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Space Vehicles for Exploration & Propulsion for Deep Space (3)
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THERMAL PROTECTION AND STRUCTURAL DESIGN FOR ENTRY AND RE-ENTRY IN DEEP-SPACE EXPLORATION VEHICLES

Abstract

In the field of space exploration, ensuring the safe entry and landing of deep-space vehicles is of utmost importance. Especially when the missions extend beyond low Earth orbit and face the harsh conditions of planetary atmospheres. Atmospheric re-entry is one of the crucial phases of a space mission and ensuring structural integrity and Thermal Protection System (TPS) materials to withstand the extreme heat, aerodynamic forces and thermal stresses encountered by spacecraft during descent. Prevailing materials and construction of TPS and structural designs are often limited in their capacity to balance high thermal resistance with low mass, presenting a challenge in safely sustaining human and robotic missions to deep space. This research delves into developing and analyzing advanced Thermal Protection Systems (TPS) and structural frameworks tailored to the high demands of deep-space missions. As the TPS is a critical component that shields vehicles from intense aerodynamic heating, particularly as they enter planetary atmospheres at high speeds. To overcome these challenges, the study places special emphasis on a range of TPS materials, including ablative, ceramic, and flexible heat shields. This study pays particular attention to high-performance materials like carbon-carbon (C-C) composites and reinforced carbon-carbon (RCC), which have demonstrated superior performance in high-temperature environments. They are also highly durable and exhibit high strength-to-weight ratio, making them suitable for applications where both resilience and weight savings are critical. The exploration begins with the use of Finite Element Analysis (FEA) coupled with Computational Fluid Dynamics (CFD). This research probe multi-layered TPS systems under the intense mechanical and thermal loads experienced during re-entry, enabling detailed insights into stress distribution, potential points of failure, and overall structural integrity. CFD complements this by simulating the complex fluid dynamics of re-entry, allowing researchers to analyze the heating patterns caused by friction with the atmosphere, identifying areas of high thermal stress, and optimize heat distribution across the TPS. The study also incorporates shape optimization techniques aimed at designing TPS structures to minimize aerodynamic shock loads upon re-entry. To counteract these risks, the study explores lightweight, thermally resistant materials that can endure such stresses without significant degradation, allowing efficient integration into vehicle structures. Through these analyses, this research contributes a hybrid TPS and structural framework that optimizes thermal protection, mass, stability and overcoming core challenges for long-duration space missions. Keywords - Thermal protection system, carbon-carbon, reinforced carbon-carbon, composite materials, Finite Element Analysis, Computational Fluid Dynamics