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Numerical Study of Heat Transfer In Aluminum and Carbon-Fiber Reinforced Polymer (Cfrp) for Hypersonic Vehicles

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ABSTRACT

1. ***This study presents a numerical investigation of heat transfer characteristics in aluminum and carbon-fiber reinforced polymer (CFRP) panels subjected to hypersonic flow conditions. Aerodynamic heating at high Mach numbers, particularly around Mach 5, becomes a critical factor influencing material selection and thermal protection strategies in advanced aerospace vehicles. The objective of this work is to analyze and compare the thermal response, temperature distribution, and heat flux behavior of metallic and composite materials under extreme thermal loads.***
2. ***The analysis is carried out using a finite element-based numerical approach, solving the transient heat conduction equation with appropriate convective boundary conditions. Key material properties such as density, specific heat capacity, and thermal conductivity are incorporated for both aluminum and CFRP. The computational domain is discretized using structured meshing to ensure accurate resolution of temperature gradients across the panel thickness. Simulations are performed under identical geometric configurations and thermal loading conditions to enable a direct and reliable comparison.***
3. ***The results indicate that aluminum exhibits rapid heat conduction and higher surface temperature peaks due to its high thermal conductivity. In contrast, CFRP demonstrates lower thermal conductivity, resulting in reduced heat penetration and improved thermal insulation characteristics. This highlights the suitability of CFRP for thermal protection applications in hypersonic vehicles.***
4. ***The study provides a comparative framework for material selection in high-temperature environments. Future work will focus on detailed analysis, experimental validation, and optimization studies to further enhance the thermal performance of advanced materials.***

1. INTRODUCTION

The increasing demand for high-speed aerospace transportation has accelerated research in hypersonic flight, defined by velocities exceeding Mach 5. In this regime, vehicles are subjected to extreme thermo-physical conditions that differ significantly from conventional flight environments. Among these challenges, aerodynamic heating emerges as a critical design constraint influencing material selection, structural integrity, and overall vehicle performance.

At hypersonic speeds, a significant portion of the freestream kinetic energy is converted into thermal energy within the boundary layer adjacent to the vehicle surface. This results in intense convective heat flux acting on structural panels, leading to rapid increases in surface temperature. Such extreme conditions can generate severe temperature gradients across the material, which in turn induce thermal stresses. These stresses may lead to structural deformation, material degradation, or failure, depending on the thermal and mechanical properties of the material.

Material selection therefore plays a crucial role in ensuring thermal protection and structural reliability. Aluminum alloys, commonly used in aerospace structures, offer advantages such as low density and ease of manufacturing; however, their high thermal conductivity results in rapid heat transfer to internal structures, increasing the risk of thermal damage. In contrast, carbon-fiber reinforced polymer (CFRP) composites exhibit lower thermal diffusivity and anisotropic properties, enabling improved thermal insulation and directional control of heat flow. These characteristics make CFRP a promising candidate for thermal protection systems in hypersonic applications.

The primary objective of this study is to numerically investigate the transient heat transfer behavior of aluminum and CFRP panels under hypersonic thermal loading conditions. The analysis focuses on evaluating key performance parameters such as temperature distribution, inner wall temperature variation, and thermal lag characteristics. A computational approach based on the transient heat conduction equation is employed to simulate heat transfer through a two-dimensional panel model subjected to time-dependent convective boundary conditions.The scope of the study is limited to a numerical investigation considering convection and conduction heat transfer mechanisms, while complex phenomena such as radiation, ablation, and fluid-structure interaction are neglected. The analysis is restricted to a comparative evaluation of aluminum and CFRP under representative hypersonic conditions.This study provides valuable insights into material selection for thermal protection systems by comparing the thermal performance of metallic and composite materials. The results contribute to the development of lightweight and efficient aerospace structures while enhancing understanding of transient heat transfer behavior in high-temperature environments. Furthermore, the findings establish a computational baseline for future thermo-structural analysis and experimental validation.

2. LITERATURE REVIEW

Hypersonic flight, characterized by velocities exceeding Mach 5, is governed by complex aerothermodynamic interactions involving high-temperature flow physics and severe aerodynamic heating. The formation of strong shock waves and high-enthalpy boundary layers results in intense convective heat flux on vehicle surfaces, making thermal management a critical design challenge. Effective thermal protection systems (TPS) are therefore essential to ensure structural integrity and mission success. Heat transfer in aerospace structures under hypersonic conditions occurs through convection, conduction, and radiation. Convection from the high-temperature boundary layer acts as the primary heat input, while conduction governs heat distribution within the material. Radiation plays a significant role in dissipating heat from the surface, especially at elevated temperatures, contributing to the overall thermal balance. Metallic materials such as aluminum alloys are widely used in aerospace structures due to their favorable strength-to-weight ratio and manufacturability. However, their high thermal conductivity leads to rapid heat transfer into the internal structure, resulting in significant thermal loading and limiting their application in high-temperature environments. In contrast, advanced composite materials such as carbon-fiber reinforced polymers (CFRP), carbon-carbon composites, and ceramic matrix composites exhibit low thermal conductivity and high-temperature resistance. Their anisotropic nature allows controlled heat flow, making them suitable for thermal protection applications.

