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SUPERSONIC NOZZLE TEST USING HIGH PRESSURE COMPRESSOR

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a project report entitled "Supersonic Nozzle Test using High Pressure Compressor" submitted by Bibek Gautam, Kamal Budhathoki and Manjil Sitoula in partial fulfillment of the requirements for the degree of Bachelor of Aerospace Engineering.

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ABSTRACT

Design procedures of the supersonic converging-diverging nozzle along with visualization of the supersonic compressible flow using the optical methods (shadowgraph and schlieren) is presented. CD nozzle was designed using the online MATLAB code [17] giving more emphasis on the diverging section. Subsonic flow at the circular inlet was augmented to the sonic velocity at the rectangular throat. Further the flow becomes supersonic at the diverging section which was also rectangular in cross section. The design of planar nozzle was made such that flow properties remains the same along the planes between the walls. Significant pressure ratio, creating sonic flow at the throat and a bigger pressure difference is what causes the usual shock wave to originate within the diverging segment. Back pressure's influence causes it to go from the throat to the outlet region as the pressure gradient rises. According to the ambient pressure, a further rise in the pressure differential can result in a flow that is either perfectly expanded or under-expanded. The experimental setup was designed in such a way that the thrust from the nozzle don't interfere with the flow visualization process. The flow shows high gradient in pressure, temperature and density. The flows visualized using these optical methods were as expected. The property of shadowgraph photography to de-emphasize the less abrupt flow made the visualization of flow characteristics easier.

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LIST OF SYMBOLS

γ	specific Heat ratio	
A_e	Exit area	m^2
A_t	Throat area	m^2
M	Mach number	
\dot{m}	Mass flow rate	Kg/s
P	Pressure at any section of nozzle	Pascal
P_0	Stagnation pressure at inlet	Pascal
P_a	Atmospheric pressure	Pascal
P_e	Pressure at nozzle exit	Pascal
P_t	Pressure at throat	Pascal
T	Temperature	Pascal
T_t	Critical temperature	Kelvin
T_0	Stagnation temperature	Kelvin
T_e	Temperature at nozzle exit	Kelvin
T_t	Temperature at throat	Kelvin
ρ	Density	Kg/m ³
R	Universal gas constant	J/(Kg.K)

LIST OF ABBREVIATIONS

MOC	Method of Characteristics
CD	Converging Diverging

Chapter 1: INTRODUCTION

1.1 Background

Human desire for the dominance into the Earth's atmosphere and the space above it goes back to 18th century leading to the introduction of the Aerospace engineering. Considerable amount of developments and theories conceived by various authors and researchers have enhanced the beauty of this field. Along with the advancements in this field, various new problems related to high speed flows have aroused. The behavior of the nozzle flow has proven to have assisted these problems to some extent.

Numerous studies related to the nozzle flow have been carried out over the decades and they have been considered to be one of the break-through in aerospace industry. These studies on the behavior of the high-speed nozzles suggests that the high-speed nozzles have dropped the financial and technical requirements of the supersonic vehicles by large gap [1]. Studies show that certain research points related to the design, operation and its behaviour to the compressible flow have been seen promising in the advancement of the propulsion systems [design and evaluation].

The geometry of the Convergent-Divergent (CD) nozzle, also known as the De Laval nozzle, is a simple cross section changing tube with a throat, or minimum cross section, between the inlet and outlet. One of the most common uses for a CD nozzle is in a propulsion system, which accelerates and expands combusted gas to a supersonic state. The majority of gas turbine and rocket engines employ nozzles to increase thrust by accelerating hot exhaust gas. The amount of thrust created is governed by a number of flow factors, and this action is explicable by Newton's third law of motion. Compressible flows get accelerated to supersonic speeds in the axial directions. The basic working principle of the supersonic nozzles is the conversion of the potential energy of the flow into kinetic energy. Thus, obtained kinetic energy acts as the driving factor for the vehicles. In converging diverging nozzles, the subsonic flow provided at the inlet of the nozzle is

enhanced to sonic velocity at the throat and the flow gets finally expanded to supersonic velocities at the exit of the nozzle.

The design and operation of high-speed vehicles, ballistic missiles, and spacecrafts have heavily relied on the performance of supersonic nozzles. Along with the introduction of these supersonic nozzles, the integrated propulsion systems have improved to large extent [design and evaluation]. In the present days vast number of researches and studies have been conducted on propulsion arrangements of nozzles. These implementations and their corresponding consequences have shown a large amount of reduction of cost, which sounds more comforting matter in the aerospace industry.

1.2 Problem Statement

More research needs to be done on the application of flow visualization to forecast nozzle performance. The proposed study's primary objectives are the advancement of numerical tools and methodologies, test rigs, and experimental setups for the gathering of data on performance parameters. Further the visualization of flow utilizing a density-based imaging technique. The high-pressure compressor is used to provide necessary pressure at the inlet. The compressor possesses a constraint as the pressure cannot be increased superficially. So, for a specific pressure, the nozzle is to be designed and visualization is to be carried properly with proper stand set up.

1.3 Objective

1.3.1 Primary Objective

The primary goal of this study is to analyze the flow characteristics from a CD nozzle at certain operating pressure ratio and forecast the nozzle's performance by visualizing the exhaust flow.

1.3.2 Specific Objective

- To design and manufacture a stable experimental setup for generation of supersonic free jet.
- To design a CD nozzle and carry out numerical simulation.
- To observe overexpanded, perfectly expanded and under expanded jet.
- To compare and analyze the experimental result with numerical result.

1.4 Feasibility Analysis

1.4.1 Economic Feasibility

The project's initial capital expenses were Rs 20,000 including the cost of the system's design, construction, and installation. Till the completion, total expense of 6200 is met. Since the project is being conducted for educational and scientific goals, its advantages centers on providing academics and students with simple access to flow visualization and further works related to it.

1.4.2 Technical Feasibility

Resources for the project, including persons, tools, and financing, have been evaluated to make sure it can be carried out successfully. Breakages, compatibility issues, and security hazards are only a few of the technology's potential risks that have been recognized and debated. According to the findings of this evaluation, which demonstrate that the risks associated with the technology are low and can be effectively managed through the implementation of suitable mitigation strategies, the technological feasibility of the proposed project is favorable, with the needed technology being easily accessible, the necessary resources in place, and the potential risks manageable.

1.4.3 Operational Feasibility

To make sure that the resources are available to fulfill the project's goals, the project structure were assessed. The requirements for the project's process, including those for project planning, execution, and monitoring were defined and evaluated. The current processes can support the project, and any extra processes that are necessary can simply be added. At the completion, the project is supported successfully by the team's current organizational structure with pure dedication and it is finished within the allotted time period with little disruption to ongoing activities.

1.5 System Requirements

1.5.1 Software Requirements

The design and analysis of CD nozzle is a complex topic. In order to obtain the expected outcomes from the nozzles, different software were used during the entire project. Following software were used for design of CD nozzle, stable experimental stand and flow visualization process.

- **MATLAB**

MATLAB is a programming and numeric computing platform used for data analysis, graphics design, programming, app building and many more. Using MATLAB 2023R1, the curve for the diverging section was generated. This curve is vital for the design of CD nozzle.

- **CATIA**

From the curve generated using the MOC code, further designs related to the 3D developments of different section were done in CATIA V5R21. The final touch was given to diverging section along with the development of converging section and throat. The stable experimental stand was also designed using CATIA.

- **ANSYS**

ANSYS is a commercially available software package that is widely used for structural, thermal, fluid, electrical, magnetic, and other system analysis. A specific problem is defined in the software along with its boundary and other known conditions. The software then numerically computes the system by discretizing it in terms of algebraic equations and solves the problems. ANSYS Fluent is a CFD software program that can numerically solve compressible flows as well. The student version of ANSYS 2023 R2 is used for simulation.

1.5.2 Hardware Requirements

- High pressure compressor: A compressor is a device used to increase the pressure of gas. In our experiment, a reciprocating type was used to supply air at various pressures. High pressure compressors are used in various devices to generate supersonic flow like blowdown tunnels, expansion shock tunnel etc. The compressor was operated at maximum pressure of 100 psi.
- Reservoir: Reservoir is a tank to store the compressed air from the compressor. The reservoir increases the flow time and also reduces losses. Due to bends in the compressor outlet, the losses are more. So, the reservoir is selected such that losses are minimized in the outlet and mass flow rate is increased [2].
- Schlieren setup: To visualize the flow out of the nozzle, a proper visualization technique is required. Schlieren photography is the method of flow visualization that relies in the simple fact that the light rays' bends whenever they encounter the change in fluid density. A concave mirror of 20cm focal length was used. A bright light source cutoff by a sharp-edge was placed 40cm away from the mirror. A white led was used as light source.
- White screen: Apart from schlieren, shadowgraph was also used as flow visualization. The shadow of the flow was formed at white screen placed behind. The system does not need any optical component except a light source and a recording plane (white screen) to project the shadow of the varying density field.
- Light source: A bright led white light was used as light source in schlieren method. The light was first made as a point source as it provides a large coherence area which gives sharper results. The reflected light was then blocked using knife edge to reduce the intensity of light.
- Polyurethane pipe: The air was passed from reservoir to the nozzle using polyurethane pipe. The pipe diameter was 8mm and length 150mm. The pipe could sustain a total pressure of 10 kg/cm^2 .

