

A Comparative CFD Analysis of Aerothermal Behaviour of an Orion-Like Capsule in Different Planetary Atmospheres

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Abstract: This paper investigates the atmospheric reentry of an Orion-like space capsule across multiple planetary environments under varying wall temperature conditions. To represent these environments, viscous flow modelling is performed using two different approaches to solve the Reynolds-Averaged Navier–Stokes (RANS) equations. The study focuses on high-altitude aerothermodynamic behaviour over a blunt body in high Mach number flow. The results show that heating characteristics are strongly dependent on the planetary atmosphere and corresponding free-stream conditions. While similar flow assumptions can be applied for Earth and Mars, a significant change in flow behaviour is observed in the case of Titan, despite its comparable atmospheric composition to Earth. This difference is primarily driven by variations in atmospheric density and resulting flow regimes. The findings highlight the importance of accurately selecting free-stream properties and appropriate flow models for predicting aerothermal loads. This work contributes to improving the design and analysis of thermal protection systems for future planetary entry missions.

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1. Introduction

Atmospheric entry remains one of the most daunting challenges in space exploration. Whether a mission is landing on a distant planet or returning home to Earth, a spacecraft must survive a high-speed plunge through a wall of gas. As vehicles hit the atmosphere at hypersonic speeds, they don't just move through the air, they compress it so violently that they create a massive "bow shock"[1]. This compression generates intense heat and aerodynamic pressure that would destroy a craft without a sophisticated thermal protection system (TPS). While we have relied on heat shields since the days of the Apollo missions, modern technology, like the SpaceX Dragon, is pushing the boundaries of what these materials can do. However, re-entry is not a one-size-fits-all problem. Each planet offers a unique challenge:

1. Earth has a dense atmosphere that creates high drag and extreme heat.
2. Mars offers a thin, CO₂-rich veil that is harder to use for braking but still generates significant thermal loads.
3. Titan presents a thick, nitrogen-heavy environment that behaves differently even at its frigid temperatures. Understanding these nuances is the key to designing the next generation of planetary explorers.[2]

A. Characteristics of Re-entry of blunt body

1. Knudsen Number (Kn):

It is a non-dimensional number that is the ratio of the mean free path to the characteristic length of the body. It determines whether the flow is rarefied or continuum.

$$Kn < 0.01 \text{ then the flow is continuum}$$

$$Kn > 10 \text{ flow is rarefied}$$

The Knudsen number was found to be less than 0.01 for each atmosphere, confirming that the flow remains in the continuum regime and validating the analytical approach used in this paper.

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$$kn = \frac{\lambda}{L}$$

$$\lambda = \frac{KT}{\sqrt{2}\pi d^2 P}$$

1. Reynolds Number (Re)

It is the ratio of internal force to the viscous force. It determines whether the flow is turbulent or laminar. The Reynolds number varies significantly across planetary atmospheres due to differences in density, velocity, and temperature. For the Earth and Mars conditions considered in this study, the Reynolds numbers are on the order of 106; however, the relatively low freestream pressures (40 Pa and 28 Pa, respectively) correspond to low-density environments where disturbance growth is limited, supporting a laminar flow assumption. In contrast, Titan's significantly denser atmosphere, characterised by a higher freestream pressure (150 Pa), results in stronger viscous interactions and enhanced instability growth within the boundary layer. This increases the likelihood of transition, indicating a tendency toward transitional or turbulent flow behaviour.

$$Re = \frac{\rho VL}{\mu}$$

3. Ablation

The phenomenon in which the material is corroded due to extreme temperature. In the reentry of the capsule, the heat and friction produce a high temperature that causes the protective sheet to melt or vaporise. This is called an ablative heat shield.

4. Sutton-Graves equation

it is a widely used empirical way to estimate the convective heat flux at the stagnation point of a blunt body moving at very high speeds

$$q = k \sqrt{\frac{\rho}{R}} V^3$$

B. Literature Review

A significant amount of research has been carried out to understand the complex physics of atmospheric re-entry, especially under hypersonic conditions where strong shock waves, extreme temperatures, and nonequilibrium effects dominate the flow. Early work by K. Sutton and R. A. Graves [3] laid the foundation for estimating stagnation-point heating, which is still widely used to predict thermal loads on re-entry vehicles. Later, C. Park introduced the two-temperature model, making it possible to better capture high-temperature gas effects and ionization in hypersonic flows [4][5]. Reviews by P. A. Gnoffo further highlighted how challenging these flows are, particularly due to shock-layer chemistry, viscous interactions, and the numerical difficulties involved in solving them accurately. [6]

