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Flow Analysis Of Supersonic Nozzle For Rocket Propulsion System

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Abstract- A supersonic nozzle normally has a converging-diverging shape, in which high-pressure gases pass through the throat and expand in the diverging section to attain supersonic velocity and generate thrust. When the exit area of the nozzle is changed, the expansion of gases at the outlet also changes, which directly affects pressure, velocity, Mach number, temperature, and thrust performance. In this project, the basic nozzle profile is maintained and only the exit area is varied by creating three different nozzle models to study the influence of exit area on the flow characteristics of a rocket propulsion system. The main purpose of changing the exit area is to identify which nozzle configuration provides better gas expansion and improved propulsion performance. A proper exit area can increase exhaust velocity, reduce pressure losses, improve thrust efficiency, and provide stable supersonic flow at the nozzle outlet. All three models are designed in Creo using Ni-Co-Cr- alloy-_wrought alloy as the selected material, and the flow analysis is carried out in ANSYS Fluent through CFD simulation. By comparing the results of the three models, the most suitable exit area can be identified based on better pressure distribution, velocity, Mach number, and thrust behavior. Thus, this project provides a simple and effective method for optimizing supersonic nozzle design and improving the efficiency of rocket propulsion systems.

keywords: Supersonic nozzle, Rocket Propulsion, Mach number, Nozzle Exit Area, Thrust Performance, CREO, ANSYS Fluent.

I. INTRODUCTION

Rocket propulsion systems use supersonic nozzles to accelerate exhaust gases from subsonic speeds at the throat to supersonic velocities at the exit. This acceleration generates thrust based on Newton's third law of motion. The most common supersonic nozzle type is the convergent- divergent (C-D) nozzle, also called a de Laval nozzle

Three Main Section:

Convergent Section-Compresses and accelerates the flow to sonic speed (Mach1) at the throat.

Throat -The narrowest point where the flow reaches Mach 1.

Divergent Section -Expands the flow beyond Mach 1, increasing velocity and producing thrust.

- Improve propulsive efficiency by converting thermal energy into kinetic energy.
- Enable rockets to operate efficiently in space, where there is no atmospheric pressure.
- Allow high Mach number exhaust flow, leading to higher thrust.

Need for the Study

- Supersonic nozzle performance depends on nozzle geometry.
- Exit diameter directly affects expansion ratio.
- Improper exit diameter reduces propulsion.

Problem Statement

- In rocket propulsion systems, selecting the correct nozzle exit diameter is important.

- Smaller exit diameter may lead to incomplete expansion.
- Larger exit diameter may lead to over-
- expansion.

Aim of the Project

To analyze the flow behavior of a supersonic nozzle for rocket propulsion system by varying the exit diameter using CFD.

Scope of the Project

- The project focuses on internal flow analysis of a supersonic nozzle.
- Exit diameter is varied while other dimensions are kept constant.
- CFD simulation is carried out using ANSYS Fluent.
- Pressure, velocity, Mach number, and temperature are studied.
- The project is limited to numerical analysis only.

II. OBJECTIVE OF THE STUDY

Main objective of this study is to analyze the flow characteristics of a supersonic nozzle used in a rocket propulsion system. In rocket engines, the nozzle plays an important role in converting high-pressure and high-temperature gases into high-velocity exhaust flow to generate thrust. This study focuses on understanding how the gas flows through the converging section, throat, and diverging section of the nozzle, and how the nozzle helps in achieving supersonic velocity at the exit.

III. LITERATURE REVIEW

Rao, G. V. R., "Exhaust Nozzle Contour for Optimum Thrust," Jet Propulsion, Vol. 28, No. 6, 19presentezzone of the most important theoretical foundations for rocket nozzle design. In this work, the author explained that the geometry of converging- diverging nozzle strongly affects the expansion of exhaust gases and the overall thrust performance. The study highlighted that the nozzle exit area, which is directly related to the exit diameter, plays a major role in determining the expansion ratio and the conversion of pressure energy into kinetic energy. It was concluded that proper selection of nozzle contour and exit dimensions is essential for achieving maximum thrust in rocket propulsion systems.

