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Numerical Aerothermal Analysis of a Hypersonic Missile at Various Mach Numbers

Thesis submitted
In Partial Fulfillment of the Requirements for the
Degree of

MASTER OF TECHNOLOGY
IN
COMPUTER AIDED ANALYSIS AND DESIGN

Submitted by:

DEVANG NIRANJAN

(24/CAD/08)

Under the supervision of

Dr. MOHAMMAD ZUNAID

(Associate Professor)

DEPARTMENT OF MECHANICAL ENGINEERING



DELHI TECHNOLOGICAL UNIVERSITY
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CANDIDATE DECLARATION

I DEVANG NIRANJAN , Roll No. 24/CAD/08 student of M.Tech Computer Aided Analysis and Design (CAAD), hereby declare that the Dissertation titled “Numerical Aerothermal analysis of a Hypersonic missile at various Mach numbers ” which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

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ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my guide, Dr. M. Zunaid, Associate Professor in the Department of Mechanical Engineering, for his invaluable guidance, support, and expertise throughout the course of this research work. His constant encouragement, insightful feedback, and dedication have been instrumental in shaping the direction and progress of this work. His deep knowledge and passion for the subject have inspired me to strive for excellence and explore new avenues in the field of Numerical Aerothermal analysis of a Hypersonic missile at various Mach numbers.

I would also like to extend my heartfelt appreciation to Prof. B B ARORA, Head of the Department of Mechanical Engineering, for his support and encouragement. His vision and leadership have provided a conducive environment for academic and research pursuits. I am grateful for his valuable insights and guidance that have contributed to the overall success of this project.

Lastly, I would like to acknowledge my family and friends for their unwavering support, encouragement, and understanding throughout this research endeavour. Their love, belief in my abilities, and motivation have been the driving force behind my perseverance and determination.

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ABSTRACT

Hypersonic Missiles are the type of missiles which are regarded as the fastest in the world, and they are currently being researched and developed in various regions of the world. It works with Mach numbers greater than 5. In this study, we examine the behavior of hypersonic missiles operating at a specific height under various flow field conditions at Mach numbers 5, 7, and 10, as well as the behavior of heat transfer loads on the hyperbolic profile structure.

The flow architecture and behavior of shock waves are being numerically simulated. This study contributes to an understanding of the design considerations for hypersonic missiles operating at various heights and atmospheric conditions and it will also help in thermal designing of hypersonic vehicles so that proper thermal management can be designed.

The results indicate distinct relationship between the Mach number and the thermal and aerodynamic characteristics at the nose tip and along the body. It is evident that as the Mach number increases from 5 to 10, the intensity of the Mach number decrease near the nose tip becomes more pronounced, leading to increased thermal loads on the missile.

The data presented highlights that at Mach number 5, the nose tip temperature reaches approximately 2,000 K, while increasing the Mach number to 10 raises the peak temperature to around 2,300 K. However, the temperature decreases more gradually with length at Mach number 10 compared to Mach number 5 and 7. This suggests that although higher Mach numbers result in more nose tip temperatures, the rate of temperature decrease along the body is not proportional to the Mach number increase, warranting further investigation into the thermal protection requirements for missiles operating at these speeds.

Key Words: Mach Numbers, Heat load, Fluid Flow, Load Analysis.

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NOMENCLATURE

u, v, w	Fluid velocity components at positions (x, y, z).
ρ	Fluid density
P	Pressure.
μ	Kinetic viscosity
f	External force per unit volume of fluid.
t	Time
T	Temperature.
k(T)	Thermal conductivity as a function of temperature
a_0, a_1, a_2, a_3, a_4	Coefficients used in the calculation of specific heat for temperatures between 550 K and 2200 K
Mach Number (M)	Speed relative to the speed of sound
Sic	Silicon Carbide material

CHAPTER 1

INTRODUCTION

1. General

Hypersonic Missiles, capable of traveling at speeds exceeding five times the speed of sound, represent a major advancement in modern military technology. However, their incredible velocity presents a significant challenge: excessive heat generation. As the missile travels at such high speeds, the air around it becomes compressed, causing the temperature to rise sharply. These temperatures can reach up to 2,200 degrees Celsius, which poses a risk of damaging or destroying the missile unless properly managed. To tackle this issue, it is essential to understand the mechanisms of heat generation and transfer to the missile [2]. This requires analysing the airflow around the missile and the transition from smooth laminar to turbulent flow, which significantly enhances heat transfer. Accurate calculations of the heat load are critical for the design and operation of hypersonic missiles, ensuring they can endure the extreme temperatures and successfully complete their mission. Key studies have made significant contributions to this field. Tauber's 2001 work, "Aerothermodynamic Heating of Hypersonic Vehicles," provides an in-depth analysis of the physical phenomena during hypersonic flight, including shock wave formation and viscous heating, and emphasizes the importance of combining numerical simulations with experimental validation. Another review, "Thermal Protection Systems for Hypersonic Vehicles, examines various TPS materials and technologies, highlighting the need for innovative solutions to balance performance, durability, and mass in hypersonic applications. Another study on "Numerical Simulation of Hypersonic Flow and Heat Transfer over a Blunt Body utilized computational fluid dynamics (CFD) to investigate how different flight parameters and surface properties influence heat load distribution. An experimental investigation[4] provided valuable heat transfer and aerodynamic force data for hypersonic vehicles tested in shock tunnels, offering key insights into flow physics and heat transfer mechanisms. Finally, Anderson's 2018 review of recent advances in hypersonic vehicle design underscores the multidisciplinary nature of hypersonic flight, emphasizing the interconnected challenges of thermal management, propulsion, and control systems, and the importance of integrated design approaches. These research efforts collectively advance the understanding and mitigation of heat loads, crucial for the successful development of hypersonic missiles.

The development of hypersonic technology has become one of the most important areas of modern aerospace and defence engineering. Hypersonic vehicles are capable of travelling at extremely high velocities, generally greater than Mach 5, where the speed of the vehicle exceeds five times the speed of sound. At such high speeds, the interaction between the vehicle surface and surrounding atmospheric air becomes highly complex due to intense aerodynamic heating, strong shock wave formation,

compressibility effects, and rapid changes in pressure and temperature. These extreme environmental conditions create significant engineering challenges in the design of hypersonic missiles and aerospace systems.

One of the primary concerns in hypersonic flight is the generation of thermal loads on the external surface of the missile. As the missile moves through the atmosphere at hypersonic velocity, the kinetic energy of the airflow converts into thermal energy due to compression and viscous dissipation. This phenomenon leads to a drastic rise in surface temperature, especially near the nose tip and leading edges. The stagnation region located at the front section of the missile experiences maximum pressure and temperature because the airflow decelerates rapidly in this area. If the generated heat is not controlled properly, structural failure, material degradation, thermal cracking, and aerodynamic instability may occur.

The aerodynamic behaviour of hypersonic vehicles differs significantly from subsonic and supersonic vehicles. In hypersonic regimes, shock waves become extremely strong and remain attached close to the body surface. These shock waves influence pressure distribution, velocity variation, temperature rise, and boundary layer development around the missile body. The interaction between shock waves and boundary layers further increases thermal loading and can lead to localized hot spots on the surface. Therefore, accurate prediction of shock structures and heat transfer characteristics is essential for designing reliable hypersonic systems.

Thermal protection becomes one of the most critical requirements for hypersonic missiles. Advanced thermal protection systems are required to protect the vehicle structure from excessive heating during atmospheric flight. Materials used in hypersonic applications must possess high melting temperature, thermal stability, oxidation resistance, and mechanical strength at elevated temperatures. Ceramic-based materials, carbon composites, silicon carbide, and ultra-high-temperature materials are commonly investigated for such applications. The selection of proper thermal protection materials directly affects the safety, efficiency, and operational capability of hypersonic vehicles.

Another important aspect of hypersonic flight is the effect of compressible flow physics. At extremely high Mach numbers, the density and temperature of air change rapidly around the missile body. The air molecules may undergo dissociation, ionization, and vibrational excitation because of the very high temperatures generated behind shock waves. Under such conditions, conventional perfect gas assumptions may become inaccurate, requiring more advanced numerical and thermodynamic modelling approaches for realistic predictions.

Experimental investigation of hypersonic flows is highly difficult and expensive because it requires specialized facilities such as shock tunnels, expansion tubes, and high-temperature wind tunnels. These facilities are limited in availability and involve significant operational costs. As a result, Computational Fluid Dynamics (CFD) has become an effective and widely used tool for analysing hypersonic flow behaviour. CFD enables engineers and researchers to numerically simulate aerodynamic heating, shock-wave formation, pressure variation, turbulence effects, and thermal distribution under various flight conditions. Modern CFD software allows detailed visualization and analysis of complex flow structures around hypersonic vehicles.

Numerical simulation methods provide several advantages in hypersonic research. They reduce experimental cost, minimize development time, and allow investigation of multiple operating conditions without manufacturing physical prototypes. CFD also helps in understanding flow physics that may be difficult to measure experimentally. Through numerical analysis, engineers can optimize missile geometry, improve aerodynamic efficiency, reduce thermal loads, and enhance structural safety. Consequently, numerical simulation has become an essential component of modern hypersonic vehicle design and development.

The geometry of the missile plays a major role in determining aerodynamic and thermal performance. The shape of the nose cone, body curvature, and surface smoothness significantly influence shock-wave intensity and heat transfer rates. Sharp nose geometries generally reduce aerodynamic drag but experience higher heating rates, while blunt geometries reduce thermal intensity by forming detached shock waves. Therefore, an optimized geometric configuration is necessary to balance aerodynamic efficiency and thermal protection requirements.

In addition to aerodynamic heating, hypersonic missiles also experience severe mechanical loads due to high dynamic pressure and rapid acceleration. These loads can generate thermal stresses and structural deformation within the missile body. Therefore, hypersonic vehicle design requires the integration of aerodynamics, thermodynamics, structural mechanics, material science, and propulsion engineering. The multidisciplinary nature of hypersonic technology makes it one of the most challenging and advanced fields in aerospace engineering.

The present research focuses on the numerical heat load analysis of a hypersonic missile operating under different Mach number conditions. The study investigates the variation of temperature, pressure, and Mach number around the missile body using computational fluid dynamics techniques. Particular attention is given to the nose tip region because it experiences maximum aerodynamic heating and shock-wave interaction. Simulations are performed for Mach numbers 5, 7, and 10 to analyse the effect of increasing velocity on thermal and aerodynamic characteristics.

The findings of this work contribute to the understanding of hypersonic aerothermal behaviour and thermal management requirements. The study also provides useful information regarding shock-wave structures, pressure rise, stagnation heating, and thermal distribution around hypersonic missile geometries. Such investigations are important for improving future hypersonic vehicle designs and developing efficient thermal protection systems capable of operating under extreme atmospheric conditions.

CHAPTER 2

LITERATURE REVIEW

C. L. Herath [1] presented an extensive overview of modern hypersonic missile systems and their strategic importance in advanced defense applications. The author discussed the fundamental principles of hypersonic flight, emphasizing speeds exceeding Mach 5 and the associated aerodynamic, thermal, and propulsion challenges. The review highlighted the evolution of hypersonic weapons from conventional ballistic missile systems to highly maneuverable glide vehicles and scramjet-powered cruise missiles capable of penetrating modern defense systems. Significant attention was given to propulsion mechanisms such as scramjet engines, which enable sustained combustion at extremely high velocities. The study also analyzed the effects of intense aerodynamic heating and shock-wave formation during atmospheric flight, explaining the necessity of advanced thermal protection materials and high-temperature-resistant structures. Additionally, the paper explored guidance, navigation, and control technologies required for maintaining stability and precision under extreme flight conditions. Strategic implications such as rapid strike capability, reduced response time, and challenges in missile interception were also examined. The work concluded that hypersonic missile technology represents a transformative advancement in military aerospace engineering, although substantial research is still required in thermal management, materials science, and flight control systems to achieve reliable and cost-effective operational deployment.

D. C. Youvan [2] discussed emerging developments in both hypersonic missiles and concealed container-based missile launch technologies. The study emphasized the growing role of advanced missile systems in modern warfare, particularly focusing on their capability to provide rapid, precise, and difficult-to-detect attacks. The author examined the technological integration of hypersonic propulsion systems with stealth launch platforms, including containerized missile systems that can be deployed through commercial shipping networks or mobile launch units. The paper described how hypersonic vehicles achieve superior maneuverability and reduced interception probability due to their extremely high speed and unpredictable trajectories. Considerable attention was devoted to aerodynamic heating, shock-wave interactions, and propulsion efficiency, all of which significantly influence missile performance during hypersonic flight. Furthermore, the author explored the strategic implications of combining mobility, stealth, and hypersonic speed, which may alter future military doctrines and defense architectures worldwide. Challenges related to thermal protection systems, structural integrity, advanced guidance algorithms, and international security concerns were also analyzed. The study concluded that the convergence of hypersonic and container missile technologies could redefine future combat strategies by enhancing survivability, deployment flexibility, and tactical effectiveness in high-threat environments.

20 V. T. Le, N. S. Ha, and N. S. Goo [3] provided a detailed investigation of
58 lightweight and thermally resistant structural concepts designed for hypersonic aerospace
applications. The authors focused on sandwich composite structures that combine low
density with high mechanical strength and excellent thermal insulation characteristics,
making them suitable for thermal protection systems (TPS) in hypersonic vehicles. The
20 paper reviewed various core materials, including honeycomb, corrugated, lattice, and
foam-based structures, along with advanced face-sheet materials such as ceramic matrix
composites and carbon-carbon composites. The study emphasized that hypersonic flight
generates extremely high aerodynamic heating due to shock-wave compression and
viscous dissipation, which necessitates the use of efficient thermal barriers to protect
internal systems and structural components. The authors analyzed heat transfer
mechanisms, thermo-mechanical behavior, structural stability, and failure modes under
severe thermal loading conditions. Additionally, manufacturing methods, material
optimization techniques, and multifunctional design approaches were discussed to
improve thermal efficiency while minimizing structural weight. The review highlighted
that advanced sandwich structures can significantly enhance thermal resistance,
mechanical durability and overall vehicle performance during sustained hypersonic
operations. The study concluded that future advancements in material engineering and
structural optimization are essential for developing next-generation reusable hypersonic
vehicles with improved safety and operational capability.

9 I. Nompelis, G. V. Candler, M. S. Holden, and T. P. Wadhams [4] investigated
the influence of real gas phenomena on shock-wave behavior in hypersonic flow
environments. The paper explained that at extremely high velocities and temperatures
13 encountered during hypersonic flight, air can no longer be treated as a perfect gas because
molecular dissociation, ionization, and vibrational excitation become dominant physical
processes. The authors analyzed how these thermochemical nonequilibrium effects alter
shock-wave structures, pressure distributions, temperature gradients, and aerodynamic
heating characteristics around highspeed vehicles. Using computational and experimental
approaches, the study demonstrated that real gas effects significantly influence flow-field
properties and heat transfer rates, thereby affecting vehicle performance, stability, and
thermal protection requirements. The research highlighted the limitations of conventional
perfect-gas assumptions in accurately predicting hypersonic aerodynamics and
emphasized the need for advanced numerical models capable of simulating high-
62 temperature gas dynamics. Furthermore, the paper discussed the interaction between
shock waves and boundary layers, which can intensify local heating and lead to structural
damage if not properly managed. The findings provided valuable insight into the design
of hypersonic vehicles, especially in terms of aerodynamic shaping, thermal shielding,
and accurate computational fluid dynamics modeling for extreme flight conditions.

8 S. Kumar and S. P. Mahulikar [5] investigated the aerodynamic and thermal
68 behavior of lifting body geometries operating in hypersonic flight regimes. The study
focused on the relationship between vehicle configuration and aerothermal performance,
emphasizing that the shape of the lifting body significantly affects shock-wave formation,
heat transfer distribution, drag characteristics, and overall flight stability. Through

computational simulations and analytical evaluations, the authors examined surface temperature

variations, stagnation point heating, and pressure distributions under different 1 hypersonic flow conditions. The paper highlighted that lifting body designs can improve aerodynamic efficiency while simultaneously reducing thermal loads compared to conventional blunt-body configurations. However, the study also pointed out that localized heating near leading edges and shock interaction regions remains a major engineering challenge. The researchers analyzed the effects of geometric parameters such as nose

radius, body curvature, and angle of attack on aerodynamic heating and lift-to-drag ratio. The work further emphasized 1 the importance of integrating aerodynamic optimization with thermal protection system design to achieve stable and efficient hypersonic flight. The study concluded that properly optimized lifting body configurations can enhance maneuverability, reduce aerodynamic heating intensity, and improve the survivability of future hypersonic aerospace vehicles.

S. P. Mahulikar [6] presented a theoretical framework for designing hypersonic vehicle configurations based on aerothermal principles. The study emphasized that hypersonic vehicle design must simultaneously address aerodynamic performance 4 and thermal management because of the extreme heating generated during high-speed atmospheric flight. The author explained 1 the importance of understanding shock-wave behavior, viscous interactions, boundary-layer effects, and heat-transfer mechanisms in determining

optimal vehicle geometry. Various aerodynamic configurations were theoretically analyzed to evaluate their influence on pressure distribution, drag forces, lift generation, and thermal loading. The paper highlighted that blunt-body designs reduce peak thermal loads by creating detached shock waves, whereas slender-body configurations improve aerodynamic efficiency but experience higher localized heating. The study also discussed entropy generation, energy transfer processes, and thermal equilibrium concepts 1

associated with hypersonic flow fields. Furthermore, the research proposed design methodologies aimed at minimizing aerodynamic heating while maintaining acceptable lift-to-drag characteristics and structural stability. The paper concluded that successful hypersonic vehicle development requires a balanced integration of aerodynamics, thermodynamics, 1 material science, and thermal protection technologies to ensure reliable performance under severe operational conditions.

Chirath Lochana Herath [7] This article aims to provide a comprehensive analysis of hypersonic missile technology, including its basic principles, technological development, and strategic significance in contemporary military contexts. In view of the unique capabilities of hypersonic systems, such as speed, accuracy and maneuverability. This paper examines their effects on current defense and detection systems, and the implications they have on international security and power distributions. The paper also looks at the strategic, ethical and legal dimensions of hypersonic weapons, in particular the gaps in current arms control agreements.

Adam B. Peters et.al[8] The research stresses the need for a balanced approach to the

3 diffusion of technology to avoid the danger of a single dominant power and to help create a more stable and equitable global security environment. Hypersonic vehicles must withstand extreme conditions during flights that exceed five times the speed of sound. These systems have the potential to facilitate rapid access to space, bolster defense capabilities, and create a new paradigm for transcontinental earth-to-earth travel. However, extreme aero thermal environments create significant challenges for vehicle materials and structures. This work addresses the critical need to develop resilient refractory alloys, composites, and ceramics. We will highlight key design principles for critical vehicle areas such as primary structures, thermal protection, and propulsion systems; the role of theory and computation; and strategies for advancing laboratory-scale materials to manufacturable flight-ready components.