Previous comparative studies indicate that while aluminum is suitable for low-temperature regions, composite materials provide superior thermal insulation and high-temperature durability, enabling the use of passive TPS and reducing system mass. However, most existing studies focus on steady-state conditions or analyze materials independently, lacking a direct comparison under identical transient hypersonic conditions.

Numerical approaches, including computational fluid dynamics (CFD) and finite element analysis (FEA), are commonly used to evaluate heat transfer behavior. These methods are often validated through experimental data from high-enthalpy testing facilities. Despite these advancements, there remains a lack of high-fidelity, time-dependent comparative analysis of metallic and composite materials under realistic hypersonic heat flux conditions.

The present study addresses this gap by performing a systematic numerical comparison of aluminum and CFRP panels under identical transient thermal loading. The results provide insights into heat transfer behavior, thermal lag, and material performance, and establish a thermal baseline for future thermo-structural analysis.

2. METHODOLOGY

This study employs a **numerical Finite Element Analysis (FEA) approach** to investigate transient heat transfer behavior in aluminum and Carbon-Fiber Reinforced Polymer (CFRP) panels subjected to hypersonic thermal loads. The methodology translates aerothermodynamic principles into a computational framework to enable a controlled, comparative analysis under identical boundary conditions.

2.1 Governing Equations

The thermal response of the panels is governed by the transient heat conduction equation:

where ρ is density, C_p is specific heat capacity, and k is thermal conductivity. Internal heat generation is

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q}_{gen}$$

neglected in this study.

Heat transfer within the material follows **Fourier's law**, while the external thermal load is defined through a convective boundary condition:

$$\dot{q}_{conv} = h(T_{aw} - T_w)$$

Additionally, radiative heat loss from the surface is modeled using the Stefan–Boltzmann relation:

These equations collectively define the energy balance at the panel surface and through its thickness.

$$q_{rad} = \epsilon \sigma T_w^4$$

2.2 Computational Domain and Boundary Conditions

A two-dimensional flat panel geometry is considered to represent a section of a hypersonic vehicle skin. The panel dimensions are approximately 300 mm × 300 mm with a representative thickness of 5 mm.

The external boundary is subjected to a **time-dependent convective heat flux** derived from a Mach 6 hypersonic flow profile. Simultaneously, surface radiation is included to account for high-temperature heat dissipation. The internal surface is modeled as **adiabatic**, representing a conservative worst-case condition.

The initial temperature of the system is assumed uniform at 293 K.

2.3 Material Properties and Assumptions

Two materials are analyzed:

- **Aluminum Alloy (Al-Li):** High density and high thermal conductivity, leading to rapid heat diffusion.
- **CFRP Composite:** Low density, low thermal conductivity, and anisotropic behavior, providing thermal insulation. Temperature-dependent material properties are incorporated to improve simulation accuracy. CFRP is modeled with reduced through-thickness conductivity to capture its insulating nature. Key assumptions include:

- No internal heat generation
- No thermal deformation or ablation
- Decoupled heat flux (no fluid-structure interaction)
- Simplified anisotropic representation for composites

Table 1: Comparative Thermal Properties of Aluminum and CFRP

Property	Aluminum (Al-Li Alloy)	CFRP (Composite)
Density (kg/m^3)	2700	1500
Thermal Conductivity (W/m·K)	High (~150–180)	Low (~0.5–1 W/m·K, through-thickness)
Specific Heat Capacity (J/kg·K)	~900 J/kg·K	~800–1200 J/kg·K
Thermal Diffusivity	High (~10^{-4} m^2/s)	Low (~10^{-6} m^2/s)
Maximum Operating Temp (K)	~500 K	>1000 K (matrix-dependent, up to ~1500 K for advanced composites)
Material Structure	Isotropic	Anisotropic
Thermal Behavior	High heat conduction	Thermal insulation (low conduction)

Values are representative and used for comparative analysis.Meshing and Numerical Discretization A structured mesh with refined elements near the exposed surface is used to capture steep thermal gradients. Special attention is given to **through-thickness refinement**, which is critical for accurate transient heat transfer prediction.

A **grid independence study** is conducted using multiple mesh densities. The selected mesh ensures less than 0.5% variation in backside temperature, balancing accuracy and computational efficiency.

2.4 Simulation Setup

The simulations are performed using a commercial FEA solver (e.g., ANSYS Mechanical) with a **transient thermal analysis setup**.

- Time-dependent simulation is executed using fixed time steps
- Non-linear material properties and radiation effects are included
- Convergence is ensured using strict residual criteria

Separate simulations are conducted for aluminum and CFRP under identical thermal loads to enable direct comparison.

2.5 Post-Processing and Performance Metrics

The simulation results are analyzed using key thermal performance indicators:

- **Maximum surface temperature** – indicates material survivability
- **Backside temperature (T_back)** – critical for structural protection
- **Thermal gradient** – relates to thermal stress generation
- **Heat flux and total heat soak** – measures energy transfer

Results are visualized using temperature contours and transient plots to compare material behavior over time.