Sutton, G. P., and Biblarz, O., "Rocket Propulsion Elements," John Wiley & Sons, 8th Edition, 2010, discussed the operating principles of supersonic nozzles used in rocket engines. Their work explained that the exit diameter of a nozzle directly influences the expansion ratio, which governs the pressure drop, exit velocity, and Mach number at the nozzle outlet. The authors stated that an increase in exit diameter generally increases the expansion of exhaust gases, allowing the nozzle to produce higher exit velocity under ideal conditions. However, they also pointed out that excessive exit diameter may lead to over- expansion, flow separation, and loss in thrust when operating at lower ambient pressures.

IV. METHODOLOGY

The methodology of the present study focuses on the design and flow analysis of a supersonic converging- diverging nozzle used in a rocket propulsion system by varying the exit diameter. In this project, the nozzle is first modeled in Creo using standard dimensions such as inlet diameter, throat diameter, and nozzle length. The inlet diameter, throat diameter, and nozzle length are kept constant, while only the exit diameter is changed to create different nozzle models. These models are then imported into ANSYS Fluent for CFD analysis. The internal flow region of the nozzle is considered for simulation, and suitable meshing is applied. The analysis is carried out under the same boundary conditions for all models to compare the effect of exit diameter on pressure, velocity, temperature, and Mach number. Based on the CFD results, the nozzle model with better supersonic flow characteristics and improved propulsion performance is identified.

Literature Review

- Study the basic theory of supersonic converging-diverging nozzle.
- Review previous works related to rocket nozzle flow analysis.

- Understand the effect of exit diameter variation on nozzle performance.

Selection of Design Parameters
Select the important nozzle dimensions such as:

- Inlet diameter
- Throat diameter
- Nozzle length
- Exit diameter
- Thrust performance Nozzle Design in Creo

  - Create the base nozzle profile in Creo.
  - Use the selected dimensions to sketch the nozzle shape.

  - Generate the 3D model using the revolve
- feature.
  - Exit Diameter Variation
- Export and Import of Model
  - Export the nozzle models from Creo in STEP
- / IGES format.
  - Import the models into ANSYS Workbench
- / Fluent for CFD analysis.

Material and Boundary Conditions
Select air as the working fluid for simplified analysis. Apply the same boundary conditions for all models:

- Inlet pressure
- Outlet pressure
- Wall condition

Result Analysis
Observe the flow parameters such as:

- Pressure
- Velocity
- Temperature
- Mach number

Study the variation of these parameters from inlet to exit.

V. TYPES OF NOZZLES

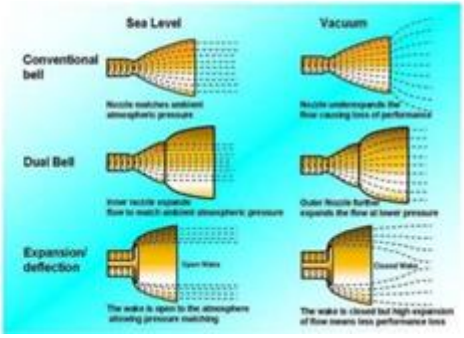

Fig 1: Types of Nozzles

VI. EXIT DIAMETER VARIATION IN SUPERSONIC NOZZLE

The exit diameter of a bell-shaped supersonic nozzle significantly affects the exhaust flow, thrust, and overall rocket propulsion performance. In this study, the bell nozzle's exit diameter was varied at three levels-65 mm, 75 mm, and 85 mm-to analyze its impact on flow characteristics and efficiency. The 65 mm diameter produces higher expansion ratio and exits velocity, while the 85 mm diameter allows higher mass flow but slightly lower exit velocity. The 75 mm diameter serves as a baseline for balanced performance. By modifying the bell nozzle exit diameter, the study evaluates changes in thrust, flow expansion, and nozzle efficiency, providing insight for optimal design in rocket propulsion systems.

65 mm Exit Diameter:
Higher expansion ratio, higher exit velocity, suitable for high-altitude operation.

75 mm Exit Diameter:
Balanced performance, baseline for comparison.

85 mm Exit Diameter:
Higher mass flow, slightly lower exit velocity, suitable for lower altitudes.

Thrust and Efficiency Trends:
Exit diameter variation directly influences nozzle performance.

Design Implication:
Guides selection of bell nozzle exit diameter for optimal rocket performance.

