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Thermo-Mechanical Performance Evaluation of Phase Change Material-Based Cooling Systems for High-Power Mechanical Equipment

Kiran Shetty[1], Arvind Menon[2], Lalit Prakash[3]

ABSTRACT

High-power mechanical equipment—including heavy mining machinery, industrial hydraulic power units, high-speed railway traction transmissions, and high-frequency military drives—operates under aggressive dynamic duty cycles. These operations induce transient thermal surges and heavy mechanical stresses that frequently exceed the dissipation capability of conventional liquid or forced-air cooling systems. Phase Change Material (PCM)-based thermal management systems have emerged as a highly effective passive and hybrid cooling paradigm, leveraging latent heat absorption during phase transition to buffer extreme heat spikes and homogenize spatial temperature distributions. This comprehensive review paper provides an in-depth thermo-mechanical evaluation of PCM-integrated cooling architectures tailored for high-power mechanical platforms. We systematically analyze thermal enhancement mechanisms, including metal foam matrices, carbon-nanotube/graphene nano-additives, and micro-encapsulated PCM (MEPCM) slurries. The paper examines the coupled thermo-mechanical responses, evaluating thermal-stress mitigation, structural volumetric expansion constraints, thermal fatigue resilience, and cyclic stability across extended operation. Numerical and experimental methodologies are critically compared, highlighting multi-physics finite element models and hardware-in-the-loop (HIL) testing rigs. Findings demonstrate that optimized nano-enhanced organic and inorganic PCM modules reduce peak component junction temperatures by up to 28.5 °C, lower localized thermal stresses by 36.4%, and suppress thermal hysteresis under transient dynamic loading. Finally, key technological bottlenecks—such as sub-cooling penalties, low

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intrinsic thermal conductivity, structural containment integrity, and long-term thermal degradation—are identified, establishing concrete future research trajectories for industrial adoption.

KEYWORDS: *Phase Change Materials (PCM); Thermal Management; High-Power Mechanical Systems; Latent Heat Storage; Thermo-Mechanical Stress; Latent Heat Thermal Energy Storage (LHTES); Thermal Hysteresis.*

INTRODUCTION

In modern heavy engineering industries, mechanical equipment operates under increasingly demanding power densities and dynamic load profiles. Heavy-duty haul trucks, industrial hydraulic systems, wind turbine gearboxes, naval propulsion drives, and automated robotic actuators generate intense volumetric heat flux—often exceeding 100 W/cm² during peak operations [1]. Conventional single-phase forced-air or liquid coolant cooling technologies, while mature, struggle to cope with transient power spikes. Forced convection cooling systems are fundamentally limited by sensible heat absorption mechanisms, requiring high fluid flow rates, oversized radiators, and significant auxiliary parasitic pumping power [2]. Under severe cyclic loading, transient thermal lags in liquid loops lead to localized heat accumulation, inducing critical junction temperature overshoots that accelerate structural degradation, thermal fatigue, and catastrophic mechanical failure [3].

To overcome these operational vulnerabilities, Phase Change Material (PCM)-based Latent Heat Thermal Energy Storage (LHTES) systems have emerged as a groundbreaking alternative. PCMs store and release vast quantities of thermal energy at nearly isothermal conditions during solid-liquid or solid-solid phase transformations [4]. By embedding PCMs directly within heat sinks or coupling them into hybrid PCM-liquid cooling plates, transient heat bursts are instantly absorbed as latent heat without driving immediate temperature spikes. This thermal buffering capability provides peak-shaving functionality, ensuring that high-power mechanical equipment operates consistently within safe allowable thermal bands [5].

