Thermal Performance Analysis of Heat Sink with and without PCM

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Abstract— **The effective thermal management of high-power electronic devices is essential for maintaining reliable performance and preventing overheating. Phase change material (PCM)-integrated heat sinks offer a promising passive cooling approach by absorbing and storing excess thermal energy during phase transition. This study investigates the thermal performance of a PCM-based heat sink using three-dimensional transient numerical simulations in ANSYS Fluent. Temperature distribution, phase change behavior, and heat transfer characteristics are analyzed and compared with those of a conventional heat sink without PCM. The results indicate that incorporating PCM significantly reduces the base and average temperatures of the heat sink. Complete melting of the PCM occurs after 2000 seconds under steady heat input conditions, demonstrating its thermal energy storage and temperature regulation capabilities. Furthermore, the numerical results are validated against previously published experimental data, showing close agreement and supporting the reliability of the simulation methodology. The study concludes that PCM-integrated heat sinks provide an effective passive cooling solution for improving the thermal management of high-power electronic devices.**

Index Terms— **Heat sink optimization, Phase transition material, Cooling of Electronic components, Heat dissipation, Passive thermal regulation, High energy electronic system, Overheating in electronics, Energy storage material.**

I. INTRODUCTION

The rapid development of modern electronic devices has resulted in increasingly compact systems with higher processing speeds and power densities. Consequently, the amount of heat generated during operation has increased, making effective thermal management essential for maintaining device performance, reliability, and service life. Excessive temperature can reduce electronic efficiency, accelerate component degradation, and lead to premature system failure [1]. Conventional cooling techniques, such as forced-air cooling and liquid-based cooling systems, are widely used to dissipate this heat. However, these methods may require additional power, space, and maintenance, creating challenges for compact and portable electronic applications. Passive cooling techniques have gained attention as an alternative for improving thermal management without requiring additional mechanical power. Heat sinks are commonly used in electronic cooling because their extended surfaces and fin configurations increase the area available for heat transfer through conduction and convection. However, conventional heat sinks primarily dissipate heat and have limited capacity to store excess thermal energy during temporary increases in heat load. To overcome this limitation, phase change materials (PCMs) can be integrated into heat sinks. PCMs absorb and store thermal energy as latent heat during melting, thereby delaying temperature rise and improving thermal regulation [2], [3]. Previous experimental and numerical investigations have demonstrated the potential of PCM-based heat sinks to reduce component temperatures and extend the thermal regulation period [3]–[5]. Nevertheless, the relatively low thermal conductivity of many PCMs can restrict heat transfer, while repeated melting and solidification cycles require consideration when evaluating long-term performance [2]. Considering these characteristics, the present study investigates and compares the thermal performance of heat sinks with and without PCM. A three-dimensional transient numerical analysis is conducted using ANSYS Fluent to evaluate temperature distribution, heat transfer behavior, and PCM phase change characteristics. The

study aims to identify the advantages and limitations of both configurations and provide useful insights for developing efficient, compact, and reliable thermal management solutions for high-power electronic devices. The relevant research contributions are discussed in the following section.