VII. CFD ANALYSIS AND RESULTS

Nozzle Model – 1 (Exit diameter 65mm)

Pressure:

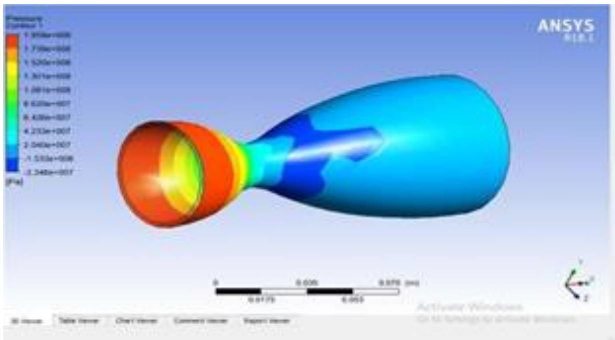

Fig 2: Pressure Distribution In Nozzle

The pressure distribution obtained from the CFD analysis indicates that the pressure is maximum at the inlet section of the nozzle and gradually decreases towards the outlet. As the fluid moves through the converging-diverging section, the pressure energy is converted into velocity, resulting in a significant pressure drop along the nozzle length. This pressure variation confirms the proper flow expansion and acceleration inside the supersonic nozzle.

A supersonic nozzle is an important part of a rocket propulsion system. It is used to convert the high-pressure and high-temperature gases from the combustion chamber into high-speed exhaust flow. This high-speed exhaust produces thrust to move the rocket. In this project, the flow inside the nozzle is analyzed by studying parameters like pressure, velocity, temperature, and Mach number to understand the performance of the nozzle.

Velocity:
Outlet velocity:

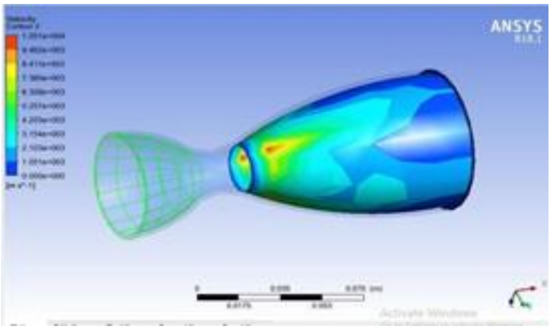

Fig 3: Outlet Velocity Distribution In Nozzle

The velocity contour obtained from the CFD analysis shows that the fluid velocity increases significantly as it passes through the converging-diverging section of the nozzle. The maximum velocity is observed near the throat and exit region, which indicates the effective acceleration of the flow. This increase in velocity confirms the conversion of pressure energy into kinetic energy, demonstrating the efficient performance of the supersonic nozzle. Outlet Velocity – 65 mm Nozzle For the 65 mm exit diameter nozzle, the outlet velocity is significantly higher at the nozzle exit because the gases expand rapidly in the divergent section. After passing through the throat, the flow accelerates due to the decreasing pressure and increasing area of the nozzle. This process converts the pressure and thermal energy of the gases into kinetic energy, which results in a high- speed exhaust flow. In a properly designed supersonic nozzle, the outlet velocity can reach supersonic conditions, which is essential for effective thrust generation.

Inlet velocity:

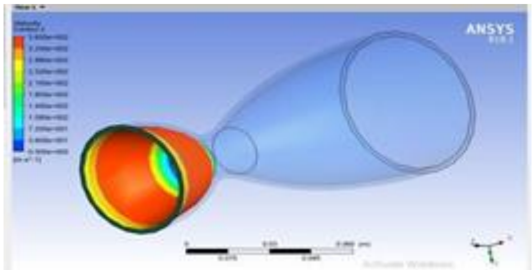

Fig 4: Inlet Pressure Distribution In Nozzle

The velocity contour at the inlet section shows the initial flow condition of the fluid entering the nozzle. The velocity is relatively higher at the inlet region

and gradually changes as the flow approaches the converging section. This indicates the proper entry of the fluid into the nozzle and provides the necessary initial condition for further acceleration through the throat and exit region. Nozzle For the 65 mm exit diameter nozzle, the pressure is maximum at the inlet region and gradually decreases along the length of the nozzle toward the exit. This pressure drop occurs because the high-pressure gases expand and accelerate through the convergent-divergent nozzle. The pressure energy available at the inlet is progressively converted into kinetic energy as the flow moves through the throat and divergent section.