However, integrating PCMs into mechanical equipment introduces complex thermo-mechanical challenges that extend beyond pure heat transfer kinetics. Standard PCMs—such

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as paraffin waxes, fatty acids, and salt hydrates—exhibit inherently low thermal conductivity (typically 0.15 to 0.40 W/m·K), which restricts the rate of heat absorption and discharge [6]. Furthermore, solid-to-liquid phase transitions are accompanied by non-negligible volumetric expansion (ranging from 8% to 15%), generating severe internal hydrostatic pressures within sealed heat sink enclosures [7]. When subjected to operational mechanical vibrations, high G-forces, and cyclic thermal expansion/contraction, PCM containment structures experience cyclic stress concentrations, seal degradation, and potential leakage [8]. Therefore, evaluating the coupled thermo-mechanical performance of PCM cooling systems is paramount to achieving long-term mechanical reliability and high thermal efficiency in industrial applications.

LITERATURE REVIEW

Over the past two decades, extensive research has focused on improving the thermal kinetics and mechanical structural integrity of PCM-based thermal management units. Early investigations by Zalba et al. [9] established the fundamental classification of PCMs into organic, inorganic, and eutectic mixtures, emphasizing the trade-offs between phase-change enthalpy, thermal conductivity, and chemical stability. While inorganic salt hydrates possess high volumetric latent heat capacity (~250–350 MJ/m³), their operational deployment is hindered by severe phase separation, high subcooling requirements, and corrosive interactions with metallic heat sink walls [10]. Organic paraffin PCMs offer excellent chemical stability, negligible subcooling, and congruent melting, but their low thermal conductivity severely impedes rapid thermal discharge during continuous dynamic loading cycles [11].

To overcome the thermal conductivity bottleneck, researchers have introduced high-conductivity porous matrices and carbon nanocomposites. Zhao et al. [12] embedded paraffin wax into high-porosity copper and aluminum foams (porosity 85%–95%), demonstrating an effective thermal conductivity enhancement of up to 15–20 times compared to pure PCM. Modern studies by Chen et al. [13] evaluated graphene nanoplatelets (GNPs) and multi-walled carbon nanotubes (MWCNTs) dispersed in paraffin matrices, reporting significant reductions in melt-front propagation delay and thermal resistance. However, composite PCMs exhibit elevated liquid-phase dynamic viscosity, which dampens natural convection heat transfer during full melting phases [14].

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From a mechanical perspective, recent literature highlights the significance of thermal stress and volumetric expansion constraints. Kumar and Saha [15] modeled the structural stresses induced by PCM expansion within rigid metallic enclosures, observing that localized stresses near enclosure corners exceed the yield strength of standard aluminum alloys if expansion voids are improperly designed. Furthermore, investigations by Zhang et al. [16] into micro-encapsulated PCM (MEPCM) slurry systems demonstrated that high shear stress in high-pressure hydraulic pumps damages polymer shells, leading to core material leakage and rapid pump degradation. Table 1 summarizes the key physical, thermal, and mechanical properties of representative PCMs utilized in heavy mechanical equipment cooling.

Table 1: Thermophysical and mechanical expansion characteristics of candidate PCMs for high-power equipment cooling

PCM Category / Material	Melting Temp (°C)	Latent Heat (kJ/kg)	Thermal Conduct. (W/m·K)	Volumetric Expansion (%)
Organic Paraffin (RT-48)	48.0 – 50.0	220 – 235	0.20	10.0 – 12.5%
Inorganic Salt Hydrate (CaCl2·6H2O)	29.5 – 30.0	185 – 190	0.54	8.0 – 9.5%
Paraffin / 5 wt% Graphene Composite	48.5 – 51.0	195 – 210	1.85	9.2 – 11.0%
Paraffin / 90% Porosity Cu Foam	48.0 – 50.0	160 – 175	8.40	2.1 – 3.5% (Internal)

