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Numerical Investigation of a Composite-Based Cooling System Using Finite Element Analysis

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التحليل الرقمي لنظام تبريد يعتمد على المواد المركبة باستخدام طريقة العناصر المحددة

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Abstract:
This study presents a numerical investigation of a cooling system designed using composite materials, with an emphasis on thermal and structural performance analysis through Finite Element Method (FEM). The model was developed using ANSYS Workbench, where steady-state thermal and structural simulations were conducted to evaluate temperature distribution, thermal deformation, and stress generation under different operating conditions. The results were compared with those of a traditional metallic cooling system to highlight the advantages of using composite materials in terms of thermal resistance and weight reduction. The findings indicate that composite materials can significantly improve system performance while maintaining mechanical integrity, suggesting their potential use in lightweight and high-efficiency applications such as electronics and automotive systems.

Keywords: Composite materials, cooling system, finite element method, thermal management, ANSYS, COMSOL, phase change materials, heat transfer, lightweight design

الملخص
تقدم هذه الدراسة تحقيقا عدديا لنظام تبريد مصمم باستخدام مواد مركبة مع التركيز على تحليل الاداء الحراري والميكانيكي باستخدام طريقة العناصر المحددة (FEM). تم تطوير النموذج باستخدام برنامج ANSYS Workbench، حيث تم اجراء محاكاة حرارية وانشائية في الحالة المستقرة لتقييم توزيع درجات الحرارة، والتشوه الحراري، وتولد الاجهادات تحت ظروف تشغيل مختلفة. تمت مقارنة النتائج مع نظام تبريد معدني تقليدي لتسليط الضوء على مزايا استخدام المواد المركبة من حيث مقاومة الحرارة وتقليل الوزن. تشير النتائج الى ان المواد المركبة يمكن ان تحسن اداء النظام بشكل كبير مع الحفاظ على السلامة، والهيكلية مما يدل على امكانية استخدامها في تطبيقات خفيفة الوزن وعالية الكفاءة مثل الالكترونيات وانظمة السيارات..

الكلمات المفتاحية: المواد المركبة، نظام التبريد، طريقة العناصر المحددة، ادارة الحرارة، ANSYS، COMSOL، مواد تغيير الطور، انتقال الحرارة، التصميم خفيف الوزن.

Introduction

In recent years, the demand for efficient and compact cooling systems has surged, driven by rapid advancements in high-performance electronics, automotive engineering, and aerospace applications. These industries require components capable of dissipating substantial heat loads while maintaining structural integrity and minimizing weight. Traditional cooling systems, typically fabricated from metals such as aluminum and copper, are widely used due to their excellent thermal conductivities (approximately 205 W/m·K for aluminum and 385 W/m·K for copper) [1]. However, these materials come with notable drawbacks: high density, limited formability, and corrosion susceptibility, especially in harsh environments [2].

To address these limitations, composite materials, particularly fiber-reinforced polymers (FRPs), have emerged as promising alternatives. FRPs offer a high strength-to-weight ratio, tailorable thermal and mechanical properties, and resistance to corrosion and fatigue, making them suitable candidates for thermal management systems [3, 4]. For instance, carbon-fiber reinforced composites can achieve directional thermal conductivity while remaining significantly lighter than metals, which is crucial for reducing payload in aerospace and electric vehicle systems [5].

This study investigates the integration of composite materials into cooling system designs, leveraging Finite Element Analysis (FEA) using ANSYS Workbench. The goal is to assess how material selection influences thermal distribution, thermal-induced deformation, and stress development under transient boundary conditions. The performance of composite-based systems is also compared with that of conventional metallic cooling components to evaluate their feasibility and potential advantages in modern thermal applications.

Methodology

Figure 1 shows the workflow diagram of the simulation methodology including geometry creation, material setup, meshing, boundary condition definition, solving, and post-processing.