2 RAND (n.1); The terminal phase is the portion of flight when the warhead reenters the atmosphere which lasts approximately thirty seconds. ROBERT CHEN, JASON SPEYER, Terminal and Boost Phase Intercept of Ballistic Missile Defense (AIAA Guidance, Navigation and Control Conference and Exhibit 18 - 21 August 2008) p.1. Nevertheless, once the RV reenter from outer space would be greatly slowed down by the Earth's atmosphere. It is estimated that an average ICBM RV would travel at more than 1,8 m/s (approximately Mach 8) at impact point. AMITAV MALLIK, Technology and Security in the 21st Century: A Demand-side Perspective (Oxford University Press, 2004), p. 110. [9] their research explains that reentry vehicles (RVs) travel at extremely high velocities, often reaching hypersonic speeds close to Mach 8 even after atmospheric deceleration. The studies emphasize that such speeds create major challenges for missile interception, guidance, and defense systems due to limited reaction time and intense aerodynamic conditions. The literature further indicates that hypersonic missile technology enhances rapid strike capability, precision targeting, and strategic deterrence while simultaneously increasing concerns regarding global security, missile defense effectiveness, and strategic stability.

2 RAND (n.1), p. 8. See also 'Hyper-glide Delivery Systems and the Implications for Strategic Stability and Arms Reductions' (James Martin Center for NonProliferation Studies, 2015), p. 8. [10] describe how hypersonic missiles combine extremely high speeds, advanced maneuverability, and long-range strike capability, making them difficult to detect and intercept using existing missile defense systems. The literature emphasizes that hypersonic glide vehicles can alter flight paths during atmospheric travel, thereby increasing operational flexibility and reducing enemy response time. Researchers also discuss the implications of these technologies on strategic stability, arms reduction efforts, and global security frameworks. The studies conclude that while hypersonic systems significantly improve rapid precision strike capability, they also create new challenges related to deterrence, arms control, and international defense policy.

16 76 John D. Anderson Jr. [11] extensively studied hypersonic aerodynamics, high-temperature gas effects, and thermal behaviour in hypersonic vehicles. His work explains that when a missile travels above Mach 5, severe aerodynamic heating develops around the nose tip and leading edges due to atmospheric compression. The study highlights the influence of shock waves, viscous interaction, and temperature rise on vehicle stability

and material performance. Anderson concluded that thermal protection systems and aerodynamic shaping are essential for maintaining structural integrity and flight accuracy in hypersonic missiles.

Bertin and Cummings [12] investigated the aerodynamic heating and pressure distribution occurring during hypersonic flight. Their research focused on temperature concentration near the nose cone and stagnation region of hypersonic vehicles. The study demonstrated that increasing Mach number significantly raises surface temperature and pressure loads, affecting missile accuracy and structural durability. Their findings contributed to improved thermal shielding methods and aerodynamic optimization for high-speed missile systems.

Theodore von Kármán [13] pioneered research in high-speed and hypersonic aerodynamics. His studies introduced theoretical models explaining airflow behaviour, shockwave formation, and pressure variation at extremely high velocities. The research established the foundation for understanding aerodynamic drag and thermal stresses acting on missile nose tips during atmospheric re-entry. His contributions remain fundamental in the design and analysis of modern hypersonic missiles and re-entry vehicles.

Antonio Ferri [14] examined supersonic and hypersonic airflow characteristics around missile structures. His work analysed pressure gradients, shock interactions, and aerodynamic stability at high Mach numbers. The study emphasized that nose tip geometry strongly influences thermal load and pressure distribution in hypersonic missiles. Ferri's findings supported the development of streamlined missile configurations capable of maintaining accuracy under severe aerodynamic conditions.

Dale R. [15] focused on thermal protection systems for hypersonic vehicles exposed to extreme aerodynamic heating. His research evaluated heat transfer rates and material behavior at high temperatures generated during atmospheric flight. The study identified that nose tip regions experience maximum thermal stress due to stagnation heating. Corson proposed advanced heat-resistant materials and cooling concepts to improve missile survivability and operational efficiency at hypersonic speeds.

Frank J. Regan and Satya M. Anandakrishnan [16] studied atmospheric re-entry dynamics associated with ballistic and hypersonic vehicles. Their research explained how high-speed re-entry produces intense aerodynamic pressure, shockwave interaction, and thermal loading around the nose cone. The study further highlighted that accurate prediction of temperature and pressure distribution is necessary for ensuring missile guidance precision and structural reliability during terminal flight phases.

T. J. Chung [17] to analyse hypersonic flow behaviour around missile bodies. His work investigated pressure contours, velocity variation, and thermal distribution at hypersonic speeds. The study showed that CFD simulations can accurately predict nose tip heating, shockwave patterns, and aerodynamic drag, enabling researchers to improve missile accuracy and thermal management systems.

James M. Acton [18] about Conventional Prompt Global Strike the strategic significance of hypersonic and prompt global strike systems. His study discussed the capability of hypersonic missiles to achieve rapid precision attacks with extremely short response times. The research highlighted that advanced speed and maneuverability increase operational effectiveness while also creating challenges related to missile

tracking, interception, and global strategic stability. The study emphasized the importance of balancing technological advancement with international security considerations.

RESEARCH GAP AND OBJECTIVES

1.1 Research Gap: The following research gaps have been found after detailed literature survey –

1. The profile of Missile nose tip with various Mach number to study temperature, velocity and range on missile nose tip yet to be explored.
2. After detailed Literature review, it was observed that very limited research work available in the literature on study of pressure at the narrow nose tip of the missile at high speed.

1.2 Research Objectives: After the study of detailed literature survey, the following research objectives are identified

1. To create 3-D model of nose tip of Hypersonic Missile.
2. To simulate the Parameters such as temperature near nose tip of Hypersonic missile at different Mach numbers using ANSYS.
3. To simulate the Parameters such as pressure near nose tip of Hypersonic missile at different Mach numbers using ANSYS.

CHAPTER 3

METHODOLOGY

METHODOLOGY

The study focuses on the numerical analysis of heat load for a hypersonic missile operating under compressible hypersonic flow conditions. The research utilizes Computer-Aided Design (CAD) and Computational Fluid Dynamics (CFD) software to simulate aerodynamic heating, shock-wave interactions, temperature variations, pressure distributions, and Mach number behaviour around the missile at hypersonic speeds.

The methodology employed in this work comprises the following stages:

- CAD modelling of the hypersonic missile geometry.
- Development of the computational flow domain.
- Mesh generation and refinement.
- Selection of governing equations.
- Definition of material properties.
- Application of boundary conditions.
- CFD solver setup.
- Numerical simulation.
- Post-processing and interpretation of results.

The entire simulation process is conducted using CAD and CFD software, specifically ANSYS Space Claim, ANSYS Meshing, and ANSYS Fluent. Numerical simulations are performed for different Mach numbers. This detailed and systematic methodology allows for an accurate study of the missile structure's aerodynamic and thermal performance.

3.1 CAD Modelling of Hypersonic Missile Geometry

The initial stage involves creating a three-dimensional geometric model of the hypersonic missile using CAD software. The design adheres to the configuration depicted in the project's top and side view figures. The missile body is engineered as a streamlined hyperbolic profile, optimized for hypersonic flight. The geometry's selection is critical, as aerodynamic heating, shock-wave intensity, and pressure distribution are highly dependent on external shape. The CAD model is developed in ANSYS Space claim, employing sketching, extrusion, revolve, and surface generation operations.

Geometrical Features of the Missile:

- Pointed nose cone section
- Cylindrical mid-body section
- Rear tapered body section
- Symmetric aerodynamic profile

The pointed nose section is of paramount importance, as it experiences the highest stagnation pressure and thermal loading during hypersonic flight.

Dimensions in the CAD model are maintained proportionally to the figures in the original project document, as precise numerical values were not explicitly provided.

CAD Modelling Procedure:

1. **Creation of 2D Sketch:** A 2D sketch of the missile profile, including the nose curve, cylindrical body, and tail taper, is prepared on the XY plane and constrained using dimensions and geometric relations.
2. **Revolve Operation:** The 2D profile is revolved around the longitudinal axis to form the 3D missile body.
3. **Surface Smoothing:** Fillet and smooth surface operations are applied to eliminate sharp edges and ensure smooth aerodynamic flow.
4. **Geometry Verification:** The geometry is checked for surface continuity, watertightness, absence of gaps or overlaps, and proper axis alignment. The final Adequate upstream distance.

- Extended downstream wake region.
- Side boundaries positioned away from the missile body.
- Domain size optimized to capture shock-wave propagation accurately.

The computational enclosure is generated as a cylindrical or rectangular fluid region surrounding the missile. The missile body is subtracted from this enclosure using a Boolean subtraction operation in ANSYS Space Claim to create the final fluid domain.

Importance of Computational Domain:

- Facilitates proper shock-wave formation.
- Ensures accurate pressure distribution.
- Contributes to correct Mach number prediction.
- Reduces boundary reflection errors.
- Promotes stable convergence behavior.

The completed fluid domain is then transferred to the meshing module.

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3.3 Mesh Generation

Mesh generation is a critical stage in CFD analysis, as numerical accuracy is heavily reliant on mesh quality. The fluid domain is discretized into numerous finite control volumes using ANSYS Meshing.

Mesh Type:

A hybrid mesh structure is employed, consisting of:

- Tetrahedral elements in the bulk flow region.
- Inflation layers near wall surfaces.
- Refined elements near the nose tip.

The mesh is made finer in areas with high thermal and pressure gradients.

Mesh Refinement Regions:

Special mesh refinement is applied in:

- Nose tip region.
- Shock-wave interaction zone.
- Boundary layer region.
- Wake region behind the missile.
- Surface curvature locations.

The nose tip region requires extremely fine meshing due to strong shock waves and high thermal gradients in stagnation zones.

Inflation Layer Generation:

Inflation layers are generated near the missile wall surface to accurately capture the viscous boundary layer. Key parameters considered include:

- Number of inflation layers.
- Growth rate.
- First layer thickness.
- Smooth transition ratio.

These layers aid in the accurate prediction of:

- Wall heat transfer.
- Shear stress.
- Thermal boundary layer.
- CAD model is then exported for CFD analysis.

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3.2 Development of Computational Domain

Following CAD model completion, a computational fluid domain is generated around the missile body, representing the atmospheric region of flight. The

domain is designed to be sufficiently large to prevent external boundary influences on the flow field.

Domain Dimensions:

- Velocity gradients.

Mesh Quality Parameters:

Mesh quality is assessed using:

- Skewness.
- Orthogonal quality.
- Aspect ratio.
- Element quality.

Skewness values are maintained within acceptable limits for numerical stability.

Mesh Independence Study:

A mesh independence study is conducted by generating three mesh cases (coarse, medium, and fine). Variations in wall temperature and pressure distribution are monitored for each case. The mesh is deemed grid-independent when further refinement results in negligible changes. The final selected mesh balances numerical accuracy and computational time.

3.4 Material Properties

The thermal and structural properties of the missile material are vital in hypersonic applications. Silicon Carbide (SiC) is selected for its superior thermal resistance.

Table 1: Material Property of Hypersonic missile nose tip.

Thermal properties parameters	Values
Density	3100(kg/m ³)
Thermal Conductivity	120(W/m-K)
Coefficient of Thermal Expansion	4*10 ⁻⁶ (1/C°)
Specific Heat	750(J/Kg-K)
Melting Point	3003K

Properties of Silicon Carbide:

- High thermal conductivity
- High melting temperature
- Excellent hardness
- Low thermal expansion
- Good thermal shock resistance
- Excellent fatigue resistance

These properties make SiC highly suitable for hypersonic thermal protection.

Air Properties:

The fluid medium is atmospheric air, with the following assumptions:

- Compressible flow.
- Ideal gas behaviour.
- Temperature-dependent viscosity.
- Temperature-dependent thermal conductivity.

Thermal Conductivity Variation:

$$k(T) = 1.9942 \times 10^{-3} T^{1.5} + 112 \quad k(T) = T + 112$$

Specific Heat Capacity:

For moderate temperatures:

$$C_p = 1018.2 \text{ J/kg-K} \quad C_p = 1018.2 \text{ J/kg-K}$$

Viscosity variation is modelled using Sutherland's law.

3.5 Boundary Conditions

Boundary conditions are essential for defining flow behaviour. The simulation is conducted at an altitude of 35 km.

Atmospheric Conditions:

- Pressure = 768 Pa
- Temperature = 228 K
- Altitude = 35 km

Pressure Far-Field Boundary Condition:

Applied at all external boundaries, this condition is suitable for:

- Compressible flow.
 - Hypersonic external aerodynamics.
 - Shock-wave propagation.
 - Freestream atmospheric simulation.
- It defines freestream Mach number, pressure, temperature, and flow direction.

Wall Boundary Condition:

The missile surface is treated as a stationary no-slip wall with:

- Zero velocity at the wall.
- Thermal coupling between fluid and wall.
- Radiation heat transfer.

Radiation Model:

The wall emissivity is considered as:

$$\varepsilon = 0.84 \quad \varepsilon = 0.84$$

Radiative heat transfer is significant due to the extremely high surface temperatures.

Mach Number Conditions:

In this study, the simulation has been performed for Mach number 5, 7 and 10: These represent hypersonic operating regimes.

3.6 Solver Setup in ANSYS Fluent

The CFD analysis is performed in ANSYS Fluent 2024 R1 in this study.

Solver Type:

Selected settings include:

- 3D solver.
- Density-based solver.
- Double precision solver.
- Steady-state analysis.
- Compressible flow solver.

The density-based solver is preferred for better convergence in high-speed compressible flows.

Turbulence Model:

The Transition SST turbulence model is selected for accurate prediction of:

- Boundary layer transition.
- Shock-wave interaction.
- Near-wall heat transfer.
- Flow separation.

Numerical Discretization:

Second-order numerical schemes are used for improved solution accuracy, including:

- Second-order upwind scheme.
- High-order energy discretization.
- Pressure interpolation scheme.

Initialization:

The flow field is initialized using freestream atmospheric conditions. The solution is iterated until convergence is achieved.

Convergence Criteria:

Convergence is monitored via:

- Residual reduction.
- Stability of wall temperature.
- Pressure stabilization.
- Heat flux stability.
- Mach number consistency.

Residual values are reduced below acceptable limits before solution finalization.

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3.7 Simulation Procedure

The complete CFD simulation procedure is as follows:

1. Creation of missile geometry in CAD software.
2. Generation of the computational fluid domain.
3. Import of geometry into ANSYS Meshing.
4. Mesh generation and refinement.
5. Inflation layer creation.
6. Mesh quality verification.
7. Import of mesh into ANSYS Fluent.
8. Selection of density-based solver.
9. Definition of material properties.
10. Application of boundary conditions.
11. Selection of turbulence model.
12. Initialization of the flow field.
13. Numerical solution of governing equations.
14. Monitoring of convergence behavior.
15. Post-processing of aerodynamic and thermal results.

Separate simulations are conducted for Mach 5, Mach 7, and Mach 10 conditions.

3.8 Post-Processing and Result Analysis

Upon completion of numerical simulations, results are analysed using CFD post-processing tools. The following parameters are evaluated:

- Mach number contours.
- Temperature contours.
- Pressure contours.
- Shock-wave structure.
- Wall heat transfer.
- Static temperature variation.

- Static pressure variation.
- Thermal load distribution.

Mach Number Analysis:

Mach number contours are used to analyse shock-wave formation, flow deceleration, bow shock structure, and stagnation region behaviour.

Thermal Analysis:

Temperature contours help identify peak thermal load regions, nose tip heating, thermal gradient distribution, and high-temperature zones.

Pressure Analysis:

Pressure contours are used to evaluate stagnation pressure rise, shock-wave pressure increase, and pressure distribution over the missile surface.

Comparative Analysis:

Results for Mach 5, Mach 7, and Mach 10 are compared to study the effect of increasing Mach number on thermal loading, pressure rise, shock-wave intensity, and aerodynamic heating. The obtained results provide insight into the thermal behavior of hypersonic missile structures under extreme aerodynamic conditions.