With the growth of computational power, CFD has become a widely used tool for studying re-entry flows. Researchers such as Z. Bouyahiaoui [7] and S. Rathnavel [8] have shown that modern solvers can reasonably capture important flow features like bow shocks, pressure distribution, and surface heating around re-entry bodies. Other studies, including those by Datthathireyan et al [9] and Vala et al [9], have used commercial tools to simulate hypersonic conditions, emphasizing the importance of mesh quality and turbulence modeling in obtaining reliable results. While these studies demonstrate the effectiveness of CFD for re-entry analysis, they also point out that careful setup and validation are necessary to ensure meaningful predictions.

Beyond Earth-based studies, planetary missions have provided valuable real-world insight into how different atmospheres influence re-entry behavior. The Huygens Probe, discussed by J.-P. Lebreton [10] and others, offered important data for Titan's dense and cold atmosphere, which behaves quite differently from Earth or Mars. Similarly, work on Titan entry aerothermodynamics highlights how such environments can significantly alter shock structure and heat transfer. On the other hand, Earth entry missions like Apollo 4, analysed by S. T. Surzhikov [11], have been crucial for validating high-temperature and radiative heating models. Together, these studies provide a strong foundation for comparing re-entry behavior across different planetary environments.



2. Literature Review

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3. Methodology

A. Geometry

To represent the spacecraft, I modeled the geometry of the Orion space crew module within an x-y plane. Given the capsule's symmetrical nature, I chose to simplify the complex three-dimensional problem into a two-dimensional axisymmetric formulation. This allowed for a highly efficient computational process without sacrificing the essential flow physics of the vehicle, which features a base radius of 5m and a total length of 6.58m. The geometry used in the present study is derived from the Orion Crew Exploration Vehicle (CEV) configuration reported in [12].

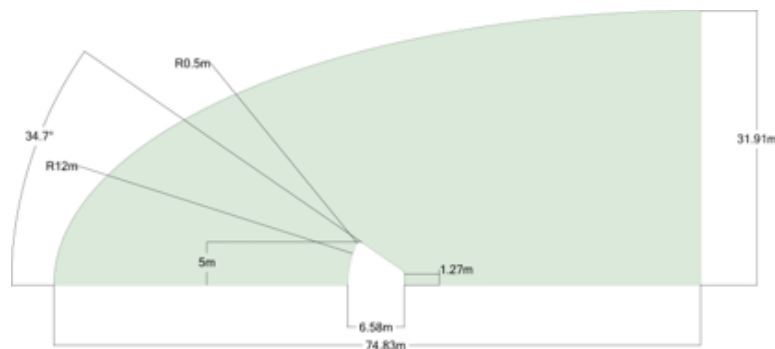


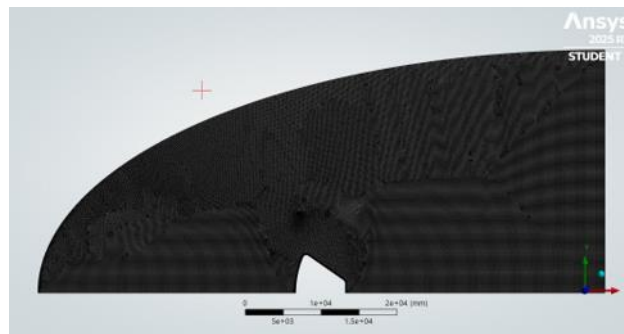
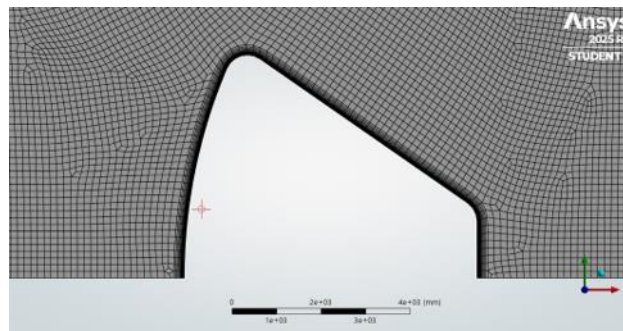
Figure. 1 Domain

B. Meshing

Precision in the flow field depends heavily on the quality of the mesh. I developed a structured quadrilateral mesh to ensure both numerical stability and higher accuracy during the simulation. Because the most critical physics, such as heat flux and friction, happen right at the capsule's surface, I applied boundary-layer inflation. By setting the first inflation layer to a minute 0.5 mm, I was able to "zoom in" on the viscous sub-layer. This fine resolution is vital for capturing the steep velocity and thermal gradients that occur as the atmosphere slams into the heat shield at hypersonic speeds.

