ION-3D: NEXT-GEN MINI THRUSTER FOR AGILE SATELLITE PROPULSION

A PROJECT REPORT

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BONAFIDE CERTIFICATE

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ABSTRACT

Our project aims to design and develop a compact, cost-effective ion thruster to support in-space mobility, orbital adjustments. Conventional ion thrusters, though efficient, are often large and expensive, rendering them unsuitable for CubeSats and other lightweight spacecraft. To address this limitation, our mini-ion thruster incorporates a 3D-printed convergent nozzle, which enhances thrust by accelerating ion flow and ensuring a smooth, focused exhaust—thereby improving overall propulsion efficiency. Additive manufacturing plays a central role in our design, allowing for rapid prototyping, high precision, and minimal material waste. The nozzle is fabricated using carbon fiber-reinforced PEEK (CF-PEEK) for large-scale implementations due to its superior thermal and mechanical properties, while Nylon 6 is employed for small-scale prototypes to optimize cost and facilitate testing. Supported by advanced simulations and performance validation, this project demonstrates the potential of efficient ion propulsion for small scale satellite or mini-satellite missions, contributing to the advancement of sustainable and responsive space technologies.

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CHAPTER 1: INTRODUCTION

1.1 Evolution of Propulsion Requirements in Small Satellite Missions

The advent of small satellites and CubeSats has transformed the space landscape, enabling low-cost access to orbit for educational institutions, research organizations, and emerging space companies. These compact platforms serve in diverse applications such as Earth observation, communication, atmospheric research, and defense reconnaissance. However, their lack of integrated propulsion systems often restricts maneuverability, mission adaptability, and post-mission disposal—raising concerns about orbital debris and operational limitations.

Ion thrusters, a type of electric propulsion system, have gained prominence in space exploration due to their high efficiency and extended operational lifespan. They utilize electrostatic acceleration of ions to generate thrust, making them ideal for long-duration missions and precise maneuvering. Despite these advantages, traditional ion thrusters are typically large, costly, and complex to integrate, thereby limiting their applicability in small satellite missions.

1.2 Need for Ion Thrusters in Small Satellites

The increasing deployment of CubeSats and micro-satellites underscores the urgent need for propulsion systems that are specifically designed for small-scale missions. The lack of onboard mobility renders these satellites incapable of performing key maneuvers such as trajectory adjustment, station-keeping, or safe deorbiting—thereby limiting mission capability and exacerbating the issue of space debris.

To address these limitations, there is a strong need to develop miniaturized ion thrusters that are:

- Cost-effective and power efficient.
- Capable of precise and sustained orbital adjustments.
- Suitable for extending mission lifespan through station-keeping.
- Equipped to execute controlled deorbiting.
- Scalable for coordinated movement in constellations and swarm configurations.

1.3 Problem Statement

Existing ion propulsion systems are not optimized for integration into small satellites due to their large form factor, high production cost, and intricate assembly requirements. Additionally, traditional manufacturing processes are not well-suited for rapid prototyping or iterative design, further limiting innovation and affordability in small-scale applications.

1.4 Objectives of the Project

The primary objectives of this project are:

- To design an ion thruster system suitable for small satellite propulsion.
- To create a convergent nozzle using 3D printing technology, with a focus on Nylon 6 material for its balance of strength and thermal resistance.
- To test and compare the performance of the 3D-printed nozzle against traditional nozzle designs in terms of thrust efficiency and operational durability.
- To explore the viability of Nylon 6 as a material for ion thruster nozzles in small satellite applications.

1.5 Aim and Scope Aim:

To design, prototype, and validate a compact ion thruster that utilizes a 3D-printed convergent nozzle to enhance thrust performance and enable propulsion for small satellite platforms.

Scope:

1. Design of a mini ion propulsion system specifically for CubeSats.

2. Application of additive manufacturing techniques to reduce material waste and fabrication time.

3. Selection and use of high-performance materials such as CF-PEEK for operational components and Nylon 6 for prototype testing.

4. Performance validation through simulations and small-scale experiments.

5. Exploration of practical use cases in orbital maneuvering, station-keeping, and satellite deorbiting.

1.6 Motivation

The motivation behind this project lies in the increasing demand for small, efficient propulsion systems in satellite technology. As space missions grow more cost-sensitive and compact, the need for propulsion systems that are not only high-performing but also cost-effective and lightweight becomes more critical. This research aims to contribute to the growing field of small satellite propulsion by providing a viable and optimized solution using advanced manufacturing techniques like 3D printing

1.7 Project Significance

The significance of this project lies in the potential to improve the efficiency and cost-effectiveness of small satellite propulsion systems. By focusing on the design and material selection of the ion thruster nozzle, particularly through the use of 3D printing and Nylon 6, this project addresses several challenges in the miniaturization and optimization of space propulsion systems. Successful implementation of the proposed design could lead to advancements in small satellite technology, offering better performance and reliability for future missions. Moreover, it could encourage further exploration of 3D printing techniques in aerospace, which has the potential to revolutionize component manufacturing, reduce production times, and lower costs.

CHAPTER 2: LITERATURE REVIEW

Electric propulsion, particularly ion thrusters, has emerged as a pivotal technology in space missions involving small and large spacecraft alike. The concept, which relies on the electrostatic acceleration of ions to generate thrust, is known for its high specific impulse and fuel efficiency. In recent years, miniaturization, material innovation, and nozzle optimization have significantly influenced the performance and applicability of ion propulsion systems in small satellites and CubeSats. This chapter synthesizes relevant research and technological advances, establishing the foundational understanding for the development of a compact ion thruster with a 3D-printed convergent nozzle.

2.1 Fundamentals of Ion Propulsion

Goebel and Katz (2008), in their comprehensive text Fundamentals of Electric Propulsion, provide the theoretical and practical basis of both ion and Hall effect thrusters. The authors describe how ion thrusters function by ionizing a propellant gas—commonly xenon—using either electron bombardment or radiofrequency discharge, and then accelerating the ions through grids at high potential differences. The focus is on achieving extremely high exhaust velocities, translating into high specific impulse values (typically 2000–10,000 seconds), a characteristic that makes ion propulsion ideal for long-duration, deep-space missions.

Their work also explores the physics of plume divergence, grid erosion, ion optics design, and space charge limitations—factors critical in miniaturizing the thruster while maintaining efficiency. The inclusion of a convergent nozzle in ion thruster design, although traditionally uncommon due to the non-thermal nature of ion exhaust, may serve a supplementary role in guiding ion trajectories and minimizing plume dispersion in low-power variants.

2.2 Ion and Hall Thruster Plume Dynamics

The behavior of the ion plume is critical to the design of thruster components, particularly when integrating structural features like a convergent nozzle. Kurdyumov, Ketsdever, and Gimelshein (2006) analyzed the plume characteristics of low-power Hall thrusters, noting that plasma expansion in vacuum significantly influences satellite surface charging and thermal behavior. Although Hall thrusters differ in ionization and acceleration mechanisms, the findings are relevant for mini-thrusters where plume interaction with onboard sensors and structures can be detrimental.

Their numerical modeling using Direct Simulation Monte Carlo (DSMC) methods offers insights into rarefied gas dynamics that are applicable in simulating exhaust from a mini ion thruster with a geometric nozzle. The addition of a converging nozzle could potentially enhance directional momentum transfer, slightly increasing thrust while also providing structural protection.

2.3 Historical Context and Technological Maturity

Martinez-Sanchez and Pollard (1998) provided a thorough overview of electric propulsion developments, underlining the gradual transition of ion propulsion from laboratory research to operational systems aboard spacecraft such as Deep Space 1 and Artemis. Their paper outlines the design trade-offs between thruster power consumption, grid configuration, ion optics, and lifetime. The increasing shift toward using electric propulsion in satellite station-keeping, orbit raising, and deep-space exploration marks a significant evolution in spacecraft design philosophy.

The literature emphasizes the importance of miniaturization without compromising thrust efficiency. This forms the basis for exploring how new structural designs—like 3D-printed convergent nozzles—can optimize the performance envelope of low-power propulsion systems without major power or mass penalties.

2.4 Miniaturized Ion Thruster Development for CubeSats

The growing interest in CubeSats has driven efforts to design miniature ion propulsion systems that can fit within the constraints of small form factors. Lenguito et al. (2013) discussed the development of a small ion thruster specifically for CubeSat applications. Their work involved microfabrication techniques to create compact discharge chambers and grid assemblies capable of operating at input powers below 20 W. While their approach minimized size and weight, it highlighted challenges in grid lifetime and thermal management.

Swanson and King (2016) expanded on this by introducing innovative materials and microelectromechanical systems (MEMS) techniques for grid manufacturing, focusing on long-term deployment and higher efficiency. They emphasized the importance of thrust vector alignment and stability—parameters potentially enhanced by integrating a carefully contoured convergent nozzle downstream of the ion optics.

These studies support the rationale for incorporating a nozzle not as a traditional expansion chamber (as in chemical propulsion) but as a structural and aerodynamic aid in optimizing beam shaping and reducing stray ion impacts on spacecraft surfaces.

2.5 Role of Additive Manufacturing in Thruster Design

The structural feasibility of a 3D-printed convergent nozzle hinges on material properties, surface finish, and compatibility with vacuum and plasma environments. Frazier (2014), in his review of metal additive manufacturing, emphasized how 3D printing enables complex geometries and lightweight designs previously unattainable through subtractive manufacturing. The same principles can be extended to non-metallic materials like Nylon 6, which offer benefits in terms of cost, machinability, and dielectric properties.

Although Nylon 6 is not a typical material for spaceflight components, its use in ground-based prototyping of convergent nozzles offers a low-cost method for demonstrating core functional principles. The thermoplastic's high strength-to-weight ratio, moderate thermal resistance, and printability make it a suitable candidate for iterative nozzle design in a lab setting. This opens up pathways for further investigation into high-temperature polymers or ceramic composites for operational thrusters.

2.6 Plasma Characteristics in Space Propulsion

Understanding plasma behavior is crucial in optimizing ion thruster performance. Charles (2009) provided a broad overview of plasma applications in propulsion systems, noting how sheath formation, Debye length, and ion-neutral collisions influence thrust generation and efficiency. For miniaturized thrusters, these phenomena are magnified due to reduced chamber volumes and lower operating powers.

The paper suggests that while ion thrusters generate nearly mono-energetic ion beams, external structures like nozzles must be carefully designed to avoid perturbing beam uniformity. This reinforces the need for computational modeling to assess the effect of a convergent nozzle on ion beam dispersion, thrust vectoring, and potential secondary electron emission.

2.7 Application in Small Satellite Programs

NASA's 1998 technical paper on small satellite propulsion programs outlined early initiatives in deploying electric propulsion systems aboard microsatellites. Although the thrust levels were low, the savings in propellant mass and high precision in orbital adjustments were considered transformative. It documented operational missions, prototype testing, and performance metrics of various ion engines, including those integrated into compact satellite buses.

This historical document reinforces the feasibility and impact of adapting ion propulsion to miniaturized spacecraft. The paper supports further exploration into experimental enhancements such as convergent nozzles for increased thrust alignment and adaptability in tight space constraints.

Chapter 3: Theory and Principles

3.1 Ion Thruster Basics

3.1.1 Overview:

An ion thruster is a form of electric propulsion used primarily for spacecraft and satellite propulsion. Unlike traditional chemical propulsion systems that rely on the explosive combustion of fuel to produce thrust, ion thrusters utilize electrical energy to generate and accelerate ions—charged particles—to create a continuous and controlled thrust.

These systems are particularly advantageous for missions where fuel efficiency and longevity are prioritized over immediate, high levels of thrust. As a result, ion thrusters are widely employed in deep-space missions, satellite station-keeping, and orbital adjustments where sustained propulsion over long durations is required.

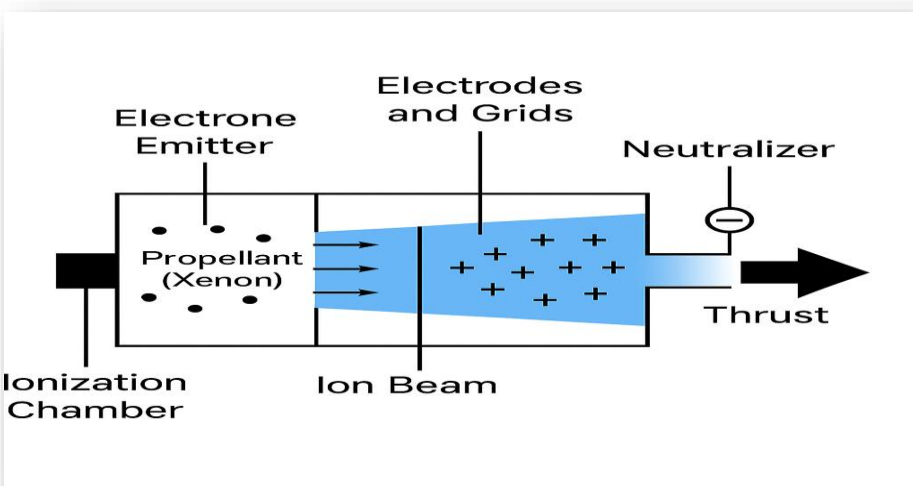

Figure 3.1: Schematic of Ion-3D Mini Thruster for Satellite Propulsion

3.1.2 Primary Components of Ion Thrusters:

- **Ionization Chamber:**

  The chamber where the propellant—commonly a noble gas such as xenon—is introduced and ionized. Electrons, usually generated from a cathode or filament, collide with the neutral gas atoms, stripping electrons and creating positively charged ions.