Nozzle Model – 2 (Exit diameter – 75mm):
Pressure:

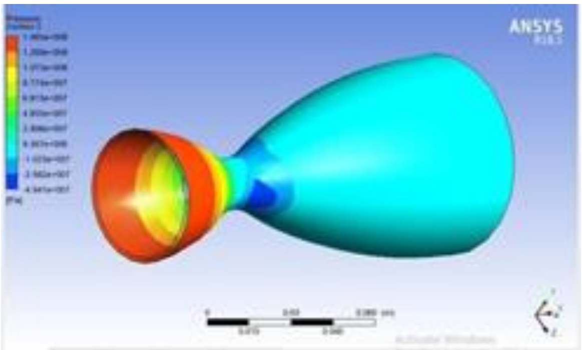

Fig 5: Pressure Distribution In Nozzle

The ANSYS CFD analysis of Nozzle Model 2 with an exit diameter of 75 mm shows that the pressure is maximum at the inlet section and gradually decreases towards the nozzle exit. This pressure reduction indicates the effective conversion of pressure energy into kinetic energy as the fluid accelerates through the nozzle. The pressure contour confirms smooth flow expansion and proper pressure variation along the nozzle length, which is essential for efficient thrust generation in rocket propulsion applications.

Outlet velocity:

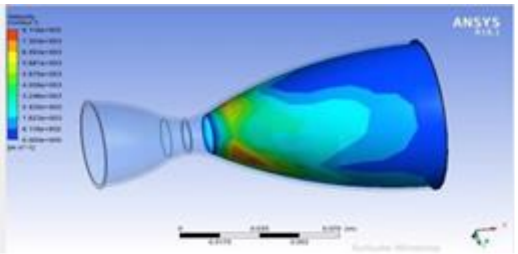

Fig 6: Outlet velocity

The ANSYS CFD analysis shows that the outlet velocity of Nozzle Model 2 (Exit Diameter = 75 mm) is significantly higher compared to the inlet region, indicating effective acceleration of the fluid through the converging-diverging nozzle. The increase in outlet velocity confirms the efficient conversion of pressure energy into kinetic energy, which is essential for producing high-speed exhaust flow and generating thrust in rocket propulsion applications.

The increase in outlet velocity confirms the efficient conversion of pressure energy into kinetic energy, which is essential for producing high-speed exhaust flow and generating thrust in rocket propulsion applications.

Inlet velocity:

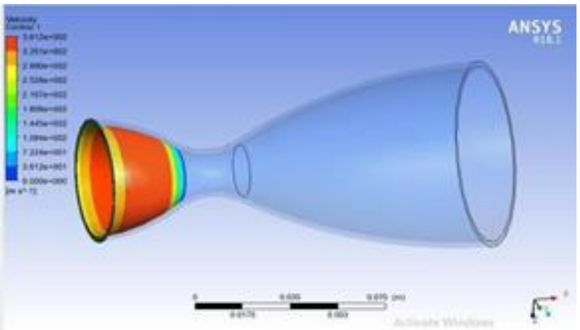

Fig 7: Inlet Velocity Distribution In Nozzle

The ANSYS CFD analysis of Nozzle Model 2 (Exit Diameter = 75 mm) shows that the fluid enters the nozzle with a nearly uniform inlet velocity distribution. As the flow approaches the converging section, the velocity begins to increase gradually, indicating the start of flow acceleration inside the nozzle. This confirms proper inlet flow conditions and establishes an effective initial boundary condition for efficient nozzle performance in rocket propulsion applications.

Nozzle Model – 3 (exit diameter – 85mm): Pressure:

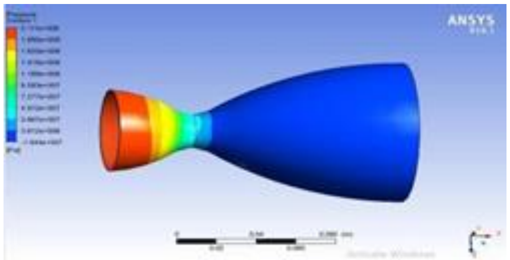

Fig 8: Pressure Distribution In Nozzle

The ANSYS CFD analysis of Nozzle Model 3 (Exit Diameter = 85 mm) shows that the pressure is maximum at the inlet section and gradually decreases towards the nozzle exit. This pressure reduction indicates effective conversion of pressure energy into kinetic energy and confirms proper flow expansion through the nozzle.

