COUPLED THERMAL AND STRUCTURAL ANALYSIS OF A HYBRID ROCKET'S NOZZLE

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Abstract - *This study explores the Computational Fluid Dynamics (CFD) and static structural analysis of a Diverging-Exit (DE) nozzle for a hybrid rocket systemusing Hydroxyl-Terminated Polybutadiene (HTPB) as solid fuel and Nitrous Oxide (N_2O) as the oxidizer. CFD simulations analysed internal flow characteristics, including pressure distribution, velocity profiles, and thermal gradients, to optimize expansion efficiency, thrust performance, and identify shock formations. Static structural analysis evaluated the nozzle's mechanical integrity under operational conditions, focusing on thermal stresses and material deformations. Results indicate that nozzle performance is highly sensitive to back pressure, with shock waves significantly affecting thrust and exit velocity. Ti-6Al-4V was identified as the optimal material due to its superior mechanical and thermal properties. The findings provide valuable insights for optimizing nozzle design, enhancing the performance, reliability, and longevity of hybrid rocket propulsion systems.*

***Key Words*: Hybrid Rocket Propulsion, Nozzle Design Optimization, CFD, Material Selection, Thrust Efficiency, Thermal Stress.**

1.INTRODUCTION

1.1 Hybrid Rocket Propulsion

Rocket propulsion systems are critical for space exploration, defence, and scientific research. Among the various propulsion systems, hybrid rockets have gained attention due to their unique combination of solid and liquid rocket characteristics. Hybrid rockets use a solid fuel, typically Hydroxyl-Terminated Polybutadiene (HTPB), and a liquid or gaseous oxidizer, such as Nitrous Oxide (N_2O). This configuration provides several advantages, including enhanced safety, controllability, and cost-effectiveness compared to traditional solid and liquid rockets.

One of the key advantages of hybrid rocket propulsion is its inherent safety. Unlike solid rockets, where the fuel and oxidizer are premixed, hybrid rockets store the fuel and oxidizer separately, significantly reducing the risk of accidental detonation. Additionally, hybrid rockets offer throttling and restart capabilities, making them ideal for missions requiring variable thrust levels, such as precision landings or multiple burn sequences in space exploration.

1.2 Importance of Nozzle Design in Hybrid Rockets

The nozzle is a critical component of any rocket propulsion system, responsible for converting the high-pressure, high-temperature combustion gases into a high-velocity exhaust jet, thereby generating thrust. In hybrid rockets, the nozzle's design and material selection significantly impact the overall efficiency, stability, and thrust generation. The Convergent-Divergent (C-D) nozzle, also known as the De Laval nozzle, is commonly used in hybrid rockets to accelerate exhaust gases to supersonic speeds, maximizing thrust efficiency.

This study focuses on the design, CFD analysis, and static structural evaluation of a C-D nozzle for hybrid rocket engines utilizing HTPB as the fuel and N_2O as the oxidizer. The primary objectives are to optimize nozzle performance, minimize energy losses, and ensure structural resilience under extreme operational conditions.

1.3 Nozzle Design and Performance

Numerous studies have explored the design and performance of rocket nozzles, particularly in the context of hybrid propulsion systems. Berens (2019) investigated the impact of thrust vectoring on nozzle performance, highlighting the importance of nozzle geometry in achieving optimal thrust and stability. Anderson et al. (1997) conducted experimental studies on hybrid fluidic/mechanical thrust vectoring, demonstrating the feasibility of using fixed-exit nozzles for enhanced manoeuvrability.

Recent advancements in CFD have enabled more accurate simulations of nozzle flow dynamics. Pansari and Jilani (2013) conducted a numerical investigation of the performance of C-D nozzles, identifying the formation of shock waves as a critical factor affecting thrust efficiency. Similarly, Ande and Yerraboina (2018) studied the effect of divergent angle on nozzle performance, concluding that an optimal divergent angle of 15° maximizes exhaust velocity.

1.4 Material Selection for Nozzles

Material selection is crucial for ensuring the structural integrity and longevity of rocket nozzles. Ablative materials, such as carbon composites, are commonly used in high-temperature environments due to their ability to dissipate heat through gradual erosion. However, these materials have limited lifespans and require frequent replacement (Chiaverini & Kuo, 2007). Regeneratively cooled nozzles, which use circulating coolant to prevent overheating, offer extended lifespans but increase design complexity and weight (Sutton & Biblarz, 2016).

Recent studies have explored the use of advanced materials, such as Ti-6Al-4V and Inconel 718, for nozzle construction. These materials offer excellent thermal resistance and mechanical strength, making them suitable for high-thrust, long-duration missions (Belega et al., 2015).

