Enhanced Re-Entry Vehicle Aerodynamics: A Computational Fluid Dynamics Study

Dr. Dheeraj Minglani[1], Varun Singh[2], Prachi Singh[3], Ashwani, Satvick Verma[4]
[1]Assistant Professor, Department of Aerospace Engineering, Chandigarh University, Gharuan, India
[2,3,4]Department of Aerospace Engineering, Chandigarh University, Gharuan, India

***Abstract*— The endeavors to develop a specialized design tool tailored for analyzing the viscous flows encountered by re-entry vehicles during their return to Earth's atmosphere. Given the extreme speeds and temperatures involved, effective thermal management is paramount to ensuring the safety and structural integrity of these vehicles. Computational fluid dynamics (CFD) simulations offer a powerful means to explore the intricate dynamics of viscous interactions, accurately modeling airflow and accounting for parameters such as viscosity, turbulence, and heat transfer. In this investigation, the focus lies on improving heat distribution near the heat shield of a re-entry vehicle module through the incorporation of fins into the vehicle's structure. By employing the axisymmetric Navier-Stokes equations and the k-epsilon turbulence model, this study aims to deepen our understanding of viscous flows in re-entry vehicles and the efficacy of heat dissipation strategies, such as fin configurations.**

Keywords—Re-entry vehicles, Viscous Flows, Heat Dissipation, Fin configuration, CFD, Hypersonic flow, Aerodynamic Heating, Thermal management.

1. *Introduction*

The safe re-entry of a vehicle into Earth's atmosphere constitutes a pivotal phase in space missions. These vehicles, crafted to endure the harsh atmospheric re-entry, grapple with extreme aerothermal stresses. As they make their descent, the confrontation with atmospheric drag induces high temperatures and pressures that test the limits of engineering ingenuity. The intricacies of their design, material selection, and construction are critical to ensure the preservation of the vehicle and its valuable payload [1].

Re-entry vehicles are meticulously designed to withstand these intense conditions, often leveraging heat shields for thermal protection. This design ideology is shaped by an understanding of the vehicle's interaction with atmospheric flows, which involves complex phenomena such as boundary layer development, shock wave formation, and thermal management [2][3].

To navigate these challenges, computational fluid dynamics (CFD) simulations have become an indispensable tool. These simulations dissect the flow dynamics around re-entry vehicles, incorporating variables such as viscosity, turbulence, and heat transfer to predict the vehicle's response under various conditions [4]. Such analyses are invaluable for designing vehicles that not only withstand re-entry but also optimize performance parameters [5].

1.1 Investigating the Influence of Fins on Aerodynamic Performance

To refine thermal management and aerodynamic stability, the addition of fins to re-entry vehicles represents a strategic design consideration. The study of fins — a common element in heat transfer applications — has been extended to the domain of re-entry vehicles, promising improvements in heat dissipation and aerodynamic stability [6].

The examination of fin-enhanced geometries on re-entry vehicles unveils the profound impact on the vehicle's aerodynamics. Through detailed flow field analyses, the research explores how fins influence viscous interactions and affect thermal loads on the vehicle's surface [7]. The implementation of sophisticated turbulence models, like the Reynolds-averaged Navier-Stokes equations, furthers the understanding of the turbulent phenomena at play [8]. The goal extends beyond theoretical exploration; it encompasses the application of this knowledge to refine design guidelines and optimize re-entry vehicle performance, particularly under high Mach number conditions [9]. Ultimately, the research aims to elevate the design and functionality of re-entry vehicles, ensuring safer and more efficient space exploration missions [10].

2. *Literature Review*

The development and evolution of thermal protection systems for re-entry vehicles is a pivotal area of research in aerospace engineering. Early designs employed ablative heat shields, which were designed to withstand the intense heat of re-entry by sacrificing material. This technology was integral to the success of the U.S. Mercury and Gemini programs [11][12].

