JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Shaping Supersonic Flow: Numerical Insights into a Mach 3 Rocket Nozzle

TANMOY SAHA, AYUSH GOYAL, NIKHIL GANGAMKOTE

Aerospace Engineering student

SRM Institute of Science and Technology

ABSTRACT

Rocket propulsion systems in aerospace require the basic component of convergent-divergent (CD) nozzles. Exhaust gas supersonics is the main operational objective of this device. The convergent section compresses flow to Mach 1 level at the throat while the divergent section uses expansion to boost exit velocities of the material. This design functionally enhances thrust generation by reducing shock wave losses while delivering better thermal resistance properties thus ensuring smooth flow expansion. Defence operations and space launch vehicles use CD nozzles because they ensure stable supersonic flow during all operational phases. Numerical analyses conducted for a CD nozzle having Mach 3 speed produce this research's key results about both aerodynamic behaviour and thermal response. The nozzle modelling process used CATIA V5 while ANSYS Fluent performed the CFD simulations. The model operated at 20-kilometers of altitude using 15-MPa chamber pressure together with an exit ambient pressure of 5529 Pa. The analysis achieved results for flow parameters such as temperature and pressure and velocity. This study verified efficient supersonic expansion that occurred with minimal shock interactions along with achieving the maximum possible pressure recovery. A temperature distribution assessment confirmed that extreme environmental conditions do not damage the nozzle design. The findings demonstrate the **nozzle's aerodynamic efficiency** and its feasibility for high-speed propulsion applications. Future work may involve optimizing nozzle contouring, implementing **altitude-adaptive designs**, and exploring **advanced materials** to further enhance performance and durability in extreme aerospace environments.

Convergent-divergent (CD) rocket nozzle Basics and working

It is an essential part of propulsion systems, which are made to speed up exhaust gasses to supersonic speeds. It has two primary sections: a converging region, where the subsonic flow speeds up as it approaches the throat, and a diverging segment, when the flow expands and speeds up to supersonic speeds. The gas reaches sonic velocity (Mach 1) at the nozzle's throat, which is the narrowest point of the nozzle. The diverging portion, which is located beyond the throat, lets the gas to expand and reach higher supersonic speeds, which increases thrust to the maximum level.

Purpose and Functionality

CD rocket nozzle serves to:

• **Acceleration to Supersonic Speeds**: The nozzle expands exhaust gases in the diverging region, which causes them to accelerate to supersonic speeds and maximizes thrust generation.
• **Efficient Energy Conversion**: It transforms the high-pressure, high-temperature gas energy from the combustion chamber into high-velocity kinetic energy for effective propulsion.
• **Optimal Flow Expansion**: The diverging section guarantees that gases are expanded properly to match the ambient pressure, which reduces energy losses and improves performance.

• **Thrust Optimization**: By carefully designing the nozzle, it increases thrust while also retaining structural integrity and efficiency at different altitudes.
• **Shock Wave Control**: The shape of the nozzle helps to regulate shock waves and avoid flow separation in supersonic regimes, which allows for stable and efficient operation.

Components and Materials

A typical CD rocket nozzle consists of:

• **Convergent Section**: Narrows the flow, which increases the speed of the gas until it reaches Mach 1 at the throat.
• **Throat**: The point at which the gas reaches sonic speed (Mach 1) and is at its narrowest.
• **Divergent Section**: Increases the flow and speeds it up to Mach 4.

• **Nozzle Walls**: Surfaces that are shaped with precision to direct the flow and reduce energy losses.
• **Exit Plane**: The end of the nozzle where exhaust gasses exit, providing thrust.
The materials that are used for the CD nozzle must be able to tolerate the corrosive qualities of propellants. Liquid propellants include kerosene and hydrogen peroxide, while aluminum powder is an example of a solid propellant. Cold gas propellants include nitrogen and helium gas, among other examples. Some of the most frequently chosen materials include stainless steel, titanium, and advanced alloys that are resistant to corrosion.

Pintle Injector Design

The rocket engine industry uses the pintle injector as a simple innovative solution which performs effectively. Engineers use a central pintle element in this design to distribute propellant through the ring-shaped opening for fuel-oxidizer mixture effectiveness. Stable combustion and reduced combustion instability occur together with excellent thrust control through this design approach. The aerospace industry strongly favours pintle injectors because of their straightforward design which brings advantages of reliability and simplified production processes.

Flow Dynamics

The flow rate together with the spray pattern needs setup via computational fluid dynamics (CFD) simulations combined with practical testing sessions. The design of systems should use propellant efficiently and minimize energy waste.

Propulsion Systems

Propellants are materials that generate thrust by expelling mass, commonly utilized in rocket engines. They are categorized into three primary types:
• **Solid Propellants**: Comprised of a fuel and oxidizer amalgamated into a solid mass. They are straightforward, dependable, and utilized in missiles and launch vehicles.
• **Liquid Propellants**: Comprise distinct liquid fuel (e.g., RP-1, liquid hydrogen) and oxidizer (e.g., liquid oxygen). They provide exact regulation of thrust and are employed in rockets for space exploration.
• **Cold Gas Propellants**: This system utilizes compressed, inert gases (such as nitrogen or helium) released via a nozzle to produce thrust. It is straightforward, dependable, and optimal for tiny satellites and attitude regulation.
Essential specifications for the propulsion system encompass: • Accurate flow regulation to avert catalyst bed overload.
• Uniform distribution to guarantee thorough and effective decomposition.
• Insignificant pressure reduction to uphold system efficacy.

Conceptual Design and Optimization

Various elements determine how a convergent-divergent nozzle should be designed.

Flow Dynamics gives exhaust gas propulsion to supersonic velocities after minimizing energy waste.

Engineers must build the throat with precise specifications because it helps reach Mach 1 velocity along with subsonic-supersonic transition.

The nozzle requires materials that can endure high temperatures together with elevated pressures alongside thermal and mechanical strains caused by exhaust gases.

Manufacturability reaches its goal through the selection of cost-effective materials followed by advanced fabrication methods and optimal nozzle design.

Engineers have designed these components to excel throughout different pressure levels especially within rocket systems that need staged operations.

Types of Nozzles and Their Concepts

1. The convergent-divergent nozzle includes a converging section that leads to a nozzle throat and an outward diverging section to boost subsonic exhaust into supersonic speeds. • Benefits: High efficiency and appropriate for supersonic flows. Launch vehicles together with rocket stages utilize these nozzles for their operations.