2. PROBLEM DESCRIPTION

Despite the growing interest in hybrid rocket propulsion, several technical challenges remain in optimizing nozzle performance. The primary concerns include:

2.1 Flow Behaviour and Performance Optimization

The nozzle geometry significantly influences the expansion efficiency of exhaust gases. Inefficiencies in the design can lead to shock formations, pressure losses, and thermal inefficiencies, ultimately reducing thrust. A lack of comprehensive CFD simulations in hybrid rocket nozzles has resulted in limited understanding of internal flow dynamics.

2.2 Structural Integrity Under High Thermal and Mechanical Loads

Hybrid rockets generate extreme thermal and mechanical stresses on the nozzle due to high-temperature combustion and rapid exhaust gas expansion. Nozzles must withstand high thermal gradients, mechanical stresses, and material fatigue.

2.3 Material Selection and Cooling Strategies

The choice of materials for the nozzle is crucial in determining its lifespan, efficiency, and cost-effectiveness. A trade-off exists between using ablative materials, ceramic composites, and actively cooled metallic alloys.

3. METHODOLOGY

3.1 Nozzle Design

The design of the C-D nozzle was based on the De Laval nozzle geometry, which consists of a converging section, a throat, and a diverging section. The key parameters for nozzle design include the throat diameter (Dt), exit diameter (De), expansion ratio (ε), and nozzle length. The throat diameter was calculated using the mass flow rate equation:

$$\dot{m} = \rho_0 A_t v_0 \qquad (1)$$

Where, $\dot{m}$ is the mass flow rate, ρ_0 is the density of the propellant at the chamber pressure, A_t is the cross-sectional area of the throat $A_t = \frac{\pi D_t^2}{4}$,

v_0 is the exhaust velocity at the throat.

Increasing the chamber's temperature will increase the rocket's efficiency. Less pronounced is the effect of pressure ratio and basic heat dissipation. The coefficient of nozzle expansion is also an important parameter of nozzle design: $\varepsilon = \frac{A_e}{A_t} = \left(\frac{P_c}{P_e}\right)^{\frac{1}{\gamma-1}}$ (2)

The output pressure of a rocket nozzle is typically designed to be equal to or slightly higher than the surrounding atmospheric pressure at a specific altitude (often at sea level or the design altitude). This ensures optimal performance and minimizes losses due to over- or under-expansion of the exhaust gases. However, as the rocket ascends and the atmospheric pressure decreases, the pressure thrust component of the total thrust changes

$$F=\dot{m}\cdot v_e+(P_e-P_a)\cdot A_e \qquad (3)$$

The exhaust velocity (v_e) is calculated using the enthalpy change between the chamber and the exit:

$$v_e=\sqrt{2\cdot(h_e-h_o)} \qquad (4)$$

Using isentropic relations, the exhaust velocity can also be expressed in terms of temperature and pressure ratios

$$v_e = \sqrt{\frac{2\gamma}{\gamma-1} RT_c\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{(\gamma-1)}{\gamma}}\right]} \qquad (5)$$

3.2 Computational Fluid Dynamics (CFD) Analysis

CFD simulations were conducted using ANSYS Fluent to analyse the internal flow dynamics within the nozzle. The simulations focused on pressure distribution, velocity profiles, and thermal gradients. The governing equations for compressible flow, including the Navier-Stokes equations, were solved using a finite volume method. The simulations were performed for various back pressures to study the impact of shock waves on nozzle performance. In the nozzle CFD analysis, the following steps were performed:

1. Modelling
2. Meshing
3. Pre-Processing
4. Solution
5. Post-Processing

3.3 Static Structural Analysis

Static structural analysis was conducted using ANSYS Mechanical to evaluate the nozzle's mechanical integrity under operational conditions. The analysis focused on thermal stresses, material deformation, and structural stability. The nozzle was modelled using Ti-6Al-4V, Inconel 718, and AlSi10Mg, and the results were compared to determine the most suitable material for nozzle construction.

4. CALCULATIONS

The design of a De Laval nozzle for a hybrid rocket engine involves several calculations. For a typical hybrid rocket propellant, such as nitrous oxide (N_2O) as the oxidizer and HTPB as the fuel, the following parameters were calculated:

- **Throat Diameter (D_t):** 6.43 cm
- **Exit Diameter (D_e):** 59.5 cm
- **Expansion Ratio (ε):** 85.74
- **Exit Velocity (v_e):** 951.2 m/s
- **Nozzle Length (L):** 25.7 cm
- **Wall Thickness (t):** 2 cm

5. INTRODUCTION TO CAD

Computer-Aided Design (CAD) is a powerful tool for designing and analysing engineering components. SOLIDWORKS, a widely used CAD software, was employed to create a 3D model of the C-D nozzle. The nozzle was designed using sketch-based modelling, extrusions, and revolves, and the final model was saved in IGES format for further analysis.