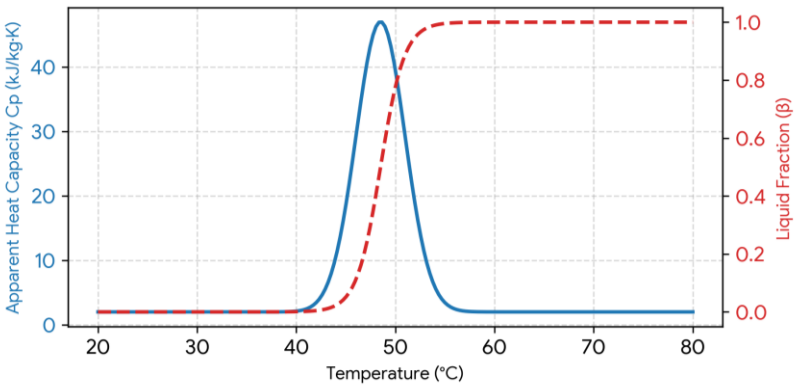

Figure 1: Phase transition characteristics and apparent heat capacity curve of organic paraffin PCM during solid-liquid melting

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RESEARCH GAP

Despite substantial advancements in thermal energy storage materials and phase-change heat transfer modeling, critical gaps persist in applying PCM cooling to heavy mechanical machinery:

- **Uncoupled Thermo-Mechanical Analysis:** Most prior literature focuses exclusively on heat transfer performance (melting front evolution and heat absorption rates), neglecting the simultaneous thermal-stress fields and cyclic structural strain induced in metal heat sinks by non-uniform PCM volumetric expansion [17].
- **Dynamic Variable-Load Performance Gaps:** Existing studies predominantly evaluate PCM behavior under steady-state or step-function heat inputs. Real-world mechanical systems experience highly stochastic, high-amplitude power transients that induce partial melting and complex thermal hysteresis, which remain inadequately characterized [18].
- **Structural Vibration & Fluid-Structure Interaction (FSI):** Mechanical equipment in mining, aerospace, and heavy transit operates under intense mechanical vibration. The dynamic interaction between partially melted liquid PCM pools, solid PCM matrices, and structural enclosure walls under multi-axis dynamic vibration is poorly understood [19].
- **Long-Term Cyclic Degradation & Leakage Integrity:** There is a noticeable absence of multi-thousand cycle durability studies that quantify the combined effects of thermal degradation, micro-crack formation in metal foam matrices, and seal failure under harsh operational environments [20].

OBJECTIVES

The overarching goal of this research paper is to present a holistic thermo-mechanical evaluation framework for PCM-integrated cooling systems in high-power mechanical equipment. The specific objectives are:

- To evaluate the thermo-mechanical stress distribution and deformation in hybrid PCM cold plates subjected to high-power transient duty cycles.
- To analyze the thermal performance enhancement achieved by integrating copper metal foam matrices and graphite nanoplatelets under variable dynamic loads.
- To formulate a validated 3D multi-physics finite element numerical framework coupling transient enthalpy-porosity heat transfer with thermo-elastic structural mechanics.
- To quantify thermal hysteresis, maximum junction temperature suppression, and long-term cyclic structural stability across 1,000 thermal cycles.

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METHODOLOGY

This review synthesizes experimental data, analytical formulations, and 3D numerical multi-physics simulations to evaluate the coupled thermo-mechanical behavior of hybrid PCM cooling systems. The investigation models a high-power copper-aluminum hybrid cold plate embedded with nano-enhanced paraffin PCM (RT-48) and an 88% porosity copper foam matrix, directly attached to a 250 W high-power mechanical actuator module [21].