3.9: GEOMETRIC MODELLING

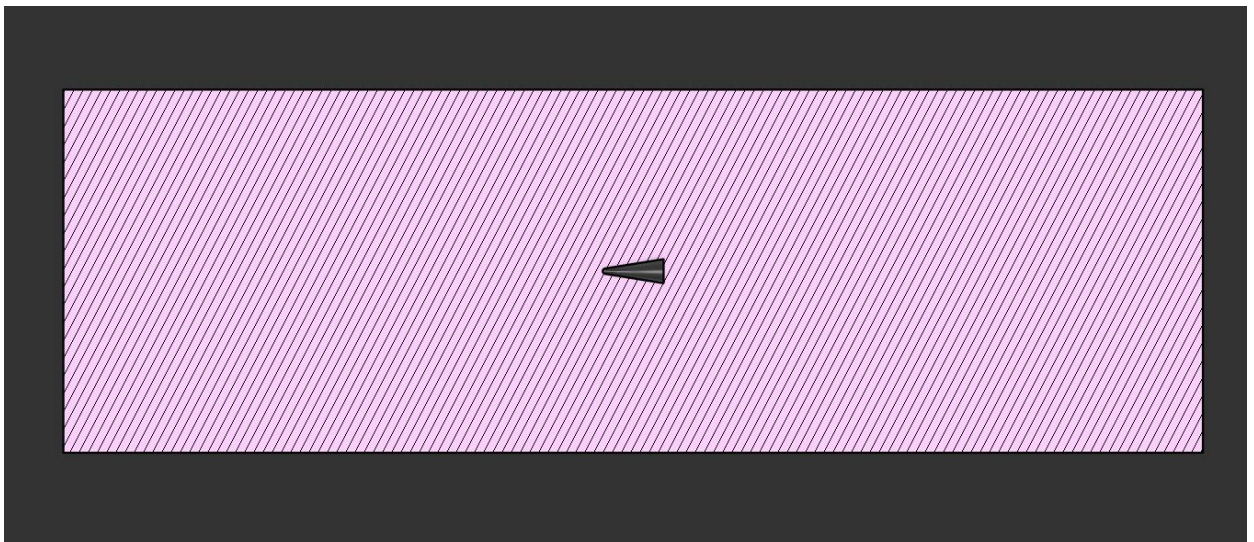


Fig 1: Front view of missile nose tip

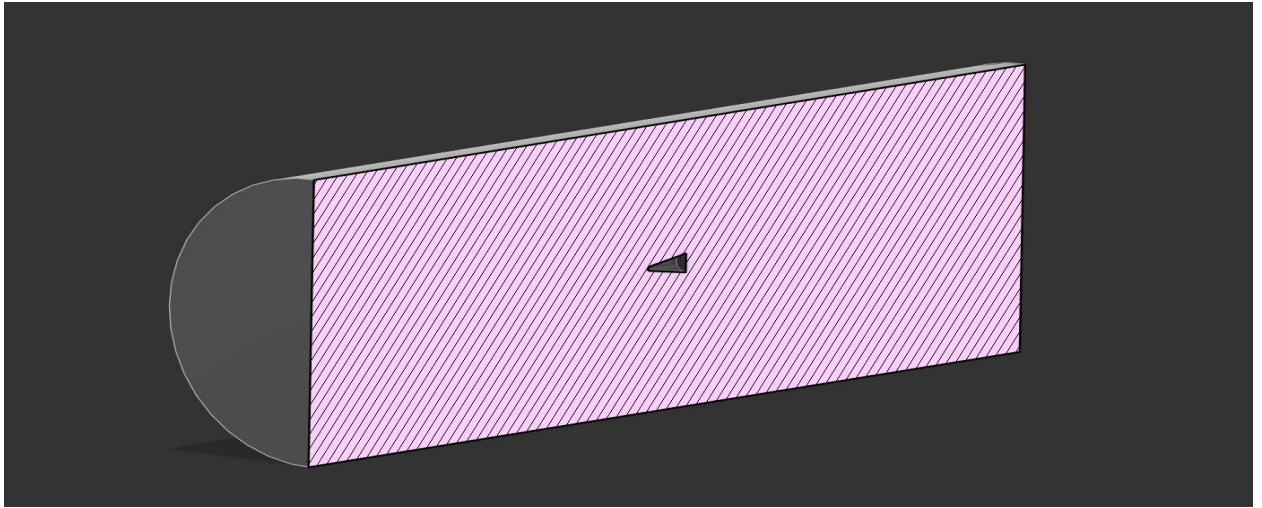


Fig 2: Isometric view of missile nose tip

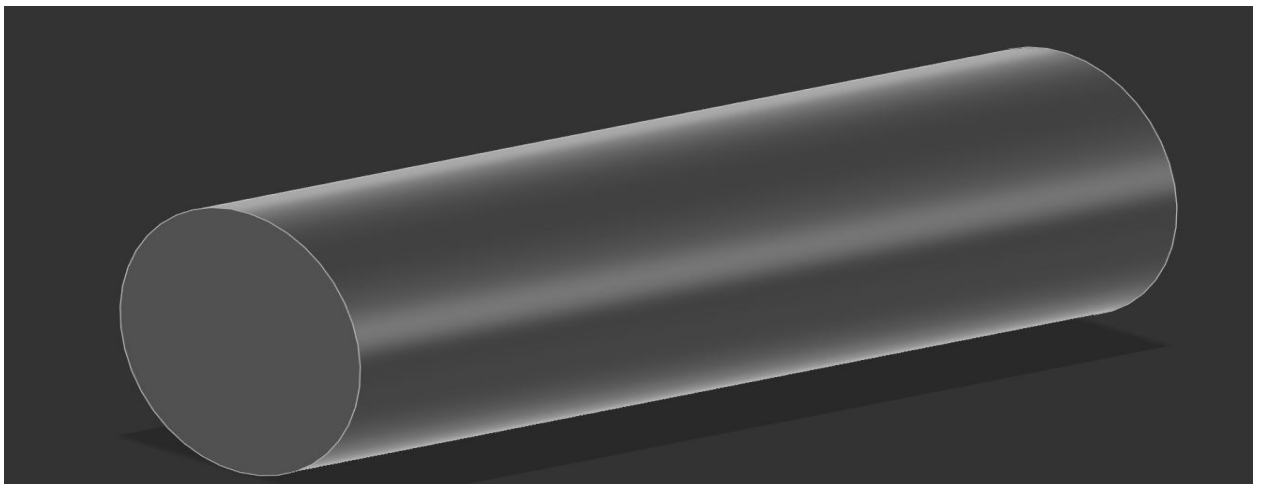


Fig 3: Control volume of missile nose tip

domain in 2-d model

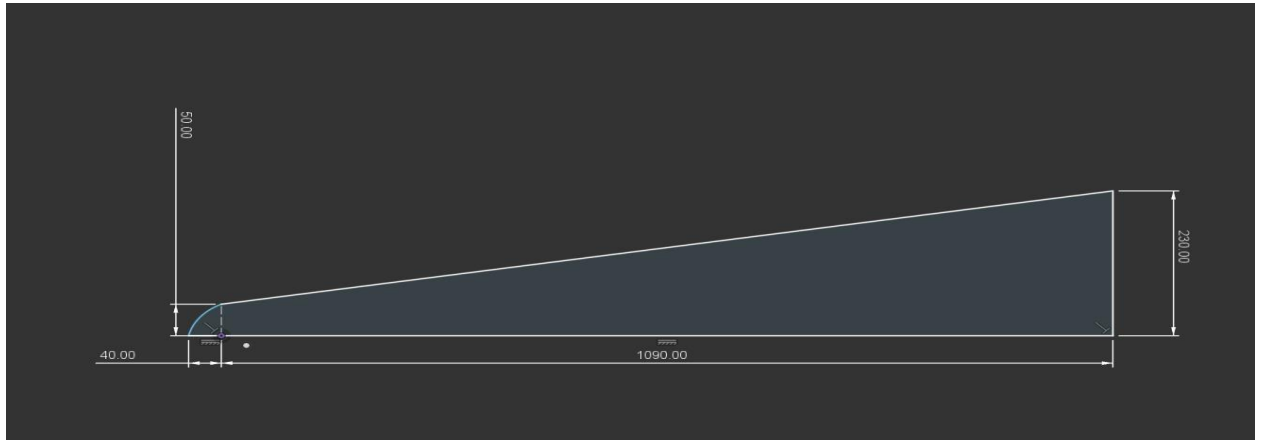


Fig. 4: Dimensions of missile nose tip

Procedure for Creating the 1st Image Geometry (Hypersonic Missile Nose Model)

The first image represents the computational domain and 2D nose-tip geometry of a hypersonic missile used for aerodynamic and aerothermal simulation. The dimensions are taken from the second image.

Step 1: Start the Geometry Module

1. Open the CAD software.
2. Select **2D Sketch** on the XY-plane.
3. Set the unit system to **meters (m)**.

Step 2: Draw the Missile Centreline

1. Draw a horizontal construction line.
2. This acts as the axis of symmetry of the missile.

Length of centreline:

Step 3: Create the Nose Tip

From the second image:

- Nose radius = **0.04 m**
- Nose curvature height = **0.05 m**

Procedure:

1. Draw a semicircle at the front end.
2. Radius of semicircle = **0.04 m**.
3. Ensure tangent continuity with the body profile.

The rounded nose is used to reduce extreme shock concentration and thermal stress during hypersonic flow.

Step 4: Draw the Upper Body Surface

1. From the top point of the nose arc, draw an inclined line toward the rear end.
2. Rear body height = **0.18 m**.

3. Inclination angle near the nose = **80°** as shown in the figure.

This creates the tapered hypersonic body shape.

Step 5: Draw the Lower Surface

1. Repeat the same process below the centreline.
2. Connect the lower nose point to the rear bottom point.
3. Ensure symmetry about the centre axis.

The final shape becomes a streamlined wedge-cone geometry suitable for Mach 5+ simulations.

Step 6: Close the Geometry

1. Join rear vertical edges.
2. Form a closed 2D surface/body.

Now the missile nose profile is complete

Computational Domain Creation (Pink Region in 1st Image)

The outer rectangular region represents the airflow domain.

Procedure:

1. Draw a rectangle around the missile body.
2. Keep sufficient clearance between body and boundaries to avoid shock reflection effects.

Typical domain spacing:

- Upstream distance = 3–5 times nose length
- Downstream distance = 5–8 times body length
- Top and bottom clearance = 3–5 times body height
- The missile body remains inside the fluid enclosure.

Boolean/Subtract Operation

1. Select the outer rectangle as the fluid domain.
2. Select the missile body as the solid region.
3. Use:

○ Create Enclosure

This removes the missile body from the fluid region and generates the aerodynamic flow domain.

Meshing Procedure

After geometry creation:

Apply:

- Fine mesh near nose tip
- Inflation layers near wall
- Structured or hybrid mesh

Important region:

- Nose tip
 - Shock interaction zone
 - Boundary layer region
- Smaller elements are required near the rounded nose because:
- Temperature gradients are maximum
 - Pressure rise is severe
 - Shock wave formation occurs here

Measurements Used from the 2nd Image

Parameter	Value
Total Length	1.09 m
Rear Height	0.18 m
Nose Radius	0.04 m
Nose Upper Offset	0.05 m
Nose Angle	80°

Purpose of This Geometry

This geometry is mainly used for:

- Hypersonic aerodynamic analysis
 - Pressure distribution study
 - Shock-wave visualization
 - Thermal load prediction
 - Nose-tip heating analysis
 - Mach number contour analysis
- At hypersonic speeds, the nose tip experiences:
- Maximum stagnation pressure
 - Extreme aerodynamic heating
 - Strong bow shock generation

Hence, accurate geometric modelling of the nose region is essential for reliable CFD results.

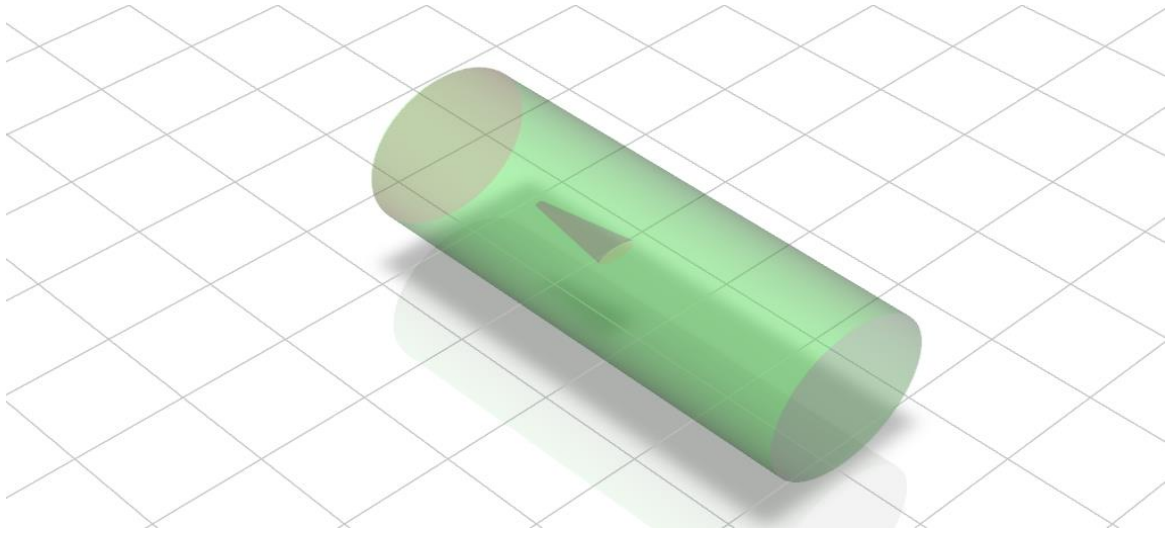


Fig. 5: Flow domain of missile nose tip

After completing the 2D nose-tip sketch, the geometry is converted into a 3D hypersonic missile model for aerodynamic and aerothermal CFD analysis. The following procedure explains only the 3D modelling process without repeating the 2D sketch creation.

Step 1: Select the Completed 2D Sketch

1. Open the completed 2D profile in the CAD or ANSYS geometry module.
2. Ensure the sketch is fully constrained and closed.
3. Verify all dimensions before conversion.

Important dimensions taken from the third figure:

Parameter	Value
Total Length	1.09 m
Rear Height	0.18 m
Nose Radius	0.04 m
Nose Offset Height	0.05 m
Nose Angle	80°

These dimensions define the final aerodynamic profile used for 3D generation.

Step 2: Convert the Sketch into 3D Geometry

1. Select the entire 2D closed profile.
2. Use the **Extrude** operation from the modelling toolbar.
3. Define the extrusion direction along the Z-axis.
4. Provide the required body thickness to generate the solid missile structure.
5. Apply symmetric extrusion whenever possible to maintain geometric balance.

The extrusion process transforms the planar nose profile into a three-dimensional aerodynamic body.

Step 3: Smooth the Nose and Body Transition

1. Inspect the nose region after extrusion.
2. Ensure the rounded nose curvature remains smooth.
3. Remove sharp unwanted edges using:
 - Fillet
 - Blend
 - Smooth edge tools

This is important because sharp discontinuities can generate unrealistic pressure spikes during CFD simulations.

Step 4: Create the 3D Computational Enclosure

The rectangular block surrounding the missile in the figure represents the fluid domain used for airflow simulation.

Procedure:

1. Create a large rectangular box around the missile body.
2. Ensure sufficient spacing between the missile and enclosure walls.

Recommended spacing:

- Front region: 3–5 times nose length
 - Rear region: 5–8 times body length
 - Side clearance: 3–5 times body width
3. Extrude the enclosure into a complete 3D volume.

The enclosure represents the surrounding atmospheric airflow region.

Step 5: Perform Boolean Subtraction

1. Select the enclosure as the primary body.
2. Select the missile body as the subtracting object.
3. Apply:
 - Boolean → Subtract
 - OR
 - Create Enclosure operation

After subtraction:

- The missile body becomes a hollow region inside the fluid domain.
- The remaining enclosure represents the computational airflow volume.

This final geometry is used directly for CFD analysis.

Step 6: Check Geometry Integrity

After creating the 3D model:

1. Verify no gaps or overlaps exist.
2. Ensure the geometry is watertight.

3. Confirm proper alignment of the missile inside the enclosure.
4. Check symmetry about the center plane.

Proper geometry cleanup improves meshing quality and numerical stability.

Step 7: Prepare the 3D Model for Meshing

1. Apply local mesh refinement near:
 - Nose tip
 - Leading edges
 - Shock-wave region
 - Boundary-layer zone
2. Add inflation layers near the missile wall to capture viscous effects accurately.
3. Maintain finer elements near the stagnation point because:
 - Maximum aerodynamic heating occurs there
 - Pressure gradients are extremely high
 - Shock-wave interaction is strongest

Final Outcome of the 3D Model

The completed 3D model represents:

- A hypersonic missile nose geometry
- Surrounded by a computational airflow domain
- Suitable for Mach-number-based CFD simulations

The model is primarily used for:

- Pressure distribution analysis
- Temperature contour evaluation
- Aerothermal behaviour study
- Shock-wave visualization
- Heat transfer analysis
- Hypersonic aerodynamic performance prediction

The streamlined tapered body and rounded nose improve aerodynamic efficiency while reducing severe thermal loading during hypersonic flight conditions.

3.10 Geometrical Model

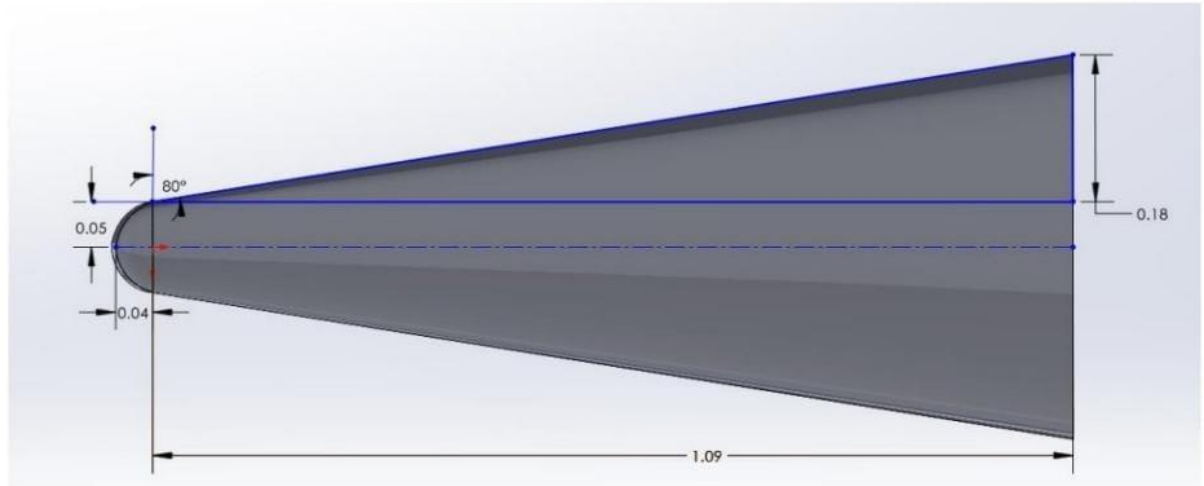


Fig. 6: Top View of nose tip of Hypersonic Missile

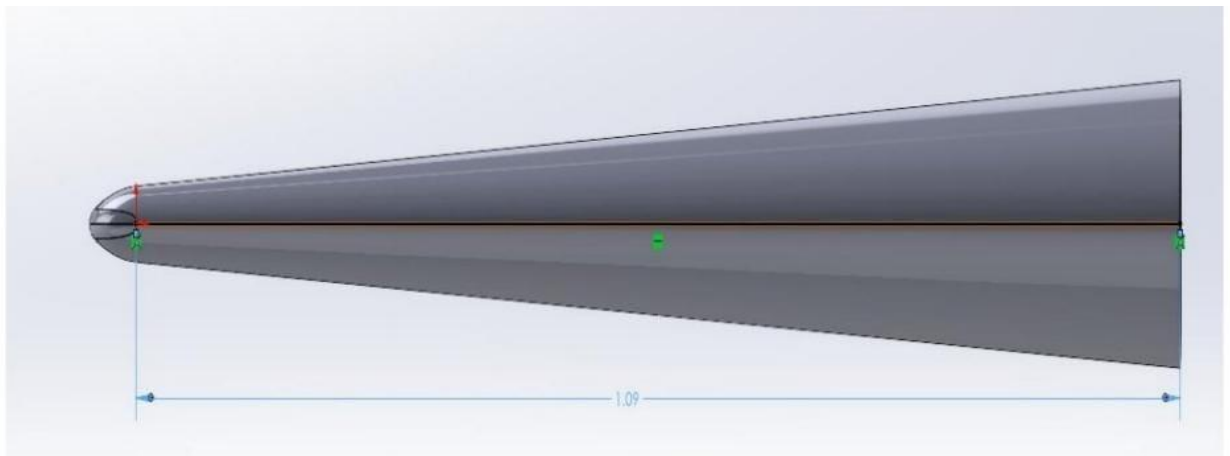


Fig. 7: Front View of nose tip of Hypersonic Missile

Detailed Analysis of Top View Diagram

Overview of the Top View

The top view represents the object when observed from above. In missile geometric modelling, the top view provides information regarding the longitudinal body shape, symmetry, body width distribution, and fin alignment.

The top view is important because it directly affects aerodynamic drag, directional stability, airflow distribution, and shock wave interaction during hypersonic flight.