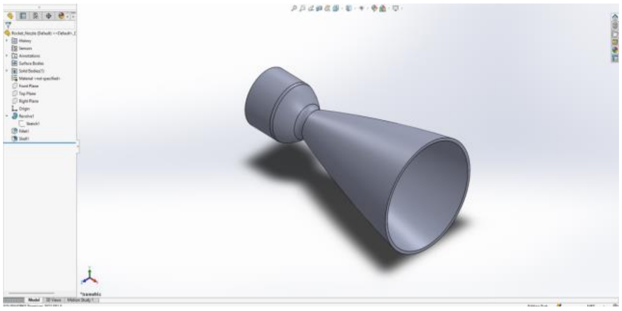

Fig5.1: Final 3D model of CD Nozzle.

6.SIMULATION AND EXPERIMENTAL WORK

6.1 Computational Fluid Dynamics (CFD) Simulation

CFD simulations were conducted using ANSYS Fluent to analyse the internal flow characteristics of the C-D nozzle. The simulations focused on pressure distribution, velocity profiles, and thermal gradients within the nozzle. The results were used to optimize the nozzle design for maximum thrust and efficiency.

6.1.1 Meshing and Boundary Conditions

The nozzle geometry was discretized into finite elements, and boundary conditions were applied to simulate the flow of exhaust gases. The inlet pressure was set to 9.8 MPa, and the outlet pressure was varied to study the effect of back pressure on nozzle performance.

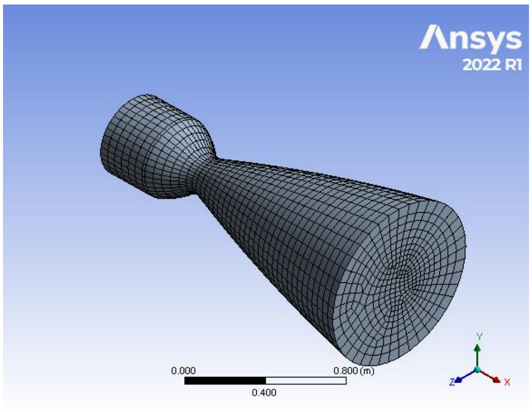

Fig6.1: Meshed part of fluid domain

6.1.2 Results of CFD Simulation

The CFD simulation results showed that the nozzle achieved supersonic flow at the exit, with a Mach number of 3.647. The pressure and velocity distributions within the nozzle were analysed to identify areas of high stress and potential shock wave formation.

7. FINITE ELEMENT ANALYSIS (FEA)

Finite Element Analysis (FEA) was used to evaluate the structural integrity of the nozzle under operational conditions. The analysis involved discretizing the nozzle into finite elements, applying boundary conditions, and solving for nodal displacements, stresses, and strains. The results were used to assess the performance of different materials, including Ti-6Al-4V, Inconel 718, and AlSi10Mg.

7.1 Material Analysis

- **Ti-6Al-4V:** This material exhibited the lowest deformation and highest equivalent elastic strain, making it the most suitable for CD nozzles.
- **Inconel 718:** While offering slightly higher stress resistance, Inconel 718 had low elastic strain, making it less suitable for CD nozzles.
- **AlSi10Mg:** Despite its high stress resistance, excessive deformation made AlSi10Mg inadequate for high-precision, high-stress applications.

