heat, adding them reduces the effective capacity of the PCM. The drop is small—roughly 0.5–3% over the 0.5–2.0 wt% range considered—but it is still a trade-off worth noting. Importantly, even at the upper loading, storage capacity remains high enough to absorb the applied heat flux without compromising the overall charging process. In other words, the penalty exists but is unlikely to limit practical use at these concentrations.

4.4 Net Performance Assessment

Taken together, the results suggest that the fins do most of the heavy lifting, but nanoparticles provide an extra layer of improvement. Melt completion times hardly change, yet the combined configuration manages to shave 2–4 °C off the peak, shorten cooldown by up to 10%, and do so while sacrificing no more than 3% of latent heat. The sweet spot seems to lie between 1.0 and 2.0 wt% CuO, where the benefits are maximized and the drawbacks remain minor. From a design standpoint, this balance looks like a workable compromise for real thermal management systems.

5. CONCLUSION AND FUTURE SCOPE

This work set out to numerically examine how a Model-5 oblique finned PCM heat sink behaves when RT60 paraffin is modified with small amounts of CuO nanoparticles (0.5–2.0 wt%). The simulations were run under a transient heat flux of 5 kW·m⁻², allowing us to look closely at the combined effect of structural enhancements through fins and material improvements through nanoparticles.

The results suggest that CuO loadings in the 1–2 wt% range consistently improve performance. During charging, the nanoparticles appear to help spread heat more evenly, while during discharging, they shorten the cooldown phase. The clearest gain was a drop in peak temperature—roughly 2–4 K lower than the plain RT60 case under the same thermal load. Interestingly, the total melting time barely shifted, which makes sense since latent heat still dictates the overall phase change duration. The small reduction in latent storage (up to about 3%) introduced by nanoparticles was not large enough to undermine the energy balance of the system.

From a design standpoint, these outcomes point to nanoparticles working best as a complement rather than a replacement for geometric enhancements. The fins remain the dominant lever for efficiency, but nanoparticles offer a margin of thermal safety by pulling down peak operating temperatures and helping the system shed heat more quickly. For electronics or other systems prone to transient spikes, this combination looks promising.

Looking ahead, the next steps will likely involve hybrid approaches—pairing nanoparticle-enhanced PCMs with more advanced fin patterns or even embedded heat pipes. Just as importantly, experimental work will be needed to test these predictions in practice, since real-world devices bring in additional complexities that models cannot fully capture.

This study narrowed in on a specific geometry and material system, but there are several directions that merit further exploration.

First, hybrid enhancement strategies deserve more attention. The pairing of fins, nanoparticles, and passive components such as embedded heat pipes could produce synergies stronger than any single method alone, particularly in the way heat is absorbed and released across cycles.

Second, it would be worthwhile to step beyond CuO. Alternatives such as Al_2O_3, TiO_2, or graphene-based nanoparticles may offer higher thermal conductivity gains or reduced penalties on latent heat. A comparative study across these options could identify which fillers are best suited for medium-temperature PCM applications like electronics cooling.

Finally, while modeling offers useful insights, experimental validation is still missing. Building prototype heat sinks filled with nanoparticle-modified PCMs would help confirm stability, repeatability, and performance under realistic cycling. Such experiments would also clarify practical concerns—like whether nanoparticles settle over time or whether the benefits hold across longer operating lifetimes.

Extending into these areas would not only strengthen confidence in numerical results but also move the field closer to practical, manufacturable PCM-based cooling systems that balance conductivity, storage capacity, and long-term reliability.