Table 2 Mesh table

parameter	value
element size	0.15m
No. of nodes	85103
No. of elements	84462
First layer thickness	0.5mm
No. of layers	25

**Fig. 2 Mesh****Fig. 3 Inflation**

C. Domain Strategy

The simulation boundaries were explicitly defined and labelled to ensure seamless integration with the ANSYS Fluent solver. This structured approach allowed for precise control over the boundary conditions, ensuring that the final model was both robust and physically representative of a real-world planetary entry.

D. Setup

To capture thermal effects within the flow field, the energy equation was activated in ANSYS Fluent[13]. A density-based solver was employed to achieve higher accuracy for compressible flow conditions. Given the hypersonic Mach number and the resulting shock-wave intensity, I opted for a density-based solver. This choice specifically addresses the stability often seen in the pressure-based formulations in high-speed and compressible regimes. The turbulence model was selected based on atmospheric conditions to represent flow physics across different regimes better. The governing equations for the flow are the Navier–Stokes equations, which conserve momentum. These nonlinear partial differential equations are used to compute velocity, pressure, and temperature fields within the domain. In general, the equations consist of convective, diffusive, and source terms that collectively describe fluid motion. In addition to the standard conservation equations, species transport equations were also considered. These equations differ from the conventional formulation by incorporating mass fractions of



multiple chemical species, enabling the simulation of reacting or high-temperature gas mixtures relevant to re-entry conditions. The selection of the Spalart–Allmaras model for the Titan case is motivated by the significantly higher Reynolds number and atmospheric density, which promote boundary layer transition and turbulence. In contrast, the Earth and Mars cases, characterised by lower effective densities at the selected altitudes, remain within a predominantly laminar regime, justifying the use of a laminar flow model.

The wall temperatures of 1000 K and 2000 K are selected to represent different thermal protection system (TPS) operating regimes. A wall temperature of 1000 K corresponds to a moderate heating scenario typical of reusable or low-heat-load TPS materials, where surface temperatures are maintained within structural limits. In contrast, a wall temperature of 2000 K represents a severe re-entry heating condition, characteristic of high-enthalpy flows where advanced or ablative TPS materials are required to withstand extreme thermal loads. These two temperature limits are therefore chosen to bracket a realistic range of TPS performance, from nominal to worst-case thermal environments encountered during atmospheric entry.

To discretise the governing equations, an implicit solver formulation was employed in conjunction with the Advection Upstream Splitting Method (AUSM) scheme. The AUSM scheme provides enhanced numerical stability and improved shock-capturing capability compared to the Roe Flux Difference Splitting (Roe-FDS) method, particularly for high-speed compressible flows. A first-order upwind discretisation scheme was initially adopted to ensure numerical stability during the early stages of the solution. Additionally, high-speed numerical options and mesh convergence criteria were enabled within the solver settings to further enhance robustness and accuracy. The Courant–Friedrichs–Lewy (CFL) number plays a critical role in solution stability and convergence. In this study, a low CFL number was used at the start of the simulation to maintain stability. Once a stable solution behaviour was achieved, the CFL number was gradually increased to accelerate convergence. The boundary conditions were specified as summarized in Table 3. The operating pressure was set to 0 Pa to accurately capture shock structures and compressibility effects without artificial pressure offsets. Post-processing and visualisation of the simulation data were carried out using ParaView [14].

4. Results and Discussions

The flow regimes were defined based on the calculated Reynolds numbers for each planetary environment. For the Earth and Mars cases, the flow was modeled as laminar due to the lower atmospheric densities at the simulated altitudes. Conversely, the higher density of the Titan atmosphere necessitated a turbulent flow approach; for these cases, the Reynolds-Averaged Navier-Stokes (RANS) equations were solved using the laminar and Spalart–Allmaras models within ANSYS Fluent to capture the eddy viscosity effects.

This section presents the aerodynamic and aero-thermodynamic behaviour of the blunt body under hypersonic flow conditions. The results include an analysis of drag forces, drag coefficients, and flow-field characteristics obtained from pressure, temperature, and Mach number contours. By examining these across different atmospheric conditions, the study aims to highlight how planetary environments influence the overall flow behaviour and aerodynamic performance. The freestream conditions considered for each case, along with the corresponding computed values, are summarised in Table 4. These parameters provide the basis for evaluating the aerodynamic response of the blunt body under varying atmospheric environments.