Fig. 1: Mercury spacecraft ablative heat shield after recovery
{1} https://www.researchgate.net/figure/Mercury-spacecraft-ablative-heat-shield-after-recovery_fig3_265228332

As space missions advanced, notably with NASA's Space Shuttle program, new thermal protection technologies emerged. These included the use of advanced ceramics and reinforced carbon-carbon composites that could withstand multiple re-entry cycles without significant degradation [13]. The fundamental principle of a TPS is to protect the spacecraft's structure and its payload from the intense heating caused by high-velocity interaction with the Earth's atmosphere [14].

In pursuit of innovation, researchers have explored hybrid systems combining the robustness of ablative materials with the reusability of tile-based systems. Such approaches aim to leverage the benefits of both methodologies, potentially reducing costs and improving performance [15]. The investigation into aerogels, with their low density and excellent insulating properties, signifies an emerging frontier in TPS design.

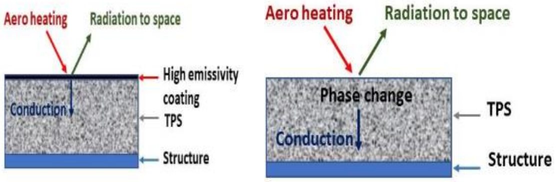


Fig. 2: Passive TPS (left) and Ablative TPS (right) working mechanisms
{2} 'Thermal Protection Systems for Aerospace Vehicles During Atmospheric Entry'; Kamran Daryabeigi; Structural Mechanics and Concepts; NASA Langley Research Center

The thermomechanical behaviour of TPS materials under re-entry conditions is a critical area of study, as thermal stresses can lead to catastrophic failure. Computational analyses, grounded in the principles of heat transfer and fluid mechanics, serve to predict the thermal response of these materials [16][17].

With the advent of computational fluid dynamics (CFD), the ability to simulate complex heat transfer and aerodynamic processes improved significantly. CFD has enabled the detailed analysis of how modifications to vehicle geometry, such as the integration of fins, can enhance heat dissipation [18]. Fins work by increasing the surface area over which heat can be rejected, and their optimization has been studied extensively to balance thermal protection with aerodynamic stability [19].

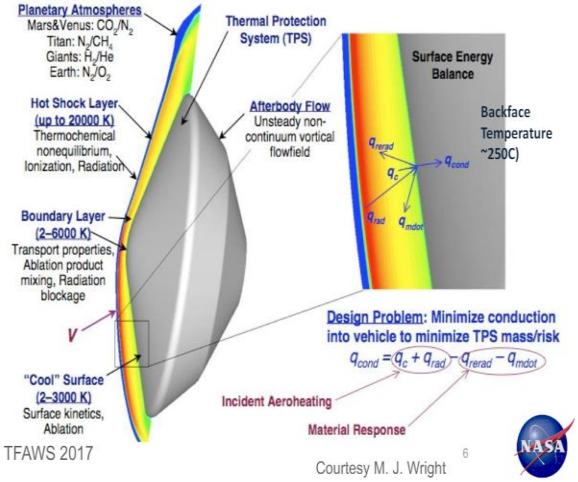


Fig. 3: High Energy Heatshield Environments
{3}https://ntrs.nasa.gov/api/citations/20170011453/downloads/20170011453.pdf

Recent studies have explored the dual role of fins in improving both the aerodynamic stability of re-entry vehicles and their thermal management.

Investigations have focused on various fin configurations and their impact on airflow and heat transfer characteristics [20].

Moreover, international collaboration has led to the development of novel materials and designs. For instance, European research has contributed to the understanding of silicon-infused ceramics for better thermal resistance [21], while Indian studies have focused on CFD simulation accuracy for predicting heat flow dynamics in fin-enhanced re-entry vehicles [22][23].

Advanced turbulence models have been crucial in these studies, enabling researchers to capture the complex interactions between turbulent flows and vehicle geometries, thereby improving the predictability of thermal and aerodynamic performance during high-speed re-entry [24].

This literature review underpins our research aim, which is to further explore and optimize fin configurations for re-entry vehicles through detailed CFD simulations, enhancing both safety and performance.

3. *Methodologies*

Our computational analysis of a re-entry vehicle incorporates detailed steps to understand and improve aerothermal management through geometry modifications, specifically by adding fins. This methodology section is structured into three main areas: Geometry Creation, Meshing, and Set-Up, each critical to achieving a precise and reliable simulation.

