

NUMERICAL AND EXPERIMENTAL ANALYSIS ON MIXING CHARACTERISTICS OF A CIRCULAR FREE JET USING TABS

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in
Aeronautical Engineering

By

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SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade "A++" by NAAC

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APRIL 2024



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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **Eshwar S (40260010)** and **Santhoshkumar K (40260021)** who carried out the project entitled **"Numerical and Experimental Analysis on Mixing Characteristics of a Circular Free Jet Using Tabs"** under my supervision from November 2023 to April 2024.

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ACKNOWLEDGEMENT

We are pleased to acknowledge our sincere thanks to Board of Management of **SATHYABAMA** for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

We convey our sincere thanks to **Dr. A. Anderson., M.E., Ph.D.**, Head of the Department, Department of Aeronautical Engineering for providing me necessary support and details at the right time during the progressive reviews.

We would like to express our sincere and deep sense of gratitude to my Project Guide **Mr. S. VENKATESH., M.E.,(Ph.D.,)** for his valuable guidance, suggestions and constant encouragement paved the way for the successful completion of our project work.

We also express our thanks to all Teaching and Non-teaching staff members of the Department of Aeronautical Engineering who were helpful in many ways for the completion of the project.

ABSTRACT

The main objective of the paper is to study the effectiveness of crosswire for different aspect ratios such as AR 25, AR 16, AR 10 in circular convergent nozzle at under expanded condition. In this study, the effects of different tab aspect ratios on the mixing characteristics of a circular free jet were investigated under Nozzle Pressure Ratios (NPR) of 1.5, 2.5 and 3 by keeping the blockage ratio 5% as constant. The mixing process was evaluated by measuring the jet velocity decay, rapid decay of velocity represents better entrainment. The study found that the aspect ratio of the tab of aspect ratio 16 has a significant effect on the mixing process, compared to other aspect ratios leading to improved mixing characteristics. The study showed that as the NPR increases the shock structure formation increases leading to longer core region and the effectiveness of tab increases with the increase in the NPR. This finding can have important implications for the design and optimization of mixing processes involving circular free jets with tabs.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS	DESCRIPTION
NPR	Nozzle Pressure Ratio
P_o	Stagnation Pressure
P_e	Exit Pressure
P_a	Ambient Pressure
D	Diameter
D_e	Exit Diameter
L	Length
W	Width
H	Height
M	Mach number
AR	Aspect ratio

CHAPTER 1

INTRODUCTION

1.1 JETS

A pressure-driven shear flow that maintains a constant width-to-axial distance, with the constant decreasing as the Mach number increases, is commonly referred to as a jet. In modern aircraft applications, proper mixing of the jet at an appropriate ratio plays a crucial role in reducing noise and improving thrust. Effective mixing is necessary in airbreathing engines to regulate the size of the combustion chamber and improve the vehicle's overall efficiency.

1.2 CHARACTERISTICS OF JETS

1.2.1 *Potential Core Region*

A subsonic jet's potential core frequently stretches up to six times the diameter (D_e) of the nozzle exits downstream from the exit point. This is due to the fact that an area with a constant axial velocity exists because the mixing process, which begins at the jet's edge, has not yet spread across the entire flow field.

1.2.2 *Transition region*

This is the point where the jet's centerline velocity begins to decrease. A notable feature is the decay zone, which stretches from around $5D_e$ to $10D_e$ downstream and represents the transition of the turbulence distribution from an annular to a somewhat pseudo cylindrical structure. As a result, the velocity disparity between the jet's high-speed core region and its surrounding which lessens the shear pressures keeping the jet's vortical rings in place as the jet moves forward, the velocity profiles become smoother.

The wave instability of the vortex rings cores causes surge in three-dimensional flow. Large eddies that can stay coherent around the possible jet core are produced when these warped vortices coalesce. surrounding fluid, which lessens the jet moves forward, the velocity profiles become smoother. The wave instability flow, which is indicative of the transition zone. Large eddies that can stay coherent vortices coalesce.

1.2.3 Fully developed region

After the transition region is passed, the jet's appearance resembles a fluid flow coming from a source that is incredibly thin. The source is a point in an axially symmetric configuration and a straight line perpendicular to the jet's flow plane in a parallel plane configuration, though, in actuality the jet's velocity starts to decrease sharply after about $30D_e$.

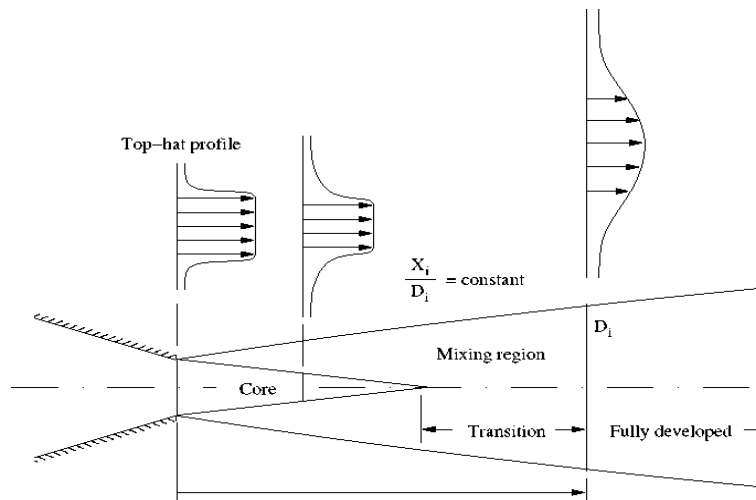


Fig:1.1 : Various zones of a subsonic jet

1.3 TYPES OF JET

The two main types of jets are compressible and incompressible. As a result of their relative incompressibility, jets having a Mach number of less than 0.3 are regarded as incompressible. In contrast, compressible jets—which can be classified as subsonic, sonic, or supersonic—have a Mach number higher than 0.3. Subsonic jets have a Mach number less than 1.0, whereas supersonic and sonic planes have Mach numbers of 1.0 and greater, respectively. In addition, there are three types of compressible jets: mis inflated, under expanded, and over expanded.

1.4 COMPRESSIBLE FLOW

1.4.1 Compressibility

Compressible flows are defined as those that exhibit considerable compressibility. Variable density flow is the simplest definition of compressible flow. The property of compressibility causes a flow to alter in density as speed changes. One definition of compressibility is the pressure's volume modulus.

1.4.2 Types of nozzles

These can be divided into three groups: incorrectly expanded, under expanded, and overexpanded.

1.4.3 Over-Expanded Nozzle

A nozzle is overextended when the pressure at its exit (P_e) is less than the surrounding air pressure (P_a), as shown by the expression $P_e < P_a$. Oblique shock waves are created at the nozzle exit to rectify this, compressing the jet flow and raising the exit pressure to equal the ambient

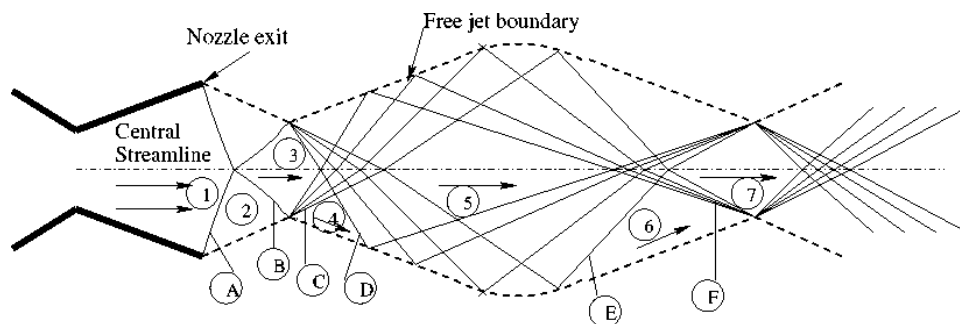


Fig:1.2 : Shock structure in over-expanded nozzle

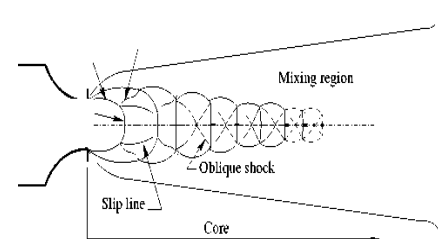
1.4.4 Correctly Expanded Nozzle

When the nozzle exit pressure of a jet matches the ambient pressure, it is considered adequately expanded ($P_e = P_a$). Unlike nozzles that are either under expanded or overexpanded, the flow does not require compression or expansion once it exits the nozzle. This suggests that no compression or expansion waves are created at the nozzle exit when the flow is appropriately expanded.

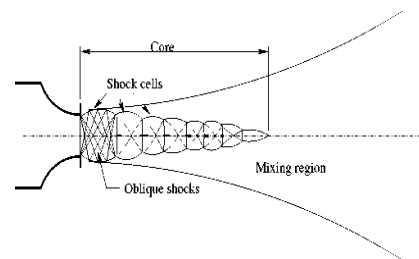
Even when correctly expanded flow exits a nozzle, the flow still Needs to turn away from the nozzle axis in order to occupy the available area. As a result, expansion waves are produced at the nozzle exit, although they are significantly less powerful than those brought on by an under expansion of the flow. It should be mentioned that expansion for both appropriately expanded and under-expanded flows happen at the nozzle exit. Correctly expanded flows are turned away from the nozzle axis by the expansion; under-expanded flows require the expansion to both shift the flow away from the nozzle axis and lower the static pressure.

1.4.5 Under-Expanded Nozzle

The jet is said to be under-expanded when the nozzle exit pressure (P_e) is greater than the surrounding air pressure (P_a). This produces expansion waves at the nozzle's edge that are wedge-shaped. These waves then cross over and reflect back as compression waves from the jet flow field's boundaries. Subsequent to their intersection, the compression waves bounce back as expansion waves off the jet's limits.



a) Highly under expanded jet



b) Moderately under expanded jet

Fig: 1.3 : Shock structure in under-expanded nozzle

1.5 TYPES OF CONTROL METHOD

Jet mixing methods are generally classified into two types, namely active control, and passive control.

1.5.1 Active Control

Active control involves using an auxiliary power source, such as micro jets, to manipulate the characteristics of a jet. These methods are chosen based on the desired level of receptivity in the given medium. Various techniques can be used to excite the flow, including mechanical methods like fluctuating flaps, vibrating ribbons, and piezoelectric surfaces, hydrodynamic methods like periodic suction and blowing, thermal techniques like heating strips or electrical discharge, or modulation of the free stream.

1.5.2 Passive control

Since passive controls don't need an external power source, they are preferable to active controllers. Passive control involves changing the shear layer stability properties by means of geometric adjustments to the nozzle exit.

Using tooth-like tabs and vortex generators in the jet, altering the nozzle's exit shape, and putting a cross-wire across the jet's diameter are a few examples of passive control techniques. In order to produce the required flow behavior, these strategies try to perturb the boundary layer at the nozzle exit. For example, the cross-wire generates stream wise vortices that reduce the intensity of the shocks in the jet core and accelerate the decline of the centerline pitot pressure. All expansion levels benefit from this passive control.

1.6 APPLICATION OF JET CONTROL

1.6.1 Infra-Red Signature Reduction

A powerful radar system on another aircraft will detect a strong jet plume emerging from the exhaust of an aircraft with a stronger infra-red signature. As a result, an aircraft's or missile's ability to survive depends on its infrared exhaust gas signature. Combining cold air with low motion and hot gas with high momentum can lessen this signature. The temperature in the jet field close to the nozzle decreases as a result of this mixing. Use of this is possible in turbofan engines with large bypass ratios. One potential method for reducing the infra-red signature is to employ tab-shaped vortex generators to induce instability at the nozzle exit. At the nozzle exit, these tabs create stream wise vortices, and the vortices are efficiently.

1.6.2 Jet Noise Reduction

Due to the shock-associated noise that high-speed jets make during takeoff-known as scream noise people who live close to the airport are disturbed. It might even put one's ability to hear in peril. Furthermore, at supersonic Mach values, jet noise can potentially cause damage to a fighter aircraft's tail surfaces. By increasing the amount of ambient air mixed with the jet, which lowers the potential core region and increases velocity decay, the jet noise can be minimized. The reduction in velocity in the jet flow files significantly lesser than sound associated with the jet emerging from a supersonic aircraft's engine since the acoustic output of the jet is exactly related to the eighth power of the velocity.

1.6.3 Combustion System

The efficient mixing of fuel and air in the combustion chamber of internal accost combustion chamber of intern combustion and gas turbine engines determine the combustion efficiency. A well-designed injection nozzle that regulates the fuel jet in the combustion chamber can improve mixing. Furthermore, adequate mixing may even short time it takes for the fuel to ignite and improve the fuel's atomization into tiny droplets.

1.6.4 Base Heat Reduction of Launch Vehicles

A tremendous amount of heat is delivered to the launch vehicles' base when the high-temperature plume from the engine nozzle is drawn towards the base region when the base pressure is low, below atmospheric levels.

CHAPTER 2

LITERATURE SURVEY

P Lovaraju and **E Rathakrishnan (2006)** investigated the effects of axisymmetric jets fired from a convergent nozzle fitted with a cross-wire at the exit along a diameter at Mach 0.4, 0.6, 0.8, and 1.0. Their findings showed that the cross-wire was effective in enhancing jet mixing right out of the nozzle output, regardless of the Mach values. Furthermore, the jets of the nozzle fitted with a cross-wire expanded faster in the direction perpendicular to the wire. For nozzle pressure ratios of 3, 5, and 7, the cross-wire had an effect on the shock cells and the core of the under expanded sonic jet. For all under expansion levels, this led to a large decrease in the shock intensity and a significant reduction in the core length. In particular, as a result.

P Lovaraju, S Clement and **E Rathakrishnan (2007)** carried out an experiment at three under-expansion levels (NPR 3, 5, and 7) to examine the efficacy of passive controls at the nozzle exit. The controls consisted of small tabs and a cross-wire that protruded typically into the flow. The investigation demonstrated that the jet structure may be considerably altered by the cross-wire and tabs, leading to a faster decay at all NPRs. In contrast to the cross-wire controlled jets, it was discovered that the tabbed jets grew significantly wider. The expansion of the supersonic zone normal to the tabs/cross-wire was captured in shadow-graph images. These controls improved in diffusing the shock-cells in their respective planes as the NPR rose.

P Lovaraju, K P V Paparao and **E Rathakrishnan (2004)** carried out an experimental investigation into the efficacy of a shifted cross-wire on supersonic jets as a passive control. According to the study, the relocated cross-wire at all places efficiently lessens centerline Pitot pressure oscillations downstream of it. The investigation looked into Laval's Mach 1.83, 1.86, and 1.94 jets.

nozzles of rectangular cross-section operating at correctly expanded, overexpanded, and under-expanded conditions. According to the study, the relocated cross-wire encourages mixing and lessens core shocks. At NPR 7, a maximum 30% core reduction was attained for the Mach 1.86 jet. Additionally, the study discovered that the cross-wire at the nozzle's exit experiences thrust loss that is almost equal to the blockage area. It discovered that the cross-wire at 1.0D site worked best for mixing promotion of the study's scheme.

Y H Kweon, Y Miyazato and T Aoki (2005) have suggested a unique technique for lowering the noise produced by supersonic jets that makes use of a cross-wire, an easy-to-implement, basic gadget. Evaluation of the supersonic jet flow field with and without the cross-wire using an excellent schlieren optical system was done to determine how effective this device is. The apparatus was positioned perpendicular to the jet stream and its location was altered in order to assess its impacts on the jet structure and acoustic field, which depended on the jet pressure ratio. The cross wire ruptured and debilitated the shock-cell structure, while simultaneously slightly increasing the jet's downstream spreading rate. Moreover, it decreased the overall sound pressure level when positioned closer than three times the nozzle's exit diameter.

A Khan and R Kumar (2018) investigated the impact of the relative azimuthal orientation of cross-wire tabs mounted at the exit plane of two identical C-D nozzles on Mach 1.8 jet flow field through experimentation. According to the study when the cross-wire is utilized as a passive control for twin jets, its orientation significantly affects how the jet flow field develops. It was discovered that both cross-wires worked extremely well at improving mixing properties, shortening core length, and reducing shock wave strength when positioned vertically near the nozzle exit. Additionally, this orientation encouraged twin jet and produced the greatest jet dispersion in the transverse direction.

P Arun Kumar, M Aileni and E Rathakrishnan (2019) rectangular tabs were used to investigate the mixing enhancement of a Mach 2.0 jet in both overexpanded and perfectly expanded states. The tabs used had an aspect ratio of 2 and were placed at four different locations downstream of the nozzle exit: 0De, 0.25De, 0.5De, and 0.95De. The study identified three flow categories, namely jet

bifurcation, complex and strong shock-cell structure, and weak shock structure, which were found to depend on the location of the tabs. The results of the study showed that the tabs should be placed downstream of the first shock crossover point to achieve a shorter core length and higher jet mixing.

N K Singh and E Rathakrishnan (2002) conducted research on the decay characteristics of sonic free jets that are correctly and under-expanded, with and without tabs. The introduction of streamwise vortices by the tabs leads to a faster decay of the jet center line pressure and a significant weakening of shocks in the jet core. In terms of enhancing mixing, the length of the tab is more effective than its width for the same projected area. The study found that tabs can reduce jet core length by up to 80%. The research also indicates that tabs are more effective in under-expanded jets than in correctly expanded ones.

S M Aravindh Kumar and E Rathakrishnan (2015) were able to demonstrate the capability of modifying the mixing characteristics of an elliptic jet at Mach 2. Among the different tab positions, it was found that the tabs along the minor axis were the most effective in reducing the core length by 65% at an overexpansion level of NPR 4. Additionally, it was observed that the waves in the core of the jet with tabs along the minor axis were weaker compared to those of the jet with tabs along the major axis and the uncontrolled jet.

K Anusindhiya and G Vinayagamurthy (2021) conducted a study to evaluate the effectiveness of a rectangular tab with a slot connecting the adjacent faces at a jet exit Mach number of 0.4. The slotted tab's performance was contrasted with that of the solid rectangular tab and the free jet. When compared to the free jet, the study indicated that the slotted tab reduced core length by a greater proportion (84.1%) than the solid tab (74%) did. In contrast to the solid rectangular tab, it was discovered that the slotted tab distorted the jet more in the near field.

K B M Q Zaman, M F Reeder, and M Samimy (1992) examines the use of delta-tabs for enhancing mixing in supersonic jets, focusing on triangular tabs and testing at equivalent Mach numbers up to 1.8. Bifurcation of the jet was achieved with two delta-tabs spaced 180° apart, while four delta-tabs significantly increased jet mixing beyond other methods previously tried. In fact, the mass flux at 14 De downstream from the nozzle was found to increase by approximately 50%

compared to the case with no tabs. The effectiveness of the tabs was demonstrated in both laminar and turbulent boundary layers.

T Berrueta and E Rathakrishnan (2017) conducted an experimental study on the mixing of subsonic and sonic jets using limiting tabs, both plain and corrugated. The study found that the tab located at the nozzle exit resulted in better mixing compared to the tab positioned at $0.5D$ for both plain and corrugated geometries. The results also revealed that the tabs improved the mixing of under-expanded sonic jets more than correctly expanded sonic jets and subsonic jets. At NPR 3, the plain tab positioned at the nozzle exit reduced the core by around 56%, and the corrugated tab reduced it by about 51%. Additionally, the shifted corrugated tab caused a maximum reduction of 14% in core for the Mach 0.8 jet.

S Akram and E Rathakrishnan (2017) investigated the use of ventilated triangular tabs for controlling Mach 1.5 elliptic jets under various levels of nozzle exit pressure gradient. They found that at an NPR of 3, the trapezoidal ventilated tab was the most effective, resulting in up to 92% reduction in core length. At an NPR of 5, both unventilated and trapezoidal ventilated tabs achieved an equal core length reduction of 84%. Hence, the ventilated tab is considered a more preferable option since it leads to around 25-30% less thrust loss than the identical unventilated tab.

B P Chiranjeevi and E Rathakrishnan (2010) through experimental means. Results showed that at NPR 7, corrugated tabs led to a core length reduction of up to 78%, while plain tabs only achieved 54% reduction. Furthermore, the effectiveness of corrugated tabs in promoting mixing was observed to increase with an increase in NPR, whereas plain tabs were found to be most effective at the correctly expanded state. The corrugated tabs were also found to cause a greater reduction in shock strength compared to the plain tabs.

DG Bohl and JF Foss (1996) investigated qualitative and quantitative measurements that were taken in the near field of a jet with tabs. Their study revealed that adding secondary tabs on each side of the primary tab led to an increase in the flux of vorticity into the flow, which in turn significantly increased the rate at which the jet core and ambient fluid interacted. This modification also had a positive effect on the flux of vorticity into the flow.

E Rathakrishnan (2018) conducted a study to assess the effectiveness of passive control, specifically in the form of a cross-wire placed at the nozzle exit, on the decay and noise characteristics of Mach 1.6, 1.79, and 2.0 jets emanating from C-D circular nozzles. The study was carried out at different levels of expansion. The results showed that the cross-wire caused a reduction in core length of up to 50% for $M=1.79$ at NPR 5.66. The maximum core length reduction occurred at the correct expansion, around NPR 4.25 for the Mach 1.6 jet and NPR 5.66 for the Mach 1.79 jet. The study also revealed that the cross-wire was an effective means of promoting mixing even in the presence of unfavorable pressure gradients.

S Zhang and SP Schneider (2018) analyzed the impact of tabs, Reynolds number, and chemical equivalence ratio on molecular mixing in a range of Reynolds numbers from 5.2×10^3 to 3.2×10^5 . The addition of two tabs increased the chemical product present 6D downstream of the jet exit by 35%, while four tabs increased it by 45%, at a Reynolds number of 1.49×10^5 . Even though two tabs resulted in more rapid velocity decay and jet spreading, four tabs enhanced molecular mixing to a greater extent. The effects of the tabs were less pronounced in a transitional jet than in a turbulent jet.

R M Kelso and T T Linz (2010) investigated the structure of round jets in cross-flow. The study focused on Reynolds numbers based on the jet diameter and free-stream velocity ranging from 440 to 6200 and jet to free-stream velocity ratios ranging from 2.0 to 6.0. The study revealed that the formation mechanism of unsteady upright vortices in the wake may differ for Reynolds numbers ranging from 4.0 to 6.0.

L L Yuan and R L Street (2004) conducted a study on the behavior of a round jet in crossflow, focusing on its trajectory and entrainment characteristics. The study utilized large eddy simulations at Reynolds numbers of 1050 and 2100, and at jet to crossflow velocity ratios of 2.0 and 3.3. The mean streamlines on the center plane of the jet were used to determine trajectories, which were found to converge to a single curve far from the jet exit, and could be described using a power law fit. Entrainment of crossflow fluid within this power-law region was identified as the main mechanism driving changes in the jet's course.

L L Yuan and R L Street (2004) conducted a study on the behavior of a round jet in crossflow using large-eddy simulations. The simulations were conducted at two different jet-to-crossflow velocity ratios (2.0 and 3.3) and two different Reynolds numbers (1050 and 2100), based on the jet diameter and crossflow velocity. The study shows that minor alterations in the initial conditions of the pipe flow during experiments can have significant impacts on the mean flow. In addition, the study found that the formation of upright vortices is caused by the reorientation of streamwise vortices near the wall by the strain field directly behind the jet.

P Surks and C B Rogers (2004) the effects of streamwise vortex structures on acoustic and entrainment properties vary significantly based on the vortex direction. It was observed that co-rotating vortices tend to induce more fluid entrainment, up to 50%, with less noise compared to counter-rotating vortices. Co-rotating vortices also decreased low-frequency noise up to 3 dB but increased high-frequency noise by up to 8 dB. As the low-frequency noise mainly propagates downstream of the jet, the vortex configurations effectively reduced the OASPL (Overall Sound Pressure Level) downstream of the jet.

CHAPTER 3

AIM AND SCOPE

3.1 AIM OF THE STUDY

To investigate the most effective aspect ratio of a cross-wire as a passive control for improving the mixing characteristics of a circular nozzle at under expanded state of jet.

3.2 SCOPE AND OBJECTIVES

To study the mixing characteristics of a circular jet in the presence of rectangular tab or cross-wire of different aspect ratios in under-expanded condition. The current investigations evaluate the mixing features of high-speed jet controls of subsonic and supersonic jets using tabs with rectangular, arc-in, and arc-out shapes, respectively. This dissertation examines the efficacy of semicircular arc tabs as passive controlling devices for subsonic, sonic, and supersonic jets. The effectiveness of the arc tab was contrasted with that of plain (uncontrolled or un-tabbed) jets and rectangular tabs at the nozzle outlet. For the subsonic and sonic correctly expanded and under expanded levels of the high-speed jet control, the three different tab configurations—rectangular, arc-in, and arc-out—are

- (i) passive control devices,
- (ii) study of the effect of tab lengths on centerline
- (iii) Mach decay, Mach number Profile, and iso-contours.