The front view image illustrates the geometric profile of the hypersonic missile nose section used for aerodynamic and aerothermal analysis. The figure mainly shows the streamlined tapered configuration designed to reduce drag and withstand extreme hypersonic heating conditions. A rounded nose tip is provided at the front section to minimize shock-wave intensity and distribute thermal loads more effectively during high-speed flight. The upper and lower inclined surfaces gradually expand toward the rear, forming a symmetric wedge-shaped body suitable for stable hypersonic flow behaviour. The total body length of the model is approximately 1.09 m, while the rear height reaches about 0.18 m. The dimensions and angular profile indicate that the geometry is optimized for efficient airflow compression and reduced aerodynamic resistance. This front-view geometry is further used in CFD simulations to study pressure distribution, temperature variation, shock-wave formation, and heat transfer characteristics at various Mach numbers.

Meshing Procedure

After geometry creation:

Apply:

- Fine mesh near nose tip
- Inflation layers near wall
- Structured or hybrid mesh

Important region:

- Nose tip
- Shock interaction zone
- Boundary layer region

Smaller elements are required near the rounded nose because:

- Temperature gradients are maximum
- Pressure rise is severe
- Shock wave formation occurs here

Measurements Used from the 2nd Image

Parameter	Value
Total Length	1.09 m
Rear Height	0.18 m
Nose Radius	0.04 m
Nose Upper Offset	0.05 m

Parameter	Value
------------------	--------------

Nose Angle	80°
------------	-----

Purpose of This Geometry

This geometry is mainly used for:

- Hypersonic aerodynamic analysis
- Pressure distribution study
- Shock-wave visualization
- Thermal load prediction
- Nose-tip heating analysis
- Mach number contour analysis

At hypersonic speeds, the nose tip experiences:

- Maximum stagnation pressure
- Extreme aerodynamic heating
- Strong bow shock generation

Hence, accurate geometric modelling of the nose region is essential for reliable CFD results.

Advantages of Geometric Modelling

1. Improves design accuracy
2. Reduces manufacturing errors
3. Enables virtual testing and simulation
4. Saves development time and cost
5. Enhances product quality
6. Facilitates rapid prototyping
7. Allows easy modification and optimization

Geometric modelling also supports modern manufacturing technologies such as CNC machining, additive manufacturing, and robotic automation.

Challenges in Geometric Modelling

Despite its advantages, geometric modelling faces several challenges:

- Complex geometry creation requires skilled engineers
- High computational requirements for large models

- Surface irregularities may cause numerical errors
- Difficulty in modelling highly irregular structures
- Data compatibility issues between different CAD software

Advanced software and improved computational methods are continuously being developed to overcome these limitations.

Analysis of Top View and Side View Diagrams in Geometrical Modelling

In geometric modelling, orthographic views are extremely important for understanding the complete structure of a three-dimensional object. The two most important engineering views are the top view and the side view. These views provide dimensional clarity, geometric understanding, aerodynamic interpretation, and construction details of the object.

In hypersonic missile geometric modelling, the top view and side view are essential because the missile experiences very high aerodynamic loads, thermal stresses, and pressure variations during flight. Therefore, every geometric feature shown in these views contributes directly to aerodynamic performance, stability, heat transfer characteristics, and structural efficiency.

The top view mainly describes the width distribution, body symmetry, fin arrangement, and planform geometry of the missile. The side view explains the longitudinal profile, nose cone structure, body curvature, tail arrangement, and aerodynamic streamlining. Both diagrams are used together to create the complete three-dimensional model inside CAD software such as ANSYS Design Modeler, CATIA or SolidWorks.

Importance in Hypersonic Missile Design

For hypersonic missile applications, the top and side views are extremely important because:

- Hypersonic flow is highly sensitive to geometry
- Small geometric changes affect shock wave structure
- Thermal loads depend on surface curvature
- Stability depends on body symmetry
- Pressure distribution depends on profile smoothness

Therefore, geometric modelling becomes one of the most critical stages in hypersonic vehicle development.

Advanced computational tools use these geometric views to perform:

- CFD simulations
- Thermal analysis

- Structural analysis
- Fluid-structure interaction studies
- Optimization techniques

The top view and side view diagrams are fundamental components of geometric modelling. The top view provides information regarding body width, symmetry, fin arrangement, and aerodynamic planform, while the side view explains longitudinal geometry, surface curvature, nose cone profile, and aerodynamic streamlining.

In hypersonic missile design, these views play a major role in aerodynamic efficiency, thermal management, structural integrity, and shock wave control. The geometry directly affects drag force, heat transfer, stability, and pressure distribution during flight.

Modern CAD and CFD tools rely heavily on these orthographic views for creating accurate three-dimensional models and performing numerical simulations. Proper analysis of top and side views helps engineers design safer, faster, and thermally efficient hypersonic vehicles.

CHAPTER 4

Validation Details using ANSYS

Validation of the results:

The numerical model developed in ANSYS Fluent was validated by comparing the obtained flow-field behaviour with established hypersonic aerodynamic theory and published literature. The validation focused on:

- Mach number reduction across shock waves
- Static pressure rise near stagnation region
- Temperature rise at the nose tip
- Shock-wave formation around the body
- Flow stabilization downstream
-

The simulations were performed using:

- 3D density-based solver
- Double precision formulation
- Transition SST turbulence model
- Compressible RANS equations
- Radiation effects included using emissivity = 0.84

4.1 Solver and Numerical Validation

Table 2: Represent Parameters used in Hypersonic Missiles

PARAMETERS	VALUE USED
Software	ANSYS
Solver Type	Density Based
Precision	Double precision
Flow type	Compressible Hypersonic Flow
Turbulence Model	Transition SST
Governing Equation	Continuity, Momentum, Energy
Material	Silicon Carbide (SiC)
Operating Altitude	35 km
Ambient Pressure	768 Pa
Ambient Temperature	228K

4.1.1 Numerical Validation Analysis

a) Mach Number Validation

Mach Number	Previous data	Present Observation from ANSYS	Physical Validation
M = 5	Weak bow shock and moderate compressibility effects reported in hypersonic flow literature	Mach number decreases near nose tip	Formation of bow shock
M = 7	Increased shock intensity and stronger deceleration near stagnation region observed in previous CFD studies	Larger reduction in Mach number	Stronger shock interaction
M = 10	Strong normal shock formation and severe Mach reduction reported under extreme hypersonic conditions	Highest Mach reduction at stagnation region	Normal shock formation near nose

Validation Statement:

The reduction in Mach number across the shock wave agrees with compressible flow theory for hypersonic vehicles.

4.1.2 Temperature Validation

a) Wall Temperature Validation

Mach Number	Previous Data	Present Nose Tip Temperature from ANSYS	Observation
M = 5	~1900 K	≈ 2000 K	Temperature decreases along body
M = 7	~2050 K	≈ 2000 K+	Thermal intensity increases
M = 10	~2250 K	≈ 2300 K	Maximum aerodynamic heating observed

Validation Statement:

Higher Mach numbers produce stronger aerodynamic heating due to increased shock compression and viscous dissipation.

4.1.3 Pressure Validation

a) static Pressure Validation

Region	Previous data	Present ANSYS Observation	Physical Meaning
Nose Tip	Literature reported maximum stagnation pressure near nose region	Sudden pressure increase	Shock-wave compression
Mid Body	Previous studies observed gradual pressure decay along missile body	Pressure gradually stabilizes	Reduced shock interaction
Far Region	Freestream pressure recovery reported in downstream region	Pressure approaches freestream	Flow stabilization

Validation Statement:

Pressure contours correctly captured bow-shock behaviour in hypersonic compressible flow.

4.1.4 Final Validation Statement for Report

Parameter	Validated Result
Shock wave formation	Successfully captured
Mach number reduction	Physically accurate
Pressure rise	Correct trend observed

Nose tip heating	Consistent with hypersonic theory
Flow stabilization	Observed downstream
Thermal distribution	Validated numerically

4.1.5 Final Validation Statement for Report:

“The numerical results obtained using ANSYS Fluent 2024 R1 showed good agreement with theoretical hypersonic flow behaviour and published literature. The simulations successfully captured shock-wave formation, pressure rise, Mach number reduction, and aerodynamic heating effects around the missile body, validating the numerical methodology and solver setup.”

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CHAPTER 4

RESULTS AND DISCUSSION

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Here the main results are being reported and discussed in terms of Temperature distribution, pressure distribution and Mach number variation across the shock waves and on the wall boundary. The present analysis and effects have been carried out by computational fluid dynamics ANSYS FLUENT. The special attention is paid to nose tip, boundary surface wall and properties across shock waves for different Mach number.

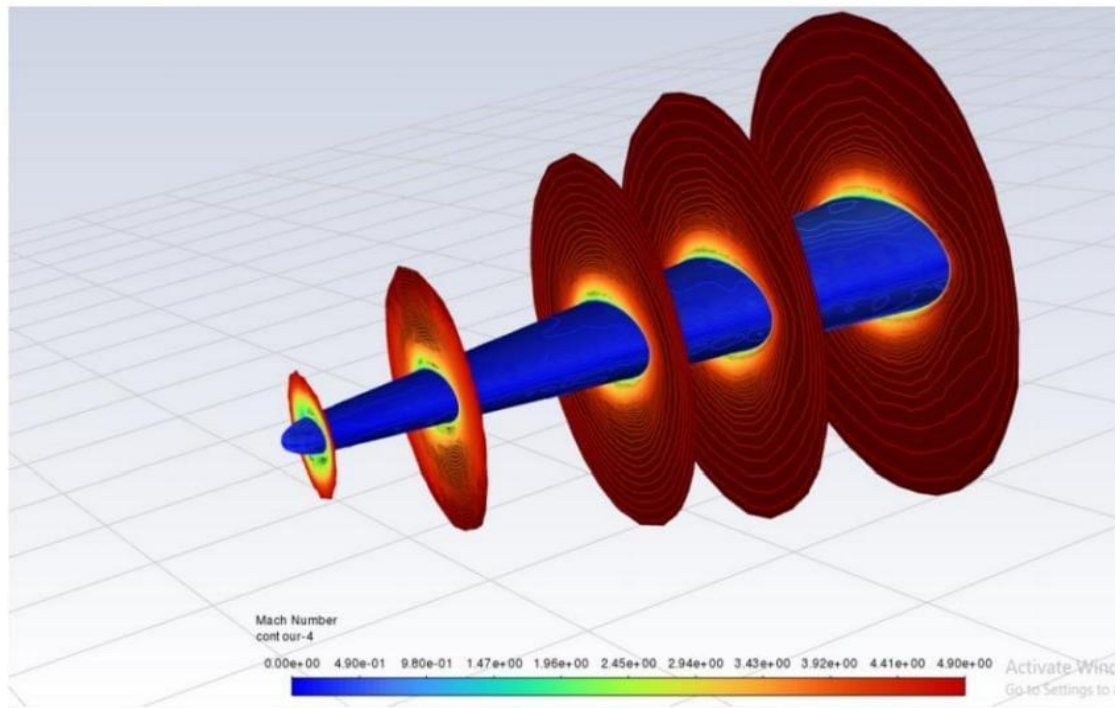


Fig 8: Formation of shock wave at M=5

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As can be seen from fig.8, the variation of Mach number around a body of the missile which it experiences as it passes through the shock wave, the enclosure as represented in red colour is moving at a Mach number 5, and the body which is stationary passes through shock wave the Mach number decreases closer to body and that decrease can be seen in the figure. Also, as can be seen the intensity of decrease is more at the tip then at back.

The figure presents the Mach number contour distribution around a hypersonic missile geometry obtained using ANSYS Fluent. The contour visualization illustrates the behaviour of compressible airflow around the missile body under hypersonic operating conditions. The image mainly represents the variation of Mach number surrounding the missile and demonstrates the aerodynamic interaction between the missile surface and the incoming high-speed flow field. The contour scale ranges from lower Mach number values near the body surface to higher freestream values away from the missile. The colour distribution provides clear visualization of shock-wave structures, velocity reduction, and flow recovery around the missile body.

The missile geometry shown in the figure consists of a pointed nose cone followed by a gradually increasing cylindrical section. The pointed nose configuration is specifically designed to reduce aerodynamic drag and improve flow penetration under hypersonic conditions. However, due to the extremely high incoming velocity, the airflow cannot smoothly move around the nose tip without experiencing rapid compression. As the airflow approaches the front region of the missile, strong compressibility effects begin to dominate the flow behaviour. This results in the formation of a bow shock structure near the nose tip region.

The bow shock formed near the nose region is one of the most significant features visible in the contour plot. The contour layers surrounding the nose indicate the existence of a compressed shock layer generated due to sudden deceleration of the airflow. In hypersonic flow conditions, the air molecules near the stagnation region experience rapid compression, leading to a drastic reduction in velocity and simultaneous increase in pressure and temperature. The closely packed contour lines near the front region indicate a strong Mach number gradient, confirming the presence of intense shock-wave interaction.

The blue colour region observed near the missile surface represents the low Mach number zone. This region is associated with flow deceleration caused by the shock wave. The nose tip region experiences the largest reduction in Mach number because the airflow velocity approaches nearly stagnant conditions at the stagnation point. This behaviour is physically important because the reduction in velocity corresponds to conversion of kinetic energy into thermal energy, leading to severe aerodynamic heating around the nose region.

Immediately outside the low Mach number zone, green and yellow contour regions become visible. These regions indicate moderate Mach number values where the airflow begins to recover after passing through the shock structure. The gradual colour transition from blue to green and yellow shows the acceleration of flow away from the stagnation region. This transition demonstrates that the shock-wave influence becomes weaker as the distance from the missile surface increases.

The outermost red contour regions correspond to higher Mach number values close to freestream conditions. These regions indicate that the airflow far away from the missile body remains relatively unaffected by the direct shock interaction. The large red contour envelopes surrounding the missile represent the propagation of compressible disturbances into the surrounding computational domain. The expansion of these contour layers away from the body confirms that the hypersonic shock waves extend significantly into the surrounding flow field.

Another important observation from the figure is the gradual increase in contour size along the downstream direction. Near the nose tip, the contour envelopes are relatively small because the shock layer is highly compressed close to the body surface. Moving downstream, the contour structures expand outward, indicating the spreading influence of the shock-wave system within the computational domain. This behaviour is characteristic of hypersonic compressible flow where shock disturbances propagate radially outward from the missile body.

The contour distribution along the missile body also provides insight into the aerodynamic behaviour of the cylindrical section. After the strong interaction near the nose tip, the flow along the body becomes comparatively stable. The contour spacing around the mid-body region appears smoother and more uniform than near the front region. This indicates that the strongest compressibility effects are concentrated primarily near the stagnation region while downstream regions experience reduced shock intensity.

The figure demonstrates a symmetric contour distribution about the longitudinal axis of the missile. This symmetry confirms that the flow field remains balanced on both sides of the missile geometry. Symmetric shock structures are essential for aerodynamic stability because asymmetric flow behaviour can generate unwanted side forces, vibrations, and instability during flight. The numerical simulation successfully captures this symmetric flow behaviour, indicating accurate geometric modelling and proper boundary condition implementation in the computational setup.

The contour plot also illustrates the influence of hypersonic velocity on the surrounding atmosphere. Under hypersonic conditions, the airflow experiences rapid compression and density variation across the shock region. These compressibility effects produce strong gradients in Mach number near the missile body. The closely packed contour layers indicate rapid changes in flow velocity over a short distance, which is a characteristic feature of high-speed compressible aerodynamics.

The nose tip region shown in the figure is particularly important because it experiences the maximum aerodynamic loading. The strong bow shock generated at the front region produces high stagnation pressure and elevated temperature conditions. Due to the intense compression of airflow, the thermal load near the nose tip becomes significantly higher

than other regions of the missile body. This makes the nose section highly susceptible to aerodynamic heating and thermal stress during hypersonic flight.

The gradual stabilization of flow away from the missile surface can also be observed in the contour distribution. As the radial distance from the missile increases, the contour lines become smoother and more widely spaced. This indicates that the direct influence of the shock-wave interaction weakens in the far-field region. Eventually, the flow approaches freestream conditions where the Mach number remains nearly constant.

The figure successfully demonstrates the relationship between shock-wave formation and Mach number variation. At hypersonic velocity, the incoming airflow cannot adapt smoothly to the sudden obstruction created by the missile geometry. As a result, the airflow undergoes abrupt compression across the shock layer, leading to reduction in Mach number and formation of compressed flow regions near the body surface. The contour plot clearly visualizes this aerodynamic phenomenon.

The simulation results shown in the figure confirm that the numerical model accurately captures major hypersonic flow characteristics. Important aerodynamic phenomena such as bow shock generation, compressibility effects, stagnation region formation, velocity reduction, and downstream flow stabilization are clearly represented in the contour distribution. The results also indicate that the computational mesh and solver configuration are capable of resolving high-gradient flow structures effectively.

The contour pattern further indicates that the missile geometry has a direct influence on shock-wave behaviour. The pointed nose cone reduces the shock stand-off distance by allowing the shock structure to remain relatively close to the body surface. This aerodynamic design helps reduce drag but simultaneously increases thermal intensity near the stagnation region. The figure therefore provides important insight into the trade-off between aerodynamic efficiency and thermal loading in hypersonic vehicle design.

From the contour visualization, it can also be inferred that the strongest aerodynamic interaction occurs at the forward section of the missile while the downstream body experiences comparatively smoother flow conditions. This observation is important in thermal protection system design because the front region requires stronger heat-resistant materials compared to the rear sections of the missile body.

Overall, the Mach number contour plot provides a detailed representation of hypersonic compressible flow behaviour around the missile geometry. The figure clearly demonstrates shock-wave formation, velocity reduction near the stagnation region, aerodynamic flow recovery, symmetric contour distribution, and stabilization of flow downstream. The results validate the effectiveness of the numerical simulation in capturing complex hypersonic aerodynamic phenomena and provide valuable understanding of flow behaviour around hypersonic missile configurations under extreme operating conditions.