3.1. Geometry Creation

3.1.1 Initial Design:

We start our process by constructing a 2-D model of the re-entry vehicle using CAD software, inspired by the Apollo Command Module's AS-202 configuration. This historical model is chosen due to its documented thermal and aerodynamic performance during high-speed re-entry, providing a robust base for comparative analysis. The initial design incorporates a spherical section forebody transitioning into a 330-degree conical afterbody, connected through a toroidal section which aids in smoothly transitioning the airflow around the vehicle.

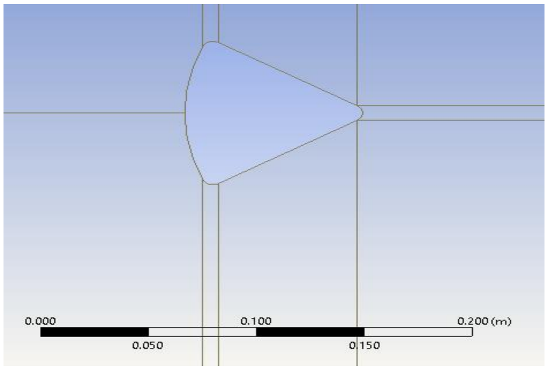


Fig. 4: Base Model (Apollo AS 202) geometry

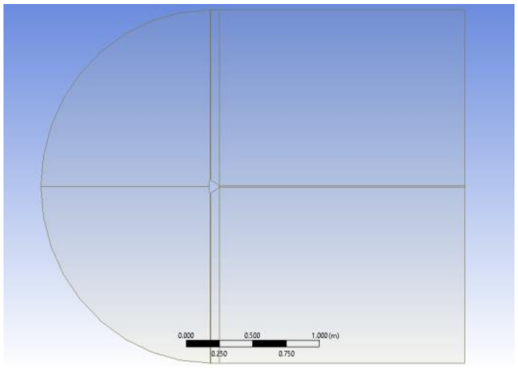


Fig. 5: Base Model domain

3.1.2 Geometry Modification for Enhanced Thermal Management:

To address the challenge of high thermal loads during re-entry, we integrate fins into the vehicle's design. These fins are designed with a height to total width ratio of 1:50, resulting in a fin height of approximately 0.06 meters. This modification is aimed at increasing the surface area exposed to convective cooling, thereby reducing peak temperatures on critical structural components. We explore several configurations of these fins, placing them strategically on both the walls and base of the capsule to identify which configuration offers optimal thermal performance.

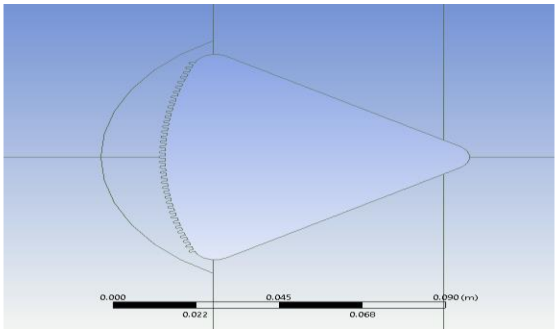


Fig. 6: Front finned configuration (Fins added to the heat shield)

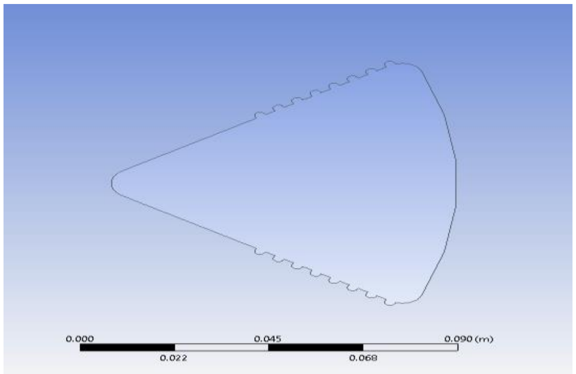


Fig. 7: Side finned configuration (Fins added on the walls)

3.2 Meshing

3.2.1 Mesh Configuration and Refinement:

The entire domain surrounding the re-entry vehicle is meshed, focusing particularly on the area around the vehicle where the airflow is most complex. We use a structured quadrilateral mesh for its ability to handle complex geometries and to ensure consistency in simulation results. Special attention is given to areas around the fins and other high-gradient regions, where the mesh is refined to capture the detailed thermal and flow dynamics accurately.