CHAPTER 4

DESIGN AND ANALYSIS

4.1 METHODOLOGY

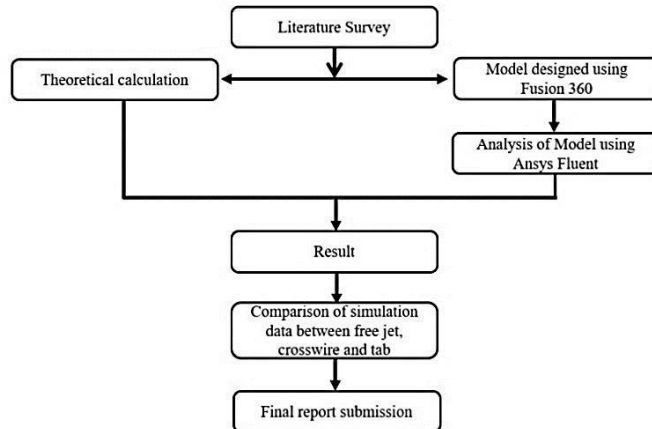


Fig:4.1 : Methodology to carry out project work

4.2 NOZZLE DESIGN

All the design work were carried out in Autodesk fusion 360. Fusion 360 is a cloud-based 3D CAD, CAM, and CAE software platform for product development. It allows users to design, engineer, and manufacture products using a single platform.

4.2.1 Circular Nozzle

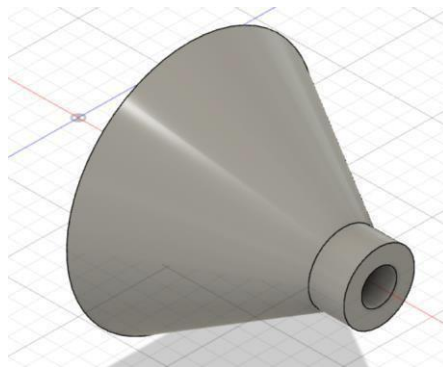


Fig:4.2 : Circular nozzle

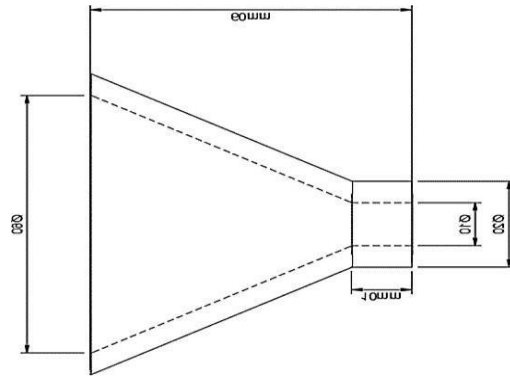


Fig:4.3 : Geometry of nozzle

Table 4.1 : Circular nozzle dimension

GEOMETRY OF NOZZLE	DIMENSION
Inner Diameter of Inlet Inner	60mm
Diameter of Outlet	10mm
Outer Diameter of Outlet	20mm
Length	60 mm

4.2.2 Nozzle with Crosswire (AR 25)

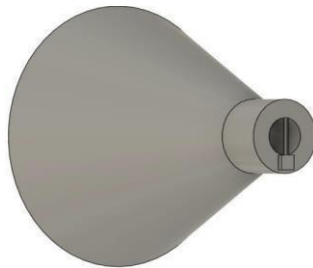


Fig: 4.4 : Nozzle with cross-wire (AR 25)

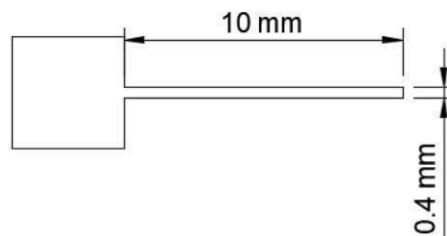


Fig: 4.5 : Cross-wire (AR 25) geometry

Table 4.2 : Cross-wire (AR 25) dimension

GEOMETRY OF CROSS-WIRE	DIMENSION
Length	10mm
Breadth	0.4mm
Thickness	1mm

4.2.3 Nozzle with Tab (AR 16)

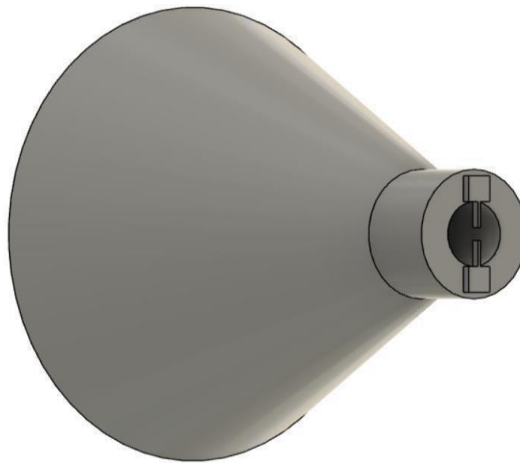


Fig: 4.6 : Nozzle with tab (AR 16)

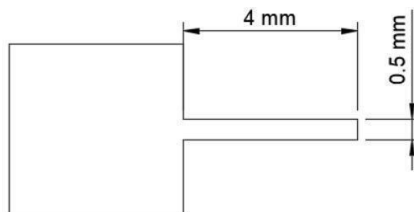


Fig: 4.7 : Tab (AR 16) geometry

Table 4.3 : Tab (AR 16) dimension

GEOMETRY OF TAB	DIMENSION
Length	8mm
Breadth	0.5mm
Thickness	1mm

4.2.4 Nozzle with Tab (AR 10)



Fig: 4.8 : Nozzle with tab (AR 10)

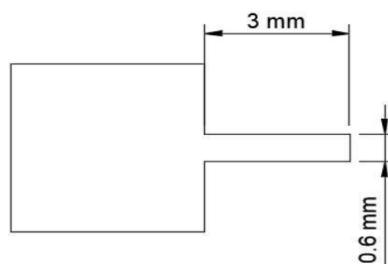


Fig: 4.9 : Tab (AR 10) geometry

Table 4.4 : Tab (AR 10) Dimension

GEOMETRY OF TAB	DIMENSION
Length	6mm
Breadth	0.6mm
Thickness	1mm

4.3 ANALYSIS

An Axisymmetric nozzle convergent nozzle was used for the numerical simulation of this study. The exit diameter of the nozzle is 10 mm. The jet is controlled by placing crosswire of length 10 mm and width 0.4 mm and two tabs of different aspect ratio of AR 16 and AR 10. The AR 16 tab is of length 4mm and width 0.5mm and AR 10 tab of length 3 mm and width 0.6mm were placed diametrically opposite to each other. The computational analysis is done in ANSYS FLUENT software which is suitable for all purpose of numerical analysis. The Ansys fluent is a software package for computational fluid dynamics (CFD) that can simulate complex systems involving fluid flow, heat transfer, and chemical reactions. It is a component of the Ansys simulation platform and offers advanced solvers and modeling capabilities, including multiphase and reacting flows and turbulence modeling. This tool can analyze and optimize the performance of different types of systems such as automotivesystems, aircraft engines, and industrial equipment. Ansysfluent is useful in various applications, including aerospace, automotive, chemical processing, electronics, energy, and manufacturing.

4.3.1 Computational Domain:

To visualize the flow domain has to be created with certain conditions. In this study cylindrical domain is created from the nozzle exit of standard dimension of length 50D and Diameter of 20D. For this study domain is created for 500 mm and diameter of the domain is 200 mm.

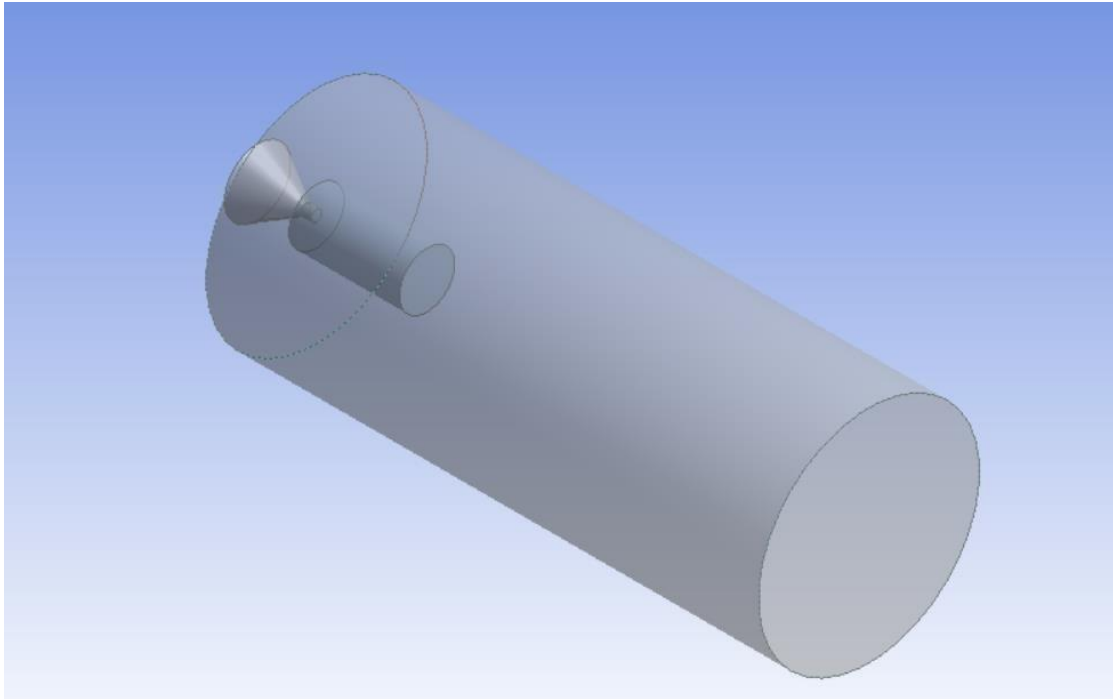


Fig:4.10 : Cylindrical domain with internal sub domain

Another Sub domain is created for length of 100 mm and radius of 20 mm. Internal domain is created to increase the fineness of the mesh at the near field region of the nozzle to visualize the potential core.

4.4 MESHING

The process of generating a mesh, or grid, to cover the entire domain of a fluid flow problem in Computational Fluid Dynamics (CFD) is known as meshing. This mesh is used to discretize the domain into interconnected cells or elements, which are used to solve the governing equations of fluid flow numerically. CFD uses several types of meshes, including structured, unstructured, and hybrid meshes. Structured meshes consist of regularly arranged cells, while unstructured meshes consist of cells with different shapes and sizes. Hybrid meshes combine elements of both types. The quality of the mesh is critical to the accuracy and convergence of the CFD solution. The mesh cells should be small enough to capture fine flow details but not so small that the computational cost becomes too high. The shape and size of the cells should also be selected to minimize discretization errors introduced by the numerical solution. Specialized software tools are typically

used in CFD meshing to automate the process of generating and refining the mesh based on various meshing algorithms and criteria.

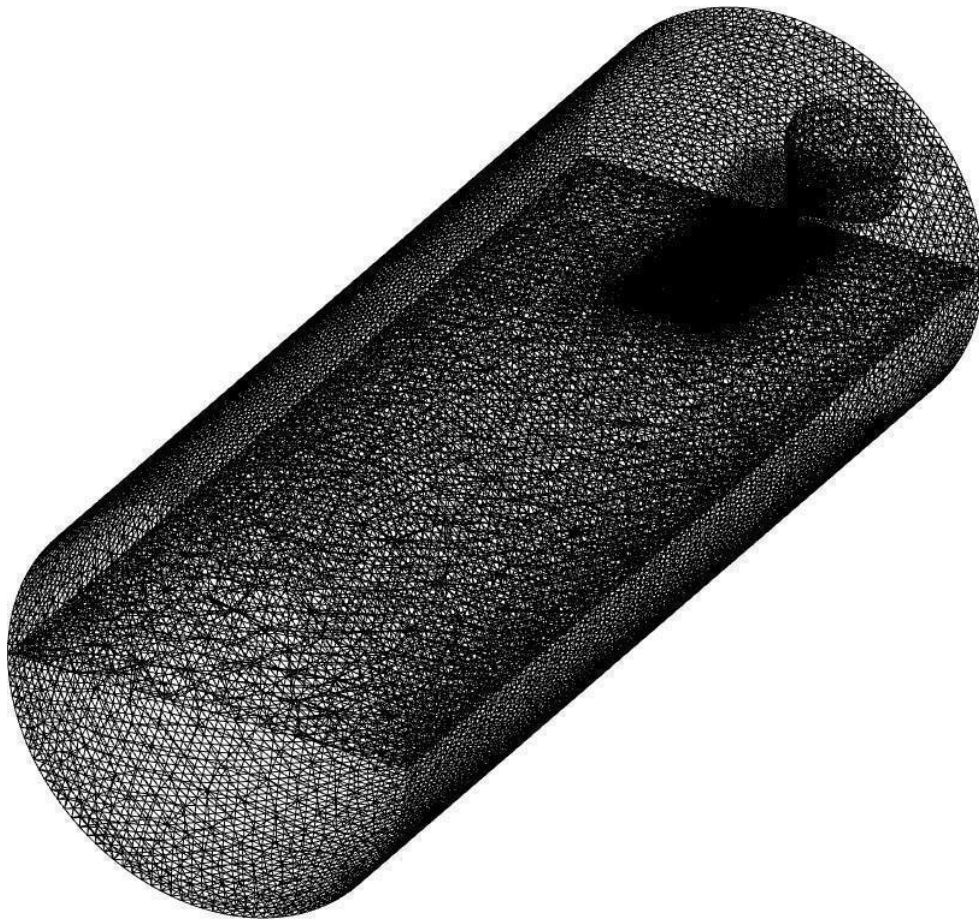


Fig: 4.11 : Meshing of cylindrical domain

The meshing plays a major role in visualizing and determining the flow properties. An outer domain mesh of 10 mm is provided and the inner domain is provided with a 1 mm fine mesh in order to capture the shock cell formations and characteristic decay at higher NPR's.

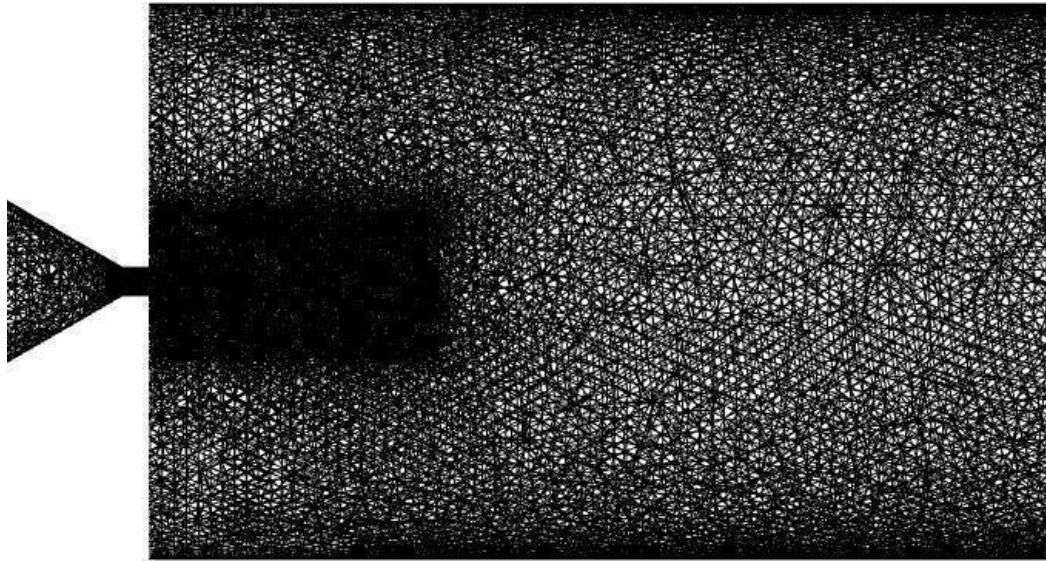


Fig:4.12 : Section view of mesh

4.4.1 Fluent Pre-Processing

Viscosity conditions have been used for the steady state analysis. The viscosity was enabled using the k-omega SST model. ANSYS Fluent and other computational fluid dynamics (CFD) simulation programs frequently use the k-omega SST turbulence model. This turbulence model, which can simulate turbulent flows in a variety of applications, is based on the Reynolds-averaged Navier-Stokes equations. Two transport equations make up the model: one for turbulent dissipation rate (ω) and the other for turbulent kinetic energy (k). The epsilon equation explains how turbulent kinetic energy is transformed into heat, whereas the k equation discusses how turbulent kinetic energy is created and destroyed.

The k-omega model is relatively simple to implement, computationally efficient, and validated for different flow types, it has limitations in predicting specific flow situations such as near-wall flows, separation, and flows with strong swirl or rotation. ANSYS Fluent provides built-in support for the k-omega turbulence model, and it is readily accessible through the software's user interface. Users can quickly switch between different turbulence models, depending on the problem requirements and the desired level of accuracy. Air is provided as fluid with density as ideal gas and viscosity of air is Sutherland. The inlet pressure is provided as absolute pressure in fluent. The inlet pressure for NPR of 1.5, 2.5 and 3 were given for circular free jet and nozzle with crosswire and tabs. The methods were changed to second order upwind for accurate results.

Table 4.5 : Boundary condition

Fluent setup	Condition
Turbulence model	K omega SST
Model	Air
Inlet	Pressure inlet
Outlet	Pressure outlet
Residuals	1×10^{-6}
Initialization	Hybrid initialization
No. of iteration	1000

4.5 VELOCITY CONTOURS

A plane was created along the axial distance to visualize the velocity and pressure from the exit of the nozzle.

4.5.1 Circular Nozzle with Different NPR

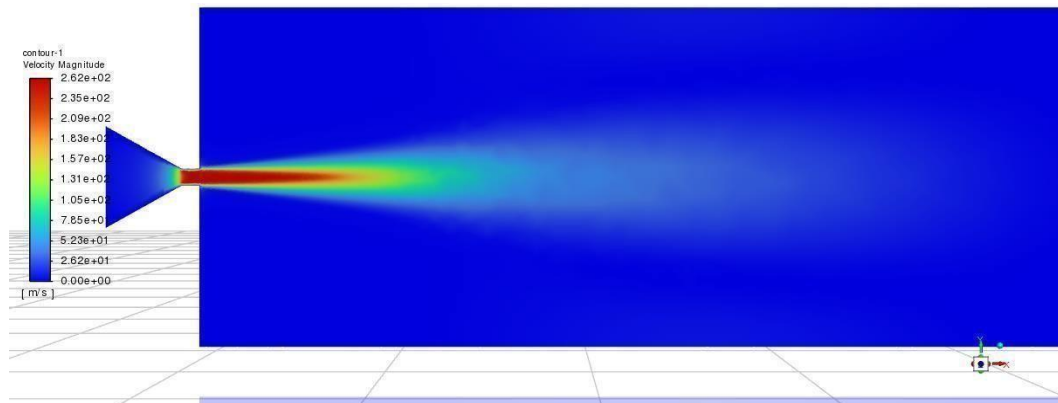


Fig:4.13 : Circular nozzle of NPR 1.5

It represents the velocity contour of circular nozzle at NPR 1.5 and the maximum velocity obtained 262 m/s.

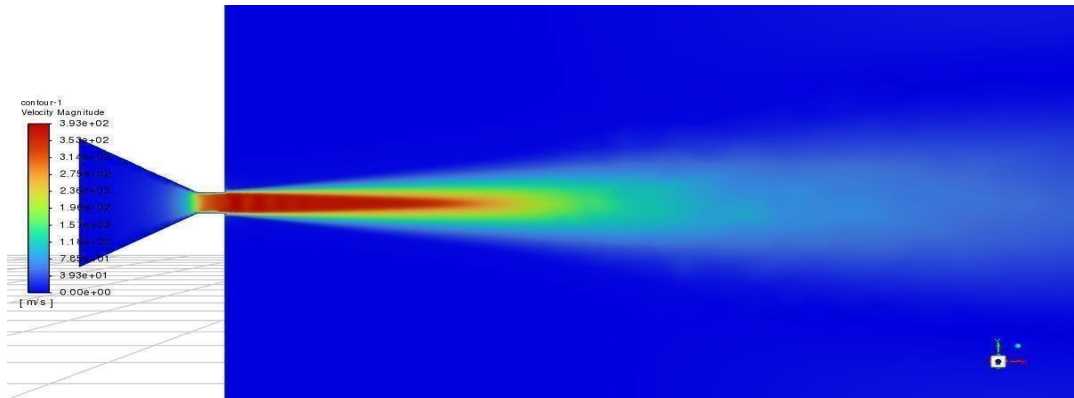


Fig: 4.14 : Circular nozzle of NPR 2.5

It represents the velocity contour of circular nozzle at NPR 2.5 and the maximum velocity obtained 393 m/s.

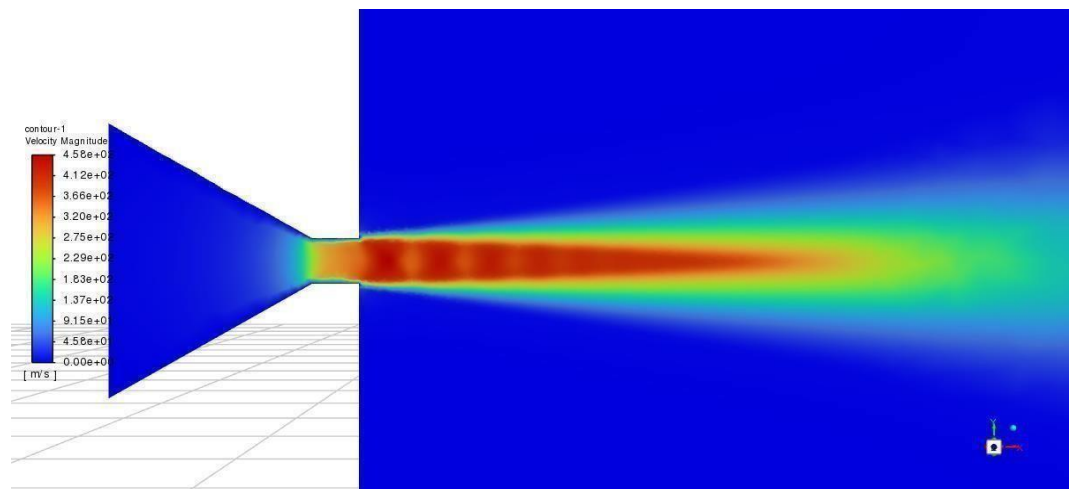


Fig: 4.15 : Circular nozzle of NPR 3

It represents the velocity contour of circular nozzle at NPR 3 and the maximum velocity obtained 458 m/s.

4.5.2 Nozzle with Cross-Wire (AR 25) with Different NPR

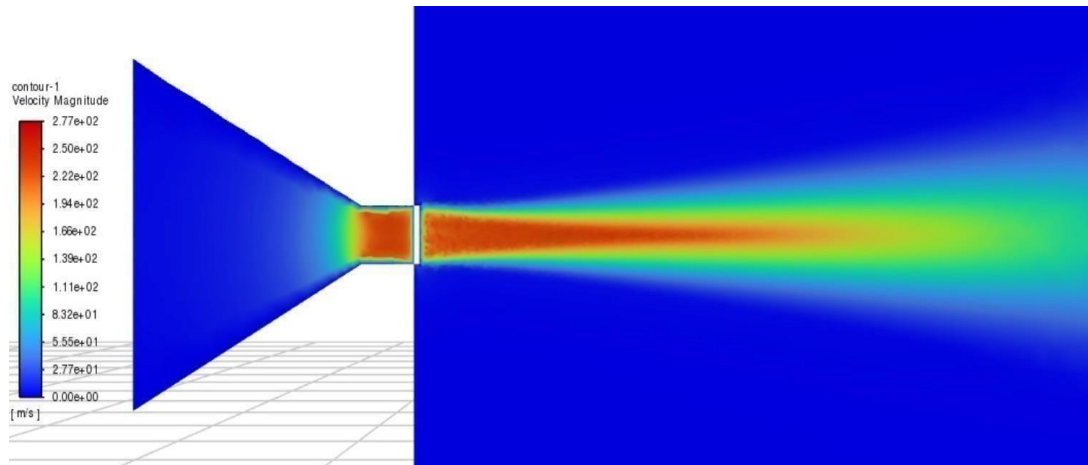


Fig: 4.16 : Nozzle with crosswire of NPR 1.5

It represents the velocity contour of Nozzle with crosswire AR25 at NPR 1.5 and the maximum velocity obtained 277 m/s.