Chapter 2: LITERATURE REVIEW

2.1 Brief Overview

The key reason for the invention of the nozzles was to alter the flow behavior, such as pressure and velocity. A convergent-divergent nozzle created in 1890 by Carl Gustav Patrik de Laval could boost a steam jet to supersonic speed [3] Later, this nozzle, also known as a de Laval nozzle, was employed in the propelling of rockets. Robert Goddard, an American engineer, was the first to combine a de Laval nozzle with a combustion chamber, improving the rocket's efficiency and enabling supersonic velocities around Mach 7 [4].

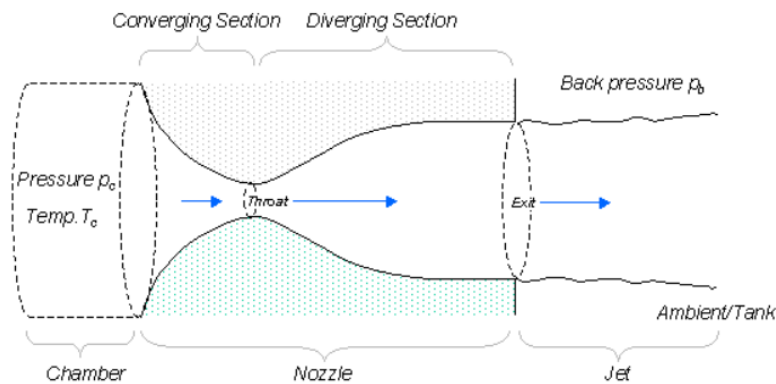


Figure 2.1 Converging Diverging Nozzle [5]

A Convergent-Divergent nozzle is a tube which is pinched in the middle, making a carefully balanced, asymmetric hourglass shape. It is characterized by inlet and outlet section between which a small area is located. At the throat of a converging-divergent nozzle, the flow accelerates from subsonic to sonic velocity, and it is further increased to supersonic speeds at the exit.

In simple words, the nozzle increases the magnitude of propulsion by accelerating the combustion products to a supersonic velocity by using the pressure created inside the combustion chamber. The area ratio, the ratio of the nozzle exit area to the throat area, can be used to control the nozzle departure velocity. Some of the key characteristics that make a rocket nozzle attractive include maximum performance, minimal design intricacy and weight, and simplicity of manufacture [6].

Numerous nozzle configurations are available, including ideal, cylindrical, bell, plug, expansion-deflection (E-D), and dual bell, in addition to the newly developed multi nozzle grid (MNG). The definition of an ideal nozzle is one that generates an isentropic flow (free

of internal shocks) and provides a uniform velocity at the outlet. Using the method of characteristics, the shape of such a nozzle can be created [7].

The nozzle thrust is at its greatest when there is a parallel uniform flow and the exit pressure at the nozzle outlet matches the ambient pressure. Such nozzles are referred to as perfect nozzles. Such a nozzle's area at exit A_e to area at throat A can be stated as follows [11]:

$$\frac{A_e}{A_t} = \left(\frac{\gamma - 1}{2}\right)^{1/2} \left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/2(\gamma-1)} \left(\frac{P_a}{P_c}\right)^{-(1/\gamma)} \left[1 - \left(\frac{P_a}{P_c}\right)^{(\gamma-1)/\gamma}\right]^{-1/2}$$

2.2 Governing Theories

In a quasi-one-dimensional flow, all variables mainly vary along one direction, let's say x . The situation under consideration is a flow in a duct with slowly varying area $A(x)$. This effectively indicates that the conduit walls' slope is minimal. Additionally, x -velocity component u outweighs y and z -velocity components v and w .

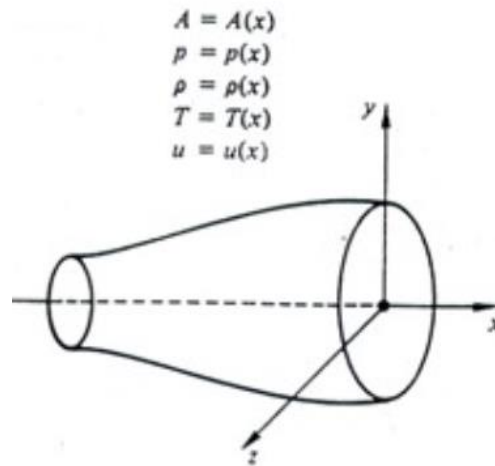


Figure 2.2 Quasi-one-dimensional flow [8]

The governing equations for a quasi-one-dimensional flow are: -

Continuity: $\rho_1 u_1 A_1 = \rho_2 u_2 A_2$

Momentum: $P_1 A_1 + \rho_1 u_1^2 A_1 + \int_{A_1}^{A_2} P dA = P_2 A_2 + \rho_2 u_2^2 A_2$

Energy: $h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2}$

Area-velocity relation

The area-velocity relation is obtained from the continuity equation, the momentum equation, and the assumption of isentropic flow. This relationship makes a significant addition to the field of compressible flow engineering because it explains how to enhance a flow to supersonic speeds. The area-velocity relation is given by:

$$\frac{dA}{A} = (M^2 - 1) \frac{du}{u}$$

- For $0 \leq M \leq 1$ (i.e. subsonic flow), when area decreases, velocity increases and vice-versa.
- For $M > 1$ (i.e. supersonic flow), when area decreases, velocity also decreases. Similarly, when area increases, velocity also increases.
- For $M = 1$ (i.e. sonic flow), this shows local maximum or minimum distribution in area. But considering above points into considerations, it denotes minimum area.

Area-Mach-number relation

The relationship between area and Mach number describes how local area to throat area changes with Mach number. For isentropic flows, in which there are no shocks, and calorically ideal gases, the area-Mach number connection holds true.

$$\frac{A}{A_t} = \frac{1}{M} \left(\frac{1 + \frac{\gamma-1}{2} M^2}{\frac{\gamma+1}{2}} \right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

Given the area distribution of a nozzle, we can calculate the Mach number as a function of x and, consequently, also of (using the isentropic equations) $p/p_0, T/T_0$, etc. It should be noted that while there are an infinite number of situations where isentropic subsonic flow occurs throughout the entire nozzle, there is only one situation in which supersonic flow occurs in the nozzle's divergent portion.

Back pressure has a big impact on nozzle movement. An axial position in the divergent portion of the nozzle will experience a normal shock if the back pressure is too high. The

flow will follow the isentropic supersonic solution upstream of the typical shock and subsonic flow will be present downstream. As the back-pressure decreases, the normal shock moves downstream the nozzle until it is standing at the nozzle departure plane for that particular back pressure. As a result, the divergent portion of the opening will have supersonic flow that is isentropically shock-free. Further back pressure reduction causes over expanded conditions that cause oblique shocks to be generated at the nozzle departure as the nozzle is exiting. We may achieve pressure-matched circumstances (flow without shocks or expansion waves) with further back pressure reduction, and if we do so after that, we will experience the formation of expansion waves at the nozzle exit. In the latter scenario, it is said that the nozzle is working under expanded conditions [8].

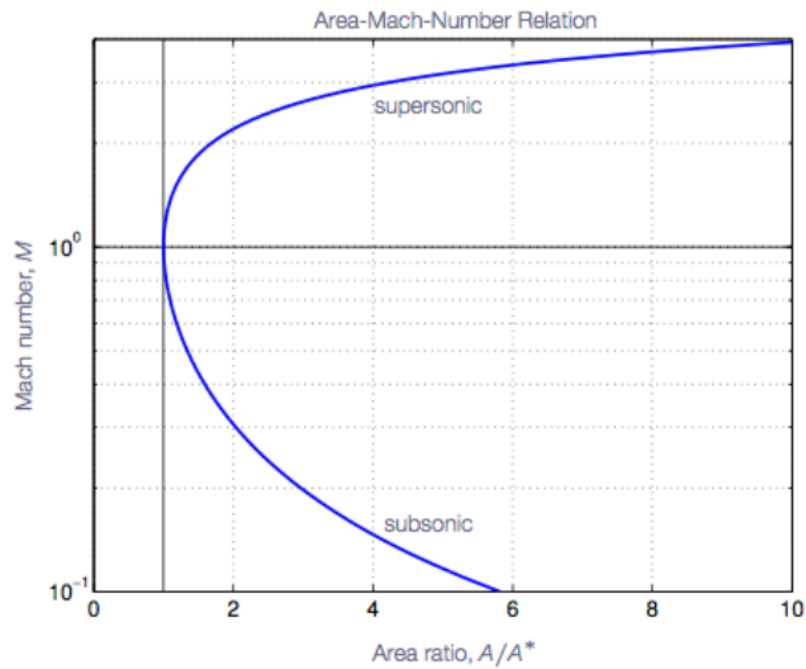


Figure 2.3 Area-Mach number relation [9]