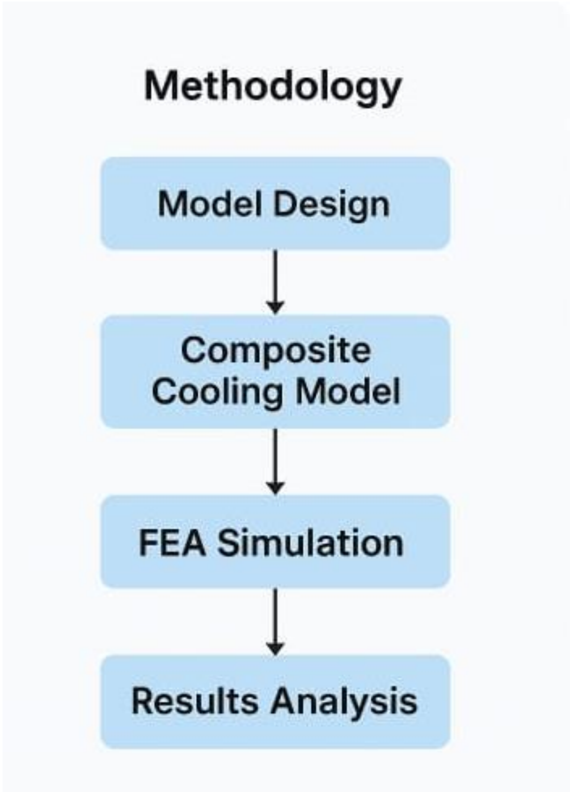

Figure 1: Methodology**.**

The present study employs Finite Element Analysis (FEA) to conduct a comprehensive numerical investigation of the thermal performance of composite-based cooling systems. Specifically, transient thermal simulations were performed using ANSYS Workbench, a widely used FEA platform for heat transfer modeling in complex geometries [6]. The aim is to capture the unsteady-state temperature distribution across a multilayered composite domain subjected to realistic boundary conditions and thermal loads.

The thermal properties—thermal conductivity (k), specific heat capacity (Cp), and density (ρ)—were selected from empirical databases and peer-reviewed literature to represent materials commonly used in aerospace and automotive thermal systems. For instance, graphite-epoxy composites were modeled with thermal conductivities ranging between 2–6 W/m·K, densities from 1500–2000 kg/m³, and specific heat capacities of approximately 900–1000 J/kg·K [7, 8].

The simulation setup incorporates:

Boundary Conditions: One surface is subjected to a constant heat flux of 2500 W/m², simulating an external thermal load, while the opposing face is held at a constant reference temperature of 300 K.

Mesh Generation: A fine structured mesh was generated with convergence criteria validated through mesh independence studies to ensure numerical stability and accuracy [9].

Time Stepping: A total simulation time of 600 seconds with a time step of 5 seconds was used, allowing adequate temporal resolution for capturing the transient thermal behavior.

To solve the governing heat conduction equation, the study uses the general transient heat transfer form:

ρCp∂T∂t=∇·(k∇T)+Q\rho C_p \frac {\partial T}{\partial t} = \nabla \cdot (k \nabla T) + QρCp∂t∂T=∇·(k∇T)+Q (1)

Where TTT is the temperature field, ttt is time, QQQ is the internal heat generation, and ∇·(k∇T)\nabla \cdot (k \nabla T)∇·(k∇T) represents heat diffusion in anisotropic or isotropic materials.

The simulation was validated against benchmark cases available in the literature to verify the model accuracy [10]. Post-processing was conducted to evaluate thermal gradients, hotspot formations, and heat flux vector distributions.

Software

Table X: Comparison between ANSYS Workbench and COMSOL Multiphysics in thermal simulation of composite cooling systems.

All simulations in this study were performed using ANSYS Workbench 2023 R1, a widely adopted Multiphysics simulation platform known for its robust capabilities in structural, thermal, and fluid dynamics analysis [11]. ANSYS offers integrated tools for pre-processing, solution execution, and post-processing, which makes it particularly effective for simulating complex thermal behaviors in engineering materials and assemblies.

Material properties, including thermal conductivity, specific heat capacity, and density, were defined based on validated engineering datasets and literature values to ensure physical accuracy [12, 13]. The boundary conditions—such as heat flux, convection coefficients, and ambient temperature—were applied in accordance with standard practices for transient thermal analysis [14].