1.1 Literature Review

Cooling methods are widely used in electronic systems to maintain operating temperatures, improve performance, and prevent component failure. With the increasing power density and compact size of modern electronic devices, effective thermal management has become an important research area. Several researchers have investigated conventional and advanced cooling techniques, different heat sink configurations, and phase change materials (PCMs) to enhance heat transfer performance and improve the thermal regulation of electronic components. S. M. Murshed, C. A. Nieto de Castro, et al. (2017) presented an overview of conventional and advanced cooling methods and working fluids used in electronic systems. The study discussed the limitations of conventional coolants, such as air and water, in managing the increasing heat generated by modern electronic devices. The authors also examined advanced cooling techniques, including nanofluids and microchannel cooling, highlighting their potential to improve heat transfer and manage high thermal loads in compact electronic applications [1]. M. Ismail (2024) investigated the thermal performance of heat sinks with different cylindrical pin-fin arrangements using experimental and computational approaches. The study considered parallel, cross, and double-cross fin configurations to evaluate their influence on heat transfer performance. The results indicated that the double-cross configuration generated greater turbulence and enhanced heat transfer, achieving an improvement of up to 32.8%. The findings demonstrated that the arrangement of fins plays an important role in improving heat dissipation from electronic components [2]. M. Arqam, L. S. Raffa, L. Clemon, et al. (2024) conducted a numerical and experimental investigation of a phase change material-based radial fin heat sink for electronic cooling applications. The study focused on a three-dimensional printed stainless-steel heat sink integrated with paraffin wax as a PCM. The effects of power input and fin dimensions on thermal performance were investigated through numerical simulations and experimental testing. The results showed that the PCM-integrated heat sink reduced temperature rise, delayed the heating process, and provided improved thermal regulation compared with a conventional heat sink without PCM [3]. The reviewed literature highlights the importance of cooling techniques, fin configurations, and PCM integration in improving the thermal performance of electronic cooling systems. The findings of these studies provide a useful foundation for the present investigation, which focuses on comparing the thermal performance of heat sinks with and without PCM through three-dimensional transient numerical analysis using ANSYS Fluent.

1.2 Research gaps

Despite significant research on conventional heat sinks and PCM-based cooling systems, several limitations still exist in evaluating their thermal performance under transient operating conditions.

1. Most existing studies focus on either conventional heat sinks or PCM-integrated heat sinks, with limited direct comparative analysis under identical operating and boundary conditions.
2. Several studies investigate temperature reduction using PCM, but the influence of PCM integration on base temperature, average temperature, and overall thermal regulation requires further evaluation.
3. Many investigations focus on heat transfer enhancement, while the relationship between PCM melting behavior, liquid fraction, and temperature variation over time needs further analysis.
4. Existing studies have examined different PCM materials and heat sink configurations, but simplified three-dimensional transient numerical analysis comparing heat sinks with and without PCM using ANSYS Fluent remains relevant for evaluating their thermal performance.

Therefore, based on the identified research gaps, the present study focuses on developing a three-dimensional transient numerical model to investigate and compare the thermal performance of heat sinks with and without PCM, which leads to the formulation of the problem statement in the next section.

1.3 Problem definition

Three-phase induction motors are widely used in industrial applications due to their simple

construction; high Heat sinks are widely used in electronic cooling applications because of their ability to dissipate excess heat and maintain suitable operating temperatures. With increasing heat generation in modern electronic devices, improving the thermal performance of heat sinks has become essential.

1. Although many studies have investigated conventional heat sinks and PCM-based cooling techniques, a comparative evaluation of their thermal performance under similar operating conditions is important to understand the effectiveness of PCM integration.
2. Conventional heat sinks primarily depend on conduction and convection for heat dissipation, whereas PCM-based heat sinks additionally absorb and store thermal energy through the phase change process. However, the influence of PCM on temperature distribution, heat transfer characteristics, and melting behavior requires further numerical investigation.

Therefore, this study develops a three-dimensional transient numerical model using ANSYS Fluent to compare heat sinks with and without PCM. The analysis focuses on temperature distribution, base and average temperatures, heat transfer performance, and PCM melting behavior to evaluate the effectiveness of PCM integration for electronic cooling applications.

1.4 Objectives

1 To see the difference in cooling performance of a heat sink with phase change material and without it.
2 To study the effect of fin cross-sectional dimension, fin extension length, and base plate thickness after heat dissipation.
3 To evaluate how PCM reduces peak temperature and delays thermal rise.
4 To suggest design improvements for efficient heat sinks in electronic devices.

II. METHODOLOGY

The methodology adopted in this study involves five main stages: heat sink design and modelling, material selection, numerical simulation, comparative thermal analysis, and validation. Initially, a three-dimensional heat sink model is developed for two configurations, one without PCM and another integrated with PCM. Stainless steel 316L is selected as the heat sink material, while paraffin wax is used as the phase change material. The numerical simulations are performed using ANSYS Fluent to investigate temperature distribution, heat transfer characteristics, and PCM melting behavior under transient heating conditions. The results obtained from both configurations are compared to evaluate the influence of PCM on thermal performance. Finally, the simulation results are compared with published experimental data to assess the reliability of the numerical approach.

