"DESIGN OF VAPORIZING LIQUID MICRO-THRUSTER FOR MICROSATELLITE APPLICATION"

A report submitted in partial fulfillment of the requirements for the degree of

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In

Aerospace Engineering

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It is certified that the work contained in the project titled **"*Design of Vapourising Liquid Microthrusters for Microsatellites Application*"** by following students has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

This abstract analyzes the basic aspects of Vaporizing Liquid Micro-Thrusters (VLMTs) systems, that concern themselves with the application of fluid, heat, and phase change phenomena within the boundaries of the thruster's functioning. Design problems are outlined that include VLMTs integration of a satellite system, selection of materials for heat goodness, as well as nozzles design for thrust producing efficiency. VLMT performance metrics include responsiveness, specific impulse, and thrust per power relations. These metrics help when comparing VLMTs to propulsion devices such as electrospray, cold gas, or monopropellant thrusters.

VLMTs are capable of delivering accurate attitude control and orbital maneuvering of small satellites. Since the propellant exists as a liquid, VLMTs can directly vaporize it, avoiding complex and bulky pumps. Furthermore, the propulsion system becomes increasingly reliable because there exist no moving parts within that deteriorate the whole system. The absence of mechanical moving parts improves the lifetime of the average satellite greatly also. This abstract examines diverse working principles of VLMTs along with the specific design limitations and performance criteria. Additionally, the advantages as well as limitations of VLMTs are discussed, along with their potential applications for nanosatellite and microsatellite propulsion.

Propulsion systems have greatly aided the rapid expansion of concepts focused on nano-satellites and microsatellites. The expansion is predominantly in the direction of miniaturization using microelectromechanical system (MEMS) technology. Today, MEMS-based micropropulsion systems are popular for their extensively adjustable thrust at the microscale level. VLMT is one of the many recently created MEMS microthrusters that enable researchers to continuously vary thrust within the range of micronewtons to millinewtons. This level of precision makes VLMTs suitable for mission-critical applications such as formation flying, drag compensation, and station- keeping tasks in low Earth Orbit (LEO) and even deep space missions.

In addition to their accuracy and precision, VLMTs are also highly scalable and can adapt to different liquid propellant needs: water, ethanol, and even layers ionic liquids. Current work revolves around the optimization of thermal control in an attempt to streamline the vaporization process and boost thrust efficacy. Moreover, the future design of VLMTs is anticipated to be positively impacted by the use of additive manufacturing and nanomaterials.

Acknowledgement

We take this opportunity to express our sincere thanks to my supervisor **Dr Harshit Shukla** for their guidance and support. We would also like to express our gratitude towards them for showing confidence in us. It was a privilege to have a great experience working under him in a cordial environment.

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Chapter 1 Introduction

CubeSats, tiny satellites that many research institutions worldwide find fascinating, are revolutionizing space exploration. These small spacecrafts are cheap and reliable. With more interest in microsatellites, as seen in the images below, CubeSats need a functional propulsion system for attitude control, drag compensation, orbit adjustment, station-keeping, and maintaining their position.[1]

Figure 1.1: CubeSat[2]

Consider a miniature device that could assist in powering a satellite situated in orbit. This may appear to be ye of high-tech fiction, but it is an example of today's existing technology. Cubesats and small satellites greatly benefit from the advancements made in Microelectromechanical systems, MEMS for short. MEMS is straightforward, they use silicon, the same element found in computer chips, to build tiny mechanical systems. The versatility of MEMS is not just limited to silicon; it can also involve other processes of micro fabrication like high-aspect-ratio micromachining which intertwines electrochemical and mechanical techniques. The construction of micron-scale devices like MEMS is made more precise, allowing for incorporation into lightweight and compact structures. While researchers work on improving microthruster technologies, many possibilities open up with how propulsion systems and MEMS enhanced the efficiency of propellant use along with the devices. Studying microthrusters involve exploring various designs, their operational principles, and the newest technologies in propulsion anatomy that stem from MEMS. There are several types of microthrusters, each with its own unique benefits. Some of the most important types include: Free Molecule Micro-Resistojets (FMMRs), Electrospray micro thrusters, Cold gas microthrusters (CGMs), Colloid micro thrusters, Plasma microthrusters

An example of a microthruster that is capturing people's attention is the Vaporizing Liquid Micro-Thruster (VLMT). This one use microheaters to turn a liquid propellant into vapor. The propellant is ejected through a nozzle, creating thrust. The simplicity of VLMTs is where their elegance lies. Because they do not have elaborate pressurization or pumping systems, they are less complicated, efficient, and reliable.

1.1 Advancements and Applications of MEMS-Based Propulsion

Let's say you're working on a space mission, one which requires an engine that will keep your spacecraft propulsed. Conventional propulsion systems were the only option for a long period of time, but their drawbacks were rather considerable. Their complexity, weight, and power consumption expenditure were a high and unnecessary burden. Those days are behind us, however, given rise from the need provided by small satellites like CubeSats, there is increase demand for compact and efficient engines capable of sustaining operation for months on end, if not years. This where MEMS (Microelectromechanical systems) propulsion comes in. The possibilities get even broader with MEMS enabling construction of small low powered engines which are remarkably light on weight. Within this category, one type of MEMS engine stands out, and that's VLMTs, or Vaporizing Liquid Micro-Thrusters. Why exactly is that the case? For one, they operate under a variety of fuels, including water, ethanol, and even ionic liquids. This allows mission planners to tailor the fuel, performance, storage, and even the environmental impact assessing. Another benefit of MEMS technology is enabling us to incorporate the tiny engines right on the design of the small satellites. Achieving supersonic speed with minimal power means optimization of power distribution and reduction in heat loss throughout the control system, improving total system efficiency. In other words, MEMS propulsion is changing the way we travel through space. Smaller, more efficient engines make it possible to design compact smart satellites that travel further and remain in orbit longer. It is an incredible time for space exploration, with MEMS taking the lead!

1.1.1 The Benefits of MEMS Propulsion

MEMS propulsion offers several benefits. compact design, MEMS engines are incredibly small, making them perfect for small satellites. Low power consumption, MEMS engines consume minimal power, which is essential for small satellites with limited power resources. Lightweight, these engines are designed to be lightweight, which reduces the overall weight of the spacecraft and makes it more efficient.

The Advantages of Integrating MEMS Engines, MEMS technology enables us to integrate tiny engines directly into the design of small satellites. This offers several advantages, including:

- Optimization of power distribute on: By integrating MEMS engines, we can optimize power distribution and reduce heat loss throughout the control system.

- Improved system efficiency: MEMS engines improve the overall efficiency of the spacecraft, enabling it to operate for longer periods.
- Supersonic speeds: MEMS engines can achieve supersonic speeds with minimal power, making them perfect for small satellites.

1.1.2 The Future of Space Exploration

MEMS propulsion is revolutionizing the way we travel through space. With smaller, more efficient engines, we can design compact smart satellites that can travel further and remain in orbit longer. The possibilities are endless, and MEMS technology is leading the way.

As we continue to explore space, MEMS propulsion will play an increasingly important role. With its compact design, low power consumption, and lightweight construction, MEMS engines are perfect for small satellites. The future of space exploration is exciting, and MEMS technology is at the forefront of this revolution.

1.1 Performance of Vaporizing Liquid Micro thruster

Imagine a tiny engine that can propel a small satellite through space with incredible precision. This is made possible by a technology called Vaporizing Liquid Microthrusters, or VLMs. But how does it work? In simple terms, a VLM uses heat to turn a liquid into vapor. This vapor is then expelled, creating a tiny force that propels the satellite forward. It's a remarkably efficient process that allows for precise control, which is essential for small satellites and other miniature space systems. These tiny satellites, like CubeSats, need to be able to make precise adjustments to their trajectory and orientation in space. VLMs provide the perfect solution, offering a reliable and efficient way to generate the small amounts of thrust required. The process is quite fascinating. The liquid propellant is heated until it vaporizes, creating pressure that pushes the vapor out of a tiny nozzle. As the vapor exits, it generates a force that propels the satellite forward. By carefully controlling the amount of heat and vapor produced, the satellite can make precise adjustments to its movement. VLMs are particularly useful for small satellites because they're compact, efficient, and reliable. They also offer a high degree of precision, which is critical for many space missions. Whether it's maintaining a stable orbit or making precise maneuvers, VLMs provide the control and reliability that small satellites need to succeed. As the demand for small satellites continues to grow, technologies like VLMs will play an increasingly important role in enabling these tiny spacecrafts to perform complex tasks with precision and accuracy.

1.2.1 Measuring Performance

To understand how well a VLM performs, we need to examine eight critical factors:

Analyzing Performance, In order to evaluate a VLM and its performance, a thorough analysis of the following eight factors is needed:

- Thrust production: Thrust is defined as the movement of a spacecraft forwards in a linear direction. With VLMs, thrust is performed with smooth movements which require minute yet exact measures of thrust.
- How much fuel is needed to provide thrust? To be efficient, the fuel economized need to be maximized.
- Fuel Consumption: What is the rate of speed at which fuel is being consumed by the thruster? The spacecraft and all its parts and equipment need to last for a considerable duration of time. Balance of fuel consumption becomes important, especially if the thruster consumes fuel too quickly.
- Energy expenditure: Power tends to be a concern with the VLMs as energy is needed to warm up the liquid, which has to be sourced from the sun or batteries.
- Heat Efficiency: The ratio of thrust provided to the power being consumed is maximized as deftly accepting heat is achieved and thus conducted energy to the thruster system. Micro-thusters tend to get powered up using swiftly.
- The Nozzle: The vapor configured gas has to the body divided to undergo acceleration for smoother thrust. With a proper functioning nozzle, the high thrust is ensured to be enabled while the fuel is vended at a requisite limit ensuring active consumption.

Selection of Propellant: The selection of a fuel will change the efficiency and storage parameters of the fuel. Water, ethanol, and even hydrogen peroxide are candidates for propellants.

Propellant Choice**:** The type of liquid fuel used affects efficiency, storage, and more.

1.4 Objective

Objective 1

Selection and Design of the Vaporizing Liquid Micro-Thruster

Mission is to create a game-changing propulsion system for micro-satellites. Talking about a tiny engine that's not only super-efficient but also ultra-reliable. To get started, dive into existing technologies to find the best designs and materials. Goal is to build a thruster that uses minimal fuel while packing a powerful punch, allowing the satellite to move with precision through space. But before starting to building, use advanced computer simulations to design and optimize the thruster. This will help get it just right before creating prototypes for real-world testing.

Objective 2

Experimental Analysis and Testing of the Optimized Vaporizing Liquid MicroThruster

Now that designed the vaporizing liquid microthruster, it's time to put it to the test. The next goal is to see how well it performs in different conditions. Set up a series of experiments to evaluate its thrust, power efficiency, and reliability. But to make sure the results are accurate; need to simulate the harsh conditions of space. That means testing the thruster in a vacuum and at different temperatures. By collecting data from these tests, to be able to identify the thruster's strengths and weaknesses.

Chapter 2 Literature Survey

2.1 The Vaporizing Liquid Micro-thruster

Throughout this study, "micropropulsion" refers to systems that can generate tiny amounts of thrust (in the range of micro or millinewtons) to help nanosatellites or picosatellites navigate, based on their mass, size, and power needs. MEMS (Microelectromechanical Systems) technology, which uses small-scale fabrication techniques, has been successfully applied in micropropulsion for these small satellites. Over the past few years, different types of micropropulsion systems using MEMS have been explored. These can be categorized by the methods they use to create thrust.[4]

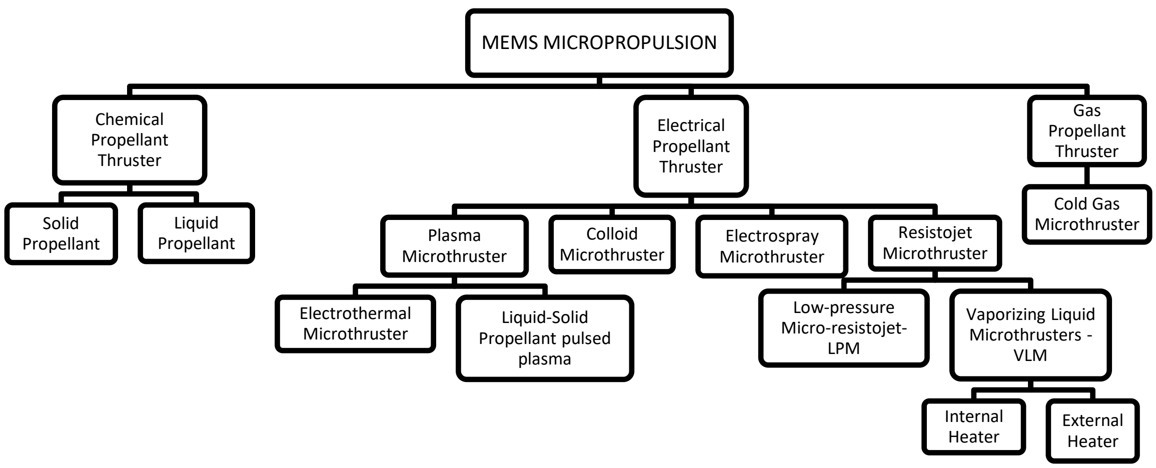


Figure 2.1: Types of MEMS microthruster

Microthrusters utilizing MEMS technology are continuously being developed to enhance the efficiency and precision of small satellite propulsion. This study provides an overview of the current advancements in various MEMS-based microthrusters, highlighting their operational principles, advantages, and limitations. While some microthruster technologies, such as Vaporizing Liquid Micro-Thrusters (VLMTs) and Free Molecule Micro-Resistojets (FMMRs), have received significant research attention, others—such as cold gas microthrusters, plasma microthrusters, electrospray microthrusters, and colloid microthrusters—remain relatively less explored. Therefore, this study includes a brief discussion of these microthruster types, examining their structures, working mechanisms, and potential applications in space missions. When it comes to powering small satellites, we need engines that are both efficient and reliable.

2.2 Chemical MEMS Micro thruster

When a spacecraft's propulsion system is activated, it transforms the chemical energy stored in the propellant into a powerful force that accelerates the spacecraft. It all happens in a tiny nozzle that's carefully designed to maximize efficiency. As the propellant is burned, it produces hot gases that want to expand rapidly. The nozzle is shaped in such a way that it focuses these gases into a narrow beam, which shoots out of the back of the spacecraft, producing thrust. There are many different types of propulsion systems, and they can be classified based on the type of propellant they use and how they convert energy. For example, some microthrusters use solid propellants, while others use liquid propellants. Each type has its own strengths and weaknesses, and scientists are constantly working to improve their design and efficiency.