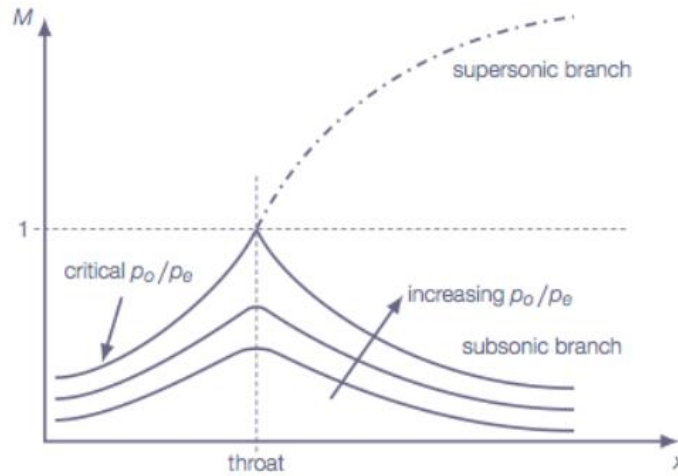


Figure 2.4 Variation of Mach along nozzle [9]

Isentropic flow relationships

When a fluid movement is both adiabatic and reversible, it is said to be in an isentropic state. that is, no heat is introduced into the flow and no energy changes as a result of friction or dissipative effects take place. Several relations that describe the pressure, density, and temperature along a streamline for an isentropic flow of a perfect gas can be derived.

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

$$\frac{P_0}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

$$\frac{\rho_0}{\rho} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{1}{\gamma - 1}}$$

Here, we see these ratios of total to static properties depends only on the local Mach number. The nozzle is said to be choked when the throat conditions meet with the critical state. For this critical state, the flow reaches the sonic state ($M=1$) at the throat. These relations get simplified as: -

$$\frac{T^*}{T_0} = \left(\frac{2}{\gamma + 1}\right)$$

$$\frac{P^*}{P_0} = \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}$$

$$\frac{\rho^*}{\rho_0} = \left(\frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}}$$

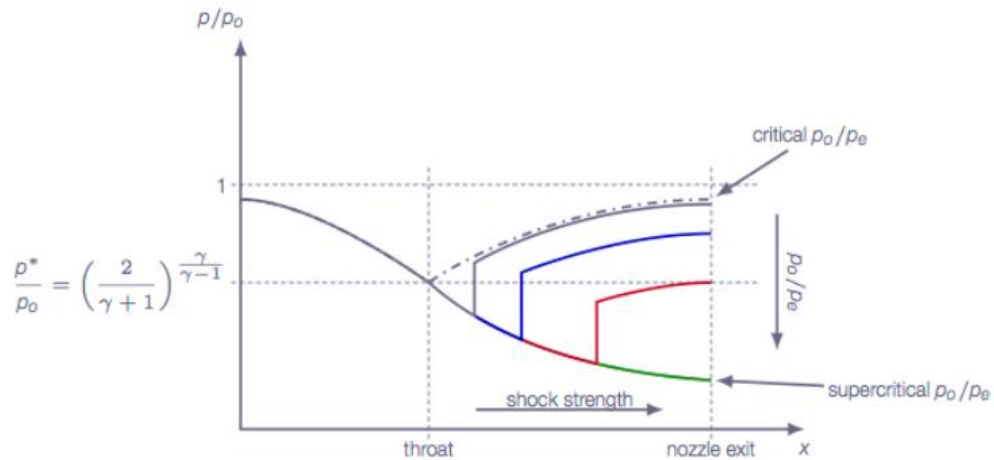


Figure 2.5 Normal shock location for different pressure ratios [9]

The exit pressure (P_e) must match the ambient air pressure in order to get the exit exhaust to flow parallel (P_a). For the condition when ambient surrounding pressure is greater than the exhaust fluid pressure at exit, the exhaust flow is squeezed by ambient air pressure and the gas will not flow parallel to the nozzle. Higher gas pressure relative to the surrounding pressure at the exit causes the exhaust to expand as exit flow pushes against the surrounding air, deviating flow from intended parallel path. hence nozzle area ratio is optimum when exhaust exit pressure is equal to ambient air pressure. The following figure shows three different nozzle conditions: the most effective nozzle being in the center.

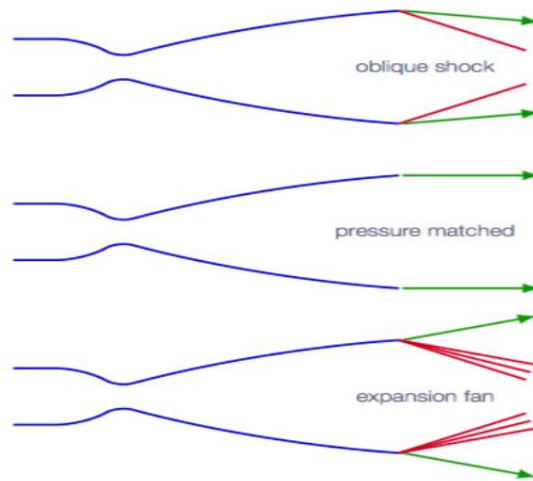


Figure 2.6 Effect of ambient pressure at exit of the nozzle [9]

The complete device will experience subsonic, isentropic flow when the back-pressure ratio is high enough. The flow will become choked with subsonic flow in the converging section, sonic flow at the throat, and subsonic flow in the diverging section when the back-pressure ratio hits a critical value.

A shock wave (represented as a red line) forms within the diverging section as a consequence of a further drop in the back-pressure ratio. It will be a supersonic flow entering the impact wave. With pressure, temperature, and density all rising across the shock wave, the flow properties abruptly shift. The downstream Mach number will be below that of the impact wave. The shock is situated so that the back pressure and the pressure at the exit of the diverging portion will be equal. Although the flow upstream and downstream of a shock wave may be regarded as isentropic, the flow through the shock wave is not.

The shock wave travels away from the throat in the direction of the device's exit as the back-pressure ratio is reduced further. The shock wave's strength, which is measured by the pressure ratio across the shock, rises as it travels away from the throat. The shock wave is eventually found at the exit of the diverging section, where a critical back pressure is eventually attained.

A further reduction causes the shock wave to exit the nozzle and transform into angled shock waves. Since there are no shock waves inside the converging-diverging tube, the

flow within it is isentropic. Because the flow static pressure at the exit is lower than the back pressure, the flow must be compressed in order to ultimately reach the back pressure, which causes oblique shock waves to appear outside the nozzle. Since the nozzle exit area is too big and causes an exit pressure that is lower than the back pressure, this type of flow is known as over-expanded flow.

Up until a critical back pressure ratio is reached, where the exit pressure is precisely equal to the back pressure, over expanded flow persists as the back-pressure ratio is reduced. Perfectly expanded flow or flow at design circumstances are two names for this kind of flow. Under-expanded flow is a phenomenon that develops when the back-pressure ratio is reduced further. Because the pressure at the exit is higher than the back pressure in this situation, the flow must keep expanding after exiting the device. At the exit, a pair of expansion fans causes this. Further reducing the back pressure keeps the flow from expanding too much.

Optical methods

In experimental fluid mechanics, flow visualization is a crucial tool that can give a detailed overview of the complete flow field. The flow of air around aerodynamic models is a very complicated phenomenon. A fluid flow field is an optically transparent object with a complex distribution of light refraction index. When a light beam passes through such an environment, its direction and phase change [10].

Shadow, Schlieren, and Interferometry are the three main optical techniques for flow imaging. There exists a systematic difference among these techniques. Schlieren is sensitive to changes in the first derivative of density, while shadowgraph is sensitive to changes in the second derivative of density. Interferometry can detect changes in absolute density. Here, we discuss about the first two optical methods [11].

Shadowgraph

The shadowgraph is the most basic optical technique and is appropriate for observing flows with fluctuating densities. It is one of the best methods due to the ease of flow visualization and the cheap cost utility. It is regarded as one of the most effective techniques for

capturing shock waves. The shock waves are plainly visible due to this method's de-emphasis of less abrupt flow features [12].

The most recent advancement in shadowgraph is the substitution of the fairly painful conventional high-speed photographic methods with digital imaging, which simplifies high-speed shadowgraph and encourages quantitative analysis. It also produces high-resolution still photos as well as high-speed videography at a lower (but still useful) resolution, in addition to the conventional qualitative analyses.