2. Bell Nozzles A Small C-D nozzle possesses a flared bell shape for its design. The system provides better altitude adjustment capability and reduces aircraft weight because of its design. • Uses: Contemporary rockets and spacecraft.

3. Nozzles for Aerospike The exhaust expands by external means using a central spike as the primary design. Adjustment for altitude becomes possible due to these nozzles and they also demonstrate efficiency across different pressure ranges. • Uses: SSTOs and reusable rockets.

4. Nozzles for plugging • Concept: Merges internal and exterior flow expansion. The system provides both improved thrust-to-weight ratio and performance and allows performance adjustments through specific benefits. • Uses: Advanced aerospace systems.

5. Expansion-Deflection (ED) Nozzles Expansion within the device adapts according to the outside pressure forces. Such nozzles demonstrate flexibility when working at different elevations. The design features two operational environments for these engines.

Why C-D Nozzle Design

1. Efficiency of Flow Expansion

• C-D Nozzle: Guarantees a smooth transition from subsonic to supersonic speeds with minimal losses. • Other Nozzles:

- Bell: Optimized for specific altitudes but less versatile.

The structure of Aerospike nozzle allows it to work at different altitudes despite having complex implementation requirements.

2. Adapting to Pressure

The C-D Nozzle system adapts to surrounding atmospheric pressures properly.

• Additional Nozzles:

Standards of the bell nozzle do not match the lower elevations.

- Aerospike: Performs exceptionally well at different heights.

3. Thermal and Structural Characteristics

• C-D Nozzle: Can withstand high thermal loads.

The aerospike component faces significant thermal strain when operating.

4. Manufacturing and cost efficiency align well with C-D nozzle construction since it is simple to produce and affordable to buy.

• Other Nozzles: Aerospike: 50% more expensive.

5. Dependability

The C-D nozzle presents a construction that demands minimal maintenance activities.

The other nozzle designs which include Aerospike require additional maintenance due to increased material wear.

Methodology

1. CAD Design Using CATIA V5:

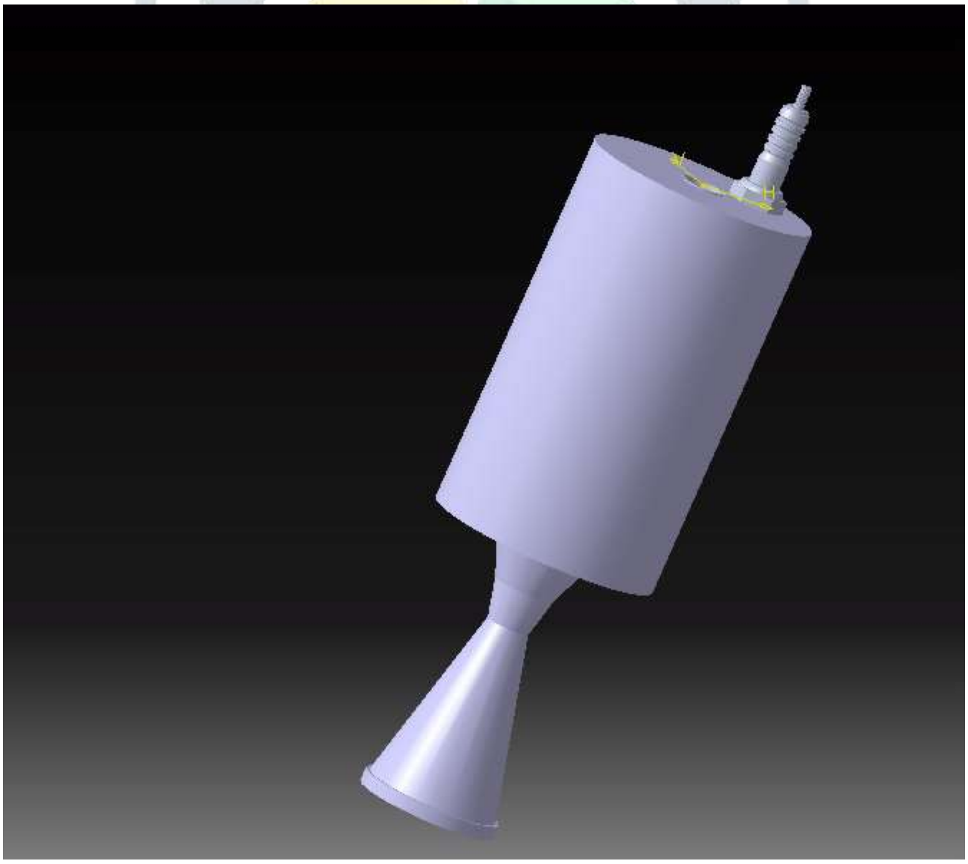
CD Nozzle has been designed to establish stable supersonic flow conditions which shuts off shock waves while allowing efficient expansion to Mach 3 levels.

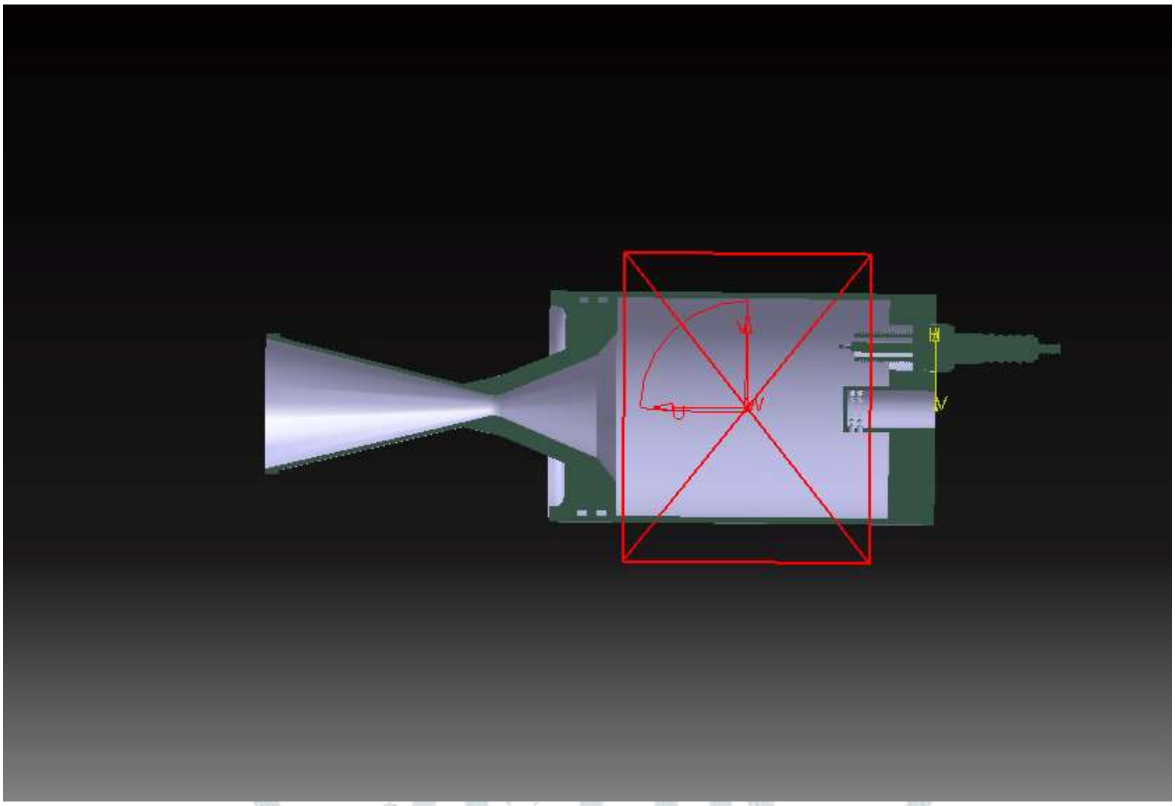
The Combustion Chamber receives specific design attention on high pressure and thermal durability to sustain smooth gas flow through the chamber.