2.2.1 Solid Propellant Microthruster (SPM)

Solid propellant micro thrusters simple, compact, and can deliver a quick burst of thrust when needed. One of the best things about solid propellant microthrusters is their flexibility. They can be designed to fit into tight spaces, either standing upright or lying flat. This makes them perfect for small spacecraft where every inch counts. These tiny engines have some other benefits too. They're easy to use, compact, and can deliver a quick burst of thrust when needed. However, they do have some limitations. For example, you can't adjust the amount of thrust they produce, and they're usually designed to be used only once. Overall, solid propellant microthrusters are a great option when you need a simple, compact, and reliable source of thrust Liquid Propellant Microthruster (LPM).

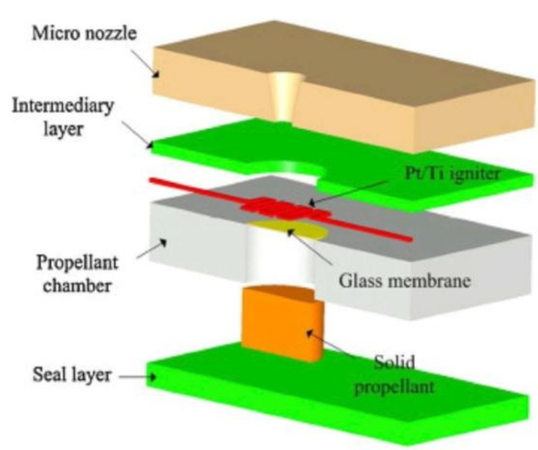


Figure 2.2: Solid Propellant[6]

2.2.2 Liquid propellant microthrusters

Liquid propellant microthrusters has engines come in two main types: bipropellant and monopropellant. The first type uses a combination of fuel and oxidizer to create a chemical reaction, while the second type uses a catalyst to break down the fuel. They're a lot more flexible than their solid-fuel counterparts. You can throttle them up or down, and even restart them multiple times. This makes them perfect for delicate maneuvering tasks, like adjusting a satellite's orbit or attitude. However, liquid microthrusters are also more complex. They need extra components like storage tanks, valves, and injection mechanisms, which can make them more difficult to design and build. Despite this, they're a popular choice for many space missions, where precision and flexibility are essential.

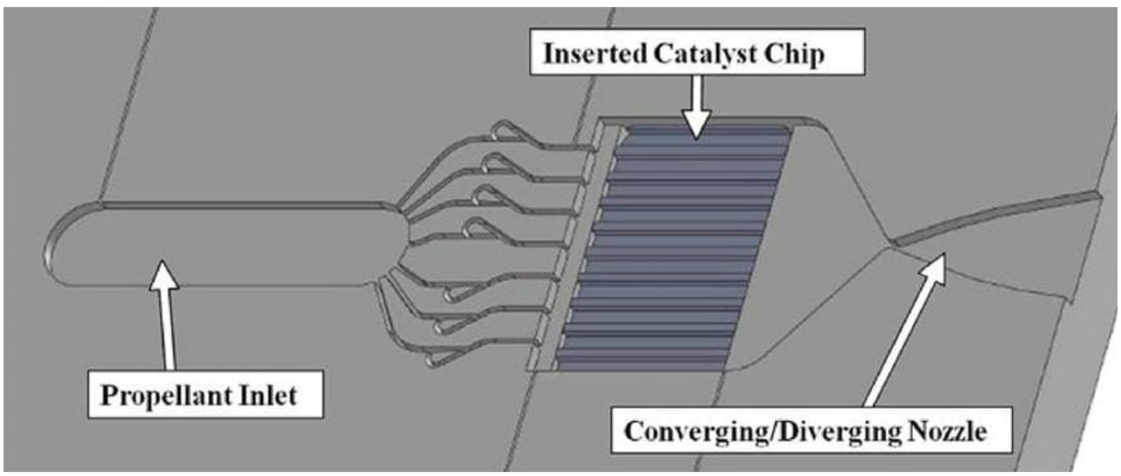


Figure 2.3: Liquid Propellant[11]

2.3 Gas Propellant Thruster

Imagine a super-simple engine that runs on compressed gas. No flames, no explosions – just a quiet, reliable, and safe way to propel a small satellite through space. This is what's known as a cold gas thruster. These engines are perfect for small satellites, like CubeSats, that need to make tiny adjustments in space. They're great for attitude control, station-keeping, and small orbital tweaks. And the best part? They're incredibly reliable, use very little energy, and are easy to integrate into small satellite systems. So, what makes cold gas thrusters so special? For starters, they provide very accurate and controlled thrust. This is essential for delicate maneuvers in space, where even the tiniest mistake can have big consequences. They're also very safe, since they don't involve combustion or any other hazardous processes.

2.3.1 Cold Gas Microthrusters (CGM)

Cold gas micropropulsion the engine stores pressurized gas, which is then released through a tiny nozzle at high speed, creating thrust. The gas can be stored in different forms, like liquid or solid, depending on the mission requirements. When it's time to use the gas, it undergoes a phase change, turning back into a gas that can be expelled through the nozzle. Their performance depends on three main factors: storage pressure, nozzle design, and the type of gas used. Common gases include nitrogen, carbon dioxide, and inert gases like xenon or argon. One of the best things about cold gas microthrusters is their simplicity. They don't have complicated parts like ignition systems or high-power electrical components, which makes them super reliable and less likely to fail. Plus, they're clean and don't produce any combustion byproducts, making them perfect for missions that require minimal contamination, like scientific observations or formation flying. However, these engines do have some limitations. They're not as efficient as other types of propulsion systems, like chemical or electric thrusters, which means they don't pack as much punch. But they're still super useful for specific tasks, like precise attitude control, maintaining formation in satellite constellations, and controlled deorbiting. Right now, researchers are working to improve these engines by developing more efficient gas storage systems, refining nozzle designs, and combining cold gas systems with other propulsion methods to create even more maneuverable satellites.

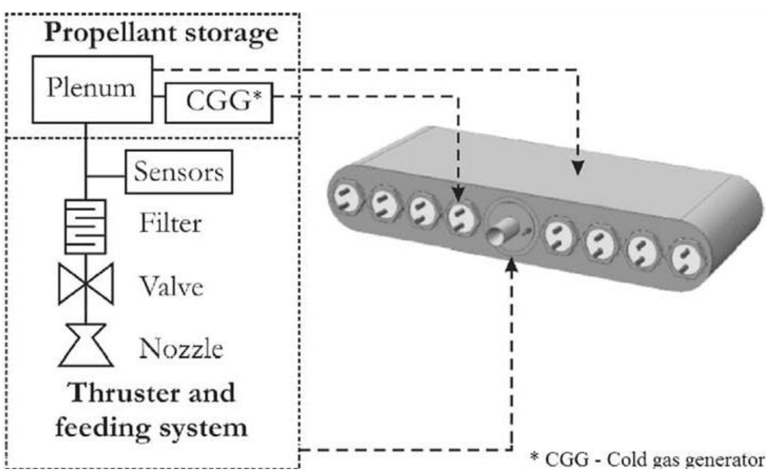


Figure 2.4: Cold Gas Propellant [3]

2.4 Electric MEMS Micro thruster

These engines use electrical energy to ionize a propellant, like xenon gas, and then propel it out of the back of the spaceship to create thrust. This process is way more efficient than traditional chemical propulsion systems, which rely on combustion. As a result, electric propulsion systems can support long-duration space missions while using significantly less propellant. At the heart of these systems is a specialized energy-processing unit that manages the power needed to ionize and propel the propellant. This ensures that the engine runs efficiently and effectively. They're perfect for deep-space missions, attitude control, and making precise orbital adjustments. They offer high specific impulse (a measure of efficiency) and can operate for a long time, making them ideal for long-duration space missions. As space technology continues to evolve, scientists are developing new types of microelectric thrusters to meet the unique demands of various space missions. These advancements will help pave the way for even more efficient and effective space travel.

2.4.1 Plasma Micro thruster

These engines take a neutral gas, like xenon or argon, and turn it into plasma by stripping away its electrons. Then, they use electric or magnetic fields to accelerate the plasma, creating a high-speed exhaust that generates thrust. Plasma microthrusters have some big advantages over traditional chemical propulsion systems. They're way more efficient, which means they can achieve higher speeds using less fuel. This makes them perfect for deep-space missions, station-keeping, and even coordinating the flight of small satellites. However, there's a catch. Plasma microthrusters need a lot of power to operate, and they require sophisticated electronics to manage that power. This means they're only suitable for missions that have access to plenty of energy.

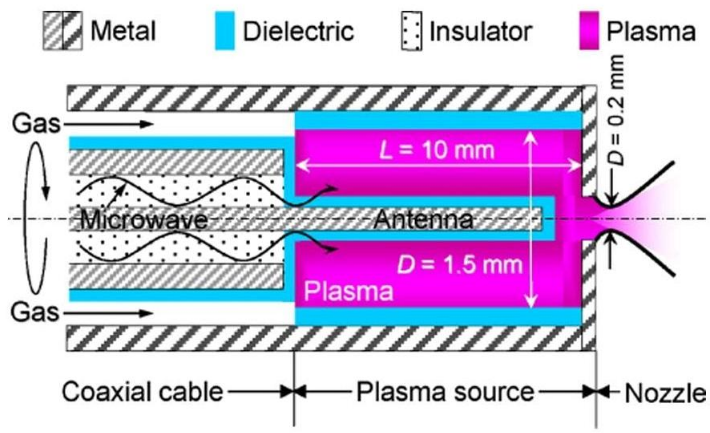


Figure 2.5: Plasma Microthruster [10]

2.4.2 Colloid Microthruster

These droplets are then accelerated by an electric field to create a precise and controlled thrust. This is the basic idea behind colloid microthrusters. Here's how it works: a conductive liquid is fragmented into tiny droplets, which are then charged and propelled by an electrostatic field. This creates a super-precise thrust that's perfect for delicate tasks like adjusting a satellite's attitude, flying in formation, or operating in a drag-free environment. One of the best things about colloid microthrusters is their ability to provide exceptionally precise thrust control – we're talking at the micronewton level. This makes them ideal for missions that require a gentle touch.

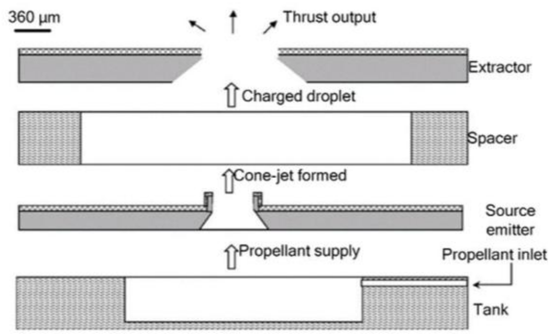


Figure 2.6: Colloid Microthruster [7]

2.4.3 Electrospray Micro thruster

When an electric field is applied, it creates a unique cone-shaped formation called a Taylor cone. This cone helps to create a steady flow of charged droplets or ions, which are then accelerated by electrostatic forces to produce thrust. For starters, they're incredibly efficient, using minimal energy to provide super-accurate thrust control. This makes them perfect for delicate tasks like adjusting the attitude of a CubeSat or navigating the challenges of deep-space exploration. When precision maneuvering is key, electrospray thrusters are the go-to choice.

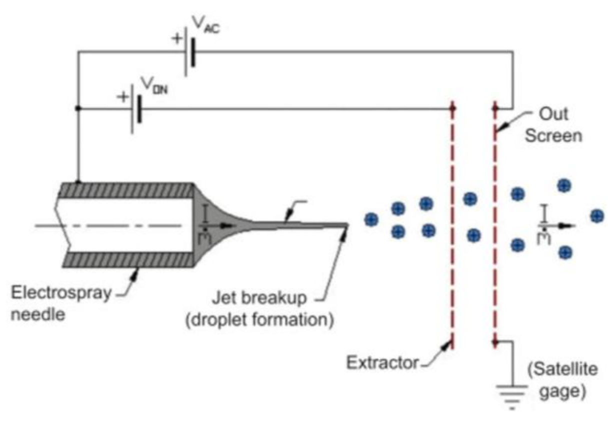


Figure 2.7: Electrospray Micro thruster[3]

2.4.4 Resistojet Microthrusters

The engine uses electrical resistive heating to warm up a stored propellant, like nitrogen or ammonia. This heat exchange process raises the pressure of the propellant, causing it to be expelled at high speeds and create thrust. What's unique about resistojets is that they don't use combustion like traditional chemical thrusters. Instead, they rely on electrical heating to get the job done. This process boosts the propellant's expansion velocity, making the engine more efficient. So, why are resistojet microthrusters so popular? They're simple, reliable, and get the job done with moderate efficiency. Plus, they're perfect for low-power spacecraft applications where energy is limited.

2.4.5 Low-Pressure Microresistojet (LPM)

These engines work best in low-pressure conditions, typically between 0.1 to 10 kilonewtons. They're designed to operate in a special region called the transitional flow regime, where the air is too thin for normal engines to work efficiently. That's why LPMs are also known as Free Molecule Microresistojets, or FMMRs. They're super-efficient in these rarefied gas conditions, making them ideal for small satellites that need just a tiny nudge to stay on course. In fact, LPMs are perfect for tasks like attitude control and station-keeping, where minimal thrust is all that's needed. They're a game-changer for small satellites, offering a reliable and efficient way to maneuver in space.

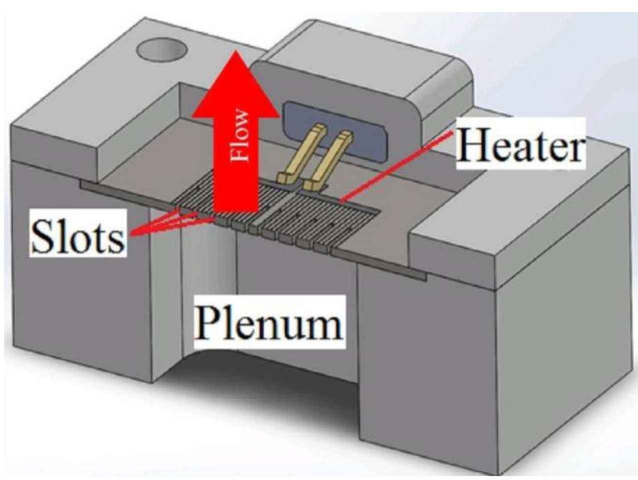


Figure 2.8: Low-Pressure Micro thruster[14]

2.5 Vaporizing Liquid Microthrusters (VLMs)

These engines are gaining popularity because of their simple design and effective performance. Here's how they work: a liquid propellant is heated using a resistance-based mechanism, turning it into vapor. This vapor is then expelled through a tiny nozzle, creating a gentle but precise thrust. What's exciting about VLMs is that they've been miniaturized using cutting-edge MEMS technology. This means that these tiny engines can be built with incredible precision, making them perfect for small-scale propulsion systems. With VLMs, CubeSats can now navigate space with greater accuracy and control.