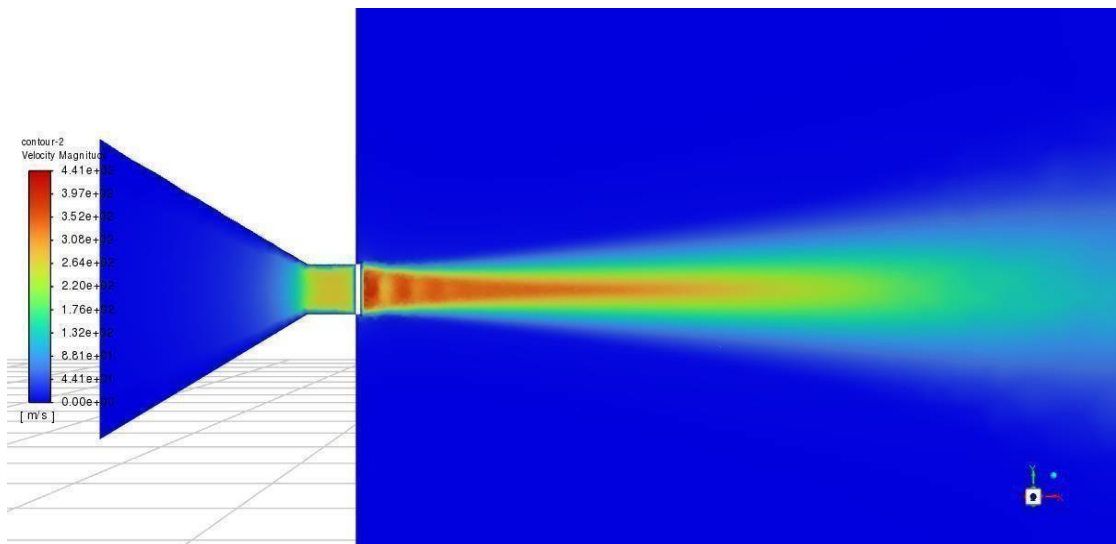


Fig: 4.17 : Nozzle with crosswire of NPR 2.5

It represents the velocity contour of Nozzle with crosswire AR25 at NPR 2.5 and the maximum velocity obtained 390 m/s.

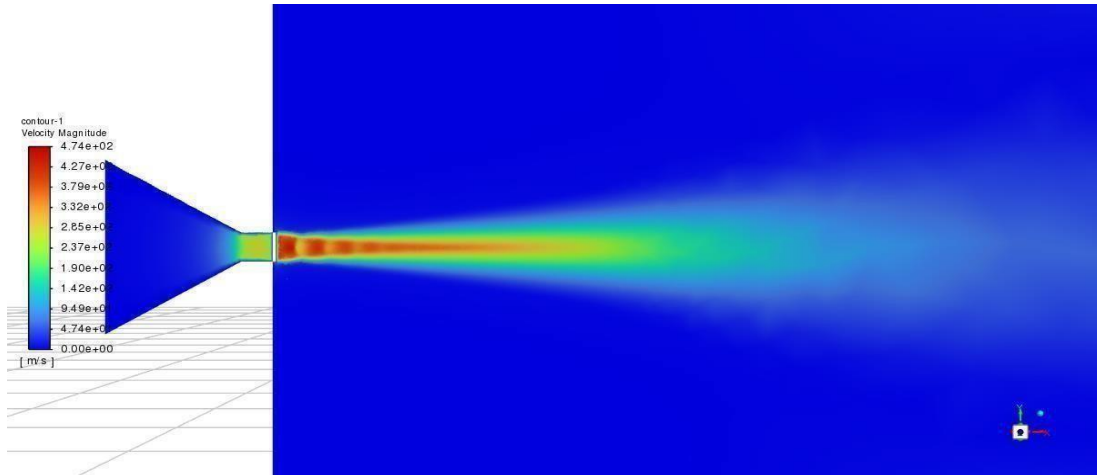


Fig:4.18 : Nozzle with crosswire of NPR 3

It represents the velocity contour of Nozzle with crosswire AR25 at NPR 3 and the maximum velocity obtained 474 m/s.

4.5.3 Nozzle with Tab (AR 16) with Different NPR

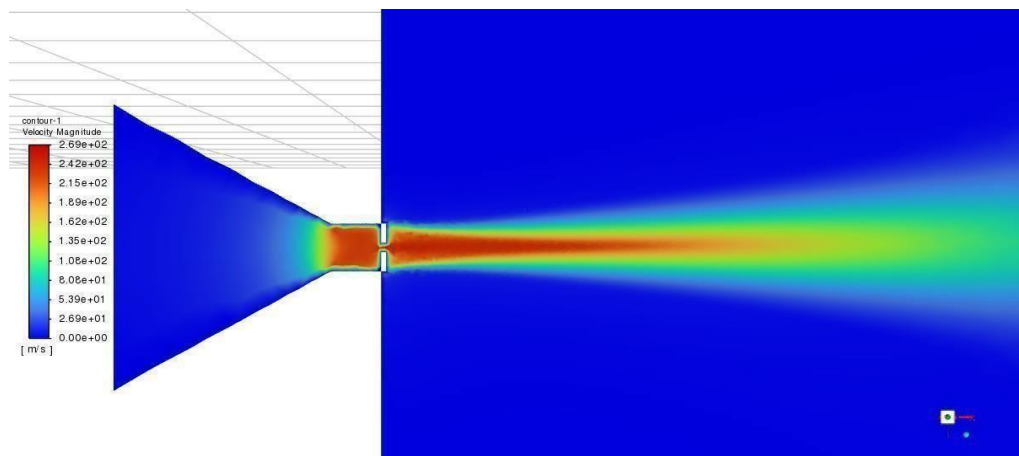


Fig: 4.19 : Nozzle with tab (AR 16) at NPR 1.5

It represents the velocity contour of Nozzle with Tab AR 16 at NPR 1.5 and the maximum velocity obtained 269 m/s.

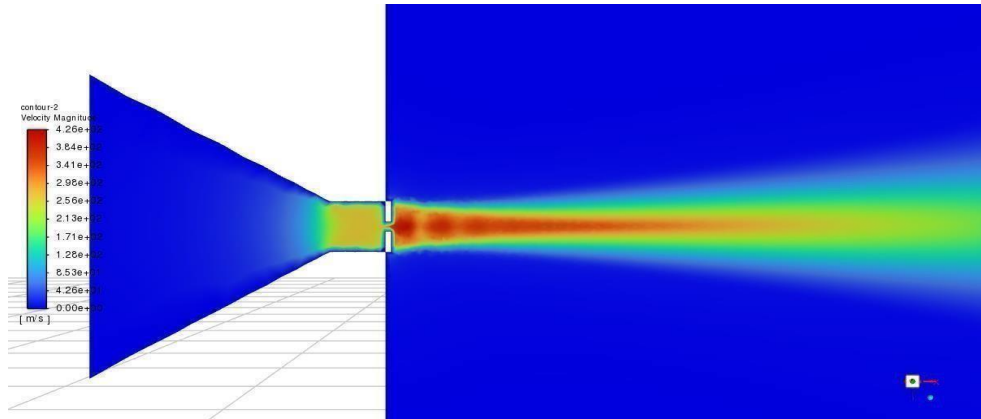


Fig: 4.20 : Nozzle with tab (AR 16) at NPR 2.5

It represents the velocity contour of Nozzle with Tab AR 16 at NPR 2.5 and the maximum velocity obtained 390 m/s.

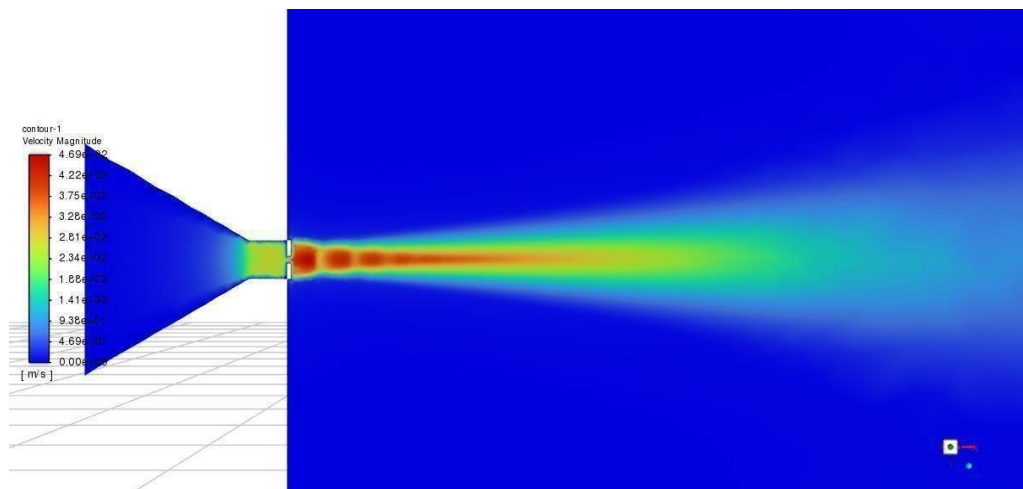


Fig: 4.21: Nozzle with tab (AR 16) at NPR 3

It represents the velocity contour of Nozzle with Tab AR 16 at NPR 3 and the maximum velocity obtained 469 m/s.

4.5.4 Nozzle with Tab (AR 10) with Different NPR

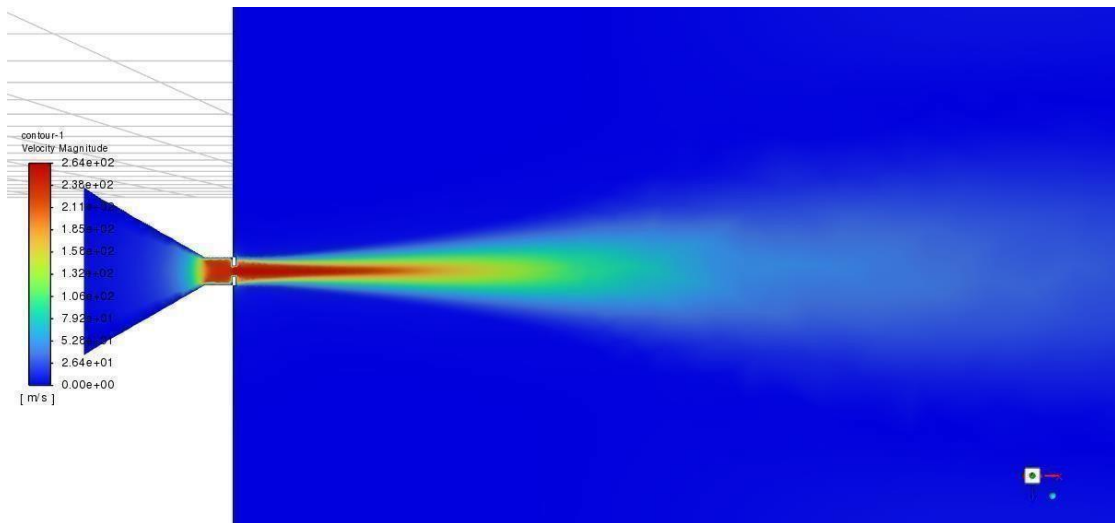


Fig: 4.22 : Nozzle with tab (AR 10) at NPR 1.5

It represents the velocity contour of Nozzle with Tab AR 10 at NPR 1.5 and the maximum velocity obtained 264 m/s.

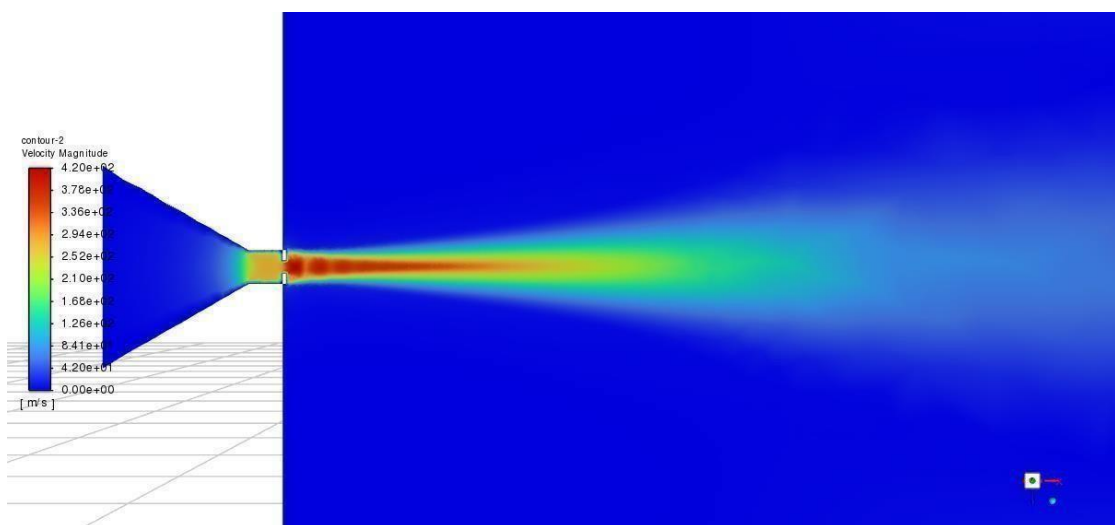


Fig: 4.23 : Nozzle with tab (AR 10) at NPR 2.5

It represents the velocity contour of Nozzle with Tab AR 10 at NPR 2.5 and the maximum velocity obtained 380 m/s.

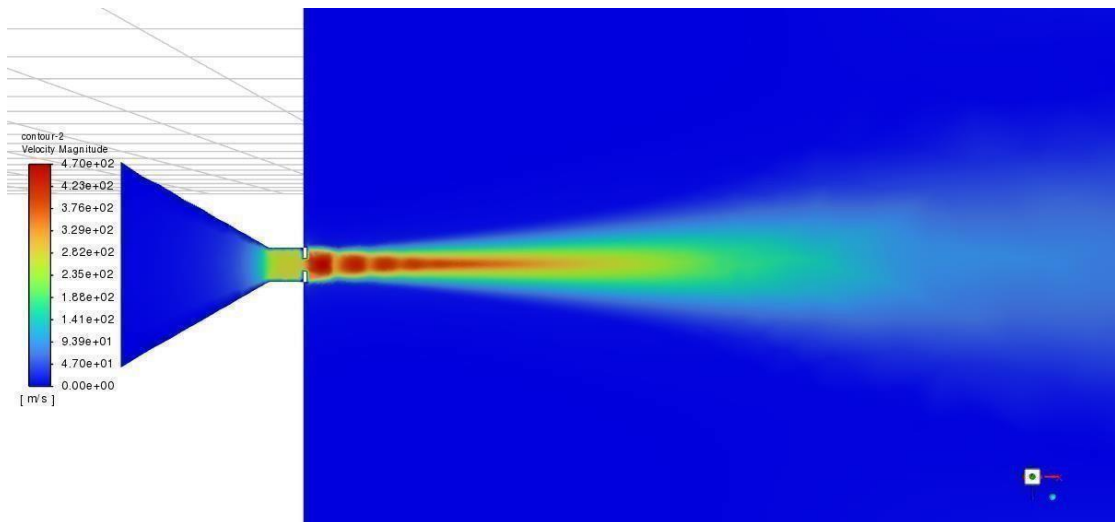


Fig: 4.24 : Nozzle with tab (AR 10) at NPR 3

It represents the velocity contour of Nozzle with Tab AR 10 at NPR 3 and the maximum velocity obtained 470 m/s.

CHAPTER 5

COMPUTATIONAL RESULT AND DISCUSSION

5.1 RESULTS OF CIRCULAR FREEJET AND CROSSWIRE OF ASPECT RATIO 25, 16, 10

From the computational analysis of circular nozzle with and without passive control were extracted from Ansys fluent CFD post processing to Microsoft excel. The values were calculated for (X/D) and (V/V_{max}) for the nozzles and crosswires for NPR 1.5, 2 and 3 and those values were displayed in form of scatter graph plots. The potential core values of circular nozzle and tabs of different aspect ratio were compared to determine the effective mixing of jet. Shorter the core length is more effective in increasing the mixing characteristics.

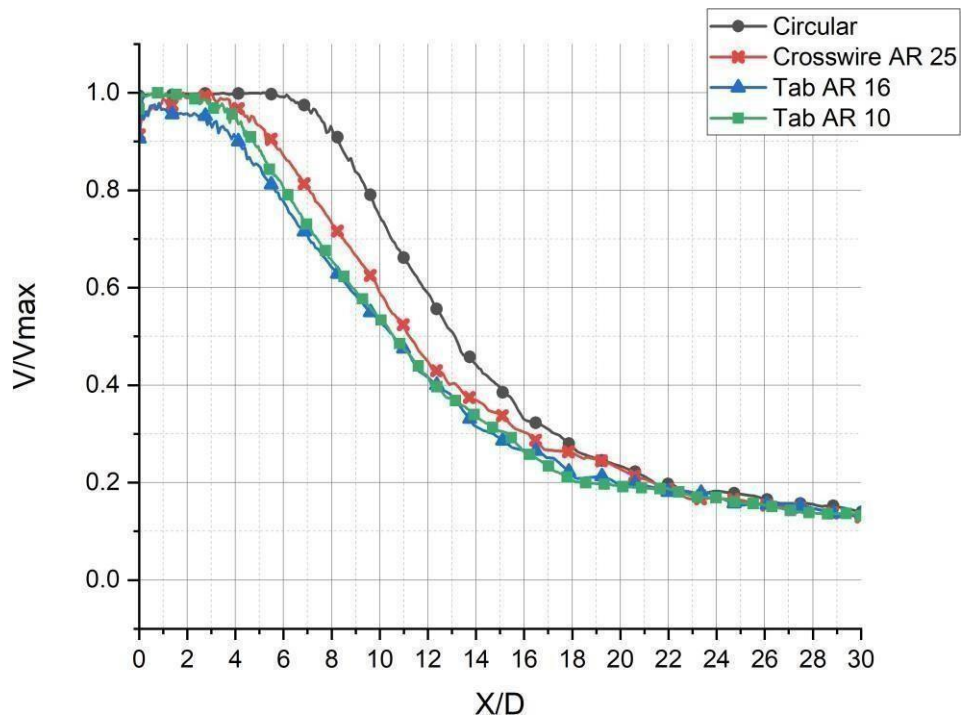


Fig: 5.1 : Potential decay graph of nozzle with crosswire of different aspect ratio at NPR 1.5

It represents that the Circular free jet, Crosswire of AR 25, Tab of AR 16 and Tab of AR 10 the core begins to decay at 6D, 4D, 3D and 3.5D respectively. From the above graph at NPR 1.5 it is clear that the Tab of AR 16 (8x0.5) the potential core started to decay rapidly compared to other Aspect ratio, at the same time Tab of AR 10 (6x0.6) mixed rapidly with atmosphere and reached the self-similar region soon compared to that of the Tab of AR 16.

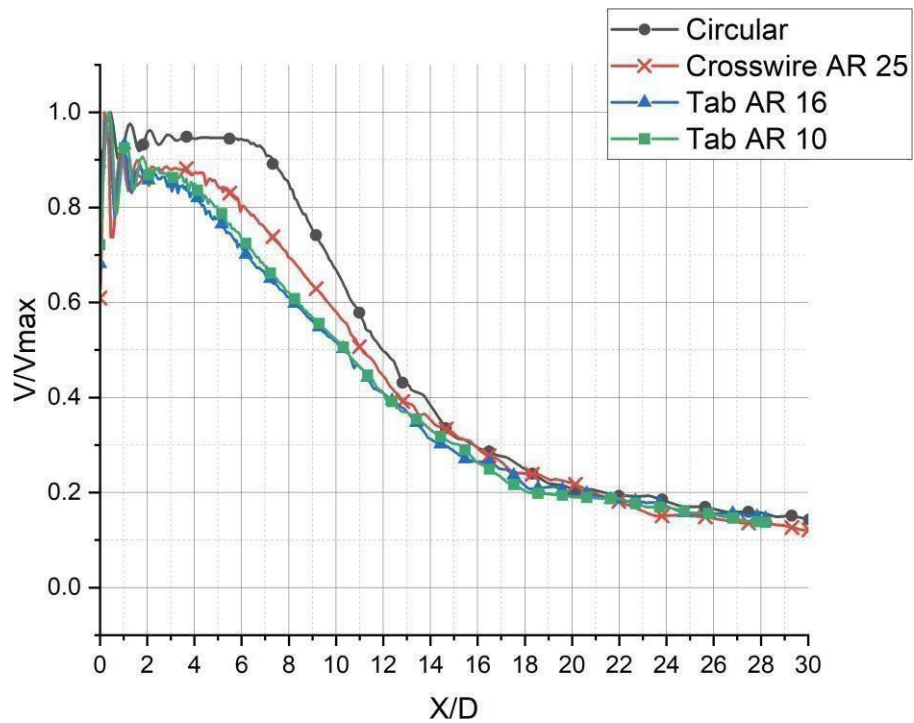


Fig:5.2 : Characteristic decay graph of nozzle with crosswire of different aspect ratio at NPR 2.5

It represents that the Circular free jet, Crosswire of AR 25, Tab of AR 16 and Tab of AR 10 the core begins to decay at 7D, 5D, 4D and 4D respectively. From the above graph at NPR 2.5 the oscillations in the graph shows the formation of weak shock structures as the NPR is low. In NPR 2.5 Tab of AR 16 (8x0.5) and Tab of AR 10 (6x0.6) started to decay at 4D and diffused the shock cell formation. But compared to AR 16 the Tab of AR 10 mixed rapidly with atmosphere and reached the self-similar region faster than AR 16.

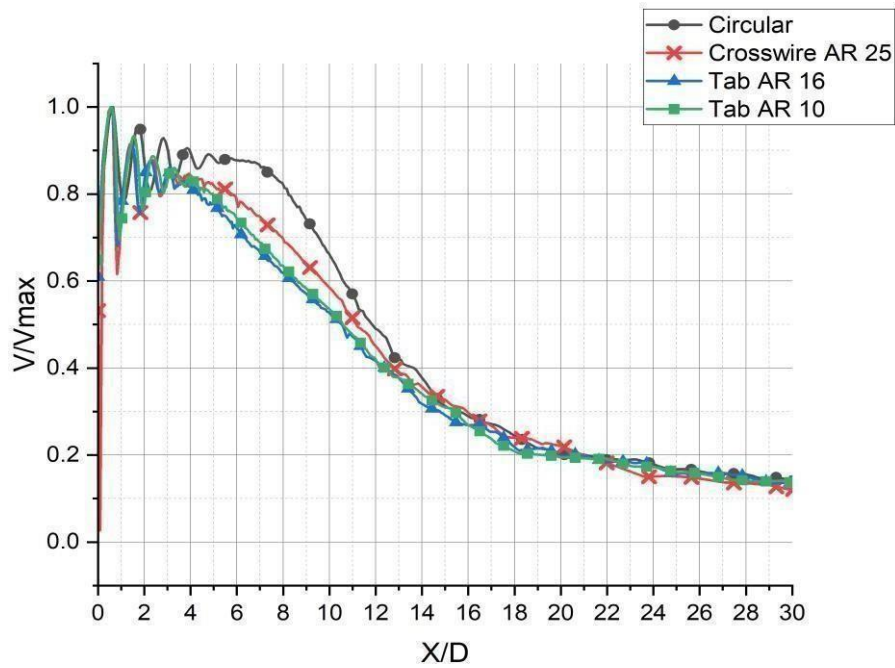


Fig:5.3 : Characteristic decay graph of nozzle with crosswire of different aspect ratio at NPR 3

It shows that as the NPR increases the formation of shock cells increases and it increased the duration of characteristic decay to begin. The graph represents that the Circular free jet, Crosswire of AR 25, Tab of AR 16 and Tab of AR 10 the core begins to decay at 8D, 6D, 4.5D and 5D respectively. From the above graph at NPR 3 the oscillations in the graph show the formation of weak shock structures as the NPR is high. In NPR 3 Tab of AR16 (8x0.5) started to decay at 4.5D and the Tab of AR 10 (6x0.6) at 5D.

5.1.1 Conclusion From the Graphs

From the above graphs it is clear that as the NPR increases the core region and it decreases the rate of mixing of jet with atmospheric air leading to poor entrainment. The study of placing the passive control of different aspect ratios it is clearly found that compared to crosswire of AR 25 the Tab of AR 16 and AR 10 enhanced the jet mixing, especially the tab of AR 16 reduced the core length and promoted the entrainment of the jet with the atmosphere and diffusion of shock cell structure.

5.2 VELOCITY PROFILE OF NOZZLE WITH AND WITHOUT CROSSWIRE AT VARIOUS NPR

Velocity profile refers to the region where the velocity of the fluid is constant resembling the tophat shape, it is also called tophat profile. Velocity profiles were extracted from Ansys fluent software and the data was plotted in Origin pro.

