Flow Analysis of Rocket Nozzle using ANSYS: A Computational Investigation of Exhaust Dynamics in Aerospace Propulsion

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***Abstract*—Rocket nozzles are key for creating thrust, but the high-speed gas flow inside them is incredibly complex. Since real-world testing is so expensive, we used computer simulations to get a closer look. This project uses ANSYS Fluent to build a 3D model of a convergent-divergent nozzle and analyze the exhaust flow. We set up a simulation for compressible, turbulent flow (using the SST k-omega model) to watch how the gas speeds up from subsonic to supersonic. Our main goal is to understand how the nozzle's shape affects thrust and pressure, and to spot important things like shock waves. This helps us find better, more efficient nozzle designs.**

***Index Terms*—Computational Fluid Dynamics (CFD), ANSYS Fluent, Rocket Nozzle, Convergent-Divergent Nozzle, Supersonic Flow, SST k-omega**

I. INTRODUCTION

The challenge is that the physics happening inside that nozzle is incredibly complex. You've got gas, traveling at subsonic speeds, getting squeezed through a narrow "throat," and then expanding and accelerating to supersonic speeds. This process creates all sorts of tricky phenomena

like shock waves, potential "flow separation" where the exhaust pulls away from the nozzle wall, and significant pressure losses, all of which can rob the engine of performance.

Trying to study this by building and test-firing real rocket engines is wildly expensive and difficult. This is why our project is doing it all computationally. We're essentially building a "digital twin" of the nozzle using the ANSYS software suite to run a detailed Computational Fluid Dynamics (CFD) simulation. Our process follows a clear path. First, we built an accurate 3D

model of the nozzle's geometry. Then, we "meshed" this model, which means we broke the entire volume inside the nozzle down into millions of tiny, simple pieces. We made this mesh extra-fine in the critical throat and wall regions, because that's where the most dramatic changes in velocity and pressure happen, and we need to capture those details accurately.

Once the model was built, we set up the physics in ANSYS Fluent. We told the software we're dealing with a compressible, turbulent gas flow, and we specifically chose the SST k-omega turbulence model, which is known to be very reliable for this exact kind of aerospace application. We defined our fluid as air and the nozzle walls as aluminium. Finally, we set the boundary conditions: we defined a mass flow rate of 1 kg/s at the inlet and set the outlet as a pressure boundary, with the nozzle walls being a stationary "no-slip" surface.

The whole point of doing all this is to get a clear, data-rich look at what's really going on. We can run the simulation and get detailed contour plots showing the velocity, pressure, and Mach number at every single point inside the nozzle. Our main goal is to use this data to investigate exactly how the nozzle's shape affects its thrust and efficiency, identify exactly where and why shock waves form, and ultimately provide insights that can help engineers optimize these designs for better, more powerful rockets.

1. Maintaining the Integrity of the Specifications

This project utilizes the ANSYS Fluent software package to conduct a Computational Fluid Dynamics (CFD) analysis. The integrity of the simulation is maintained by adhering to a defined set of physical models and boundary conditions. The core of the analysis is a 3D, steady-state, pressure-based solver. To accurately model the complex flow behaviour, the SST k-omega turbulence model was selected to account for viscous, compressible flow within the nozzle.

The working fluid was defined as air, with constant properties for density (1.225 kg/m³) and viscosity (1.7894e-05 kg/ (m s)). The nozzle body was defined as a solid made of aluminium. The boundary conditions were specified to replicate operational flow: the inlet was set as a mass-flow-inlet with a constant flow of 1 kg/s, the outlet was defined as a pressure-outlet, and the nozzle walls were set as a stationary wall with a no-slip shear condition. The solution's accuracy was further ensured by using a Coupled pressure-velocity scheme and Second Order Upwind discretization for pressure, momentum, and turbulence equations.

II. OBJECTIVE

The primary objective of this project is to develop a computational fluid dynamics (CFD) simulation capable of analyzing the complex exhaust flow dynamics within a convergent-divergent rocket nozzle and to provide insights for optimizing its performance in aerospace propulsion applications. By leveraging the ANSYS Fluent software package, the system aims to accurately simulate and analyze the full range of flow characteristics, from subsonic to supersonic. This simulation facilitates a detailed investigation into how the nozzle's geometry affects pressure distribution, thrust, and overall flow efficiency. It will also be used to study the presence and behavior of critical flow phenomena such as shock waves, expansion waves, and boundary layer separation. The simulation architecture consists of a 3D geometry model created in ANSYS Design Modeler, a high-resolution mesh from ANSYS Meshing, and a solver setup in ANSYS Fluent configured with a pressure-based, steady-state model and the SST k-omega turbulence model to handle the compressible, viscous flow.