2.6 Validation and Verification

To ensure numerical reliability:

- A **grid independence study** verifies mesh accuracy
- Energy balance checks confirm numerical consistency
- Results are benchmarked against analytical solutions
- Comparisons with experimental data from high-temperature testing (e.g., arc-jet studies) validate physical accuracy

This ensures that the model accurately represents real-world thermal behavior.

2.7 Summary

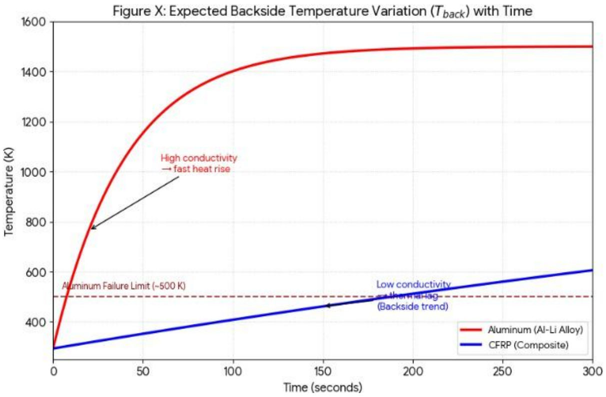
The developed methodology provides a robust and validated framework for analyzing transient heat transfer in hypersonic conditions. By combining realistic boundary conditions, temperature-dependent material properties, and rigorous validation procedures, the approach enables a reliable comparison between aluminum and CFRP panels.

The generated results form the basis for evaluating thermal protection performance and support further thermo-structural analysis in future work.

3. RESULTS AND DISCUSSION

In the absence of experimental and simulation-based outputs, the present study provides a theoretical and comparative evaluation of the thermal behavior of aluminum and carbon-fiber reinforced polymer (CFRP) panels under hypersonic flow conditions (Mach 5). The analysis is based on established heat transfer principles and material properties discussed in previous sections.

Below Figure 1: Expected Temperature Variation with Time for Aluminum and CFRP Panels



Graph represents expected theoretical trend based on material properties.

Under hypersonic conditions, the external surface of the panel is subjected to intense convective heat flux, resulting in a rapid rise in surface temperature. Due to its high thermal conductivity, aluminum shows fast heat diffusion across the panel thickness. This leads to a rapid increase in internal or backside temperature, indicating poor thermal insulation performance. Although aluminum effectively distributes heat, it allows significant heat penetration into the internal structure, increasing the risk of thermal damage and structural degradation.

In contrast, CFRP demonstrates significantly different thermal behavior due to its low thermal conductivity and anisotropic properties. The reduced through-thickness conductivity restricts heat flow into the interior, resulting in lower backside temperatures compared to aluminum. This indicates a higher thermal lag, which is beneficial for delaying heat transfer and protecting internal components. However, the lower conductivity also implies higher surface temperature accumulation, requiring materials with sufficient thermal resistance at the outer layer. The comparative analysis suggests that aluminum behaves as a heat conductor, promoting rapid heat spread, whereas CFRP acts as a thermal barrier, limiting heat penetration. From a thermal protection perspective, CFRP is expected to provide superior performance by maintaining lower internal temperatures and enhancing structural safety.

Overall, the expected results indicate that CFRP is more suitable for thermal protection applications in hypersonic vehicles, particularly in regions exposed to high heat flux. Aluminum, while structurally efficient, may require additional insulation or active cooling systems to meet thermal protection requirements.

4. CONCLUSION AND FUTURE WORK

This study presented a numerical investigation of transient heat transfer behavior in aluminum and Carbon-Fiber Reinforced Polymer (CFRP) panels under hypersonic conditions (Mach 5). A finite element–based computational framework was developed to analyze and compare the thermal response of both materials under identical high heat flux conditions.

The analysis highlights a fundamental thermal trade-off between the two material classes. Aluminum, due to its high thermal conductivity, exhibits rapid heat diffusion, leading to significant heat penetration into the internal structure. This results in a faster rise in backside temperature, limiting its effectiveness as a thermal protection material. In contrast, CFRP demonstrates superior thermal insulation characteristics owing to its low through-thickness thermal conductivity and anisotropic nature. This enables it to maintain lower internal temperatures and provide higher thermal lag, thereby enhancing structural protection.

The findings indicate that while aluminum may be suitable for regions with moderate thermal exposure, CFRP is more effective for high-temperature applications where thermal protection is critical. The study also confirms that material selection plays a key role in determining thermal performance and structural reliability in hypersonic environments.

However, the present work is limited to a simplified two-dimensional thermal analysis and does not account for thermo-structural coupling, material degradation, or fluid-structure interaction effects. Additionally, the absence of experimental validation restricts the direct applicability of the results to real-world conditions.

Future work (Phase II) will focus on extending the model to three-dimensional analysis and incorporating thermo-structural coupling to evaluate thermal stresses and deformation. Experimental validation using high-temperature testing methods will be carried out to verify numerical predictions. Further optimization studies will also be conducted to determine the optimal material configuration and panel design for lightweight and efficient thermal protection systems.

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