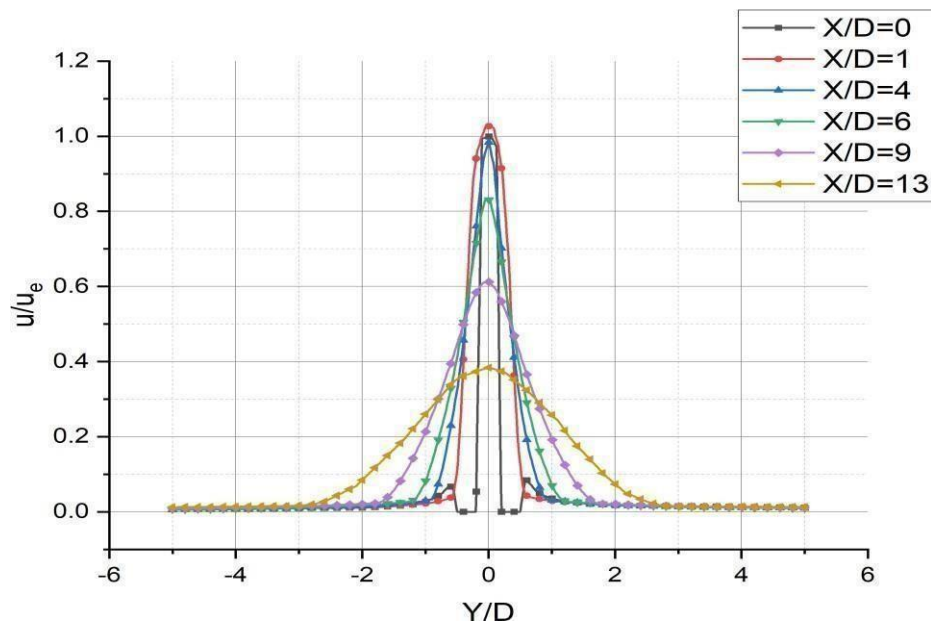


Fig: 5.4 : Velocity profile of circular nozzle at various distance at NPR 1.5

From the above figure 5.4 it is clear that the velocity profile (Top hat) decreases with increase in $X/D=1$.

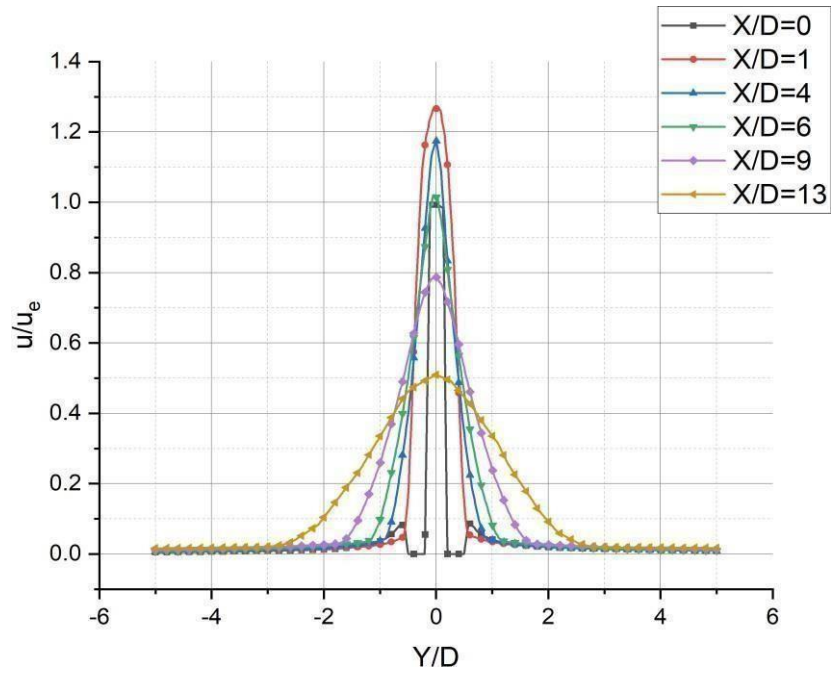


Fig:5.5 : Velocity profile of nozzle at various distance at NPR 2.5

From the above figure 5.5 it is clear that the velocity profile (Top hat) decreases with increase in $X/D=1$.

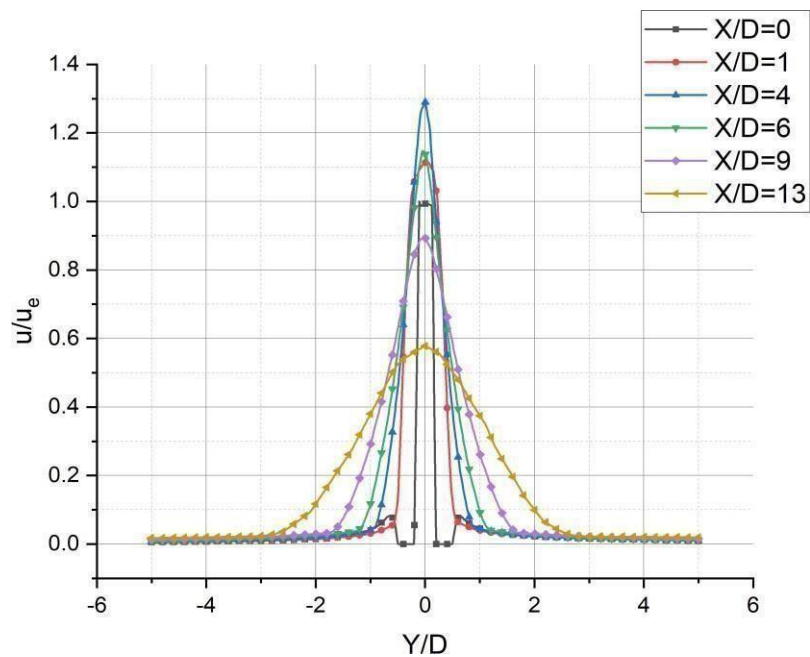


Fig:5.6 : Velocity profile of circular nozzle at various distance at NPR 3

From the above figure 5.6 it is clear that the velocity profile (Top hat) decreases with increase in $X/D=4$.

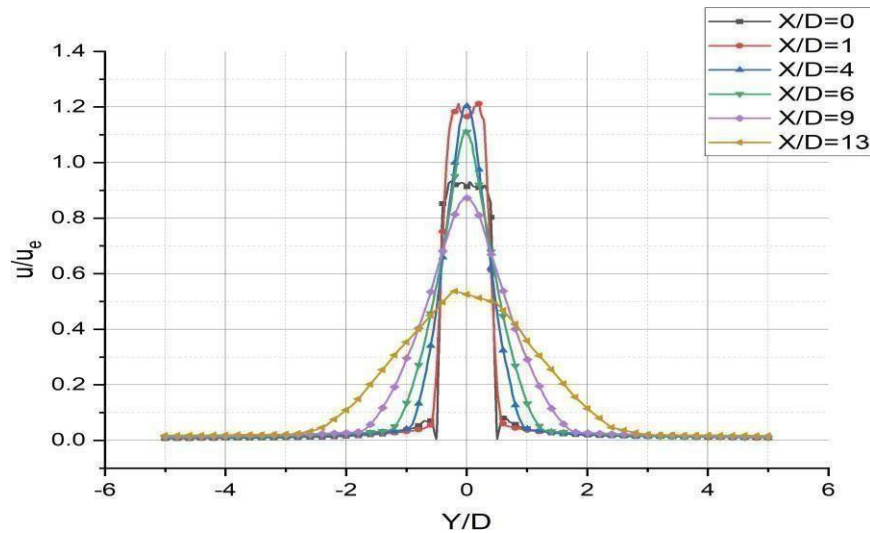


Fig: 5.7 : Velocity profile of nozzle with crosswire (AR 25) at various distance at NPR 1.5

From the above figure 5.7 it is clear that the velocity profile (Top hat) of nozzle with crosswire AR 25 decreases with increase in $X/D=1$.

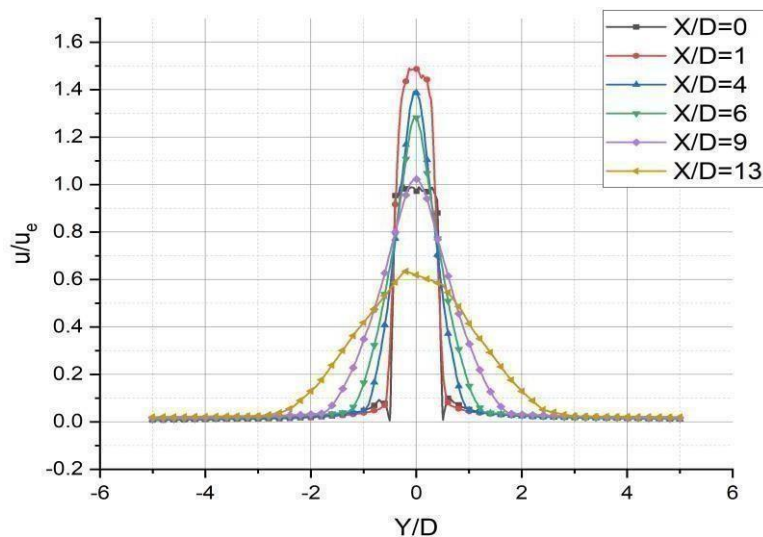


Fig:5.8 : Velocity profile of circular with crosswire (AR 25) at various distance at NPR 2.5

From the above figure 5.8 it is clear that the velocity profile (Top hat) of nozzle with crosswire AR 25 decreases with increase in $X/D=1$.

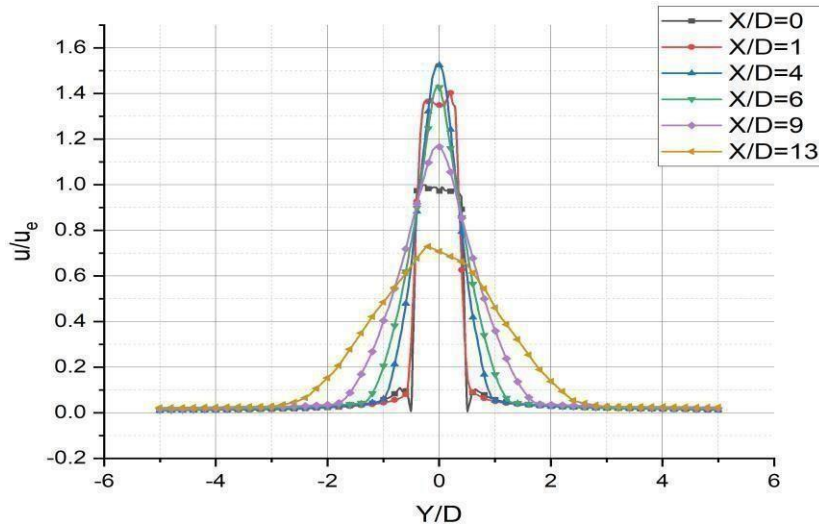


Fig:5.9 : Velocity profile of nozzle with crosswire (AR 25) at various distance at NPR 3

From the above figure 5.9 it is clear that the velocity profile (Top hat) of nozzle with crosswire AR 25 decreases with increase in $X/D=4$.

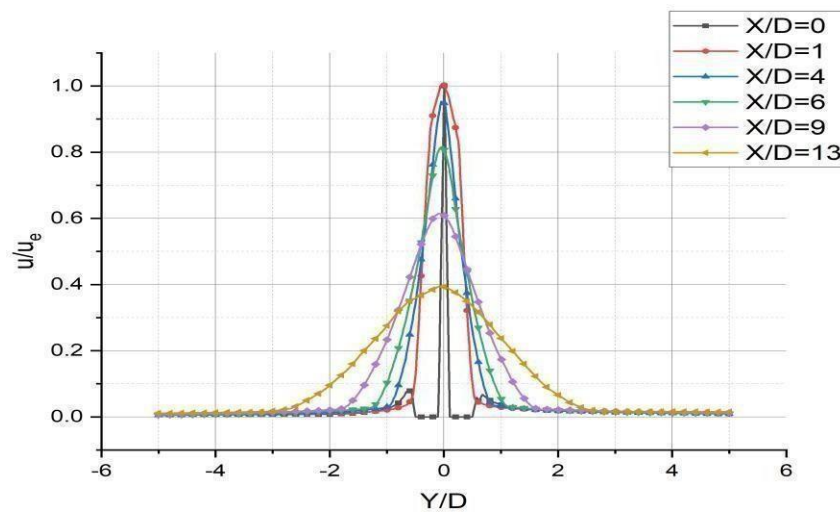


Fig: 5.10 : Velocity profile of nozzle with Tab (AR 16) at various distance at NPR 1.5

From the above figure 5.10 it is clear that the velocity profile (Top hat)of nozzle with crosswire AR 16 decreases with increase in $X/D=1$.

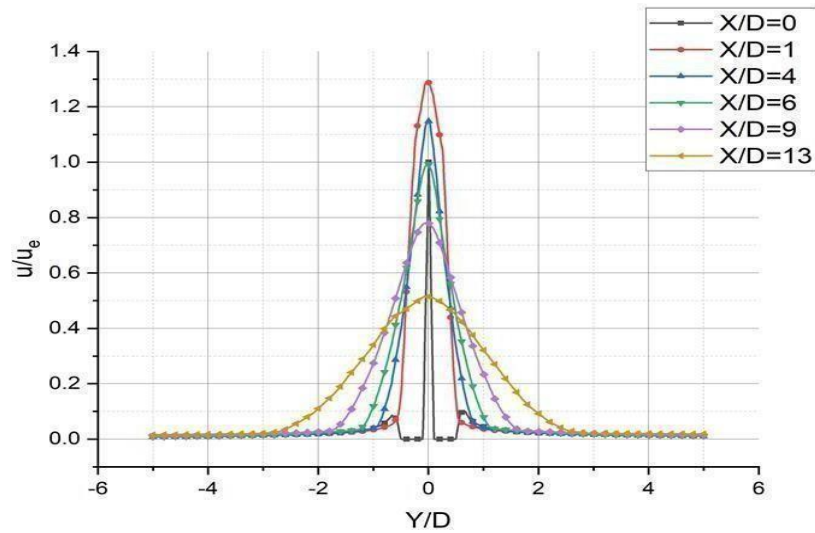


Fig: 5.11 : Velocity profile of nozzle with Tab (AR 16) at various distance at NPR 2.5

From the above figure 5.11 it is clear that the velocity profile (Top hat)of nozzle with Tab AR 16 decreases with increase in $X/D=1$.

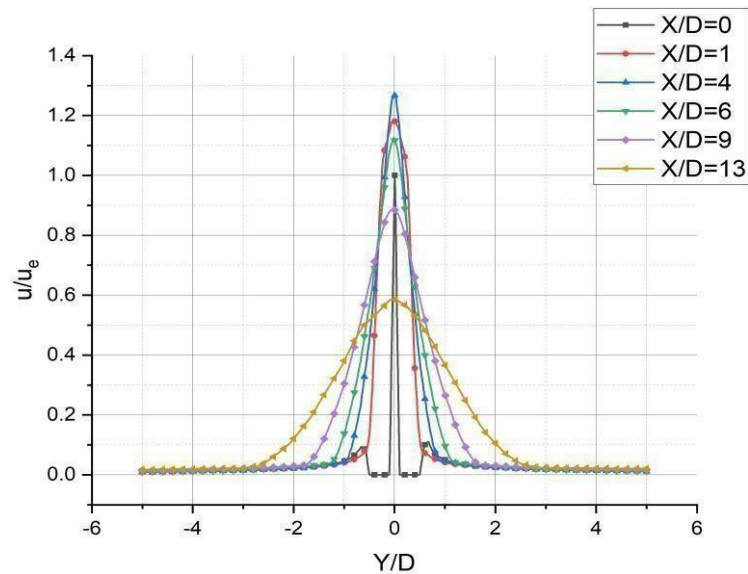


Fig: 5.12 : Velocity profile of nozzle with crosswire (AR 16) at various distance at NPR 3

From the above figure 5.12 it is clear that the velocity profile (Top hat)of nozzle with Tab AR 16 decreases with increase in $X/D=4$.

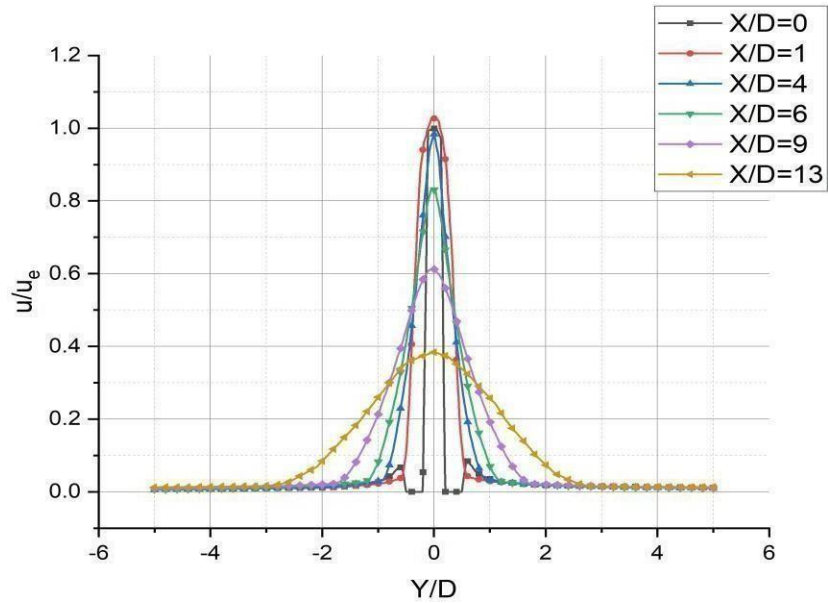


Fig:5.13 : Velocity profile of nozzle with crosswire (AR 10) at various distance at NPR 1.5.

From the above figure 5.13 it is clear that the velocity profile (Top hat)of nozzle with Tab AR 10 decreases with increase in $X/D=1$.

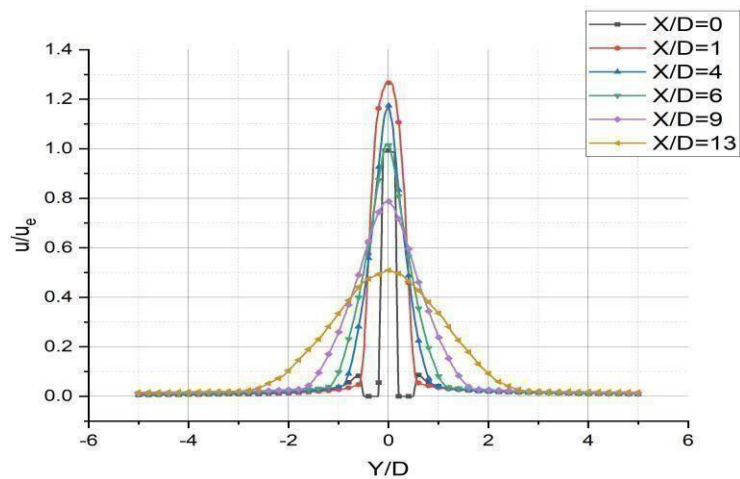


Fig: 5.14 : Velocity profile of nozzle with crosswire (AR 10) at various distance at NPR 2.5

From the above figure 5.14 it is clear that the velocity profile (Top hat) of nozzle with crosswire AR 10 decreases with increase in $X/D=1$.

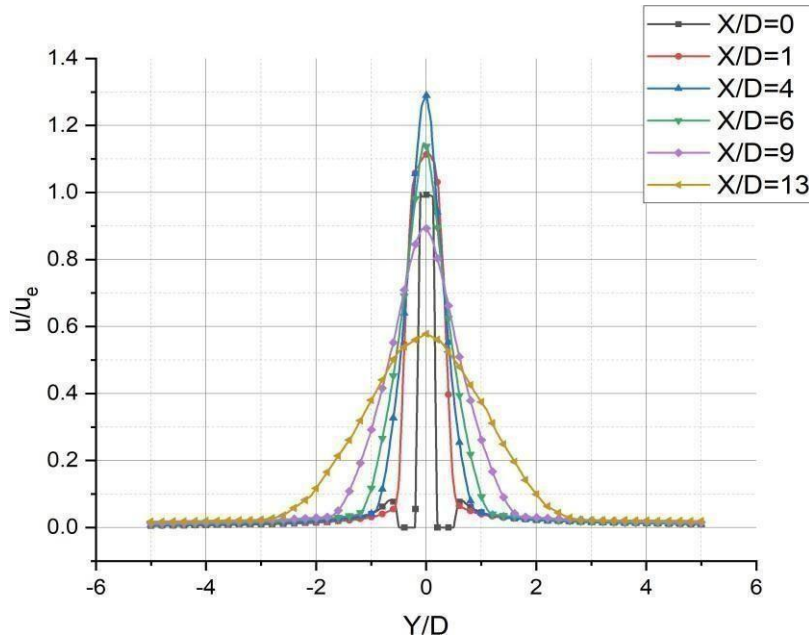


Fig:5.15 : Velocity profile of nozzle with crosswire (AR 10) at various distance at NPR 3

From the above figure 5.15 it is clear that the velocity profile (Top hat) of nozzle with crosswire AR 10 decreases with increase in $X/D=4$.

5.3 ISOMACH CONTOUR FOR CIRCULAR NOZZLE WITH AND WITHOUT TAB AT VARIOUS NPR

Isomach contour refers to a contour representing regions of equal or constant Mach number. Isomach contours are used to visualize the Mach number distribution from the nozzle at various distance. Isomach contours were extracted from solution data of Ansys fluent and were plotted in Tecplot 360 software.

5.3.1 Isomach Contour For Circular Nozzle With And Without Tab At NPR 1.5

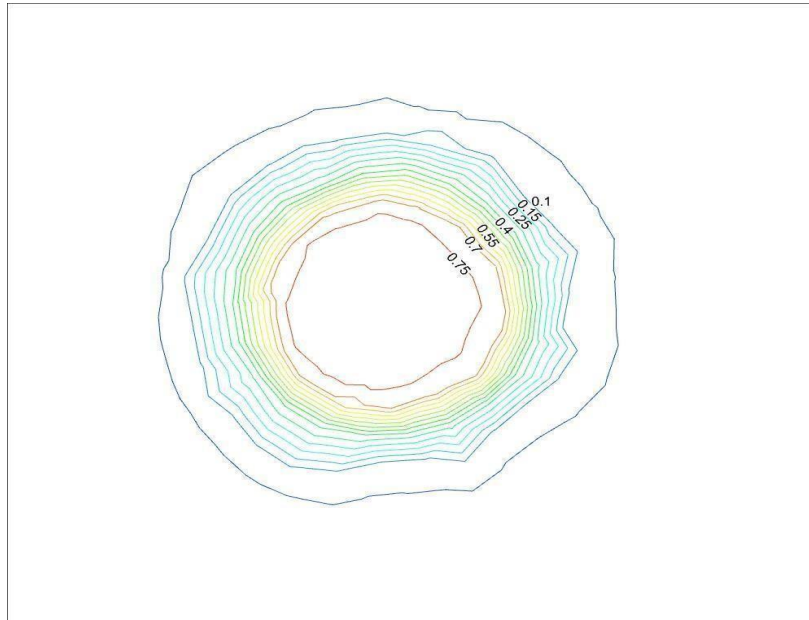


Fig:5.16 : Isomach contour of circular nozzle at $X/D=0$

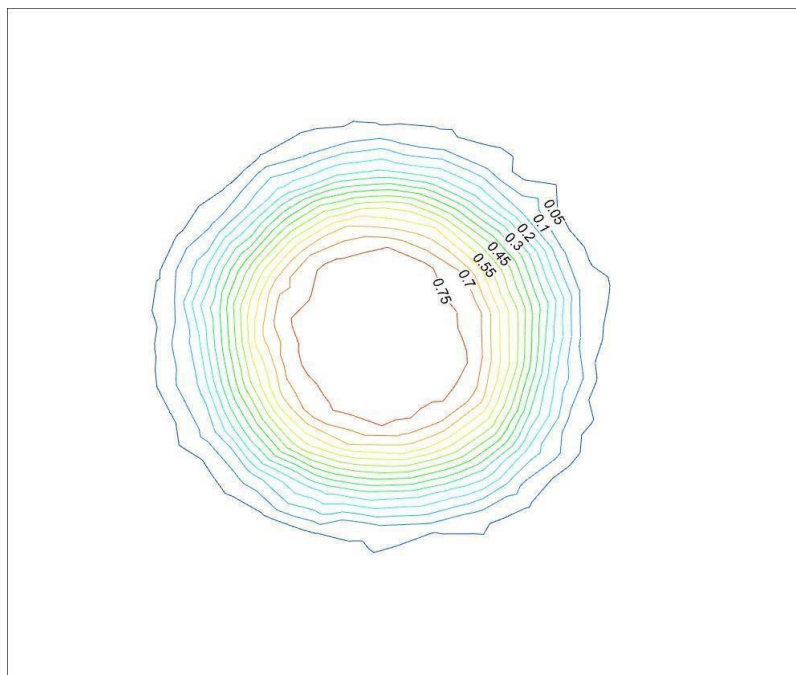


Fig: 5.17 : Isomach contour of circular nozzle at $X/D=1$

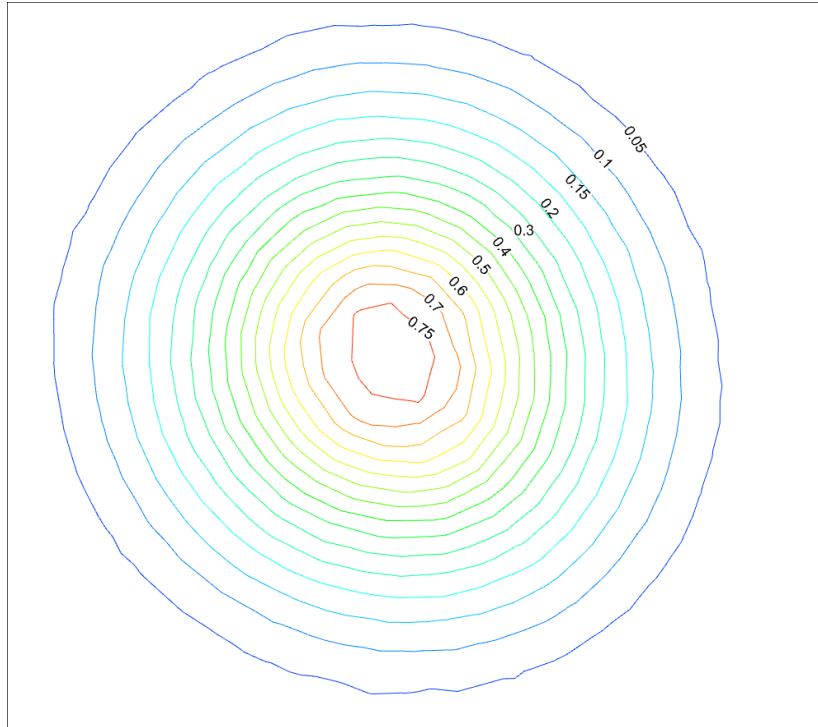


Fig: 5.18: Isomach contour of circular nozzle at $X/D=4$

Figure 5.16 to 5.18 represents the isomach contour of circular nozzle at various distance of $X/D=0, 1, 4$ at NPR 1.5.