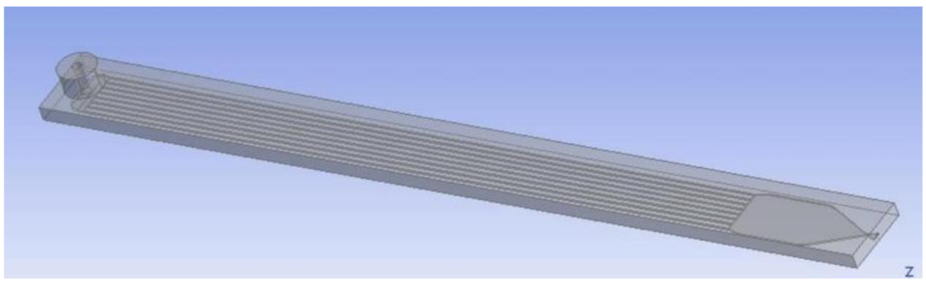


Figure 2.9: Vapourising liquid Microthruster

2.5.1 VLM With Internal Microheater

This special version of the Vaporizing Liquid Microthruster (VLM) has a clever design that makes it perfect for space missions with limited power. Here's the clever part: the engine has a tiny heater built right into the vaporization chamber. This close connection between the liquid fuel and the heater allows for really effective heat transfer. This means that less energy is wasted, and more of it is turned into thrust. This design is a game- changer for space missions that don't have a lot of power to spare. By converting thermal energy into thrust more efficiently, this engine helps spacecraft make the most of their limited resources.

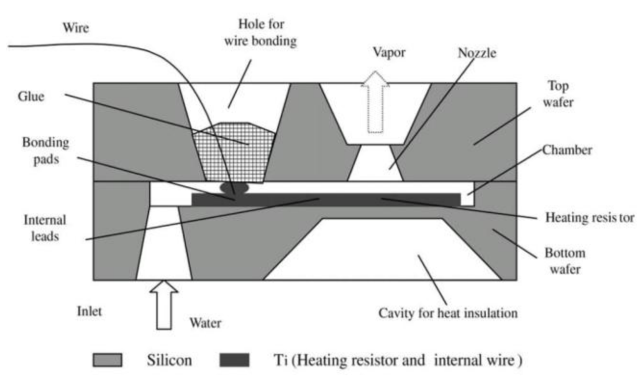


Figure 2.10: VLM Internal Microthruster [4]

2.5.2 VLM With External Microheater

When it comes to heating systems for tiny spacecraft engines, location matters. Putting the heater inside the engine, like we discussed earlier, is super-efficient. It turns out that's not as effective. When the heater is outside, a lot of the heat gets wasted, dissolving into the surrounding space. This means that external heaters need more energy to get the job done, and they might even require extra insulation to reduce heat loss. As you can imagine, this isn't ideal for spacecraft propulsion systems, where every bit of energy counts. That's why external microheaters aren't typically used in these systems – they just aren't efficient enough.

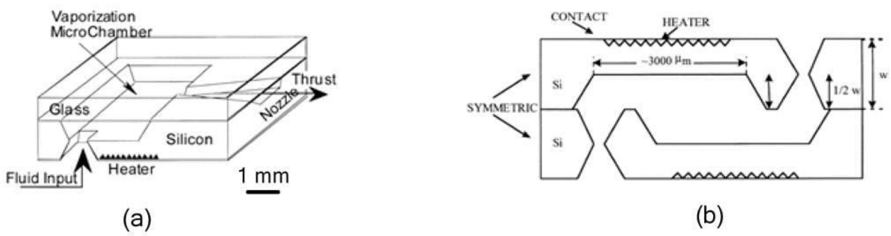


Figure 2.11: VLM External Microthruster [5]

2.6 Components of VLM

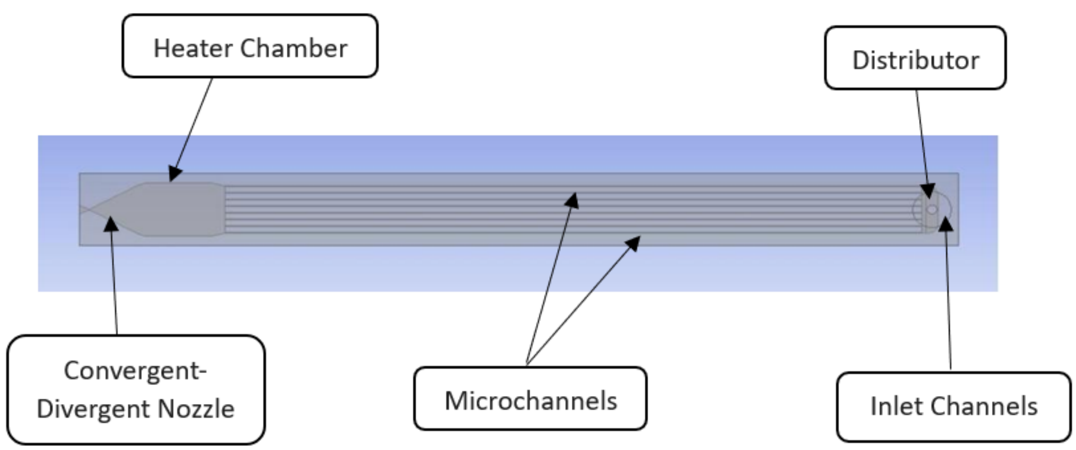


Figure 2.12: VLM Microthruster Components

2.6.1 Inlet Channel

The inlet nozzle is designed as a circular pipe, balancing between reducing pressure drop and increasing flow velocity to stabilize the flow and prevent boiling. After passing through the inlet orifice, the flow enters the distributor section at a 90-degree angle to the VLM's longitudinal axis. Key factors like fluid viscosity, surface tension, surface-to-volume ratio, and fluid resistance are crucial in microscale systems to avoid blockages and slow propellant delivery. These considerations ensure a low Reynolds number, leading to efficient, laminar flow.[5]

2.6.2 Distributor

The distributor is and important in a micropropulsion system, distributing liquid equally along the inlet to the microchannels. To prevent boiling, this portion must stay under the water saturation temperature and avoid stiff edges between the distributor and microchannel inlet.

2.6.3 Microchannels

They need to balance thermal efficiency, pressure drop, simplicity, and minimizing heat loss. In this case, the designers chose a clever layout: eight parallel rectangular channels, spaced apart and with beveled edges at both ends. It turns out that the length of these channels is crucial. By making them the right length, the designers can keep the inlet temperature of the silicon brick below the liquid's saturation point. This helps improve heat transfer and prevents unstable fluid flow – a major challenge in these tiny channels. To tackle these flow instabilities, the designers made some careful adjustments. By fine-tuning the channel design, they were able to mitigate these issues and create a more stable and efficient system.

2.6.4 Heater Chamber

This VLM system incorporates a heating chamber with dual heaters to ensure rapid and uniform heating of the liquid propellant. The chamber has been repositioned to follow the microchannels, which stabilizes the flow and expands the heat transfer area. This setup enables the propellant to boil in the middle of the microchannels, ensuring gradual and controlled vaporization. This enhances specific impulse and power efficiency, while the design ensures that the gas is thoroughly heated without forming droplets.

2.6.5 Convergent-Divergent Nozzle

The microthruster's nozzle releases the propellant to generate thrust. Designed like a De-Laval supersonic nozzle, it has a cross-sectional area that changes smoothly.[1] The nozzle's geometry produces straight sidewalls, matching the nozzle axis to the sidewall. Increasing the nozzle's Reynolds number over 2000 boosts performance, achievable by raising chamber pressure or throat area. The throat is designed to allow supersonic propellant velocity at low chamber pressure, optimizing thrust. The throat length is about 50 µm for proper fabrication. An optimal nozzle convergence angle of 28 degrees and a semi-divergent angle of 23 degrees reduce viscous losses. Proper adiabatic expansion prevents ice formation at the nozzle exit, with water as the chosen propellant presenting challenges like condensation.[3]

2.7 Comparison of different Microthrusters

Table 2.1: Types of Microthruster

Types of Microthruster	Performances	Advantages	Disadvantages
Solid propellant microthrusters (SPM)	High thrust (>100mN)Low specific impulse (< 100 s)	Easy propellant loading, no leakage of propellant, low cost and power consumption	One-shot use, lack of restart ability, and combustion instability
Liquid monopropellant microthruster	High thrust (0.3-200 mN) High specific impulse (5-180 s)	Small demand for electricity, simplified fabrication and low cost, non-toxic combustion products.	Propellants are easily to decompose, heat preservation, and ventilation of storage tanks.
Vaporizing liquid microthruster (VLM)	Low thrust (0.03-1 mN) Low specific impulse (3.42 -105 s)	Simple structure, low voltage, low cost and easy to fabricate, no pollution of propellants	Too difficult to reach more than 1mN of thrust, relatively small level of specific impulse
Plasma microthruster	Low thrust (0.04-1.4 mN) High specific impulse (50-4300 s)	Low-volume, low-cost, low- weight, and high reliability	Needs a higher operating voltage
Colloid microthruster	Low thrust (< 20 pN) High specific impulse (500-1300 s)	Relatively large specific impulse range, high thrust accuracy, and low thrust noise	Needs a higher working voltage
Electrospray microthruster	Low thrust (30-65 uN) High specific impulse (>1000 s)	A high specific impulse with low flow rate, high efficiency and operational flexibility	Too low thrust, in the micro Newton-scale
Free molecule micro-resistojet (FMMR)	Low thrust (< 35 M) High specific impulse (4000-8000 s)	Low thrust noise, high thrust accuracy, and repeatability.	Relatively bigger volume, short lifetimes, require a large power
Cold gas microthruster (CGM)	Low thrust (0.8-2.24 mN) Low specific impulse (< 50 s)	Simple structure, reliable, low energy consumption, and easy to be miniaturized	Needs high pressure gas storage tank, large volume and weight, difficult to prevent leakage

Chapter 3 Numerical Setup and Implementation

3.1 Description of VLM design

The VLM design is fundamentally based on constructing the thruster from a silicon brick. The key technological steps involved in constructing a silicon VLM include:

1. Manufacturing the bottom silicon brick.
2. Etching the silicon to create channels within the silicon brick.
3. Manufacturing the top silicon brick.
4. Applying a plasma deposition of the electric heater on the chamber side-walls.
5. Connecting the bottom and top silicon bricks together.
6. Installing the inlet nozzle.
7. Attaching electric wires to the electric heater.

These technological processes enable the creation of a complex-shaped channel within the silicon.

3.2 Governing Equation

The governing equations of the supersonic flow are the mass, momentum, and energy conservation equations which are presented in expressions below:

3.2.1 Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho\, U_{\{tp\}}\right) = 0$$

(3.2)

3.2.2 Momentum Equation

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot \left(\rho U_{tp} u\right) = -\frac{\partial p}{\partial x} + \nabla \cdot (\mu \nabla u)$$

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot \left(\rho U_{tp} v\right) = -\frac{\partial p}{\partial y} + \nabla \cdot (\mu \nabla v)$$

$$\frac{\partial(\rho w)}{\partial t} + \nabla \cdot \left(\rho U_{tp} w\right) = -\frac{\partial p}{\partial z} + \nabla \cdot (\mu \nabla w)$$

(3.3)

Where,

t is the time.

U = $\hat{\imath}u + \hat{\jmath}v + \hat{k}w$ is the velocity.

tp is the subscript denotes mixture quantities ρ is the fluid density.

P is the pressure.

μ is the dynamic viscosity.

3.2.3 Energy Equation

$$\frac{\partial(\rho\, h_0)}{\partial t} + \nabla \cdot \left(\rho\, U_{tp} h_0\right) = \nabla \cdot (K\, \nabla T) + \frac{\partial p}{\partial t} \tag{3.4}$$

$$+\left[\frac{\partial(u\,\tau_{xx})}{\partial x} + \frac{\partial\left(u\,\tau_{yx}\right)}{\partial y} + \frac{\partial(u\,\tau_{zx})}{\partial z}\right]$$
$$+\left[\frac{\partial\left(u\,\tau_{xy}\right)}{\partial x} + \frac{\partial\left(u\,\tau_{yy}\right)}{\partial y} + \frac{\partial\left(u\,\tau_{zy}\right)}{\partial z}\right]$$
$$+\left[\frac{\partial(u\,\tau_{xz})}{\partial x} + \frac{\partial\left(u\,\tau_{yz}\right)}{\partial y} + \frac{\partial(u\,\tau_{zz})}{\partial z}\right] \tag{3.5}$$

where

- h0 is the total enthalpy.
- K is the thermal conductivity of the material.
- T is the temperature.
- τij is the viscous stress tensor

3.2.4 Equation of State

from the ideal gas law flow is

$$p = \rho RT \tag{3.6}$$

where:

- R is gas constant (kJ/kg.K)

3.2.5 The k-ω SST turbulence model

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k\, u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k$$

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_i}(\rho\omega\, u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega\, \partial\omega/\partial x_j\right) + G_\omega - Y_\omega + D_\omega + S_\omega \tag{3.7}$$

where:

- Γ_k is the effective diffusivity of k.
- G_k is the generation of turbulence kinetic energy due to mean velocity gradients.
- Y_k is the dissipation of k.
- S_k is user-defined source term.
- ω is the specific dissipation rate.
- Γ_ω is the effective diffusivity of ω.
- G_ω is the generation of ω.
- Y_ω is the dissipation of ω.
- D_ω is the cross-diffusion term.
- S_ω is user-defined source term.

3.3 The major modelling assumptions

for the supersonic simulation are summarized as follows:

1. Steady-state simulation.
2. Turbulent flow k-ω SST model.
3. No-slip boundary condition.
4. Gravity effect is neglected.
5. Convective heat transfer.
6. Ideal gas.
7. Water dry steam thermophysical properties were obtained from the IAWPS-CFX library.
8. Initial conditions were set: Flow velocity 10 (m.s−1); ambient pressure level 2500 Pa, temperature 383 K.