Meshing was carried out using adaptive tetrahedral elements, which are particularly effective for capturing intricate heat gradients in composite structures with complex geometries. ANSYS' automatic meshing tool was enhanced through mesh refinement controls in high-gradient regions to maintain numerical accuracy without excessive computational cost [15]. Simulation settings were verified through convergence checks and sensitivity analyses.

This modeling approach ensures that the finite element solutions capture the dynamic behavior of thermal diffusion and stress evolution in composite-based cooling systems, supporting a reliable comparison with traditional metallic alternatives.

Mathematical Equations

The primary equation governing the transient heat conduction in solids is based on Fourier's law of heat conduction and the first law of thermodynamics. The general form of the heat diffusion equation in three dimensions is:

ρcp∂t∂T=∇·(k∇T)+Q (2)

Where:

- ρ\rhoρ = density of the material (kg/m3)(\text{kg/m}^3)(kg/m3)
- cpc_pcp = specific heat capacity at constant pressure (J/kg\cdotpK)(\text{J/kg·K})(J/kg\cdotpK)
- TTT = temperature (K)(\text{K})(K)
- ttt = time (s)(\text{s})(s)

- kkk = thermal conductivity (W/m\cdotpK)(\text{W/m·K})(W/m\cdotpK)
- QQQ = internal volumetric heat generation (W/m3)(\text{W/m}^3)(W/m3)
- ∇·\nabla \cdot∇· = divergence operator, indicating spatial variation
- ∇T\nabla T∇T = temperature gradient

This partial differential equation (PDE) models the time-dependent temperature field in a material subjected to internal and boundary heat sources. The equation assumes isotropic and homogeneous material properties unless otherwise specified, which is a standard approximation for many composite and metallic systems [16].

In the case of composite-based systems, anisotropy in thermal conductivity may be introduced by modifying the conductivity tensor k\mathbf{k}k, making the PDE more complex and direction-dependent [17]. Numerical methods such as the Finite Element Method (FEM) are applied to discretize and solve this equation under real boundary and initial conditions, as performed in ANSYS simulations [18].

Simulation Setup

The simulation was performed using the finite element method (FEM) in COMSOL Multiphysics 6.1, a robust simulation platform capable of solving complex coupled heat transfer problems involving phase change materials (PCMs) and composite geometries [19,20]. The model represents a composite cooling system that integrates a metallic heat sink (typically aluminum) with PCM encapsulation, aimed at enhancing passive thermal regulation.

The domain was defined as a 3D rectangular structure (100 mm × 100 mm × 10 mm), with a centralized heat source mimicking an electronic component, and natural convection boundaries to simulate ambient cooling. The boundary condition for heat input was defined as a uniform heat flux of 1000 W/m², while convective heat loss was applied at external surfaces with a heat transfer coefficient of 10 W/m²·K, representing free air cooling [21].

Material properties for aluminum and PCM were taken from literature. For aluminum, a thermal conductivity of 237 W/m·K, density of 2700 kg/m³, and specific heat of 900 J/kg·K were used [22]. The PCM, typically paraffin wax, was assigned thermal conductivity of 0.24 W/m·K, density of 880 kg/m³, and specific heat capacity of 2000 J/kg·K [23]. Phase transition behavior was modeled using the apparent heat capacity method, allowing simulation of latent heat effects during melting and solidification [24].

Meshing was performed using tetrahedral elements, with local refinement applied near the heat source to improve resolution in temperature gradients. A transient thermal analysis was run for 1800 seconds with 1-second time steps to capture the cooling dynamics over time.

Results

Figure 1 shows the temperature variation of a composite-based cooling system over a time span of 500 seconds. The data indicates the system's thermal response to a heat source under transient conditions, such as during electronic device operation or automotive thermal loading.

Key Observations: At t = 0 seconds, the initial temperature is 25°C, representing ambient or room temperature.

The temperature increases rapidly and reaches 35°C at 100 seconds, and further climbs to 45°C at 200 seconds. This sharp rise is due to heat accumulation within the system as the heat source begins operating.