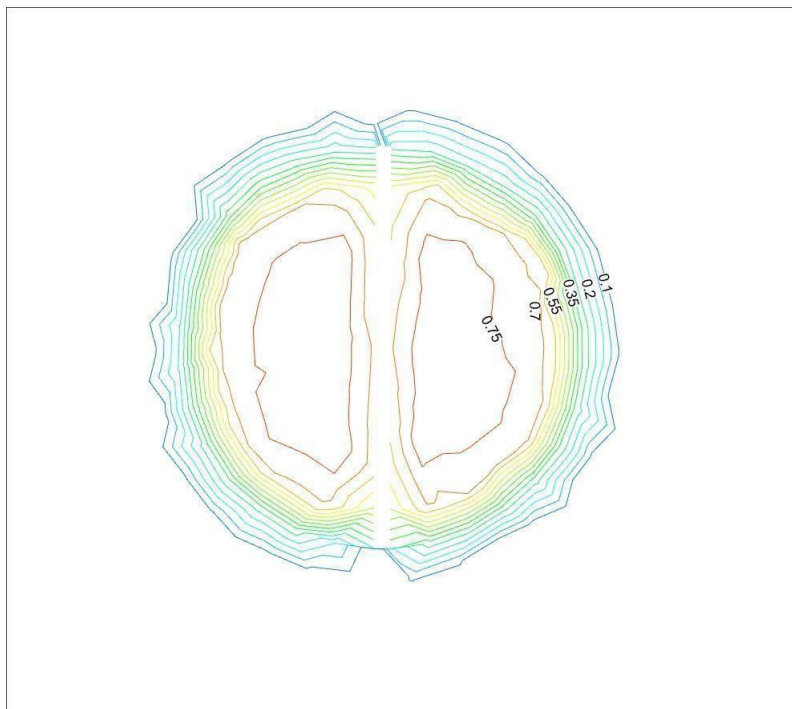


Fig: 5.19 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D=0$

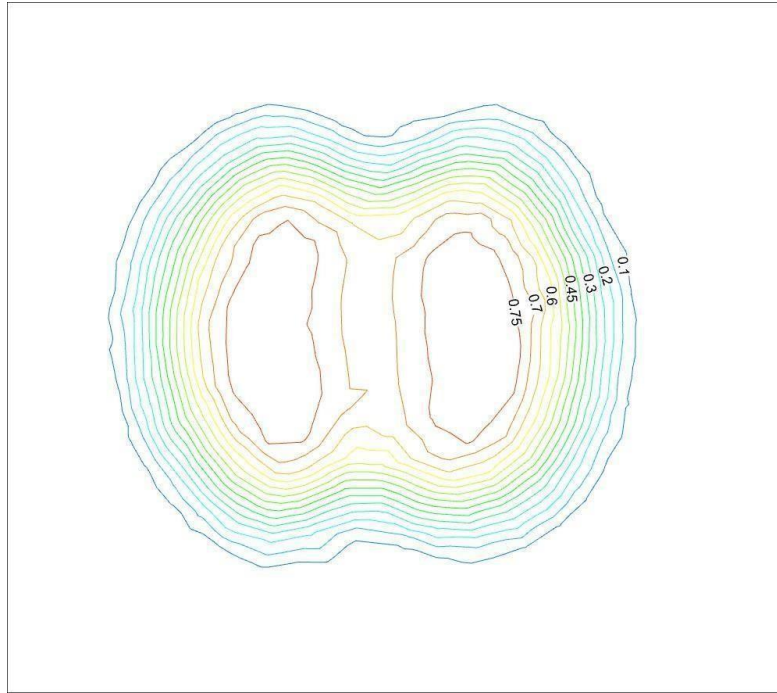


Fig: 5.20 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D=1$

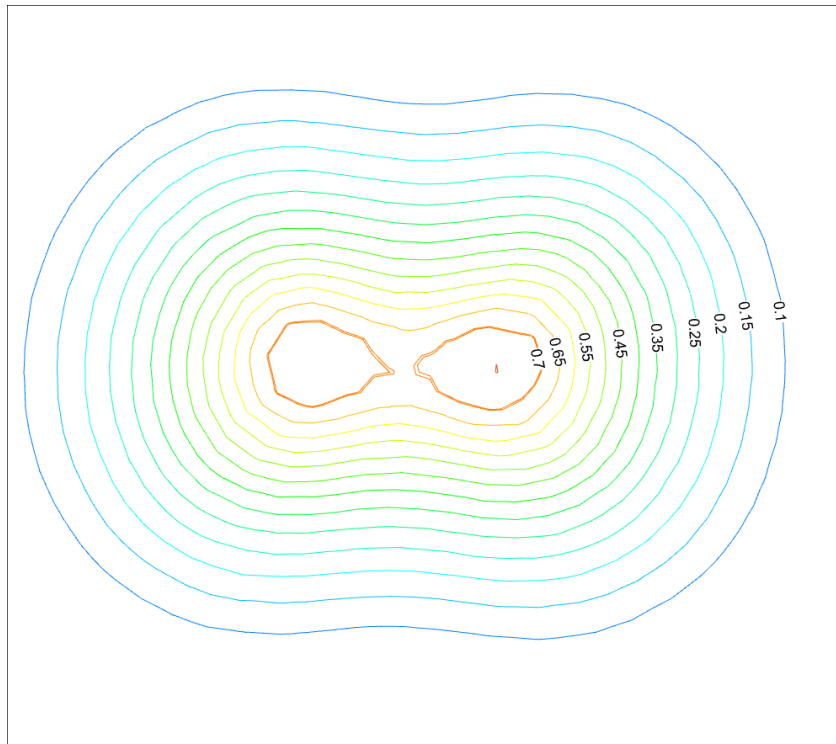


Fig: 5.21 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D=4$

Figure 5.19 to 5.21 represents the isomach contour of circular nozzle with cross-wire (AR 25) at various distance of $X/D=0, 1, 4$ at NPR 1.5.

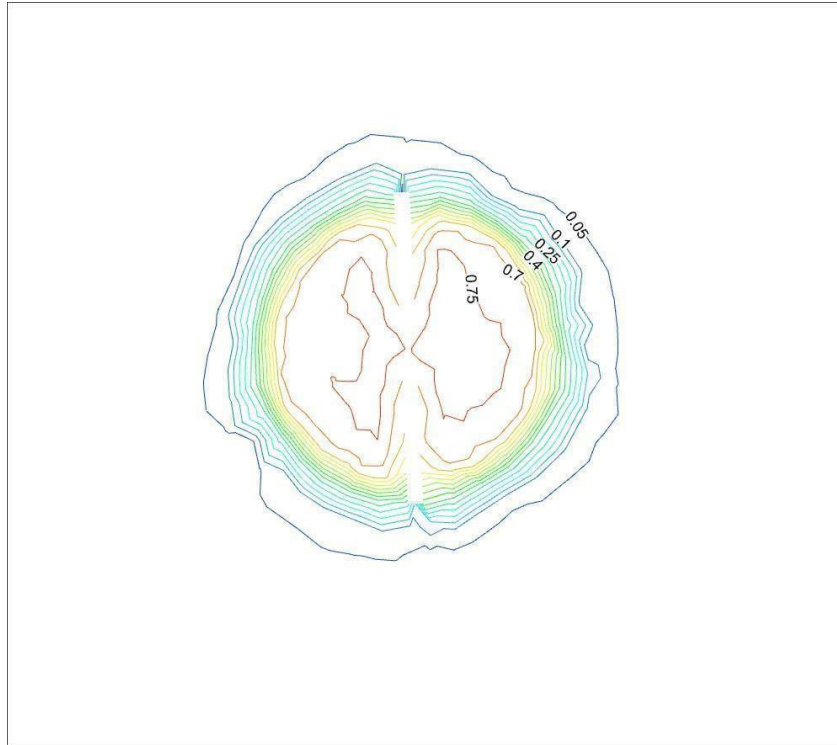


Fig: 5.22 : Isomach contour of nozzle with tab (AR 16) at $X/D=0$

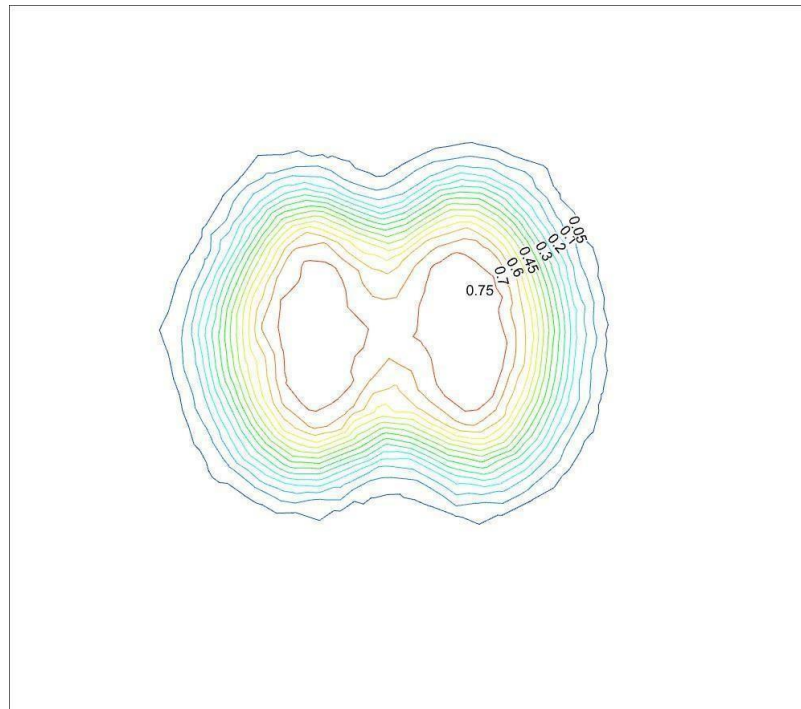


Fig:5.23 : Isomach contour of nozzle with tab (AR 16) at $X/D=1$

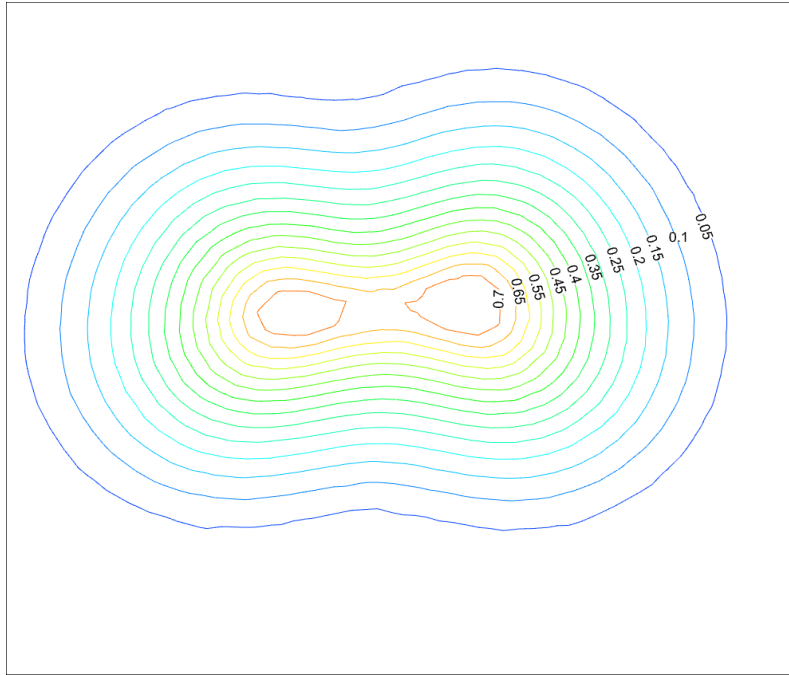


Fig:5.24 : Isomach contour of nozzle with tab (AR 16) at $X/D=4$

Figure 5.22 to 5.24 represents the isomach contour of circular nozzle with tab (AR 16) at various distance of $X/D=0, 1, 4$ at NPR 1.5.

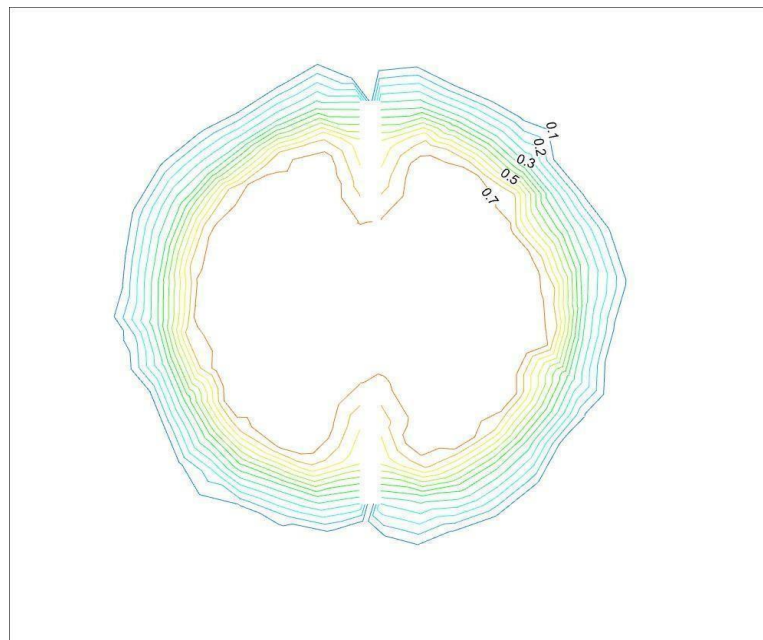


Fig: 5.25 : Isomach contour of nozzle with tab (AR 10) at $X/D=0$

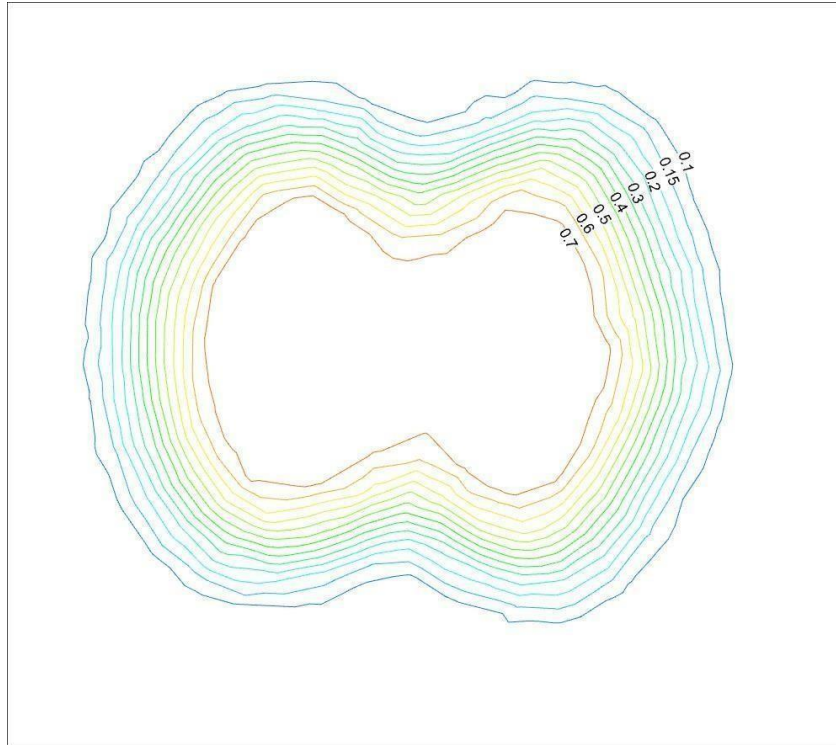


Fig: 5.26 : Isomach contour of nozzle with tab (AR 10) at $X/D=1$

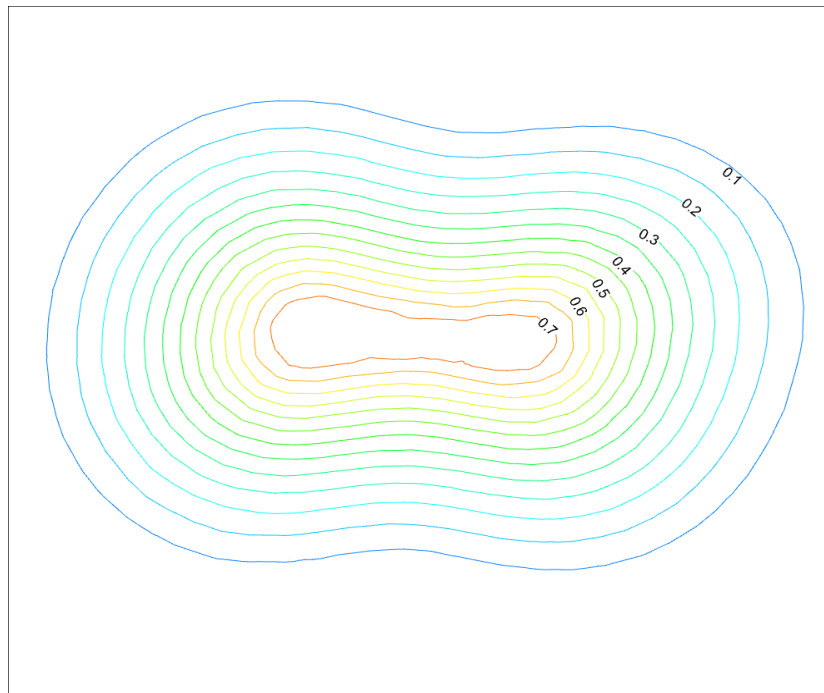


Fig: 5.27 : Isomach contour of nozzle with tab (AR 10) at $X/D=4$

Figure 5.25 to 5.27 represents the isomach contour of circular nozzle with (AR 10) at various distance of $X/D=0, 1, 4$ at NPR 1.5.

5.3.2 Isomach Contour For Circular Nozzle With And Without Tab At NPR 2.5



Fig:5.28 : Isomach contour of circular nozzle at $X/D=0$

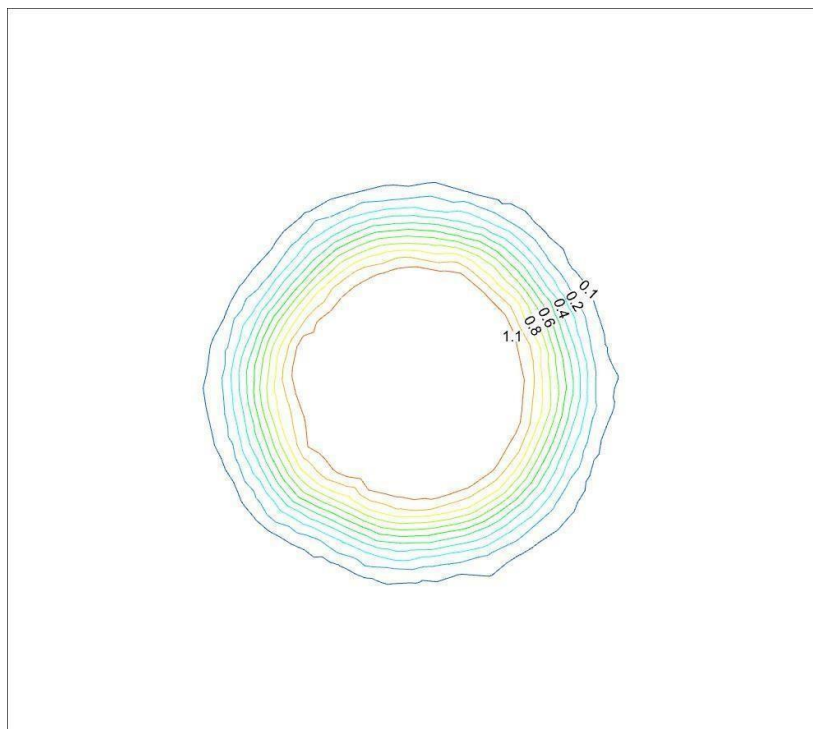


Fig:5.29 : Isomach contour of circular nozzle at $X/D=1$

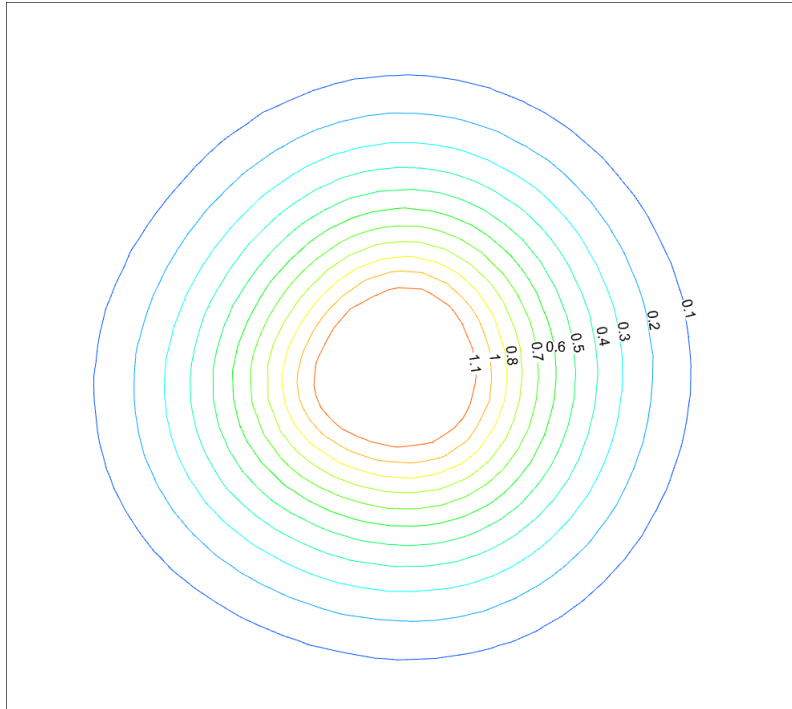


Fig: 5.30 : Isomach contour of circular nozzle at $X/D=4$

Figure 4.28 to 4.30 represents the isomach contour of circular nozzle at various distance of $X/D=0, 1, 4$ at NPR 2.5.