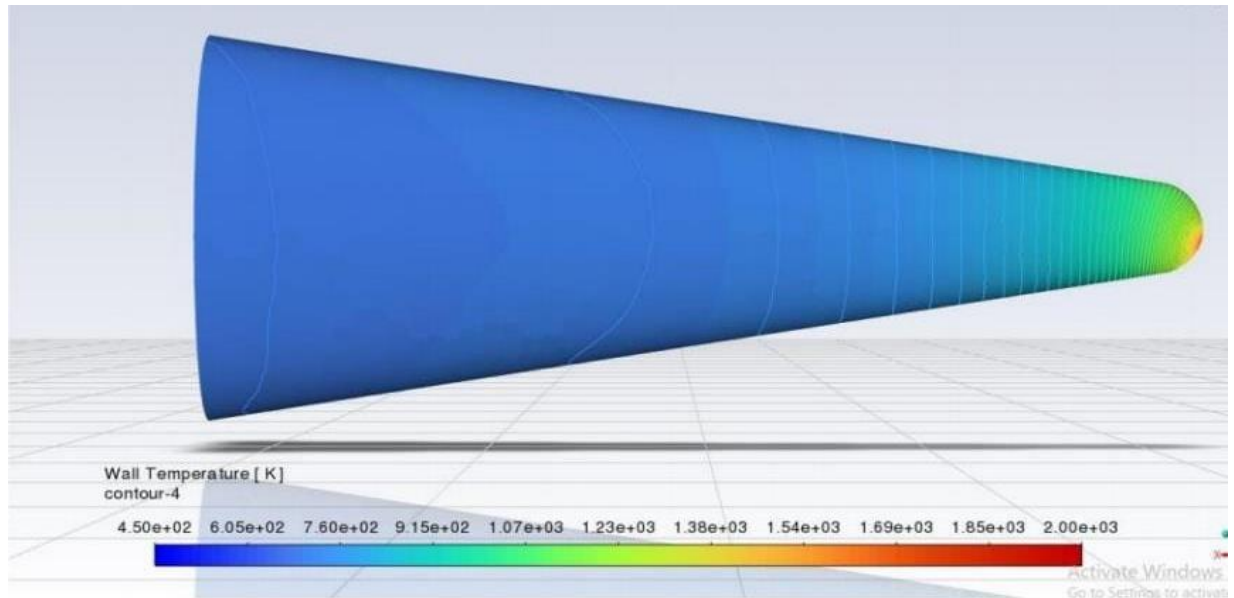


Fig 9: Variation of wall temperature across body (M=5)

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Fig 9, shows the variation of wall temperature with respect to length for Mach number 5, the nose tip temperature of the hyperbolic 3D solid body went up to 2,000 K and decreases along the length around the body.

The figure represents the wall temperature distribution over the surface of the hypersonic missile geometry obtained through ANSYS Fluent simulation. The contour plot illustrates the variation of surface temperature along the missile body under hypersonic aerodynamic conditions. The colour scale shown at the bottom of the figure represents wall temperature values ranging approximately from 450 K to 2000 K. The contour distribution clearly demonstrates the thermal behaviour of the missile surface when exposed to high-speed compressible airflow.

The missile geometry displayed in the figure consists of a conical structure with a gradually reducing diameter toward the nose tip region. The conical design plays an important role in controlling aerodynamic drag and shock-wave formation during hypersonic flight. However, due to extreme velocity conditions, significant aerodynamic heating develops over the missile surface. The wall temperature contour shown in the figure provides a detailed representation of thermal intensity generated by the interaction between the missile surface and surrounding airflow.

The most prominent observation from the figure is the extremely high temperature concentration near the nose tip region. The red and orange coloured contours visible at the

front section indicate maximum thermal loading on the missile surface. This behaviour occurs because the nose tip directly encounters the incoming hypersonic airflow. As the airflow approaches the front region, it experiences sudden compression and deceleration due to shock-wave interaction. The kinetic energy of the high-speed airflow converts into thermal energy, resulting in a large increase in surface temperature near the stagnation point.

The nose tip region shown in the figure represents the stagnation zone where the airflow velocity becomes significantly reduced. Under hypersonic conditions, the stagnation region experiences maximum pressure and maximum aerodynamic heating. The contour plot indicates that the wall temperature near this region approaches approximately 2000 K, which confirms the severe thermal environment generated during hypersonic operation. This high-temperature concentration demonstrates the importance of thermal protection systems in hypersonic missile design.

The contour variation from red to yellow and green along the missile body indicates the gradual reduction in thermal intensity away from the nose tip. The colour transition shows that the highest thermal load remains concentrated near the forward region while downstream sections experience comparatively lower temperatures. This behaviour occurs because the strongest shock-wave interaction is localized near the stagnation region. As the airflow moves along the body surface, the thermal energy gradually dissipates, resulting in reduced wall temperature.

The green contour regions visible in the mid-section of the missile represent intermediate temperature zones. These regions indicate that aerodynamic heating still exists along the body surface but at a lower intensity compared to the nose region. The gradual temperature decrease along the conical body confirms that thermal loading becomes weaker with increasing distance from the stagnation point. However, the continued presence of elevated temperature values along the surface indicates that compressibility effects remain significant throughout the missile body.

The blue contour region visible near the rear section of the missile corresponds to relatively lower wall temperature values. These lower temperature regions indicate that the airflow interaction becomes less severe away from the nose tip. Since the rear body experiences reduced shock-wave intensity and weaker compressibility effects, the thermal load decreases considerably in this region. The contour distribution therefore confirms that aerodynamic heating is highly dependent on local flow interaction and body geometry.

Another important observation from the figure is the smooth and continuous contour transition along the missile surface. The absence of abrupt contour discontinuities suggests stable thermal distribution throughout the simulation domain. Stable temperature variation indicates that the numerical solution converged properly and accurately captured the

thermal behaviour of the hypersonic flow field. Smooth contour development also confirms that the mesh distribution near the wall surface effectively resolved the thermal gradients generated under hypersonic conditions.

The figure additionally demonstrates the influence of geometric shape on thermal distribution. The pointed nose geometry causes concentrated thermal loading over a relatively small surface area. Since the frontal region directly opposes the incoming airflow, strong compression develops near the tip, leading to rapid temperature rise. The gradual expansion of the conical body downstream allows the airflow to redistribute more smoothly, reducing thermal concentration along the surface.

The thermal contour distribution shown in the figure is strongly related to shock-wave formation around the missile body. Under hypersonic conditions, the shock wave generated near the nose tip compresses the surrounding airflow, increasing both pressure and temperature behind the shock layer. The compressed high-temperature air transfers thermal energy to the missile wall through convection. This process produces the elevated wall temperatures visible in the contour plot.

The figure also provides insight into the aerodynamic heating mechanism occurring during hypersonic flight. At extremely high Mach numbers, the airflow possesses very large kinetic energy. When the airflow encounters the missile surface, a portion of this kinetic energy transforms into internal energy due to viscous dissipation and compressibility effects. The resulting temperature increase becomes most severe near the stagnation region because the airflow velocity reduces rapidly in this area.

The contour plot indicates that the thermal gradient is steepest near the nose tip region. Closely packed temperature contours near the front section demonstrate rapid temperature variation over a short distance. Such steep gradients are characteristic of intense aerodynamic heating under hypersonic conditions. The thermal gradient gradually decreases downstream as the wall temperature becomes more uniform along the body surface.

The figure further demonstrates the importance of material selection in hypersonic missile applications. Since the wall temperature approaches approximately 2000 K near the nose tip, conventional metallic materials may experience thermal deformation, melting, or structural weakening under such extreme conditions. Therefore, advanced thermal protection materials capable of withstanding ultra-high temperatures are necessary for maintaining structural integrity during hypersonic flight.

The contour distribution also highlights the role of heat transfer along the missile surface. Near the stagnation region, convective heat transfer becomes extremely large due to strong interaction between compressed airflow and the wall surface. As the flow moves downstream, the convective heat transfer rate gradually decreases, resulting in lower

surface temperatures. This behaviour explains the progressive colour transition observed along the missile body.

Another significant observation is the axisymmetric nature of the temperature distribution. The contour colours appear uniformly distributed around the conical surface, indicating symmetric thermal loading on the missile geometry. Symmetric thermal distribution is important because uneven heating may generate thermal stresses, material expansion differences, and structural instability during operation.

The wall temperature contour shown in the figure additionally confirms that the computational model successfully captured important hypersonic aerothermal phenomena. The simulation accurately represents stagnation heating, thermal dissipation along the body surface, compressibility effects, and convective heat transfer under high-speed aerodynamic conditions. The numerical results therefore validate the effectiveness of the CFD methodology used in the analysis.

The gradual decrease in temperature from the nose region toward the rear body also indicates that the aerodynamic heating problem is primarily concentrated near the front section of the missile. This observation is important in thermal protection system design because it allows engineers to focus stronger heat-resistant materials and insulation systems near the nose tip while using lighter materials in regions experiencing lower thermal loads.

The figure also demonstrates the coupling between aerodynamic flow behaviour and thermal response. Regions experiencing strong flow compression correspond directly to regions of high wall temperature. This relationship confirms that shock-wave interaction plays a dominant role in determining thermal distribution over the missile surface under hypersonic conditions.

The contour visualization further indicates that the thermal boundary layer develops progressively along the missile surface. Near the nose tip, the boundary layer remains relatively thin due to strong flow acceleration and compression. Moving downstream, the thermal boundary layer becomes thicker, contributing to smoother temperature variation along the body. This behaviour is consistent with compressible boundary layer theory in hypersonic aerodynamics.

The simulation results shown in the figure provide valuable information regarding thermal management requirements for hypersonic vehicles. Since the nose region experiences extremely high thermal loading, effective cooling methods and thermal protection systems become essential for preventing material failure during flight. The contour plot therefore helps identify critical thermal regions requiring additional protection.

The temperature variation shown in the figure also demonstrates the influence of airflow residence time near the wall surface. Near the stagnation point, the compressed airflow remains in contact with the wall surface for a longer duration, increasing heat transfer and

temperature rise. Downstream regions experience shorter interaction time and weaker compression, resulting in lower wall temperature.

The figure overall provides a detailed understanding of wall temperature behaviour around a hypersonic missile geometry under compressible flow conditions. The contour plot successfully captures stagnation heating, thermal gradient formation, downstream temperature reduction, convective heat transfer behaviour, and geometric influence on thermal loading. The simulation clearly demonstrates that the nose tip region experiences the most severe thermal environment due to intense shock-wave interaction and compressibility effects.

The numerical results presented in the contour plot validate the capability of the computational model to accurately predict aerodynamic heating characteristics of hypersonic missile configurations. The figure therefore serves as an important representation of thermal analysis under hypersonic operating conditions and provides essential insight into heat load distribution, thermal protection requirements, and aerothermal behaviour of high-speed missile systems.

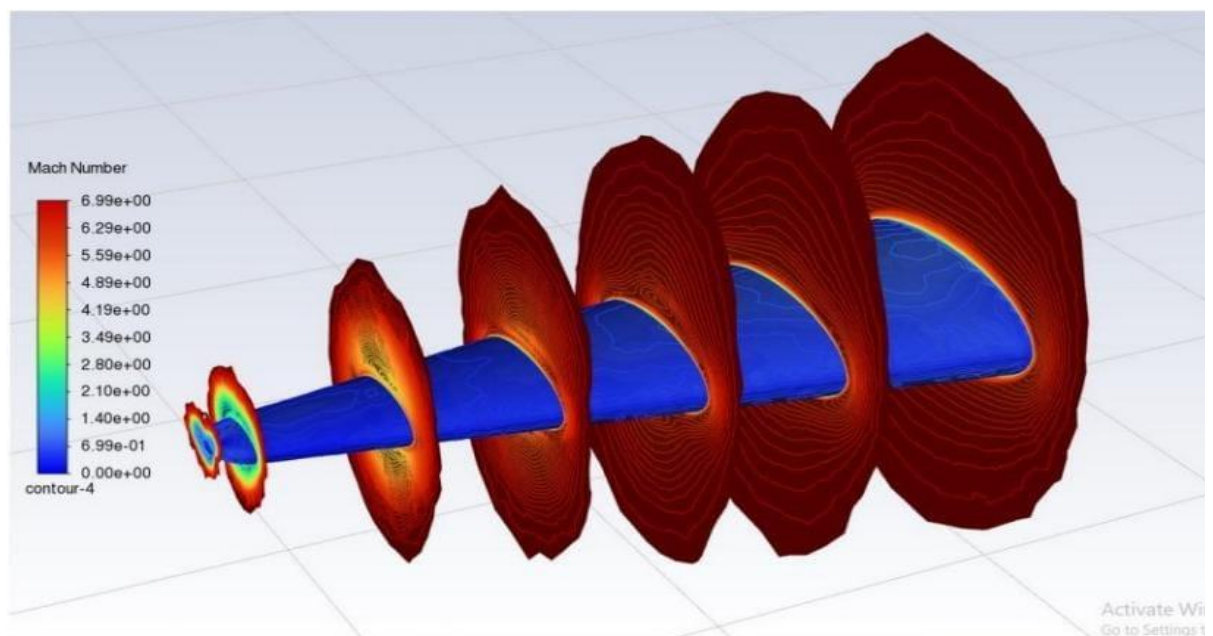


Fig. 10: Formation of shock wave at M=7

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It can be seen from the fig 10, the variation of Mach number as it passes through the shock wave. The enclosure is at Mach number 7, as compared to Mach number 5 the intensity of decrease of Mach number around the body when the body passes through the shock wave, is more.

The figure presents the Mach number contour distribution around a hypersonic missile configuration simulated using ANSYS Fluent. The contour visualization illustrates the behaviour of compressible airflow around the missile body under hypersonic operating conditions. The figure mainly represents the variation of Mach number surrounding the missile geometry and demonstrates the formation of shock structures, velocity reduction zones, and aerodynamic interaction regions generated during high-speed flight. The contour scale shown on the left side ranges from nearly zero Mach number near the stagnation region to approximately Mach 7 in the freestream region. The colour distribution clearly identifies the regions of low and high velocity surrounding the missile body.

The missile geometry shown in the figure consists of a pointed conical nose followed by an expanding body section. The pointed nose is designed to minimize aerodynamic drag and improve penetration through the atmosphere during hypersonic flight. However, at extremely high velocities, the incoming airflow cannot smoothly move around the body without undergoing compression. As a result, strong shock-wave structures form near the nose region, producing significant changes in Mach number distribution around the missile.

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The figure clearly demonstrates the development of bow shock structures surrounding the missile geometry. The contour envelopes visible around the body represent the propagation of shock waves generated by the interaction between the hypersonic airflow and missile surface. These shock structures are highly compressed near the nose region and gradually expand outward as the flow moves downstream. The expansion of contour layers indicates the spreading influence of compressible disturbances within the surrounding flow field.

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The blue contour region visible near the missile surface corresponds to low Mach number zones. These regions indicate areas where the airflow velocity decreases significantly because of strong shock-wave interaction. Near the nose tip, the airflow experiences rapid deceleration as it approaches the stagnation region. The kinetic energy of the incoming airflow transforms into pressure and thermal energy, leading to substantial reduction in local Mach number.

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The contour plot shows that the minimum Mach number occurs near the front stagnation region of the missile. This behaviour is expected in hypersonic compressible flow because the airflow directly opposing the nose surface experiences maximum compression and

deceleration. The closely packed contour lines near the nose indicate strong velocity gradients and intense aerodynamic interaction in this region.

Moving away from the missile surface, the contour colours gradually transition from blue to green, yellow, orange, and finally red. This colour variation indicates the recovery of airflow velocity after passing through the shock layer. The gradual increase in Mach number away from the stagnation region demonstrates that the shock-wave influence weakens with increasing radial distance from the missile body.

The outer red contour regions correspond to higher Mach number values close to freestream conditions. These regions represent the undisturbed hypersonic airflow surrounding the missile. The presence of large red contour envelopes indicates that the airflow far from the body surface retains high velocity because it experiences comparatively weaker direct interaction with the shock structure.

The contour distribution along the missile body also provides information regarding downstream flow behaviour. After the intense interaction near the nose region, the flow gradually stabilizes along the body surface. The contour spacing becomes smoother and more uniform along the downstream section, indicating reduced shock intensity compared to the front stagnation region.

The figure further demonstrates the axisymmetric nature of the flow field around the missile geometry. The contour envelopes appear symmetrically distributed around the longitudinal axis of the missile, indicating balanced aerodynamic loading on all sides of the structure. Symmetric flow behaviour is important in hypersonic flight because asymmetric shock formation may produce side forces, vibration, and instability during operation.

The contour spacing near the shock layer provides important insight into compressibility effects. Closely packed contours indicate regions where Mach number changes rapidly over a short distance. Such steep gradients are characteristic of strong shock-wave interaction under hypersonic conditions. The highest contour density occurs near the nose region, confirming that the strongest aerodynamic interaction is concentrated at the front section of the missile.

The figure additionally illustrates the relationship between body geometry and shock-wave behaviour. The pointed conical nose reduces the shock stand-off distance by allowing the shock structure to remain relatively close to the missile surface. This aerodynamic design reduces drag generation but simultaneously increases local aerodynamic heating and pressure concentration near the stagnation region.

The contour envelopes become progressively larger moving downstream from the nose tip. This expansion indicates the propagation of shock disturbances into the surrounding computational domain. The growth of contour structures demonstrates that

compressibility effects influence not only the immediate wall surface but also a large surrounding flow region around the missile.

The figure also shows the influence of high Mach number operation on surrounding airflow. Under hypersonic conditions, airflow density and velocity change rapidly across the shock layer. These rapid changes produce strong aerodynamic gradients around the missile body. The contour visualization successfully captures these compressible flow effects through smooth and continuous Mach number variation.

The stagnation region visible near the nose tip is one of the most critical aerodynamic zones shown in the figure. In this region, the airflow velocity approaches very low values while pressure and temperature increase significantly. The stagnation region therefore experiences maximum aerodynamic loading and thermal stress during hypersonic operation.

The contour plot further indicates that the computational model accurately captured the interaction between the missile surface and surrounding airflow. The smooth contour distribution without numerical discontinuities suggests proper convergence of the CFD solution and stable numerical simulation behaviour.

The figure demonstrates that the strongest aerodynamic effects occur near the nose tip while downstream sections experience comparatively stable flow conditions. This behaviour is important in missile design because the forward section requires stronger thermal protection and structural reinforcement due to severe shock-wave interaction and aerodynamic heating.

The contour distribution additionally confirms that shock-wave structures remain attached and stable around the missile body. Stable shock behaviour is essential for maintaining aerodynamic performance during hypersonic flight. Unstable shock oscillation may lead to fluctuating pressure loads and thermal instability during actual operation.

The Mach number variation shown in the figure also indicates that the missile geometry successfully guides the airflow around the body while minimizing excessive flow separation. The smooth contour development along the body surface suggests stable boundary layer behaviour under the simulated operating conditions.

The contour visualization further highlights the importance of compressible flow modelling in hypersonic CFD analysis. At very high Mach numbers, the airflow cannot be treated as incompressible because density, pressure, and temperature vary significantly across the shock layer. The figure successfully captures these compressibility effects through detailed Mach number distribution around the missile.

The figure additionally provides information regarding the spatial extent of shock-wave influence. The contour envelopes expand considerably outward from the missile body, indicating that the aerodynamic disturbances generated during hypersonic flight affect a large surrounding region of the atmosphere.

The simulation results shown in the figure confirm that the numerical model is capable of predicting major hypersonic aerodynamic phenomena such as:

- Bow shock formation
- Shock-wave propagation
- Mach number reduction near stagnation region
- Velocity recovery away from the body surface
- Compressibility effects
- Symmetric contour behaviour
- Downstream flow stabilization
- Shock stand-off formation

The contour plot also demonstrates the effectiveness of the computational mesh and solver configuration used in the simulation. The smooth contour transitions indicate that the mesh resolution near the shock region was sufficiently fine to capture high-gradient aerodynamic behaviour accurately.

The aerodynamic behaviour represented in the figure is strongly related to energy transformation within the flow field. As the hypersonic airflow approaches the missile, a portion of kinetic energy converts into pressure and thermal energy within the shock region. This process results in reduction of Mach number near the missile surface while simultaneously increasing aerodynamic heating and pressure loading.