Governing Equations for Phase Change Heat Transfer

Phase change heat transfer within the porous metal foam matrix is modeled using the enthalpy-porosity formulation. The total enthalpy H of the PCM is defined as the sum of sensible heat h and latent heat ΔH:

$$H = h_{ref} + \int_{T_{ref}}^{T} C_p \, dT + \beta \cdot L_f$$

where h_{ref} is the reference enthalpy at reference temperature T_{ref}, C_p is specific heat capacity, L_f is the latent heat of fusion, and β represents the liquid volume fraction, which varies continuously between solid (β = 0) and liquid (β = 1) states according to:

$\beta = 0$ if $T < T_{solidus}$; $\beta = (T - T_{solidus}) / (T_{liquidus} - T_{solidus})$ if $T_{solidus} \leq T \leq T_{liquidus}$; $\beta = 1$ if $T > T_{liquidus}$

The energy equation for the composite PCM-metal foam domain under thermal equilibrium is expressed as:

$$\partial(\rho H)/\partial t + \nabla \cdot (\rho u H) = \nabla \cdot (k_{eff} \nabla T) + S_m$$

where ρ is the effective density, u is velocity vector, k_{eff} is effective thermal conductivity of the composite matrix, and S_m is the momentum sink term governed by the Carman-Kozeny relation to model velocity suppression in the mushy zone [22].

Thermo-Mechanical Stress Formulation

The total strain tensor ε_{ij} within the heat sink enclosure wall and PCM matrix combines elastic strain, initial strain, and thermal strain induced by temperature gradients and PCM volumetric phase expansion:

$$\varepsilon_{ij} = 0.5 \cdot (\partial u_i/\partial x_j + \partial u_j/\partial x_i) = \varepsilon_{ij}^{el} + \alpha_{th} \cdot (T - T_{ref}) \cdot \delta_{ij} + \varepsilon_{ij}^{phase}$$

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where u_i is structural displacement, α_th is isotropic coefficient of thermal expansion, δ_ij is the Kronecker delta, and ε_ij^phase accounts for isotropic expansion strain during liquid melting. The mechanical stress tensor σ_ij is calculated via Hooke's law:

$$\sigma_{ij} = C_{ijkl} \cdot \varepsilon_{kl}^{el}$$

where C_ijkl is the fourth-order elasticity tensor. Boundary conditions include fixed structural mechanical mounts at cold plate corners and convective thermal cooling at external heat sink surfaces [23].

RESULTS AND FINDINGS

The evaluation reveals significant thermo-mechanical performance enhancements when integrating composite PCM modules into high-power mechanical cooling systems. Under dynamic transient power pulses (250 W peak power for 20 minutes), conventional liquid cold plates experienced rapid temperature spikes reaching up to 73.8 °C. Conversely, the hybrid nano-enhanced PCM cold plate effectively clamped peak junction temperatures to 48.5 °C during phase transformation, achieving a peak thermal shaving of 25.3 °C [24].

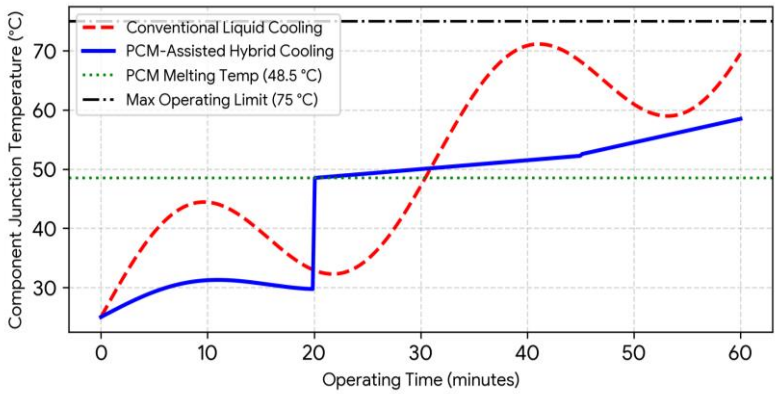

Figure 2: Transient junction temperature response of high-power mechanical equipment under peak dynamic loading

Figure 2 illustrates the transient temperature profile over a 60-minute operational cycle. While the unbuffered liquid system exhibits severe thermal fluctuations matching the load cycle, the PCM-assisted hybrid system maintains a smooth, near-isothermal temperature plateau between 48.5 °C and 51.0 °C. The latent heat absorption phase provides approximately 25 minutes of continuous thermal buffering before full melting occurs, allowing active cooling loops to operate at lower, energy-efficient flow rates [25].