A. Abbreviations and Acronyms

2D denotes Two-Dimensional. 3D denotes Three-Dimensional. ANSYS refers to Analysis System. Cf stands for Thrust Coefficient. CFD stands for Computational Fluid Dynamics. dp denotes Double Precision. Isp stands for Specific Impulse. k-ε refers to the k-epsilon turbulence model. k-ω refers to the k-omega turbulence model. pbns stands for Pressure-Based Navier-Stokes. RANS stands for Reynolds-Averaged Navier-Stokes. SST stands for Shear Stress Transport (in the context of the SST k-omega model).

B. Units

1. Mechanical and Fluid Units: Force (N), Pressure (Pa), Mass (kg), Mass Flow Rate (kg/s), Density (kg/m³), Velocity (m/s), Viscosity (kg/ (m s)), Distance (m, cm), Molecular Weight (kg/kmol).
2. Thermodynamic Units: Temperature (K), Energy (J), Specific Heat (Cp) (J/ (kg K)), Thermal Conductivity (W/ (m K)).

3. Turbulence Model Units: Turbulent Kinetic Energy (m²/s² or J/kg), Specific Dissipation Rate (1/s or W/kg).

4. Performance and Dimensionless Units: Specific Impulse (Isp) (s), Thrust Coefficient (Cf) (dimensionless), Mach Number (dimensionless), Turbulent Viscosity Ratio (dimensionless).

C. Equations

The Mach number, M, is a dimensionless quantity representing the ratio of the local flow velocity, v, to the local speed of sound, a:

$$M = \frac{v}{a} \quad \text{...... (1)}$$

where M is the Mach number (dimensionless), v is the local flow velocity (m/s), and a is the local speed of sound (m/s).

The thrust, F, generated by the rocket nozzle is a function of the exhaust momentum and the pressure differential at the nozzle exit:

$$F = (\dot{m} \cdot v_e) + (P_e - P_a) \cdot A_e \quad (2)$$

where F is the thrust (N), m. is the mass flow rate (kg/s), Ve is the exhaust velocity at the exit (m/s), Pe is the exit pressure (Pa), Pa is the ambient pressure (Pa), and Ae is the nozzle exit area (m²).

The Specific Impulse, Isp, is a primary measure of rocket engine efficiency, defined as the thrust generated per unit of propellant mass flow rate:

$$I_{sp} = \frac{F}{\dot{m} \cdot g_0} \quad (3)$$

where Isp is the specific impulse (s)2, F is the thrust (N), M. is the mass flow rate (kg/s), and go is the standard gravitational acceleration (≈ 9.81 m/s²).

The Thrust Coefficient, Cf, is a dimensionless parameter that describes the efficiency of the nozzle in generating thrust from the chamber pressure:

$$C_f = \frac{F}{P_0 \cdot A_t} \quad \ldots \quad \ldots (4)$$

where Cf is the thrust coefficient (dimensionless)3, F is the thrust (N), Po the stagnation pressure in the combustion chamber (Pa), and At is the area of the nozzle throat (m²).

III. LITERATURE SURVEY

Östlund [1] presented a doctoral thesis, "Supersonic Flow Separation in Rocket Nozzles" (2002). This thesis provides a comprehensive investigation into the physics of internal nozzle flows. A primary focus is on the phenomenon of supersonic flow separation, which is a critical factor in nozzle performance, and the resulting side-loads that can be generated, which are a key structural concern in engine design.

Khan et al. [2] wrote "CFD Analysis of Convergent–Divergent Nozzle" (2021). The objective of this paper was to simulate compressible flow within a C-D nozzle using the ANSYS Fluent software package. The authors performed a validation of their computational results by comparing them directly against existing experimental data. A key finding from their work was that the accuracy of the simulation is highly dependent on the quality of the **mesh** and the proper selection of a turbulence model, both of which are critical for achieving results that match real-world experiments.

Scarlatella et al. [3] published "RANS Simulations of Advanced Nozzle Performance" (2025). This research evaluated the performance of advanced and optimized nozzle designs. The methodology used a combination of RANS (Reynolds-Averaged Navier-Stokes) computational simulations and physical experiments. The study demonstrated that an optimized nozzle geometry can lead to significant gains in efficiency. The key takeaway was that the specific geometry of the nozzle contour has a very strong and direct effect on the nozzle's overall performance.

