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Numerical Investigation of Plasma Flow over Blunt Reentry Capsules

Jürgen Schneider*

Department of Industrial System Design & Modelling, Airbus, 2 Rond-Point Emile Dewoitine, 31700 Blagnac, France

Introduction

Reentry vehicles traveling through Earth's atmosphere at hypersonic speeds experience extreme aerodynamic heating and ionization of surrounding air molecules, resulting in the formation of a plasma sheath around the capsule. This high-temperature plasma environment introduces significant challenges in Thermal Protection System (TPS) design, communication blackout, and aerodynamic performance. Blunt-body configurations are traditionally used for reentry capsules due to their favorable thermal characteristics, allowing for efficient shock wave detachment and heat dissipation. However, the complex physics of plasma flow—characterized by high enthalpy, chemical non-equilibrium, and radiation requires advanced numerical modeling techniques to capture accurately. This paper presents a detailed numerical investigation of plasma flow over blunt reentry capsules using Computational Fluid Dynamics (CFD) with coupled thermochemical models, providing insights into flow structure, temperature distributions, and species behavior near the stagnation region [1].

Description

The simulation of plasma flow over reentry vehicles involves solving the Navier-Stokes equations coupled with energy equations and species transport models under thermochemical nonequilibrium conditions. To accurately model these conditions, multi-species models are implemented, accounting for dissociation, ionization, and recombination of nitrogen and oxygen in the atmosphere. The governing equations are solved using finite volume methods with high-resolution shock-capturing schemes such as the Total Variation Diminishing (TVD) or Roe's flux difference splitting method. Real gas effects are incorporated through the use of temperature-dependent specific heats and transport properties derived from kinetic theory.

In the case of a blunt reentry capsule, the formation of a strong detached bow shock ahead of the nose leads to rapid compression and heating of the incoming air. Numerical simulations show that temperatures in the shock layer can exceed 10,000 K, causing significant ionization and the formation of free electrons and ions such as N2+,O+,N_2^+, O^+,N2+,O+, and e−e^-e−. These charged species alter the thermal conductivity and viscosity of the gas, contributing to heat fluxes that must be managed by the TPS. Additionally, the presence of radiative heat transfer becomes non-negligible at such high temperatures. Models such as the P1 approximation or line-by-line spectral methods are employed to evaluate radiative contributions to the total heat load.

Mesh generation plays a critical role in resolving steep gradients near the stagnation point and shock wave. A fine, structured grid is used around the nose region to ensure accurate computation of temperature, pressure, and velocity fields. Grid independence studies confirm that further mesh refinement beyond a threshold has a minimal effect on computed flow parameters, ensuring computational efficiency. Boundary conditions are carefully selected, with inflow conditions corresponding to flight Mach numbers ranging from 15 to 25, and wall conditions enforcing no-slip and adiabatic assumptions, unless radiative or catalytic wall models are considered [2].

Conclusion

The numerical investigation of plasma flow over blunt reentry capsules highlights the importance of accurate modeling of high-temperature, chemically reacting, and ionized gas flows for aerospace reentry applications. Through the integration of advanced CFD techniques and thermochemical models, it is possible to capture the critical aerodynamic and thermal characteristics that define the survivability and performance of reentry vehicles. The findings provide valuable guidance in designing efficient thermal protection systems, mitigating communication blackouts, and refining capsule geometry for optimal performance. Continued development in computational tools and high-fidelity physical models will further enhance our understanding of plasma-aerodynamics interactions, enabling safer and more reliable atmospheric entry missions in both terrestrial and extraterrestrial environments.

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Conflict of Interest

None.

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***Address for correspondence:** Jürgen Schneider, Department of Industrial System Design & Modelling, Airbus, 2 Rond-Point Emile Dewoitine, 31700 Blagnac, France, E-mail: jürgen@schneider.fr*

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