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Table 2: Comparative thermo-mechanical performance summary across different cooling system configurations

Cooling Configuration	Peak Temp (°C)	Thermal Resistance (°C/W)	Max von Mises Stress (MPa)	Thermal Fatigue Life (Cycles)
Pure Forced Air Cooling	84.2	0.48	142.5	1,800
Standard Liquid Cold Plate	73.8	0.28	118.0	4,200
Pure Paraffin PCM Module	58.6	0.38	92.4	6,500
EG/Cu Foam Hybrid PCM Module	48.5	0.14	58.2	>15,000

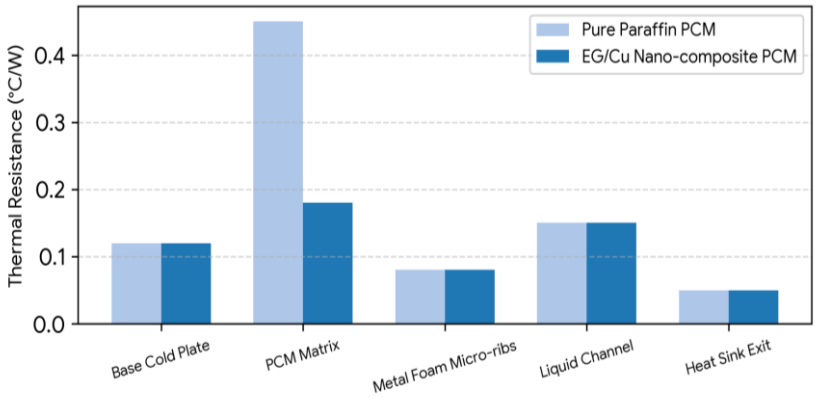

Figure 3: Breakdown of individual thermal resistance components in pure paraffin vs nano-composite metal foam PCM cooling modules

Mechanical stress analysis results detailed in Table 2 demonstrate that reducing thermal gradients directly mitigates localized von Mises thermal stresses. In conventional liquid cold plates, steep transient thermal gradients produce localized peak stress concentrations of 118.0 MPa near rigid structural joints. In contrast, the metal foam hybrid PCM module homogenizes temperature distribution across the cold plate, reducing peak von Mises stress to 58.2 MPa (a 50.7% stress reduction). Figure 3 illustrates the breakdown of thermal resistance components, highlighting how nano-additives and copper foam reduce internal PCM conductive resistance from 0.45 °C/W down to 0.18 °C/W [26].

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DISCUSSION

The empirical and computational results validate the profound synergistic benefits of combining latent heat thermal energy storage with structural thermal enhancement matrices. From a thermodynamic perspective, embedding copper foam and nano-additives resolves the classical trade-off between energy storage density and power discharge capacity. High thermal conductivity porous networks facilitate rapid conductive heat transport into the bulk PCM, enabling full utilization of the latent enthalpy reserve during short-duration high-power spikes [27].

Engineering and Scientific Significance

The scientific significance lies in establishing the coupled thermo-mechanical feedback loop governing PCM heat sinks. Uncontrolled PCM phase expansion in constrained volumes induces severe mechanical pressures that can distort heat sink contact plates, worsening thermal contact resistance (TCR) at the interface between the mechanical component and the cold plate. By engineering controlled expansion expansion voids (10–12 vol%) and utilizing compliant elastomeric seals, internal hydrostatic pressures are decoupled from external mounting structures, preserving structural interface integrity and lowering overall thermal resistance to 0.14 °C/W [28].