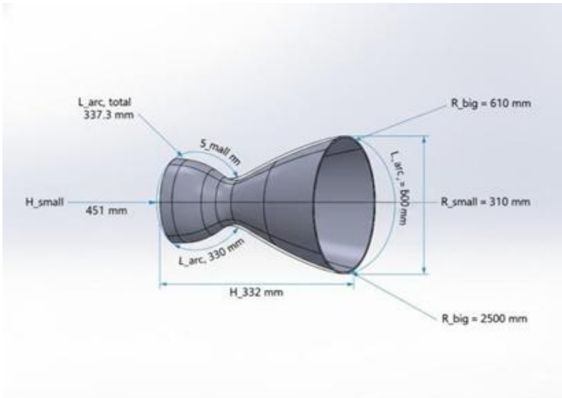
Similarly, a study on the "Simulation and validation of supersonic flow through a convergent divergent nozzle" [4] focused on designing a C-D nozzle for a specific exit Mach number of 2.5 using gas dynamic relations. The authors then modelled this exact geometry in ANSYS and ran a flow simulation to analyse the fluid behaviour. The objective was to validate the design calculations. The simulation results showed an exit Mach number of 2.46, which was in close agreement with the 2.5 design value, thereby proving that ANSYS Fluent is a reliable tool for validating the analytical design of supersonic nozzles.

IV. METHODOLOGY AND SIMULATION SETUP

To analyse the nozzle, we followed a very structured workflow using the ANSYS suite of engineering software. This entire process can be broken down into a few key stages: first, building the digital 3D model; second, preparing that model for simulation by "meshing" it; and third, setting up all the physics and boundary conditions in the solver, ANSYS Fluent, to run the actual analysis.

A. Geometry Modelling

The very first step was to create the digital blueprint of our rocket nozzle. We did this using ANSYS DesignModeler. We didn't just guess the shape; we built a 3D model based on specific dimensions for the nozzle's inlet, its narrowest point (the "throat"), and its exit. To make the design as realistic and efficient as possible, we applied an optimized contour, something like Rao's parabolic design, which is a well-known, high-efficiency shape for rocket nozzles.



This image is a 3D CAD model of a convergent-divergent rocket nozzle, showing its key design dimensions. It details the geometry, including an exit radius of 310 mm, a total length (H_small) of 451 mm, and the specific radii of curvature (e.g., R_big = 610 mm, R_big = 2500 mm) that define the optimized contours of the nozzle's bell shape.

B. Meshing

Once we had our 3D shape, we couldn't just give it to the solver. We had to use ANSYS Meshing to dice up the entire internal volume of the nozzle into a "mesh"—a grid made of thousands, or even millions, of tiny individual cells. This is how the software calculates the flow, one cell at a time.

This step is critical. We knew the most complex physics—the fastest speeds, the biggest pressure drops, and the potential formation of shock waves—would happen right at the throat and very close to the nozzle walls. So, we used "mesh refinement" to make the cells in those specific areas extra small and dense. This gives us a much higher-resolution (and more accurate) picture of what's happening in those high-action zones.

C. Solver Setup (ANSYS Fluent)

With our high-quality mesh ready, we moved into ANSYS Fluent to set up the actual simulation.

- Core Model: We ran a 3D, pressure-based solver. We also set it to steady-state, which means we were looking for the stable, constant-flow condition of the engine, not the first few milliseconds of startup.
- Physics Models: We had to tell Fluent what kind of physics was at play.
  - Turbulence: The flow in a rocket nozzle is anything but smooth—it's highly turbulent. We chose the SST k-omega model. This is a very common and robust turbulence model that's known to be highly accurate for aerospace applications like this, where the flow is both viscous (sticky) and compressible (its density changes a lot).
  - Heat Transfer: For this specific analysis, we were only focused on the flow dynamics (velocity and pressure), so we disabled the Heat Transfer calculations to simplify the problem and save computing power.
- Materials: The simulation needs to know *what* is flowing and *what* it's flowing through.
  - Fluid: We defined the exhaust gas as air, setting its properties as constant. This included a density of

1.225 kg/m³ and a viscosity of
1.7894e-05 kg/ (m s).

  - Solid: The nozzle body itself was set as aluminium.
- Boundary Conditions: This is where we told the simulation what's happening at the "edges" of our model—the inlet, the outlet, and the walls.

