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Design and Analysis of Crew Module for Atmospheric Re-Entry

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Abstract:

This study presents the design and comprehensive analysis of a two-person crew module intended for safe atmospheric re-entry. The work focuses on evaluating aerodynamic behavior, thermal loading, and structural integrity under hypersonic conditions. Computational Fluid Dynamics (CFD) simulations were performed at Mach 5, Mach 15, and Mach 20 to capture flow characteristics, shock behavior, and heat transfer phenomena. Results indicate the formation of a stable detached bow shock at lower Mach numbers, while higher velocities produce significant compression heating, with peak temperatures exceeding 8000 K and heat flux reaching up to 5.76×10^5 W/m².

Ablation-based Thermal Protection System (TPS) design using Phenolic Impregnated Carbon Ablator (PICA) material was developed based on the obtained heat flux data, resulting in a thickness of 75 mm at the stagnation region and 30 mm along the conical surfaces. Structural validation using Finite Element Analysis (FEA) shows a maximum stress of approximately 120 MPa, maintaining a factor of safety greater than 2.

The results demonstrate that the proposed crew module configuration provides adequate aerodynamic stability, thermal protection, and structural reliability for re-entry missions. This study establishes a validated framework for integrated aerodynamic and structural design of crewed re-entry vehicles.

Keywords **Crew Module, Atmospheric Re-entry, Hypersonic Flow, Computational Fluid Dynamics, Thermal Protection System, Finite Element**

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I. INTRODUCTION

Atmospheric re-entry remains one of the most critical phases in space missions due to the extreme aerodynamic heating, high stagnation pressures, and structural loads encountered at hypersonic velocities. The design of crew modules capable of withstanding such conditions requires an integrated approach involving aerodynamic shaping, thermal protection systems, and structural integrity analysis. Blunt body configurations have historically been adopted in spacecraft such as Apollo and Orion to generate detached bow shocks, thereby reducing heat transfer to the structure.

In recent years, the growing interest in crewed space exploration and reusable space systems has emphasized the need for efficient and reliable re-entry vehicle designs. The primary challenges associated with such systems include managing severe thermal loads, maintaining aerodynamic stability, and ensuring structural safety under combined thermo-mechanical stresses.

This study focuses on the design and analysis of a two-person crew module intended for atmospheric re-entry and recovery. The proposed configuration consists of a blunt cone geometry with optimized mass distribution to achieve inherent aerodynamic stability. The structure is primarily composed of Aluminum 6061-T6, selected for its favorable strength-to-weight ratio and manufacturability.

To evaluate the aerodynamic and thermal performance, Computational Fluid Dynamics (CFD) simulations are conducted at Mach 5, Mach 15, and Mach 20, representing different phases of re-entry. The simulations capture key flow features such as shock formation, pressure distribution, and temperature gradients. The resulting heat flux data is further utilized to design an ablation-based Thermal Protection System (TPS) using Phenolic Impregnated Carbon Ablator (PICA).

In addition to aerodynamic analysis, structural validation is performed using Finite Element Analysis (FEA) to assess stress distribution and factor of safety under extreme loading conditions. The integration of CFD-derived thermal loads with structural analysis provides a comprehensive evaluation of the module's survivability.

The objective of this work is to develop a validated crew module design framework that ensures aerodynamic stability, thermal protection, and structural reliability during atmospheric re-entry. The outcomes of this study contribute to the preliminary design and analysis of future crewed re-entry vehicles.

II. METHODOLOGY

The design and analysis of the crew module were carried out using an integrated multi-disciplinary approach combining aerodynamic simulation, thermal analysis, and structural validation. The methodology consists of five key stages: geometric modeling, Computational Fluid Dynamics (CFD) analysis, thermal protection system (TPS) design, structural analysis, and integrated performance evaluation..

A. Geometric Modeling

The crew module is designed as a blunt cone configuration to ensure aerodynamic stability and controlled deceleration during atmospheric re-entry. The geometry consists of a spherical forebody and a conical aft section with a cone angle of 40°. The module has an overall height of 3122 mm and a base diameter of 3500 mm.

The blunt geometry is selected to promote the formation of a detached bow shock, which reduces heat transfer to the structure. Additionally, the configuration ensures that the center of pressure remains behind the center of gravity, enabling passive aerodynamic stability during descent.