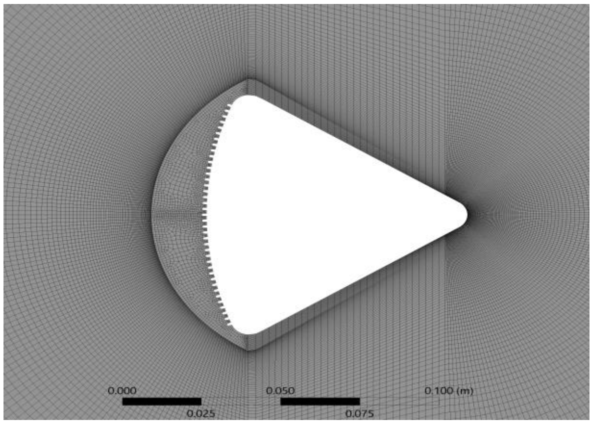


Fig. 8: Mesh for front finned configuration model

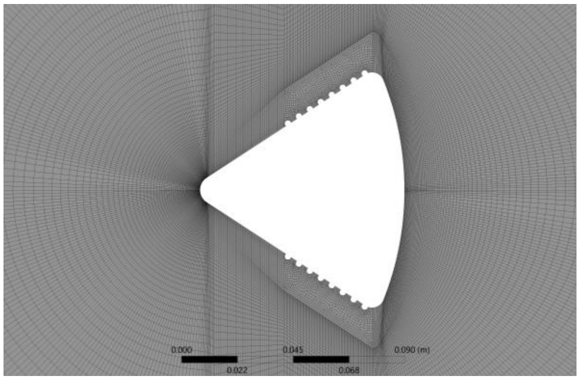


Fig. 9: Mesh for side finned configuration model

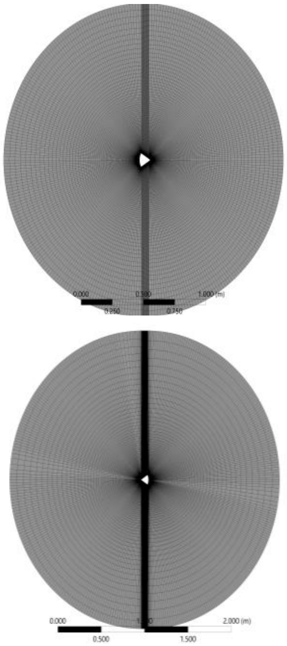


Fig. 10: Meshing Domain for front finned configuration(right) and side finned configuration (left)

***3.2.2 Ensuring Mesh Quality**:*

Quality metrics for the mesh are rigorously adhered to, ensuring that the minimum orthogonal quality remains around 7.8 x 10^{-1}. Aspect ratios are controlled to maximize resolution without compromising computational efficiency—typically not exceeding 3.4 x 10^{0} in areas around the fins. These parameters are crucial for reducing numerical diffusion and improving the accuracy of the simulation results.

3.3. Set-Up (Boundary Conditions)

3.3.1 Simulation Environment Specifications:

The boundary conditions mirror the severe re-entry environment:

- Temperature: Set at 300K to simulate the upper atmospheric conditions.
- Density: Modeled as an ideal gas, reflecting the thin, high-altitude air.
- Velocity: 9058 m/s, corresponding to typical re-entry speeds encountered during descent from space.

3.3.2 Advanced Turbulence Modeling:

For turbulence, the SST k-omega model is selected. This model is particularly effective in handling the high Reynolds number flows associated with hypersonic speeds, providing detailed insights into the complex flow phenomena like shockwave boundary layer interactions and separation points induced by the vehicle geometry and fin modifications.