2.1 Overview

The present study is carried out to investigate the cooling performance of conventional and PCM-integrated heat sinks. The methodology consists of heat sink geometry development, assignment of thermophysical properties, application of boundary conditions, transient numerical simulation, comparative analysis, and validation. Both configurations are analyzed under similar operating conditions to understand the effect of PCM integration on temperature regulation and heat dissipation.2.2 Heat sink design & modelling

A three-dimensional heat sink model is developed with overall dimensions of 30 × 30 × 30 mm using CAD software. Stainless steel 316L is considered as the reference heat sink material. The model consists of a base plate, internal fins, mounting lugs, and two openings on the upper surface for PCM filling. The internal fins have a thickness of 1 mm and help distribute heat from the base throughout the structure.

Two configurations are considered for the numerical investigation:

1. Heat sink without PCM: The conventional heat sink configuration without phase change material.
2. Heat sink with PCM: The heat sink configuration containing paraffin wax around the internal fin structure.

These two configurations are developed to evaluate the influence of PCM integration on the thermal performance of the heat sink.

2.3 Rationale

The main purpose of comparing PCM-based and conventional heat sinks is to understand their respective thermal management capabilities. A PCM-integrated heat sink absorbs and stores excess thermal

energy in the form of latent heat during melting. This process helps reduce peak temperatures and delays the temperature rise during continuous heating conditions. In contrast, a conventional heat sink primarily transfers heat through conduction and convection without additional latent heat storage. Although it does not provide the same thermal storage capability, it allows direct heat dissipation to the surrounding environment. Therefore, comparing both configurations help evaluate their cooling behavior and suitability for electronic applications.

2.4 Numerical Procedure

The three-dimensional heat sink models are prepared for two cases, with PCM and without PCM. The numerical analysis is performed using ANSYS Fluent 2023 R1, which solves the heat transfer problem using the finite volume method. The PRESTO pressure interpolation scheme and PISO pressure-velocity coupling method are used in the numerical setup. Second-order discretization schemes are applied to the energy and momentum equations, while a first-order method is used for time discretization with a fixed time step. For the PCM configuration, the phase change process is modelled using the enthalpy-porosity method with a mushy-zone approach. The PCM is considered laminar, Newtonian, and incompressible, with buoyancy effects included. PCM expansion, radiation losses, and thermal contact resistance are neglected to simplify the numerical model. The numerical analysis considers different parameters, including input power, heat transfer coefficient, base thickness, and fin dimensions. The thermophysical properties of stainless steel 316L and paraffin wax are assigned according to the material data presented in Table 1.

Table 1: Thermophysical properties

Material properties	Density (Kg/m^3)	Specific Heat (J/Kg. k)	Thermal Conductivity (W/m. k)	Viscosity (Kg/m. s)	Material properties	Thermal expansion coefficientβ (1/K)	Latent heat (J/kg)	Solidius Temperature (◦C)
Stainless Steel	8030	502.5	16.3	-	Stainless Steel	-	-	-
Paraffin wax	880	2000	0.2	0.03	Paraffin wax	0.00011	170,000	53