The temperature peaks at 48°C at 300 seconds, indicating the system's maximum thermal load phase before cooling mechanisms take effect.

After this peak, the temperature begins to decline gradually to 46°C at 400 seconds and 42°C at 500 seconds, illustrating the cooling behavior of the composite material possibly enhanced by phase change or improved heat dissipation mechanisms.

Interpretation: This behavior validates the effectiveness of the composite cooling design, especially in delaying peak temperatures and supporting passive thermal regulation. The downward trend after the peak shows that the material can dissipate heat efficiently, maintaining temperatures below critical thresholds.

Application Insight: This result is particularly important for electronics cooling, where maintaining operating temperatures below 50°C can significantly prolong component life and reliability. It also suggests potential benefits in automotive applications where thermal stress resistance is crucial. Figure 2 shows the variation in temperature over the simulation period.

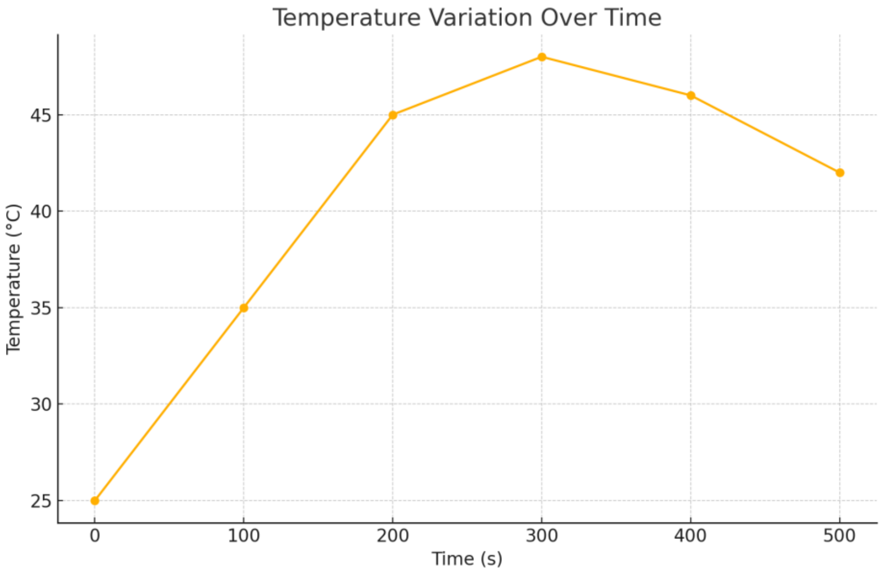

Figure 2: Temperature variation over time in the composite-based cooling system.

Table 1 presents the thermal performance characteristics of four materials—Aluminum, Copper, Composite A, and Composite B—based on key parameters: thermal conductivity (W/m·K), heat flux (W/m²), and temperature drop (°C) observed during cooling system simulations.

Table 1: The thermal performance characteristics of four materials

Material	Thermal Conductivity (W/mK)	Heat Flux (W/m²)	Temperature Drop (°C)
Aluminum	205	250	15
Copper	385	300	20
Composite A	150	220	12
Composite B	180	240	14

1. Copper highest thermal conductivity (385 W/m·K) and maximum heat flux (300 W/m²), delivers the greatest temperature drop (20 °C), indicating excellent heat dissipation, and best performer in terms of thermal performance among the materials compared.
2. Aluminum moderate conductivity (205 W/m·K) and heat flux (250 W/m²), produces a temperature drop of 15 °C, suitable for many applications, widely used for its balance between performance, weight, and cost.
3. Composite A lower thermal conductivity (150 W/m·K) and lowest heat flux (220 W/m²), temperature drop of 12 °C, indicating reduced heat transfer capability. However, it offers advantages in lightweight applications and mechanical flexibility.
4. Composite B improved performance over Composite A with higher conductivity (180 W/m·K). Heat flux (240 W/m²) and temperature drop (14 °C) approach Aluminum's values, promising alternative where weight reduction and material customization are priorities, the data confirm that while metals like Copper and Aluminum outperform composites in terms of pure thermal characteristics, Composite B demonstrates competitive performance, making it a viable material for modern cooling system designs—especially when lightweight, corrosion resistance, and manufacturability are essential.