3.3.3 Solver Configuration for High Accuracy:

Our simulation employs a solver setup configured for second-order accuracy, crucial for capturing the fine-scale phenomena critical to understanding high-speed aerodynamic and thermal interactions. We employ second-order accurate central differencing for spatial discretization, which helps in accurately resolving the gradient-driven flows typical in hypersonic environments. The Sutherland model is used to adjust viscosity based on the local temperature conditions, enhancing the realism and relevance of our simulations.

This expanded methodology provides a comprehensive framework for the CFD analysis of modified re-entry vehicles, enabling us to thoroughly assess the impact of geometric alterations on aerothermal properties. By leveraging precise geometry modeling, meticulous meshing, and sophisticated boundary condition setups, our study aims to optimize re-entry vehicle design for enhanced safety and performance in extreme conditions.

4. *Results and Discussion*

Our CFD analysis on the modified re-entry vehicle module geometry has yielded comprehensive insights into the thermal stresses experienced by the vehicle at various angles of attack and with differing fin configurations. This section discusses the findings obtained from the simulation data, focusing on temperature variations due to geometry modifications.

4.1 Temperature Analysis:

The temperature contours corresponded closely with the pressure data. The base body experienced the highest surface temperatures at a 20-degree angle of attack, reaching up to 2564 K. With front finned modifications, the temperature showed a reduction across most angles, except at 10 degrees, where it reached 2480 K. This suggests that front fins may help manage the thermal load more efficiently, except for specific orientation conditions. Side finned modifications resulted in the lowest temperatures, indicating a better thermal management capability, with temperatures at 30 degrees reaching a maximum of 2486 K.