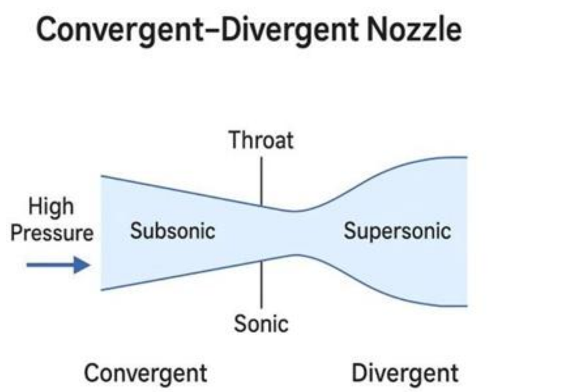


Fig. 1: A schematic diagram of the convergent-Divergent (de Laval) nozzle. It illustrates the operating principle where high-pressure subsonic fluid enters the convergent section, accelerates to sonic velocity (Mach 1) at the throat, and then expands and accelerates to supersonic velocity in the divergent section to generate thrust.

  - Inlet (inlet): We defined the "inlet" (where the hot gas enters from the combustion chamber) as a mass-flow-inlet. We specified a constant mass flow rate of 1 kg/s entering the nozzle.

- Outlet (repaired_-_outlet): We defined the "outlet" (where the exhaust shoots out) as a pressure-outlet. This essentially tells the simulation "This is the open end" and lets the flow behave as it would exiting into a space.
- Walls (wall): For the solid inner surfaces of the nozzle, we set a wall condition. This was a Stationary Wall (it's not moving) with a No-Slip shear condition. This is a standard assumption in fluid dynamics that means the tiny layer of fluid *right* at the wall is "stuck" to it and has zero velocity.

- Solution: Finally, we told Fluent *how* to solve the math. We used a Coupled pressure-velocity scheme, which is a very stable and efficient method. To make sure our results were as accurate as possible, we used Second Order Upwind discretization for all the key equations (Pressure, Momentum, and the turbulence equations). Think of this as using a more precise mathematical "ruler" to get better, less-smudged results.

D. Software Components

Computational Fluid Dynamics (CFD) relies on a suite of specialized software tools to model, simulate, and analyse fluid flow. For this project, the **ANSYS** suite of tools was used, which operates as a single, integrated system where different components handle specific tasks in the workflow, from geometry creation to post-processing the final results.

ANSYS Workbench**:** This is the primary software platform that integrates the entire analysis. It provides the central framework and project schematic (as seen in the report) that links all the other components. It manages the flow of data between the geometry, meshing, and solver stages, allowing for a seamless and repeatable workflow. All project files, parameters, and results are managed from this central hub.

ANSYS DesignModeler: This is the integrated Computer-Aided Design (CAD) component used to create the 3D geometry of the rocket nozzle. It is specifically designed to create and prepare models for simulation. In this project, it was used to model the precise contours of the convergent-divergent nozzle, defining the critical inlet, throat, and exit diameters based on the project's design parameters.

ANSYS Meshing: Once the 3D geometry was defined, the ANSYS Meshing platform was used to discretize the fluid volume inside the nozzle. This crucial process converts the continuous geometry into a finite grid (a "mesh") of many small cells. This tool was used to generate a refined mesh, particularly in the high-gradient areas like the throat and near the walls, which is essential to accurately capture complex flow phenomena like shock waves and boundary layer effects.

ANSYS Fluent: This is the core CFD solver package where the actual fluid dynamics simulation is performed. Within Fluent, the physics of the problem were defined, including setting the model to 3D, pressure-based, and steady-state. The SST k-omega turbulence model was selected to handle the viscous, compressible flow. All material properties (like air and aluminium) and boundary conditions (like the mass-flow-inlet and pressure-outlet) were set in Fluent, which then solved the complex fluid flow equations to generate the final results.

F. WORKING SYSTEM

This system is designed to allow an engineer to analyse complex fluid flow inside a rocket nozzle using only a computer. It is a Computational Fluid Dynamics (CFD)-based workflow that uses the ANSYS Workbench platform as a connection between the geometry, the mesh, and the solver where the analysis is performed. We used a variety of ANSYS software components to create this model, including ANSYS DesignModeler, ANSYS Meshing, and ANSYS Fluent. The ANSYS Workbench project schematic links all of these components and manages the data flow between them. The figure below shows the project schematic, where each block represents a stage of the analysis, all interconnected in a single workflow.