Engineers establish the fuel and oxidizer delivery system using Pintle Injectors to enhance combustion outcomes.

The Spark Plug maintains trustworthy ignition functioning while operating in extreme heat settings.

DESIGN





2. Material Selection:

• Titanium: Selected for the nozzle and combustion chamber due to its outstanding thermal resistance and durability.

The injector along with the spark plug housing uses stainless steel due to its strength properties which help withstand operational stresses.

3. Simulation Using ANSYS Fluent:

The analysis used enhanced mesh boundaries and narrow mesh structures to enhance simulation flow prediction accuracy.

• Boundary Conditions:

• Inlet: Chamber pressure of 15 MPa at a temperature of 890 K.

• Outlet: Atmospheric pressure (~5529 Pa) at a temperature of 216.65 K 20 km above sea level.

The analysis of walls included an assumption of adiabatic conditions to evaluate thermal performance.

• Analysis:

The analysis verified flow characteristics as well as velocity and pressure and temperature values to validate nozzle efficiency.

The simulation conducted thermal analysis to monitor both extreme thermal loading effects and structural performance of the system.

ANALSIS

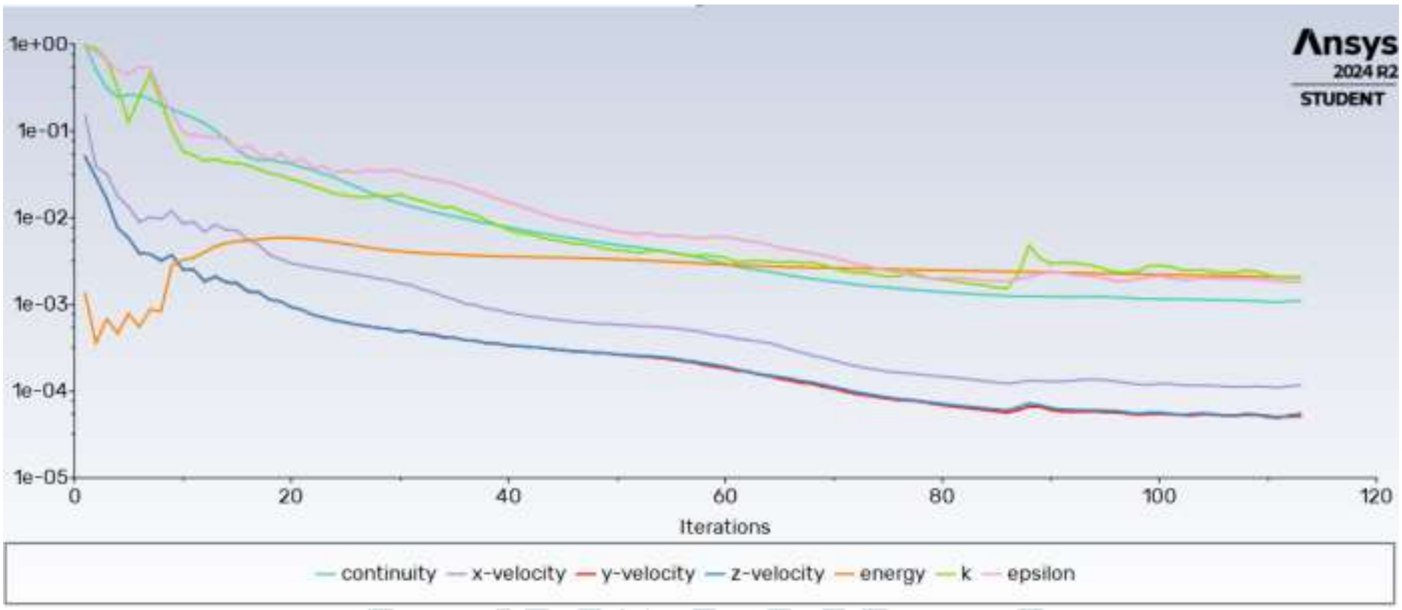


Fig:1- Scaled residual of convergence

Velocity

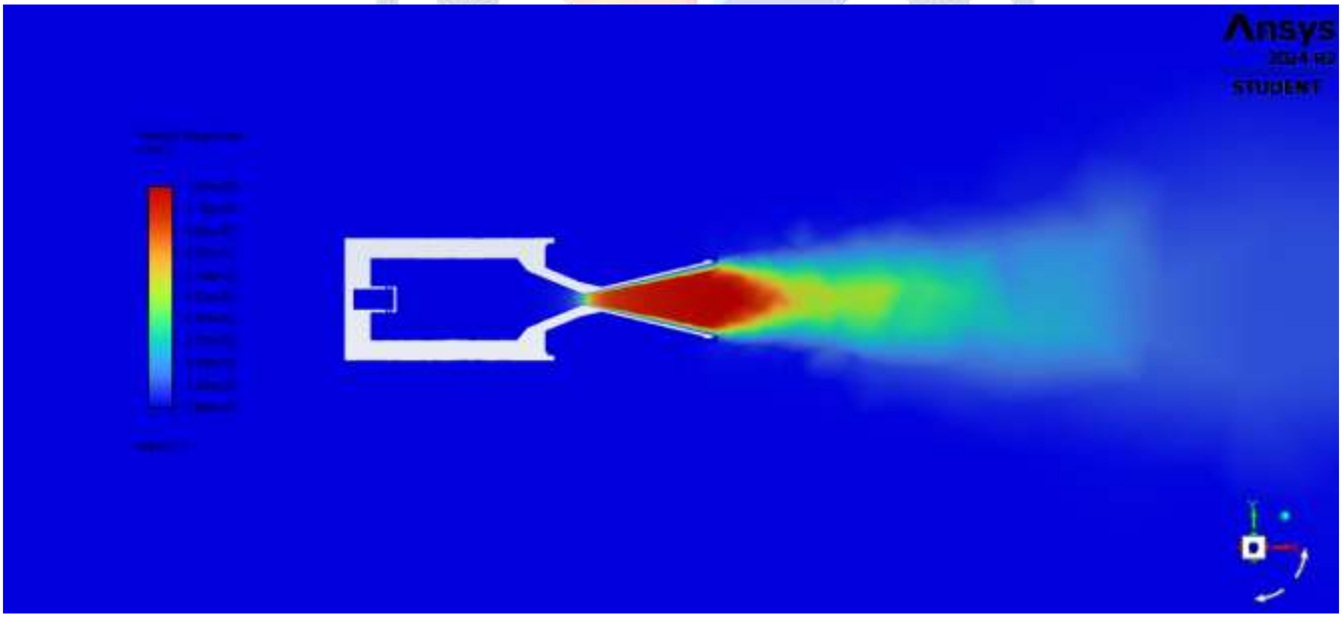


Fig:2- velocity

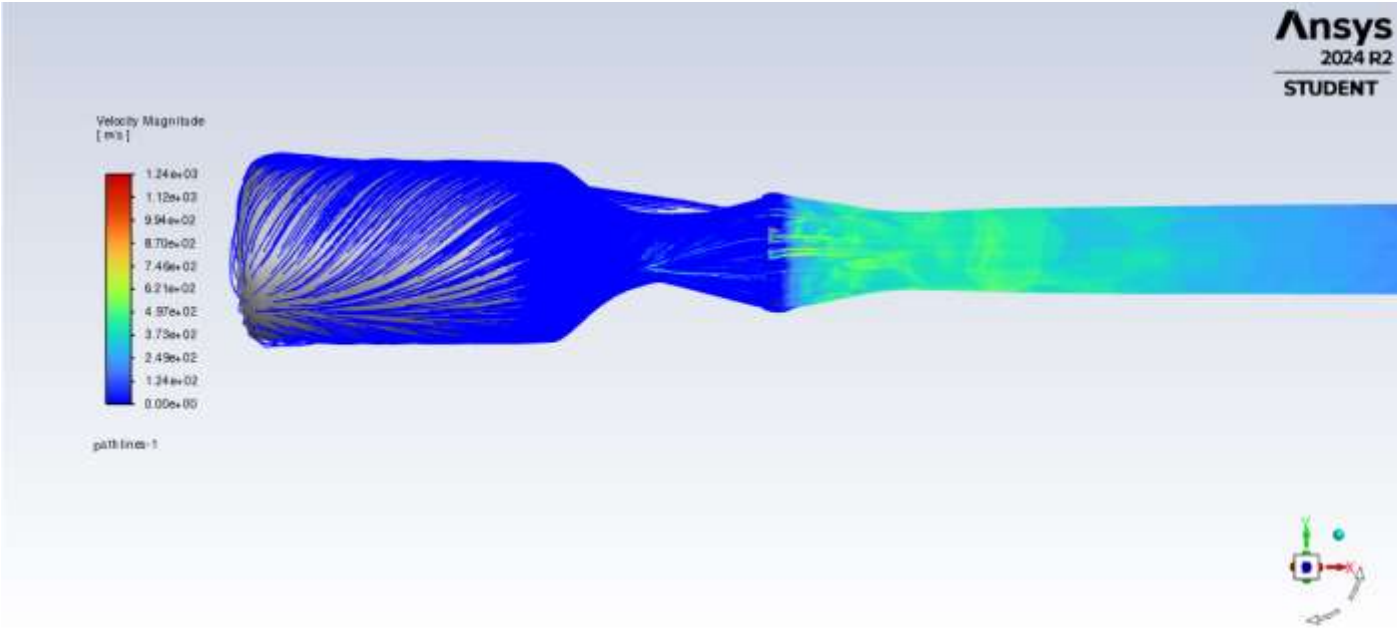


Fig:3 – Velocity Pathlines

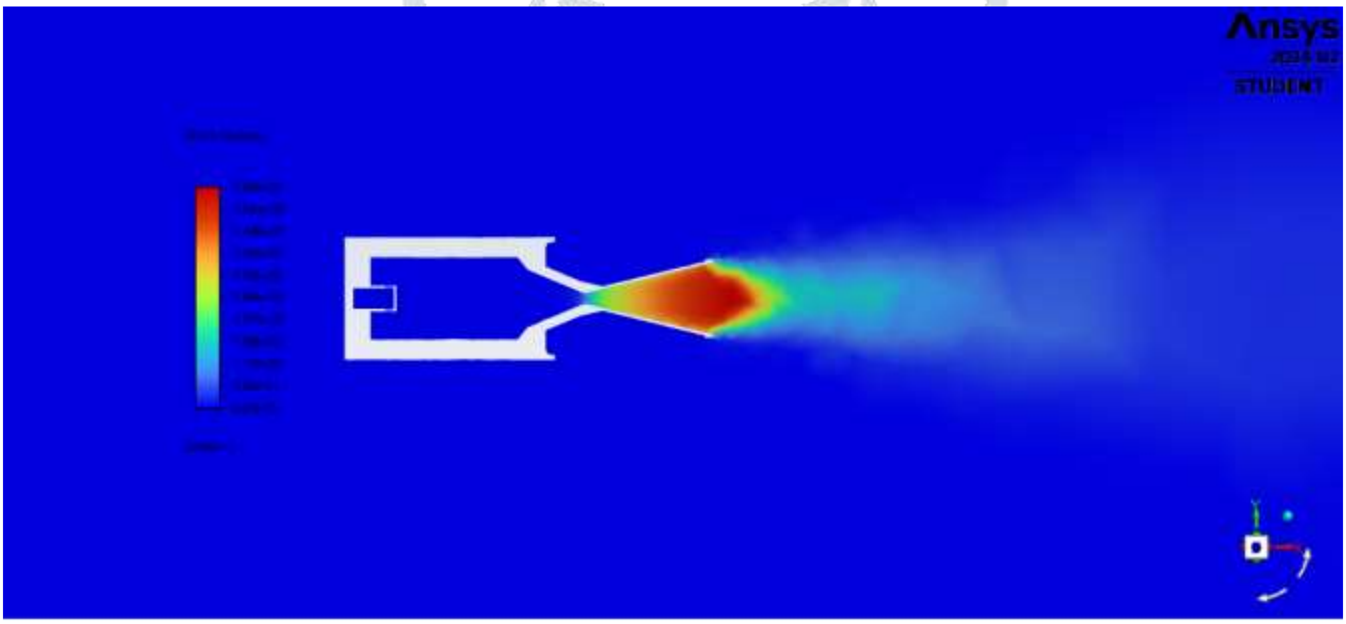


Fig:4- Mach Number

The velocity contour reveals how the exhaust gases decelerate through the nozzle and beyond:

1. Supersonic to Subsonic Transition:

The divergent segment initializes with supersonic airflow that experiences deceleration as the flow travels through the nozzle.

The flow moves from supersonic to subsonic speeds at the throat because of shape changes and pressure increases.

2. Controlled Deceleration:

- The design of the convergent section facilitates a controlled deceleration of the exhaust gases.

Near the nozzle walls the flow vectors demonstrate velocity reduction which minimizes both shock formation and pressure losses.

3. Exit Velocity:

Energy dissipation along with pressure recovery occurs within the flow which results in a significant reduction of exit velocity.

For particular uses that need controlled propulsion combined with thrust stability lower velocities represent a necessary design element.