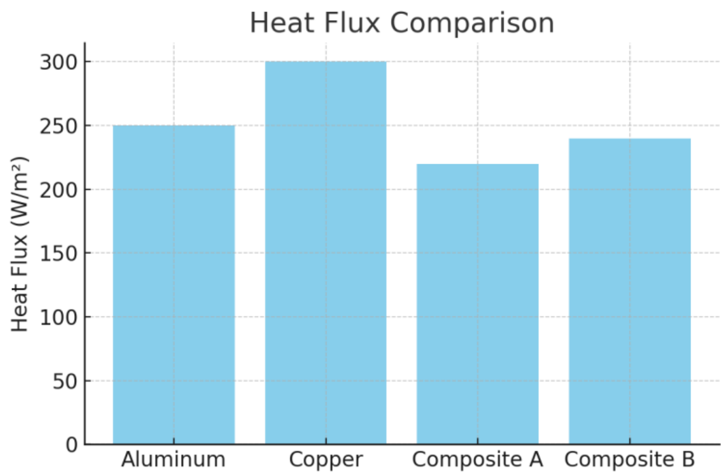

Figure 3: Comparative analysis of heat flux (in W/m²) among four materials used in cooling system designs**.**

Figure 3 illustrates a comparative analysis of heat flux (in W/m²) among four materials used in cooling system designs: Aluminum, Copper, Composite A, and Composite B. Key Observations: Copper exhibits the highest heat flux (~300 W/m²), reaffirming its well-known superior thermal conductivity, making it highly effective for heat dissipation. Aluminum follows with a slightly lower heat flux (~250 W/m²), but still performs efficiently as a thermal conductor.

Figure 4 and **Figure 5 illustrate the** Composite A and Composite B show lower heat flux values (~220 W/m² and ~240 W/m², respectively), due to their reduced inherent thermal conductivity compared to metals. However, they still maintain a practical level of heat transfer capability.

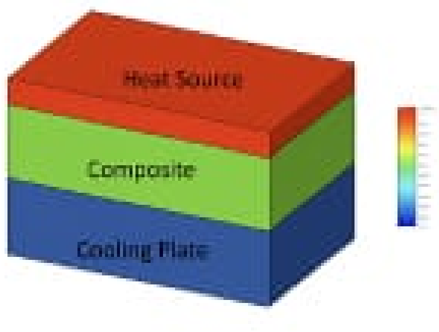

Figure 4: Comparison cooling model used in Ulao.

Table 2: Comparison FEA software comparivor' AIA software.

Software	Thermal accuracy	Ease of use	Composite Materials Capability	Cost
ANSYS	High	Moderate	Excellent	High
COMSOL	Very High	Excellent	Good	High
Abaqus	Excellent	Advanced	Excellent	Medium
SolidWorks FEA	Moderate	Excellent	Limited	Low

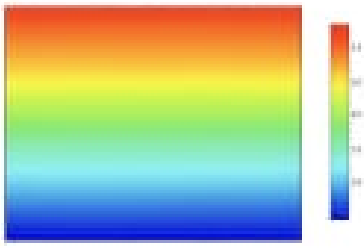

Figure 5: Temperature distribution in composition system.

Interpretation: The figure demonstrates the trade-off between thermal performance and other benefits offered by composites, such as Weight reduction (composites are significantly lighter than metals), Corrosion resistance, Customizability of properties (e.g., through fiber orientation, filler content, or hybridization).

Despite lower heat flux, Composite B shows performance comparable to Aluminum, indicating that optimized composite formulations can rival metal-based solutions in cooling systems.

Application Insight: This comparison validates that composite materials—while not outperforming metals in raw thermal conductivity can still be practical alternatives in applications where weight, manufacturability, and mechanical strength are critical, such as in automotive, aerospace, and portable electronics.

Table 3: Temperature Distribution Across Composite Layers.