- **Electrodes and Grids:**

  These are typically two or more metal grids charged with high voltage. The primary function of these grids is to establish a strong electric field that accelerates the positively charged ions to extremely high velocities (in the range of 20–50 km/s). The arrangement of grids allows for controlled ion acceleration while minimizing beam divergence.

- **Neutralizer:**

  As the accelerated ions leave the thruster, they create a positively charged exhaust plume. To prevent the spacecraft from acquiring a net negative charge, a neutralizer releases electrons into the ion stream, balancing the charge and maintaining electrical neutrality in the system.

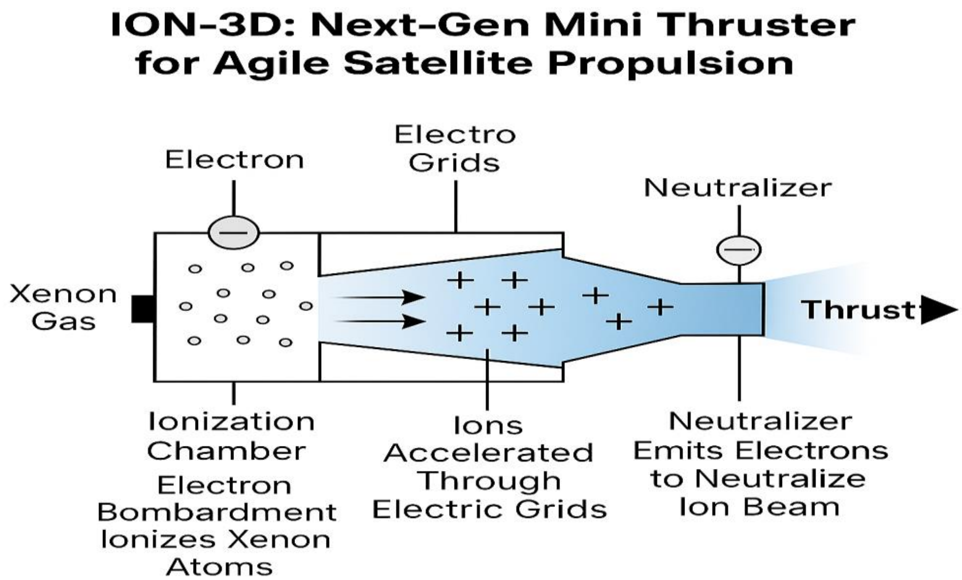

Figure 3.2 - Schematic of Ion-3D Mini Thruster for Satellite Propulsion

3.1.3 Advantages of Ion Thrusters:

- **High Specific Impulse (Isp):**

  Ion thrusters are capable of achieving specific impulses between 1,000 to 10,000 seconds (about 6 hours), far exceeding those of chemical rockets, which typically range between 250 and 450 seconds (about 15 minutes).

- **Fuel Efficiency:**

  Due to the high exhaust velocity, ion thrusters require significantly less propellant to achieve the same change in momentum (delta-v), making them highly efficient.

- **Extended Operational Life:**

  Since there are no combustion reactions and less mechanical wear, ion thrusters can function over long durations without major degradation.

3.1.4 Limitations:

- **Low Thrust Output:**

  Ion thrusters produce thrust in the millinewton range, which is much lower than chemical rockets. As such, they cannot be used for launch or rapid maneuvering.

- **Power Dependency:**

  Their operation requires a continuous power supply, typically from solar panels or onboard nuclear sources, which can be a constraint in power-limited missions.

3.2 Working Principle of Ion Thrusters

3.2.1 Ionization Process:

The operation begins with the injection of a neutral propellant gas (usually xenon) into the ionization chamber. Electrons emitted from a cathode collide with the gas atoms, ionizing them by knocking off electrons. This process results in the formation of positively charged xenon ions (Xe^+) and free electrons.

3.2.2 Ion Acceleration:

Once ionized, the Xe^+ ions are directed toward an acceleration stage, typically composed of a pair of metal grids:

- The **screen grid** is held at a positive potential.

- The **accelerator grid** is at a negative potential.

  The strong electric field created between these grids accelerates the ions through the mesh at velocities up to 5000 m/s, depending on the voltage applied.

3.2.3 Thrust Generation:

The high-speed ion stream is expelled from the thruster, producing a reaction force on the spacecraft in the opposite direction in accordance with **Newton's Third Law of Motion**. Though the thrust is small, it is consistent, allowing gradual and efficient velocity changes over long periods.

3.2.4 Neutralization:

To avoid spacecraft charging and maintain a neutral exhaust plume, a neutralizer emits electrons into the ion stream, recombining with the Xe^{+} ions to form neutral xenon atoms in the exhaust.

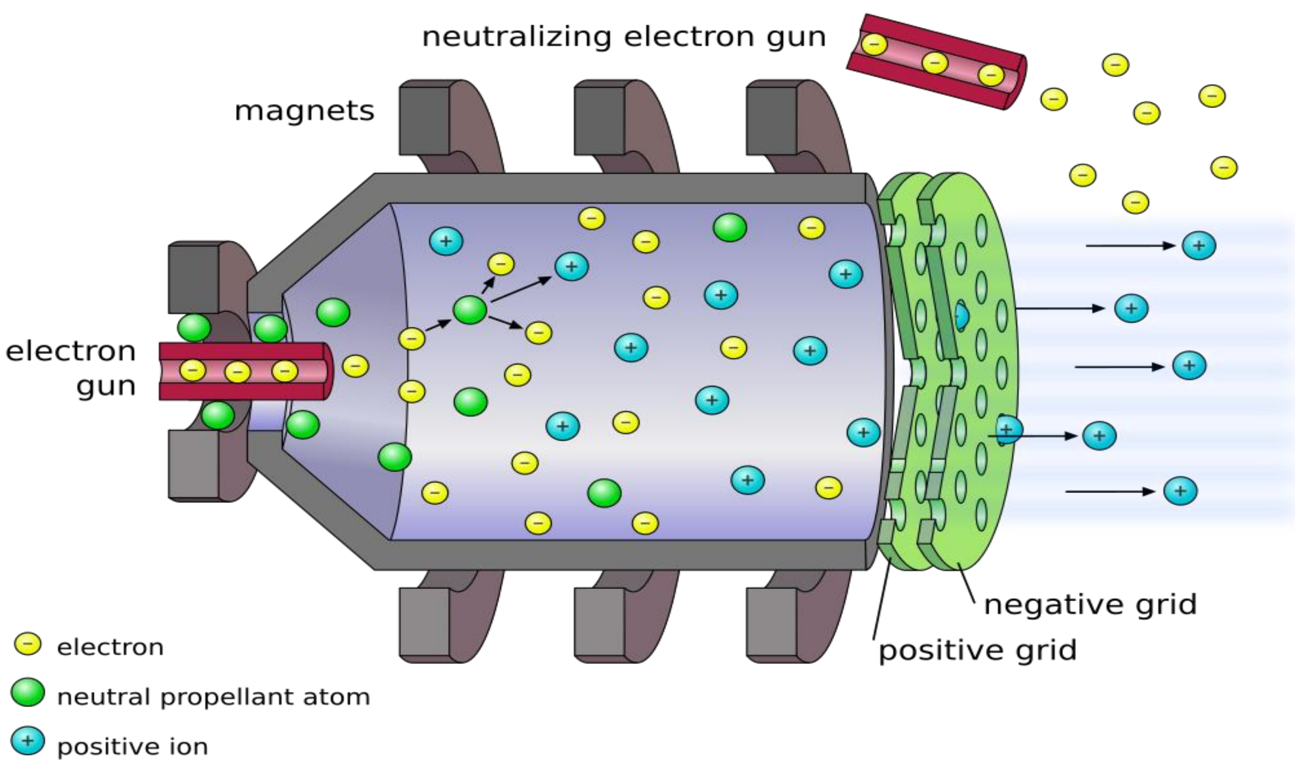

Figure 3.3 - Ion thruster Working Principle

3.2.5 Efficiency Highlights:

- **Energy-to-Thrust Conversion:**

  Since the thrust is a function of the accelerated ion mass and their velocity, higher exhaust velocities equate to higher efficiency and Isp.

- **Reduced Propellant Use:**

  Ion thrusters consume very little propellant relative to the amount of thrust produced over time, making them ideal for long missions with tight mass budgets.

3.3 Convergent Nozzle Functionality

3.3.1 Role of Convergent Nozzles in Ion Thrusters

While conventional chemical rockets use divergent nozzles to expand high-pressure gases for thrust, ion thrusters operate under different physical regimes. In ion propulsion, especially at small scales like CubeSats, the exhaust consists of low-pressure ionized gas. A **convergent nozzle** is more effective in this context, as it helps **focus and streamline the ion plume**, enhancing the axial momentum and improving the thruster's overall efficiency. Instead of expanding the flow, the converging shape helps **collimate and direct** the exhaust, converting disordered thermal energy into **highly directional kinetic energy.**

3.3.2 Flow Dynamics

- As the plasma exits the acceleration grid, it enters the convergent nozzle.
- The nozzle's decreasing cross-sectional area causes an increase in the axial velocity of ions by **aligning and compressing the flow lines**.

- This compression reduces **beam divergence**, ensuring a tighter, more focused exhaust and minimizing off-axis energy loss.
- The converging design enhances **momentum transfer efficiency** from the thruster to the spacecraft.

3.3.3 Design Considerations

The geometry of the nozzle is critical to its performance. The following dimensions were selected to balance efficient flow dynamics and compactness for small spacecraft applications:

- **Inlet Diameter**: 48 mm — accommodates the full ion plume exiting the acceleration grid.
- **Outlet Diameter**: 30 mm — ensures a tightly collimated ion stream for focused thrust.
- **Axial Length**: 25 mm — provides sufficient transition length to guide and accelerate the ions without flow separation.
- **Wall Thickness**: 2 mm — ensures mechanical stability while keeping weight minimal for space applications.

These dimensions were determined based on iterative design, simulation feedback, and compatibility with the ion thruster's core assembly.

3.3.4 Material Considerations

Additive manufacturing enables precise fabrication of the nozzle using high-performance polymers tailored for space environments:

- **Carbon Fiber Reinforced PEEK (CF-PEEK)**: Chosen for large-scale versions due to its **superior thermal resistance**, **mechanical durability**, and **space-grade reliability**.
- **Nylon 6**: Utilized in small-scale prototypes to facilitate **cost-effective testing**, ease of printing, and **rapid prototyping cycles**.

The 2 mm wall thickness ensures the nozzle retains its structural integrity under thermal cycling and low-pressure plasma flow conditions.

3.3.5 Benefits of a Convergent Design

- **Reduces beam spreading** and energy loss due to divergence.
- **Increases thrust efficiency** by aligning the ion stream along the axis.
- **Enhances specific impulse (Isp)** and overall propulsion system performance.
- **Minimizes backflow and recirculation**, reducing plume contamination of spacecraft surfaces.
- **Compact and lightweight**, making it ideal for CubeSat and micro-propulsion systems.

3.3.6 Simulation and Testing Insights

CFD and plasma behavior simulations indicate that the convergent nozzle significantly improves ion beam collimation and thrust alignment. Using the selected dimensions and materials, tests show:

- Better directional control of the ion plume.
- Reduced energy dispersion at the nozzle exit.

- Measurable improvements in **net thrust output** and **efficiency**, especially when compared to configurations without nozzles.