Table 3 Freestream conditions for Earth, Mars, and Titan

Parameter	Earth	Mars	Titan
Pressure (Pa)	40	28	150
Temperature (K)	219	150	170
Mach Number	18	18	08
Characteristic Length (m)	6.58	6.58	6.58
Gas Constant (J/kg·K)	287	188.9	297
Adiabatic Constant	1.4	1.29	1.4
Molecular diameter (in $10^{-10}m$)	3.7	3.3	3.7

The drag coefficients obtained from the simulations show consistent behaviour across all cases, with values remaining within the expected range for hypersonic blunt body configurations. It is observed that pressure forces contribute predominantly to the total drag, while viscous effects remain comparatively negligible. The computed drag coefficients are in good agreement with reported values for Orion spacecraft-type blunt bodies, which typically exhibit drag coefficients in the range of 1.4–1.5 under hypersonic conditions. Minor deviations observed in the present study can be attributed to slight geometric variations and differences in freestream assumptions. To further understand the flow physics, contour visualisations of pressure, temperature, and Mach number were analysed. These provide insight into the shock structure and thermal behaviour of the flow around the blunt body.

Table 4 Calculated flow properties

Parameter	Earth	Mars	Titan
Density (in 10^{-4} kg/m ³)	6.36	9.87	29.7
speed of sound (m/s)	296.64	191.19	265.78
Velocity (m/s)	5340	3441.35	2126.23
Dynamic Viscosity (in 10^{-5} Pa·s)	1.4	1.0	1.2
Reynolds Number (in 10 ⁶)	1.596	2.234	3.4626
Knudsen Number(10^{-5})	1.88	4.1	3.9

Table 5 Drag forces and coefficients under different atmospheric conditions

Planet	Wall Temp. (K)	F_p (N)	F_v (N)	F_{total} (N)	Cd, p	Cd, tot
Earth	1000	1052634.6	1276.0759	1053910.7	1.4760848	1.4778742
Earth	2000	1036486.4	1466.2623	1037952.6	1.4534405	1.4554966
Mars	1000	730017.89	788.79732	730806.69	1.522656	1.5243012
Mars	2000	729998.67	895.43127	730894.1	1.522656	1.5244835
Titan	1000	773729.13	552.29744	774281.43	1.4757908	1.4768443
Titan	2000	773682.87	498.13178	774181	1.4757026	1.4757026

A. Temperature and heat flux:

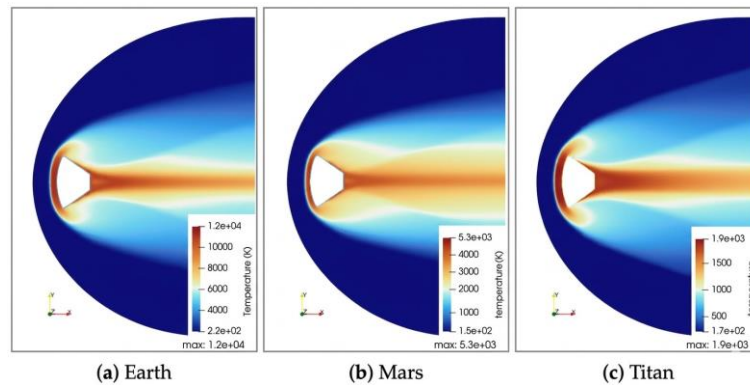


Fig. 4 Wall temp 1000K



The Martian flow field exhibits a significantly elongated wake compared with Earth and Titan. This behaviour is primarily attributed to the low atmospheric density, which weakens post-shock re-compression and delays pressure recovery in the downstream region.

Consequently, the shear layers originating from the forebody expand more gradually, resulting in a broader and more extended wake. In contrast, the higher-density atmospheres of Earth and Titan promote stronger intermolecular interactions, leading to faster momentum exchange and a more compact wake closure.