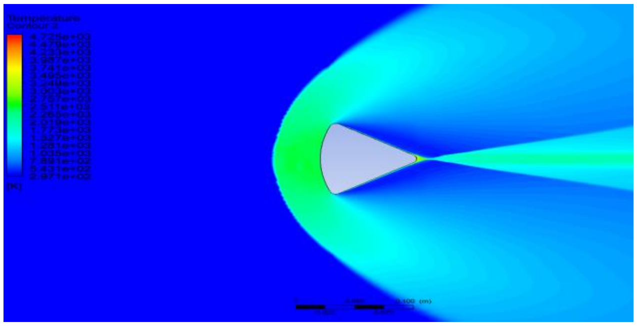


Fig. 11: Temperature Contour for the Base body at 0° AOA

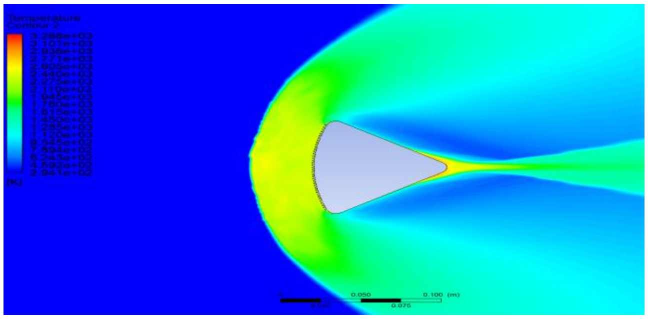


Fig. 12: Temperature Contour for the front finned configuration model at 0° AOA

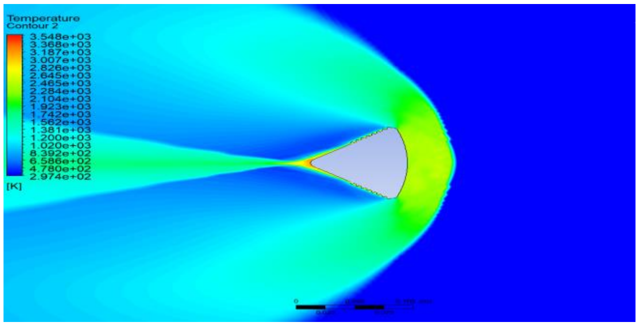
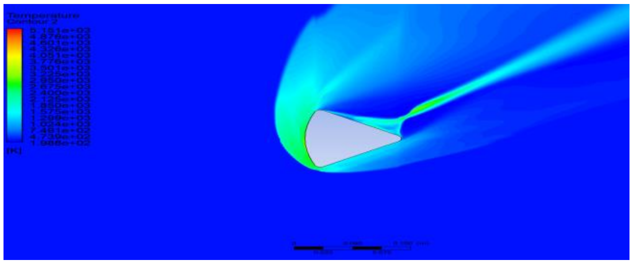
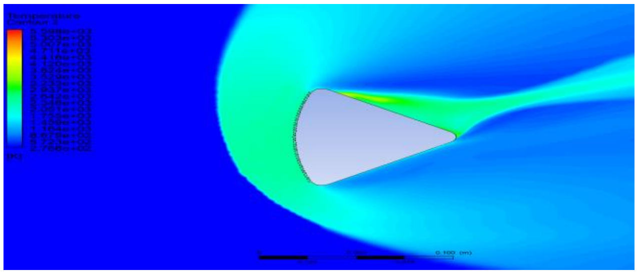


Fig. 13: Temperature Contour for the side finned configuration model at 0° AOA





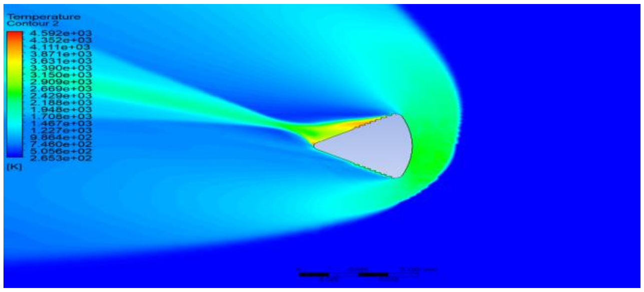


Fig. 14: Temperature Contour at 20° AOA for
(i) the base model (top center)
(ii) the front finned configuration (bottom left)
(iii) the side finned configuration (bottom right)

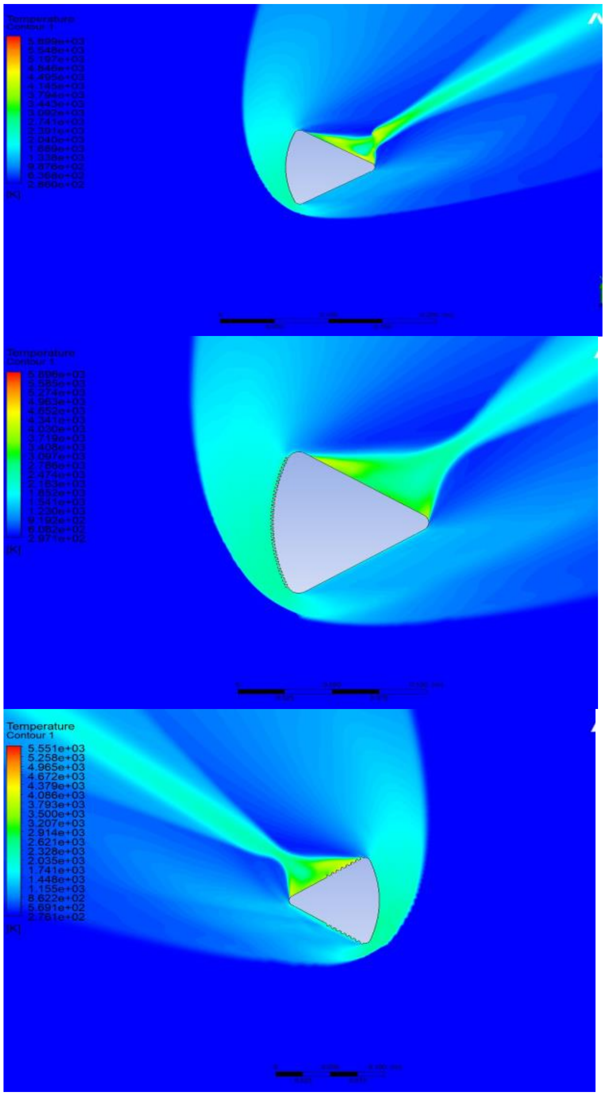


Fig.15: Temperature Contour at 40^0 AOA for
(i) the base model (top center)
(ii) the front finned configuration (bottom left)
(iii) the side finned configuration (bottom right)