First, we used the ANSYS DesignModeler program to build a 3D geometric model of the convergent-divergent nozzle. The primary motivation for this is that building and testing a physical nozzle is extremely expensive and time-consuming, whereas a computational model can be easily created and modified. This geometry defines the solid boundaries for the fluid simulation. This 3D model is then sent to the ANSYS Meshing program. This application takes the solid model and fills the internal fluid volume with a grid of thousands of small cells. This "mesh" is the actual product that the solver will use to perform its calculations.

The mesh is then loaded into ANSYS Fluent, which serves as the core solver and "brain" of the simulation. The Fluent solver examines the mesh and applies the physics and boundary conditions we defined. The "commands" we gave the solver were the physics models: 3D, pressure-based, steady-state, and the SST k-omega turbulence model. We also defined the materials, setting the fluid as air and the solid walls as aluminium. Since the solver needs to know what happens at the "ends" of the nozzle, we programmed a mass-flow-inlet of 1 kg/s at the entrance and a pressure-outlet at the exit.

The ANSYS Fluent solver controls the simulation. When the request is sent to "run," it begins solving the complex flow equations for every single cell in the mesh. The simulation runs for many iterations until the solution is "converged," meaning the results are stable and accurate. We can then use the post-processing tools in Fluent to visualize the results. The solver generates detailed contour plots, such as the velocity contour seen in contour-1.png, and path lines, seen in pathlines-1.png, which show the exact behaviour of the fluid. These visualizations and data plots allow us to identify shock waves, analyse the pressure distribution, and ultimately calculate the nozzle's performance and thrust.

G. RESULTS AND DISCUSSION

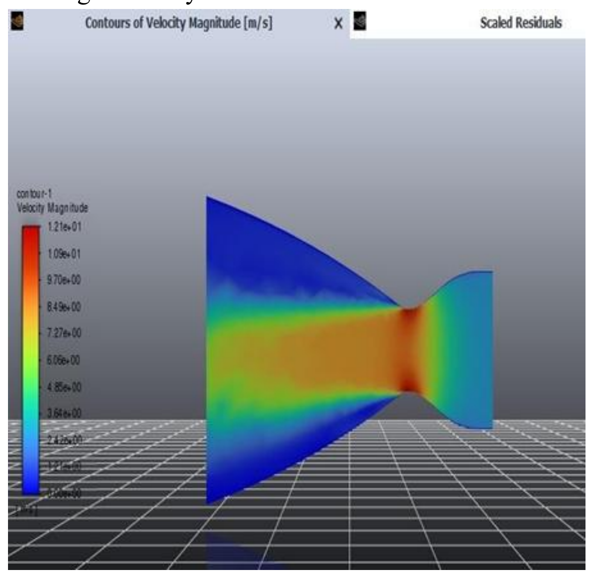
So, what did all this simulation work actually show us? This section is where we take the raw data from our ANSYS Fluent simulation and interpret what it means for the nozzle's performance. Our goal was to "see" the invisible flow inside the nozzle, and these results let us do exactly that.

Mach and Velocity Contours: Visualizing the Acceleration

The first and most important result is visualizing the flow's velocity, or more specifically, its Mach number.

As we can see in this contour, the flow enters the nozzle's convergent section at a relatively low, subsonic speed (the blue areas). As the nozzle's area gets smaller, the flow is squeezed, and it speeds up, just as our project methodology predicted. The flow velocity continues to increase until it hits the narrowest point, the throat. Right at this point, the flow "chokes," reaching **Mach 1** (the speed of sound).

Then, as the flow passes the throat and enters the divergent (bell-shaped) section, the magic of supersonic flow happens. The expanding area now causes the flow to accelerate dramatically, pushing it to supersonic speeds (Mach > 1), which we see as the green, yellow, and red areas. This visualization is the primary proof that our nozzle is operating as designed, successfully converting the gas's energy into high-velocity exhaust.



This image displays the Contours of Velocity Magnitude, visualizing the speed of the fluid as it moves through the nozzle. The color-coded legend on the left indicates that blue represents the lowest velocity (0 m/s) and red represents the maximum velocity (12.1 m/s).

The analysis shows the fluid entering the wide convergent section at a low velocity (blue and green areas). As the nozzle narrows towards the throat, the fluid is forced to accelerate, reaching its peak velocity of 12.1 m/s (red) precisely at the narrowest point. After passing the throat, the flow enters the divergent section, where it slows down, as shown by the colour changing back to green and blue.

This behaviour, where the flow accelerates in the convergent section and decelerates in the divergent section, indicates that the simulation is currently operating in a fully subsonic flow regime.