3.4 Proposed Model

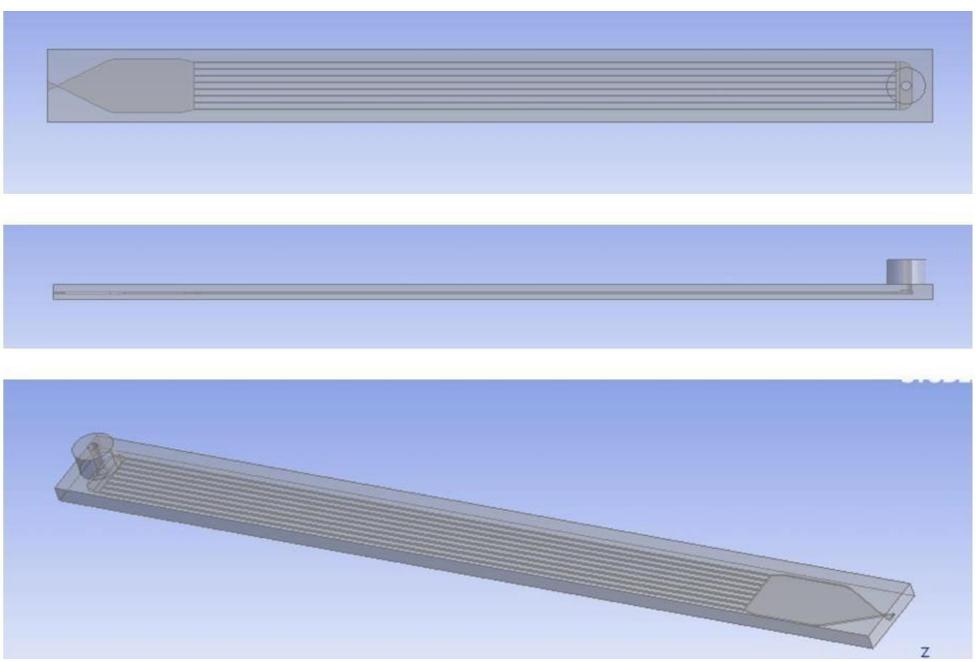


Figure 3.1: Concept Model of the VLM

3.5 Comparison of Different Nozzle Design using MATLAB:

The Comparison of different Nozzle design under different parameters using MATLAB to compare understand the thrust production of different design. This analysis using MATLAB will enable us to estimate for a best thrust producing design satisfying the other parameters simultaneously. [Appendix A] We're using MATLAB to compare different nozzle designs and understand how they affect thrust production. By analyzing various design parameters, we can identify the best design that produces the most thrust while meeting other important requirements.

MATLAB is a powerful tool that allows us to simulate and analyze different nozzle designs. We can input various design parameters, such as nozzle shape, size, and angle, and MATLAB will calculate the thrust produced by each design. The outcome of this analysis will be a nozzle design that produces optimal thrust while meeting other important parameters. This will help us to develop more efficient and effective propulsion systems.

3.5.1The Governing equation used in the code:

3.5.1.a Isentropic Relation:

$$\frac{T}{T_0} = \frac{1}{\left(1 + \frac{\gamma - 1}{2} M^2\right)} \tag{3.8}$$

$$\frac{P}{P_0} = \left(\frac{T}{T_0}\right)^{\frac{\gamma}{(\gamma - 1)}} \tag{3.9}$$

3.5.1.b Ideal Gas Law:

$$\rho = \frac{P}{R.T} \tag{3.10}$$

3.5.1.c Velocity from Mach Number:

$$V = M * \sqrt{\gamma * R * T} \tag{3.11}$$

3.5.1.d Thrust Calculation:

$$F = \dot{m} \cdot V_e + (P_e - P_{ambient}) \cdot A_e \tag{3.12}$$

3.5.2 Flow chart Sketch of the code run

The Code is run that follows this Flow chart depicted below is enclosed in [Appendix A]:

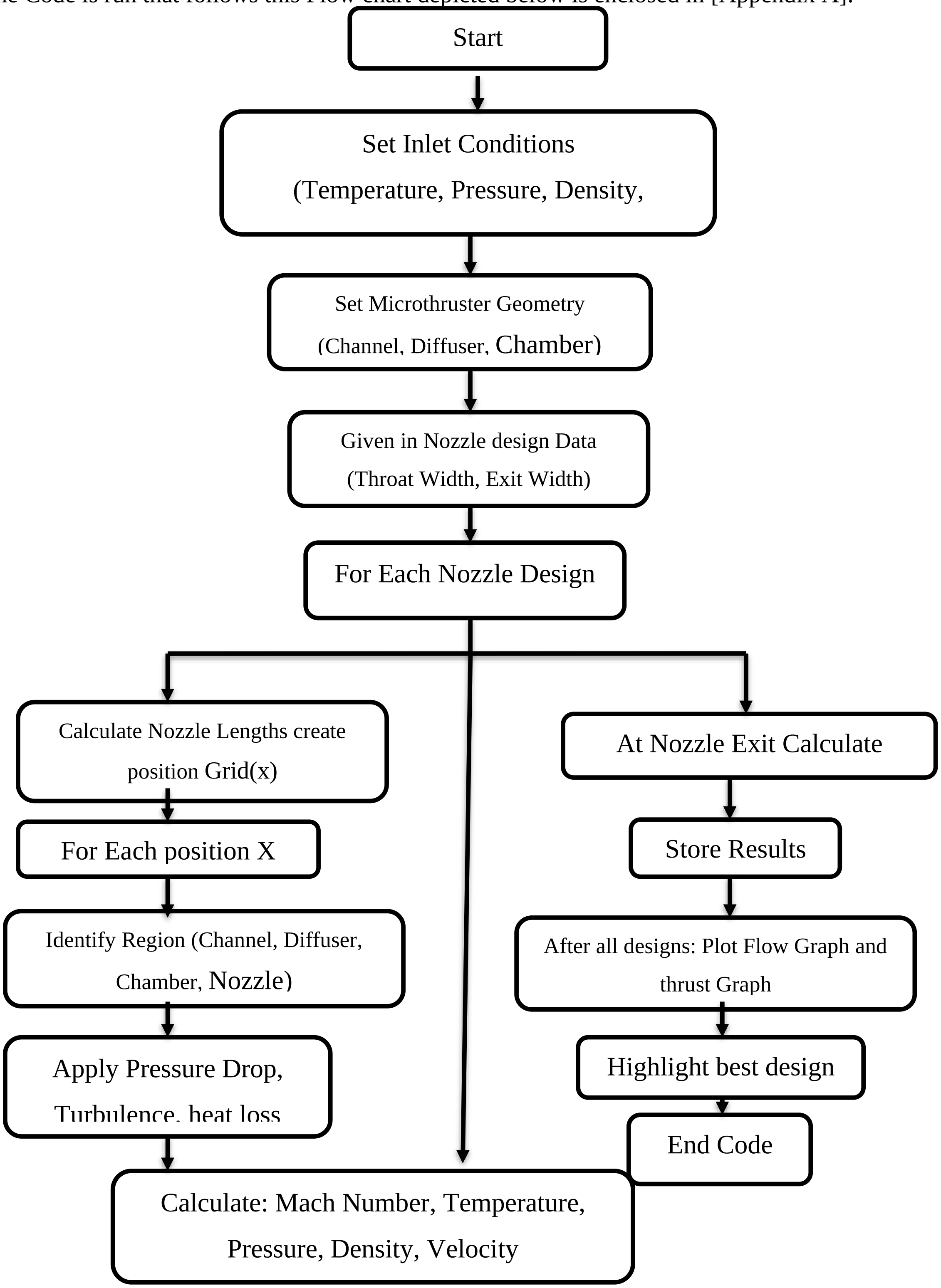


Figure 3.2: Flow Chart of the MATLAB code for comparison of different Nozzle Design

3.5.3 Dimensions of the Vaporizing Liquid Micro thruster

Table 3.1: Finalized Dimensions

Component	Dimension(s)	Value [mm]
Inlet Channels (1 to 8)	Width x Height	Varies (0.05–0.065) x 0.1
Each Channel Length	Length	1.0
Spacing Between Channels	Width	Varies (0.3–0.31)
Inlet Diverging Section	Length	0.709
Inlet Diverging Section	Inlet Width x Height	2.62 x 0.1
Inlet Diverging Section	Outlet Width x Height	3.0 x 0.1
Inlet Diverging Half Angle	Angle	15°
Chamber	Length x Width x Height	3.0 x 3.0 x 0.1
Nozzle Converging Section	Length	2.774
Nozzle Converging Section	Inlet Width x Height	3.0 x 0.1
Nozzle Converging Section	Throat Width x Height	0.05 x 0.1
Converging Half Angle	Angle	28°
Nozzle Diverging Section	Length	0.494
Nozzle Diverging Section	Throat Width x Height	0.05 x 0.1
Nozzle Diverging Section	Exit Width x Height	0.469 x 0.1
Diverging Half Angle	Angle	23°
Total Microthruster Length	Overall Length	6.977

3.6 Numerical Setup

3.6.1 CFD Model Setup of the VLM Supersonic Region

The boundary conditions for the numerical simulations are as follow:

- The water's mass flow rate at the inlet was set to 2.0 mg/s, with an inlet temperature of 293 K.
- The pressure at the outlet was adjusted to 0.26 MPa to align with the supersonic simulation parameters.
- The internal side-walls of the chamber had a constant wall heat flux, with different heating powers of 3.7 W, 2.3 W, and 2.0 W applied to the heater section.
- The silicon side-wall was set to have zero heat flux, indicating adiabatic boundary conditions.

3.6.2 Simulation setup of ANSYS Fluent

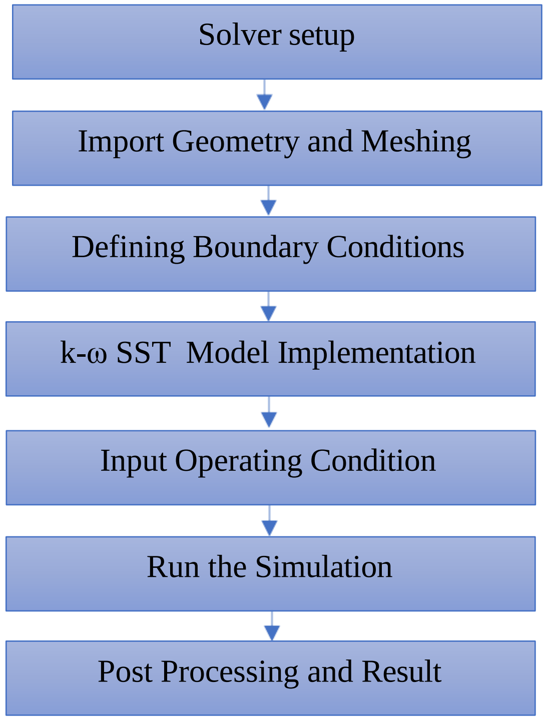


Figure 3.3: ANSYS Fluent simulation setup

Engineers may model and examine fluid flow, heat transfer, chemical reactions, and multiphase flows using the popular CFD solver ANSYS Fluent. It can use sophisticated numerical techniques to solve Navier-Stokes equations for compressible and incompressible flows. Fluent is appropriate for a range of engineering applications since it supports many turbulences, multiphase, and combustion model The governing equations, which solve the continuity, momentum, and energy equations to represent fluid behaviour, are one of ANSYS Fluent's primary features.

1. **Turbulence Models**: To address various flow regimes, there are k-ε, k-ω, LES, and RANS models.
2. **Multiphase Flow:** Supports liquid-gas interaction models such as VOF (Volume of Fluid), which are crucial for VLM simulations.
3. **Heat Transfer Analysis:** This method examines thermal management in microthrusters by combining conduction, convection, and radiation.

3.6.3 Analysing VLM with ANSYS Fluent

To design and analyze our microthruster, we use a powerful simulation tool called ANSYS Fluent. Here's a step- by-step guide on how we use it:

Step 1: Importing the Mesh

We start by importing a high-quality mesh from ICEM CFD into Fluent. This ensures our results are accurate and reliable.

Step 2: Defining Material Properties

Next, we specify the properties of the propellant, such as its density, viscosity, thermal conductivity, and specific heat capacity. This could be water, ethanol, or even an ionic liquid.

Step 3: Setting Boundary Conditions

We then set the boundary conditions for our simulation. This includes:

- Inlet conditions, such as pressure or mass flow rate
- Heater wall conditions, such as temperature or heat flux
- Nozzle outlet conditions, such as supersonic flow or pressure outlet

Step 4: Choosing the Multiphase Model

To simulate the liquid-vapor transition in the vaporization chamber, we use the Volume of Fluid (VOF) model. This captures the dynamics of phase transition, including evaporation and condensation.

Step 5: Running the Simulation and Analyzing Results

We then run the simulation to compute variables like thrust forces, temperature gradients, pressure distribution, and velocity. To understand the performance of our microthruster, we use post-processing techniques like heat transfer analysis, velocity streamlines, and contour plots.

3.7 ANSYS ICEM CFD: VLM Design

In computational fluid dynamics (CFD) simulations, ANSYS ICEM CFD serves as an advanced pre-processing tool utilized for generating meshes, enhancing grid quality, and developing geometry. It enables engineers to produce superior structured and unstructured meshes that enhance the accuracy and efficiency of numerical simulations. The importance of high-precision meshing is particularly evident in micropropulsion systems like Vaporising Liquid Microthrusters (VLMs) due to the complex physics involved, which encompasses phase transitions, boundary layer phenomena, and behavior under supersonic flow conditions.

3.7.1Essential Elements of ANSYS ICEM CFD

Building a precise model of a microthruster requires careful attention to detail. Here's how we bring it to life:

Step 1: Designing the Components

We start by modeling the individual parts of the microthruster using computer-aided design (CAD) software. This includes:

- Convergent-divergent nozzles that accelerate the propellant
- Vaporization zones where the propellant turns into gas

Step 2: Choosing the Right Mesh

Next, we select the best type of mesh to use for our simulation. We have several options, including:

- Prism layers for precise modeling of complex shapes
- Hybrid layers that combine different mesh types for optimal results
- Unstructured layers (tetrahedral) for modeling complex geometries
- Structured layers (hexahedral) for simulating large-scale flows

Step 3: Refining the Mesh

To get the most accurate results, we use advanced meshing techniques, such as:

- Structured meshing methods like Octree, Delaunay, and Multi-Block
- Local and global refinement to focus on critical areas, like the vaporization chamber and nozzle throat

Step 4: Capturing Boundary Layer Effects

We also add special inflation layers to our mesh to accurately capture the effects of:

- Viscous sublayers, where the fluid interacts with the surface
- Near-wall heat transfer, which is crucial for microfluidic applications

Step 5: Exporting for Simulation

Finally, we ensure a smooth transition to numerical simulation by producing meshes that are compatible with popular solvers like ANSYS Fluent, CFX, Open FOAM, and more.

In order to precisely simulate the propellant's behaviour as it travels through heating, vaporisation, and supersonic expansion through the nozzle, exact mesh generation is necessary for Vaporising Liquid Microthruster (VLM) study using ICEM CFD.

3.7.2 Procedures for Computational Domain (ICEM CFD)

3.7.2A Establishing the Geometry

An external CAD program or ANSYS ICEM CFD are used to construct or import a 3D CAD model of the VLM. The heater portion, where liquid propellant vaporises, is one of the model's essential parts. chamber for vaporisation (phase change area). Supersonic propellant vapour is released from a convergent-diverging nozzle. To guarantee a waterproof structure, the geometry is examined for overlaps, gaps, and inconsistencies.