B.Computational Fluid Dynamics (CFD) Analysis

CFD simulations were performed to evaluate aerodynamic behavior and thermal loading under hypersonic conditions. A density-based solver was employed to accurately capture compressible flow phenomena, including shock waves and high-temperature gradients.

Simulations were conducted at Mach numbers of 5, 15, and 20 to represent different phases of atmospheric re-entry. Air was modeled as an ideal gas, and turbulence effects were accounted for using the k–ω SST model, which provides reliable predictions for high-speed boundary layer flows and adverse pressure gradients.

A. The convective heat transfer at the surface is governed by:

$$q = h(T_s - T_\infty)$$

where (q) is the heat flux, (h) is the convective heat transfer coefficient, (T_s) is the surface temperature, and (T_infinity) is the freestream temperature.

The aerodynamic performance of the module is evaluated using the drag coefficient:

$$C_d = \frac{2F_d}{\rho V^2 A}$$

where (F_d) is the drag force, (ρ) is the fluid density, (V) is the velocity, and (A) is the reference area.

Key outputs obtained from CFD simulations include pressure distribution, temperature contours, drag coefficient, and surface heat flux. Special emphasis is placed on the stagnation region, where peak thermal loads are observed.

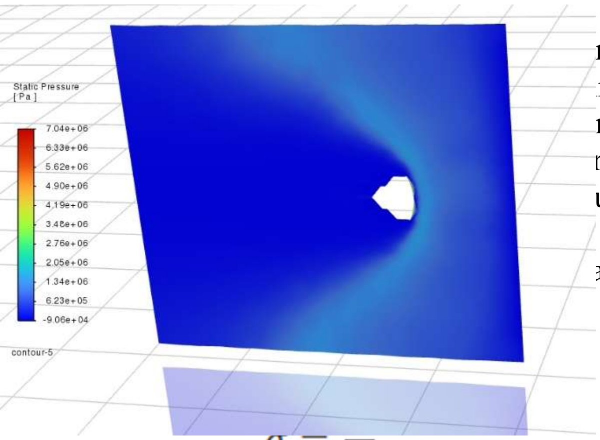
C Thermal Protection System (TPS) Design

The Thermal Protection System (TPS) was designed based on the heat flux data obtained from CFD simulations. An ablation-based approach using Phenolic Impregnated Carbon Ablator (PICA) material was adopted due to its high thermal resistance and proven application in re-entry vehicles.

B. The ablation process is governed by the mass loss rate:

$$\dot{m} = \frac{q}{L}$$

Using the estimated heat flux values and exposure duration, the required TPS thickness was determined. A variable thickness distribution was implemented, with a maximum thickness of 75 mm at the stagnation region and reduced thickness of 30 mm along the conical surfaces to optimize weight while maintaining thermal safety.



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$$\sigma = \frac{\quad}{A}$$

The primary structural material selected is Aluminum 6061-T6 due to its high strength-to-weight ratio and good manufacturability. The analysis focuses on identifying maximum stress regions and ensuring that stress levels remain within allowable limits. The factor of safety is calculated to verify structural reliability under extreme loading conditions.

III. RESULT AND DISCUSSIONS

A. Aerodynamic Performance

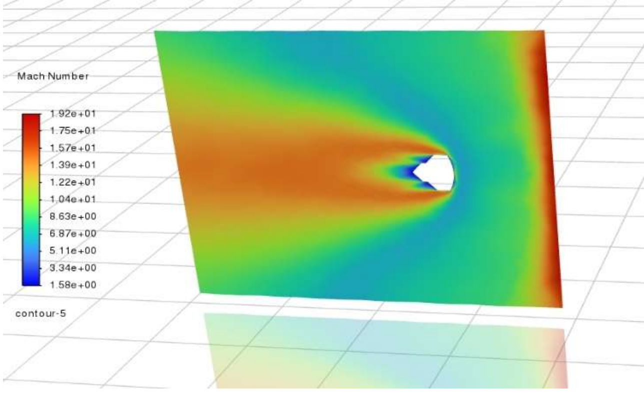

Fig1: Mach 20 Contour

Fig 2 Pressure distribution around the crew module at Mach 20 showing detached bow shock formation