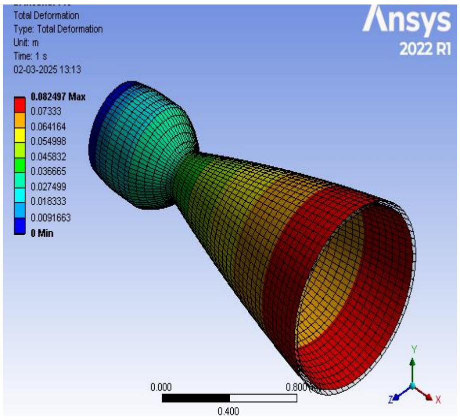

Fig 7.1: Total deformation on Ti-6Al-4V

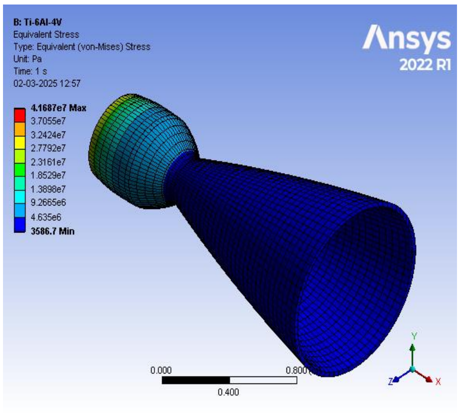

Fig7.2: Equivalent stress on Ti-6Al-4V

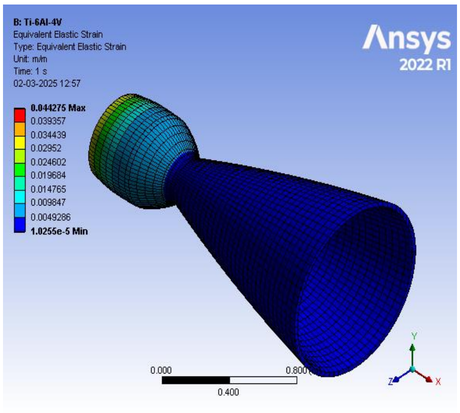

Fig7.3: Equivalent strain on Ti-6Al-4V

TABLE1: Compared the stress value the maximum yield strength and the material satisfied.

Material	**Max. Deformation (m)**	**Max. Equivalent stress (Pa)**	**Max. Equivalent elastic strain (m/m)**
Ti-6Al-4V	0.055394	$4.1687e^{7}$	0.044275
Inconel 718	0.082497	$4.2878e^{7}$	0.0013047
AlSi10Mg	0.1088	$2.1276e^{8}$	0.0031809

8.RESULTS

The CFD simulations were conducted to analyse the internal flow characteristics of the C-D nozzle, including pressure distribution, velocity profiles, and thermal gradients. The residuals graph, shown below, illustrates the convergence of the simulation, indicating that the solution reached a stable and accurate state.

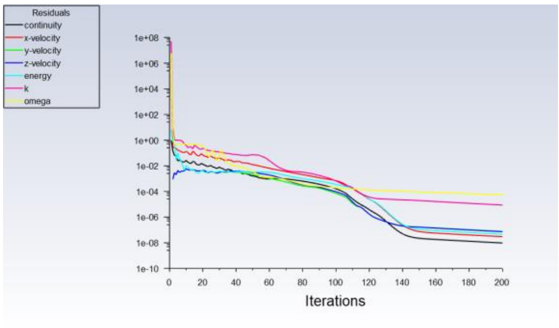

Fig8.1: Residual graph

This graph confirms that the CFD simulation achieved sufficient accuracy, providing reliable results for further analysis. The convergence of residuals is a critical indicator of the simulation's stability and validity, ensuring that the results can be trusted for optimizing nozzle performance.

8.1 Back Pressure vs. Exit Velocity

The graph highlights the inverse relationship between back pressure and exit velocity in a C-D nozzle. As back pressure increases, the exit velocity of exhaust gases progressively declines, signifying a loss of kinetic energy.

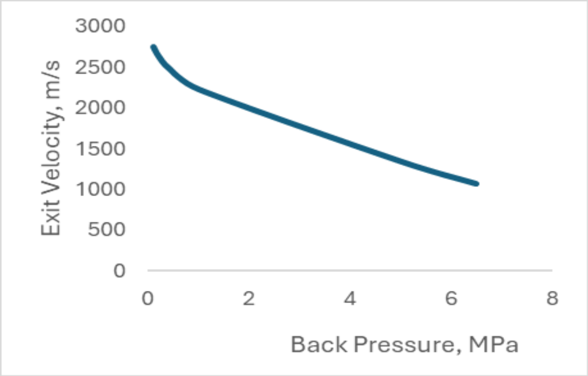

Fig8.2: Back Pressure vs. Exit Velocity

8.2 Back Pressure vs. Exit Temperature

The graph illustrates the direct relationship between back pressure and exit temperature. As back pressure rises, the exit temperature of the exhaust gases increases, indicating a reduction in the efficiency of thermal energy conversion into kinetic energy.