3.7.2B Outlining the Meshing Approach

The choice of structured meshing, ideally hexahedral, is made to increase computing efficiency and accuracy. For complex geometries where flow properties rapidly alter, hybrid meshing—which combines structured and unstructured meshing—is utilised. Mesh refinement is used in the nozzle's throat to precisely resolve pressure gradients.

3.7.2C Applying Mesh Inlet Boundary Conditions Boundary

Described as a pressure or mass flow intake where liquid propellant is introduced. Heater walls are a type of temperature boundary condition or heat flux used to mimic vaporisation. **Nozzle Outlet:** To replicate the expansion of exhaust flow, set it as a pressure outlet or supersonic outlet. **Conditions of the Wall:** firm surfaces with non-slip characteristics.

3.7.2D Verifying Mesh Quality

To guarantee a numerically stable simulation in Fluent, mesh quality parameters are evaluated prior to exporting:

- **Skewness:** Making sure mesh components have a proper form to avoid numerical errors.
- **Aspect Ratio:** Keeping the height-to-width ratio within a reasonable range, particularly in border layers. For precise gradient computations, orthogonality refers to making sure cells are orientated in the direction of the flow.
- **Grid Independence Test:** Confirming that there is enough mesh resolution to capture important flow characteristics without incurring undue computing expense.

3.7.2E Using Fluent to Export the Mesh:

The mesh is exported in Fluent-compatible formats (.msh) after it has been verified. After importing the mesh, fluid dynamics and thermal simulations are carried out in ANSYS Fluent. High-quality meshing is essential for VLM simulation.

3.8 Quality of Computational mesh:

Has a direct impact on how well VLM performance predictions work. A properly designed mesh guarantee:

- **Accurate Microfluidic Effects Capture** The mechanics of heat transmission and boundary layer flow are accurately determined. Accurate calculations of shear stress and velocity gradients are made close to solid surfaces.
- **Better Numerical Stability and Convergence** minimises numerical mistakes and keeps simulations from diverging, reduces interpolation mistakes and false diffusion, increasing the results' dependability.
- **Efficiency of Computation:** Accuracy is maintained while computational costs are decreased with an optimised mesh density, guarantees quicker simulation times without compromising accuracy.
- **Improved Phase Transition Phenomena Resolution** accurately simulates the heater section's liquid- to-vapor conversion process. makes use of the VOF (Volume of Fluid) approach to guarantee a seamless transition between the liquid and vapour phase.

Chapter 4 Results and Discussion

4.1 MATLAB Comparison of Different Nozzle Designs

- When it comes to designing nozzles for propulsion systems, the shape and geometry can make a huge difference in performance. In this study, we used MATLAB to compare different nozzle designs and analyze their effects on thrust and efficiency.
- The results showed that different nozzle designs can have a significant impact on performance. For example, some nozzle shapes were better suited for high-altitude applications, while others performed better in low-altitude environments. By comparing different nozzle designs using MATLAB, we can optimize nozzle performance for specific applications.
- This can lead to improved thrust, efficiency, and overall system performance. Whether you're designing a propulsion system for a spacecraft or a rocket, understanding the effects of nozzle design is crucial for achieving optimal performance.
- When designing propulsion systems, the shape and geometry of the nozzle play a critical role in determining performance. A study using MATLAB compared different nozzle designs to analyze their impact on thrust and efficiency.
- Different nozzle shapes significantly affect performance.
- Some nozzle designs excel in high-altitude applications, while others perform better in low-altitude environments.
- Improved thrust and efficiency.
- Enhanced overall system performance.
- Understanding the effects of nozzle design is crucial for achieving optimal performance in propulsion systems, whether for spacecraft or rockets. By using MATLAB to compare and optimize nozzle designs, engineers can:
- Tailor nozzle shapes for specific applications.
- Maximize performance and efficiency.
- This research highlights the importance of nozzle design in propulsion systems and demonstrates the value of using MATLAB for optimization. By applying these findings, engineers can create more efficient and effective propulsion systems for a wide range of applications.

4.1.1 Comparison Graph Results from MATLAB:

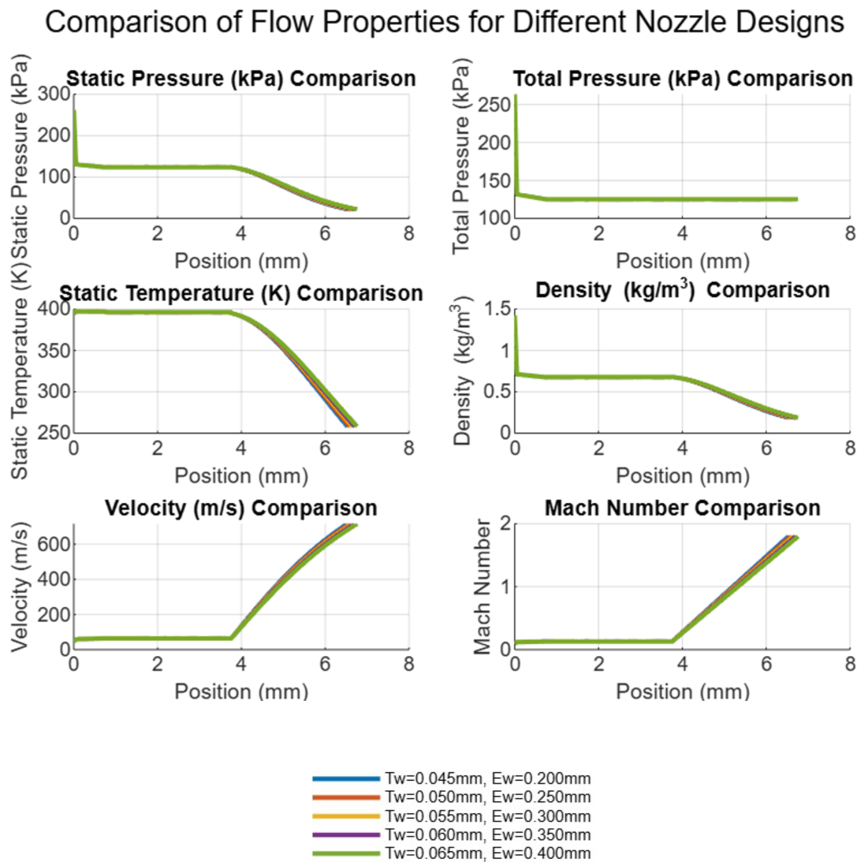


Figure 4.1: Comparison graphs of Different Nozzle Design under different Parameters

The result graph shows the performance comparison of different nozzle design dimensions under various parameters. The graph has multiple plots, each representing a specific performance metric.

- Thrust vs. Nozzle Design Dimension: This plot shows how the thrust generated by the nozzle changes with different design dimensions, such as throat diameter or exit diameter.

- Specific Impulse vs. Nozzle Design Dimension: This plot shows how the specific impulse (a measure of efficiency) changes with different design dimensions.

- Efficiency vs. Nozzle Design Dimension: This plot shows how the nozzle efficiency changes with different design dimensions.

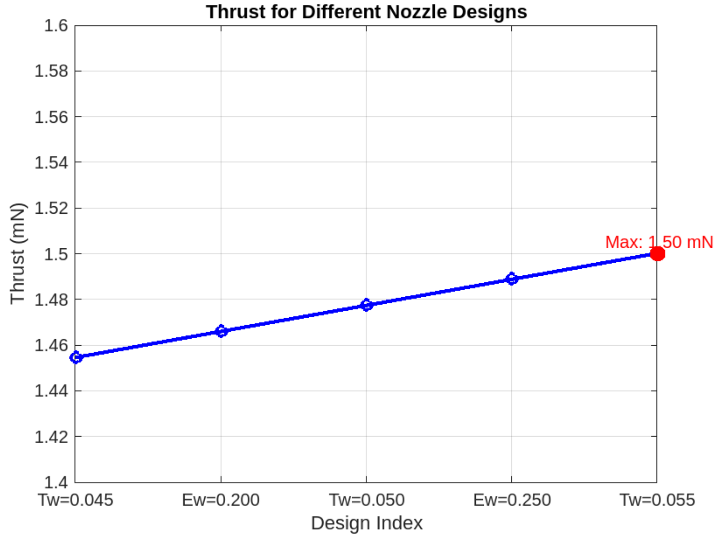


Figure 4.2: Thrust Index Comparison graph of Different Nozzle Design

The Thrust Index Comparison Graph provides valuable insights into the performance of different nozzle design dimensions. This graph compares the thrust produced by various nozzle designs, highlighting the relationship between thrust and design index ratio.

- Compare nozzle designs: Evaluate the performance of different nozzle designs and identify which ones produce the most thrust.

- Optimize design: Use the graph to optimize nozzle design dimensions for specific applications or performance requirements.

- Understand design trade-offs: Gain insight into the trade-offs between thrust and design index ratio, enabling informed design decisions.

4.2 Meshing of the CD-Nozzle thruster design

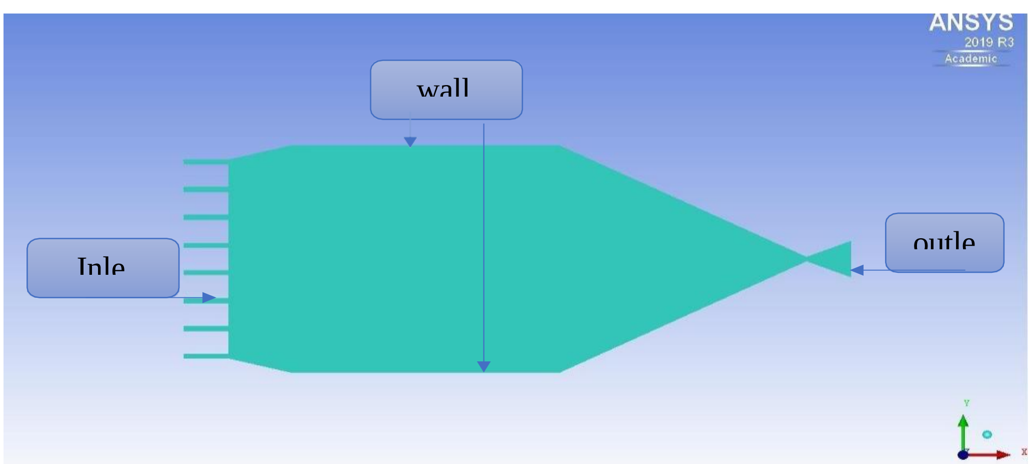


Figure 4.3: Labelled design of CD Nozzle thruster

4.2.1 Block Meshing – 1st Meshing Model

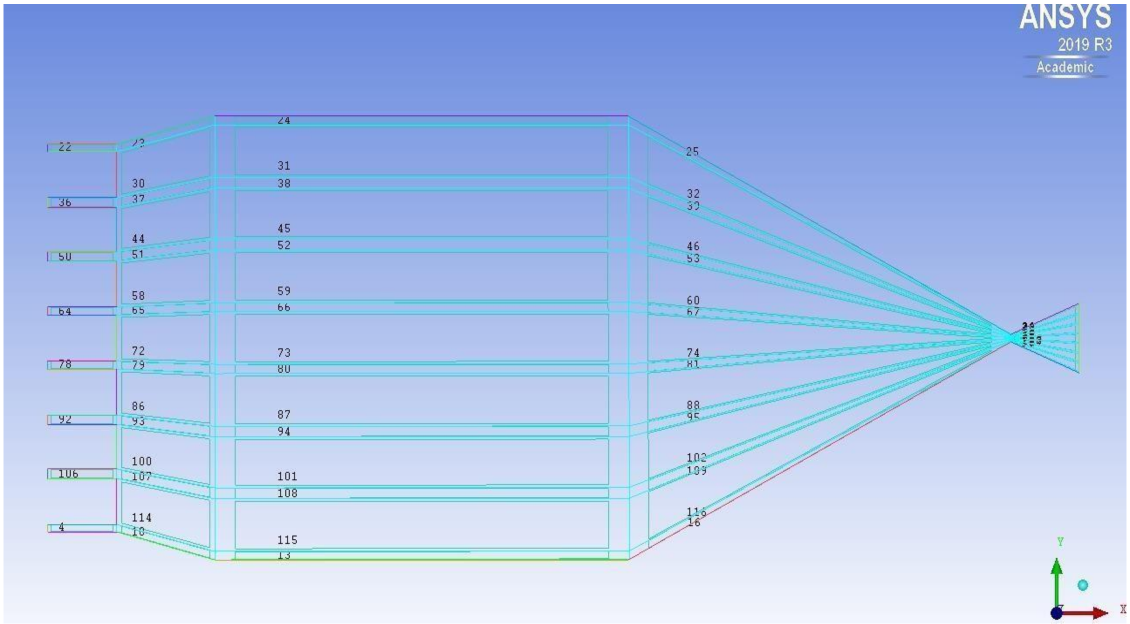


Figure 4.4: Block Meshing model of CD-Nozzle Thruster Design

NODES = 758532

QUADS = 755993

We created a meshing model for our finalized nozzle design, focusing on the CD-Nozzle Thruster Design. The goal was to divide the design into smaller parts, called blocks, to analyze its performance. Our block meshing model, shown in Figure 4.2, consists of 758,532 nodes. This model was our first attempt at meshing the nozzle design, and it had some limitations. The nozzle area posed a significant challenge due to its tiny size, measuring only 0.05mm. This small size made it difficult to create an accurate meshing model. Despite the challenges, our simulation was able to calculate and show the divergence of flow at the throat of the nozzle. This is an important insight, as it can help us understand how the nozzle performs under different conditions. While our block meshing model was a good starting point, it had some constraints and drawbacks. We're likely to refine our meshing model further to improve its accuracy and better capture the complex behavior of the nozzle.

The above meshing models have been first attempts of meshing the finalized Nozzle design on the basis of the thrust produced. Figure 4.2 is the Block meshing model attempted on the CD-Nozzle Thruster Design with 758532 Nodes where the design has been divided into multiple blocked and division. This meshing model had many constrains and drawbacks at the nozzle area where, area of the micro thruster is very small to 0.05mm. This meshing under simulation could calculate and show the divergence of flow at the throat.