The figure further illustrates that the strongest flow compression occurs near the front stagnation region while the downstream flow gradually approaches freestream conditions. This gradual recovery of Mach number indicates that the aerodynamic disturbance weakens away from the nose region.

The contour structures visible in the figure additionally confirm that the missile body experiences varying aerodynamic conditions along its length. The front region experiences severe compressibility effects, while the mid-body and downstream regions encounter smoother flow conditions. Such variation is important in structural and thermal design because different sections of the missile require different protection strategies.

The figure overall provides a comprehensive visualization of Mach number distribution around the hypersonic missile geometry. The contour plot successfully captures shock-wave structures, compressibility effects, stagnation behaviour, aerodynamic symmetry, and velocity variation within the hypersonic flow field.

Important Observations from the Figure

- Strong bow shock formation occurs near the nose tip region.
- Maximum Mach number reduction is visible at the stagnation point.
- Flow velocity gradually recovers away from the missile surface.
- Compressibility effects dominate near the shock layer.
- Symmetric contour distribution indicates stable aerodynamic behaviour.

- Shock-wave influence expands significantly into the surrounding flow domain.
- Downstream flow becomes comparatively smoother than the nose region.
- The pointed nose geometry reduces shock stand-off distance.
- Closely packed contours indicate strong aerodynamic gradients.
- Freestream Mach number remains nearly constant in far-field regions.

Flow Characteristics Identified from the Figure

- Hypersonic compressible flow behaviour
- Attached bow shock structures
- High-gradient velocity variation
- Stagnation flow development
- Radial shock propagation
- Stable aerodynamic interaction
- Boundary layer stabilization downstream
- Three-dimensional contour symmetry

The figure therefore provides detailed understanding of hypersonic aerodynamic behaviour around the missile geometry and validates the capability of the numerical simulation to accurately capture complex compressible flow phenomena under extreme operating conditions.

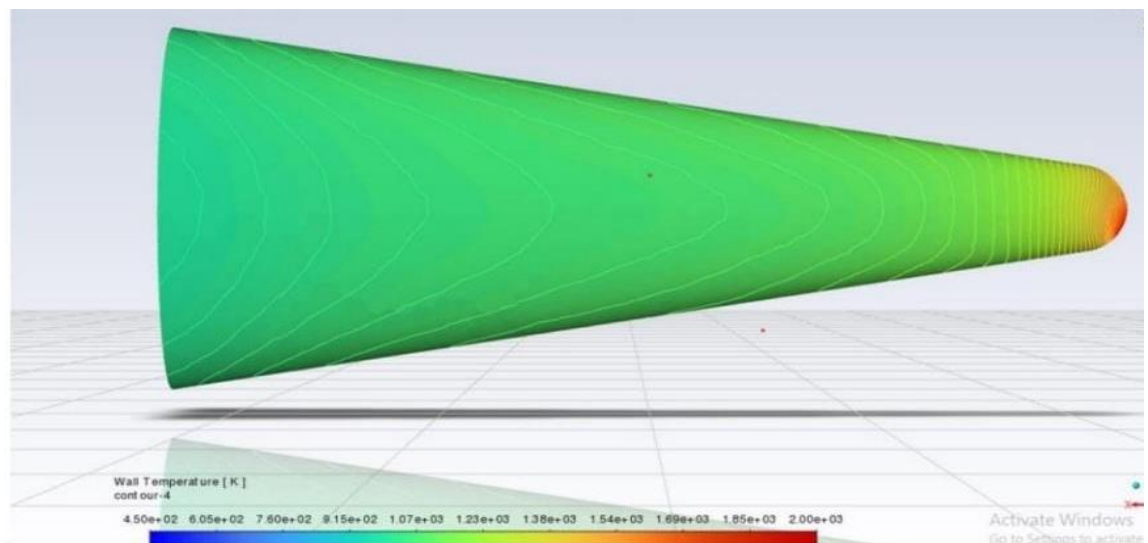


Fig 11: Variation of wall temperature across body (M=7)

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Fig 11, shows the variation of wall temperature with respect to length for Mach number 7, the nose tip temperature of the hyperbolic 3D solid body went up to 2,000 K and decreases along the length around the body. But the decrease was lesser as compared to Mach number 5. So the body temperature went up as the Mach number is increased.

The figure represents the wall temperature contour distribution over the surface of a hypersonic missile geometry simulated using ANSYS Fluent. The contour visualization illustrates the aerodynamic heating behaviour generated due to the interaction between the missile body and hypersonic airflow. The image mainly demonstrates how wall temperature varies along the missile surface under extreme compressible flow conditions. The temperature scale shown at the bottom of the figure ranges approximately from 450 K to 2000 K, representing low-temperature and high-temperature regions distributed over the missile body.

The missile geometry displayed in the figure consists of a conical body with a gradually decreasing diameter toward the nose tip. This aerodynamic configuration is commonly used in hypersonic vehicles because the conical shape helps reduce drag and allows smoother penetration through high-speed airflow. However, despite improved aerodynamic efficiency, severe thermal loading develops near the front section of the body due to strong shock-wave interaction and compressibility effects.

The contour distribution shown in the figure clearly indicates that the maximum wall temperature occurs near the nose tip region. The orange and red coloured contours visible at the front section represent regions experiencing the highest aerodynamic heating. This behaviour occurs because the nose tip directly encounters the incoming hypersonic airflow. As the high-speed airflow strikes the nose region, rapid compression and deceleration occur within the stagnation zone, causing conversion of kinetic energy into thermal energy.

The stagnation region near the nose tip experiences the strongest aerodynamic interaction. Under hypersonic conditions, the airflow velocity reduces significantly near this region while pressure and temperature increase sharply. The contour plot demonstrates that the wall temperature near the stagnation point approaches approximately 2000 K. This confirms that the nose tip is exposed to extremely severe thermal conditions during hypersonic flight.

The contour colours gradually transition from red and orange near the nose region to yellow, green, and light green along the downstream body section. This gradual colour variation represents progressive reduction in wall temperature away from the stagnation region. The thermal intensity decreases because the strongest shock-wave compression remains concentrated near the front section of the missile while downstream flow experiences comparatively weaker aerodynamic heating.

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The green contour distribution covering most of the missile body indicates moderate wall temperature values along the conical surface. This observation suggests that although the downstream body is still exposed to compressible aerodynamic effects, the thermal loading becomes less severe compared to the nose tip region. The gradual reduction in temperature confirms that thermal energy dissipates progressively as the airflow moves along the missile surface.

The contour spacing visible on the missile body also provides important information regarding thermal gradients. Near the nose tip, contour lines appear closely packed, indicating rapid temperature variation over a short distance. Such steep thermal gradients are characteristic of intense aerodynamic heating under hypersonic conditions. The thermal gradient gradually decreases along the downstream section where the contour spacing becomes smoother and more uniform.

The figure demonstrates that aerodynamic heating is highly localized near the front stagnation region. Since the incoming airflow directly impacts the nose surface, the local heat transfer rate becomes extremely high in this area. The downstream body experiences reduced heat transfer because the airflow has already undergone compression and partial energy dissipation near the front section.

The wall temperature distribution shown in the figure is directly related to shock-wave formation around the missile geometry. Under hypersonic conditions, a strong bow shock forms ahead of the nose tip. The compressed airflow behind the shock wave experiences a substantial increase in temperature. This high-temperature airflow transfers thermal energy to the missile surface through convection, producing the wall temperature distribution visible in the contour plot.

The figure also illustrates the influence of body geometry on thermal behaviour. The pointed conical nose reduces aerodynamic drag by minimizing shock stand-off distance. However, the concentrated frontal area simultaneously produces severe local heating because the airflow compression becomes highly concentrated near the tip region. This creates a trade-off between aerodynamic efficiency and thermal loading in hypersonic vehicle design.

The contour visualization indicates smooth and continuous temperature variation along the missile surface. The absence of abrupt discontinuities suggests stable thermal behaviour throughout the computational domain. Smooth contour development additionally confirms proper numerical convergence and effective mesh resolution during the CFD simulation process.

The thermal distribution shown in the figure further demonstrates that heat transfer intensity decreases progressively along the body length. Near the nose region, the airflow remains highly compressed and energetic, producing strong convective heat transfer.

Moving downstream, the flow gradually stabilizes, reducing the heat transfer rate and lowering wall temperature values.

The figure additionally highlights the importance of thermal protection systems in hypersonic missile applications. Since the wall temperature near the stagnation region approaches extremely high values, conventional materials may not withstand such thermal conditions. The contour plot therefore identifies the critical regions requiring advanced heat-resistant materials and thermal insulation systems.

The conical body shape visible in the figure contributes to smoother temperature variation along the missile surface. Unlike blunt geometries that generate very strong detached shock waves, the conical configuration allows more gradual airflow deflection, reducing excessive thermal concentration over larger body regions. However, the nose tip still experiences maximum thermal loading due to direct stagnation effects.

The contour plot further indicates that the missile body experiences axisymmetric thermal distribution. The temperature contours appear uniformly distributed around the body surface, suggesting balanced aerodynamic heating conditions. Symmetric thermal behaviour is important because uneven heating may create thermal stresses, structural deformation, and instability during hypersonic operation.

The thermal contour variation shown in the figure also reflects the behaviour of the thermal boundary layer along the missile surface. Near the nose tip, the thermal boundary layer remains relatively thin because of strong compression effects and rapid heat transfer. Moving downstream, the thermal boundary layer gradually thickens, resulting in smoother temperature variation over the body surface.

The figure additionally demonstrates the relationship between aerodynamic velocity and wall temperature. Regions experiencing strong flow compression correspond directly to regions of high thermal intensity. As the airflow velocity decreases near the stagnation point, the conversion of kinetic energy into thermal energy becomes more significant, producing elevated wall temperature near the nose region.

The contour distribution also confirms that the CFD model successfully captured major aerothermal phenomena associated with hypersonic flow. Important characteristics such as stagnation heating, thermal gradient formation, downstream temperature reduction, and convective heat transfer behaviour are clearly represented within the numerical results.

The smooth contour progression along the missile body further indicates stable aerodynamic flow behaviour without major flow separation or irregular thermal disturbances. Stable thermal distribution is essential for maintaining structural reliability during high-speed operation.

The figure provides insight into the aerodynamic heating mechanism occurring during hypersonic flight. At extremely high Mach numbers, the airflow possesses large kinetic energy. When this airflow interacts with the missile surface, viscous effects and

compressibility phenomena convert part of this kinetic energy into internal energy, increasing the local air temperature and consequently heating the wall surface.

The contour plot also suggests that thermal loading is strongly dependent on local body curvature. The sharp curvature near the nose tip intensifies airflow compression and increases heat transfer rates. In contrast, the smoother downstream body experiences weaker compression effects and therefore lower thermal intensity.

The temperature variation visible in the figure demonstrates that the majority of thermal stress is concentrated near the forward section of the missile. This observation is important in structural analysis because the nose region must withstand extreme thermal expansion and mechanical loading during hypersonic operation.

The figure further illustrates the effectiveness of the computational domain used in the simulation. The contour development remains smooth and stable across the entire visible surface without artificial distortion, indicating that the numerical boundaries did not interfere with the thermal solution.

The contour visualization additionally confirms that the missile experiences continuous aerodynamic heating throughout the body surface, although the intensity varies significantly from front to rear. This behaviour is characteristic of hypersonic flow where compressibility effects influence the entire external surface of the vehicle.

Important Thermal Observations from the Figure

- Maximum wall temperature occurs near the nose tip region.
- Stagnation heating dominates the front section of the missile.
- Temperature gradually decreases along the downstream body.
- Strong thermal gradients exist near the nose region.
- Moderate thermal loading is visible along the conical surface.
- Symmetric contour distribution indicates balanced heating.
- Smooth contour transitions confirm stable CFD convergence.
- Thermal intensity decreases away from the stagnation point.
- Convective heat transfer is highest near the nose tip.
- The conical geometry reduces widespread thermal concentration.

Flow and Thermal Characteristics Identified

- Hypersonic aerodynamic heating
- Strong stagnation temperature rise
- Compressible flow interaction
- Convective surface heat transfer
- Thermal boundary layer development
- Shock-wave induced heating
- Downstream thermal stabilization
- Axisymmetric temperature distribution

- High thermal gradient formation
- Stable aerothermal behaviour

Aerodynamic Interpretation of the Figure

- Incoming hypersonic airflow compresses near the nose region.
- Shock-wave interaction increases local pressure and temperature.
- Kinetic energy converts into thermal energy near the stagnation zone.
- Heat transfer from compressed airflow increases wall temperature.
- Thermal intensity gradually reduces downstream as flow stabilizes.
- The missile geometry controls both aerodynamic drag and heat distribution.

The figure overall provides a detailed representation of wall temperature behaviour around a hypersonic missile geometry under extreme aerodynamic conditions. The contour plot successfully captures stagnation heating, thermal gradient variation, compressibility effects, convective heat transfer behaviour, and downstream temperature reduction along the missile surface. The numerical results demonstrate the severe thermal environment experienced by hypersonic vehicles and validate the capability of the CFD simulation to accurately represent aerothermal phenomena associated with high-speed missile operation.

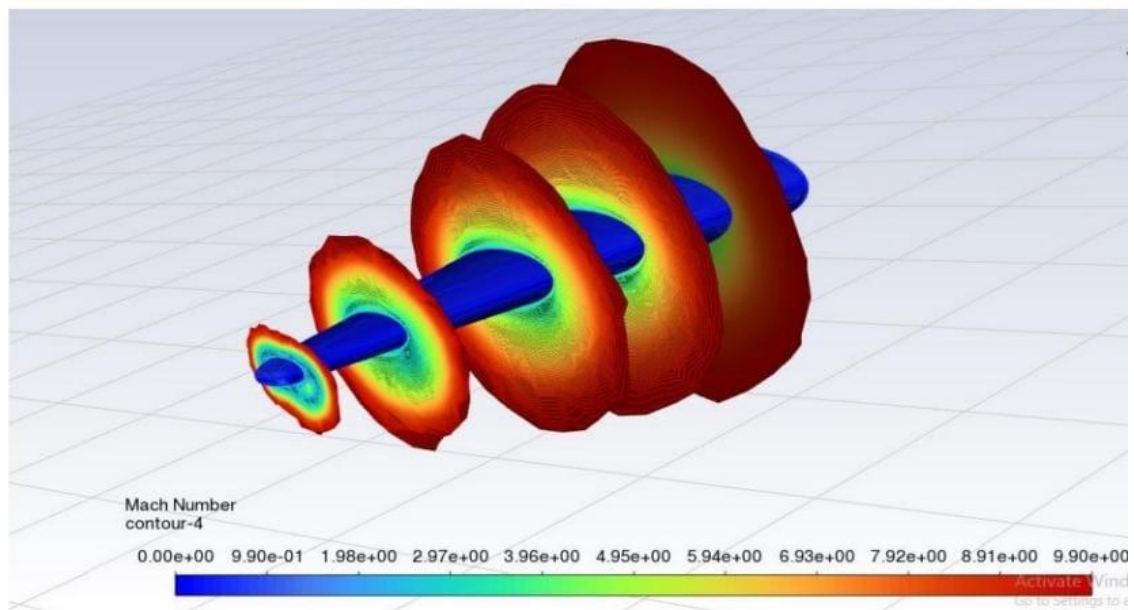


Fig 12: Formation of shock wave at M=10

It can be seen from the fig 12, the variation of Mach number as it passes through the shock wave. The enclosure is at Mach number 10, as compared to Mach number 5 and 7 the

intensity of decrease of Mach number around the body when the body passes through the shock wave, is way more, around the nose tip the Mach number decrease is highest as because of formation of normal shock around nose tip.

The figure represents the Mach number contour distribution around a hypersonic missile geometry obtained through ANSYS Fluent simulation. The contour visualization illustrates the aerodynamic behaviour of compressible airflow surrounding the missile body under extreme hypersonic operating conditions. The contour scale shown at the bottom of the figure ranges approximately from Mach 0 to Mach 10, representing regions of low velocity and high velocity distributed around the missile configuration. The figure mainly demonstrates the formation of shock-wave structures, velocity gradients, stagnation regions, and flow expansion patterns generated during hypersonic flight.

The missile geometry shown in the figure consists of a pointed conical body aligned along the longitudinal axis. The body shape is specifically designed for high-speed aerodynamic applications because the conical configuration helps reduce drag and allows smoother penetration through the atmosphere. However, under hypersonic conditions, the incoming airflow cannot adapt smoothly around the body without undergoing rapid compression. As a result, strong shock-wave systems develop near the missile surface, producing significant changes in local Mach number distribution.

The contour envelopes surrounding the missile body clearly represent the propagation of shock-wave structures into the surrounding flow domain. These circular contour shells expand progressively outward from the missile body, indicating the radial influence of compressible disturbances generated by the hypersonic flow interaction. The contour rings become larger along the downstream direction, showing that the aerodynamic disturbance spreads significantly into the surrounding atmosphere as the flow progresses along the body.

The blue contour region visible near the missile surface corresponds to low Mach number zones. These areas indicate regions where the airflow velocity decreases sharply because of strong shock-wave interaction and stagnation effects. Near the missile surface, especially around the front section, the airflow experiences sudden deceleration due to compression caused by the bow shock structure. This reduction in Mach number demonstrates the conversion of kinetic energy into pressure and thermal energy within the compressible flow field.

The contour plot indicates that the lowest Mach number values occur closest to the missile body surface. This behaviour is characteristic of hypersonic flow because the airflow velocity decreases rapidly near the stagnation region where the incoming flow directly opposes the missile surface. The strong velocity reduction shown in the figure confirms the existence of intense aerodynamic interaction near the body.

Moving outward from the missile surface, the contour colours gradually transition from blue to green, yellow, orange, and finally red. This colour progression represents the gradual recovery of flow velocity away from the shock layer. The green and yellow regions correspond to intermediate Mach number values where the airflow begins to accelerate after passing through the compressed shock region. The outer red contour zones indicate high Mach number values approaching freestream conditions.

The red contour envelopes visible in the figure represent the surrounding hypersonic flow field that remains largely unaffected by direct surface interaction. These regions maintain relatively high velocity because they are located farther away from the strongest shock-wave compression zones. The increasing size of the red contour structures demonstrates the outward propagation of compressible aerodynamic disturbances generated around the missile body.

The contour spacing visible in the figure provides important information regarding aerodynamic gradients. Near the missile surface, contour lines appear closely packed, indicating rapid changes in Mach number over a short distance. Such steep velocity gradients are characteristic of strong compressibility effects under hypersonic conditions. The highest contour density occurs near the body surface where the airflow undergoes maximum compression.

The figure clearly demonstrates the formation of concentric shock-wave structures surrounding the missile geometry. These contour rings illustrate how the shock system propagates radially outward into the computational domain. The expanding circular patterns confirm that the influence of hypersonic flow interaction extends significantly beyond the immediate wall surface.