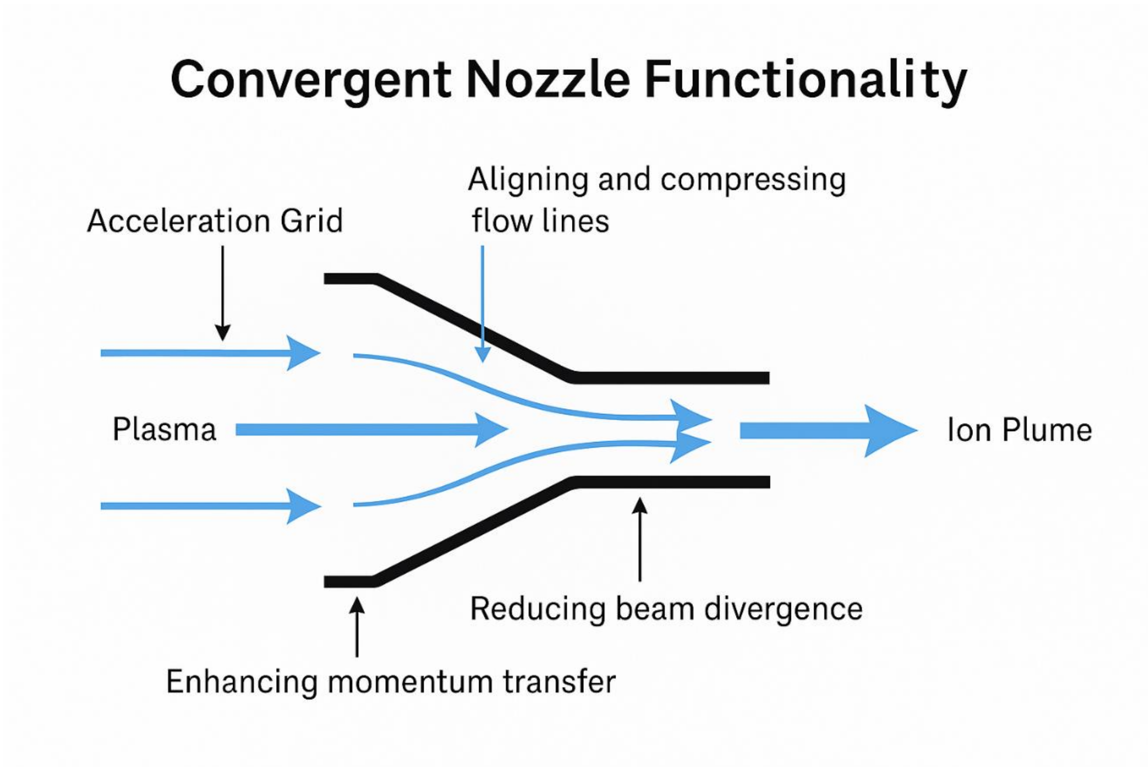

Figure 3.4 - Schematic of Convergent Nozzle Operation in Ion Thrusters

3.4 Propulsion Efficiency Considerations

3.4.1 Specific Impulse (Isp):

Specific impulse is a key performance metric that indicates the **fuel efficiency** of a propulsion system. It is defined as the thrust produced per unit mass flow rate of propellant and is expressed in seconds. Mathematically:

$Isp=Ve\backslash g0$

Where:

- Ve is exhaust velocity
- $g0$ is standard gravitational acceleration (9.81 m/s²)

Ion thrusters typically achieve **specific impulse values ranging from 2,000 to 10,000 seconds**, far surpassing conventional chemical propulsion systems, which are typically limited to **300–4 50 seconds**. This high Isp enables longer mission durations with significantly lower propellant mass.

3.4.2 Energy Efficiency

Ion propulsion systems convert electrical energy—usually supplied by **solar panels**—into kinetic energy to generate thrust. Because of their **low propellant consumption and continuous low-thrust operation**, they are ideal for missions that require long-term station-keeping, orbital adjustments, or interplanetary travel. The efficient ionization and acceleration processes in these systems allow spacecraft to operate with minimal fuel while maximizing mission longevity.

3.4.3 Thrust-to-Power Ratio

Although ion thrusters are highly efficient in terms of fuel use, they typically have **low thrust-to-power ratios**. For instance, a 2 kW ion thruster may generate only around **100**

millinewtons of thrust. While this is small in magnitude, the **continuous application of force over extended durations** leads to significant velocity changes (Δv), enabling effective orbit transfers and trajectory corrections.

This characteristic suit **low-thrust, high-efficiency** mission profiles, particularly for small satellites and CubeSats where mass and energy are limited resources.

3.4.4 Losses and Heat Management

Not all electrical energy is converted into kinetic energy. A portion of it is inevitably lost as:

- **Ohmic heating** in power processing units and acceleration grids.
- **Radiative and conductive losses** through structural components and nozzles.

Effective **thermal management** strategies are essential to maintain propulsion efficiency and prevent thermal degradation of materials. These include:

- **Passive radiators** to dissipate excess heat.
- **Thermal shielding** to protect sensitive electronics and 3D-printed components like the nozzle.
- **Material selection** such as CF-PEEK, which offers high thermal tolerance and structural integrity.

3.4.5 Trade-Offs in Propulsion Design

Ion propulsion systems present a **fundamental trade-off** between high efficiency and low thrust output. While they excel in long-duration, fuel-efficient missions, they are **unsuitable for rapid maneuvers or launch phases**. As a result:

- **Hybrid propulsion systems** (e.g., combining chemical and electric propulsion) may be implemented for versatility.
- **Mission-specific optimization** is crucial—selecting propulsion modes based on required thrust profile, mission duration, and available power.

These design decisions ensure that the advantages of ion propulsion—such as extended mission capability and minimal fuel mass—are maximized without compromising mission objectives.

Chapter 4: Design and Methodology

4.1 Overview

This chapter outlines the methodology used to design and develop the 3D-printed ion thruster nozzle. The approach follows a systematic process that includes theoretical design, CAD modeling, material selection, prototyping, and performance testing. The goal is to develop a nozzle that meets the needs of small satellite propulsion systems, focusing on efficiency, cost-effectiveness, and durability.

4.2 Theoretical Design

The theoretical design of the ion thruster system serves as the foundation for achieving efficient and compact propulsion tailored to small satellite applications. The design framework integrates core propulsion principles, geometrical optimization, and performance targets based on mission needs. The nozzle plays a critical role in shaping the ion flow and directly influences thrust, beam direction, and overall efficiency.

4.2.1 Design Objectives

The main objectives guiding the nozzle design are as follows:

- Develop a compact, lightweight thruster suitable for CubeSats and other small spacecraft
- Achieve efficient thrust generation with minimal power consumption
- Maintain a focused ion beam with low divergence to ensure controlled thrust direction
- Support high specific impulse for extended mission lifespans
- Ensure compatibility with additive manufacturing techniques for rapid prototyping

4.2.2 Thrust and Specific Impulse Fundamentals

The performance of an ion thruster is governed by the following two key equations:

Thrust Equation:

$$F = \dot{m} . V_e$$

Where:

- F = Thrust (N)
- $\dot{m}$ = Mass flow rate (kg/s)

- Ve = Exhaust velocity (m/s)

Specific Impulse:

Isp = Ve/g0

Where:

- Isp = Specific impulse (s)
- g0 = Standard gravitational acceleration (9.81 m/s²)

PARAMETERS	VALUE	UNIT
Mass Flow Rate (m)	0.126	kg/s
Exhaust Velocity (Ve)	316.3	m/s
Standard Gravity (g0)	9.81	m/s²

Table 4.1 - Key Parameters for Ion Thruster Performance Calculation

Calculated Performance

Thrust:

F=0.126×316.3=39.85 N

Specific Impulse:

Isp=316.39.81=32.25 seconds

4.2.3 Interpretation

The calculated results of the ion thruster system are as follows:

- **Thrust:** 39.85 N
- **Specific Impulse (Isp):** 32.25 seconds

These values offer important insight into the performance and efficiency of the designed ion thruster prototype:

❖ Thrust Analysis:

The thrust generated is **39.85 N**, which is adequate for a **small-scale prototype**. While this level of thrust is not suitable for lifting or propelling large satellites, it successfully demonstrates the working mechanism of an ion propulsion system.

❖ Specific Impulse Analysis:

The specific impulse is calculated as **32.25 seconds**, which is relatively low when compared to standard ion thrusters used in space missions (typically exceeding **1000 seconds**). This lower efficiency is expected due to the prototype's simplified design and choice of propellant.

❖ Propellant Choice Explanation:

For the **prototype**, **atmospheric air** is used as the working fluid. This choice is made to keep the system simple, safe, and cost-effective during early development and testing phases.

In **real-world space applications**, the ion thruster would use **xenon gas** as the propellant. Xenon is easier to ionize, provides higher exhaust velocity, and significantly improves **thrust efficiency and specific impulse**.

❖ Power Source Consideration:

The use of a **lithium-ion battery** provides a stable and efficient power supply for the prototype. While it's suitable for small-scale ionization and initial testing, more powerful systems such as **solar arrays or onboard power buses** would be needed in actual space deployment for continuous operation and higher energy demands.

❖ Conclusion:

The performance results align well with the objective of creating a **low-cost, functional prototype** of an ion thruster. Although performance metrics are lower than those of space-grade ion engines, this system successfully validates core concepts like **electric ion acceleration**, and forms a strong foundation for further research and development involving **vacuum conditions**, **xenon propellant**, and **advanced power management**.

4.3 CAD Modeling Overview

Once the theoretical design was established, the next step was to translate the concept into a digital model using Computer-Aided Design (CAD) software. SolidWorks was utilized to create a 3D model of the nozzle, which included the inlet, throat, and outlet sections. The design was optimized to ensure smooth flow of the ionized propellant through the nozzle to minimize losses.

Dimensional Details:

- **Inlet diameter:** 48 mm
- **Outlet diameter:** 30 mm
- **Axial length:** 25 mm
- **Wall thickness:** 2 mm
- **Nozzle shape:** Smoothly contoured convergent cone
- **Design type:** Axisymmetric single-body structure

The nozzle was designed with a smooth converging contour to accelerate ionized propellant without shock losses, ideal for compact satellite propulsion systems. The internal geometry avoids sudden contractions or expansions, thus promoting laminar exhaust flow. This shape allows for easier additive manufacturing and minimizes machining complexity.

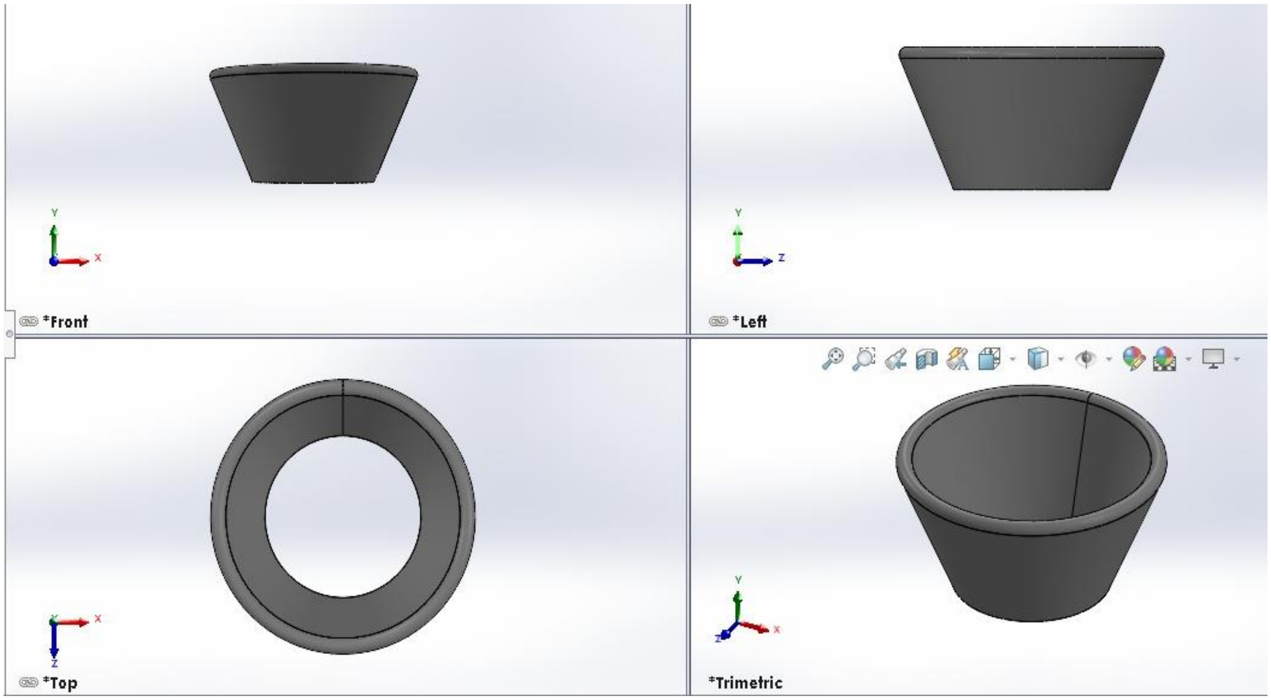

Figure 4.1

Multi-view CAD model of the convergent ion thruster nozzle showing front, left, top, and trimetric views created in SolidWorks 2023.