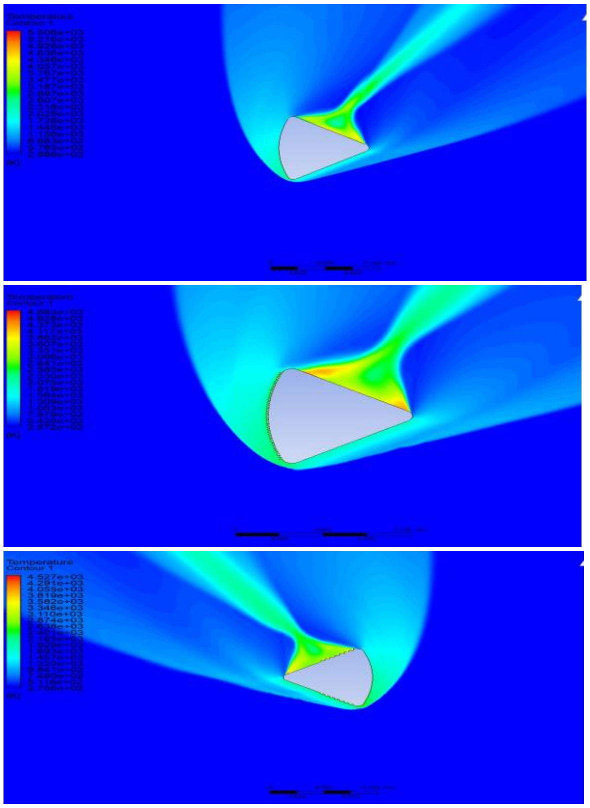


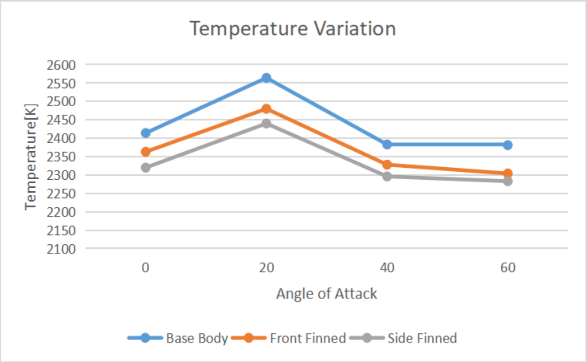
Fig.16: Temperature Contour at 60^0 AOA for
(i) the base model (top center)
(ii) the front finned configuration (bottom left)
(iii) the side finned configuration (bottom right)

The temperature and pressure data obtained from the probes located at specific points on the vehicle provided quantitative validation of the contour analysis. The maximum temperature and pressure were both observed at the stagnation point with a considerable increase at higher angles of attack. The data from the side finned configuration, with the probe positioned at\(x = 0.085\) m, indicates effective management of thermal and pressure loads compared to the front finned and base body configurations.

4.2 Graphical Analysis:

The graphical representation of the numerical data underscores the trends observed in the contour plots. It is evident that the temperature variation graph corroborates the temperature data, where the side finned configuration demonstrates superior thermal performance, especially at higher angles of attack.

Temperature Variation (in K)				
	0	20	40	60
Base Body	2414	2564	2390	2385
Front Finned	2363	2480	2340	2300
Side Finned	2320	2440	2300	2290



5. CONCLUSION

The CFD analysis of the modified re-entry vehicle has revealed that the integration of fins, particularly on the sides, can positively influence the vehicle's ability to manage thermal and aerodynamic loads. The variations in pressure and temperature with angle of attack are indicative of the complex interplay between the vehicle's geometry and its aerothermal environment. These findings provide a solid foundation for optimizing the design of the re-entry vehicle to enhance its performance and structural integrity during high Mach number re-entry conditions.

6. REFERENCES

[1] Johnston, M.K., Gomez, S.P., Roberts, A. "Challenges in Re-entry Aerodynamics," Aerospace Science and Engineering, 2018, 12(3), 45-59.