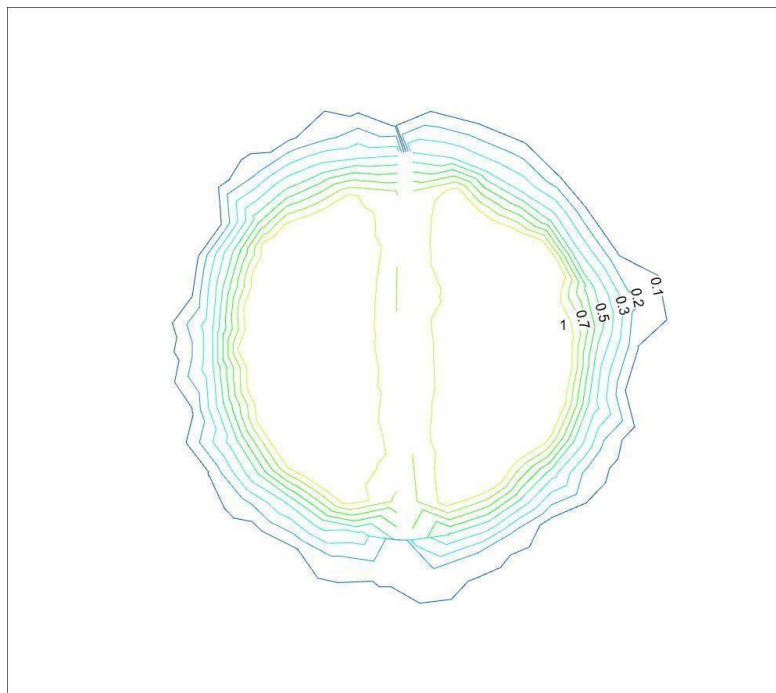


Fig: 5.31 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D=0$

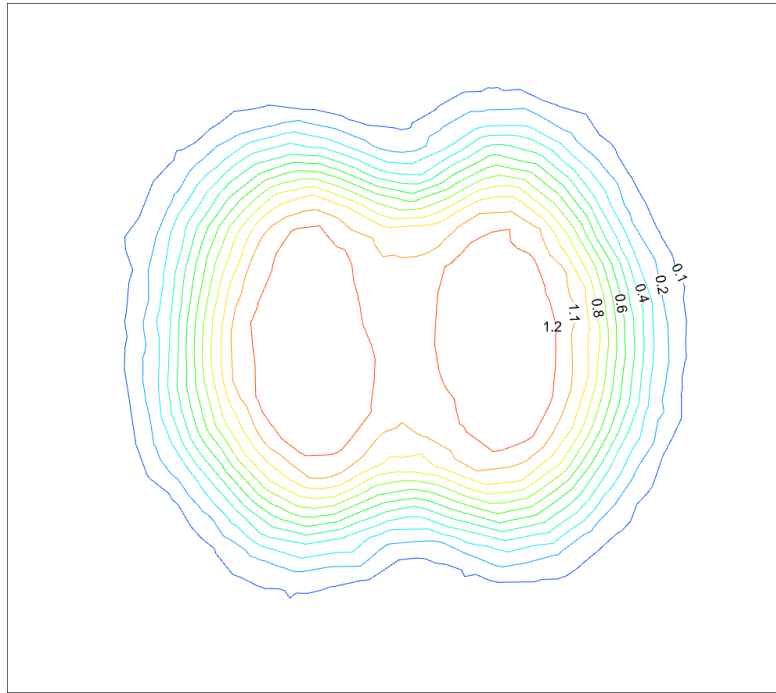


Fig:5.32 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D= 1$

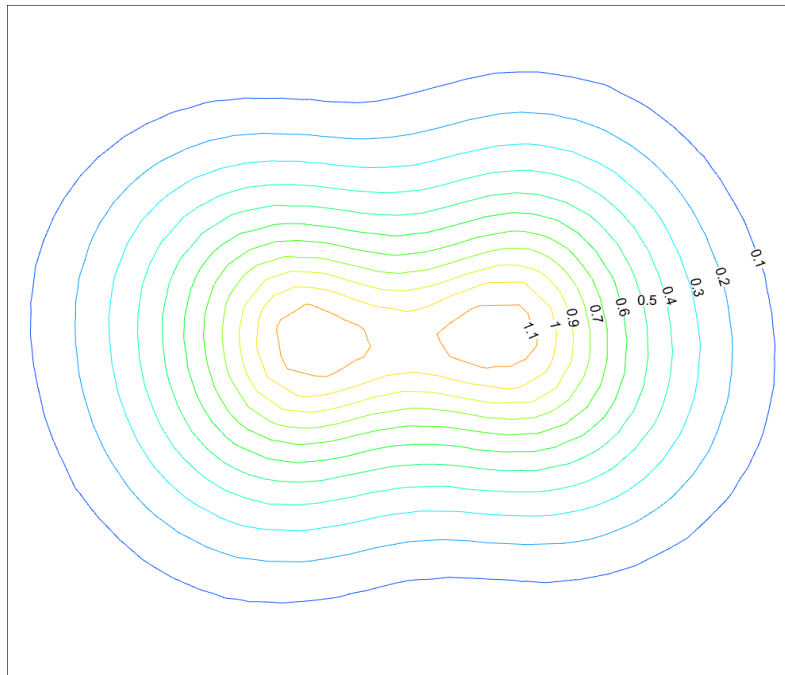


Fig: 5.33 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D= 4$

Figure 5.31 to 5.33 represents the isomach contour of circular nozzle with cross-wire (AR 25) at various distance of $X/D= 0, 1, 4$ at NPR 2.5.

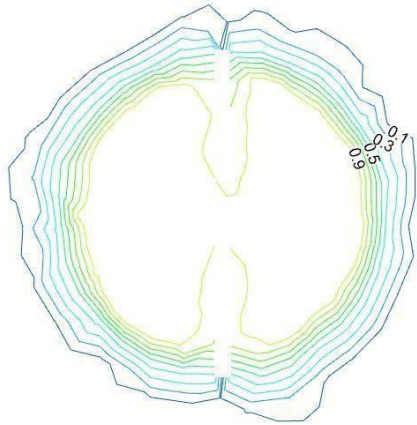


Fig: 5.34 : Isomach contour of nozzle with tab (AR 16) at $X/D=0$

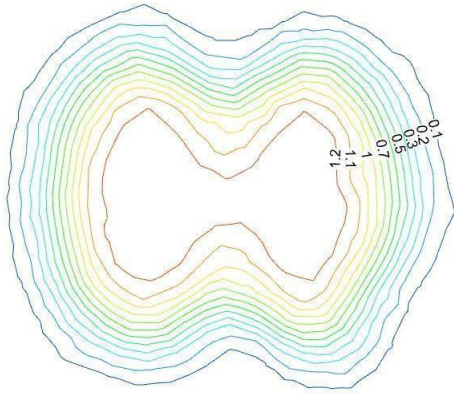


Fig: 5.35 : Isomach contour of nozzle with tab (AR 16)

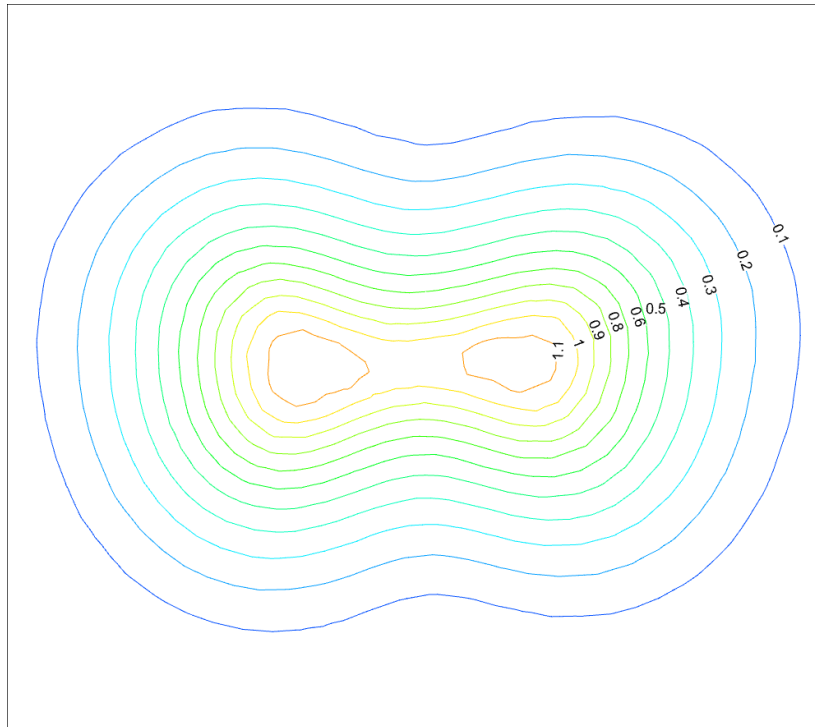


Fig: 5.36 : Isomach contour of nozzle with tab (AR 16) at $X/D=4$

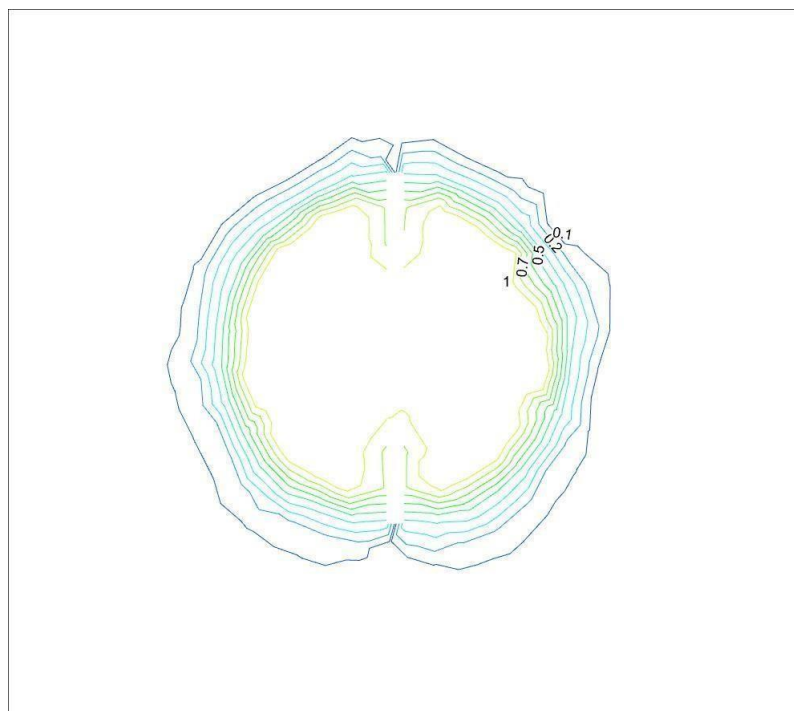


Fig:5.37 : Isomach contour of nozzle with tab (AR 10) at $X/D=0$

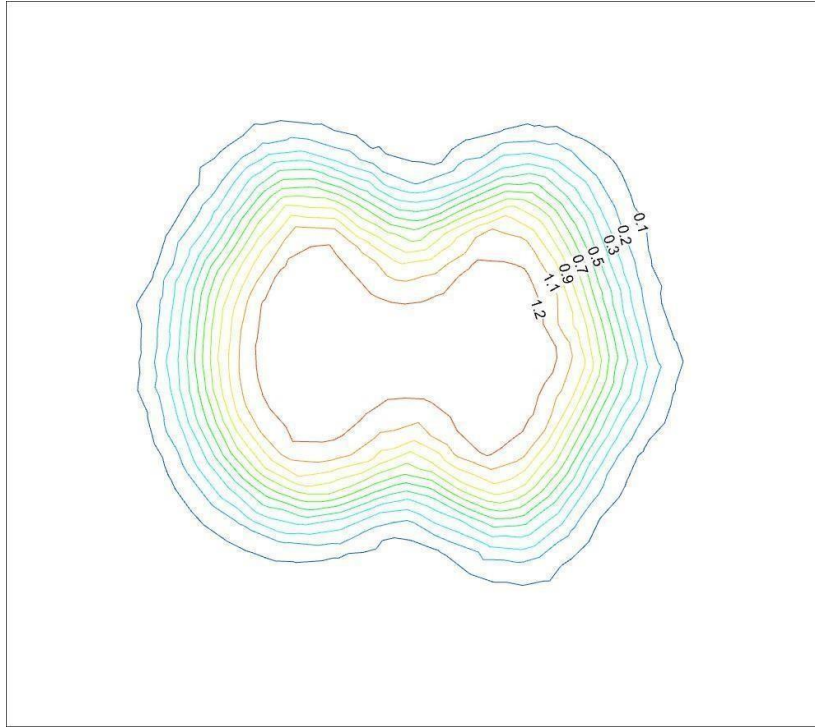


Fig:5.38 : Isomach contour of nozzle with tab (AR 10) at $X/D=1$

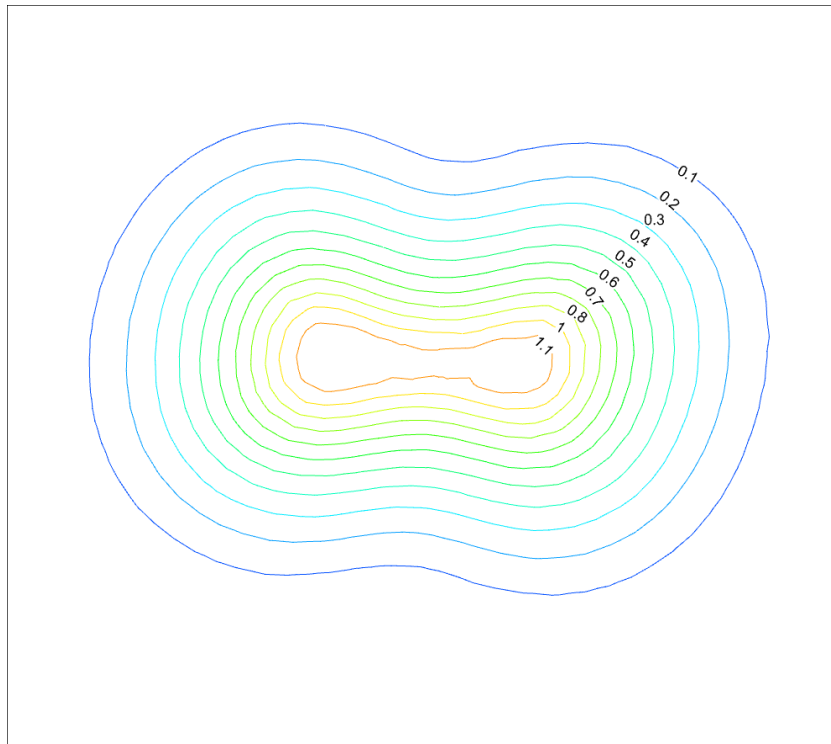


Fig:5.39 : Isomach contour of nozzle with tab (AR 10) at $X/D=4$

Figure 4.37 to 4.39 represents the isomach contour of circular nozzle with tab (AR 10) at various distance of $X/D=0, 1, 4$ at NPR 2.5.

5.3.3 Isomach Contour For Circular Nozzle With And Without Tab At NPR 3

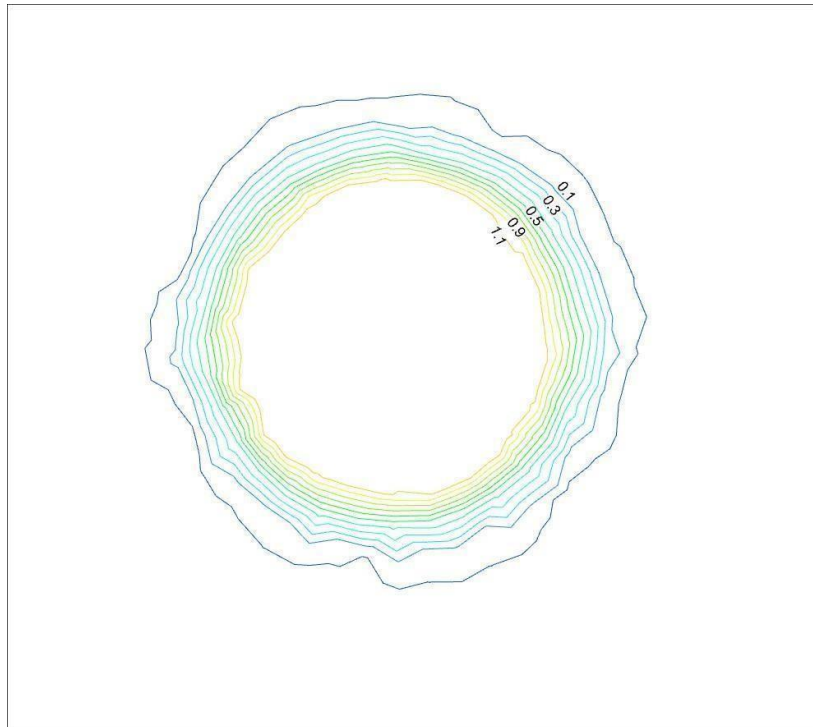


Fig: 5.40 : Isomach contour of circular nozzle at $X/D=0$

Figure 5.40 the term "isomach contour" refers to a contour line representing equal Mach numbers in a flow field. In this context, " $X/D=0$ " likely refers to a location Along the axis of a circular nozzle, where " X " is the distance along the axis and is the diameter of the nozzle. So, "isomach contour of circular nozzle at $X/D=0$ " would mean the contour line showing regions of equal Mach numbers at a specific location along the axis of a circular nozzle, where the distance from the nozzle exit plane normalized by the diameter of the nozzle. This contour provides information about the distribution of Mach numbers in the flow at that particular location.

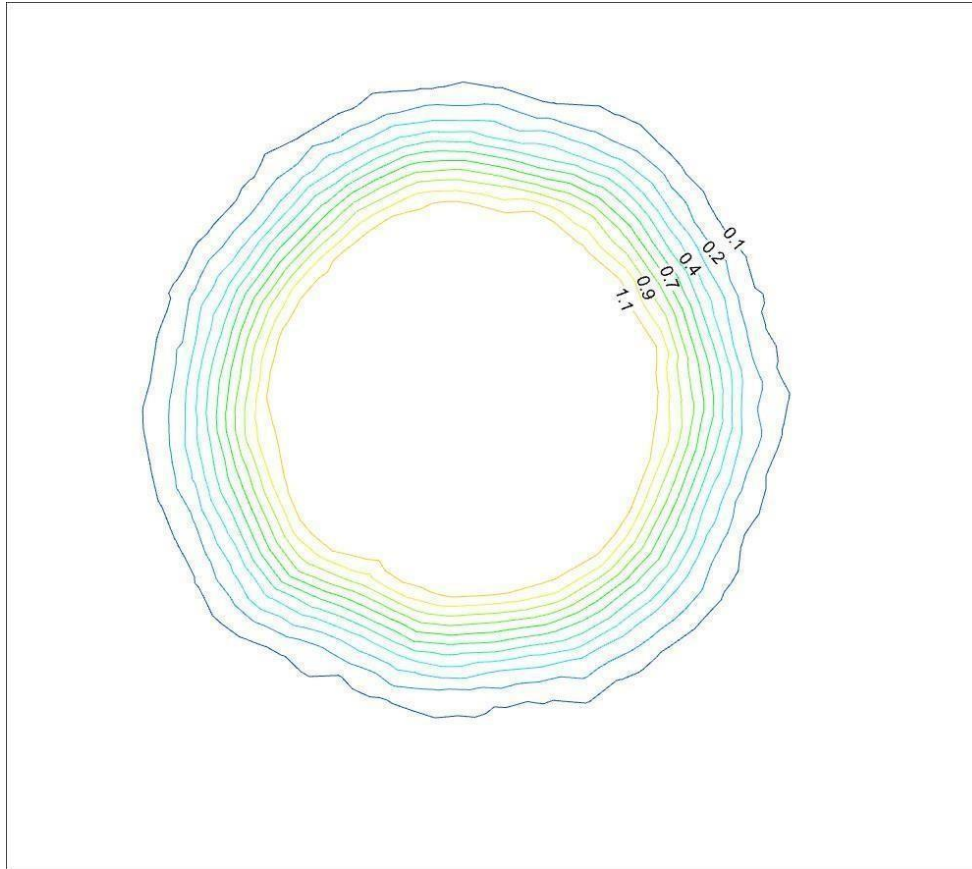


Fig: 5.41 : Isomach contour of circular nozzle at $X/D=1$

Figure 5.41 the term "Isomach contour" refers to lines of constant Mach. In the context of a circular nozzle at $X/D=1$, where X is the distance from the nozzle exit and D is the diameter of the nozzle, it means observing Mach number distribution at a specific location along the nozzle's length. For example, at $X/D=1$, you're looking at the Mach number distribution at a distance equal to the diameter of the nozzle from its exit. This can be important for understanding the flow characteristics and performance of the nozzle, especially in applications like aerospace engineering or fluid dynamics simulations.

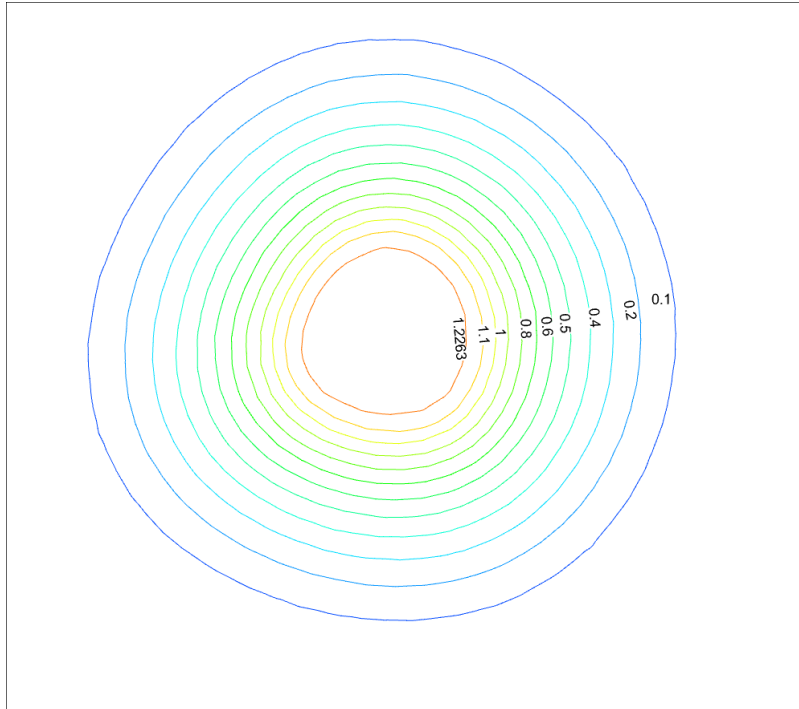


Fig:5.42 : Isomach contour of circular nozzle at $X/D=4$

Figure 4.40 to 4.42 represents the isomach contour of circular nozzle at various distance of $X/D=0, 1, 4$ at NPR 3.

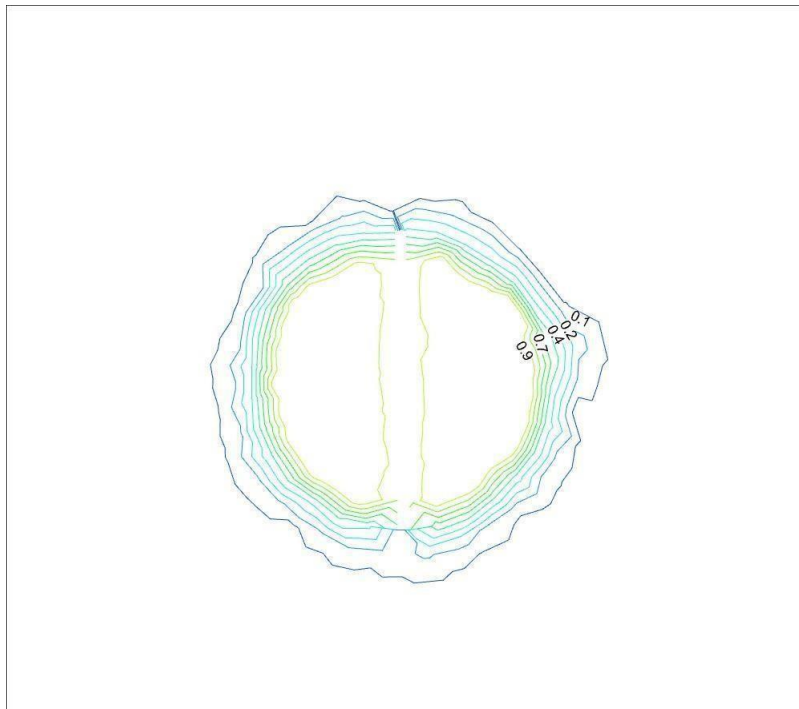


Fig:5.43 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D=0$

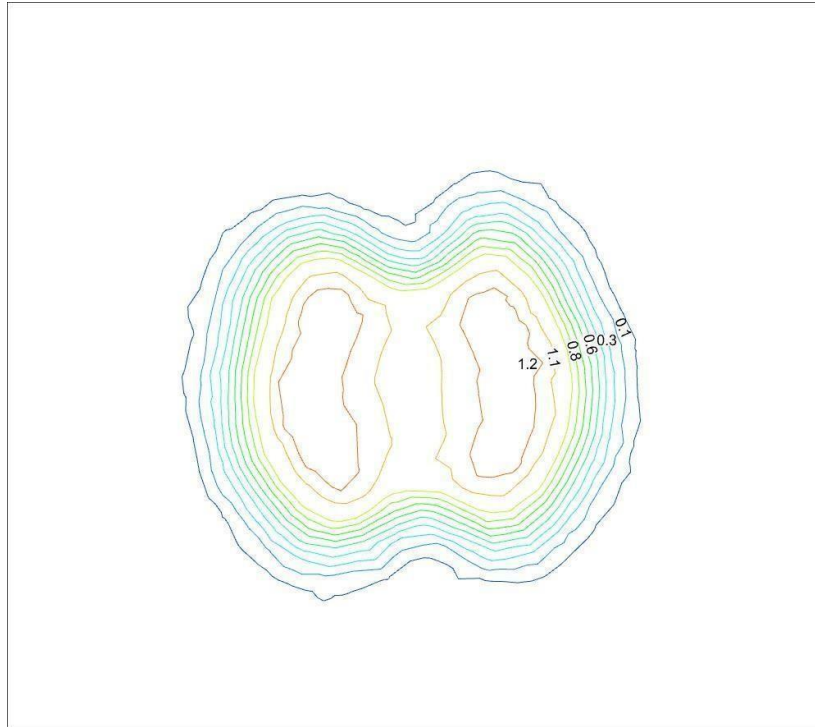


Fig: 5.44 : Isomach contour of nozzle with cross-wire (AR 25) at $X/D=1$

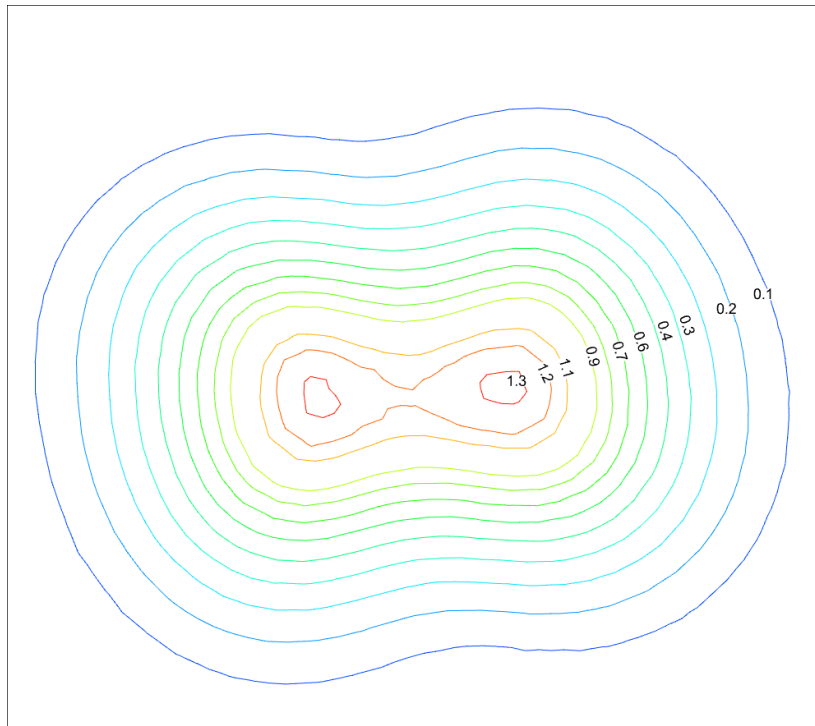


Fig:5.45 Isomach contour of nozzle with cross-wire (AR 25) at $X/D=4$

Figure 4.43 to 4.45 represents the isomach contour of circular nozzle with cross-wire (AR 25) at various distance of $X/D=0, 1, 4$ at NPR 3.