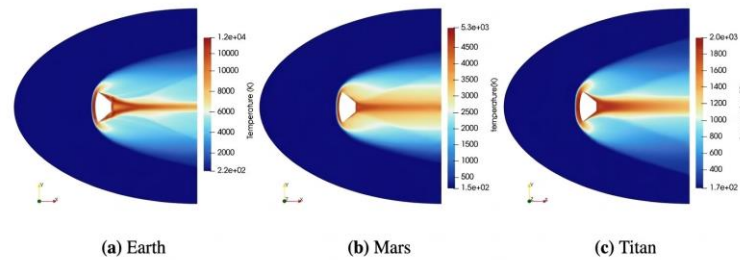


Fig. 5 Wall temperature 2000 K

Furthermore, the Martian case approaches transitional flow characteristics, where reduced collision frequency contributes to a diffuse and elongated wake structure. This highlights the strong dependence of wake dynamics on freestream density in hypersonic aero-thermodynamic environments. A negative heat flux indicates heat transfer from the flow to the vehicle surface, while a positive value represents heat transfer from the surface to the surrounding flow. For the Titan case at a wall temperature of 2000 K, an inverse heat transfer behavior is observed, wherein heat flows from the wall into the surrounding flowfield. This is attributed to the extremely low freestream temperature (170 K), which creates a strong temperature gradient between the surface and the incoming flow.

Table 6 Comparison of CFD heat flux with Sutton–Graves correlation

Planet	Wall Temp. (K)	CFD Heat Flux (W/m ²)	Sutton–Graves
Earth	1000	-34158.362	314281
Earth	2000	-27840.838	314281
Mars	1000	-10341.296	62987.27
Mars	2000	-7360.6388	62987.27
Titan	1000	-10943.045	39826.56
Titan	2000	1981.0522	39826.56

As a result, the wall acts as a thermal source rather than a sink, leading to outward heat transfer into the boundary layer. In contrast, for Earth and Mars conditions, higher freestream temperatures combined with intense shock heating result in conventional heat transfer from the fluid to the wall.

This highlights the critical role of freestream thermodynamic conditions in determining the direction and magnitude of heat transfer in hypersonic flows.

B. Mach number plots

All cases exhibit a detached bow shock characteristic of hypersonic flow over a blunt body. However, the Titan cases display a noticeably thicker shock layer and broader wake region. This behavior is attributed to the significantly lower freestream temperature and higher atmospheric density of Titan, resulting in a large wall-to-freestream temperature ratio. Consequently, enhanced viscous and thermal interactions lead to increased shock stand-off distance and smoother Mach gradients compared to Earth and Mars cases.

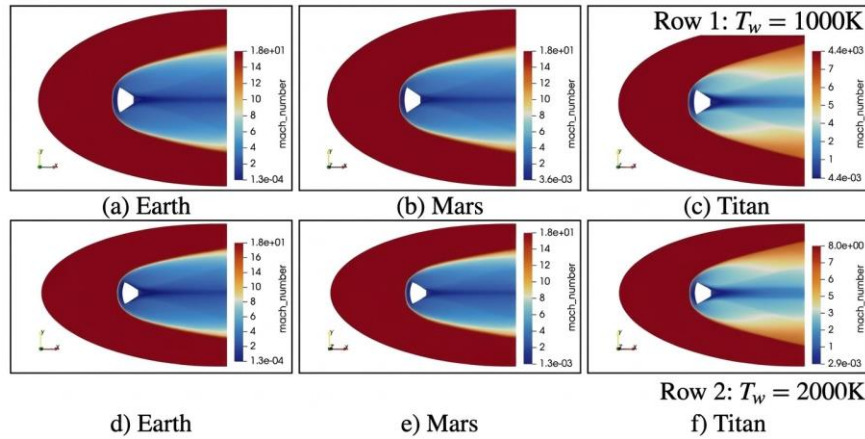


Fig. 6 Comparative analysis of Mach number in different wall temperatures

C. Pressure plots

The pressure contours exhibit minimal variation across different wall temperatures and planetary conditions. This is because the pressure rise across the bow shock is primarily governed by the freestream Mach number and compressibility effects, making it largely insensitive to wall thermal conditions