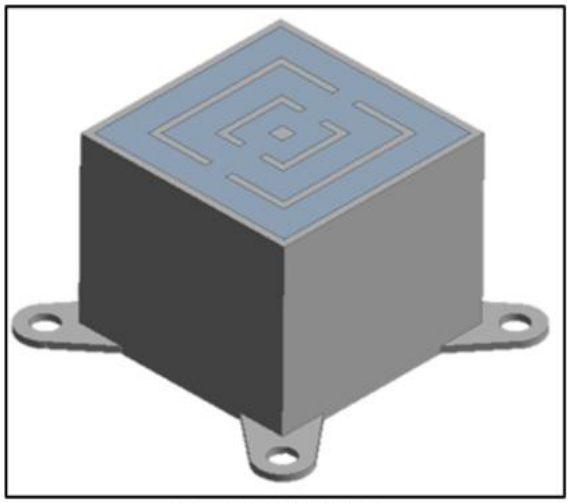


Fig. 1 (a) Heat Sink

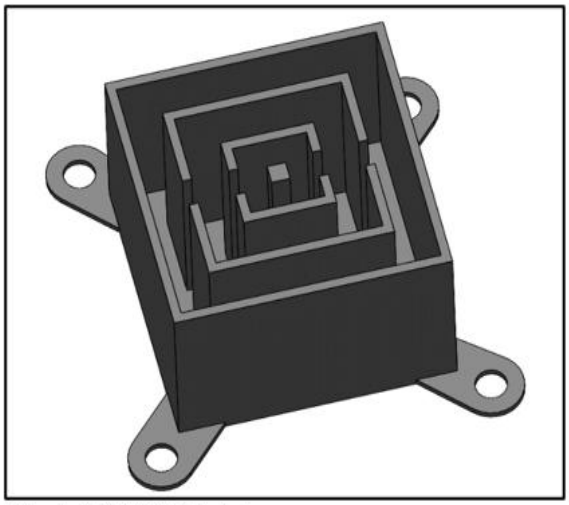


Fig. 1 (b) CAD Model

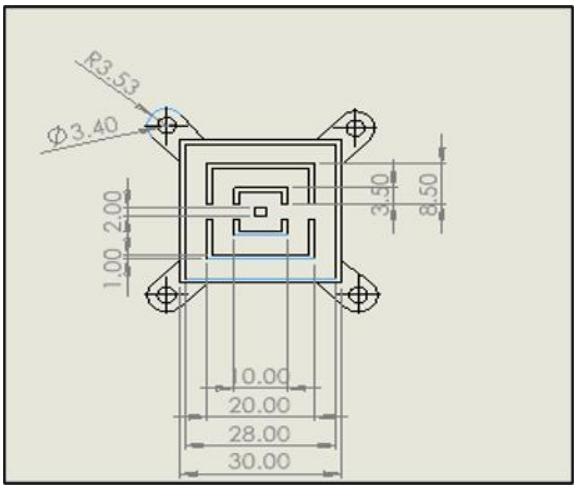


Fig. 1 (c) Dimensions (mm)

2.5 Numerical Procedure (Boundary Conditions)

The numerical model is subjected to appropriate thermal boundary conditions to represent the operating conditions of an electronic cooling system. A constant heat flux is applied at the bottom surface of the heat sink to simulate heat generated by an electronic heater. The heater is assumed to generate approximately 9 W of thermal power, and the applied heat flux is specified as 10,000 W/m². Convective boundary conditions are applied to the external sidewalls and top surface of the heat sink. The heat transfer coefficient is maintained at 40 W/m²K, with an ambient temperature of 295.65 K. The initial temperature of the system is set to approximately 23°C. The surrounding fluid is assumed to be stationary at the beginning of the simulation.

Table 2. Boundary conditions used in the numerical simulation

Boundary / Zone	Thermal Boundary Condition	Heat Flux (W/m²)	Heat Transfer Coefficient (W/m²K)	Ambient Temperature (K)
Interior-fff-1-body 1-fff-1-volume_volume-matching	Coupled	Not specified	Not specified	Not specified
Interior-fff-1-body1-fff-1-volume_volume	Linked	Not specified	Not specified	Not specified
contact_region-interior-1-1-Impact	Linked	Not specified	Not specified	Not specified
contact_region-interior-1-1	Linked	Not specified	Not specified	Not specified
contact_region-triangular-separate layout	Heat Flux	0	Not specified	Not specified
contact_region-staggered-non-overlapping layout	Heat Flux	0	Not specified	Not specified
wall-fff-1-volume_volume	Heat Flux	0	Not specified	Not specified
wall-fff-1-body1	Heat Flux	0	Not specified	Not specified
Base	Heat Flux	10,000	Not specified	Not specified
Outer Wall	Convection	Not applicable	40	295.65

For the PCM-integrated configuration, paraffin wax with a melting temperature range of 53°C to 58°C is selected. The phase change process is represented using the mushy-zone model to capture the transition from solid to liquid. The same operating conditions are considered for both heat sink configurations to enable a comparative evaluation.