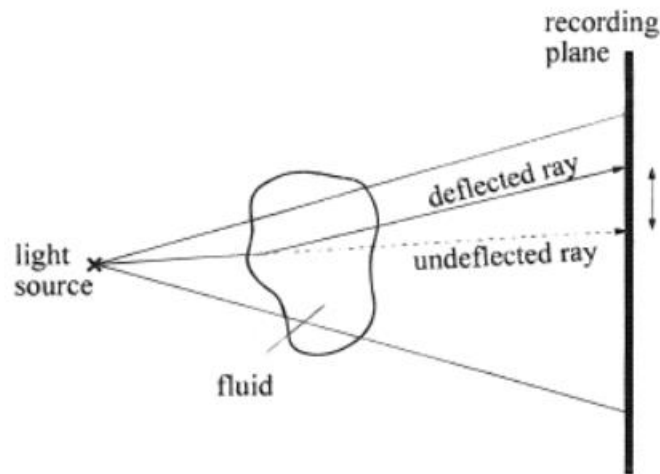


Figure 2.7 Shadowgraph technique [13]

Schlieren technique

The schlieren photography technique is considered as one of the simplest techniques to visualize the flows. This technique has been subjected to visualization since 1800s. Schlieren photography is a visual method that was developed in 1864 by German physicist August Toepler. It is frequently used to capture images of fluid movement with varying densities. The schlieren approach is still one of the most effective methods for visualizing the flow because it is simple to use, has a high and variable sensitivity, is inexpensive, and uses conventional lighting. Schlieren technique also uses concave mirrors to reflect light, and is dependent on the same principle as light reflection [14].

The knife-edge is what distinguishes the arrangement as a Schlieren system. Knife edges are crucial for blocking and creating images. The associated image point will be darker

than an image point associated with an undistributed beam. By the way, the luminance of a spot picture will change depending on the position of the knife-edge [14].

Finding a test area is essential because it can produce the best image when Schlieren image is positioned precisely. Another most crucial settings to figure out before starting the experiment is how to get the best picture from the camera. Exposure is the process of creating a picture using light on a digital sensor. Additionally, Aperture, Shutter speed, and ISO are three factors that affect illumination. The picture exposure will change if any of these are altered. The connection between aperture, shutter speed, and ISO is the exposure triangle [15].

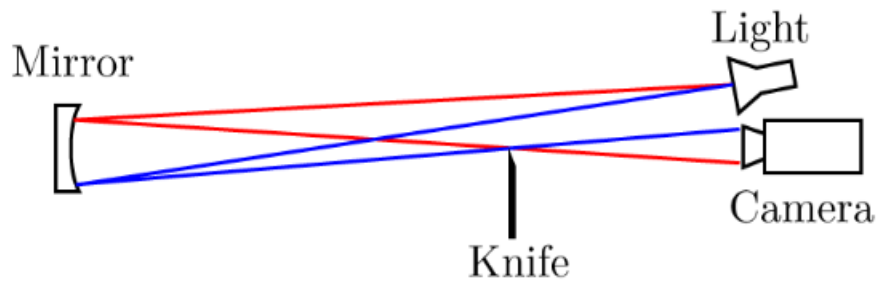


Figure 2.8 Schlieren setup [16]

Chapter 3: METHODOLOGY

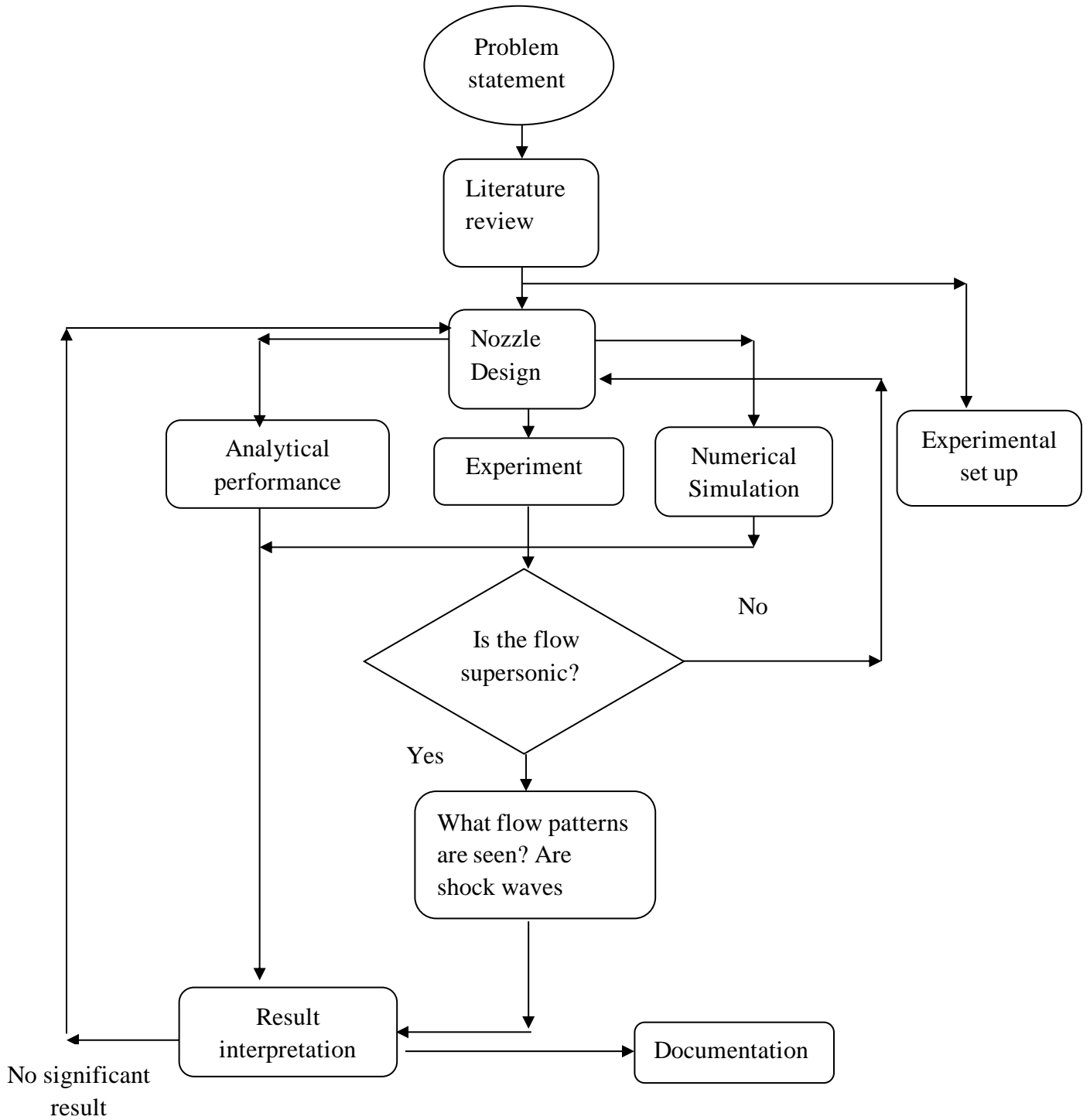


Figure 4.1 Flowchart of Methodology

Considering the problem statements in mind, thorough study of the related research paper, articles, journals and others were done. Insights to the procedures to be followed for the completion of the project were gained. From the review of research papers, we got familiar with the problems that may be encountered during the nozzle design, experimental setup and many more. After the literature review, following steps were followed.

3.1 Nozzle design

Design and fabrication of a CD nozzle is one of the first and foremost work to be done for the project. The design of nozzle is based on fundamental mathematical understanding of compressible flow and gas dynamics. From the references taken from papers and textbooks, calculations of design parameters that has to be taken into considerations were calculated. Inlet pressure (P_0), radius of throat and area expansion ratio (A_e/A_t) were the design parameters that were used during the generation of curve representing the diverging section. The diverging section was given more emphasis as the flow behavior depends solely on this section.

The isentropic pressure relation relates the stagnant inlet pressure to the local pressure value with the known local Mach number. The known pressure values are substituted to get the required exit Mach number.

$$\frac{P_0}{P_e} = \left(1 + \frac{\gamma-1}{2} M_e^2\right)^{\frac{\gamma}{\gamma-1}} \text{----- (1)}$$

After obtaining the exit Mach number, the Area-Mach relation gives the required area expansion ratio.

$$\frac{A_e}{A_t} = \left(\frac{\gamma-1}{2}\right)^{1/2} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)} \left(\frac{P_a}{P_c}\right)^{-(1/\gamma)} \left[1 - \left(\frac{P_a}{P_c}\right)^{(\gamma-1)/\gamma}\right]^{-1/2} \text{----- (2)}$$

The throat area is assumed since the mass flow rate is unknown and exit area is calculated. The choked mass flow rate is then calculated. The inlet area is arbitrarily chosen to match the setup pipe diameter.