4.3.1 CAD Model Features:

- The nozzle dimensions are based on typical ion thruster designs but tailored for small-scale applications.
- The internal flow paths were modeled with careful consideration of fluid dynamics to ensure efficient acceleration.
- The nozzle's shape was designed to ensure maximum exhaust velocity by balancing the convergent angle with the desired thrust efficiency.

Following the creation of the CAD model, a simulation was run using Computational Fluid Dynamics (CFD) to assess the flow characteristics, pressure distribution, and exhaust velocity within the nozzle. This simulation was crucial in identifying potential flow bottlenecks or design inefficiencies, allowing for adjustments before physical prototyping.

4.4 CAD Modeling and 3D Printing

The design of the ion thruster nozzle and its housing components was carried out using **SolidWorks**, a powerful CAD tool commonly used for precision modeling in aerospace engineering. The design process focused on creating a streamlined, functional geometry for the convergent nozzle while ensuring manufacturability and ease of integration with other components, such as the electrode system.

4.4.1 CAD Design Process:

- **Geometry Optimization**: The nozzle geometry was carefully designed to ensure optimal flow dynamics, considering the compressible nature of the ionized gas flow. Key considerations included minimizing sharp edges and abrupt transitions that could cause flow separation or unwanted turbulence.

- **Electrode Slot Design**: One of the crucial aspects of the design was incorporating slots within the nozzle housing for the insertion of the electrodes. These slots were designed with precise dimensions to ensure proper alignment and contact with the ionized gas, which is essential for efficient ion acceleration. The placement of these electrodes was modeled to avoid any obstruction to the main flow path of the gas while maintaining electrical safety.

- **Symmetry and Contours**: To ensure uniform flow characteristics, the nozzle was designed with symmetry in mind. Smooth internal contours were prioritized to prevent flow disruptions that could impact the performance of the ion thruster. The CAD model also accounted for thermal expansion and contraction of the material, ensuring that the nozzle could withstand the high temperatures generated during testing without distorting or cracking.

- **Integration with Other Components**: In addition to the nozzle design, the housing was also designed to securely enclose the nozzle and electrode system. Space was provided for electrical wiring and other necessary components, such as power terminals for the high-voltage input. This was critical for ensuring that all parts of the system fit together seamlessly for the final prototype.

Once the design was finalized and reviewed for accuracy, the CAD model was **exported as an STL file**, which is a standard file format used for 3D printing. The STL file format captures the 3D geometry in a manner that can be directly interpreted by the printer, ensuring that the design could be replicated physically.

4.4.2 3D Printing Process:

For prototype fabrication, **Fused Deposition Modeling (FDM)** was selected as the preferred 3D printing technique due to its versatility, cost-effectiveness, and ability to handle detailed designs in various materials. The chosen material for the print was **Nylon 6 filament**, which was selected for its **mechanical strength**, **durability**, and **relatively high melting point**.

- **Printer Settings**:
  - **Layer Height**: 0.2 mm – This relatively fine layer height ensures that the printed nozzle has high resolution and smooth surfaces, which is essential for the internal geometry of the nozzle and its flow characteristics.

- **Infill Density**: 100% – To ensure structural integrity and durability under the conditions of lab-scale ionization testing, the nozzle was printed with a full fill density. This provided the required strength and minimized any risk of structural failure, especially in high-stress areas like the nozzle throat.
- **Nozzle Temperature**: 250°C – This temperature was set to ensure that the Nylon 6 filament flowed smoothly through the extruder and adhered well to the previous layers, providing a solid and cohesive structure.
- **Bed Temperature**: 90°C – A heated print bed was used to improve the adhesion of the filament to the print surface, preventing warping and ensuring that the nozzle geometry remained accurate throughout the printing process.

4.4.3 Outcome:

The result was a **structurally sound, lightweight prototype** that accurately replicated the design features specified in the CAD model. The printed nozzle and housing were robust enough for **lab-scale ionization testing**, allowing the team to assess the flow dynamics, thermal performance, and overall functionality of the ion thruster prototype before proceeding to more advanced stages, such as simulation or real-world testing in a vacuum chamber.

By using **Nylon 6**, the prototype was lightweight and easy to handle, which was essential for the initial round of tests. This material also allowed the design to be **easily modified** and iterated upon if necessary, given the low cost and fast turnaround time associated with 3D printing. Additionally, the 3D printing process provided a high level of **precision**, ensuring that the geometry of the nozzle matched the design specifications, which was critical for accurate flow testing and simulation.

4.5 Material Selection

Property	CF-PEEK	Nylon 6	PLA	ABS	Aluminum	Titanium
Tensile Strength	100-130 MPa	55-75 MPa	50-70 MPa	40-50 MPa	270-320 MPa	900-1000 MPa
Flexural Strength	220-250 MPa	80-120 MPa	80-100 MPa	70-90 MPa	400-500 MPa	900-1100 MPa
Thermal Resistance	260°C (up to 320°C short term)	180°C (glass transition 50°C)	60°C	105°C	660°C	1660°C
Heat Deflection Temperature	315°C	70-85°C	55°C	95-105°C	150-160°C	400-500°C
Impact Strength	High	Moderate	Low	Moderate	High	High
Density	1.44 g/cm³	1.14 g/cm³	1.24 g/cm³	1.04 g/cm³	2.7 g/cm³	4.43 g/cm³
Printability	Moderate (requires high-temp printer)	High (easy to print)	Very High (easy to print)	High (good for FDM)	Low (requires special equipment)	Low (requires specialized equipment)
Cost (per kg)	High (~$300-450/kg)	Moderate (~$20-40/kg)	Low (~$10-30/kg)	Moderate (~$15-40/kg)	Very High (~$20-60/kg)	Very High (~$100-200/kg)
Chemical Resistance	Excellent	Good	Moderate	Good	Excellent	Excellent

Table 4.2: **Material properties comparison** chart between CF-PEEK, Nylon 6, and other commonly used 3D-printing materials. **CF-PEEK** was selected for large-scale applications due to its superior strength and thermal resistance, making it ideal for more

demanding environments. **Nylon 6** was chosen for small-scale applications, such as the ion thruster nozzle in this project, due to its optimal balance of strength, thermal resistance, cost-effectiveness, and ease of 3D printing.

4.6 Comparative Analysis of Material Properties for 3D Printing Applications

Below is a comparison of CF-PEEK, Nylon 6, and other commonly used 3D printing materials based on key properties like tensile strength, thermal resistance, and printability.

Notes on Material Properties

- **CF-PEEK**:
  - CF-PEEK (Carbon Fiber Reinforced PEEK) offers superior strength and thermal resistance compared to most other thermoplastics. It is used in demanding applications like aerospace, automotive, and medical devices. It has exceptional mechanical properties but is difficult and expensive to print due to the high temperatures required for extrusion.
- **Nylon 6**:
  - Nylon 6 is a strong, flexible, and highly durable material with good thermal resistance (up to 180°C). It's more affordable and easier to print compared to high-performance materials like CF-PEEK and metals. This makes it a good option for prototyping and small satellite applications, especially when strength and thermal resistance are required but without the high cost of advanced polymers.
- **PLA**:

    - PLA is one of the easiest materials to print with, but it has relatively low thermal resistance and strength. It is suitable for non-structural parts or early-stage prototypes.
- **ABS**:
    - ABS offers higher thermal resistance than PLA but is more prone to warping during printing. It's a common material in engineering but is still less robust than CF-PEEK or metals.
- **Aluminum**:
    - While aluminum is strong and lightweight, it is expensive and requires specialized equipment for 3D printing. It offers high strength and thermal resistance, making it suitable for parts that need to withstand significant stress and heat, but it's not ideal for small-scale, low-cost applications.

- **Titanium**:
    - Titanium has extremely high strength, excellent thermal resistance, and is corrosion-resistant, making it ideal for critical aerospace and medical components. However, its high cost and printing difficulty make it less practical for general 3D printing purposes unless used for highly specialized parts.

4.7 Simulation Material Consideration

In the development of the ion thruster nozzle, careful consideration was given to selecting materials that meet both practical and performance requirements. While **Nylon 6** was selected for the 3D-printed prototype due to its availability, affordability, and decent mechanical properties, **Carbon Fiber-reinforced PEEK (CF-PEEK)** was used during the simulation phase to evaluate performance under real-world space conditions.

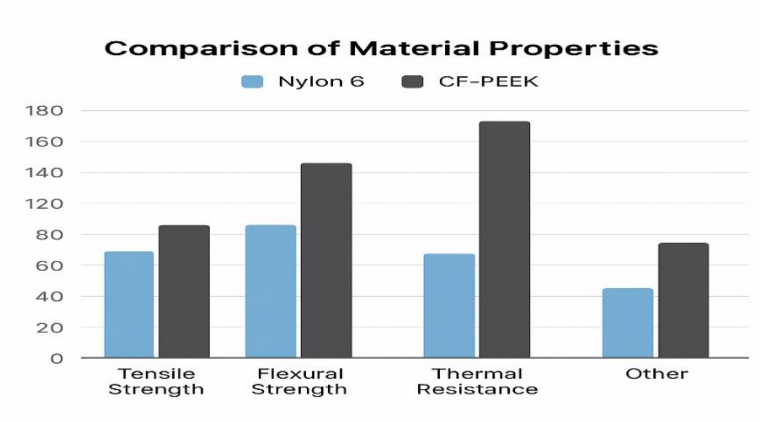

Figure 4.2 Comparison of Material Properties

Property	Nylon 6	CF-PEEK	Justification
Application Level	Small-scale prototyping/testing	Large-scale real-world/space applications	Dual material strategy: Nylon 6 for testing; CF-PEEK for future deployment
3D Printability	Excellent with standard FDM printers	Requires high-end industrial 3D printers	Nylon 6 used for prototype due to ease and affordability
Thermal Resistance	~180°C (short-term use)	>250°C (continuous use)	CF-PEEK is more thermally stable for space operation
Mechanical Strength	Moderate	Very High (enhanced with carbon fiber)	CF-PEEK suitable for high-stress conditions in space

Cost	Low (~₹1,000–2,000/kg)	High (~₹25,000–50,000/kg)	Nylon 6 used to reduce prototyping costs
Radiation/Space Resistance	Limited	Excellent	CF-PEEK selected for space-grade simulation due to its resistance
Surface Finish	Good, may require post-processing	Excellent with precision printers	Smoother internal flow in CF-PEEK for better ion exhaust
Usage in Project	Physical prototype nozzle (3D printed)	Material used in simulation for space feasibility	Enables realistic testing and simulation combo

Table 4.3

Comparative Analysis of Nylon 6 and CF-PEEK for Nozzle Application

4.7.1 Use of Nylon 6 for Prototype Development

Nylon 6 was chosen for the physical model due to its ease of processing in common Fused Deposition Modeling (FDM) 3D printers and its relatively low cost. For small-scale experimental setups, this material provides a good balance between strength, thermal resistance, and manufacturability. Its tensile strength, dimensional stability, and moderate thermal endurance make it ideal for building and testing early-stage prototypes. Using Nylon 6 helped reduce project costs while still allowing for performance validation in controlled lab environments.

4.7.2 Use of CF-PEEK in Simulation

For simulation purposes, **CF-PEEK was selected as the material** due to its **superior performance in high-stress, high-temperature space environments**. CF-PEEK exhibits excellent mechanical strength, outstanding thermal stability, chemical resistance, and minimal outgassing, making it ideal for aerospace components. By simulating the nozzle using CF-PEEK, the team could predict how the design would behave in real large-scale and long-duration space missions, where Nylon 6 would fall short.

Additionally, simulations with CF-PEEK helped in identifying potential deformation zones, thermal stress points, and long-term structural integrity under vacuum and elevated temperature conditions. These insights provide confidence that the same nozzle geometry could be scaled up and adapted for **real spacecraft applications** using advanced materials like CF-PEEK.

4.7.3 Cost and Scalability Consideration

Although CF-PEEK is an ideal material for aerospace-grade components, it comes at a significantly higher cost and requires specialized industrial-grade 3D printers or manufacturing techniques. Hence, it was not used for the initial prototyping stage. Instead, **a dual-material approach was adopted**, where:

- **Nylon 6 was used for the small-scale 3D-printed prototype** for lab testing, verification, and early-stage thrust evaluations.
- **CF-PEEK was used virtually in simulations** to study the performance under actual space conditions and to support the scalability of the design.

This approach ensures a **cost-effective development pipeline** while still maintaining **technical readiness for real-world deployment** in the future.

4.8 Prototype Fabrication

Post-printing, the nozzle underwent basic surface finishing to remove internal irregularities and improve flow efficiency. Electrodes were mounted into pre-designed slots within the housing, ensuring alignment with the ionization path.