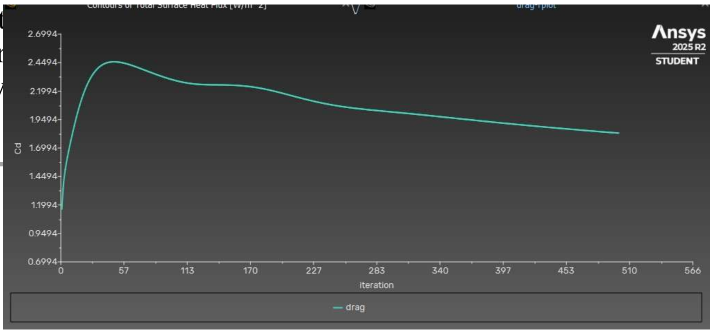

Fig3: Drag coefficient convergence plot showing numerical stability of the solution

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                                   Cd
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               capsule_walls          1.8304378
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Fig4: Drag coefficient

B.Thermal Performance

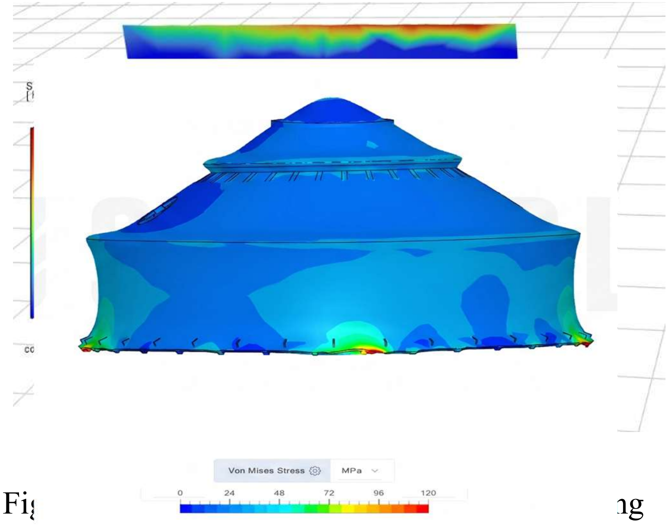
Parameter	Present Design	Apollo Command Module	Orion Crew Module
Mission Type	Earth Re-entry (LEO Return)	Lunar Return	Deep Space / Lunar
Peak Heat Flux (kW/m²)	576	500 – 1000	600 – 1200
TPS Material	PICA	AVCOAT	AVCOAT
TPS Thickness (mm)	**75**	50 – 70	70 – 100
Re-entry Velocity	Mach 20	11 km/s	11 km/s
Thermal Protection Type	Ablative	Ablative	Ablative

Mach Number	Peak Temperature	Heat Flux	Observation
Mach 5	1839 K	20,255 W/m²	Moderate heating
Mach 15	~ 5000 K	576,895 W/m²	High thermal load
Mach 20	>8000 K (Solver limitation)	Maximum observed	Extreme conditions

Fig5. Temperature distribution around the crew module at Mach 20 indicating extreme thermal loading

TABLE I
SUMMARY OF AERODYNAMIC AND THERMAL RESULTS OBTAINED FROM CFD SIMULATIONS

C. Structural Performance



Fi ng structural response under aerodynamic loading

C. TPS Validation

TABLE 2
Comparison of TPS thickness with heritage spacecraft

IV. CONCLUSION

This study presented the integrated design and analysis of a two-person crew module for atmospheric re-entry. A blunt-body configuration was adopted to ensure aerodynamic stability and effective shock stand-off, reducing thermal loading on the structure. CFD simulations across Mach 5, 15, and 20 quantified pressure, temperature, and heat flux distributions, identifying the stagnation region as the critical thermal zone.

Based on the computed heat flux, an ablation-based TPS using PICA was designed, resulting in a thickness of 75 mm at the stagnation region and 30 mm along the conical surfaces. Structural validation using FEA showed a maximum stress of approximately 120 MPa, well below the yield strength of Aluminum 6061-T6, with a factor of safety greater than 2.

The combined aerodynamic, thermal, and structural results demonstrate that the proposed configuration satisfies key re-entry requirements, including stability, thermal protection, and structural integrity. The methodology establishes a practical framework for preliminary design of crewed re-entry vehicles. Future work will include transient trajectory-coupled heating analysis and higher-fidelity thermo-structural coupling for improved accuracy.

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