Table 3-1 Design Parameters

Parameter	Values
Inlet pressure (P_0)	60 psi
Inlet Temp(T_0)	300K
Back pressure (P_b)	14.7 psi
Exit Mach (M_e)	1.572
Area expansion ratio($\frac{A_e}{A_t}$)	1.228
Specific Heat Ratio(γ)	1.4
R	287 J/kg/k
Area of Throat (A_t)	30 mm ²

3.1.1 Design of geometry

The diverging section wall contour is a useful parameter in three dimensional flows for the isentropic shock free flow inside the nozzle. Method of Characteristics (MOC) technique is used for the analysis and design of the two and three-dimensional supersonic flows [8] . An online MATLAB code was used for the design of contour [17].

Nozzle cross section

The inlet consists of circular cross section with rectangular throat and outlet. The planar nozzle enabled proper visualization with flow constrained to a two-dimensional plane and flow characteristics uniformly distributed along the plane [2]. The diverging section wall contour at the throat is 6mm apart and the other parallel surface is separated by 5mm distance. The exit contour is 7.36 mm apart and parallel surface separated by 5mm distance. The flow is allowed to expand only in contoured surfaces. The converging section is circular with diameter 32.2 mm. No specific contour is chosen.

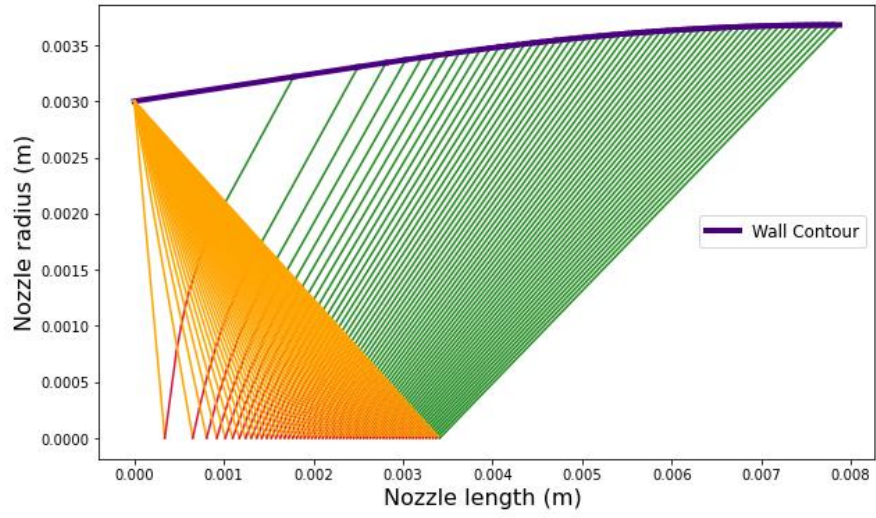


Figure 3.1 Diverging section contour using MOC

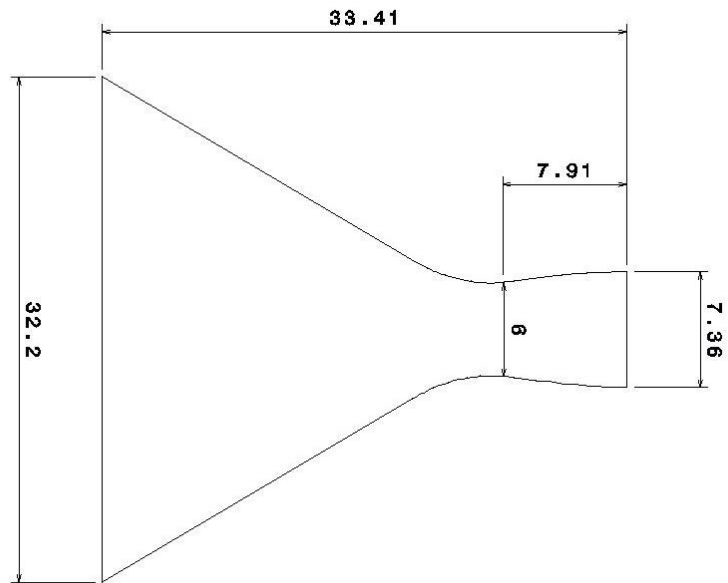


Figure 3.2 2D Sketch of Nozzle

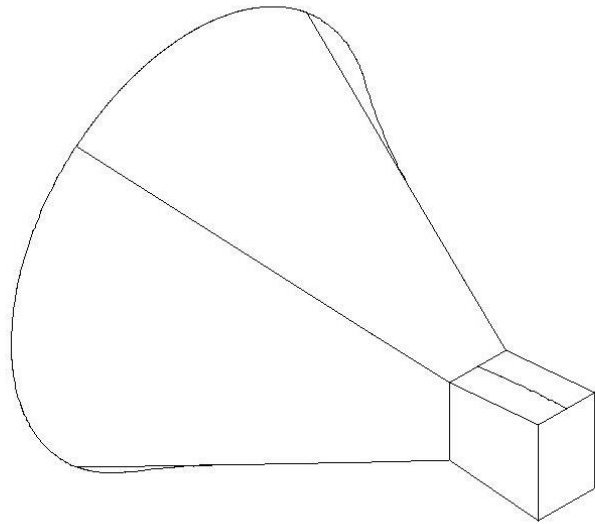


Figure 3.3 Isometric View

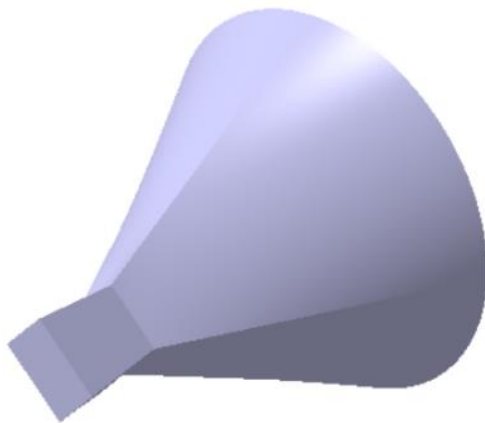


Figure 3.4 3D CAD model of nozzle

3.1.2 Nozzle thermodynamic parameters

Table 3-2 Nozzle Parameters

Inlet	Throat	Exit
Pressure (P_0) = 60 psi	Pressure (P_t)= 31.7 psi	Pressure (P_e)=14.7 psi
Temperature (T_0) = 300K	Temperature (T_t)=250K	Temperature (T_e)=200K
Density (δ_0) =4.82 kg/m ³	Density (δ_t)=3.04 kg/m ³	Density (δ_e)=1.75 kg/m ³

The parameters and values are calculated using isentropic relations. The required Mach no at the exit is 1.572. The choked mass flow rate is calculated to be 0.028 kg/s.

$$\text{Mass flow rate} = \delta_t * A_t * \sqrt{\gamma * R * T_t} = 0.028 \text{ kg/s}$$

From the method of characteristics (MOC), the analytical design representing the diverging section is generated as shown in above. Further, the shapes representing the converging section of the nozzle were designed as per this curve to obtain the final shape of nozzle. The inlet area of the nozzle was designed in such a way that it matches with the area of pipe cross-section available. The final structure of the nozzle in CATIA is shown above. The cross-section of the nozzle at the throat and the exit was made rectangular so that these shape transformations would assist during the flow visualization. The planar shapes used in the nozzle makes the flow visible during flow visualization.

3.2 Material selection for nozzle

Finally, after the completion of analytical design of nozzle in CATIA, it was 3D printed using the available resources. Initially, ABS was used as the filament for 3D printing. The most popular filament for 3D printing is possibly ABS. It is particularly useful in sturdy plastic components that need to maintain their resilience in the face of climate changes. It is primarily utilized in 3D printers that use fused deposition modeling (FDM). Acrylonitrile, butadiene, and styrene are the three monomers that make up the thermoplastic material known as ABS. The substance received its initial patent in the 1940s and rose to fame very rapidly.

One of the most frequently used substances in 3D printing is PLA. It can be printed at low temperatures without a heated bed, making it the primary filament of choice for the majority of extrusion-based 3D printers. Due to its ease of printing, low cost, and ability to produce parts with a variety of uses, PLA is a fantastic first substance to use when learning about 3D printing. One of the greenest strands on the market right now is this one. PLA is renewable and most crucially biodegradable, having been derived from crops like corn and sugarcane.

Considering the availability and cost of material for 3D printing, we used PLA as the material for the nozzle fabrication. It was strong enough to withstand series of tests.