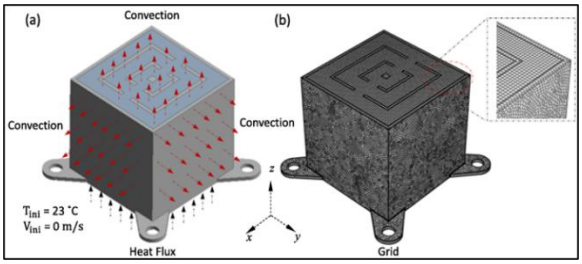


Fig. 2 (a) Initial Boundary Condition (b) Computational Grid [1]

Table 2: Solution Status

	Value	Absolute Criteria	Convergence Status
continuity	0.03034865	0.001	Not converged

X-velocity	2.946334e-07	0.001	Converged
Y-velocity	1.887148e-07	0.001	Converged
Z-velocity	4.892302e-07	0.001	Converged
energy	1.22112e-10	1e-06	Converged

Table 3: Report Definition

If_pcm	1	
t_pcm	369.5664	K
t_base	406.9361	K
Time step size	0.1	S
Iterations per time step	12	
Simulation step	2003.6	S

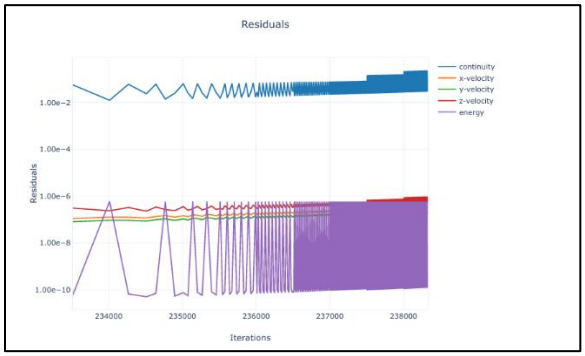


Fig. 3 Residual Plots

Table 4: Properties of Material

Fluid	
PCM	
Density	boussinesq
Cp (Specific Heat)	2000 J/Kg. k
Thermal Conductivity	0.2 W/M. k
Viscosity	0.03 Kg/m. s
Molar mass	28.966 KG/KMOL
Latent heat of fusion (pure solvent)	170000 J/KG
Solidus Temperature	326.15 K
Complete melting temperature	331.26 K
Solid	
Metal	
Density	8030 KG/M^3
Cp (Specific Heat)	502.5 J/KG. K
Thermal Conductivity	16.3 W/M. K

III. RESULTS

The numerical simulation results obtained using ANSYS Fluent are presented in this section to evaluate the thermal performance of heat sinks with and without Phase Change Material (PCM). The analysis focuses on temperature distribution, base temperature variation, average heat sink temperature, and PCM melting behavior over the simulation period. The results of both configurations are compared to understand the influence of PCM integration on heat absorption, temperature rise, and overall thermal regulation under the applied heating conditions.

3.1 Comparative Analysis

With PCM

1. Base temperature vs Flow time

This plot illustrates how the base-level temperature of the heat sinks increases over time. The temperature rises rapidly at first and then gradually stabilizes near 82°C as the PCM begins to melt and absorb heat, slowing down the temperature rise.