4.2.2 Divided Meshing – 2nd Meshing Model

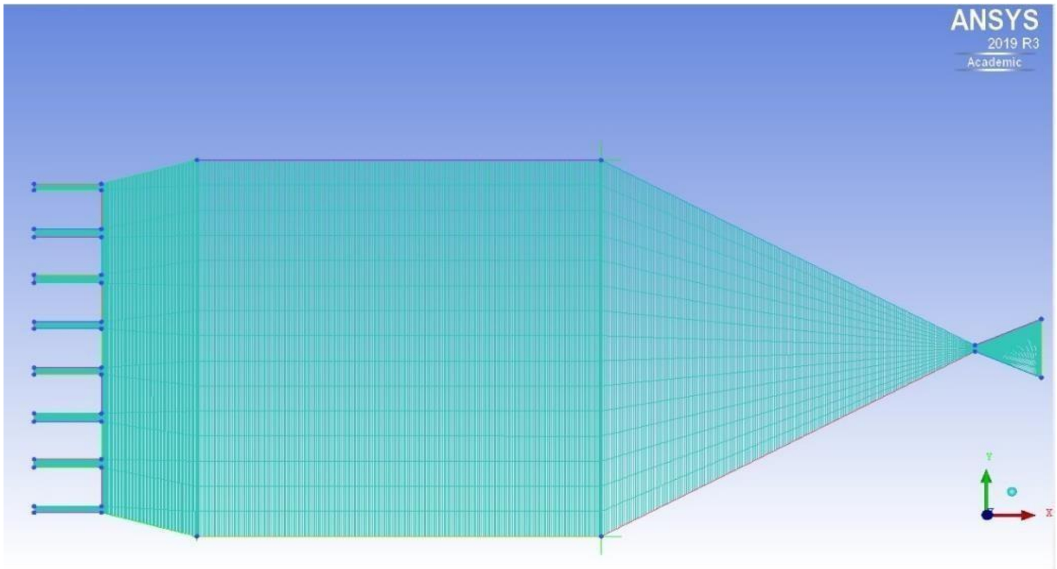


Figure 4.5.A: 2nd Meshing of the thruster model CD-Nozzle

NODES = 44092

QUADS = 43650

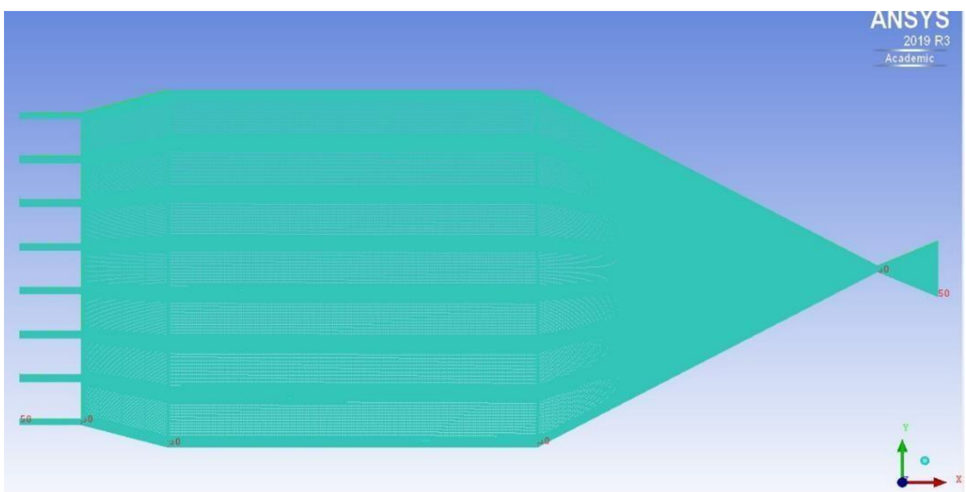


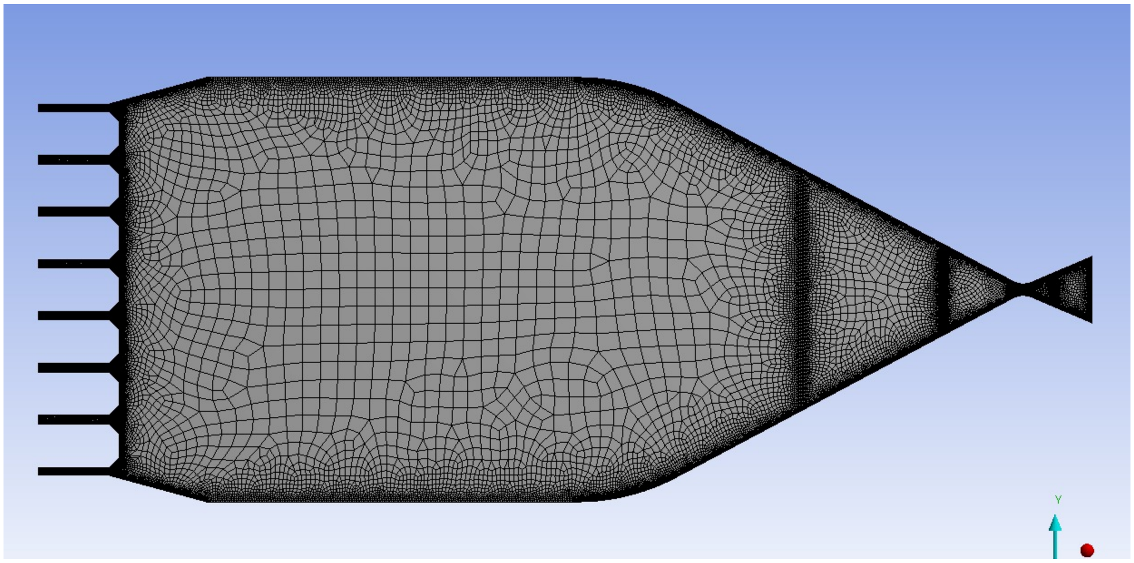
Figure 4.5.B:2nd Meshing of the thruster model CD-Nozzle

NODES = 758532

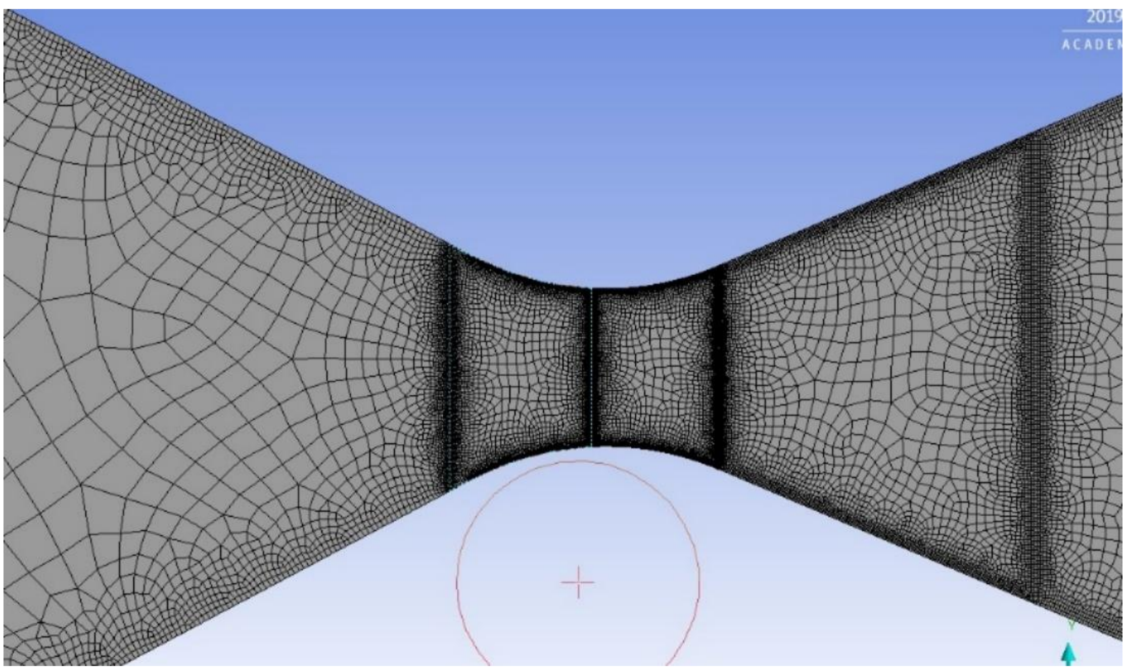
QUADS = 755993

Increasing the number of nodes further in the Block meshing basic edge, the above two figures 4.3.A and 4.3.B where the number of nodes is further increased on every meshing model step including the boundary conditions and input values forth analysis.

4.2.3 Meshing – 3rd Meshing Model



[A]Meshing

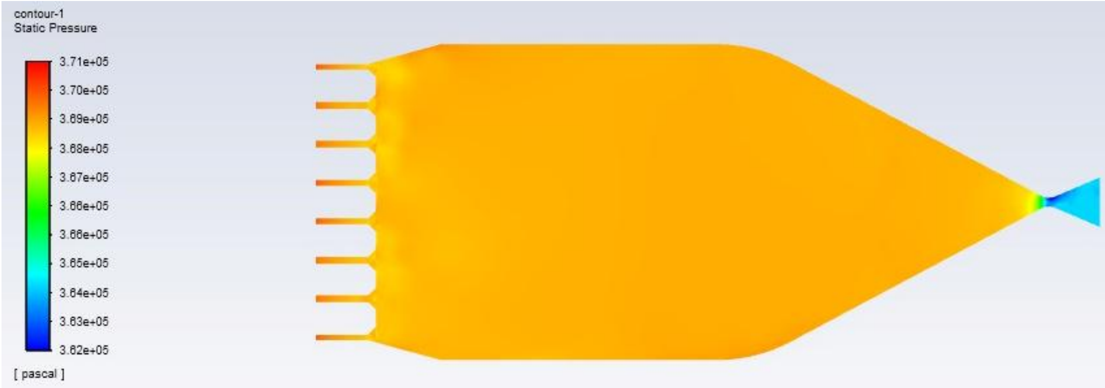


[B]CD-Nozzle at throat

Figure 4.6: Meshing of the thruster model CD-Nozzle 3rd Case

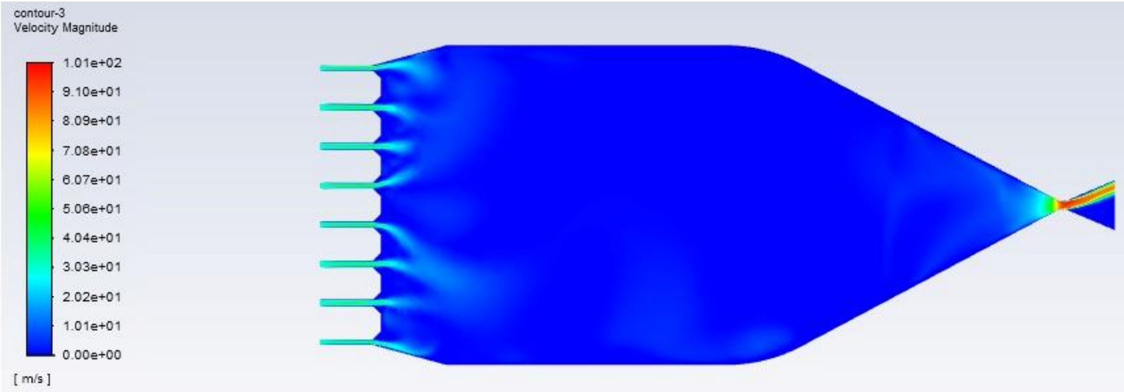
This Meshing model attempted is a unstructured face meshing and edge meshing model to setup and analyse the CD-Nozzle Thruster design. This meshing had its particular drawbacks where the meshing model resulted in increased meshing elements at the throat which crowded and discretized the analysis.

4.2..3.a 3rd Meshing different Contour Results:



[A]Static Pressure

[B]Static Temperature

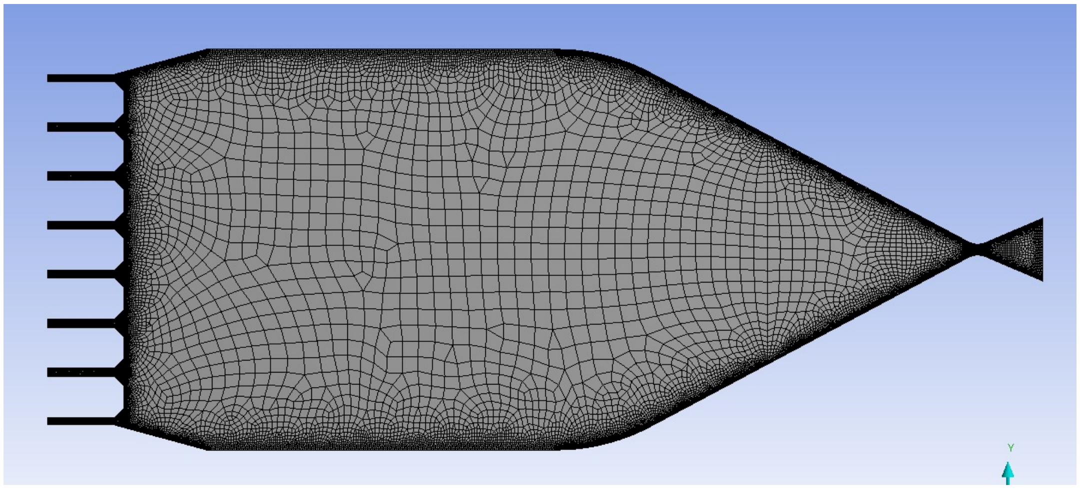


[C] Velocity Magnitude

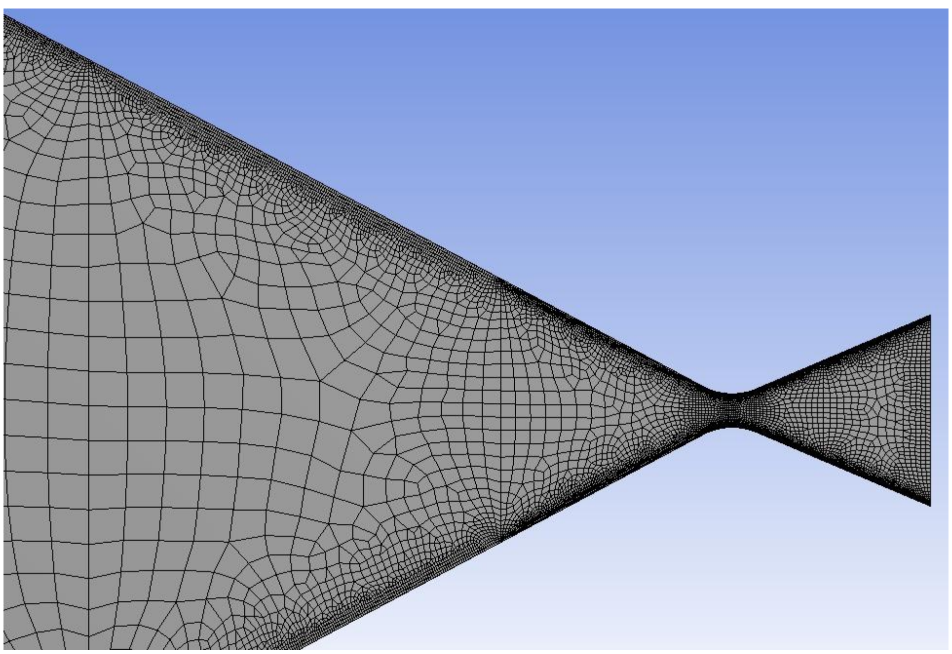
Figure4.7 distribution Contour into thruster of supersonic model 3th case Result

Due to increase in number of nodes and the elements the flow deviated more than the required flow direction. This flow is caused due to the inlet disturbances.