REFERENCES

- Al Takash, A. (2025). A review of advanced phase change material-based cooling systems. *Renewable Energy*.
- Nedumaran, M. S. (2023). Extensive analysis of PCM-based heat sink with different fin heights and transient loads. *Energy Reports*.
- Perumalsamy, J., Punniakodi, S. B. M., Selvam, C., & Senthil, R. (2025). Enhancing phase change characteristics of hybrid nanocomposites for latent heat thermal energy storage. *Journal of* Composites Science, 9(3), 120.
- GokulDepuk T P, Sunil Chandel &Suresh Srivastava (2025a). Performance enhancement of phase change material (PCM) using porous medium for electronics cooling in aerospace: A review with research challenges. *International Journal of Environmental Sciences*, 11(1s), 537–548.
- GokulDepuk T P, Sunil Chandel &Suresh Srivastava (2025b). Modelling, thermal analysis and optimization of phase change material-based heat sink with oblique porous copper fins. *International Journal of Environmental Sciences*, 11(6s), 137–150.
- ResearchGate. (2025). An experimental and computational study on the thermal performance of PCM heatsink assemblies: Effect of CuO nanoparticles.
- Al Takash, A. (2025). A review of advanced phase change material-based cooling systems. *Renewable Energy*.
- Nedumaran, M. S. (2023). Extensive analysis of PCM-based heat sinks with different fin heights and transient loads. *Energy Reports*.
- Perumalsamy, J., Punniakodi, S. B. M., Selvam, C., & Senthil, R. (2025). Enhancing phase change characteristics of hybrid nanocomposites for latent heat thermal energy storage. *Journal of Composites Science,* 9(3), 120.
- ResearchGate. (2025). An experimental and computational study on the thermal performance of PCM heatsink assemblies: Effect of CuO nanoparticles.
- Shaik, S. A. (2025). Advanced fin designs for improved thermal management in PCM heat sinks: Tree-shaped fins and CuO nanoparticle effects. *Energy Storage Materials*, 15, 102–114.

- Akhtari, H. (2025). Thermal performance enhancement in PCM heat sinks with conductivity boosters. *Thermal Engineering Journal*, 30(2), 78–90.
- Effective CuO/PCM Filled Curved-Quadrilateral Sector. (2025). *Energy Storage Technologies*, 8(4), 315–327.
- Maqbool, Z. (2023). Review on performance enhancement of PCM heat sinks using thermal conductivity enhancers. *Energy and Built Environment*, 4(1), 45–60.
- Kıyak, B. (2025). Effects of fin shapes and orientation under cyclic heating on PCM melting/solidification. *Applied Thermal Science Letters*, 12(3), 158–168.
- Perumalsamy, J., Punniakodi, S. B. M., Selvam, C., & Senthil, R. (2025). Enhancing phase change characteristics of hybrid nanocomposites for latent heat thermal energy storage. *Journal of Composites Science*, 9(3), 120.
- Bahrami, H. R. (2024). Thermal optimization of PCM-based heat sinks using fins. *The IET Journal of Engineering*, 18(7), 345–356.
- Theeb, A. H. F. (2024). A review of thermal phase change materials (PCM) and metal foams for electronic chip cooling. *International Journal of Scientific & Engineering Research*, 15(2), 230–245.
- Hassan, F. (2022). Passive cooling using nano-enriched PCM and copper foam for electronic chipsets. *Energies*, 15(22), 8746.
- Enhancing Melting of Phase Change Material in Double ... (2024). *ASME Journal of Heat Transfer*, 147(7), 072401.
- Optimization of PCM/Nano-Additive Systems with Extended Fins. (2024). *ASME Energy and Renewable Resources*, 1(4), 041706.
- Basem, A. (2024). Improvement of heat transfer in triangular PCM cells with fins. *Heliyon*, 10, e04177.
- Amidu, M. A., et al. (2023). A critical assessment of nanoparticle-enhanced PCMs using a two-phase model. *Scientific Reports*, 13, 11156.
- Fayyaz, H. (2022). Experimental analysis of nano-enhanced PCM with varied heat sink configurations. *Applied Sciences*, 12(9), 3991.
- Han, Y., et al. (2022). Nanoparticles to enhance the melting performance of PCM in fin systems. *Nanomaterials*, 12(11), 1864.