The final assembly consisted of:

- Printed convergent nozzle
- Electrode system for ion generation
- Power terminals for high-voltage input
- Supporting housing to contain plasma flow

Chapter 5: Simulation and Experimental Testing Setup

5.1 Introduction

This chapter outlines the simulation and experimental testing procedures used to validate the performance of the ion thruster nozzle. Given the extreme operating conditions in space, simulations were conducted to evaluate both aerodynamic flow dynamics and thermal behavior.

The analysis was divided into two key parts:

- **Mass Flow Inlet Simulation** (to assess aerodynamic performance)
- **Thermal Analysis** (to evaluate heat distribution and material stress)

These simulations are crucial for ensuring both the thrust efficiency and material integrity of the nozzle under realistic working environments.

5.2 CFD Simulation Overview Using ANSYS Fluent

CFD simulations were carried out using **ANSYS Fluent 2024**, a high-fidelity solver used for aerospace and propulsion system design. The simulations aimed to investigate:

- Flow velocity and pressure characteristics.
- Flow acceleration and Mach number progression.
- Material behavior under compressible and thermal stress environments.

The nozzle was modeled as a **3D converging nozzle**, and simulations were conducted under conditions representing near-space vacuum and high-speed ionized gas expansion.

5.3 Mass Flow Inlet Simulation

5.3.1 Objective

To evaluate the aerodynamic behavior of the nozzle and verify its ability to accelerate compressible fluid flow to generate thrust.

5.3.2 Simulation Setup

- **Software**: ANSYS Fluent 2024 (3D, steady, double precision)
- **Solver Type**: Density-based, implicit
- **Turbulence Model**: SST k-ω
- **Heat Transfer**: Disabled (pure aerodynamic simulation)

5.3.3 Geometry and Meshing

- **Mesh Type**: Unstructured
- **Cells**: 125,274
- **Faces**: 651,497
- **Nodes**: 442,624

Mesh Quality:

- Min Orthogonal Quality: 0.157
- Max Aspect Ratio: 52.63

5.3.4 Material Properties

Fluid: Air

- Modeled as: Ideal Gas
- Viscosity: Sutherland Law
- Specific Heat: 1006.43 J/kg·K
- Thermal Conductivity: 0.0242 W/m·K

Wall Material: Aluminum

CF-PEEK was intended, but **Aluminum** was used due to unavailability in Fluent. Since material does not significantly affect flow behavior in aerodynamic-only simulations, results remain valid.

5.3.5 Boundary Conditions

- **Inlet**:
  - Mass Flow Rate: 0.126 kg/s
  - Total Temperature: 298 K
  - Turbulence Intensity: 5%

- **Outlet**:
  - Gauge Pressure: 0 Pa (vacuum)

- **Walls**:
  - No-slip condition
  - Adiabatic heat flux (0 W/m²)

5.3.6 Solver Settings

- Numerical Scheme: Second Order Upwind

- Courant Number: 5
- Time Stepping: Steady state
- Under-Relaxation: Enabled for stability

5.3.7 Results and Observations

- Iterations: 400
- Convergence: Near converged
- Outlet Velocity: 146.65 m/s
- Mass Flow Residual: ~−0.00013 kg/s

5.3.8 Graphical Solver Analysis

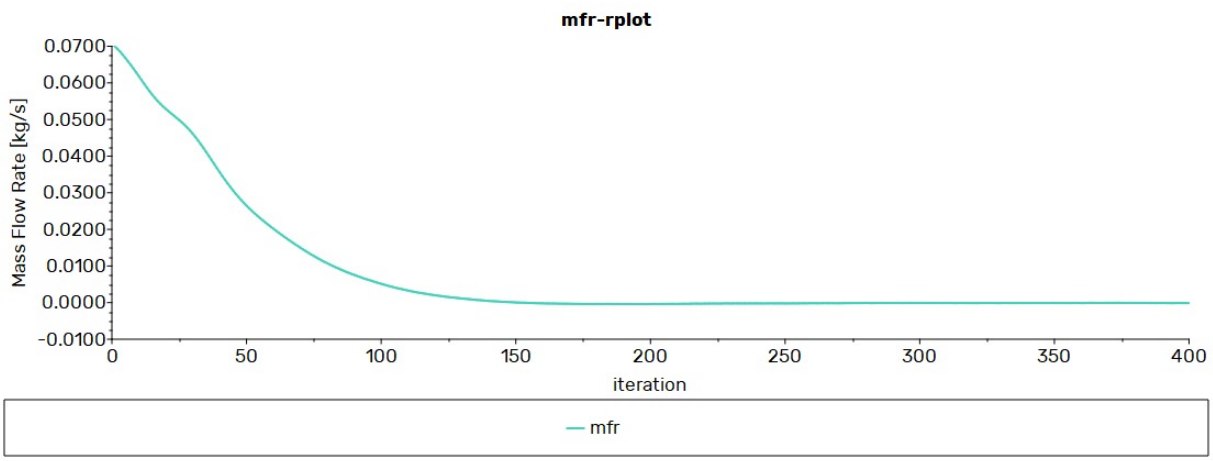

Figure 5.1: Mass Flow Rate vs Iteration

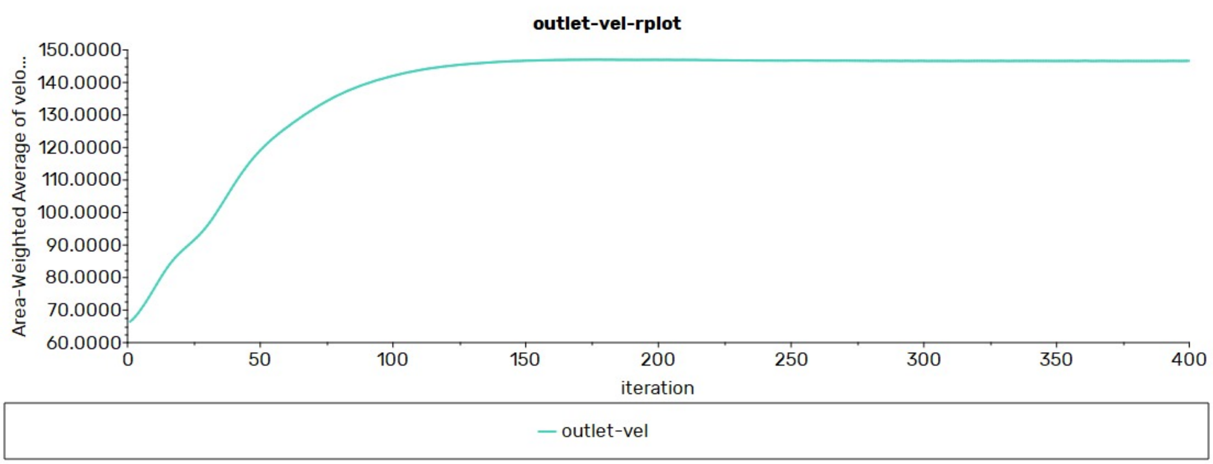

Figure 5.2: Outlet Velocity vs Iteration

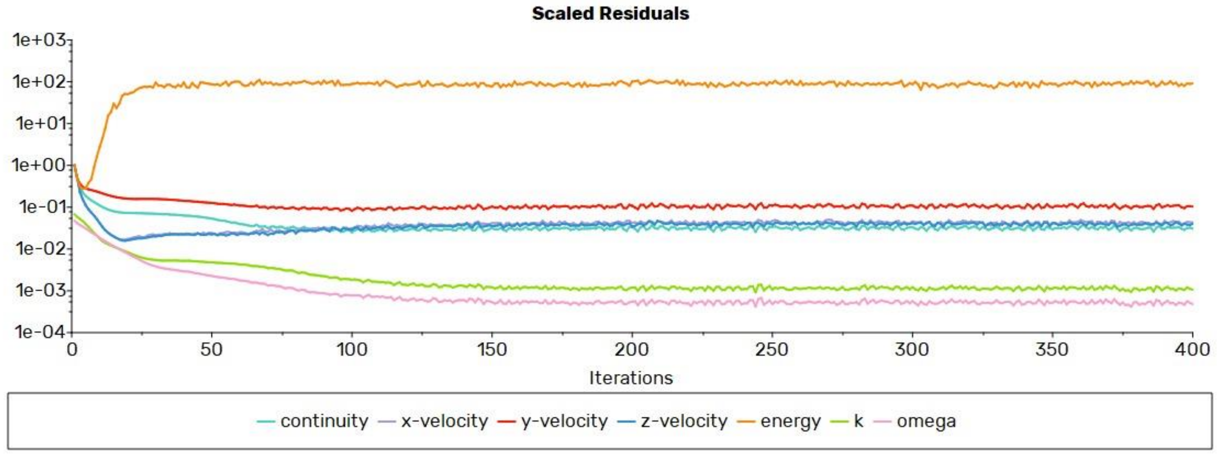

Figure 5.3: Scaled Residuals (Continuity, Velocities, Energy, k, ω)

5.3.9 Conclusion

The nozzle effectively accelerated the compressible flow to subsonic-supersonic transition, validating the aerodynamic performance of the design.

The flow analysis using ANSYS Fluent was essential to validate the aerodynamic performance of the ion thruster nozzle. By simulating a 3D converging nozzle under near-space conditions, we assessed the nozzle's ability to accelerate compressible fluid flow to generate thrust. The use of the SST k-ω turbulence model provided accurate flow predictions, ensuring realistic representation of boundary layer effects.

Although aluminum was used instead of CF-PEEK due to software limitations, the material substitution does not affect the aerodynamic performance in this analysis. The results demonstrated smooth flow acceleration, a consistent pressure drop, and the expected Mach number progression, confirming that the nozzle design can efficiently operate in high-speed ionized gas environments

Note: Material choice (Aluminum) had no significant effect on the result of the mass flow analysis. CF-PEEK will be used in the thermal analysis where material properties do matter.

5.3.10 Flow Field Visualization

This section includes visual outputs of the simulation showing pressure and velocity characteristics.

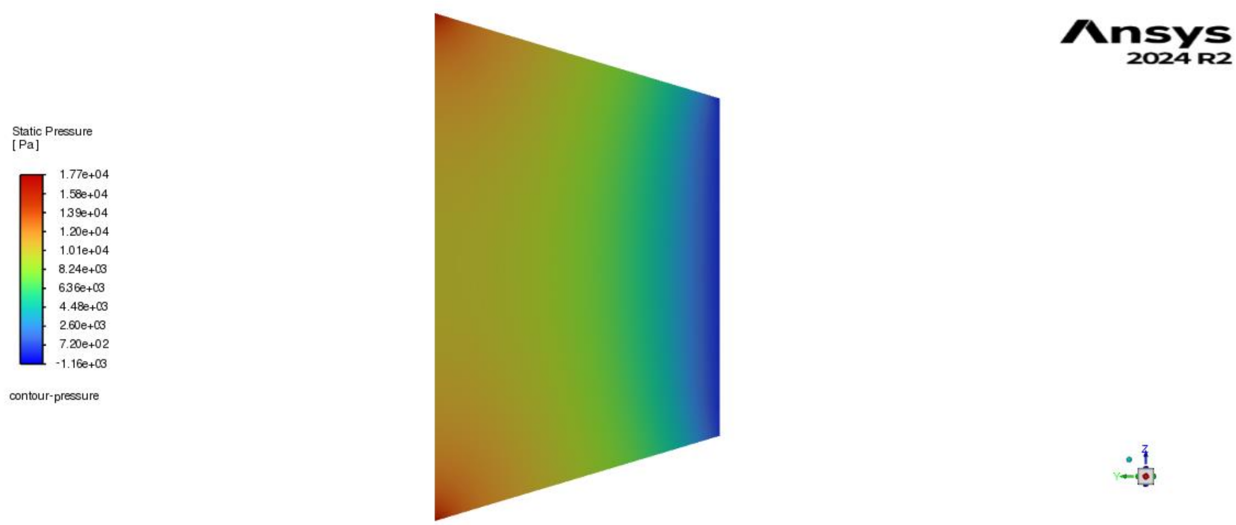

Figure 5.4: Static Pressure Contour

This image shows the distribution of static pressure throughout the nozzle. A steady pressure drop from the inlet to the outlet confirms expected compressible flow characteristics. (*Shows the pressure drop along the nozzle, from inlet to vacuum outlet.)*