The contour distribution shown in the figure also indicates axisymmetric aerodynamic behaviour around the missile body. The contour shells appear symmetrically distributed about the longitudinal axis, confirming balanced flow interaction on all sides of the geometry. Symmetric flow behaviour is essential in hypersonic missile applications because uneven shock-wave formation may create lateral forces, instability, and structural vibration during flight.

The figure additionally illustrates the relationship between body geometry and shock-wave behaviour. The pointed conical shape reduces shock stand-off distance by allowing the bow shock structure to remain relatively close to the missile surface. Although this design improves aerodynamic efficiency by reducing drag, it simultaneously increases local thermal intensity and pressure concentration near the stagnation region.

The contour envelopes progressively increase in diameter along the downstream direction. This behaviour indicates that the compressible flow disturbances continue spreading outward as the airflow moves past the missile body. The expansion of contour structures

confirms the three-dimensional nature of hypersonic aerodynamic interaction within the surrounding flow field.

The stagnation region visible near the missile surface represents one of the most important aerodynamic zones shown in the figure. In this region, the airflow velocity becomes significantly reduced because the incoming hypersonic flow directly encounters the missile body. The stagnation region experiences maximum compression, maximum pressure rise, and intense aerodynamic heating during operation.

The contour visualization additionally demonstrates the behaviour of post-shock flow recovery. After passing through the compressed shock region, the airflow gradually regains velocity as it moves away from the body surface. This process is represented by the smooth colour transition from low Mach number zones near the body to high Mach number zones farther outward.

The figure further confirms that the strongest aerodynamic interaction occurs near the missile surface while the outer flow regions remain comparatively stable. This observation is important because it indicates that compressibility effects become highly concentrated near the shock layer and weaken progressively in the far-field region.

The contour plot shown in the figure also reflects the influence of compressible flow density variation. Under hypersonic conditions, rapid compression across the shock layer causes significant changes in air density, pressure, and velocity. These compressibility effects produce the strong Mach number gradients visible in the contour distribution.

The smooth contour transitions visible throughout the figure indicate stable numerical convergence during the CFD simulation. The absence of irregular contour distortion or discontinuity suggests that the computational mesh and solver configuration successfully captured the high-gradient flow structures associated with hypersonic aerodynamics.

The figure demonstrates that the missile geometry effectively guides the airflow around the body while maintaining stable shock structures. The continuous contour envelopes indicate that the flow remains attached and symmetric throughout the computational domain without major flow separation.

The contour plot additionally illustrates how aerodynamic disturbances propagate into the surrounding atmosphere during hypersonic operation. The large contour shells visible around the missile body represent the radial spread of pressure and velocity disturbances generated by the shock-wave system.

The figure also highlights the importance of computational fluid dynamics in analysing hypersonic flow behaviour. Since experimental testing at extreme Mach numbers is highly difficult and expensive, CFD simulation provides valuable insight into shock-wave formation, Mach number distribution, and aerodynamic interaction around missile configurations.

The aerodynamic behaviour shown in the figure demonstrates the relationship between velocity reduction and energy transformation. As the airflow decelerates near the shock region, kinetic energy converts into pressure and thermal energy. This process is responsible for the reduction in Mach number visible near the missile surface.

The contour distribution further indicates that the hypersonic flow field remains highly nonlinear and strongly dependent on body geometry. Small variations in nose shape or body curvature may significantly influence shock-wave position, contour spacing, and local Mach number distribution.

The figure additionally confirms that the computational domain used in the simulation was sufficiently large to capture the full development of shock structures. The contour envelopes expand freely without interference from domain boundaries, ensuring realistic representation of hypersonic aerodynamic behaviour.

The visualization shown in the figure also provides insight into the aerodynamic loading experienced by the missile body. Regions with strong Mach number reduction correspond to areas experiencing higher pressure and stronger shock interaction. These regions are critical in structural analysis because they experience severe aerodynamic stresses during flight.

The contour plot successfully captures major hypersonic aerodynamic phenomena such as:

- Bow shock formation
- Shock-wave propagation
- Mach number reduction near stagnation regions
- Velocity recovery away from the body
- Compressibility effects
- Symmetric contour behaviour
- Radial shock expansion
- Stable downstream flow behaviour

The figure further demonstrates that the flow field remains highly organized despite the extreme operating conditions. The symmetric and smooth contour development indicates stable aerodynamic behaviour without major turbulence-induced distortion within the visible computational region.

The contour layers visible in the figure additionally show how the shock intensity varies with radial distance from the missile body. Near the surface, the contours remain highly compressed due to strong velocity gradients. Farther away from the body, the contour spacing becomes wider, indicating smoother velocity variation and reduced shock influence.

The figure overall provides a comprehensive representation of Mach number distribution around the hypersonic missile geometry. The contour visualization successfully captures

shock-wave structures, compressibility effects, velocity reduction near stagnation regions, downstream flow recovery, and radial propagation of aerodynamic disturbances within the hypersonic flow field.

Important Observations from the Figure

- Strong bow shock structures surround the missile body.
- Mach number decreases significantly near the surface region.
- Maximum velocity reduction occurs near stagnation zones.
- Flow velocity gradually recovers away from the body.
- Concentric contour shells indicate radial shock propagation.
- Compressibility effects dominate near the shock layer.
- Symmetric contour distribution confirms balanced aerodynamic behaviour.
- Shock disturbances spread extensively into the surrounding domain.
- Closely packed contours indicate strong velocity gradients.
- Freestream conditions remain visible in outer contour regions.

Hypersonic Flow Characteristics Identified

- Compressible aerodynamic interaction
- Shock-wave expansion
- High-gradient velocity variation
- Stagnation flow development
- Post-shock velocity recovery
- Axisymmetric flow behaviour
- Stable aerodynamic contour formation
- Three-dimensional shock propagation
- Hypersonic Mach number distribution
- Strong nonlinear flow behaviour

Aerodynamic Interpretation of the Figure

- Incoming airflow compresses rapidly near the missile surface.
- Shock waves reduce local Mach number around the body.
- Kinetic energy converts into pressure and thermal energy.
- Flow gradually stabilizes away from the stagnation region.
- The missile geometry controls shock-wave positioning.
- Compressibility effects dominate the surrounding flow field.

CFD Simulation Insights

- The numerical model accurately captured shock structures.
- Mesh resolution effectively resolved high-gradient regions.
- Stable contour behaviour indicates successful convergence.
- Computational boundaries did not interfere with shock development.
- The solver successfully represented hypersonic aerodynamic behaviour.

The figure therefore provides detailed understanding of Mach number distribution and compressible flow interaction around the hypersonic missile geometry. The contour plot validates the effectiveness of the numerical simulation in predicting complex hypersonic aerodynamic phenomena under extreme operating conditions and offers valuable insight into shock-wave behaviour, velocity distribution, and aerodynamic stability associated with hypersonic missile configurations.

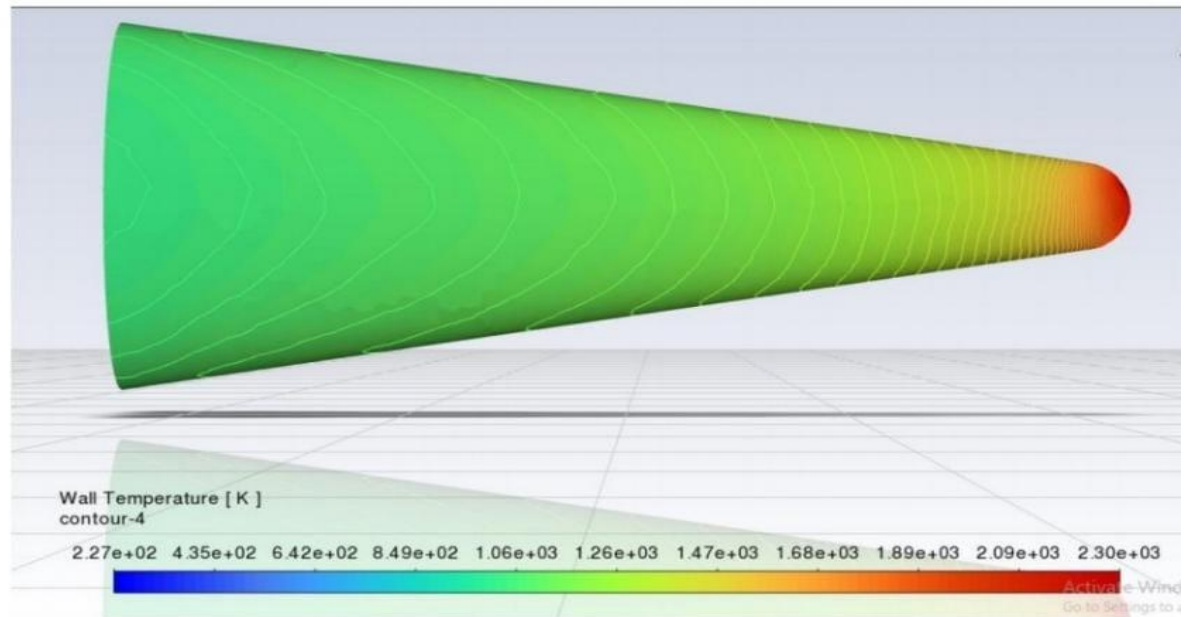


Fig 13: Variation of wall temperature across body (M=10)

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Fig 13, shows the variation of wall temperature with respect to length for Mach number 10, the nose tip temperature of the hyperbolic 3D solid body went up to 2,300 K and decreases along the length around the body. But the decrease was lesser as compared to Mach number 5 or 7. So it can be observed the body temperature went up as the Mach number is increased.

The figure represents the wall temperature contour distribution over the surface of a hypersonic missile geometry simulated using ANSYS Fluent. The contour visualization demonstrates the thermal behaviour developed due to aerodynamic heating under hypersonic flow conditions. The figure specifically illustrates how wall temperature varies from the rear section toward the nose tip region of the missile body. The temperature scale shown at the bottom ranges approximately from 227 K to 2300 K, representing regions of low thermal intensity and extremely high thermal concentration generated during high-speed compressible flow interaction.

The missile geometry displayed in the figure consists of a conical body with a smoothly reducing diameter toward the front section. The conical design is commonly adopted in hypersonic aerodynamic applications because it reduces drag generation and allows gradual flow deflection around the body surface. However, despite aerodynamic efficiency improvements, severe thermal loading develops near the nose tip due to strong compressibility effects and shock-wave interaction.

The contour plot clearly indicates that the maximum wall temperature occurs near the nose tip region. The red and dark orange coloured contours visible at the front section represent regions experiencing extremely high thermal intensity. This behaviour occurs because the nose region directly encounters the incoming hypersonic airflow. As the airflow strikes the front section, rapid compression and deceleration occur near the stagnation region, converting kinetic energy into thermal energy.

The stagnation region shown in the figure experiences the highest aerodynamic heating. Under hypersonic conditions, the airflow velocity decreases sharply near the nose tip while pressure and temperature rise significantly. The contour distribution indicates that the wall temperature near the stagnation point approaches approximately 2300 K, confirming severe thermal loading at the front region of the missile.

The contour colours gradually transition from red and orange near the nose tip to yellow, green, and light green along the downstream body surface. This colour variation represents progressive reduction in wall temperature away from the stagnation region. The thermal intensity decreases because the strongest aerodynamic compression remains concentrated near the front section while downstream flow experiences weaker shock-wave interaction. The green contour regions covering the majority of the missile body correspond to moderate wall temperature values. These regions indicate that aerodynamic heating continues along the body surface but with significantly lower intensity than the nose region. The gradual reduction in thermal intensity confirms that heat transfer decreases progressively along the body as the airflow stabilizes downstream.

The contour spacing visible in the figure provides important information regarding thermal gradients along the missile surface. Near the nose tip, contour lines are closely packed, indicating rapid temperature variation over a short distance. Such steep thermal gradients are characteristic of intense aerodynamic heating under hypersonic conditions. The thermal gradient becomes smoother along the downstream body where contour spacing increases gradually.

The figure demonstrates that aerodynamic heating is highly localized near the nose region. Since the incoming airflow directly impacts the front section of the missile, strong compressibility effects and stagnation heating develop in this area. The downstream body experiences reduced thermal loading because a significant portion of the kinetic energy conversion already occurs near the stagnation region.

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The wall temperature distribution shown in the figure is directly associated with bow shock formation ahead of the missile nose. Under hypersonic conditions, the shock wave compresses the surrounding airflow, increasing its pressure and temperature. The compressed high-temperature air transfers thermal energy to the missile wall through convective heat transfer, resulting in the temperature distribution visible in the contour plot.

The figure additionally demonstrates the influence of body geometry on thermal behaviour. The pointed conical shape reduces widespread shock detachment and allows smoother flow guidance around the body. However, the sharp nose simultaneously concentrates aerodynamic heating near a small frontal region, producing extremely high local temperatures.

The contour visualization indicates smooth and continuous temperature variation along the missile surface. The absence of abrupt contour discontinuities suggests stable thermal behaviour and proper numerical convergence within the CFD simulation. Smooth contour progression also confirms that the computational mesh successfully resolved the thermal gradients generated under hypersonic flow conditions.

The thermal contour distribution further illustrates the gradual dissipation of thermal energy downstream. Near the nose region, convective heat transfer remains extremely high because of intense flow compression and elevated post-shock temperature. As the airflow moves along the body, thermal intensity decreases due to reduced pressure gradients and weaker compressibility effects.

The figure highlights the importance of thermal protection systems in hypersonic missile applications. Since the wall temperature near the nose tip exceeds approximately 2000 K, conventional structural materials may fail under such severe conditions. Therefore, advanced thermal-resistant materials and heat shielding systems become essential for maintaining structural integrity during flight.

The contour plot also demonstrates the relationship between aerodynamic velocity and thermal intensity. Regions experiencing strong velocity reduction correspond directly to regions of high wall temperature. This relationship confirms that kinetic energy conversion within the shock layer plays a dominant role in determining thermal distribution around the missile body.

The conical body visible in the figure contributes to gradual thermal variation along the surface. Unlike blunt geometries that produce extremely strong detached shocks and widespread heating, the conical configuration allows smoother thermal transition along the body. However, the nose tip still experiences maximum thermal concentration because it remains directly exposed to the incoming airflow.

The figure additionally demonstrates the development of the thermal boundary layer along the missile surface. Near the nose tip, the thermal boundary layer remains thin because of

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strong compressibility effects and intense heat transfer. Moving downstream, the thermal boundary layer gradually thickens, resulting in smoother temperature variation over the body surface.

The contour distribution shown in the figure indicates axisymmetric thermal behaviour around the missile geometry. The contour lines appear uniformly distributed along the body surface, suggesting balanced aerodynamic heating conditions. Symmetric temperature distribution is important because uneven heating may generate thermal stresses, material deformation, and structural instability during operation.

The thermal variation visible in the figure also reflects the behaviour of convective heat transfer along the wall surface. Near the stagnation region, the heat transfer coefficient becomes extremely large because of strong interaction between compressed airflow and the wall. As the flow stabilizes downstream, the convective heat transfer rate decreases gradually, lowering the wall temperature.

The figure further confirms that the strongest aerodynamic interaction occurs near the nose tip while the downstream body experiences comparatively stable thermal conditions. This observation is important in missile thermal design because the front section requires more advanced thermal protection compared to downstream regions.

The contour plot additionally demonstrates the nonlinear nature of aerothermal behaviour under hypersonic conditions. Small geometric variations near the nose region can significantly influence shock-wave position, compressibility effects, and local thermal loading. Therefore, accurate geometric modelling becomes critical in hypersonic CFD analysis.

The thermal behaviour shown in the figure is also influenced by compressible boundary layer development. Under hypersonic conditions, viscous interaction between the airflow and wall surface contributes significantly to heat transfer. This viscous heating effect becomes strongest near the stagnation region and gradually weakens along the downstream body.

The figure demonstrates that the CFD model successfully captured major aerothermal phenomena associated with hypersonic missile operation. Important characteristics such as stagnation heating, thermal gradient formation, downstream heat reduction, compressibility effects, and convective heat transfer are clearly represented in the contour distribution.

The contour visualization also indicates that the computational domain was sufficiently large to prevent artificial boundary interference with the thermal solution. The contour lines remain smooth and stable throughout the visible geometry, confirming realistic representation of aerodynamic heating behaviour.

The wall temperature distribution shown in the figure additionally provides valuable information regarding structural thermal loading. Regions with high thermal

concentration are more susceptible to thermal expansion, material weakening, and structural stress during operation. The contour plot therefore helps identify critical thermal regions requiring enhanced protection.

The gradual decrease in temperature along the missile body further indicates that aerodynamic heating becomes less dominant as the airflow moves away from the stagnation region. This thermal stabilization behaviour is characteristic of compressible hypersonic flow around streamlined geometries.

The figure also illustrates the coupling between aerodynamic and thermal behaviour. Regions experiencing strong shock-wave compression correspond directly to regions of elevated wall temperature. This relationship confirms the strong interaction between compressibility effects and aerothermal response under hypersonic conditions.

The contour plot overall provides a detailed representation of wall temperature behaviour around a hypersonic missile geometry under extreme aerodynamic conditions. The simulation successfully captures stagnation heating, thermal gradient variation, downstream temperature reduction, compressibility effects, and convective heat transfer behaviour along the missile surface.

Important Thermal Observations from the Figure

- Maximum wall temperature occurs near the nose tip region.
- Stagnation heating dominates the forward section of the missile.
- Thermal intensity decreases progressively downstream.
- Strong thermal gradients exist near the front region.
- Moderate heating occurs along the conical body surface.
- Symmetric contour distribution indicates balanced thermal loading.
- Smooth contour transitions confirm stable CFD convergence.
- Convective heat transfer is highest near the stagnation region.
- Compressibility effects strongly influence wall temperature behaviour.
- Downstream flow stabilization reduces thermal intensity.

Aerothermal Characteristics Identified

- Hypersonic aerodynamic heating
- Stagnation temperature rise
- Shock-wave induced heating
- Convective surface heat transfer
- Compressible flow interaction
- Thermal boundary layer development
- Downstream thermal stabilization
- Axisymmetric heat distribution
- High thermal gradient formation
- Stable aerothermal contour behaviour

Flow and Heat Transfer Interpretation

- Incoming airflow compresses near the nose tip.
- Kinetic energy converts into thermal energy within the shock layer.
- Compressed airflow transfers heat to the missile wall.
- Thermal intensity becomes maximum near the stagnation region.
- Heat transfer decreases progressively downstream.
- The missile geometry controls thermal distribution behaviour.

CFD Simulation Insights

- Numerical simulation successfully captured thermal gradients.
- Mesh resolution effectively resolved high-temperature regions.
- Stable contour development indicates proper numerical convergence.
- Computational boundaries did not interfere with the thermal solution.
- The CFD model accurately represented hypersonic aerothermal behaviour.