Figure 3.6 Nozzles of various size and exit area

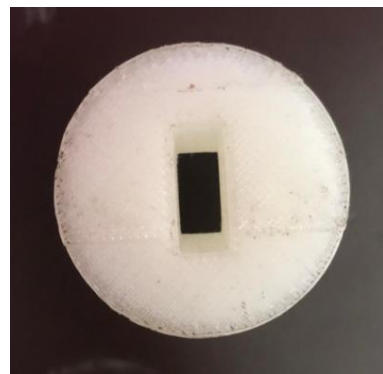


Figure 3.5 cross sectional area of exit

3.3 Experimental setup

Stability of the stand was another important factor that has to be taken into considerations. In order to visualize the supersonic flow, the stand must be able to resist the thrust provided

by the nozzle. Based on the calculation of thrust generated by the nozzle, our stand must be able sustain thrust of around 20N. Further, for the ease in flow visualization, the height of stand was kept 80cm. The rectangular base of 100cm*50cm was made. The top section, at which nozzle has to be kept, was made 120cm long so that changing nozzle would not be a problem. The final CAD design of the nozzle is shown below.

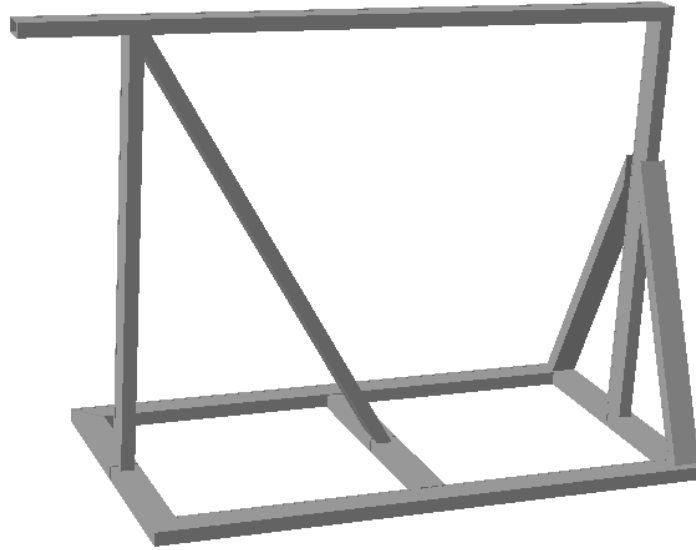


Figure 3.7 Nozzle stand design in CATIA

The reciprocating air compressor was used as a pressure source. The compressed air was stored in another reservoir with a butterfly valve. The reservoir was connected to a pipe cross-section by a polyurethane pipe of 8mm. The pipe was clamped at two different places by a 3D printed clamp as shown in figure 3.3.

The compressed air from the compressor is sent to a reservoir having a butterfly valve. The valve is placed at off position until the pressure is raised up to 80 psi. Once the required pressure is achieved, the valve is set to ON position. The compressed air passes abruptly through the polyurethane pipe across 150mm length and finally reaches the nozzle. Lock valve were used at the different sections, mainly places where change in cross-section was placed, to avoid the leaking of the flow.

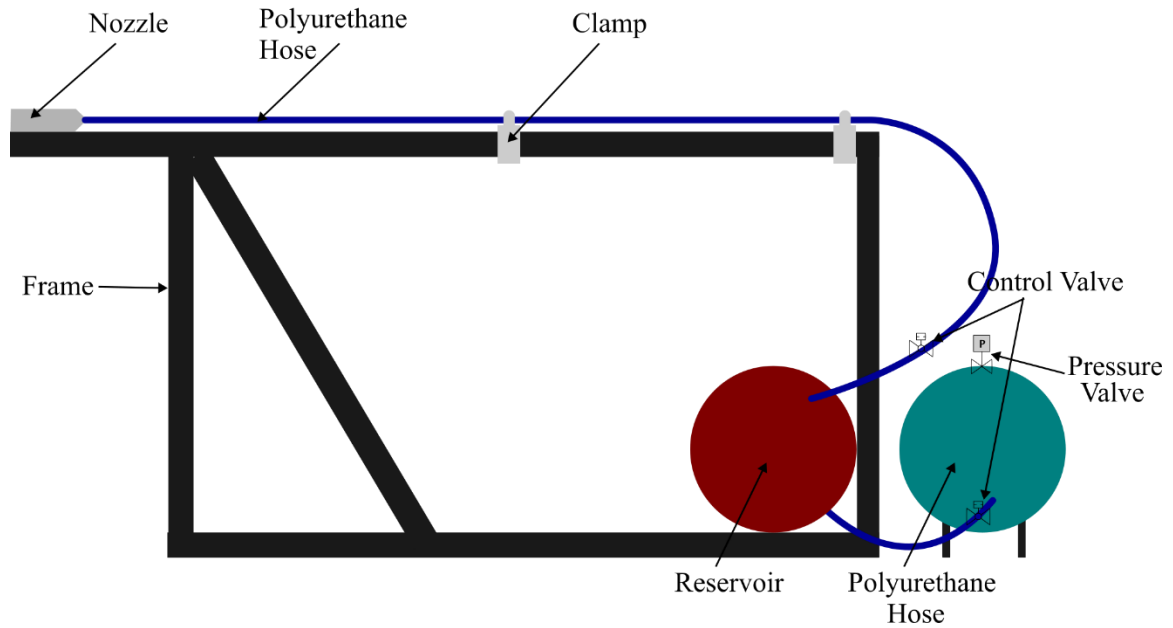


Figure 3.8 Schematic Diagram of Experimental Set Up

Series of test were carried out using this experimental setup. The stand was able to withstand the thrust provided by the nozzle. Despite the use of lock valve, there was still certain amount of leak.

The experimental set up is shown below:



Figure 3.9 Physical Setup for experiment

3.4 Visualization techniques

After the fabrication of the stand and the CD nozzle, visualization of the flow obtained from the nozzle and flow properties were of crucial importance. For the visualization of the flow from the CD nozzle, two of the optical methods was used. Flow visualizations using the shadowgraph and schlieren photography were quite satisfying. These are the one of the simplest forms of the flow visualization techniques that considers the fluctuations of density. Shock waves are the thin regions that has high gradient in pressure, temperature and density. This property of shock waves makes them easy to visualize using these optical methods.

3.4.1 Shadowgraph technique

The shadowgraph is the simplest of all the optical methods and is suitable for observing flows that shows variation in density fluctuation. The simplicity for flow visualization along with the low expense utility makes it one of the good methods. It is considered as one of the best methods for imaging shock waves. This method de-emphasizes less-abrupt flow features revealing the shock waves clearly.

During the flow visualization of the flow using shadowgraph technique, the light source was placed 20cm away from the nozzle while the white screen was placed about 250cm away from the nozzle. The light source, nozzle outlet and the white screen were aligned in such a way that they fall on a same line as shown in figure above. The shadow of the inlet was enlarged such that the clear image is obtained on the white screen.

3.4.2 Schlieren photography

Schlieren photography is one of the oldest methods of flow visualization that relies in the simple fact that the light rays' bents whenever they encounter the change in fluid density. A concave mirror of 20cm focal length was used. A bright light source cutoff by a sharp-edge was placed 40cm away from the mirror. The flow from the nozzle was made to flow through the test section as shown in figure below.



Figure 3.10 Schelerian setup

3.5 Numerical Simulation

Widely used for structural, thermal, fluid, electrical, magnetic, and other system analyses is the commercial software package ANSYS. The software defines a specific problem, its bounds, and other known circumstances. After discretizing the system in terms of algebraic equations, the software subsequently numerically computes the system. ANSYS 2023 R1 student version is used for the simulation. Simulation is also carried out in OPENFOAM.

3.5.1 Mesh method and configuration

ANSYS allow various meshing methods and controls to discretize the domain for simulation. The 2d domain is splitted to various faces creating edges where edge sizing is used. The face meshing is then performed to create structural mesh. Domain is splitted to 16 faces for proper and effective mesh control. Edge sizing with biasing is carried out on all edges and face meshing with quadrilateral elements is done to create structured mesh.



Figure 3.11 Domain splitted to 16 faces

Table 3-3 Mesh Quality and Parameters

Mesh Metric	Maximum	Minimum	Average
Element quality	0.99947	0.047907	0.5236
Aspect ratio	3.91	1	2.45
Skewness	0.34609	$1.089 * 10^{-10}$	0.173
Orthogonal Quality	1	0.85781	0.929

The value is aspect ratio is more deviated than the required but the maximum aspect ratio elements are located far from the actual flow domain towards the outlet walls. The parameters are well constructed for converged solution.

3.5.3 Solver Setup and problem definition

Density based solver is used as the flow is compressible and energy equations are utilized. A 2d steady set up is done and domain type is chosen as planar. A viscous k-ε model with standard wall functions is selected and ideal gas is used.