Outlet Velocity:

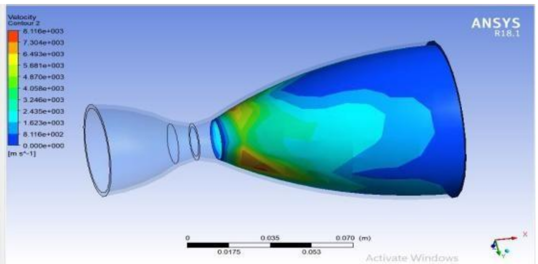

Fig 9: Outlet Velocity Distribution In Nozzle

The outlet velocity contour shows that the fluid attains a high velocity at the nozzle exit, indicating effective flow acceleration through the converging-diverging nozzle. The high outlet velocity confirms efficient thrust-generating capability for rocket propulsion.

Outlet Velocity – 85 mm Nozzle For the 85 mm exit diameter nozzle, the outlet velocity becomes very high at the nozzle exit due to the greater expansion of gases in the divergent section. Since the exit diameter is larger, the gases are allowed to expand more completely after passing through the throat. This results in a more effective conversion of pressure and thermal energy into kinetic energy. As a result, the exhaust gases leave the nozzle at a much higher velocity, often reaching stronger supersonic conditions compared to smaller exit diameters.

Inlet velocity:

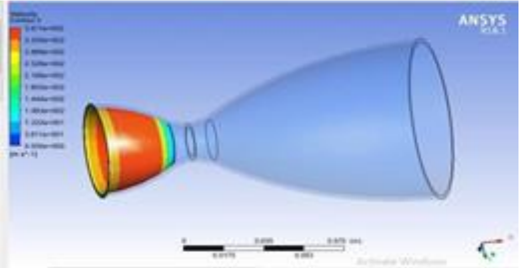

Fig 10: Inlet Velocity Distribution In Nozzle

The inlet velocity contour shows that the fluid enters the nozzle with a nearly uniform velocity distribution. As the flow approaches the converging section, the velocity gradually increases, indicating the start of the acceleration process inside the nozzle.

Inlet Velocity – 85 mm Nozzle For the 85 mm exit diameter nozzle, the inlet velocity is relatively low at the nozzle entrance compared to the outlet region. This is because the gases initially enter the nozzle from the combustion chamber in a high-pressure and high-temperature condition, where the flow has not yet fully accelerated. At the inlet section, the gases begin moving through the convergent part of the nozzle, where the reduction in area causes a gradual increase in velocity. Although the inlet velocity is low,

it acts as the starting stage of the flow acceleration process. As the gases move closer to the throat section, the velocity continuously increases due to the conversion of pressure energy into kinetic energy, which is essential for achieving supersonic flow in the divergent section.

VIII. RESULT ANALYSIS

Among the three nozzle models with exit diameters of 65 mm, 75 mm, and 85 mm, the nozzle with an exit diameter of 75 mm showed the best overall performance in the CFD analysis. The results indicate that the 75 mm nozzle provides an effective pressure drop from inlet to outlet along with a higher outlet velocity and proper flow expansion compared to the other two models. This demonstrates better conversion of pressure energy into kinetic energy, which leads to improved flow acceleration through the converging-diverging nozzle. Since rocket thrust mainly depends on the high-speed exhaust gases leaving the nozzle, the 75 mm nozzle is expected to produce the highest thrust among the three models. Therefore, Nozzle Model 2 (Exit Diameter = 75 mm) is considered the most suitable configuration for efficient rocket propulsion applications.

IX. CONCLUSION

In this project, three supersonic nozzle models with exit diameters of 65 mm, 75 mm, and 85 mm were analyzed using ANSYS CFD to study the pressure distribution, velocity variation, and thrust-producing capability for rocket propulsion applications. The results clearly showed that in all three models, the pressure was highest at the inlet and gradually decreased towards the nozzle exit, while the velocity increased from inlet to outlet. This confirms that the nozzle effectively converts pressure energy into kinetic energy, which is essential for thrust generation in rocket propulsion systems. Among the three nozzle models, the 75 mm exit diameter nozzle showed the best overall performance due to its effective pressure drop, higher outlet velocity, and proper flow expansion. These characteristics indicate better flow acceleration and improved exhaust performance at the nozzle exit. Therefore, it is concluded that Nozzle Model 2 (Exit Diameter = 75 mm) is the most suitable and efficient nozzle configuration for the rocket propulsion system and is expected to produce the highest thrust among the three models.

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