Pressure

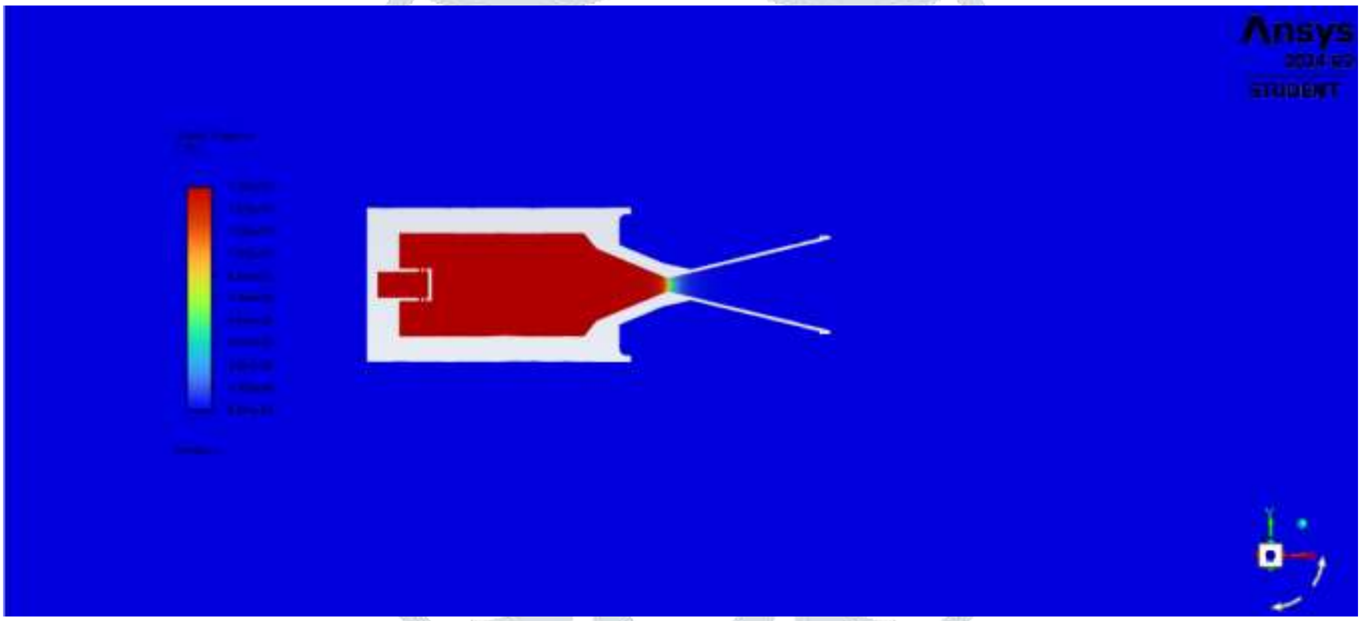


Fig:5 – Static Pressure

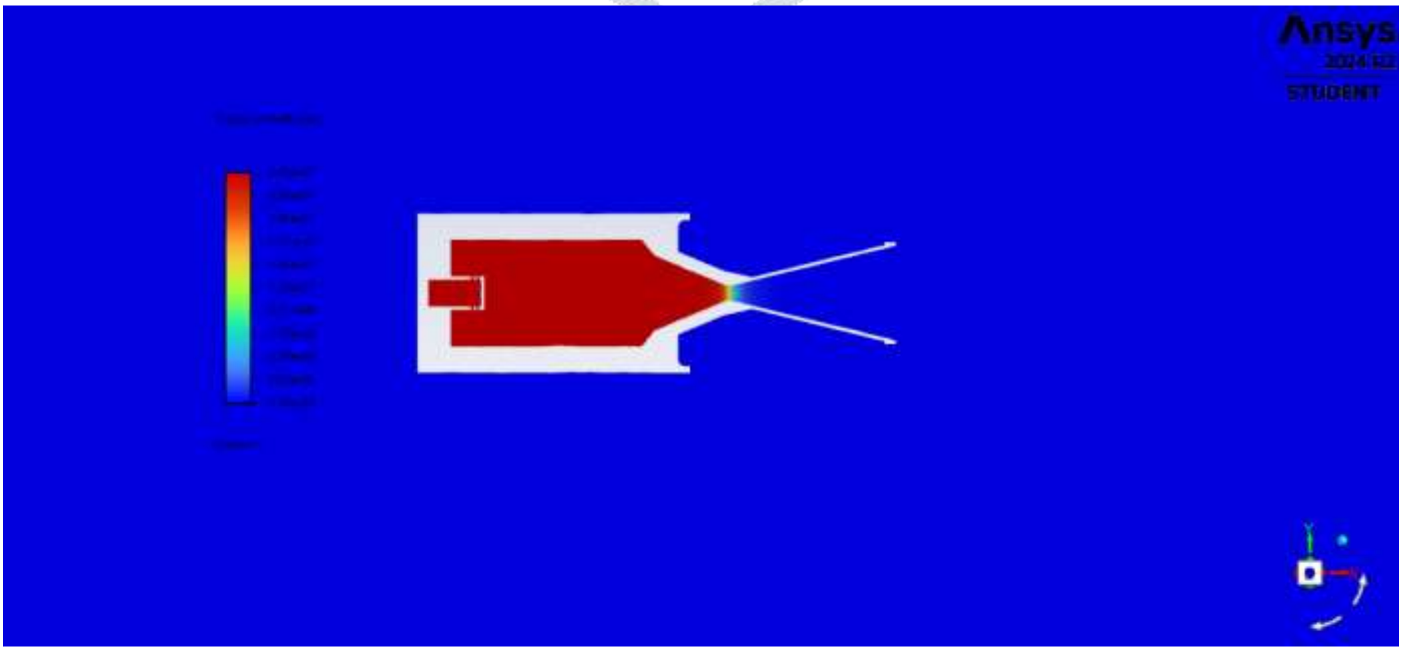


Fig:6- Pressure Coefficient

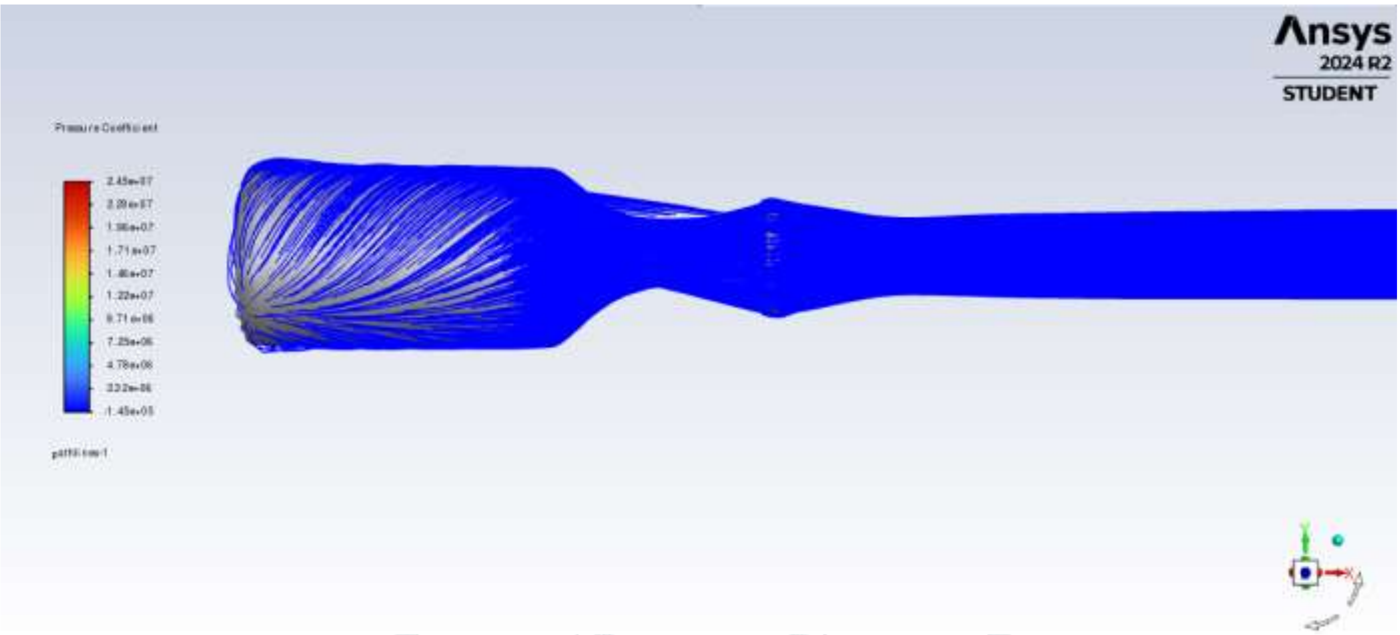


Fig:7- Pressure path lines

The pressure contour illustrates how the exhaust gases expand and interact with the nozzle walls and the external atmosphere:

1. Chamber Pressure:

The pressure level inside the combustion chamber stays at 15 MPa at the inlet.

At such high chamber pressure, the exhaust gases move through the convergent section before achieving Mach 1 speed (choked flow) within the throat.

2. Throat Region:

The flow of gases experiences an enormous pressure reduction when it transitions from subsonic to supersonic velocity.

The nozzle must have precise geometry at this moment because any irregular shapes can generate unnecessary shock waves.

3. Divergent Section:

During expansion the gases maintain their smooth acceleration path because the pressure continues to decrease until reaching supersonic velocity.

The aerospike functions as an essential element which prevents non-uniform pressure distribution inside the exhaust plume.

4. External Plume:

The specific design of the aerospike nozzle allows exhaust flow to respond automatically to changes in atmospheric pressure during flight.

The flow separation reduces and thrust efficiency improves because of a pressure ratio that maintains near-optimal conditions across all altitudes.