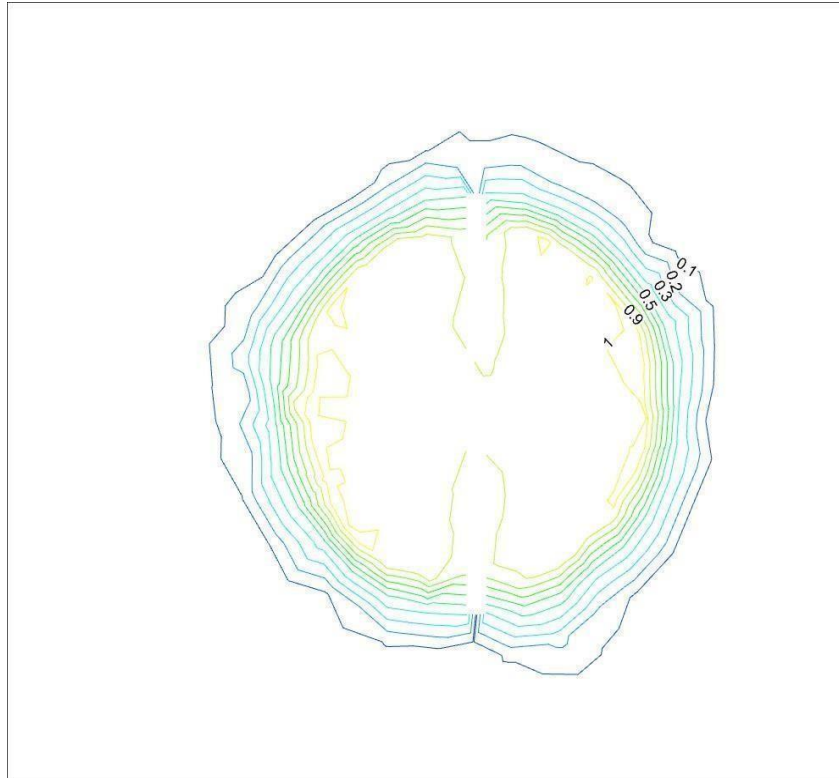


Fig:5.46 : Isomach contour of nozzle with tab (AR 16) at $X/D=0$

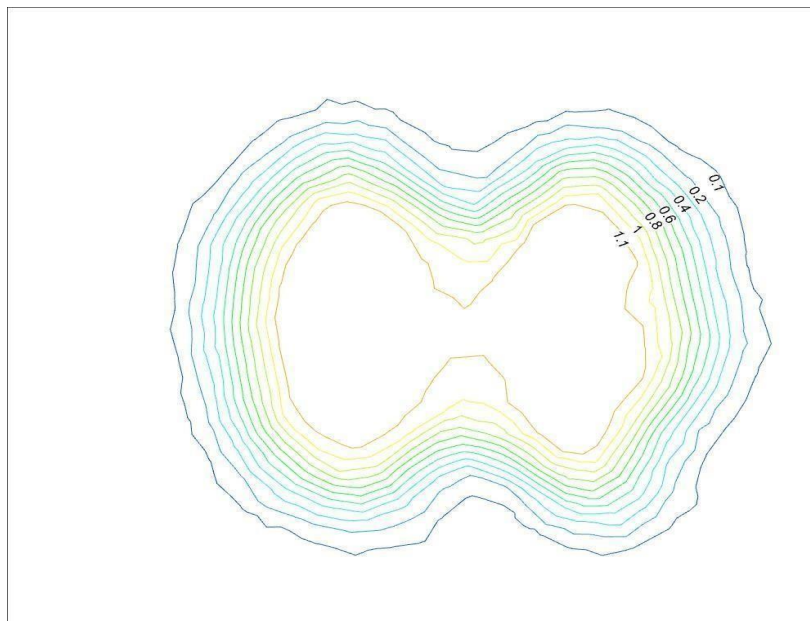


Fig: 5.47 : Isomach contour of nozzle with tab (AR 16) at $X/D=1$

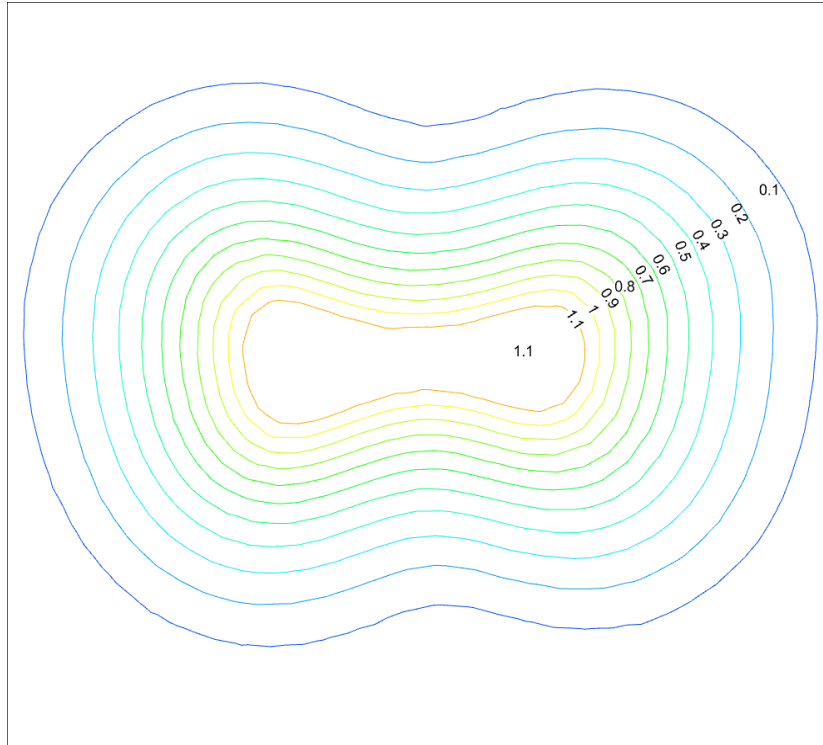


Fig: 5.48 : Isomach contour of nozzle with tab (AR 16) at $X/D=4$

Figure 5.46 to 5.48 represents the isomach contour of circular nozzle with tab (AR 16) at various distance of $X/D=0, 1, 4$ at NPR 3.

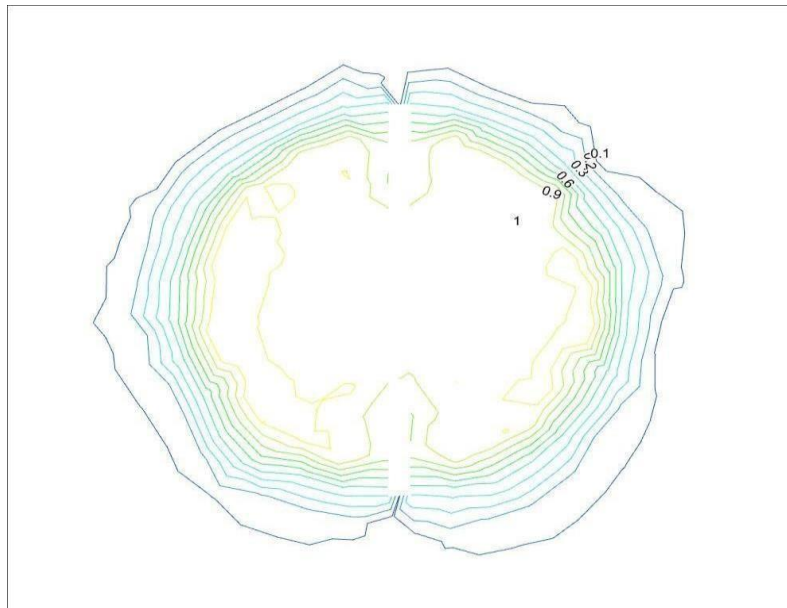


Fig: 5.49 : Isomach contour of nozzle with tab (AR 10) at $X/D=0$

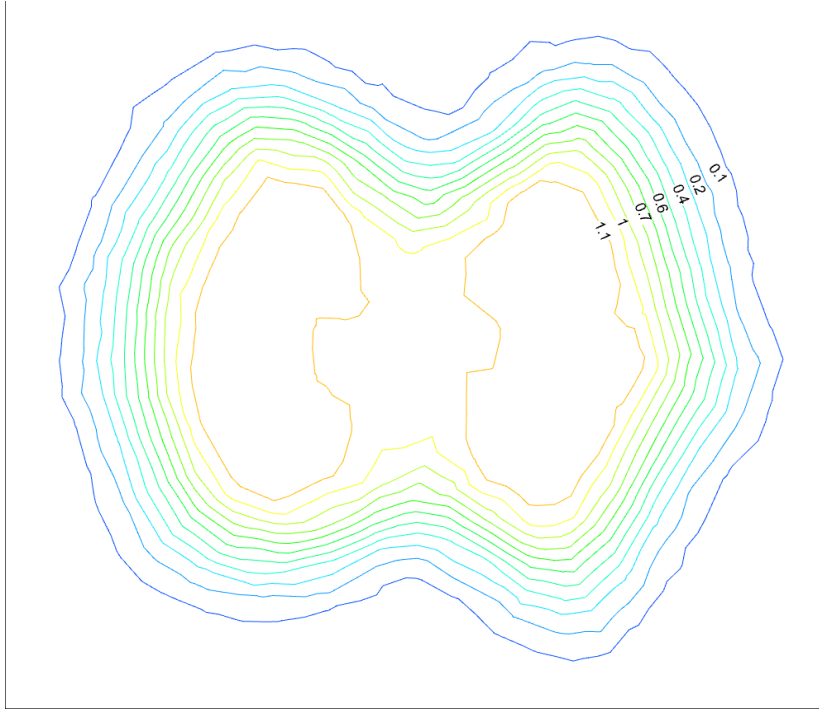


Fig: 5.50 : Isomach contour of nozzle with tab (AR 10) at $X/D=1$

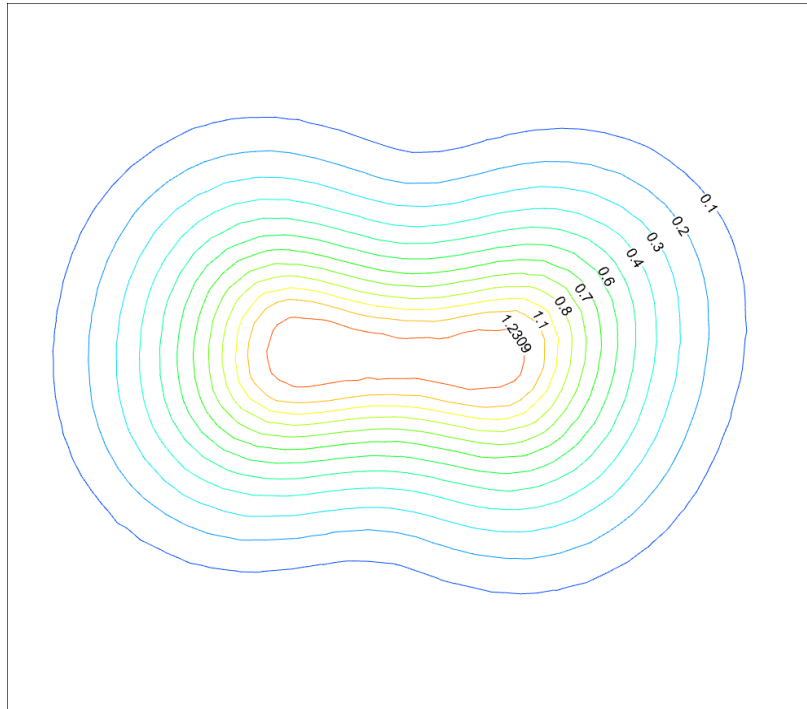


Fig:5.51 : Isomach contour of nozzle with tab (AR 10) at $X/D=4$

Figure 5.49 to 5.51 represents the isomach contour of circular nozzle with tab (AR 10) at various distance of $X/D=0, 1, 4$ at NPR 3.

Table 5.1: Isomach contour for Circular Nozzle with Crosswire at NPR 1.5 at $X/D=0$

Nozzle	Mach obtained
Circular nozzle	0.75
Nozzle with Crosswire AR 25	0.75
Nozzle with Tab AR 16	0.75
Nozzle with Tab AR 16	0.7

Table 5.2: Isomach contour for Circular Nozzle with Crosswire at NPR 1.5 at $X/D=4$

Nozzle	Mach obtained
Circular nozzle	0.75
Nozzle with Crosswire AR 25	0.7
Nozzle with Tab AR 16	0.7
Nozzle with Tab AR 16	0.7

Table 5.3: Isomach contour for Circular Nozzle with Crosswire at NPR 2.5 at $X/D=0$

Nozzle	Mach obtained
Circular nozzle	1.1
Nozzle with Crosswire AR 25	1
Nozzle with Tab AR 16	0.9
Nozzle with Tab AR 10	1

Table 5.4: Isomach contour for Circular Nozzle with Crosswire at NPR 2.5 at $X/D=0$

Nozzle	Mach obtained
Circular nozzle	1.1
Nozzle with Crosswire AR 25	1.2
Nozzle with Tab AR 16	1.2
Nozzle with Tab AR 10	1.2

Table 5.5: Isomach contour for Circular Nozzle with Crosswire at NPR 3 at $X/D=1$

Nozzle	Mach obtained
Circular nozzle	1.1
Nozzle with Crosswire AR 25	1.2
Nozzle with Tab AR 16	1.1
Nozzle with Tab AR 10	1.1

Table 5.6: Isomach contour for Circular Nozzle with Crosswire at NPR 3 at $X/D=4$

Nozzle	Mach obtained
Circular nozzle	1.2
Nozzle with Crosswire AR 25	1.3
Nozzle with Tab AR 16	1.1
Nozzle with Tab AR 10	1.2

5.4 MACH CALCULATION

$M = u/c$ M =Mach number

u = Local flow density

c = Speed of sound in the medium

Circular nozzle at NPR 1.5

$u=262$ m/s

$c=343$ m/s

$M=262/343=0.7$

Circular nozzle at NPR 2.5

$u=393$ m/s

$c=343$ m/s

$M=393/343=1.1$

Circular nozzle at NPR 3

$u=458$ m/s

$c=343$ m/s

$M=458/343=1.3$

Nozzle with crosswire (AR 25) at NPR 1.5

$u=277$ m/s

$c=343$ m/s

$M=277/343=0.8$

Nozzle with crosswire (AR 25) at NPR 2.5

$u=390$ m/s

$$c=343 \text{ m/s}$$

$$M=390/343=1.1$$

Nozzle with crosswire (AR 25) at NPR 3

$$u=474 \text{ m/s}$$

$$c=343 \text{ m/s}$$

$$M=474/343=1.3$$

Nozzle with tabs (AR 16) at NPR 1.5

$$u=269 \text{ m/s}$$

$$c=343 \text{ m/s}$$

$$M=269/343=0.7$$

Nozzle with tabs (AR 16) at NPR 2.5

$$u=390 \text{ m/s}$$

$$c=343 \text{ m/s}$$

$$M=390/343=1.1$$

Nozzle with tabs (AR 16) at NPR 3

$$u=469 \text{ m/s}$$

$$c=343 \text{ m/s}$$

$$M=469/343=1.3$$

Nozzle with tabs (AR 10) at NPR 1.5

$$u=264 \text{ m/s}$$

$$c=343 \text{ m/s}$$

$$M=264/343=0.7$$

Nozzle with tabs (AR 10) at NPR 2.5

$$u=380 \text{ m/s}$$

$$c=343 \text{ m/s } M=380/343=1.1$$

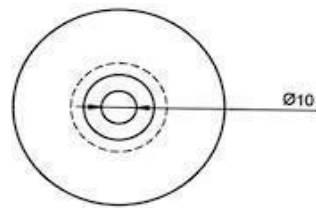
Nozzle with tabs (AR 10) at NPR 3

$$u=470 \text{ m/s}$$

$$c=343 \text{ m/s}$$

$$M=470/343=1.3$$

5.5 THEORETICAL CALCULATIONS:



Nozzle area:

Diameter of nozzle=10 mm

Radius=5 mm

Area of the nozzle = πr^2

$$\text{Area} = 78.5 \text{ mm}^2$$

$$5\% \text{ of } 78.8 = 3.925 \text{ approximately } 4 \text{ mm}^2$$

Crosswire Area:

Area of rectangle= length* breadth

$$= 10 \times 0.4$$

$$= 4 \text{ mm}^2$$

Blockage ratio = Tab Area/Nozzle exit

Blockage Ratio =5%

CHAPTER 6

EXPERIMENTAL WORK

6.1 EXPERIMENTAL TEST SETUP

A two-stage reciprocating compressor with a 500 psi air delivery capacity of 360 ft³/min is utilized in the high-speed jets experiment. The compressor is driven by a 150 horsepower three-phase induction motor. After passing through an intercooler compressed air is cooled by a cooling water circuit that is run by a different pump. Following that, solid contaminants like rust particles and oil droplets are filtered out using a pre-filter constructed of porous stone candles. An activated carbon filter is used to provide finer filtering. Compressed air is dried using a dual tower semi- automated silica gel dryer. While the other tower is operating, a portion of the dry air is heated and utilized to reactivate one tower. There was a diaphragm used to operate the back pressure valve. The compressed air is kept in three three-thousand-foot-long tanks. A gate valve and a pressure regulating valve are part of the tunnel control section. The pressure regulating valve is connected to a settling chamber and a mixing tube with a diameter of 3 inches. The investigation was conducted in an open jet facility that included high pressure storage tanks connected to a cylindrical settling chamber.

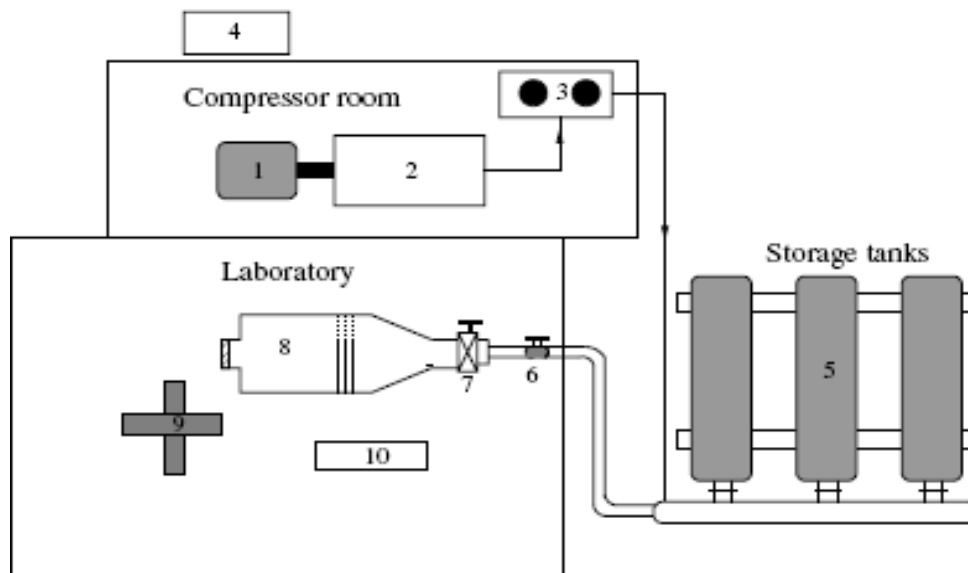


Fig: 6.1 : Layout of open jet facility

- | | |
|-------------------------------|------------------------------|
| 1. 150 hp induction motor | 6. Gate valve |
| 2. Reciprocating compressor | 7. Pressure regulating valve |
| 3. Activated charcoal filters | 8. Settling chamber |
| 4. Water cooling unit | 9. Traversing system |
| 5. Storage tanks | 10. Instrumentation desk |

Figure 6.1 shows the open jet testing facility's outline. Air can enter the settling chamber through the tunnel portion thanks to a gate valve, a pressure regulating valve, and a three-inch-diameter mixing length tube. The settling chambers and mixing tube are connected by a broad angle diffuser, then by three screens or tightly meshed grids spaced three centimetres apart to prevent turbulence at the nozzle inlet. Within the settling chamber, there is a circular segment of constant area that is 600 mm in length and 300 mm in inner diameter. In the settling chamber, there are tapes for recording the temperature and stagnation pressure. The test models are fixed at the end of the settling chamber by a slot holder arrangement, which is a brief protrusion that resembles a pipe.

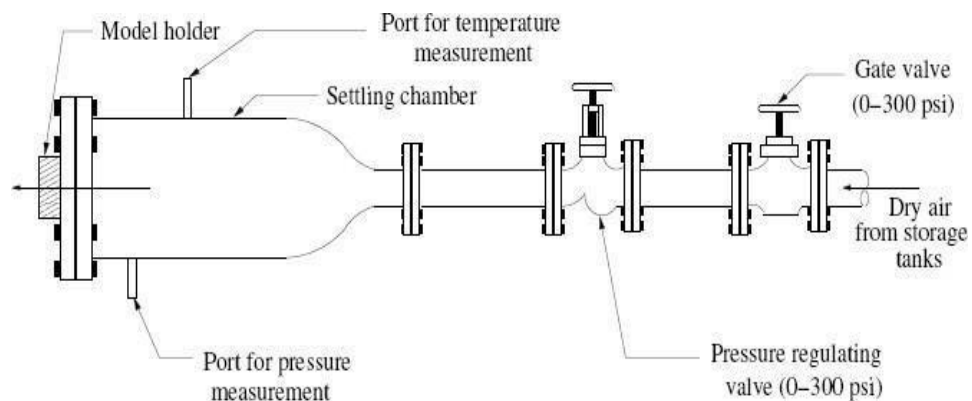


Fig: 6.2 : Schematic representation of open jet facility

The model to be studied is placed over the O-ring, and it is then securely screwed over by an annular retention sleeve with internal threads. The controlling parameter in the current investigation, the settling chamber total pressure (P_0), was maintained constant during a run by modulating the pressure regulating valve. Depending on the stagnation pressure (P_0) level in the settling chamber, different Nozzle Pressure Ratio (NPR), which are defined as the ratio of stagnation pressure to the atmospheric pressure (P_0/P_a) required for every study, can be achieved. The settling chambers temperature is the same as the ambient air temperature and the back pressure is the pressure into which the jets were discharged. The ambient temperature in the room stayed rather constant over the experimental run, staying within 0.5°C .