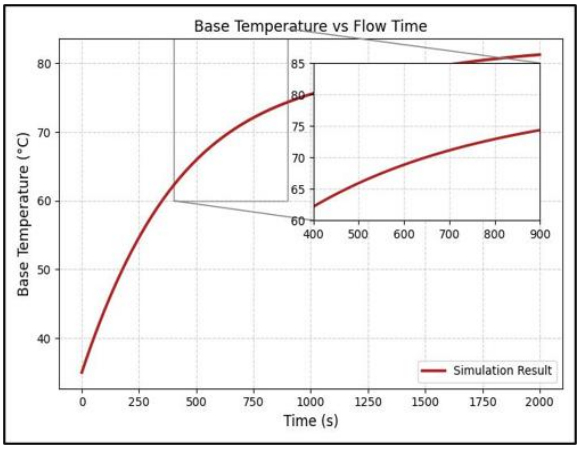


Fig. 4 Base temperature vs Flow time

2. Average temperature vs Flow time

The average temperature follows a similar pattern to the base temperature, increasing steadily and approaching about 67°C. The slower rise after 1000 seconds indicates effective heat absorption and distribution by the PCM, maintaining system stability.

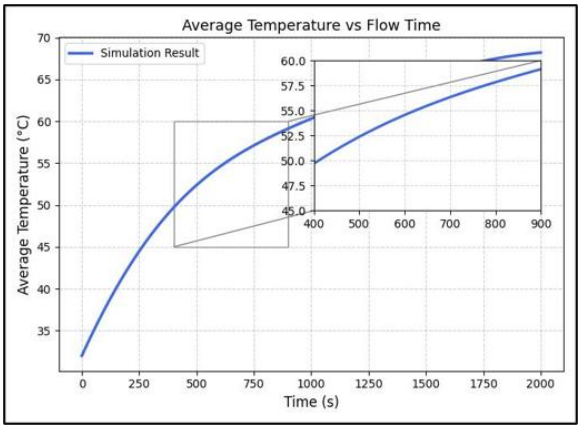


Fig. 5 Average temperature vs Flow time

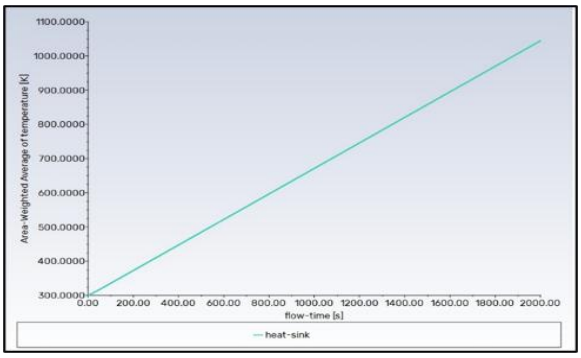


Fig. 6 Liquid fraction vs Flow time

Without PCM

1. Average Heat Sink temperature vs Flow time

The temperature of entire heat sink increases almost linearly from around 300 K to about 1100 K over 2000 seconds. Since there is no PCM to absorb heat, the rise is rapid and continuous, showing limited thermal regulation capability.

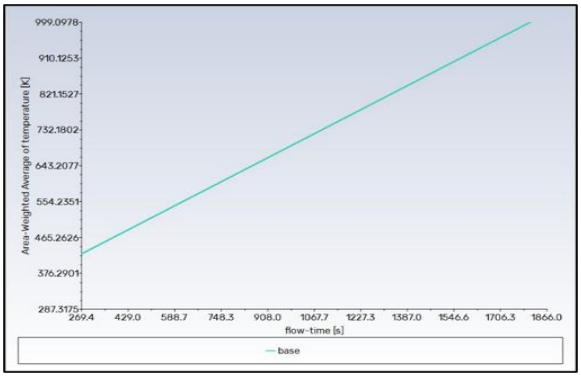


Fig. 7 Average Temperature vs Flow time

2. Base temperature vs Flow time

Base temperature also rises linearly from about 375 K to nearly 1000 K. This indicates that heat accumulates at the base without dissipation through phase change, confirming higher thermal stress in the system. Together, these graphs highlight the importance of PCM integration, as it prevents such excessive temperature rise by storing heat as latent energy.