4.2.4 Meshing – 4th Meshing Model



[A]Meshing

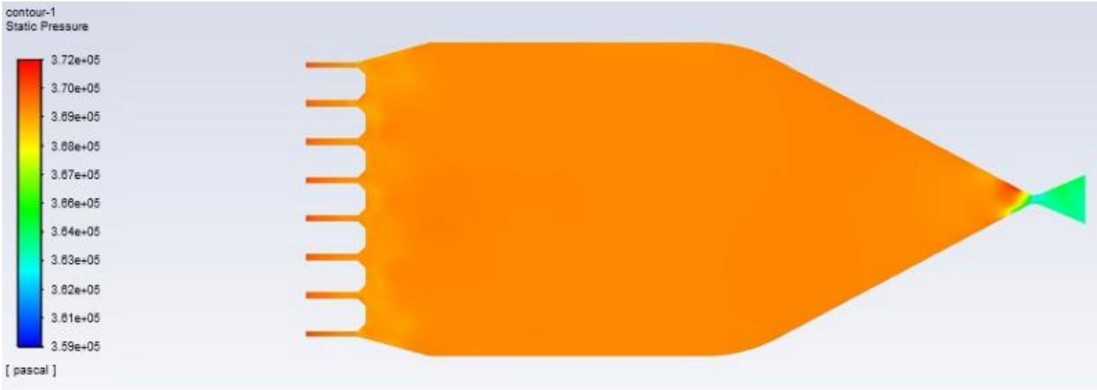


[B]CD-Nozzle Throat

Figure 4.8 Meshing of the thruster model CD-Nozzle 4th case

The Fourth Meshing model attempted is an Untrusted mission, but this meshing model was attempted using y+ calculator. This y+ Calculator is attempted to at the wall for good flow at the combustion chamber. This meshing model setup resulted in the fine meshing at throat but less elements at center of the chamber which further resulted in bad meshing at the chamber. This uneven meshing setup effected the calculations at the throat again but this time giving a clear guidance at the chamber.

4.2.4.a 4th Meshing different Contour Results:



[A]Static Pressure

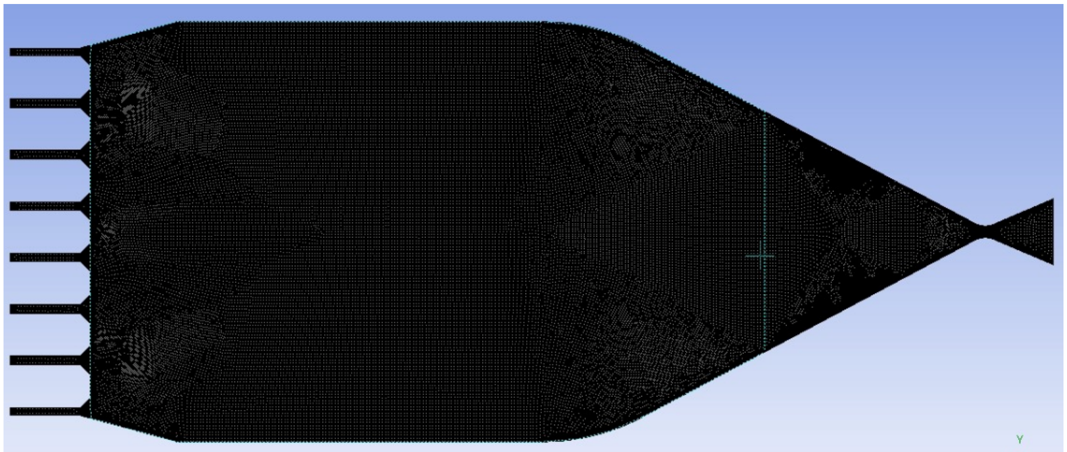
[B] Static Temperature

[C]Velocity Magnitude

Figure4.9 distribution Contour into thruster of supersonic model 4th case Result

The meshing results according to contours depict a uneven and impractical results. This is again due to the crowded meshing at the throat and distributed meshing at the chamber.

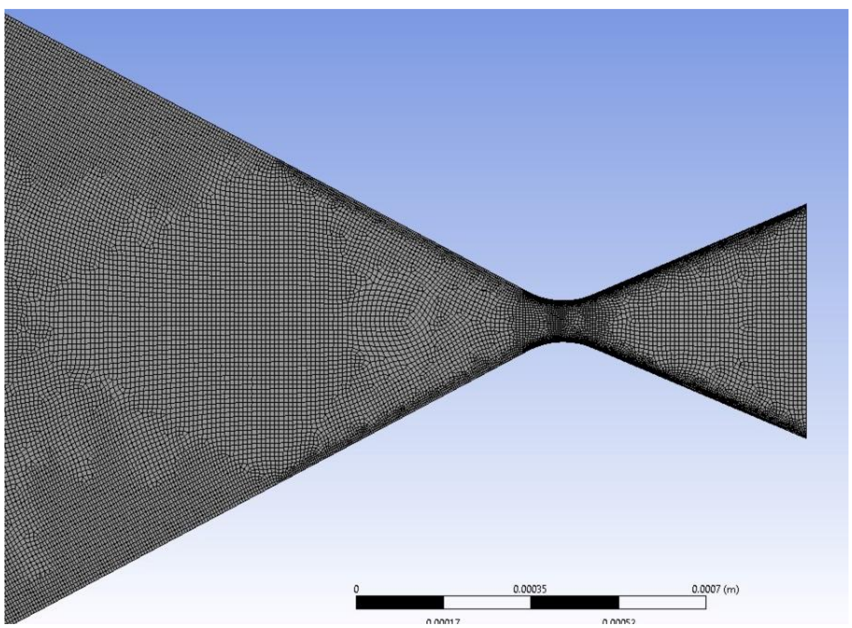
4.2.5 Meshing – 5th Final Meshing Model



[A]

NODES = 220158

QUADS = 217418



[B] CD-Nozzle throat

Figure 4.10 Meshing of the thruster model CD-Nozzle final meshing

This Fifth Meshing Attempt is and unstructured meshing model with Increasing the number of elements at the chamber region along the inlet and the complete surface of the design model. This meshing model is y+ calculation at the boundary of the chamber and every section of the nozzle design.

4.2.5.a 5th Meshing different Contour Results

[A]Velocity Magnitude

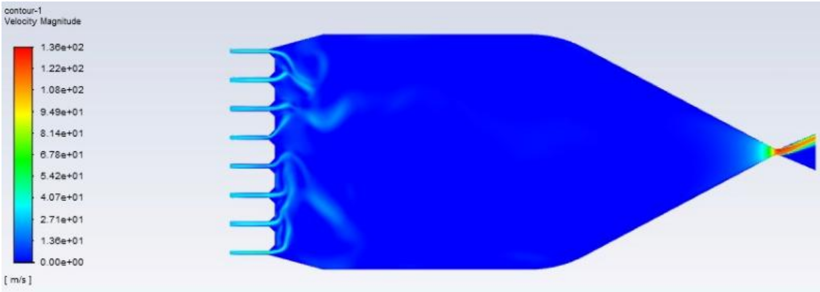
[B]Static Temperature

[C]Static Pressure

Figure4.11 distribution Contour into thruster of supersonic model 5th case 1st Result

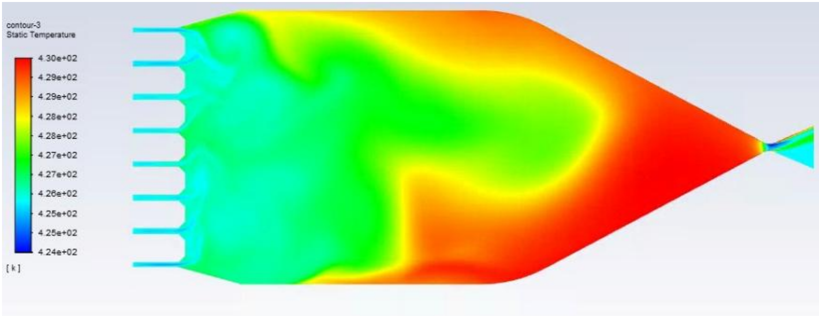
Density was taken constant over all the nozzle in the input conditions, the results of the simulation run were not as acquired at supersonic flow. Supersonic flow has variation in density, which is a basic point to be considered in inputs, but we put it constant in this simulation run.

4.2.5.b 5th Meshing different Contour Results

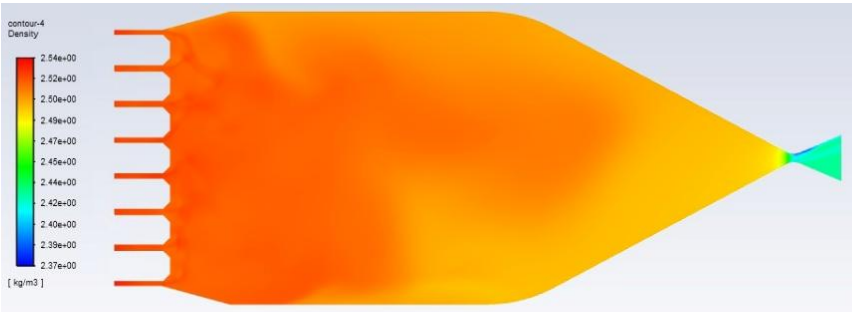


[A]Velocity Magnitude

[B]Static Pressure



[C]Static Temperature

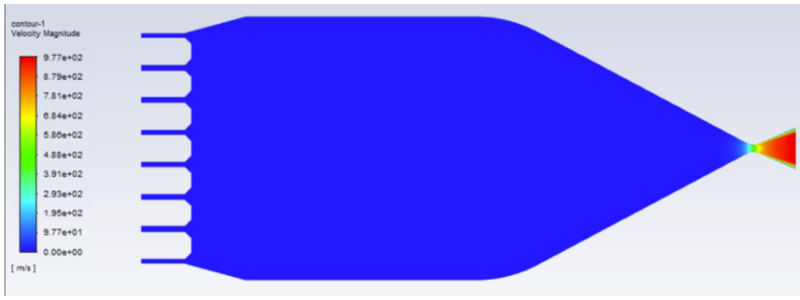


[D]Density

Figure4.12 distribution Contour into thruster of supersonic model 5th case 2nd Result

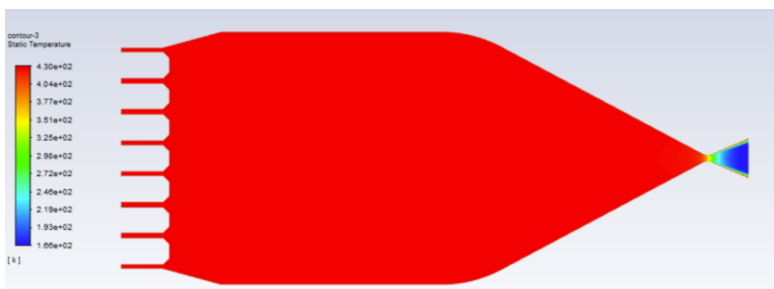
On the same previous Meshing model and setup, calculating and changing the input conditions and increasing/decreasing the mass flow rate derived varied results and flow defining contours.

4.2.5.c 5th Final Meshing different Contour Results Final Results of CFD



[A]Velocity Magnitude

[B] Static Pressure



[C]Static Temperature

[D]Density

Figure4.13 distribution Contour into thruster of supersonic model Final input

On the finalized meshing model, calculating and estimating the input data and change the input condition, flow rate increase and setting up a variant iteration of boundary conditions, The above results are the finalized results with the acquired and expected results from the CFD analysis.

Finalized Boundary Conditions of the CFD Analysis

Table 4.1: Numerical data of the nozzle simulation at chamber inlet

Geometry code No.	Bulk temperature, (K)	Average velocity, ($m.s^{-1}$)	Average Mach number	Static pressure, (Pa)	Total pressure, (Pa)	Density, ($kg.m^{-3}$)
V11.2	426	31.3	0.06	262869	263535	1.337

Table 4.2: Numerical data of the nozzle simulation at chamber inlet

Geometry code No.	Bulk temperature, (K)	Average velocity, ($m.s^{-1}$)	Average Mach number	Static pressure, (Pa)	Total pressure, (Pa)	Density, ($kg.m^{-3}$)	Thrust, (mN)
V11.2	238	751	2	5542	117331	0.047	1.38

4.3The Cumulative Results:

1. Detailed studying on Vaporizing liquid Mirco-thruster from references, their design aspects and drawbacks of few design parameters.
2. Calculated the requirements for the design of Vaporizing Liquid Micro-thruster.
3. The Bench mark design of Vaporizing Liquid Micro-thruster has been finalized and the 3D and 2D model of the design.
4. The Bench mark design was made on the calculated assumption made from the reference mentioned and require much trails to be conducted.
5. This bench mark design is analyses using MATLAB code to compare and differentiate the different Nozzle dimensions.
6. The thrust comparison of different dimensions’ is then evaluated and the design with best optimal designs is then finalized for CFD analysis.
7. The bench mark design geometry is setup on workbench and different meshing models are implemented on the design.
8. The different meshing model along with changing the input condition the final thrust results along with the required contours are acquired.
9. This finalized thruster Design is then further evaluated with hand calculation along with comparison between the analytical and practical results.

Chapter 5 Conclusions and Scope for future work

This research focused on optimizing a VLM silicon MEMS thruster using computational fluid dynamics (CFD) methods. By simulating various shapes and operating modes, we gained a deeper understanding of the underlying physics. Our optimized design boasts a 38% increase in thrust compared to existing research. With a thrust power of 1.38 mN and a specific impulse of 70 seconds, our design is a significant improvement.