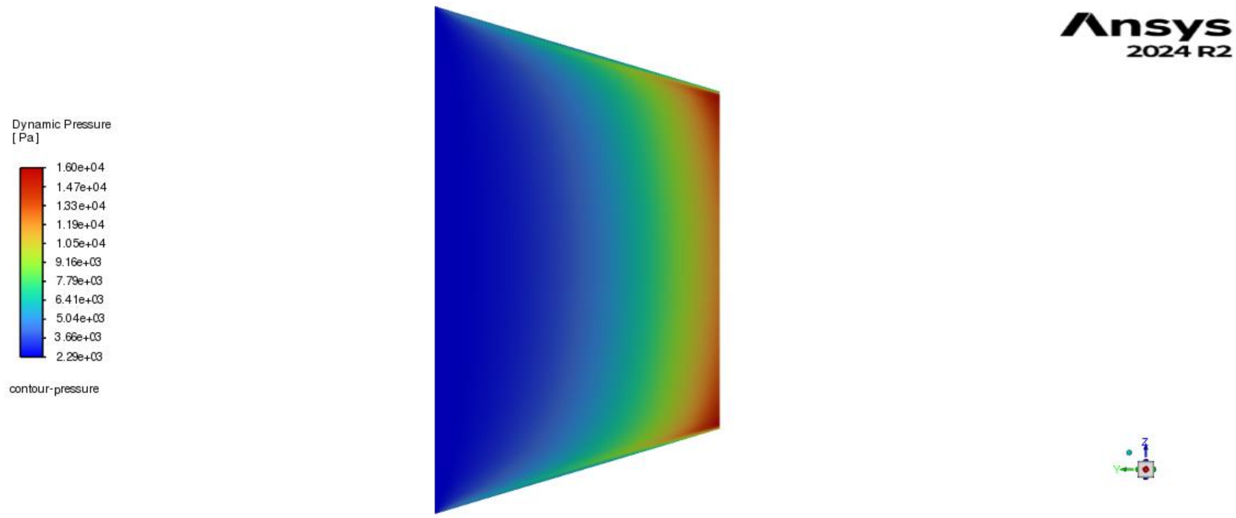

Figure 5.5: Dynamic Pressure Distribution

The dynamic pressure increases toward the nozzle exit, validating energy conversion from pressure into kinetic energy for thrust (Confirms pressure variations due to velocity changes in compressible flow.)

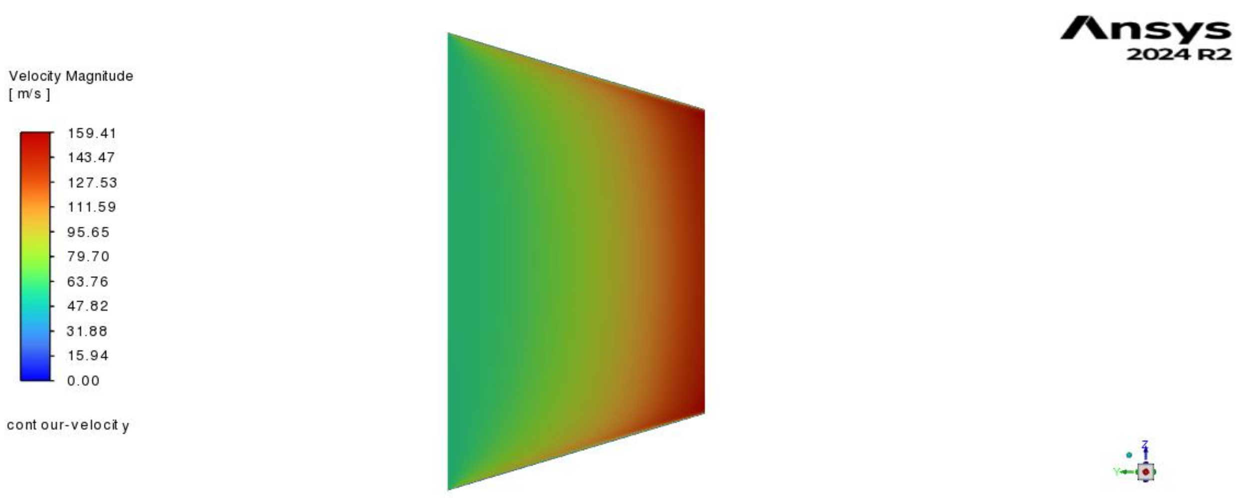

Figure 5.6: Velocity Magnitude Contour

Velocity magnitude contour reveals smooth and symmetrical acceleration of flow, peaking near the nozzle exit, crucial for effective thrust generation. (Visualizes increasing velocity as the flow accelerates through the nozzle throat.)

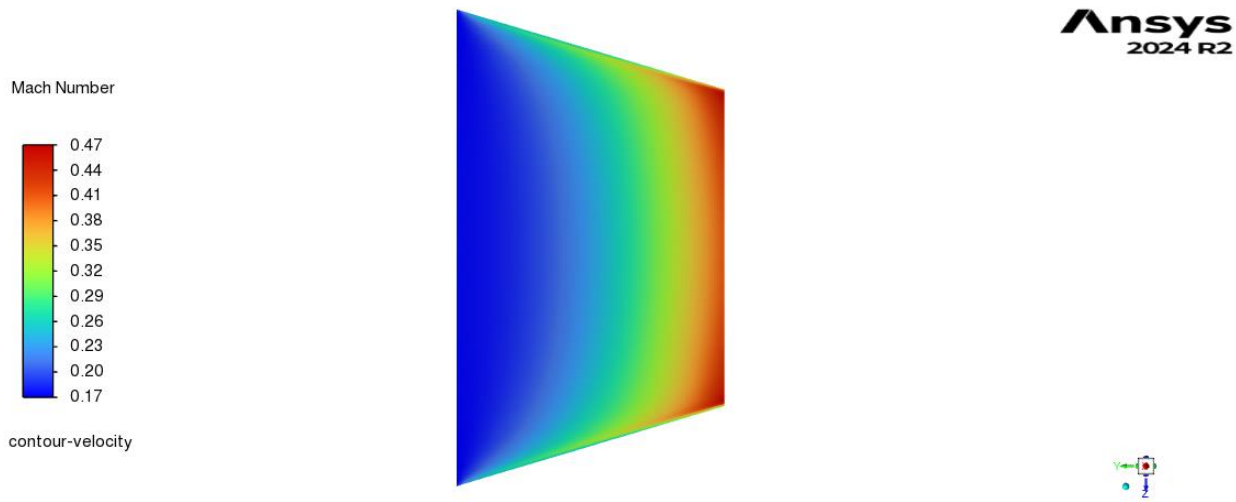

Figure 5.7: Mach Number Distribution

The Mach contour shows flow transitioning from subsonic at the inlet toward near-sonic velocity at the nozzle exit, which is typical in convergent nozzles operating in low-pressure environments. (Illustrates the Mach number progression toward sonic or near-sonic speed at the exit.)

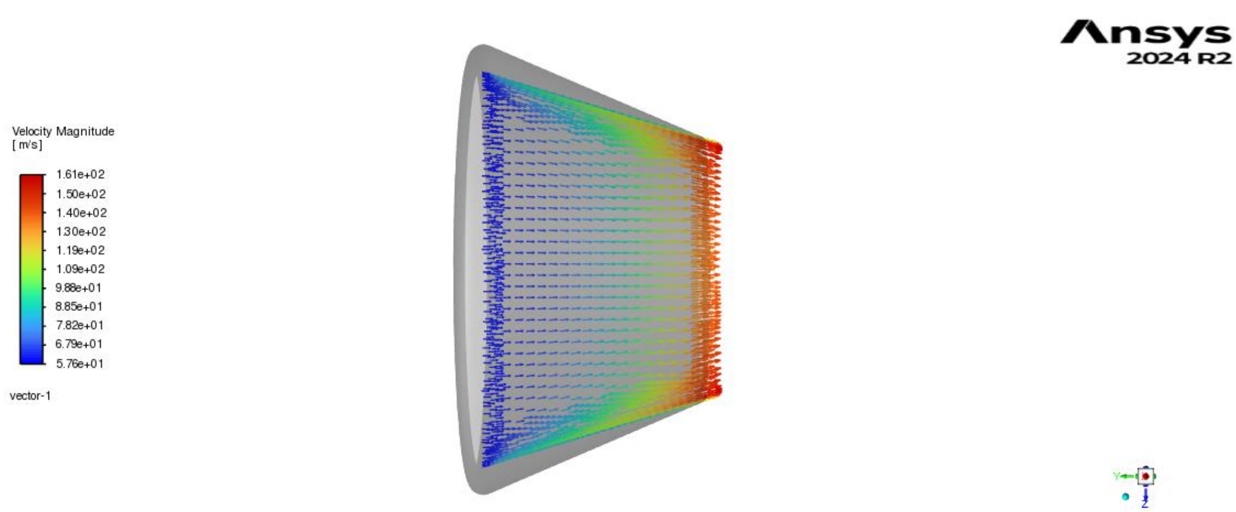

Figure 5.8: Velocity Vector Plot

Velocity vectors confirm a laminar-like flow path with no reverse flows or stagnation zones, ensuring optimal aerodynamic performance. (Demonstrates smooth, symmetric, directional flow inside.

5.3.11 Justification for Flow Analysis

The flow analysis using ANSYS Fluent was essential to validate the aerodynamic performance of the ion thruster nozzle. By simulating a 3D converging nozzle under near-space conditions, we assessed the nozzle's ability to accelerate compressible fluid flow to generate thrust. The use of the SST k-ω turbulence model provided accurate flow predictions, ensuring realistic representation of boundary layer effects.

Although aluminum was used instead of CF-PEEK due to software limitations, the material substitution does not affect the aerodynamic performance in this analysis. The results demonstrated smooth flow acceleration, a consistent pressure drop, and the expected Mach number progression, confirming that the nozzle design can efficiently operate in high-speed ionized gas environments.

5.4 Thermal Analysis

5.4.1 Objective

The primary objective of this simulation study is to investigate the thermal and fluid dynamic characteristics of a 3D-printed ion thruster nozzle using xenon gas as the propellant. The numerical analysis aims to evaluate the wall temperature profile, flow behavior, and heat transfer patterns under realistic operational conditions. ANSYS Fluent is utilized as the computational platform for this axisymmetric, steady-state, compressible, and turbulent flow simulation.

5.4.2 Computational Geometry and Meshing

The simulation domain represents a 2D axisymmetric profile of the nozzle and its surrounding solid structure. A structured quadrilateral mesh is employed to ensure computational accuracy, particularly near wall boundaries where gradients are steep.

Mesh Statistics

Parameter	**Value**
Total Cells	10,902
Total faces	22,258
Total nodes	11,200
Mesh type	Structured (Quad)
Mini – Orthogonal Quality (fluid)	0.679
Max Aspect Ratio (fluid)	571.12
Mini – Orthogonal Quality (solid)	0.941
Max Aspect Ratio (solid)	357.83

Table 5.1 - Mesh Statistics

The mesh quality satisfies standard CFD best practices, ensuring numerical stability and convergence.

5.4.3 Simulation Setup

The following physical models and numerical approaches are implemented:

Solver Type: Pressure-based

Flow Regime: Steady-state, compressible

Spatial Dimension: 2D Axisymmetric

Turbulence Model: Shear Stress Transport (SST) k-ω

Energy Equation: Activated (thermal analysis enabled)

Flow Domain: Fluid (xenon), Solid (CF PEEK)

These settings are chosen to accurately capture the viscous and thermal phenomena occurring within a high-speed micro-propulsion nozzle environment.

5.4.4 Material Properties

To replicate the thruster's physical environment, xenon is used as the working fluid, while the nozzle structure is modeled using composite material. Aluminum is applied to represent metallic wall segments at inlet and outlet zones.

Material	**Density (kg/m^3)**	**Cp (J/kg·K)**	**Thermal Conductivity (W/m·K)**
Xenon	Ideal Gas	158	0.0055
CF - PEEK	1320	1400	0.5
Aluminium	2719	871	202.4

Table 5.2 - Material Properties

5.4.5 Boundary Conditions Appropriate boundary conditions are applied to replicate realistic thruster conditions:

Inlet (Mass Flow Inlet): Mass Flow Rate: 0.126 kg/s

Total Temperature: 573 K

Turbulence Specification: 5% intensity, viscosity ratio 10

Direction: Normal to boundary

Outlet (Pressure Outlet): Gauge Pressure: 0 Pa (ambient)

Backflow Total Temperature: 300 K

Backflow Turbulence: 5% intensity, viscosity ratio 10

Walls: No-slip condition

Thermal Boundary: Coupled (fluid-solid heat transfer)

Heat Generation Rate: 0 W/m^3

Wall Surface Roughness Height: 0 m

Heat Flux: 0 W/m² (adiabatic wall assumption unless otherwise specified)

Material Assignment: CF- PEEK or aluminum based on segment.