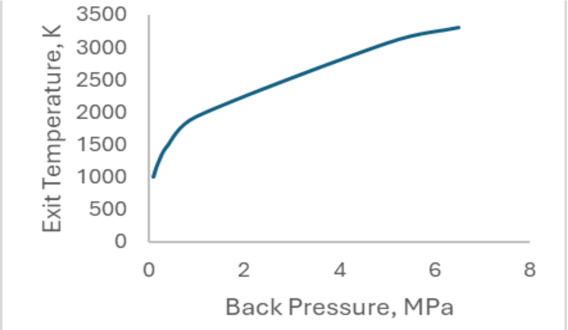

Fig8.3: Back Pressure vs. Exit Temperature

8.3 Back Pressure vs. Thrust

The graph shows the critical interplay between back pressure and thrust performance. At near-zero back pressure, there is a sharp surge in thrust, indicating optimal nozzle performance. However, even minor increases in back pressure cause a rapid thrust decline.

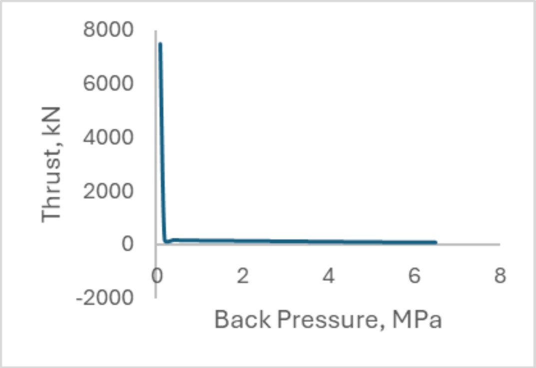

Fig 8.4: Back Pressure vs. Thrust

9.CONCLUSION

The study concludes that Ti-6Al-4V is the most suitable material for Convergent-Divergent (C-D) nozzles in hybrid rocket systems due to its superior mechanical properties, including low deformation and high elastic strain. The analysis highlights the significant impact of back pressure on nozzle performance, with increased back pressure leading to shock wave formation, reduced thrust, and higher exit temperatures. Experimental tests validated the CFD simulations, confirming the accuracy of the simulation model. The findings emphasize the need for precise nozzle design tailored to specific operating conditions, balancing thrust, efficiency, and structural integrity. Future research should focus on adaptive nozzle designs, advanced materials, and improved cooling techniques to optimize performance across varying altitudes and back pressures. This study provides a robust framework for advancing hybrid rocket propulsion systems, contributing to more efficient and reliable aerospace and space exploration applications.

Additionally, the study underscores the importance of integrating computational and experimental approaches to achieve reliable and robust nozzle designs. The combination of CFD simulations, Finite Element Analysis (FEA), and experimental validation offers a comprehensive understanding of nozzle behaviour under extreme conditions. By addressing the challenges of thermal management, material selection, and performance optimization, this research paves the way for innovative solutions in hybrid rocket propulsion. The insights gained from this study can be applied to develop next-generation nozzles capable of withstanding higher thermal and mechanical loads, ultimately enhancing the safety, efficiency, and sustainability of hybrid rocket systems for future space missions.

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BIOGRAPHIES

*Dr.J.Kalpana, an associate professor at Sanketika Vidhya Parishad Engineering College, serves as our invaluable guide for this project in Mechanical Engineering. With over 11 years of experience in to her field and holding a PhD in Mechanical Engineering from Centurion University ODISHA, Kalpana ' expertise greatly contributes to the project's success. Under her mentorship, we have conducted tests and obtained results with significant potential for future applications. Kalpana not only provides guidance but also extends extensive support throughout the project, ensuring its smooth progress. Our case study on "**Coupled Thermal and Structural Analysis of a Hybrid Rocket's Nozzle"** specifically revolves around **improving hybrid rocket nozzle design** by balancing **aerodynamic efficiency** and **structural durability**, supporting advancements in reusable and high-performance propulsion system using technologies in Mechanical Engineering, benefiting from Kalpana's profound knowledge and guidance benefiting from Kalpana's profound knowledge and guidance*

***.Vijaya Raghavendra**: M. Vijaya Raghavendra is a dedicated 4th-year Mechanical Engineering student at Sanketika Vidya Parishad Engineering College with a strong theoretical knowledge and hands-on research experience in thermal-structural analysis and aerospace propulsion systems. As a team leader to the analysis project "**Coupled Thermal and Structural Analysis of a Hybrid Rocket's Nozzle**. The student demonstrated expertise in computational fluid dynamics (CFD), finite element analysis (FEA), and material selection for high-temperature applications, His work involved optimizing nozzle performance using ANSYS simulations, validating results through experimental testing, and identifying Ti-6Al-4V as the most suitable material for rocket nozzles due to its superior thermal and mechanical properties. The candidate holds certifications in CAD/CAM/CNC operations, and Generative AI applications, reflecting a versatile skill set., they combine theoretical knowledge with practical engineering solutions. Known for strong analytical thinking, problem-solving abilities, and adaptability to emerging technologies..*