- The estimated sample design from the reference paper with thoroughly studied and calculated along with the calculations of the dimensions and the design parameters and the complete simulation setup.
- The various design parameters and dimensions hence calculated are then compared on the MATLAB software to derive a composed understanding and to further enhance the preference of a particular design model, this comparison performed using MATLAB, the expected thrust outcome was fixed to 1.50MN.
- Carefully designed the geometric dimensions of key components, including the inlet, distributor, microchannel, heater chamber, and outlet nozzle. A 2D CFD analysis reveals valuable insights into the thermodynamic behavior of the thruster, including pressure, velocity, Mach number, and temperature.
- All the possible 2D meshing models have been attempted in this project process, where the ICM method is used to generate a structured blocked meshing of the finalized Design model. Further this block meshing ICM model is further fine meshed with increasing the number of nodes and elements to increase the accuracy of the results.
- This further could not provide results are required, further using the y+ calculator at the boundary conditions and the through out the chamber section, the Mass flow rate is also varied through out the supersonic flow and the number of iterations is increased to output an much appropriate result.
- This finalized meshing and by performing various changes to the boundary conditions and the flow velocity changes the result came to 977m/s maximum velocity, and the resultant thrust after the simulation of the final mesh is1.49NM.

This Research demonstrates the effectiveness of using CFD methods to optimize a VLM silicon MEMS thruster. By carefully designing the geometric dimensions and simulating various operating modes, we were able to achieve a significant improvement in thrust and efficiency. The result have important implications for the development of small satellites and other space applications.

5.1 Research Gap

Microthrusters can meet the current thrust needs of microsatellites. Although several microthrusters have been tested on spacecraft because of their potential applications and high demand, they are still at the research and development stage. The technology is still in its early stages and requires more improvements in performance, reliability, and scalability through ongoing research and testing.

MEMS (Micro-Electro-Mechanical Systems) microthrusters are likely to dominate the field in the future due to their benefits such as excellent performance, compact size, and low power consumption. To speed up their acceptance, research efforts should concentrate on optimizing design parameters, upgrading MEMS production processes, selecting more efficient and stable fuels, and improving testing methods.

To advance microthrusters, researchers need to focus on several areas:

1. **Optimizing design parameters:** Improving design parameters for better performance and efficiency.
2. **Upgrading MEMS production processes:** Enhancing production processes for reliability and scalability.
3. **Selecting efficient fuels:** Choosing fuels that are efficient and stable.
4. **Improving testing methods:** Developing accurate and reliable testing methods.

To take microthrusters to the next level, scientists need to develop ultra-precise tools to measure their thrust. Think of it like fine-tuning a precision instrument – you need to be able to measure its performance accurately to make adjustments. By improving measurement precision, researchers can validate how well microthrusters are performing, tweak their control systems, and ensure they're reliable for a wide range of space missions. It's a crucial step that will not only boost the capabilities of microthrusters but also pave the way for their use in exciting new areas, such as small satellite missions, deep-space exploration, and even formation flying technologies.

Despite the potential of CFD and MATLAB analysis, challenges remain:

1. Accuracy and validation: Ensuring accuracy and validating results.

2. Complexity: Optimizing complex VLM design and performance.

3. Measurement precision: Developing ultra-precise tools to measure thrust.

Microthrusters have vast potential for space exploration. By addressing research gaps and challenges, researchers can advance microthrusters. Optimizing design parameters, upgrading production processes, selecting efficient fuels, and improving testing methods can take microthrusters to the next level. With further research and development, microthrusters can become crucial for future space missions.

References

[1] D. Fontanarosa, L. Francioso, M. G. De Giorgi, and M. R. Vetrano, “Mems vaporazing liquid microthruster: A comprehensive review,” Oct. 01, 2021, *MDPI*. doi: 10.3390/app11198954.

[2] A. Alnajim, A. Nowakowski, and P. Y. Zhang, “Numerical study of MEMS-Based vaporizing liquid microthruster for CubeSats,” 2021. Available: www.sheffield.ac.uk/ssid/unfair-means

[3] *Proceedings of the 2010 IEEE Students’ Technology Symposium : 3-4 April 2010, Indian Institute of Technology, Kharagpur, India*. IEEE Student Branch : IIT Kharagpur : IEEE Kharagpur Section, 2010.

[4] M. C. Louwerse, *Cold Gas Micro Propulsion*. 2009.

[5] K. V. Mani, “Combined Chemical-Electric Propulsion Design and Hybrid Trajectories for Stand- Alone Deep-Space CubeSats.”

[6] D. Fontanarosa, M. G. De Giorgi, and A. Ficarella, “Thrust augmentation of microresistojets by steady micro-jet blowing into planar micro-nozzle,” *Applied Sciences (Switzerland)*, vol. 11, no. 13, Jul. 2021, doi: 10.3390/app11135821

[7] Lee and T. Kim, “Mems solid propellant thruster array with micro membrane igniter,” Sensors and Actuators A: Physical, vol. 190, pp. 52–60, 2013.

[8] E. Mukerjee, A. Wallace, K. Yan, D. Howard, R. Smith, and S. Collins, “Vaporizing liquid microthruster,” Sensors and Actuators A: Physical, vol. 83, no. 1-3, pp. 231–236, 2000.

[9] [5] M. C. Louwerse, “Cold gas micro propulsion,” Ph.D. dissertation, University of Twente, 2009. [6] T. Takahashi, Y. Takao, K. Eriguchi, and K. Ono, “Numerical and experimental study of microwave-excited microplasma and micronozzle flow for a microplasma thruster,” Physics of plasmas, vol. 16, no. 8, p. 083505, 2009. [7] J. Aoyagi, M. Mukai, Y. Kamishima, T. Sasaki, K. Shintani, H. Takegahara, T. Wakizono, and M. Sugiki,

“Total impulse improvement of coaxial pulsed plasma thruster for small satellite,” Vacuum, vol. 83, no. 1, pp. 72–76, 2008.

[10] J. Xiong, Z. Zhou, D. Sun, and X. Ye, “Development of a mems based colloid thruster with sandwich structure,” Sensors and Actuators A: Physical, vol. 117, no. 1, pp. 168–172, 2005.

[11] Z. You, Space Microsystems and Micro/Nano Satellites. Butterworth-Heinemann, 2017.

[12] V. Pallichadath, L. Turmaine, A. Melaika, S. Gelmi, M. V. Ramisa, D. Rijlaarsdam, M. Silva, D. Guerrieri, M. Uludag, B. Zandbergen et al., “In-orbit micro-propulsion demonstrator for pico-satellite applications,” Acta Astronautica, vol. 165, pp. 414–423, 2019.

[13] J. Mueller, J. Ziemer, A. Green, and D. Bame, “Performance characterization of the vaporizing liquid micro thruster ((vlm)),” in 28th International Electric Propulsion Conference, Toulouse, France, 2003. [12] X. Ye, F. Tang, H. Ding, and Z. Zhou, “Study of a vaporizing water micro-thruster,” Sensors and Actuators A: Physical, vol. 89, no. 1-2, pp. 159–165, 2001.

[14] D. K. Maurya, S. Das, and S. Lahiri, “An analytical model of a silicon mems vaporizing liquid microthruster and some experimental studies,” Sensors and Actuators A: Physical, vol. 122, no. 1, pp. 159–166, 2005.

[15] C. C. Chen, C. W. Liu, H. C. Kan, L. H. Hu, G. S. Chang, M. C. Cheng, and B. T. Dai, “Simulation and experiment research on vaporizing liquid micro-thruster,” Sensors and Actuators A: Physical, vol. 157, no. 1, pp. 140–149, 2010.

[16] P. Kundu, T. K. Bhattacharyya, and S. Das, “Design, fabrication and performance evaluation of a vaporizing liquid microthruster,” Journal of Micromechanics and Microengineering, vol. 22, no. 2, p. 025016, 2012.

[17] M. A. Silva, D. C. Guerrieri, H. van Zeijl, A. Cervone, and E. Gill, “Vaporizing liquid microthrusters with integrated heaters and temperature measurement,” Sensors and Actuators A: Physical, vol. 265, pp. 261–274, 2017.

Appendix A

A.1 MATLAB Code for Compression of Different Nozzle Design

FINAL CODE

```
%% Microthruster - Best Designs Comparison - Combined Plots
clc; clear; close all;

%% 1. --- Inlet Conditions (Fixed) ---
T0 = 400;
P0 = 263535;
rho0 = 1.337;
V0 = 31.3;
gamma = 1.33;
R = 461.5;
P_ambient = 20000;

%% 2. --- Fixed Geometry ---
n_channels = 8;
channel_widths = [0.05, 0.065, 0.065, 0.055, 0.055, 0.065, 0.065, 0.05]; % mm
channel_height = 0.1; % mm
channel_length = 0.05; % mm

prediv_inlet_width = 2.62; prediv_outlet_width = 3.0; prediv_half_angle = 15;
prediv_length = (prediv_outlet_width - prediv_inlet_width) / (2*tand(prediv_half_angle)); % mm

chamber_length = 3.0;
chamber_width = 3.0;
chamber_height = 0.1;

%% 3. --- Loss Factors ---
loss_channel = 0.5;
loss_diffuser = 0.05;
turbulence_effect = 0.03;
```

```
heat_loss_factor = 0.01;

%% 4. --- Selected Nozzle Designs (Only 6 designs, clearly separated)
throat_widths = [0.045, 0.05, 0.055, 0.06, 0.065]; % mm
exit_widths   = [0.2, 0.25, 0.3, 0.35, 0.4];       % mm

num_designs = length(throat_widths);

conv_angle = 30; % degrees
div_angle = 20;  % degrees

% Prepare storage
N = 500;
P_all = zeros(num_designs, N);
Pt_all = zeros(num_designs, N);
T_all = zeros(num_designs, N);
V_all = zeros(num_designs, N);
M_all = zeros(num_designs, N);
rho_all = zeros(num_designs, N);
Thrust_all = zeros(num_designs, 1);
x_all = zeros(num_designs, N);

color_list = lines(num_designs); % distinct colors

%% 5. --- Simulation Loop
for d = 1:num_designs
    throat_w = throat_widths(d);
    exit_w = exit_widths(d);

    % Nozzle dimensions
    nozzle_inlet_width = 3.0;  nozzle_height = 0.1;
    nozzle_converging_length = (nozzle_inlet_width - throat_w) / (2*tand(conv_angle)); % mm
    nozzle_diverging_length = (exit_w - throat_w) / (2*tand(div_angle)); % mm
    nozzle_total_length = nozzle_converging_length + nozzle_diverging_length; % mm
```

```
L_total = channel_length + prediv_length + chamber_length + nozzle_total_length; % mm

x_real = linspace(0, L_total/1000, N); % meters
x_all(d,:) = x_real;

% Mass flow
channel_areas_mm2 = channel_widths * channel_height;
channel_areas_m2 = channel_areas_mm2 * 1e-6;
A_channels_total = sum(channel_areas_m2); % m²
mdot = rho0 * V0 * A_channels_total; % kg/s

A_exit = (exit_w * nozzle_height) * 1e-6; % m²

% Region boundaries
L1 = channel_length/1000;
L2 = L1 + prediv_length/1000;
L3 = L2 + chamber_length/1000;
L4 = L3 + nozzle_converging_length/1000;
L5 = L4 + nozzle_diverging_length/1000;

% Initialize
M = zeros(1,N); P = zeros(1,N); Pt = zeros(1,N); T = zeros(1,N); V = zeros(1,N); rho = zeros(1,N);

for i = 1:N
    xi = x_real(i);
    if xi <= L1
        Pt(i) = P0 * (1 - loss_channel * xi/L1);
        M(i) = 0.06 + 0.03 * (xi/L1) + turbulence_effect;
        T_local = T0 - heat_loss_factor * T0 * (xi/L1);
    elseif xi <= L2
        Pt(i) = P0 * (1 - loss_channel) * (1 - loss_diffuser * (xi-L1)/(L2-L1));
        M(i) = 0.09 + 0.01 * (xi-L1)/(L2-L1) + turbulence_effect;
        T_local = T0 - heat_loss_factor * T0 * 0.5;
```

```
        elseif xi <= L3
            Pt(i) = P0 * (1 - loss_channel) * (1 - loss_diffuser);
            M(i) = 0.1 + turbulence_effect;
            T_local = T0 - heat_loss_factor * T0 * 0.7;
        else
            frac = (xi-L3)/(L5-L3);
            M(i) = 0.13 + (1.8-0.13)*frac; % Target Mach ~1.7-1.8
            Pt(i) = Pt(find(x_real<=L3,1,'last'));
            T_local = T0 - heat_loss_factor * T0;
        end
        T(i) = T_local / (1 + (gamma-1)/2 * M(i)^2);
        P(i) = Pt(i) / (1 + (gamma-1)/2 * M(i)^2)^(gamma/(gamma-1));
        rho(i) = P(i) / (R * T(i));
        V(i) = M(i) * sqrt(gamma * R * T(i));
    end

    Pe = P(end); Ve = V(end); rhoe = rho(end);

    % Store
    P_all(d,:) = P;
    Pt_all(d,:) = Pt;
    T_all(d,:) = T;
    V_all(d,:) = V;
    M_all(d,:) = M;
    rho_all(d,:) = rho;
    Thrust_all(d) = mdot * Ve + (Pe - P_ambient) * A_exit; % N
end

%% 6. --- Find Best Thrust Design
[max_thrust, idx_best] = max(Thrust_all);

%% 7. --- Plot All Parameters in One Figure (Subplots)

parameters = {'Static Pressure (kPa)','Total Pressure (kPa)','Static Temperature (K)',...
```

```
            'Density (kg/m^3)','Velocity (m/s)','Mach Number'};
data_all = {P_all/1e3, Pt_all/1e3, T_all, rho_all, V_all, M_all};

figure;
for p = 1:length(parameters)
    subplot(3,2,p);
    hold on;
    for d = 1:num_designs
        plot(x_all(d,:)*1000, data_all{p}(d,:), 'LineWidth', 2, 'Color', color_list(d,:));
    end
    xlabel('Position (mm)');
    ylabel(parameters{p});
    title([parameters{p} ' Comparison']);
    grid on;
end
sgtitle('Comparison of Flow Properties for Different Nozzle Designs');

legend(arrayfun(@(d) sprintf('Tw=%.3fmm, Ew=%.3fmm', throat_widths(d), exit_widths(d)),
1:num_designs, 'UniformOutput', false), 'Location','bestoutside');

%% 8. --- Thrust Bar Chart

figure;
bar(1:num_designs, Thrust_all*1e3, 'FaceColor','flat');
colormap(lines(num_designs));
xlabel('Design Index');
ylabel('Thrust (mN)');
title('Thrust for Different Nozzle Designs');
grid on;
xticks(1:num_designs);
xticklabels(arrayfun(@(d) sprintf('Tw=%.3f\nEw=%.3f', throat_widths(d), exit_widths(d)),
1:num_designs, 'UniformOutput', false));

% Mark Best Design
```

```
hold on;
bar(idx_best, Thrust_all(idx_best)*1e3, 'FaceColor','r');
text(idx_best, Thrust_all(idx_best)*1e3 + 0.05, sprintf(' Max: %.2f mN', Thrust_all(idx_best)*1e3),
'HorizontalAlignment','center','Color','r');
end
```