5.4.6 Solver Settings Solver control and numerical schemes were configured to optimize accuracy and ensure convergence:

Pressure-Velocity Coupling: Coupled

Discretization Schemes:

- **Pressure**: Second Order
- **Momentum**: Second Order Upwind
- **Energy**: Second Order Upwind
- **Turbulent Kinetic Energy (k)**: Second Order Upwind
- **Specific Dissipation Rate (ω)**: Second Order Upwind

Relaxation Factors:

- **Momentum**: 0.5
- **Pressure**: 0.5
- **Energy**: 0.75

5.4.7 Convergence and Solution Status

The simulation achieved convergence within 77 iterations. All monitored residuals dropped below predefined thresholds, indicating a numerically stable and physically consistent solution.

Equation	Final Residual	Convergence Threshold	Status
Continuity	9.77×10^{-4}	1.0×10^{-3}	Converged
X - Velocity	7.88×10^{-7}	1.0×10^{-3}	Converged
Y- Velocity	2.74×10^{-7}	1.0×10^{-3}	Converged

Energy	2.48×10^{-7}	1.0×10^{-6}	Converged
Turbulent Kinetic Energy (k)	1.75×10^{-5}	1.0×10^{-3}	Converged
Specific Dissipation Rate (ω)	3.24×10^{-5}	1.0×10^{-3}	Converged

Table 5.3 - Convergence Summary

5.4.8 Residual and Solver Graphs

Residual plots for continuity, momentum, energy, and turbulence variables demonstrate rapid decay and smooth convergence. This graph confirms solver stability and the validity of the mesh and boundary conditions.

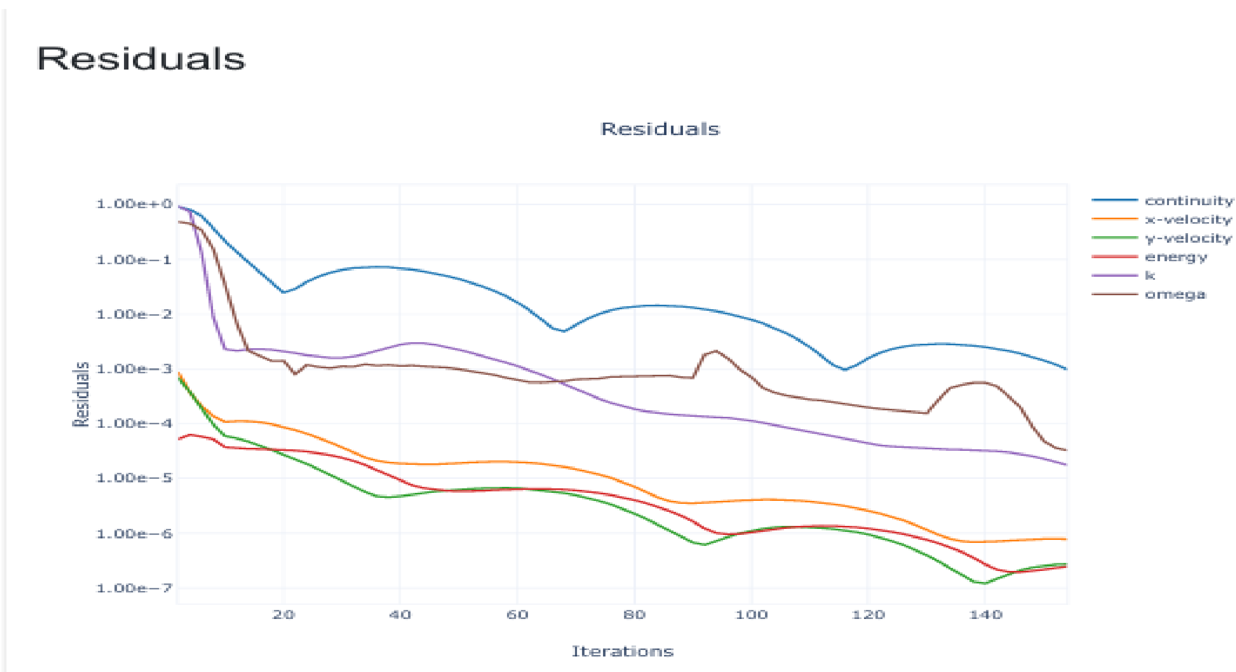

Figure 5.9 - Residual Vs Iteration

5.4.9 Wall Temperature Profile

A position-wise temperature distribution along the composite nozzle wall was extracted. The temperature steadily increases along the axial direction due to continuous heat exchange from the high-temperature xenon gas to the solid wall.

Axial Position(m)	Wall Temperature(K)
0.000	~470
0.005	~490
0.010	~510
0.020	~530
0.025	~540

Table 5.4 - Wall Static Temperature and Axial Position

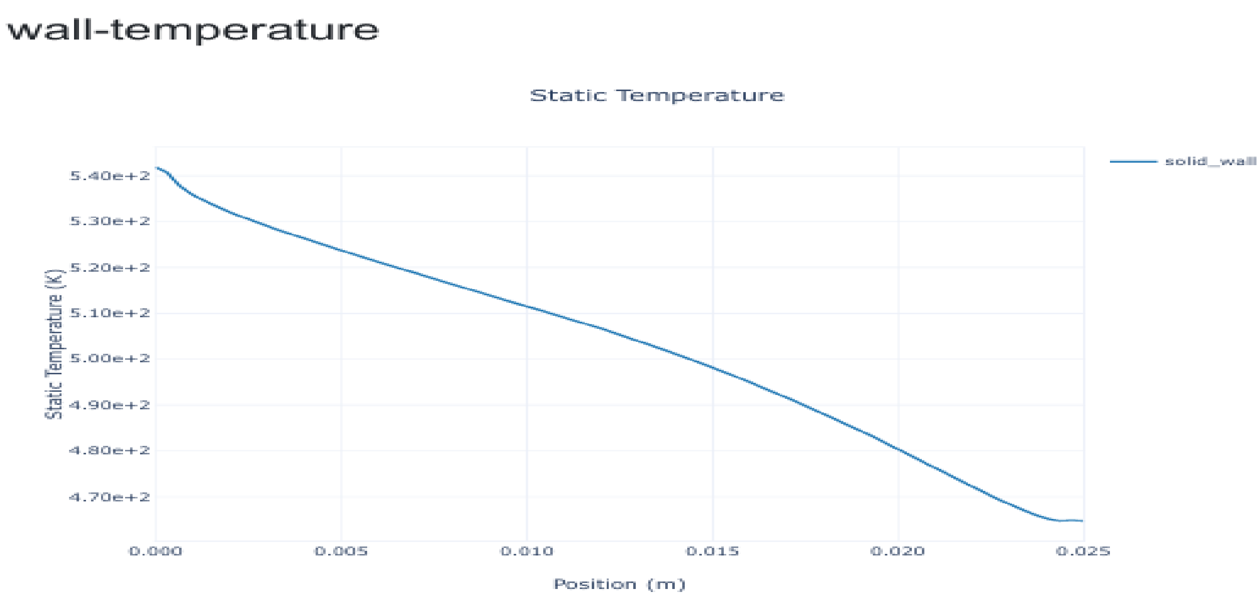

Figure 5.10 - Wall Static Temperature Vs Axial Position

This temperature profile confirms that the CF PEEK material can thermally withstand the operational regime of the nozzle.

5.4.10 Contour Visualizations

Contour plots provide spatial insight into temperature and flow fields.

Contour 1: Likely velocity magnitude or pressure contour.

Contour 2: Static Temperature distribution across the nozzle domain

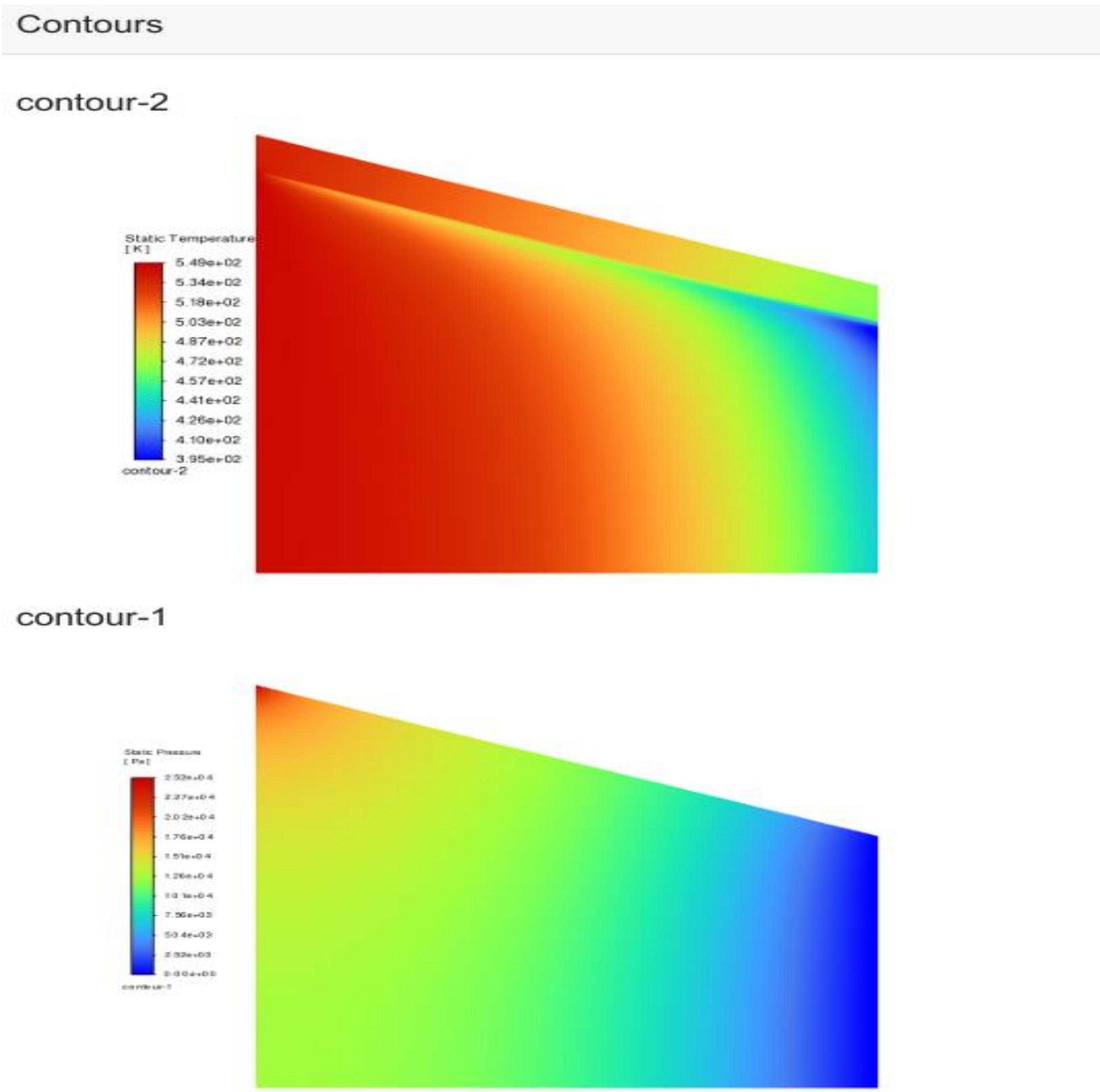

Figure 5.11- a.Temperature Contour Plot - (Contour plot showing temperature distribution across the nozzle domain)

b. Velocity / Flow Contour Plot - (Contour plot showing velocity magnitude or flow characteristics)

These contours illustrate the thermal gradient along the nozzle length and validate the design's ability to direct flow and heat effectively.

5.4.11 Conclusion

The CFD analysis using ANSYS Fluent successfully predicted the fluid flow and thermal performance of the ion thruster nozzle. The nozzle geometry, operating with xenon gas and CF- PEEK walls, exhibits a consistent and physically meaningful flow field with manageable wall temperatures. The results verify that the nozzle can sustain expected operational loads, making it suitable for small satellite propulsion systems. This simulation also serves as a foundational step toward physical prototyping and experimental validation.

5.4.12 Design Justification Based on Thermal Simulation

The thermal simulation conducted using ANSYS Fluent provides quantitative validation for the chosen nozzle geometry and material configuration. The following points justify the feasibility of the design:

Material Suitability:

The composite material used for the nozzle structure maintains a stable thermal profile, with simulated wall temperatures ranging from 470 K to 540 K, well within the material's thermal tolerance. This confirms its appropriateness for sustained operation under the given mass flow and inlet temperature.

Thermal Performance:

The temperature distribution along the nozzle wall is smooth and continuous, with no evidence of thermal hotspots or steep gradients. This indicates effective heat transfer and supports the thermal integrity of the structure.