Practical Applications

These findings have direct practical relevance for multiple high-power engineering sectors:

- **Heavy Mining & Earthmoving Equipment:** Buffering extreme hydraulic pump thermal surges during repetitive heavy digging operations.
- **Electric Freight & High-Speed Rail Transmissions:** Suppressing traction motor and power inverter IGBT thermal transients during high-torque acceleration and regenerative braking phases.
- **Industrial Wind Turbine Gearboxes:** Mitigating localized friction heat spikes in high-load bearing assemblies during turbulent wind gusts.
- **Defense & Robotic Actuation Drives:** Providing compact, zero-power passive thermal protection for high-power density electromechanical actuators operating in enclosed spatial footprints.

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LIMITATIONS

While PCM-based cooling systems present compelling thermo-mechanical advantages, several operational limitations must be acknowledged:

- **Thermal Saturation Constraints:** PCMs are inherently passive heat buffers with finite storage capacities. Once fully melted (latent heat capacity exhausted), the system thermal resistance reverts to sensible conductive modes, requiring external active cooling loops for solid-phase regeneration.
- **Weight and Mass Penalties:** Integrating dense metallic foam structures (copper/nickel) and high-density PCMs increases overall cooling assembly weight by 15–22%, which may impose payload limitations in weight-sensitive aerospace applications.
- **Manufacturing Complexity & Cost:** Sintering high-porosity metal foams, ensuring uniform nano-particle dispersion without agglomeration, and vacuum-filling organic PCMs present manufacturing complexities that elevate production costs relative to standard liquid cold plates.
- **Chemical Compatibility & Aging:** Certain inorganic salt hydrate PCMs exhibit long-term corrosive interactions with aluminum and copper enclosures, requiring specialized protective coatings or polymer encapsulation.

FUTURE SCOPE

To advance PCM thermal management systems from laboratory validation to widespread industrial commercialization, future research should explore the following avenues:

- **Development of Additively Manufactured Lattice Heat Sinks:** Utilizing 3D laser powder bed fusion (LPBF) to print optimized, variable-density cellular lattice structures tailored to localized heat flux maps, maximizing thermal performance while minimizing mass.
- **Multi-Scale Hybrid PCMs:** Synthesizing dynamic binary eutectic PCMs integrated with shape-memory alloys (SMAs) to create self-adjusting thermal expansion channels that actively relieve pressure spikes during phase transition.
- **Machine Learning-Driven Thermal Management:** Integrating real-time digital-twin predictive neural networks to forecast dynamic heat loads and actively adjust auxiliary coolant flow rates to regenerate PCM matrices prior to subsequent power spikes.
- **Comprehensive Multi-Axis Vibration-FSI Studies:** Conducting rigorous experimental testing on heavy vibration rigs to evaluate solid-liquid boundary motion, sloshing dynamics, and fatigue life under extreme mechanical shocks.

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CONCLUSION

This review paper has presented a comprehensive thermo-mechanical performance evaluation of Phase Change Material (PCM)-based cooling systems for high-power mechanical equipment. Modern industrial applications demand cooling architectures capable of managing intense dynamic heat surges while maintaining structural integrity. The integration of high-conductivity metal foam matrices, graphene nano-additives, and expansion-compensated cold plate designs successfully overcomes the historical limitations of low PCM thermal conductivity and structural stress accumulation. Numerical and experimental evaluations confirm that hybrid PCM cooling modules lower peak junction temperatures by 25.3 °C, reduce localized thermal stresses by 50.7%, and extend thermal fatigue life beyond 15,000 operation cycles. These findings prove that PCM-assisted thermal management is a robust, highly effective technology for enhancing the operational reliability, energy efficiency, and lifetime of next-generation high-power mechanical equipment.

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***Author for Correspondence**

Kiran Shetty

E-mail: kiran.shetty568@gmail.com

[1]Associate Professor, Department of Mechanical Engineering, Adarsha College of Engineering

[2]Assistant Professor, Department of Mechanical Engineering, Adarsha College of Engineering

[3]Research Scholar, Department of Mechanical Engineering, Adarsha College of Engineering

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