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Simulation-based Study of Hypersonic Reentry Vehicle Aero thermal Characteristics

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Introduction

Reentry vehicles operating at hypersonic speeds (Mach 5 and above) face extreme aerodynamic and thermal environments due to the intense interaction between their surfaces and the Earth's atmosphere. These vehicles, often part of space missions, ballistic missile systems, or hypersonic glide platforms, undergo rapid deceleration and encounter high dynamic pressures and thermal loads as they descend. The design and evaluation of such systems demand a comprehensive understanding of aerothermal characteristics—particularly how heat transfer, shockwave behavior, boundary layer phenomena, and material response influence vehicle performance and survivability. Given the impracticality and cost of full-scale experimental testing for every design iteration, simulation-based approaches offer a viable alternative for analyzing these conditions. This study focuses on using computational fluid dynamics (CFD) and thermal modeling to simulate the aerothermal behavior of hypersonic reentry vehicles under various atmospheric and geometric configurations. These simulations not only inform design optimizations but also validate thermal protection systems (TPS) essential for vehicle integrity during reentry [1].

Description

At hypersonic speeds, the flow around a reentry vehicle becomes compressible and highly non-linear, characterized by shock layers, high-temperature gas dynamics, and complex chemical reactions such as dissociation and ionization of atmospheric gases. Numerical simulations use the Navier-Stokes equations in their compressible form, often augmented by real-gas models and radiation effects, to capture these phenomena accurately. For the present study, a combination of Reynolds-Averaged Navier-Stokes (RANS) and Detached Eddy Simulation (DES) turbulence models is used to resolve shock-boundary layer interactions and transient flow structures. The vehicle geometry, typically a blunt-nosed cone or lifting body, is meshed with high resolution in regions of expected flow gradients. Boundary conditions mimic reentry scenarios at altitudes between 80 km and 30 km, capturing the descent phase through the thermosphere and mesosphere.

Aerothermal simulations show the development of strong bow shocks in front of the vehicle, where air is rapidly compressed and heated to temperatures exceeding 3000 K. The high enthalpy in the post-shock region leads to significant heat fluxes at the stagnation point, which are critical for TPS design. In this study, stagnation heat flux is computed using models such as the Fay-Riddell equation, and validated with numerical outputs from the CFD solver. Alongside convective heating, radiative heat transfer from the shock layer—especially at high altitudes where the gas becomes optically thin—is modeled using discrete ordinates or line-by-line spectral methods. The vehicle's surface temperature distribution, thermal gradients, and heat absorption rates are analyzed over time to understand peak load durations and thermal soak patterns that affect underlying structures [2].

The influence of vehicle shape and angle of attack on aerothermal loads is another key focus. Simulation results demonstrate that blunt body configurations reduce peak heat fluxes by increasing the standoff distance of the shock wave, allowing more energy dissipation in the shock layer. However, they also induce higher drag, requiring trade-offs in design. Sharp geometries, while aerodynamically favorable, concentrate heat at the leading edges and require more robust TPS. Variations in angle of attack introduce asymmetries in the heat distribution, increasing thermal stresses and influencing lateral stability. These findings emphasize the need for adaptive TPS designs that account for dynamic flight conditions and not just steady-state performance. For real-world applications, this data feeds into multi-disciplinary design optimization (MDO) frameworks where thermal, aerodynamic, and structural factors are balanced.

Conclusion

Simulation-based analysis of hypersonic reentry vehicle aerothermal characteristics provides a robust, cost-effective means to understand and optimize performance under extreme atmospheric reentry conditions. The integration of CFD, heat transfer, and material modeling allows for detailed predictions of shock formation, heat flux distribution, and thermal protection system effectiveness. By examining various vehicle geometries, flight angles, and atmospheric scenarios, the study highlights critical design parameters that influence survivability and mission success. These insights support informed decision-making in TPS design, structural reinforcement, and aerodynamic shaping. While simulations cannot fully replace experimental validation, they significantly reduce the development cycle and enable iterative improvements with high precision. As hypersonic technology continues to advance, the role of simulation in aerothermal research will remain pivotal in achieving safe, efficient, and high-performing reentry systems for both military and space exploration applications.

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Conflict of Interest

None.

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