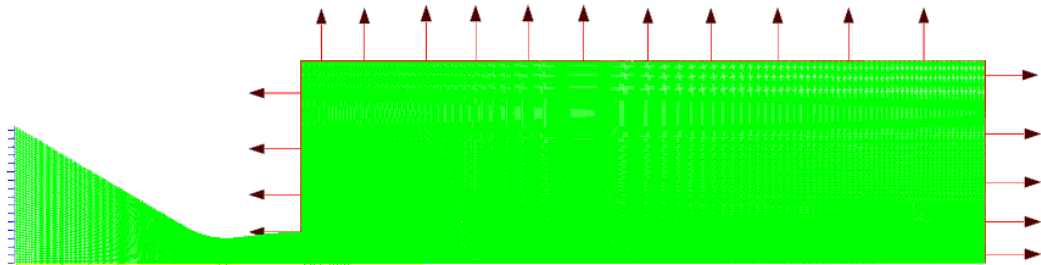


Figure 3.14 Boundary Conditions setup

Table 3-4 Boundary Conditions

Boundaries	Type	Values
Inlet	Pressure	312360 Pa(gauge)
Outlet	Pressure	0 Pa(gauge)
Walls	Fixed	
Sym	Symmetry	

Operating pressure of 101325 Pa is chosen. Supersonic/ initial gauge pressure is calculated as 312236 Pa.

3.5.4 Initialization and Calculation

Standard initialization is done from inlet and solution steering is done for calculation. The courant number is varied from 0.2 to 0.9 and flow type is selected as supersonic. The solution steering allows the quick convergence of solution with less input from the user side.

3.5.5 Mesh Independence Study

The number of elements affects the result so, a mesh independence study should be done. On changing the number of meshes, the value of any parameter should not vary. The least mesh is then selected. The simulation is done for various refined meshes. The mesh element are 84965, 109965 and 133350. These meshes are acquired by changing the edge divisions by a ratio of 1.1. Mass flow rate for these meshes is then plotted. The mass flow rate for 109965 elements and 133350 elements are similar so, 109965 element was chosen for simulation.

Table 3-5 Mesh Independence Test

No of elements	Mass Flow rate(kg/s)
84965	2.840
109965	2.833
133350	2.832

ANSYS calculates the mass flow rate considering 1m span of width. So, necessary calculations should be done to calculate mass flow rate for the nozzle geometry.

Height of throat= 0.003m

Area of throat= $30 * 10^{-6} \text{ m}^2$

Actual Mass flow rate= $\frac{2.833}{0.003} * 30 * 10^{-6} = 0.0283 \text{ kg/sec.}$

This is equal to the actual choked mass flow rate.

Chapter 4: RESULTS AND DISCUSSION

4.1 Supersonic jet Characteristics

Over expanded flow observed at the nozzle exit with shock diamonds clearly visible depicts the supersonic nature of the flow. The nozzle is analytically designed for the perfectly expanded case with atmospheric pressure at the exit but the experimental results suggests the flow as over expanded. The total pressure loss at the pipes and bends, boundary losses resulting insufficient pressure at the inlet might have caused the flow to be over expanded. On increasing the pressure to 100 psi, the flow tends to be under expanded. Long chain of Shock diamonds with oblique shocks and unclear expansion fans movement are observed as the pressure is lowered. The change of oblique shock angle with decreasing pressure to meet the ambient pressure is observed as the flow progresses.

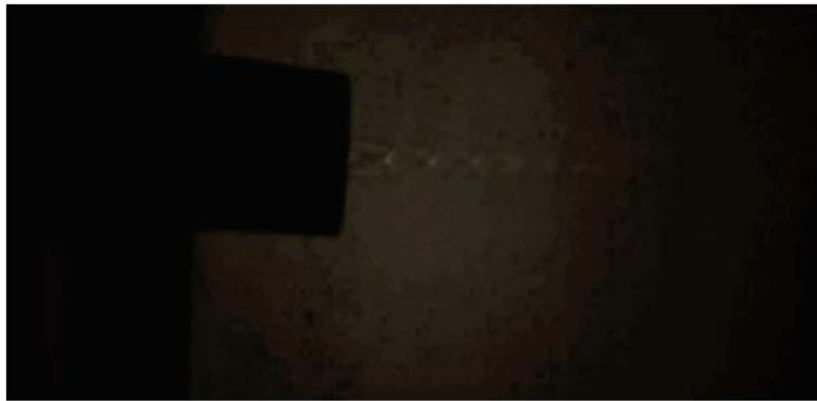


Figure 4.1 Flow visualization using shadowgraphy at 100 psi

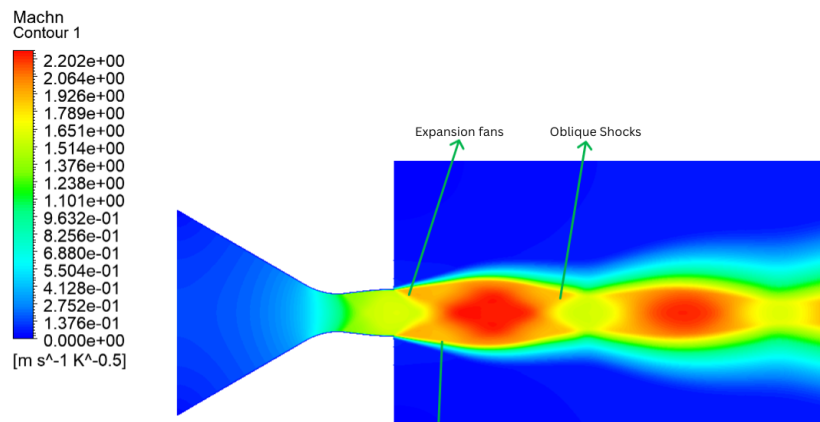


Figure 4.2 Numerical Simulation of NPR 6.8 (100 psi) Underexpanded Flow

At 100 psi, the jet boundary has enlarged as seen in fig 4.2. This is the case when exit pressure is higher than the atmospheric pressure so, the flow is under expanded and expansion as well as compression waves are formed. At the exit, pressure is above the ambient pressure so, to meet this pressure, expansion fans are formed. The Mach no also increases behind the expansion fans which can also be observed in the simulation results. The expansion fans also reflect from the free boundary layer and these reflected compression waves intercept to form oblique shock waves also called barrel shocks. The results are not exact as the simulation results(fig 4.1) where the jet boundary has expanded more. This might be due to the pressure loss in the pipe, viscous losses in the pipe and nozzle, leakages and bends in fittings.

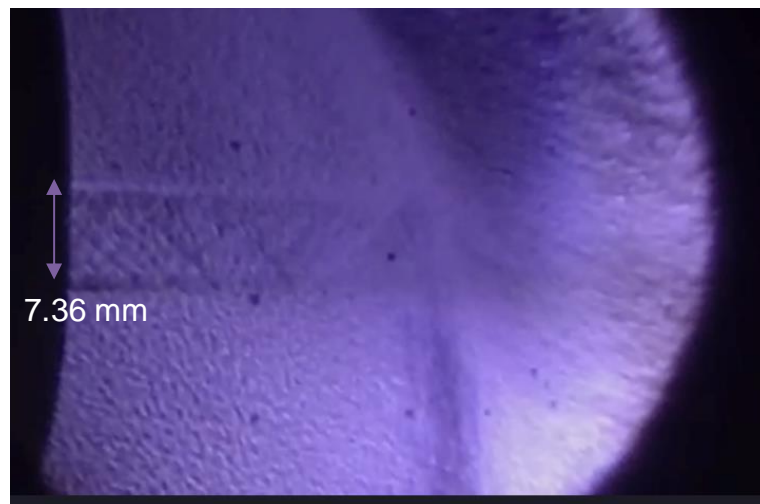


Figure 4.4 Flow Visualization using Schlieren at 60 psi

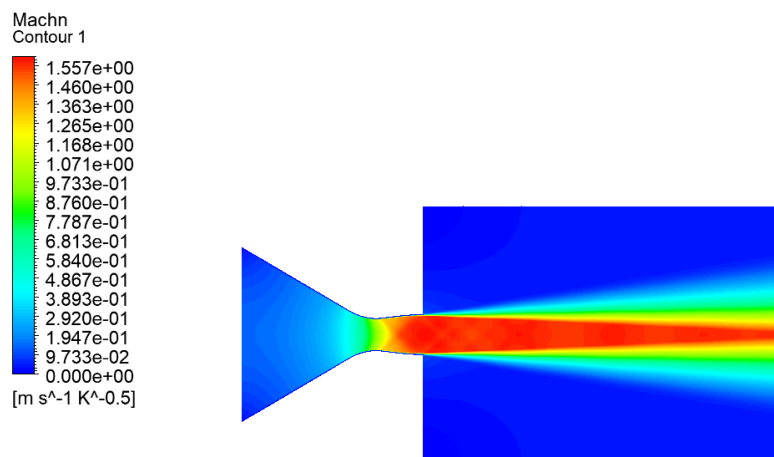


Figure 4.5 Numerical Simulation of NPR 4 (60 psi) Perfectly Expanded

The nozzle was designed analytically with 60 psi as stagnant pressure. This is the condition for isentropic supersonic flow. Yet, the experimental results suggest the flow as overexpanded with formation of shock trains. Even increasing the pressure does not yield a shock free isentropic flow so there must be significant pressure drops at pipes and bends before reaching the nozzle inlet.