Temperature

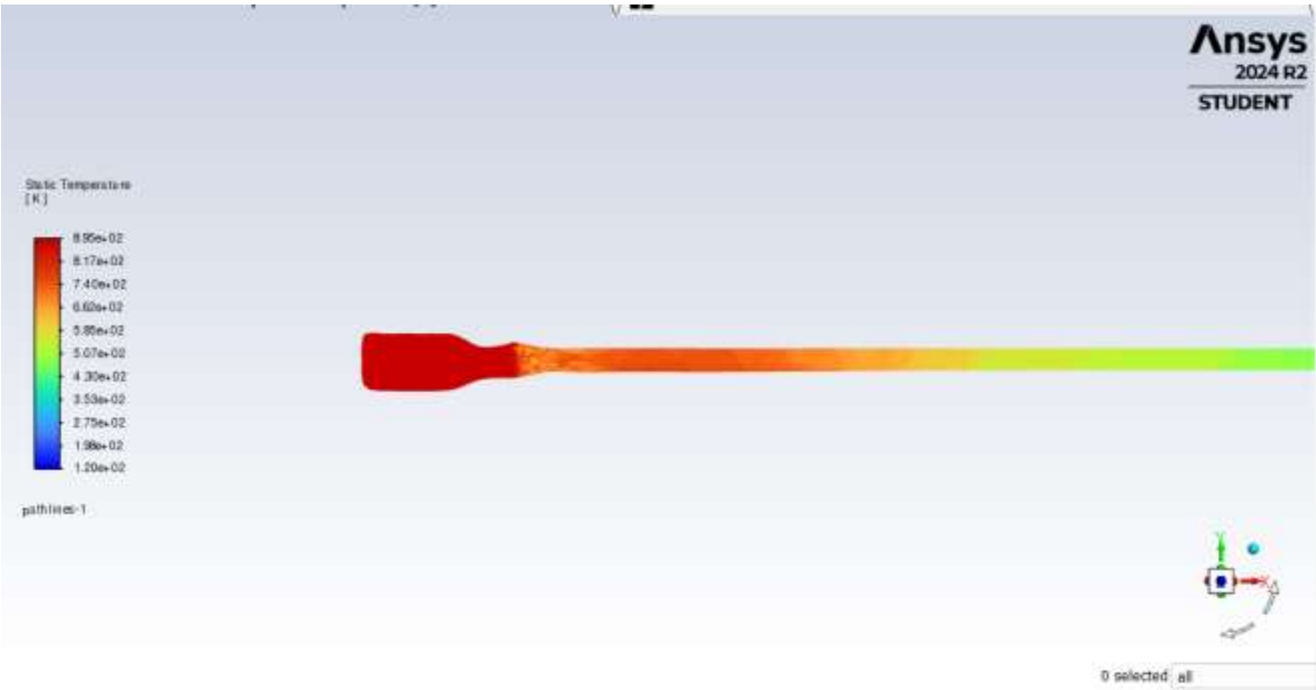


Fig:8- Static Temperature

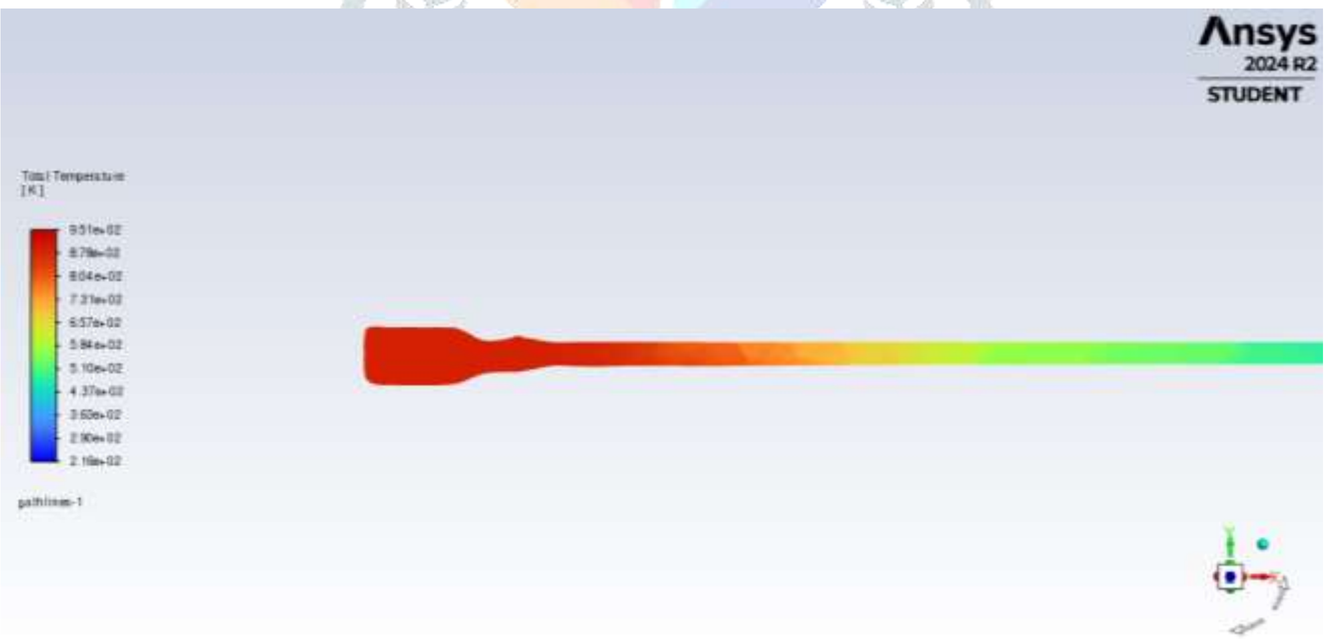


Fig:9 - Total Temperature

Temperature contours highlight the thermal characteristics of the nozzle, essential for understanding material performance and durability:

1. Combustion Chamber:

The inlet temperature stands at around 890 K which results from burning propellant materials.

Gases expand because of thermal energy which enables chemical energy conversion to create thrust through kinetic energy production.

2. Throat Region:

The throat area experiences a thermal decrease while gases accelerate because of isentropic flow behavior which states that velocity increase leads to thermal energy reduction.

Efficient energy transmission happens for propulsion through substantial temperature reduction that occurs when gases expand through the nozzle.

3. External Plume Cooling:

The gases develop additional cooling effects upon exiting the nozzle when they combine with atmospheric air and continue to expand.

The process demonstrates efficient thermal control alongside optimized energy usage because it operates at an outlet temperature of 216 K.

Results

Using ANSYS Fluent, a numerical simulation of the convergent-divergent (CD) rocket nozzle was performed, concentrating on important flow parameters as velocity, pressure, and temperature. The results show that the nozzle is effective at generating a Mach 3 exit velocity while maintaining a stable supersonic flow. The following is a summary of the most important discoveries made throughout the simulation: 1. **Velocity Distribution** • The flow goes from subsonic to supersonic speeds, reaching Mach 1 near the throat.

• The flow expands effectively in the diverging segment, reaching a maximum speed of Mach 3 near the exit of the nozzle.

• The velocity pathlines demonstrate that there is smooth acceleration with little flow separation, which guarantees optimal thrust generation.

2. Distribution of Pressure

• The inlet chamber pressure was set to 15 MPa, which provided the necessary driving force for flow expansion.
• At the throat, there is a large reduction in pressure, which is consistent with the transition from subsonic to supersonic flow.