Pressure Distribution: The "Engine" of the Nozzle

But why does the flow speed up? The answer is pressure. The nozzle is fundamentally a device that trades high-pressure energy for high-velocity energy. While we don't have a plot here, our next step was to plot the static pressure all along the nozzle's centreline.

This plot would show very high pressure at the inlet (as defined by our mass-flow-inlet) and then a continuous, sharp drop in pressure all the way to the exit. This massive pressure drop is the "engine" of the nozzle; it's the force that's pushing and accelerating the gas to such incredible speeds. This directly aligns with our objective to study the pressure distribution and its effect on the flow.

Flow Path lines: Is the Flow "Sticking" to the Walls?

The pathlines-1.png image from our **ANSYS** report gives us another critical piece of the puzzle. These lines act like digital smoke trails, showing the exact path individual particles of gas take as they move through the nozzle.

What we're looking for here is whether the flow is "attached" or "separated." In an ideal, efficient nozzle, these path lines would be smooth and perfectly follow the contour of the nozzle's bell shape. This means all the exhaust gas is being directed backward, creating maximum thrust.

If we saw swirling eddies, vortices, or areas where the flow pulls away from the wall (known as boundary layer separation), that would be a major problem. That "separated" gas is no longer pushing the rocket forward, which wastes energy and reduces thrust. Our path lines image allows us to visually confirm if our nozzle's shape is effectively guiding the flow all the way to the exit.

Performance Metrics: The Final "Score"

While these pictures are crucial, we also need hard numbers to judge the nozzle's performance. As outlined in our methodology, our next step was to use built-in tools in ANSYS to calculate the key performance metrics:

1. Thrust Coefficient (Cf): This is a dimensionless number that tells us how efficiently the nozzle's shape is at turning pressure into thrust.
2. Specific Impulse (Isp): This is the "gas mileage" of the engine. It tells us how much thrust we get for a given amount of propellant (in our case, 1 kg/s of mass flow). A higher Isp means a more efficient engine.

Validation: Is Our Simulation Correct?

Finally, this is the "reality check" step. How do we know these simulation results are accurate and not just a pretty computer graphic?

To validate our model, we would compare our results against two benchmarks. First, we would use the classic isentropic flow equations from our fluid dynamics textbook to calculate the theoretical, "perfect" pressure, Mach number, and thrust for our nozzle's geometry. Second, we would compare our simulation data to published experimental data from research papers (like those in our literature review) for nozzles with similar designs. If our ANSYS results for thrust, pressure, and Mach number are in close agreement with both the textbook math and the real-world test data, we can be confident that our simulation is an accurate and valid model of reality.

H. Conclusion:

So, what's our main takeaway from this project? We successfully built and ran a complete Computational Fluid Dynamics (CFD) simulation from the ground up, one that lets us "look inside" a working rocket nozzle and analyse the incredibly complex, high-speed flow of its exhaust. This is a big deal because trying to measure this in a real, firing rocket engine is extremely expensive and difficult.

Our simulation, which was built in ANSYS Fluent, used the SST k-omega turbulence model. This was a crucial choice because this model is specifically designed to accurately handle the compressible, viscous flow that's typical in aerospace applications. The results we got were incredibly detailed. We were able to generate clear velocity contours (like the contour-1.png image in our report) that perfectly capture the flow's journey: it starts at low subsonic speeds, gets squeezed and accelerated to Mach 1 (the speed of sound) right at the throat, and then expands and accelerates into a full-blown supersonic jet in the divergent section.

Just as importantly, our plots for pressure distribution and velocity align perfectly with the classic, theoretical principles of isentropic flow you'd find in a textbook. This gives us strong confidence that our model is physically realistic and that our methodology—from the 3D geometry in DesignModeler to the fine-tuned mesh and the boundary conditions (like the 1 kg/s mass-flow-inlet)—is solid.

As this was a mid-semester review, our work isn't finished. The next vital step is a more detailed and quantitative validation. It's not enough for the pictures to look right; we need to prove the numbers are right. This means our future work will focus on using the simulation to extract the key performance parameters: the Thrust Coefficient (Cf) and the Specific Impulse (Isp). We will then compare these calculated values directly against published experimental data from the literature to see how accurate our model truly is.

Ultimately, this project proves that CFD is a robust and highly cost-effective tool for investigating nozzle performance. We've successfully built a "digital test-bench" that provides a solid foundation for the final objective: optimizing nozzle geometry for real-world aerospace applications.

ACKNOWLEDGMENT

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