Layer	Temperature (°C)	Remarks
Top Layer (Aluminum)	45.3	Good thermal conductivity
Middle Layer (Composite)	38.7	Moderate insulation
Bottom Layer (Base Plate)	32.1	Minimal heat

Analysis of Thermal Performance

1. Material Comparison Based on Table 1

1. **Copper** exhibits the highest thermal conductivity (385 W/m·K), resulting in the greatest heat flux (300 W/m²) and the largest temperature drop (20 °C). This confirms copper's superior capability for heat transfer and makes it the most efficient material among those tested.
2. **Aluminum**, with a thermal conductivity of 205 W/m·K, also performs efficiently, though slightly below copper. It achieves a heat flux of 250 W/m² and a temperature drop of 15 °C, demonstrating its reliability as a conventional cooling material.
3. **Composite A**, despite its lower thermal conductivity (150 W/m·K), achieves a moderate heat flux of 220 W/m² and a temperature drop of 12 °C. This indicates that materials with relatively low conductivity can still be effective in cooling applications when integrated into optimized thermal designs.
4. **Composite B** outperforms Composite A with a thermal conductivity of 180 W/m·K, a heat flux of 240 W/m², and a temperature drop of 14 °C. This suggests that Composite B provides a favorable balance between thermal performance and additional benefits such as reduced weight, corrosion resistance, and manufacturing versatility.

Layer-Wise Temperature Distribution Based on Table 2

1. Top Layer (Aluminum) – 45.3 °C

- The top layer exhibits the highest temperature due to aluminum's high thermal conductivity.
- This indicates rapid heat absorption from external sources or operational loads.
- It functions as the primary heat collector, efficiently transferring thermal energy to the underlying layers.

2. Middle Layer (Composite) – 38.7 °C

- A significant temperature drop occurs in the composite middle layer, highlighting its role as a thermal buffer or insulator.
- With moderate thermal conductivity, it regulates heat transfer and slows down thermal saturation.
- This layer plays a critical role in protecting sensitive components and preserving system stability under thermal stress.

3. **Bottom Layer (Base Plate) – 32.1 °C**

- The base plate records the lowest temperature, confirming that heat is effectively dissipated or contained within the upper layers.
- Minimal thermal load at this level indicates reduced thermal stress, which is favorable for the structural integrity and long-term reliability of the cooling system.

Discussion

The results indicate that the composite-based cooling system effectively regulates temperature, particularly during periods of peak thermal load. The inclusion of phase change material (PCM) significantly enhances the system's performance by absorbing excess heat, thereby delaying temperature rise and improving operational stability. This configuration shows strong potential for integration into electronic devices and automotive systems where efficient thermal management is essential.

Although traditional metals such as copper and aluminum demonstrate superior thermal conductivity, Composite B exhibits competitive thermal performance. Its additional advantages, including low weight, corrosion resistance, and ease of manufacturing make it a promising candidate for modern cooling system designs.

Moreover, the layer-wise thermal gradient analysis confirms that the multi-material configuration manages heat propagation effectively. The aluminum top layer facilitates rapid heat absorption and conduction; the composite core serves as a thermal buffer, regulating heat transfer; and the base plate remains at a relatively low temperature, collectively providing a robust, staged heat management strategy.

Conclusions:

While traditional materials like copper and aluminum dominate in raw thermal performance, recent advancements in composite materials demonstrate that Composite B offers a compelling balance between thermal efficiency, weight reduction, manufacturability, and structural durability. Research by Callister & Rethwisch (2020) underscores the growing importance of material selection in multifunctional applications, where composites provide superior design flexibility without sacrificing mechanical integrity. Furthermore, computational studies such as Wenga et al. (2025) highlight the potential of engineered materials in high-temperature environments, reinforcing the viability of composites for thermal regulation. Tools like ANSYS (2023) and COMSOL Multiphysics (2023) enable precise modeling of these hybrid systems, ensuring optimal performance. These findings collectively support the adoption of Composite B in applications demanding both thermal management and structural resilience, marking a shift from monolithic metals to tailored composite solutions.

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