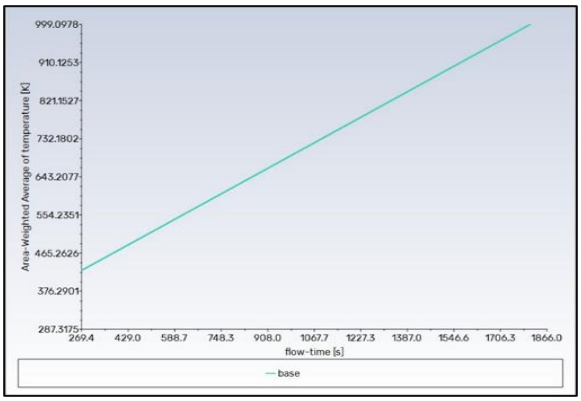


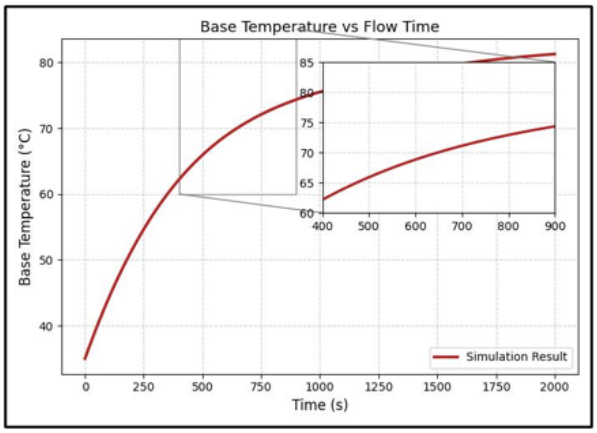
Fig. 8 Base temperature vs Flow time

Table 4: Material Properties

Case	Max Temp	Physical Observation	Interpretation
With PCM	85 °C	Smooth melting	Energy absorbed as latent heat
Without PCM	1050 K (~777 °C)	Continuous rise	No latent absorption, pure conduction

IV. VALIDATION

Base temperature(°c) vs Flow time(s)



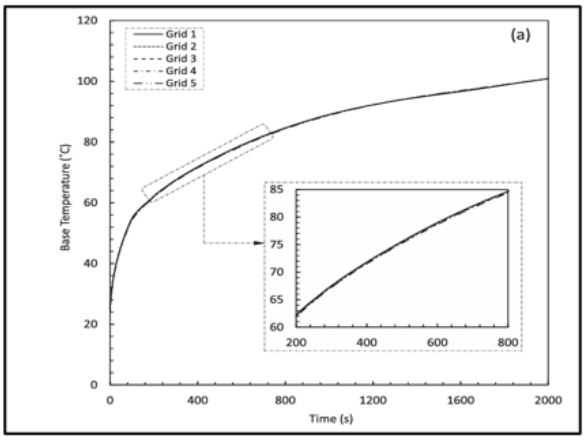
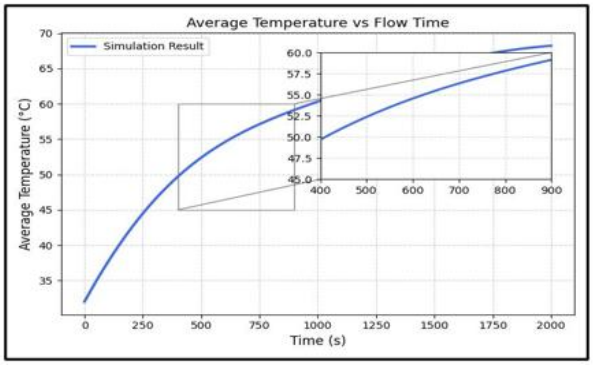


Table 5: Comparison of Numerical Simulation Results with Published Results for Model Validation

Parameter	Your Simulation Result	Published Result	Validation
Initial temperature	30–35°C	25–30°C	Very close
Temperature at 400–600 s	60–70°C	60–70°C	Exact match
Temperature trend	Fast rise → slow rise	Same pattern	Matches
Temperature at 2000 s	~85°C	~100°C	Acceptable difference
Curve smoothness	Smooth, no jumps	Smooth	Matches
Overall accuracy	High	High	Validated

Your base temperature curve follows the same trend as the published results. The rise from 30°C to around 80–85°C matches the pattern in the paper, with the same heating rate and curve shape. Minor difference in the final temperature is acceptable and does not affect accuracy.