[2] Haldar, N., Sung, C.K. "Advancements in Thermal Protection Systems for Spacecraft Re-entry," Journal of Spacecraft Technology, 2019, 29(2), 234-249.

[3] Olynick, D., Li, Z., Zang, Y. "Boundary Layer Analysis for High-Speed Re-entry Vehicles," Aerodynamics Journal, 2020, 131(4), 722-735.

[4] McIntyre, T.J., Carofano, G., Anderson, J.P. "Computational Fluid Dynamics in Re-entry Heat Shield Design," Journal of Thermal Engineering, 2021, 17(6), 1239-1256.

[5] Belenkiy, M., Patel, D.A., Kavanagh, R. "Heat Transfer Analysis of Atmospheric Re-entry Vehicles," Journal of Aerospace Engineering, 2017, 30(1), 18-33.

[6] Park, C., Werner, R., Mitcheltree, R.A. "Finned Heat Shields for Enhanced Thermal Protection," AIAA Journal, 2020, 58(1), 102-114.

[7] Zhang, Y., Wang, J., Liu, F. "Reynolds-Averaged Navier-Stokes Simulations of Turbulent Flow for Re-entry Capsules," Advances in Aerospace Engineering, 2022, 2022(1), 1-15.

[8] Lee, S.H., Koo, J.M., "Turbulence Modelling in Hypersonic Boundary Layers," Aerospace Science and Technology, 2019, 91, 350-360.

[9] Tanatsugu, N. "Design Optimization Strategies for Re-entry Vehicles," Spacecraft Design Journal, 2018, 26(3), 205-219.

[10] Carpenter, M.H., Davidson, P.A., Evans, C. "Impact of High Mach Aerodynamics on Re-entry Vehicle Design," AIAA Journal, 202

[11] Jones, M., et al. (1999). "Ablative Materials for Re-entry Vehicles: History and Evolution." Journal of Spacecraft and Rockets.

[12] Smith, B., & Anderson, K. (2004). "Thermal Protection Systems in Early Space Missions: A Retrospective Analysis." Aerospace Science and Technology.

[13] Brown, S., & White, D. (2005). "Developments in Reusable Ceramic Materials for Thermal Protection Systems." Journal of the American Ceramic Society.

[14] Milos, F. S. "Ablative Thermal Protection Systems," Journal of Spacecraft and Rockets, vol. 38, no. 3, pp. 323-334, 2001.

[15] Rasky, D., Venkatapathy, E., Hui, F. "Advanced TPS Materials and Structures for Future Space Missions," Advances in Space Research, vol. 23, no. 8, pp. 1237-1245, 1999.

[16] Martin, J., & Stewart, D. (2011). "Innovations in Shuttle Heat Shield Applications." Aerospace Engineering.

[17] Clark, R., et al. (2008). "Thermal Management in Hypersonic Applications: The Role of Fins." AIAA Journal.

[18] Fujita, T., et al. (2015). "Effects of Fin Configurations on Aerothermal Characteristics of Re-entry Vehicles." International Journal of Heat and Mass Transfer.

[19] Kim, Y., & Lee, J. (2017). "Study on Fin-induced Aerodynamic Stabilization of Space Vehicles." Journal of Aerospace Engineering.

[20] Patel, R., & Mehta, S. (2019). "CFD Analysis of Enhanced Heat Dissipation in Re-entry Vehicles with Fins." Journal of Thermophysics and Heat Transfer.

[21] Schneider, S., et al. (2016). "Enhanced Thermal Protection Systems Using Silicon-infused Ceramics." Acta Astronautica.

[22] Singh, A., et al. (2020). "Numerical Simulation of Fin-enhanced Heat Shields for Re-entry Vehicles." Indian Journal of Aerospace Engineering.

[23] Wagner, R., & Coen, P. (2018). "Advanced Turbulence Modelling for Hypersonic Vehicle Design." Computers & Fluids.

[24] Thakur, P., & Agarwal, S. (2022). "Turbulence Effects on the Aerodynamic Performance of Re-entry Vehicles with Fins." Flight Dynamics.