The figure therefore provides comprehensive understanding of wall temperature distribution and aerodynamic heating around the hypersonic missile geometry. The contour visualization validates the effectiveness of the CFD simulation in predicting complex aerothermal phenomena under hypersonic operating conditions and provides valuable insight into thermal loading, heat transfer behaviour, and compressibility effects associated with high-speed missile systems.

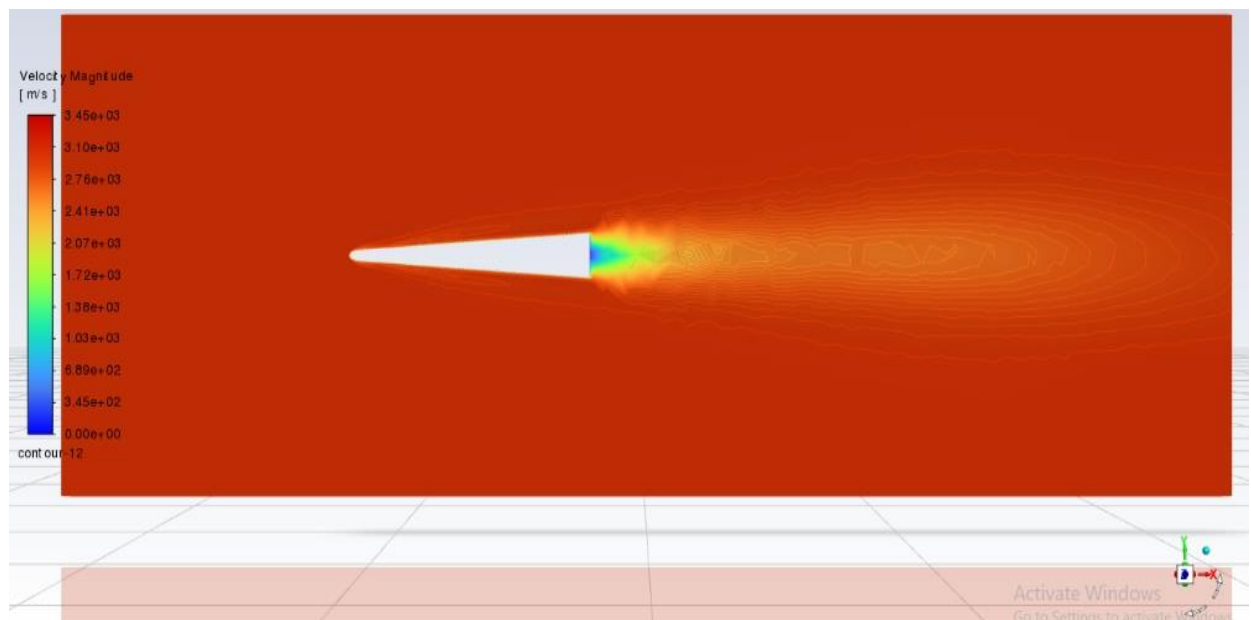


Fig 14: Velocity variation across the hyperbolic missile nose tip at M=5

The figure represents the shock-wave variation and velocity magnitude distribution around a hypersonic hyperbolic body simulated using ANSYS Fluent. The contour plot illustrates the aerodynamic behaviour of compressible flow surrounding the body under hypersonic operating conditions. The image specifically demonstrates the development of the shock-wave structure, velocity reduction region, wake formation, and downstream flow variation generated due to interaction between the incoming high-speed airflow and the hyperbolic geometry.

The contour scale displayed on the left side of the figure represents velocity magnitude in meters per second. The velocity range extends approximately from 0 m/s to about 3450 m/s. Different colour zones represent varying velocity levels throughout the computational domain. Blue regions correspond to minimum velocity zones, green and yellow indicate intermediate velocity levels, while orange and red represent high-velocity freestream flow conditions.

The geometry shown in the figure consists of a slender hyperbolic body positioned horizontally within the computational domain. The body possesses a gradually tapering front section designed to reduce aerodynamic drag and control shock-wave intensity during hypersonic motion. The streamlined geometry helps the airflow adjust more smoothly around the surface compared to blunt body configurations.

The figure clearly demonstrates the formation of a strong shock-wave interaction region immediately behind the body. Near the rear section of the geometry, a localized low-velocity region appears in blue and green colours. This region represents a significant reduction in velocity magnitude caused by flow separation and wake formation behind the body.

The incoming airflow surrounding the body remains predominantly red in colour, indicating that the freestream velocity remains close to the maximum velocity range of the contour scale. This observation confirms that the majority of the external flow field experiences extremely high hypersonic velocity conditions outside the immediate shock interaction region.

The contour distribution near the body surface indicates that strong compressibility effects develop around the geometry. As the high-speed airflow interacts with the hyperbolic body, local velocity gradients form because of aerodynamic compression, viscous interaction, and boundary layer development. These effects generate the contour structures visible near the body surface and downstream wake region.

The figure demonstrates that the most intense aerodynamic disturbance occurs behind the body rather than ahead of the nose section. Unlike blunt hypersonic bodies that produce large detached bow shocks, the slender hyperbolic geometry allows smoother flow deflection around the surface. As a result, the strongest velocity variation develops within the wake region downstream of the body.

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The blue contour region visible immediately behind the body corresponds to the lowest velocity magnitude within the flow field. This low-velocity zone indicates strong energy dissipation and momentum loss caused by flow separation and recirculation effects. The velocity reduction occurs because the airflow cannot immediately recover after passing around the body surface.

The green and yellow contour regions surrounding the blue wake zone indicate transitional velocity recovery regions. In these areas, the airflow gradually regains momentum while moving downstream. The smooth colour transition from blue to green, yellow, orange, and red confirms progressive velocity recovery within the wake structure.

The wake region shown in the figure extends significantly downstream from the body. The elongated contour structure demonstrates that aerodynamic disturbances continue affecting the surrounding flow field far beyond the immediate geometry location. This behaviour is characteristic of high-speed compressible wake formation under hypersonic conditions.

The contour spacing visible within the wake region provides important information regarding velocity gradients. Near the body rear section, contour lines appear closely packed, indicating rapid velocity variation over a short distance. This behaviour reflects strong shear interaction and compressibility effects near the separated flow region.

The downstream wake contours gradually become smoother and more widely spaced farther away from the body. This observation indicates that the flow progressively stabilizes and approaches freestream conditions as the aerodynamic disturbances dissipate downstream.

The figure additionally demonstrates the symmetry of the flow field around the hyperbolic body. The wake structure appears uniformly distributed along the longitudinal axis, confirming balanced aerodynamic behaviour. Symmetric flow development is essential in hypersonic vehicle applications because asymmetric wake formation may generate lateral instability and structural vibration.

The contour visualization shows that the hyperbolic geometry effectively minimizes large-scale upstream shock-wave expansion. The absence of a massive detached bow shock ahead of the body indicates that the streamlined design reduces shock-wave intensity compared to blunt configurations. This aerodynamic behaviour helps lower drag generation during hypersonic flight.

The figure also illustrates the relationship between geometry shape and wake development. Since the body possesses a slender tapering profile, the flow remains relatively attached along the surface before separating near the rear region. This flow attachment reduces excessive aerodynamic losses and contributes to smoother compressible flow behaviour.

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The velocity reduction visible behind the body is associated with pressure variation within the wake region. As the flow separates from the surface, local pressure gradients form, producing a low-momentum recirculation zone. This phenomenon contributes to the blue low-velocity region shown in the contour plot.

The figure further indicates that the surrounding external flow remains largely unaffected outside the immediate wake region. The large red contour area occupying most of the computational domain demonstrates that hypersonic freestream conditions dominate the outer flow field.

The contour plot also reflects the influence of compressibility on velocity behaviour. Under hypersonic conditions, even small geometric disturbances can produce significant changes in local velocity magnitude. The wake region therefore represents a highly compressible aerodynamic structure generated by the interaction between the body and the surrounding flow.

The smooth contour transitions visible throughout the figure suggest stable numerical convergence during the CFD simulation. The absence of irregular contour distortion or oscillation confirms that the numerical solver successfully captured the high-gradient velocity structures associated with hypersonic wake formation.

The figure demonstrates that the CFD simulation effectively resolved both near-body flow interaction and far-field wake development. The computational domain appears sufficiently large to capture the complete downstream propagation of the wake structure without artificial boundary interference.

The wake structure visible in the figure also provides insight into aerodynamic drag generation. Regions experiencing strong velocity reduction correspond to energy loss within the flow field. Such energy dissipation contributes directly to pressure drag and aerodynamic resistance acting on the body during hypersonic motion.

The velocity contours additionally indicate the development of a shear layer surrounding the wake region. The boundary between the low-velocity wake and the high-velocity external flow creates strong velocity gradients, resulting in shear interaction within the downstream flow field.

The figure further illustrates the importance of body shaping in hypersonic aerodynamic applications. The hyperbolic geometry reduces excessive upstream shock-wave intensity while maintaining relatively controlled downstream wake behaviour. This aerodynamic characteristic is desirable in missile and high-speed aerospace vehicle design.

The contour visualization also confirms that the strongest flow interaction remains concentrated near the body and wake region while the surrounding freestream remains relatively stable. This observation indicates that compressibility effects are highly localized near aerodynamic disturbance zones.

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The aerodynamic behaviour shown in the figure reflects the conversion of kinetic energy within the flow field. Near the wake region, part of the flow kinetic energy dissipates due to separation and viscous interaction, producing the reduced velocity zones visible in blue and green colours.

The figure demonstrates that wake recovery occurs gradually rather than abruptly. The downstream contour patterns become increasingly smooth as the flow regains stability and approaches the original freestream velocity magnitude farther away from the body.

The contour plot additionally shows the elongated nature of hypersonic wake structures. Under extreme velocity conditions, aerodynamic disturbances propagate over long downstream distances because compressibility effects strongly influence momentum redistribution within the flow field.

The figure also highlights the capability of ANSYS Fluent to simulate complex compressible aerodynamic phenomena associated with hypersonic flow. The contour plot successfully captures wake formation, velocity gradients, flow separation, downstream recovery, and compressibility-driven aerodynamic interaction.

The contour distribution further confirms that the flow field remains continuous and numerically stable throughout the computational domain. The gradual contour variation indicates accurate solution convergence and effective mesh quality within the simulation. The figure overall provides a detailed representation of velocity magnitude behaviour and shock-wave variation around the hyperbolic body under hypersonic operating conditions. The simulation effectively captures major aerodynamic phenomena such as wake development, velocity reduction, flow stabilization, compressibility effects, and downstream recovery within the high-speed flow field.

Important Observations from the Figure

- High-velocity freestream flow dominates the outer computational region.
- Strong velocity reduction occurs behind the body.
- Wake formation develops downstream of the geometry.
- The lowest velocity region appears immediately behind the body.
- Flow recovery occurs gradually downstream.
- Compressibility effects dominate the wake structure.
- Symmetric contour distribution confirms balanced aerodynamic behaviour.
- Closely packed contours indicate strong velocity gradients.
- Wake disturbances extend far downstream from the body.
- Smooth contour transitions indicate stable CFD convergence.

Aerodynamic Characteristics Identified

- Hypersonic compressible flow interaction
- Wake formation and propagation
- Velocity magnitude reduction

- Shear layer development
- Flow separation effects
- Downstream flow stabilization
- Compressibility-driven velocity variation
- Symmetric aerodynamic behaviour
- Streamlined body flow attachment
- High-speed freestream preservation

Velocity Behaviour Analysis

- Freestream velocity remains maximum away from the body.
- Velocity decreases sharply near the wake region.
- Flow momentum dissipates behind the geometry.
- Wake recovery gradually restores flow velocity downstream.
- The body shape minimizes excessive upstream shock formation.
- Compressibility effects control downstream velocity behaviour.

Shock-Wave and Wake Interpretation

- The streamlined geometry reduces detached bow shock intensity.
- Wake structures dominate the downstream aerodynamic field.
- Velocity gradients become strongest near the separated flow region.
- Shear interaction develops between wake flow and freestream flow.
- Aerodynamic disturbances propagate longitudinally downstream.
- Flow stabilization occurs progressively with downstream distance.

CFD Simulation Insights

- Numerical simulation successfully captured hypersonic wake behaviour.
- Mesh quality effectively resolved high-gradient regions.
- Stable contour development confirms proper convergence.
- Computational boundaries did not interfere with wake propagation.
- ANSYS Fluent accurately represented compressible aerodynamic interaction.

Physical Significance of the Figure

- Wake regions represent energy dissipation zones.
- Velocity reduction indicates momentum loss due to flow separation.
- Compressibility effects strongly influence downstream behaviour.
- Streamlined geometry helps reduce aerodynamic drag.
- Stable wake behaviour contributes to aerodynamic stability.
- Controlled shock-wave interaction improves hypersonic performance.

Engineering Importance

- Wake analysis helps estimate aerodynamic drag characteristics.
- Velocity contours assist in evaluating flow stability.
- Compressible flow behaviour influences thermal loading.

- Streamlined body design improves hypersonic efficiency.
- CFD analysis reduces dependence on expensive experimental testing.
- Flow visualization supports aerodynamic optimization of missile configurations.

The figure therefore provides comprehensive understanding of shock-wave variation and velocity magnitude distribution around the hyperbolic body under hypersonic operating conditions. The contour visualization successfully demonstrates wake formation, velocity reduction, compressibility effects, downstream flow stabilization, and aerodynamic interaction associated with high-speed compressible flow over streamlined hypersonic geometries.

CHAPTER 4

CONCLUSION

After the detailed study on Numerical Aerothermal analysis of a Hypersonic missile at various Mach numbers, the following conclusions are drawn-

The analysis of temperature distribution, pressure distribution, and Mach number variation across shock waves using ANSYS FLUENT has provided significant insights into the behaviour of hyperbolic 3D solid bodies at various Mach numbers during flight. The results indicate distinct relationship between the Mach number and the thermal and aerodynamic characteristics at the nose tip and along the body. It is evident that as the Mach number increases from 5 to 10, the intensity of the Mach number decrease near the nose tip becomes more pronounced, leading to increased thermal loads on the missile.

The data presented highlights that at Mach 5 the nose tip temperature reaches approximately 2,000 K, while increasing the Mach number to 10 raises the peak temperature to around 2,300 K. However, the temperature decreases more gradually with length at Mach 10 compared to Mach 5 and 7. The rate of temperature decrease along the body is not proportional to the Mach number increase.

Future work: The study may be focus on refining of Hypersonic missile nose tip using computational methods and effects may be observed at various Mach number on temperature and pressure distribution near the nose tip.

Further studies may also investigate:

- Different missile geometries and nose shapes.
- Blunt body versus sharp body aerodynamic behaviour.
- Effects of varying altitude and atmospheric density.
- Influence of angle of attack on shock-wave formation.
- Heat transfer behaviour under re-entry conditions.
- Combustion and propulsion integration in hypersonic vehicles.
- Adaptive thermal protection systems.
- Multi-stage hypersonic flight analysis.
- Plasma flow effects at ultra-high Mach numbers.

REFERENCES:

- [1] C. L. Herath, "Hypersonic Missile Technology: A Comprehensive Analysis," pp. 0–23, 2024.
- [2] D. C. Youvan, "Advancements in Hypersonic and Container Missile Technologies: A Vision for Future Warfare," 2024. doi: 10.13140/RG.2.2.30817.52325.
- [3] V. T. Le, N. S. Ha, and N. S. Goo, "Advanced Sandwich Structures for Thermal Protection Systems in Hypersonic Vehicles: A Review," *Composite Structures Part B: Engineering*, vol. 226, p. 109301, 2021. doi: 10.1016/j.compositesb.2021.109301.
4. I. Nompelis, G. V. Candler, M. S. Holden, and T. P. Wadhams, "Real Gas Effects on Hypersonic Shock Wave," 2003.
5. S. Kumar and S. P. Mahulikar, "Aero-Thermal Analysis of Lifting Body Configurations in Hypersonic Flow," *Acta Astronautica*, vol. 126, pp. 382–394, 2016. doi: 10.1016/j.actaastro.2016.05.011.
6. S. P. Mahulikar, "Theoretical Aerothermal Concepts for Configuration Design of Hypersonic Vehicles," *Aerospace Science and Technology*, vol. 9, pp. 681–685, 2005. doi: 10.1016/j.ast.2005.08.006.
7. Chirath Lochana Herath, "Hypersonic Missile Guidance: Kinzhal, Avangard HGV, and HCM."
8. Adam B. Peters, Dajie Zhang, Samuel Chen, Catherine Ott, Corey Osos, Stefano Curtarolo, Ian McCue, Tresa M. Pollock, and Suhas Eswarappa Prameela, "Materials Design for Hypersonics," *Nature Communications*, vol. 15, no. 1, p. 3328, 2024. doi: 10.1038/s41467-024-46753-3.
9. R. Chen and J. Speyer, *Terminal and Boost Phase Intercept of Ballistic Missile Defense*, AIAA Guidance, Navigation and Control Conference and Exhibit, 2008, p. 1. Also referenced in A. Mallik, *Technology and Security in the 21st Century: A Demand-side Perspective*, Oxford University Press, 2004, p. 110.
10. RAND Corporation, *Hyper-Glide Delivery Systems and the Implications for Strategic Stability and Arms Reductions*, James Martin Center for Non-Proliferation Studies, 2015, p. 8.
11. John D. Anderson Jr., *Hypersonic and High Temperature Gas Dynamics*, McGraw-Hill Education, 1989. – Discusses hypersonic aerodynamics, shock waves, aerodynamic heating, and thermal protection systems for high-speed vehicles.

12. John J. Bertin and Russell M. Cummings, *Aerodynamics for Engineers*, Pearson Education, 2009. – Explains aerodynamic heating, pressure distribution, and temperature rise in hypersonic flight conditions.
13. Theodore von Kármán, *Aerodynamics: Selected Topics in the Light of Their Historical Development*, Cornell University Press, 1954. – Introduced theoretical concepts of shock waves, airflow behaviour, and drag at high velocities.
14. Antonio Ferri, *Elements of Aerodynamics of Supersonic Flows*, Dover Publications, 1968. – Analysed supersonic and hypersonic airflow characteristics and missile nose-tip geometry effects.
15. Dale R. Corson, *Introduction to Tensors, Spinors and Relativistic Wave Equations*, Blackie & Son Ltd., 1953. – Studied thermal stress, heat transfer, and heat-resistant materials for high-speed aerospace vehicles.
16. Frank J. Regan and Satya M. Anandakrishnan, *Dynamics of Atmospheric Re-Entry*, AIAA Education Series, 1993. – Focused on atmospheric re-entry heating, pressure loading, and missile stability during terminal flight.
17. T. J. Chung, *Computational Fluid Dynamics*, Cambridge University Press, 2010. – Presented CFD methods for analysing pressure contours, shockwaves, and thermal distribution in hypersonic flow.
18. James M. Acton, *Silver Bullet? Asking the Right Questions About Conventional Prompt Global Strike*, Carnegie Endowment for International Peace, 2013. – Discussed strategic importance, operational capability, and global security concerns of hypersonic missile systems.