• The pressure coefficient figure shows that the flow is expanding correctly, with very little shock wave production inside the nozzle.

• At the exit, the pressure adjusts to levels that are close to ambient (about 5529 Pa at an altitude of 20 km), which guarantees effective propulsion.

3. Distribution of Temperature

• The expansion process begins when the temperature of the combustion chamber reaches 890 K.
• A temperature reduction is seen at the neck as a result of the increase in velocity, which is consistent with isentropic flow behaviour.

• The exit temperature stabilizes at 216 K, which means that energy conversion and thermal management are working well.

• According to thermal studies, the nozzle material is able to endure harsh circumstances without compromising its structure.

4. Analysis of Shock and Flow Stability

• The scaled residuals of convergence show that the solutions are converging effectively and that numerical stability is present.

• There was no major shock waves recorded in the diverging portion, which ensured that the expansion was smooth and that energy losses were kept to a minimum.

• The pressure path lines confirm that the pressure field is well-distributed, which prevents flow separation and keeps the nozzle working efficiently.

Discussion

The numerical simulations of the convergent-divergent (CD) rocket nozzle revealed vital insights into its aerodynamic performance, confirming that it is capable of achieving a Mach 3 exit velocity with stable supersonic flow. The following discussion interprets the results in accordance to theoretical predictions, highlighting significant performance factors and areas for prospective improvements.

1. Distribution of Velocity and Expansion of Flow

The velocity contours and path lines demonstrate that the flow follows the expected supersonic expansion profile:
• The transition from subsonic to supersonic at the throat (Mach 1) is in good condition, with no indications of negative pressure gradients or undesired shock waves.
• The flow speeds up effectively in the divergent region, reaching Mach 3 at the nozzle exit. This shows that energy is being converted from thermal energy to kinetic energy in an efficient way.
• The velocity gradient is smooth, which indicates that the nozzle's design is well-optimized for minimizing boundary layer separation and maintaining a consistent flow expansion.
However, there are some tiny flow non-uniformities near the nozzle exit, which show that there is a slight mismatch between the flow expansion and the ambient pressure. The nozzle contour might be changed to make it more adaptable to different altitudes, which would further optimize this.

2. Management of Pressure Distribution and Shock
The pressure contours give information on how efficiently the flow expands:
• The combustion chamber pressure (15 MPa) efficiently drives the gases through the throat, permitting choked flow at Mach 1.
• A large pressure decrease at the throat aligns with expected compressible flow behaviour, indicating correct flow acceleration
• The pressure coefficient plot demonstrates that the expansion is smooth and that there are very few shock forms inside the nozzle.
Even though these results are promising, it may be beneficial to conduct further analysis on probable shock interactions in the exterior plume. The presence of expansion and compression waves in the exhaust jet indicates that some energy is lost because the ambient pressure is not perfectly matched.

3. Thermal Properties and Material Factors
he temperature contours show how well the nozzle performs in terms of thermal performance:
• The high-temperature combustion gases (890 K) undergo isentropic expansion, which converts thermal energy into kinetic energy.
• The temperature decreases in the diverging part, reaching 216 K at the exit, which confirms that energy is being used effectively.
•The materials that were employed (titanium for the nozzle and stainless steel for the injector housing) are appropriate for withstanding the significant thermal and mechanical stresses that were experienced.

The thermal stress distribution should be investigated further to identify possible hot spots that could cause localized material fatigue during extended operation. Using sophisticated cooling methods, including regenerative cooling, may improve durability.

4. Analysis of Shock Wave and Flow Stability

The scaled residuals of convergence indicate numerical stability, with smooth residual decreases in the governing equations, indicating a credible simulation output.

• There was no major shock waves recorded inside the nozzle, which ensured that the expansion was smooth.

• External shock interactions that occur close to the nozzle outlet show that there are minor pressure adaption mismatches with the surrounding environment. These mismatches could be improved by changing the shape of the nozzle or by using altitude-compensating designs.

5. Improving Performance and Things to Think About in the Future

Further optimization could be explored in the following areas based on the results:

• Altitude Compensation: The design should be improved to better accommodate different air pressures, especially for rockets with several stages.

• Improvements to the Aerodynamic Shape: Changes to the nozzle contour, such as thrust-optimized parabolic nozzles (TOP) or bell-shaped profiles, could enhance flow expansion and decrease energy losses even further.

• Cooling and Material Enhancements: Future versions may use ceramic coatings or composite materials to improve thermal resistance and reduce weight.

References

1. **Anderson, J. D. (1990). *Modern Compressible Flow: With Historical Perspective*. McGraw-Hill.**
   - **A foundational text on compressible flow dynamics, essential for nozzle design principles.**
2. **Versteeg, H. K., & Malalasekera, W. (2007). *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*. Pearson Education.**
   - **Provides insights into CFD techniques used for nozzle optimization.**
3. **Chiaverini, M. J., & Kuo, K. K. (2007). *Fundamentals of Solid-Propellant Combustion*. AIAA.**
   - **Discusses material considerations for nozzles operating under extreme thermal loads.**
4. **Sutton, G. P., & Biblarz, O. (2016). *Rocket Propulsion Elements*. John Wiley & Sons.**
   - **Comprehensive coverage of rocket propulsion systems and nozzle design.**
5. **Hill, P., & Peterson, C. (1992). *Mechanics and Thermodynamics of Propulsion*. Addison-Wesley.**
   - **Offers detailed analysis of propulsion mechanics and thermodynamic processes.**
6. **Huzel, D. K., & Huang, D. H. (1992). *Modern Engineering for Design of Liquid-Propellant Rocket Engines*. AIAA.**
   - **Provides engineering perspectives on combustion chambers and nozzle integration.**
7. **Menter, F. R. (1994). "Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications." *AIAA Journal*, 32(8), 1598-1605.**
   - **Discusses turbulence modelling techniques relevant to CFD simulations of nozzle flows.**
8. **Zu crow, M. J., & Hoffman, J. D. (1976). *Gas Dynamics*. Wiley.**
   - **Focuses on gas dynamics critical for understanding supersonic flow in nozzles.**
9. **Spalding, D. B. (1974). "A Single Formula for the Law of the Wall." *Journal of Applied Mechanics*.**
   - **Fundamental for boundary layer analysis in high-speed flows.**
10. **NASA Technical Reports Server (NTRS). "Rocket Nozzle Design Optimization and Experimental Validation."**
    - **A collection of technical reports on experimental validation and optimization techniques.**