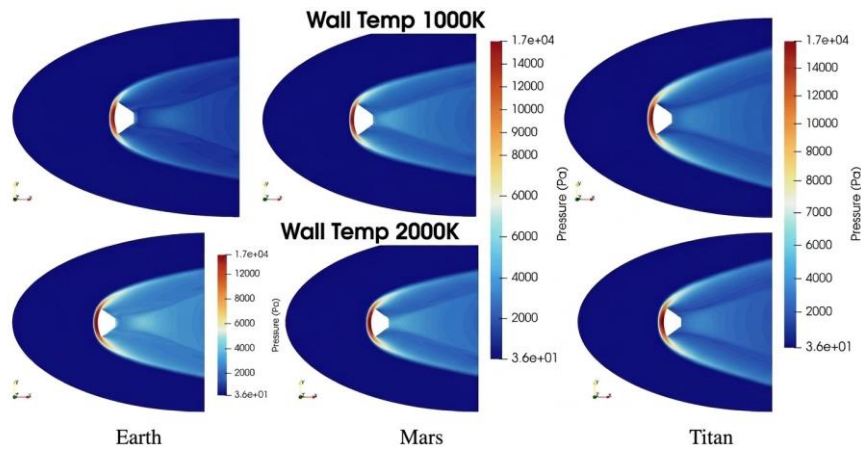


Fig. 7 Pressure over different wall temperature and atmospheres

The computed drag coefficients are in good agreement with published aerodynamic data for the Orion spacecraft. High-fidelity CFD databases developed by NASA report drag coefficients in the range of approximately 1.2-1.6 under hypersonic conditions and re-entry orientations [15]. The present results, ranging between 1.45 and 1.52, fall well within this validated range, thereby supporting the accuracy of the numerical approach.

D. Mesh Independence study:

A mesh refinement study was conducted using three progressively finer grids. The drag coefficient decreases from the coarse to the medium mesh, then increases slightly for the fine mesh, indicating convergence toward a stable solution. The variation between the medium and fine mesh is approximately 3.5%, which is considered acceptable for engineering accuracy in hypersonic flow simulations.

Similarly, the surface heat flux shows improved consistency between the medium and fine meshes, indicating adequate resolution of thermal gradients. Based on these observations, the finest mesh was selected for all simulations to ensure improved accuracy.

**Table 7 Mesh independent study**

Cell size	Nodes	Elements	Heat flux (W/m ²)	Cd
0.25 m	31,507	31,107	-51,063.39	1.645
0.15 m	85,103	84,462	-34,158.362	1.477
0.08 m	292,028	290,867	-35,630.181	1.5311

While this study provides a solid foundation using a 2D axisymmetric model, it is only the first step. As high-performance computing continues to evolve, the next logical move is to transition into high-fidelity 3D simulations. Moving to 3D will allow us to move past the limitations of symmetry and resolve the intricate, multi-dimensional flow features that define real-world flight. However, the challenge isn't just about dimensionality; it's about the physics of the gas itself.

At the extreme speeds of reentry, we can no longer treat air as a simple, "perfect" gas. The intense heat generated behind the shock wave forces us to account for real gas effects. In these conditions, molecules don't just heat up they vibrate, collide, and eventually dissociate, breaking apart into a reactive soup of individual atoms. Future versions of this framework should incorporate thermochemical non-equilibrium models to track these chemical reactions in real-time. This is particularly vital for predicting how heat is transferred to the vehicle surface, as atomic recombination can significantly spike the thermal load.

Finally, we must look at the different "faces" of the atmosphere. While we've focused on the dense air of the continuum regime, missions to places like Mars with its thin, CO₂-rich atmosphere require a different lens. By integrating Direct Simulation Monte Carlo (DSMC) methods, we can bridge the gap between the vacuum of high-altitude flight and the thick air of the lower atmosphere. Together, these advancements will transform this framework from a specialised tool into a comprehensive engine for planetary exploration.

5. Conclusion

This study shows that the thermal behaviour during atmospheric entry is strongly influenced by the surrounding planetary environment, with atmospheric density playing a key role in determining heat transfer and wall temperature levels. For the conditions analysed, both Earth and Mars exhibit predominantly laminar flow, resulting in relatively stable and predictable thermal loads. In contrast, Titan's much denser atmosphere leads to noticeably higher heating, driven by stronger viscous effects and more developed boundary layer growth.

An important observation from this work is that wall temperature predictions are highly dependent on the choice of flow model. While a laminar assumption provides reasonable results for Earth and Mars, it becomes insufficient for Titan. Under Titan-like conditions, higher Reynolds numbers indicate the onset of transitional or turbulent behaviour, which significantly increases the predicted heat flux.

These findings highlight that thermal protection system design cannot rely on a single, simplified modelling approach across different planetary environments. Instead, accurate heat transfer prediction requires careful consideration of both atmospheric properties and the corresponding flow regime.

Overall, this work underlines the importance of environment-specific aerothermal modelling and sets the stage for future studies that incorporate more complex effects such as high-temperature gas behaviour, real-gas chemistry, and surface ablation to improve prediction accuracy.

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7. Conflict of Interest

The author declares no competing conflict of interest.

8. Funding

No funding was issued for this research.