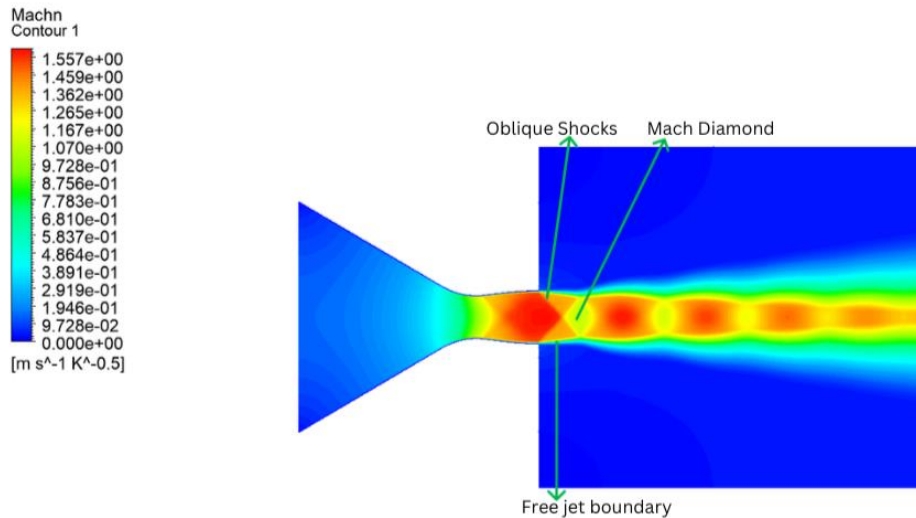


Figure 4.6 Numerical Simulation of NPR 3 (45 psi) Overexpanded flow

The numerical simulation at 45 psi was done to observe the overexpanded flow with formations of oblique shocks and Mach diamonds. Mach disk is not visible. This might be due to weak oblique shocks interaction. On further decreasing the stagnation pressure must result in normal shocks and Mach reflections.

At 80 psi, the oblique shock trains are clearly visible which means the flow is still overexpanded.



Figure 4.8 Flow Visualization Using Shadowgraphy at 80 psi





Figure 4.7 Flow Visualization using Schlieren at 80 psi.

4.2 Problem Faced

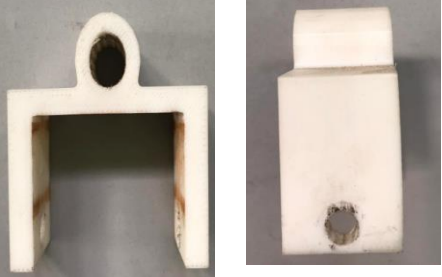


Certain problems were encountered during the design and analysis process. Many of them were terminated while some prevail. To operate compressor at high pressure was also a risk but proper safety measures were adopted. The unknown compressor flow rate also created a problem in design of throat area for choked flow. The inability to mitigate and measure losses still prevail.

4.3 Budget Analysis

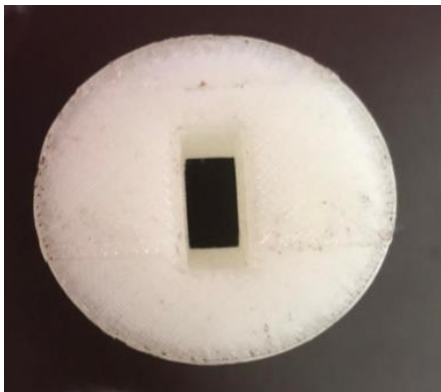
Table 4-1 Budget division

S.N.	Particulars	Amount (NRs)	Remarks
1	 Solenoid Valve	3,500	
2	 Rectangular metal section	2,500	

3	 <p>Pipes</p>	1,000	
4	 <p>Clamps</p>	300	
5	 <p>Water Tapes</p>	100	
6	 <p>Nuts and Bolts</p>	300	

7	 <p data-bbox="537 495 735 533">Pipe Supporter</p>	500	
8	 <p data-bbox="526 1026 748 1064">Hose pipe nipple</p>	200	
9	 <p data-bbox="566 1499 708 1537">Ball Valve</p>	300	

10



Nozzle


3000

11



socket

100

12	 <p data-bbox="483 611 727 642">Push-in connector</p>	550	
13	Miscellaneous Cost	1000	
	Total	13,350	

Chapter 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The nozzle analytically designed for perfectly expanded case at 60 psi inlet pressure is not experimentally achieved instead shock waves are observed suggesting over expanded flow. This might be due to the significant pressure losses in the pipes, bends, boundary layer losses, frictional losses and so on. The causes of losses and their measurement are still to be accessed in the future. On gradually increasing the pressure, hints of under expanded flow are seen. The diverging section wall contour is designed using method of characteristics using online MATLAB code [17]. Proper stand is built for the nozzle. The objective to visualize the supersonic flow is achieved with planar nozzle and is successfully captured using optical methods.

5.2 Recommendations

- Higher pressure capacity tanks would ensure the observation of under expanded flow with our designed nozzle. Also, the flow could sustain for long time enabling proper and greater visualization.
- Reservoir tanks with higher capacity and larger orifice diameter would assist proper flow visualization with reduced losses. Also, if the compressor flow rate could be known in the manufacturer catalog, it would assist in the design phase of the nozzle.
- Solenoid valve for actuation would ensure the abrupt flow from the compressor reducing losses during operation.
- The total pressure at the compressor might not be equal to the nozzle inlet pressure since the flow is not stagnant at the inlet as it flows through the pipe to reach the nozzle inlet. If actual static pressure at the inlet could be measured, the losses could also be calculated and actual calculations and deviations can be calculated.
- The experimental values could not be calculated like the exit Mach no, exit flow temp so, necessary comparisons could not be made with analytical results and proper test section can also be built for future development of blow down tunnel.
- The pressure losses values are not calculated which might have accounted for the overexpanded flow even with increasing stagnation pressures due to high pressure loss.

Chapter 6: REFERENCES

- [1] M. H. Azami, M. Faheem, A. Aabid, I. Mokashi and S. A. Khan, "Inspection of Supersonic Flows in a CD Nozzle using Experimental Method," *International Journal of Recent Technology and Engineering (IJRTE)*, vol. 8, no. 2S3, 2019.
- [2] S. Ranabhat, "Numerical and Experimental Investigation of Exhaust Flow from Convergent-Divergent Nozzle,," Masters Thesis, Kathmandu, 2022.
- [3] Linares M, Ciapitti A, Robaina M and Dulikravich G S, "Design optimization of a supersonic nozzle," 2015.
- [4] G. S. O. Biblarz, *Rocket propulsion elements*, Wiley, 2017.
- [5] W. J. Devenport, "Engapplets," [Online]. Available: <https://www.engapplets.vt.edu/fluids/CDnozzle/cdinfo.html>.
- [6] S. K. a. U. K. Saha, "Rocket nozzles: 75 years of research and development," *Indian Academy of Sciences*, 2021.
- [7] G. V. R. Rao, "Exhaust Nozzle Contour for Optimum Thrust," *Journal of Jet Propulsion*, 1958.
- [8] J. Anderson, *EBOOK: Fundamentals of Aerodynamics (SI Units)*, McGraw Hill, 2011.
- [9] N. Andersson, "OnlineflowCalculator," [Online]. Available: <https://compflow.onlineflowcalculator.com/Anderson/Chapter5/>.
- [10] W. Merzkirch, *Flow Visualization*, New York: Academic Press, 1987.
- [11] S. Ristic, "Optical methods in wind tunnel flow visualization," *FME Transactions*, vol. 34, 2006.
- [12] M.M. Biss, G.S. Settles, M.J. Hargather, L.J. Dodson and J.D. Miller, "M.M. Biss, G.S. Settles, M.J. Hargather, L.J. Dodson & J.D. Miller," in *Springer, Berlin, Heidelberg*.
- [13] J. Grune, "Hysafe Info," [Online]. Available: https://www.hysafe.info/wp-content/uploads/sites/3/2018/04/PRESLHY_Grune.pdf.

- [14] G. S. Settles, *Schlieren and shadowgraph techniques : visualizing phenomena in transparent media*, New York: Springer, 2001.
- [15] D. Samsudin, B. Manshoor, M.D. Anuar, M.S Othman, A. Khalid, "Study of Schlieren Optical Visualization Basics Technique and the Principle," *Trans Tech Publications Ltd, Switzerland.*, 2015.
- [16] M. Dai, "MIT Edu," [Online]. Available:
<http://www.mit.edu/~milesdai/projects/schlieren/index.html>.
- [17] Josh, "GITHUB," 19 Feb 2018. [Online]. Available: <https://github.com/jte0419/RocketNozzleDesign>.