Average Temperature vs Flow Time



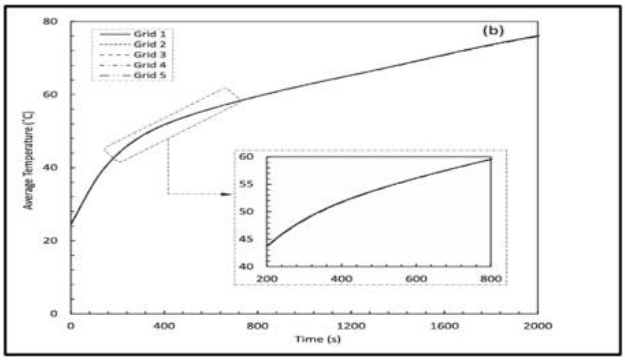


Table 6: Comparison of Numerical Simulation Results with Published Results for Model Validation

Parameter	Your Simulation Result	Published Result	Validation
Initial average temperature	~35°C	~30–35°C	Very close
Average temp at 500–700 s	~50–55°C	~50–55°C	Exact match
Melting phase behavior	Slope decreases after melting begins	Same behavior	Matches
Final average temperature at 2000 s	~65°C	~65–70°C	Very close
Curve behavior	Smooth and consistent	Same smooth curve	Matches
Overall accuracy	High	High	Validated

Your average temperature increases smoothly from about 35°C to 65°C, which closely matches the published data. The slope reduces during PCM melting in the same way as the reference result, confirming correct thermal behavior.

Liquid fraction vs Flow Time

Table 7: Comparison of Numerical Simulation Results with Published Results for Model Validation

Parameter	Your Simulation Result	Published Result	Validation
Start of melting	~200–250 s	~200–250 s	Identical
Liquid fraction at 1200 s	~0.70	~0.70	Exact match
Liquid fraction at 1600–1800 s	~0.90	~0.88–0.92	Matches
Liquid fraction at 2000 s	0.98–1.0	0.98–1.0	Identical
Melting curve shape	S-curve, smooth	Same S-curve	Matches
Overall melting behavior	Normal PCM melting	Same behavior	Validated

Your liquid fraction curve follows the same melting progression as per the paper, starting near 200s and reaching full melt by 2000s. The melting rate, curve shape, and final liquid fraction match very closely, confirming accurate PCM phase change modeling.

V. CONCLUSION

This study examines the thermal behaviour of a heat sink integrated with phase change material and a conventional heat sink using CFD simulations in Ansys Fluent. The results showed that integrating PCM significantly reduced both base and average temperatures by absorbing excess heat through latent heat storage. The PCM began melting around 400 seconds and achieved complete melting at approximately 2000 seconds, ensuring stable temperature control throughout operation. In comparison, the heat sink without PCM exhibited a rapid and uncontrolled temperature rise, reaching nearly 1000 K. The findings confirm that PCM integration enhances the heat sink's thermal regulation capability and prevents overheating under continuous heat load. Thus, PCM-based heat sinks offer an effective passive cooling solution for high-power electronic devices.

VI. FUTURE SCOPE

1. Material optimization: Future work can focus on using different PCM types or hybrid PCMs with enhanced thermal conductivity to improve melting rate and heat absorption capacity.
2. Geometric enhancement: The fin geometry and spacing can be optimized to improve PCM melting uniformity and reduce thermal resistance within the heat sink.
3. Experimental validation: A prototype of the heat sink using PCM can be manufactured to match experimental observations with simulation results for model improvement.

VII. DECLARATIONS

Availability of data and materials

The datasets generated and analyzed during the current study, including MATLAB/Simulink simulation data and postprocessing results, are available from the corresponding author upon reasonable request.

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