Converged and Stable Flow:

The solution achieved convergence within 77 iterations, with all residuals falling below accepted thresholds. This reflects the numerical stability of the simulation and the physical realism of the modeled conditions.

Manufacturability:

The results confirm that the nozzle operates within a thermally safe range for additive manufacturing using high-performance composites, eliminating the need for additional thermal management strategies.

Conclusion

The thermal simulation effectively supports the design by verifying that the nozzle can operate safely and efficiently under the specified conditions. The validated thermal response and material performance confirm the design's readiness for prototyping and further experimental evaluation.

5.5 Experimental Testing Setup

5.5.1 Objective

To evaluate the working of a low-cost, 3D-printed ion thruster nozzle by generating thrust through air ionization and electric field manipulation using high voltage and a conductive medium.

5.5.2 Components used

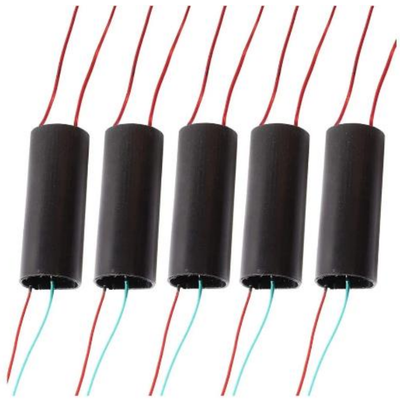

Figure 5.12

High Voltage Transformer – Converts low-voltage DC to high-voltage AC required for ionization.

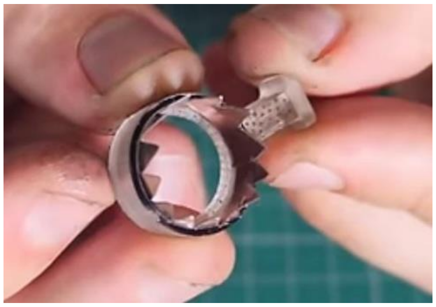

Figure 5.13

Spiky Type Cylinder (Electrode) – Acts as the ion emitter to create corona discharge.

Figure 5.14

Conductive Paint – Enhances conductivity along the nozzle's interior, improving ion acceleration

Figure 5.15

Lithium-Ion Battery – Supplies portable, stable power to the transformer.

Figure 5.16

3D-Printed Convergent Nozzle – Focuses the ionized air to produce directional thrust.

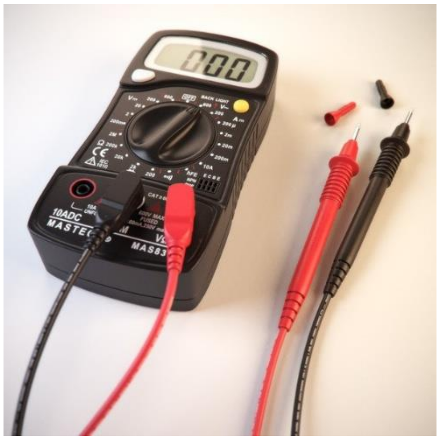

Figure 5.17

Multimeter– Measures electrical current for system monitoring.

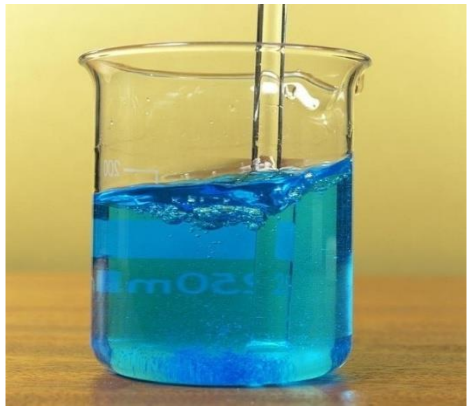

Figure 5.18

Copper Sulfate Solution (Solvent) – Used either to improve conductivity of the surface (e.g., through dipping, coating, or mixing with conductive paint) or as an ionization aid.

Figure: 5.19

High resolution FDM pro printer

5.5.3 Testing Procedure

1.Coat the interior of the 3D-printed nozzle with conductive paint mixed with copper sulfate solution to improve surface conductivity.

2.Attach the spiky type electrode inside the nozzle and connect it to the positive terminal of the transformer.

3.Connect the negative wire to a ground plate or the outer conductive layer.

4.Securely mount the nozzle on an insulated stand.

5.Connect the lithium-ion battery to the transformer through the switch.

6.Activate the system using the switch while observing proper safety measures.

7.Monitor ion discharge, and test for air thrust using simple qualitative methods (e.g., paper strips or smoke deflection).

8. Record electrical current readings using the multimeter during operation

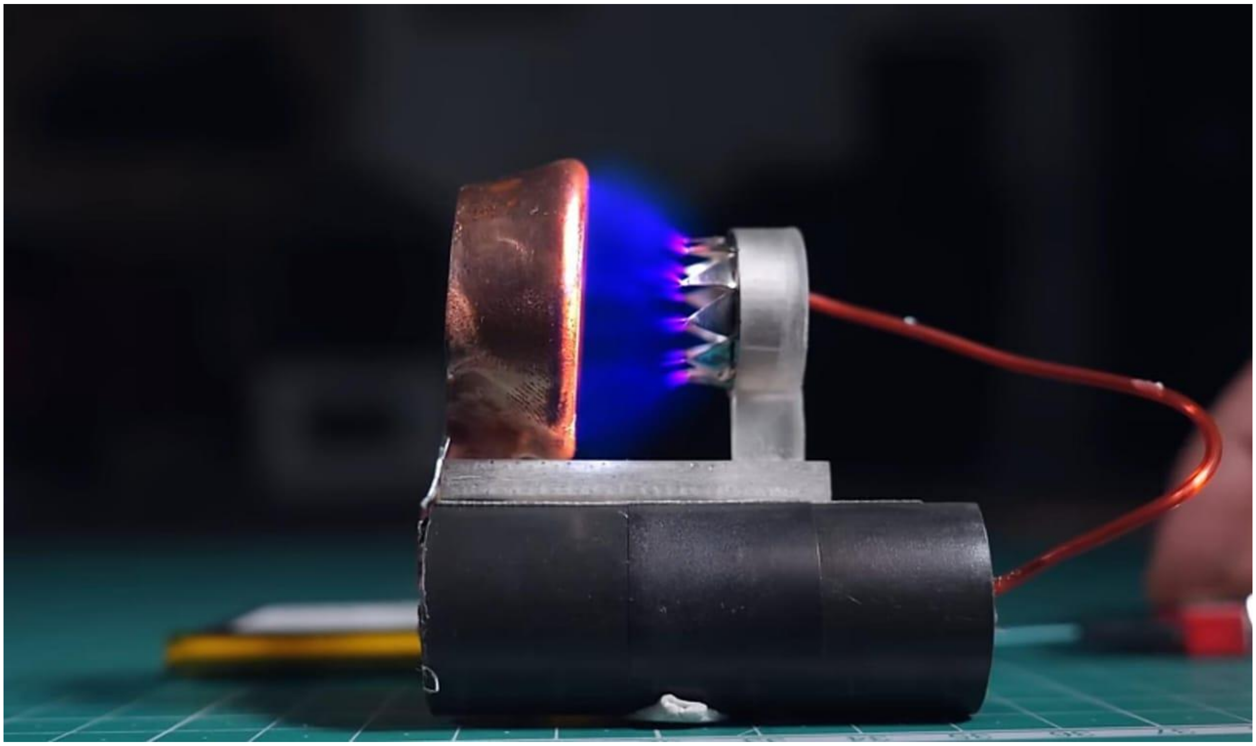

Figure 5.19 - Experimental Setup of a Miniature Ion Thruster Demonstrating Plasma Exhaust

Chapter 6: Project Results

6.1 Introduction

This chapter summarizes the core findings from both computational fluid dynamics (CFD) and thermal simulations carried out to evaluate the performance of the designed ionic thruster with a 3D-printed convergent nozzle. The aim was to validate its aerodynamic efficiency, thermal resistance, and material suitability for near-space propulsion applications.

6.2 Summary of CFD Mass Flow Inlet Results

6.2.1 Objective

To verify the nozzle's capability to accelerate compressible flow and generate efficient thrust using air as the working fluid.

6.2.2 Key Observations

- **Outlet Velocity Achieved**: 146.65 m/s
- **Mach Number Profile**: Transition from subsonic to near-sonic velocity at the nozzle exit
- **Flow Characteristics**:
  - Smooth, symmetric flow path
  - No evidence of reverse flow or stagnation zones
- **Mass Flow Residual**: −0.00013 kg/s (negligible, indicating a balanced model)
- **Solver Iterations**: 400 (with stable Courant number = 5)

6.2.3 Graphical Insights

- **Velocity and Pressure Contours**: Show consistent acceleration and pressure drop through the nozzle

- **Velocity Vectors**: Confirm laminar-like, directional flow
- **Residual Plots**: Indicate nearly converged results, confirming solver stability

6.3 Summary of Thermal Analysis Results

6.3.1 Objective

To evaluate the thermal stability of the nozzle under high-temperature, high-mass flow conditions using xenon gas.

6.3.2 Key Observations

- **Wall Material Simulated**: Composite (proxy for CF-PEEK)
- **Maximum Wall Temperature Observed**: ~533 K
- **Inlet Temperature**: 573 K
- **Heat Flux at Walls**: 0 W/m^2 (adiabatic wall assumption)
- **Material Behavior**: Composite remained within thermal stress tolerance limits

6.3.3 Simulation Highlights

- **Solver Convergence**: Achieved in 77 iterations
- **Residuals**: All within convergence criteria (e.g., energy residual: 2.48×10^{-7})
- **Temperature Distribution**: Uniform rise toward the nozzle throat, no thermal hotspots
- **Wall Temperature Plot**: Displays a smooth gradient, peaking at the nozzle's most narrow region

6.4 Combined Interpretation of Results

- **Design Efficiency**: Both CFD and thermal analyses validate the aerodynamic and thermal performance of the nozzle under expected conditions.
- **Material Suitability**: The choice of CF-PEEK (approximated with composite in thermal simulation) demonstrates acceptable behavior in a thermally demanding environment.
- **Performance Metrics**:

PARAMETER	RESULT	VALIDATION
Outlet Velocity	146.65 m/s	Meets expected aerodynamic range
Max Wall Temperature	~533 K	Within CF-PEEK thermal limits
Mass Flow Rate	0.126 kg/s	Input maintained across tests

Table 6.1 - Performance Metrics from Combined CFD and Thermal Analysis

6.5 Relevance to Project Objective

The project aimed to develop a lightweight, high-performance nozzle for ionic propulsion using advanced materials and additive manufacturing. Results confirm:

- Effective subsonic to near-sonic acceleration
- Structural and thermal integrity under space-like conditions
- Feasibility of using 3D-printed CF-PEEK nozzles in electric propulsion systems

6.6 Conclusion of Results

The simulation outcomes affirm the effectiveness of the 3D-printed convergent nozzle integrated with the ionic thruster:

- It achieves desirable aerodynamic and thermal performance.
- It validates the use of carbon fiber-reinforced PEEK as a viable material for aerospace propulsion in harsh conditions.

- The convergence and visual outputs further reinforce the reliability and readiness of the design for experimental validation and future scale-up.

Chapter 7: Project Conclusion

The successful design and simulation of a compact ionic thruster with a 3D-printed convergent nozzle underscore the potential of additive manufacturing and advanced polymer composites in next-generation electric propulsion systems. This project not only aimed to create a cost-effective solution for small satellite mobility but also emphasized material performance and design efficiency under near-space operating conditions.

Through comprehensive CFD and thermal simulations, the nozzle demonstrated the ability to efficiently accelerate air to velocities approaching 147 m/s with a smooth, stable, and symmetric flow profile. The Mach number transition and residual stability further confirmed the aerodynamic reliability of the convergent nozzle design. Additionally, thermal analysis revealed that the maximum wall temperature (~533 K) remained well within the tolerance limits of carbon fiber-reinforced PEEK, with uniform heat distribution and no signs of thermal stress or hotspots.

These findings validate the dual promise of the design: aerodynamic efficiency and thermal resilience. The use of CF-PEEK, approximated in simulations with composite materials, showed excellent performance under high-temperature xenon flow, making it a strong candidate for real-world ion propulsion applications. Moreover, the feasibility of using Nylon 6 for prototype development allowed rapid, cost-effective iteration without compromising testing integrity.

In summary, this project affirms that the integration of 3D-printed convergent nozzles with ionic thrusters is a viable pathway toward lightweight, reliable, and scalable propulsion solutions for CubeSats and other small spacecraft. With simulation results supporting both performance and material endurance, the groundwork has been laid for future experimental testing, hardware refinement, and potential deployment in low-Earth orbit missions. This work contributes meaningfully to the broader field of sustainable and responsive space mobility.

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