6.1.1 Pressure Transducer and Application Software

A PSI type 9016, 16-channel pressure transducer (interfaced with a Pentium 4 computer loaded with VI based software for data gathering) is illustrated in Figure 6.3 and was used to measure the pitot pressure sensed by the probe. The pressure that the type 9016 transducer can measure is up to 300 psi, or around 20 atm. The transducer's accuracy, upon re-zero calibration, is specified at $\pm 0.15\%$ whole scale. Also, by re-zeroing the calibration before each run, transducer offset errors were removed. TCP/IP communication is used by the application program created using Lab VIEW to connect the host computer and pressure scanner. All necessary operations, such as initialization, reset, and re-zero calibration and pressure reading, are carried out by the application program.



Fig: 6.3 : PSI Model 9016 16 Channel Pressure Transducer

6.1.2 Pitot Probe for Pressure Measurement

Pitot probes, which are essentially tubes with blunt ends pointing into flows, were used to monitor pressure. Normally, the tube's interior to outer diameter ratio is 1/2 to 3/4, and it is oriented so that its 15 to 20 tube diameters are in line with gas stream. The pitot tube utilized in this study has an exterior diameter of 0.6 mm and an inner diameter of 0.4 mm, as seen in Figure 3.4. It is reasonable to anticipate uniform flow at the downstream position farthest from a nozzle, with streamlines parallel to the X direction. Pitot pressure measurements in the vicinity of the nozzle exit, or in the near field, are deemed appropriate since the disruption caused by the nozzle. This will introduce some error in the measurement of pressure. But, the error due to the angularities of $\pm 20^\circ$ will be negligible (Rathakrishnan 2007).

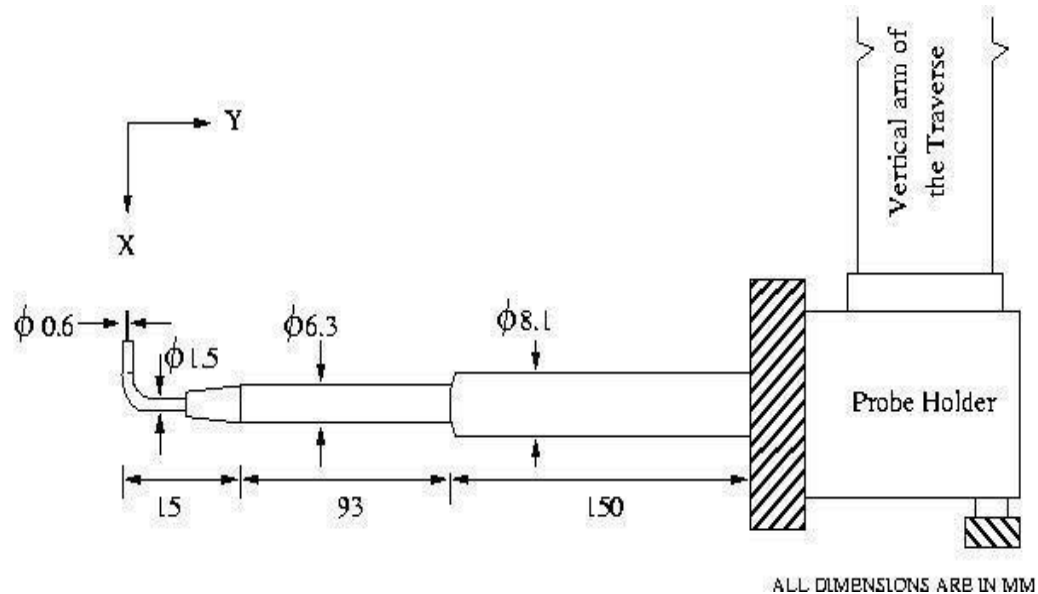


Fig: 6.4 : Schematic diagram of pitot pressure probe

The stagnation pressure is always measured using the open-end tube That faces into the flow. However, because of the pitot probe, there is a standing bow shock in the supersonic flow. In front of the blunt end will be the disconnectedshock that has formed. This indicates that the tube only measures the stagnation pressure that occurs behind a typical shock, not the actual stagnation pressure. Pitot pressure is the pressure measured after the typical shock produced by the tubes. Compared to subsonic flow, measuring static pressure in supersonic flow isfar more challenging. Any static probe at supersonic speeds will produce a shock wave at its snout, which raises the issue of using them.

6.1.3 Traversing Mechanism

A three-dimensional (X, Y and Z) traversing mechanism was used to Move pitot probe to any location in the jet field in step of 1 mm i.e. along thecenterline of the jet, vertical direction, and azimuthal directions. It has a range of 70 cm, 60 cm and 60 cm along the X, Y and Z-directions, respectively. The3-axis traversing is shown in the Figure 3.6.

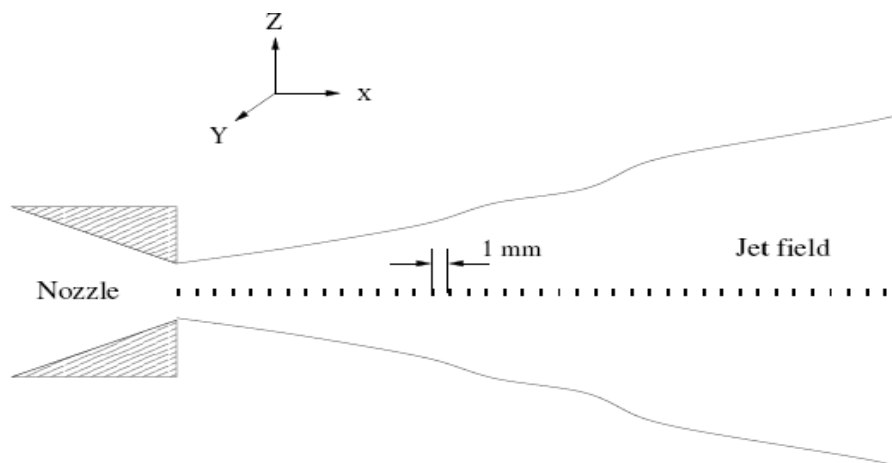
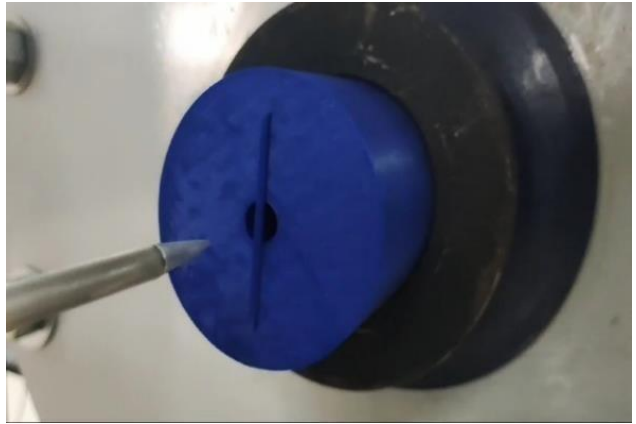


Fig: 6.5 : Schematic of jet field



A)



B)



C)

Fig: 6.6 : A photographic view of the settling chamber and Traversing Mechanism



**CIRCULAR
NOZZLE**

**CROSSWIRE
10X0.4(AR 25)**

**TAB
8X0.5(AR 16)**

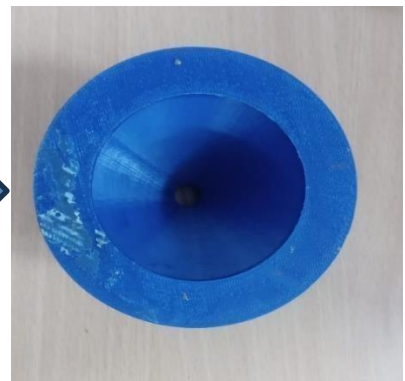
**TAB
6X0.6(AR 10)**

Fig: 6.7 : Experimental model of circular nozzle



(A)

CIRCULAR
NOZZLE WITH
FRONT AND
BACK VIEW

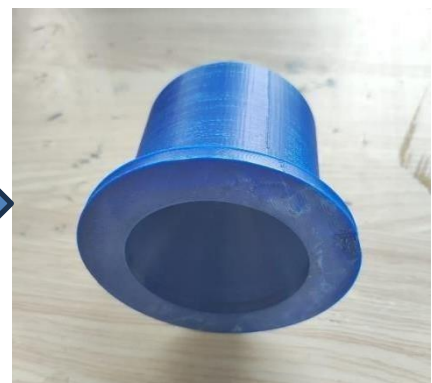


(B)



(C)

CROSSWIRE
WITH FRONT
AND BACK
VIEW

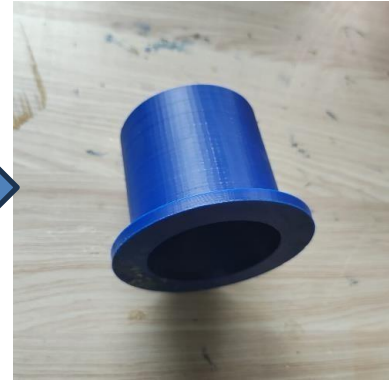


(D)

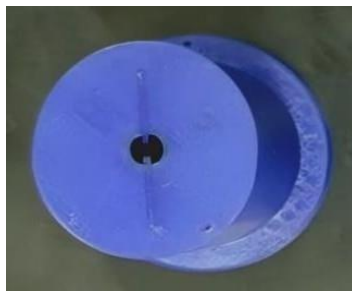


(E)

TAB
8X0.5(AR
16)WITH
FRONT
VIEW AND

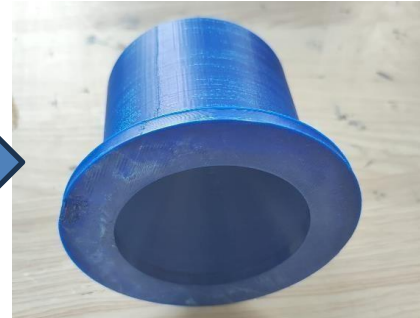


(F)



(G)

TAB
6X0.6(
AR
10)
WITH



(H)

Fig: 6.8 : Different views of circular nozzle with and without crosswire and tabs

6.2 EXPERIMENTAL RESULTS AND DISCUSSION

At Bharath University's High-Speed Aerodynamics Laboratory in Chennai, India, convergent subsonic jet experiments were carried out. To get the required Mach number, compressed air was delivered via a control valve from a storage tank to the primary settling chamber. The settling chamber pressure (P_0) was adjusted to achieve the required Mach number of 0.6, and the back pressure for the primary nozzle was set using the isentropic relations. The nozzle used in the experiment had a diameter ratio of three and a length of 10 mm. First, the air was sent into the pressure tank and stored there after the compressor was turned on. After that, an adapter was used to secure the nozzle to the high-speed jet facility. WIKA sensor The experiment was carried out for a while of 16 min and the data that was obtained from the sensor was used for the post-processing work to get accurate results of the total pressure.

6.2.1 Case I: For nozzle without cross wire

- Initial Mixing: At the beginning (low values of X/D), the P_0/P_t Without wire value is close to 1, suggesting minimal mixing with the surrounding medium. This is expected as the flow is initially confined within the nozzle
- Transition Region: As X/D increases, indicating movement away from the nozzle exit, we observe fluctuations in the P_0/P_t Without wire values. This indicates the onset of mixing as the jet interacts with the surrounding environment.
- Fully Developed Region: In the later stages (higher values of X/D), the P_0/P_t Without wire values stabilize, albeit with some fluctuations. This suggests that the jet has reached a relatively steady state where mixing with the surrounding medium is ongoing but is not changing significantly over distance.

- **Mixing Efficiency:** The decreasing trend in the P_0/P_t Without wire values towards lower values of X/D may indicate increasing mixing efficiency as the jet progresses downstream. However, the slight fluctuations could suggest some turbulence or variability in the mixing process.

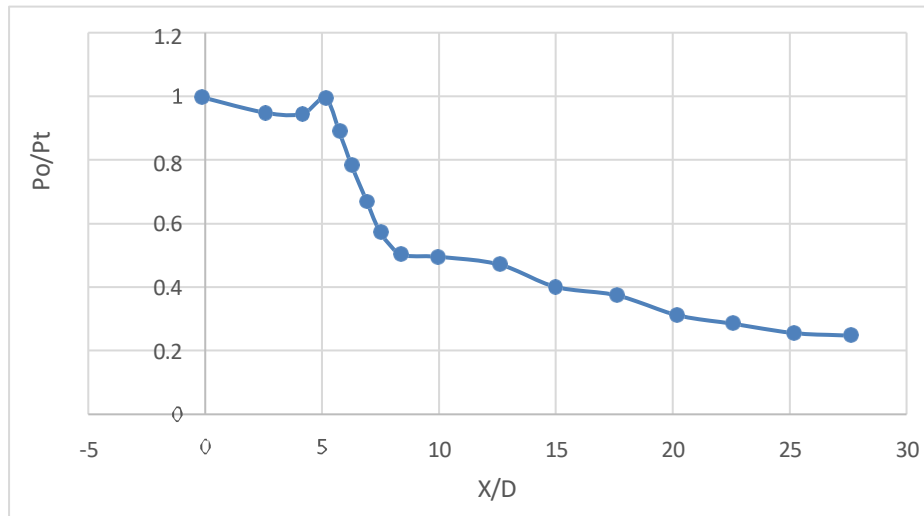


Fig: 6.9 : Center Initial Mixing for nozzle without cross wire and tabs

6.2.2 Case II: For nozzle with cross wire

Like the previous dataset, at the beginning (low values of X/D), the P_0/P_t Major axis value is relatively high, indicating minimal mixing with the surrounding medium. This suggests that the flow remains relatively coherent close to the nozzle exit

- **Transition Region:** As X/D increases, we observe fluctuations in the P_0/P_t Major axis values, indicating the onset of mixing as the jet interacts with the surrounding medium. The fluctuations seem to stabilize gradually, suggesting a transition towards a steadier mixing pattern
- **Fully Developed Region:** In the later stages (higher values of X/D), the P_0/P_t Major axis values continue to fluctuate but appear to stabilize around a certain level. This suggests that the jet has reached a relatively steady state further downstream, with mixing ongoing but at a more consistent rate.

- **Mixing Efficiency and Jet Expansion:** The decreasing trend in the P_0/P_t Major axis values towards higher values of X/D may indicate increasing mixing efficiency and jet expansion as the flow progresses downstream. This could be due to interactions with the surrounding medium and turbulence effects
- **Boundary Effects:** Towards the end of the dataset (higher values of X/D), there might be some boundary effects or interactions with the environment that influence the mixing characteristics of the jet flow. Centre line decay for nozzle without crosswire

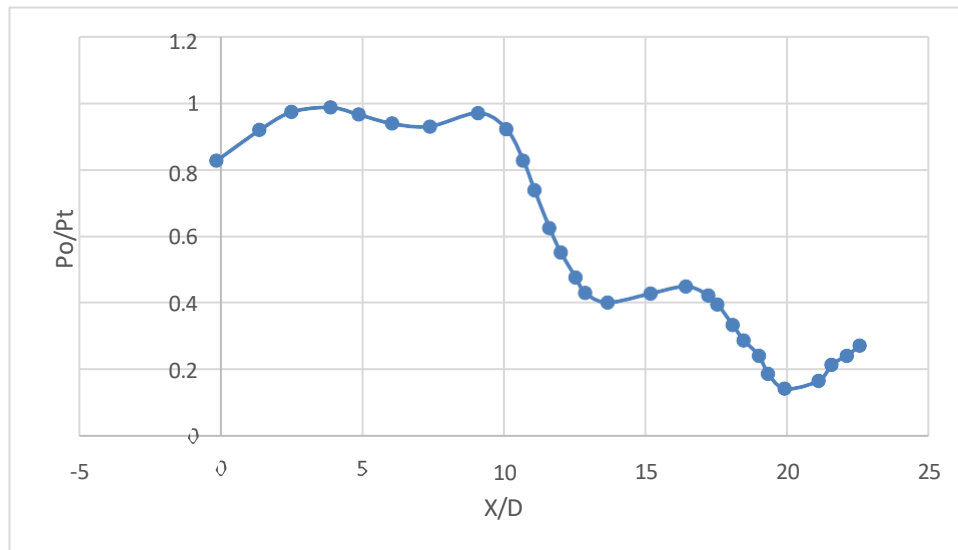


Fig 6.10 : Centerline decay for nozzle with cross-wire

6.2.3 Comparison of the centerline decay for CASE I and CASE II

- **Initial Mixing Behavior:** Both datasets show similar initial behavior with high P_0/P_t values at low X/D , indicating minimal mixing near the nozzle exit
- **Transition Region:** Both datasets exhibit fluctuations in P_0/P_t values as X/D increases indicating the onset of mixing and interaction with the surrounding medium

- **Fully Developed Region:** While both datasets stabilize towards higher X/D values, the stabilization seems more pronounced and consistent in case-II suggesting a smoother transition to a fully mixed state. **Mixing Efficiency:** nozzle with cross wire shows a more consistent downward trend in P_0/P_t values, suggesting potentially higher mixing efficiency and greater expansion compared to nozzle without cross wire.
- **Boundary Effects:** CASE-II extends further in terms of X/D , possibly indicating the presence of boundary effects or interactions with the environment at later stages.

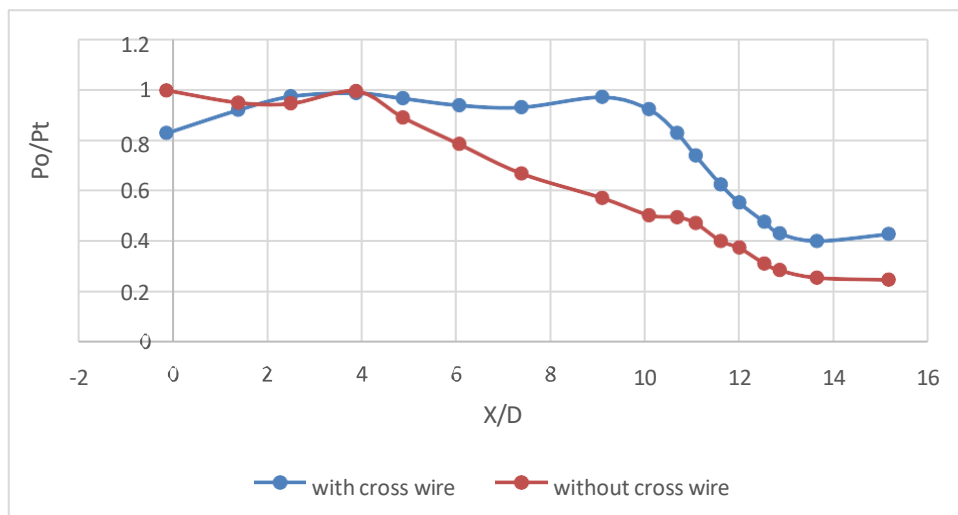


Fig: 6.11 : Comparison of Centre line decay for nozzle with and without cross wire

6.2.4 CASE-III: Nozzle with Tabs ($AR=10$)

- **Initial Behaviour:** At the beginning of the jet flow (low X/D values), the pressure ratio P_0/P_t is close to unity, indicating minimal pressure loss or mixing with the surrounding medium. This suggests that the flow remains relatively coherent near the nozzle exit.
- **Transition and Mixing:** As X/D increases, the pressure ratio starts to fluctuate, indicating the onset of mixing with the ambient medium. This is expected as the jet interacts with its surroundings, leading to variations in pressure along its path.

- **Mixing Efficiency:** The fluctuations in the pressure ratio continue throughout the dataset, suggesting ongoing mixing and expansion of the jet flow. The decreasing trend in P_0/P_t values indicates increasing mixing efficiency and expansion as the flow progresses downstream.
- **Stabilization and Boundary Effects:** Towards higher X/D values, the pressure ratio appears to stabilize around lower values. However, there are notable drops in pressure ratio towards the end of the dataset (X/D around 17.2991 and 20.1197), indicating potential boundary effects or interactions with the environment causing significant pressure losses.

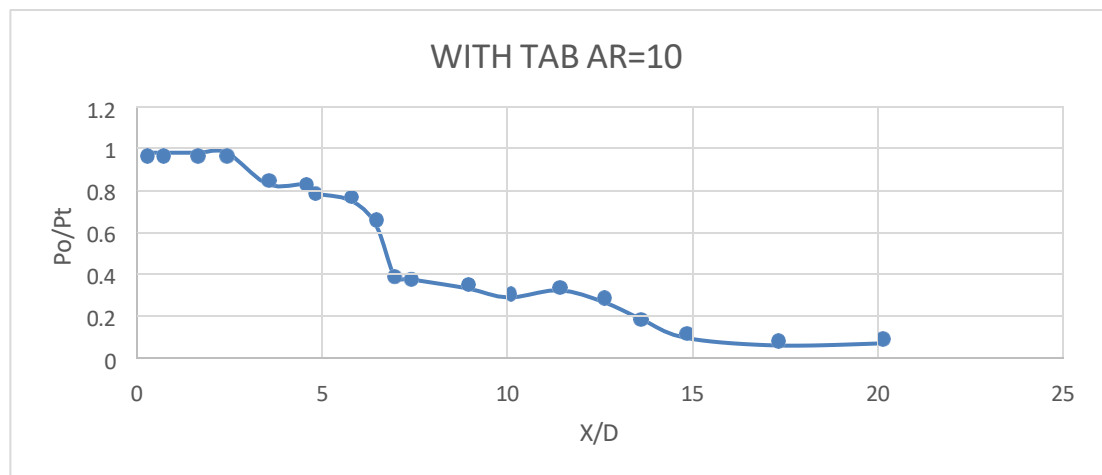


Fig: 6.12 : Centerline decay for nozzle with Tabs of AR=10

6.2.5 Comparison of CASE I and CASE II

- **Pressure Ratios Behaviour:**

Both datasets show variations in pressure ratios (P_0/P_t) as the non-dimensional parameter X/D increases, indicating changes in the flow characteristics along the jet path.

In the initial stages (lower X/D values), both datasets exhibit relatively high-pressure ratios, suggesting minimal mixing and loss of pressure with the surrounding medium.

- Transition Region:

As X/D increases, both datasets show fluctuations in pressure ratios, indicating the onset of mixing and interaction with the surrounding medium. However, there are slight discrepancies in the exact values of the pressure ratios between the two datasets at certain points, which could be attributed to differences in measurement techniques or experimental conditions.

- Fully Developed Region:

Towards higher X/D values, both datasets stabilize in terms of pressure ratios, albeit at different levels.

Case I stabilizes at relatively higher-pressure ratios compared to case III towards the end of the dataset.

- Boundary Effects:

Both datasets exhibit drops in pressure ratios towards the end of the data range (at higher X/D values), indicating potential boundary effects or interactions with the environment causing significant pressure losses.

These drops in pressure ratios seem more pronounced in case III compared to case I.

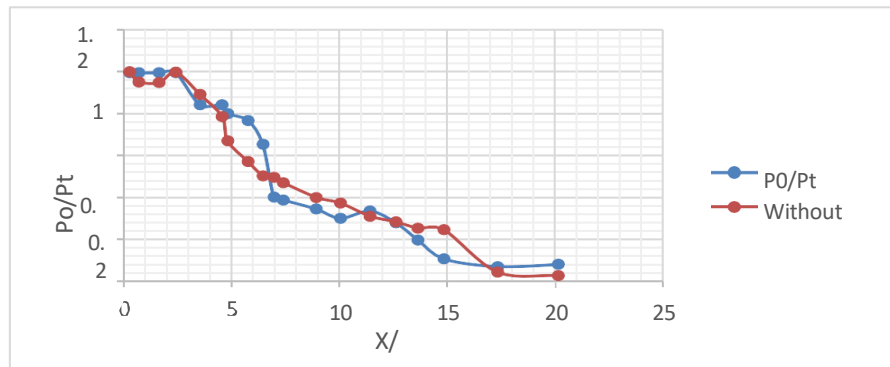


Fig: 6.13 : Comparison of Centerline decay for nozzle with Tabs of AR=10 and without tabs

6.2.6 CASE- IV: Nozzle with Tabs (AR=16)

- **Initial Conditions:** At the beginning of the jet flow (low X/D values), the pressure ratio P_0/P_t Tabs of AR=16 is relatively high (0.9914), indicating minimal pressure loss or mixing with the surrounding medium. This suggests that the flow remains relatively coherent near the nozzle exit.
- **Transition and Mixing:** As X/D increases, the pressure ratio starts to decrease gradually, indicating the onset of mixing with the ambient medium. This is expected as the jet interacts with its surroundings, leading to variations in pressure along its path.
- **Mixing Efficiency:** The pressure ratio continues to decrease as X/D further increases, suggesting ongoing mixing and expansion of the jet flow. However, the rate of decrease appears to slow down towards the later stages of the dataset, indicating a more stabilized mixing pattern.
- **Boundary Effects:** There are notable drops in pressure ratio at specific points along the dataset, such as at X/D values of 9.9487 and 14.906. These drops could be attributed to boundary effects or interactions with the environment causing significant pressure losses.

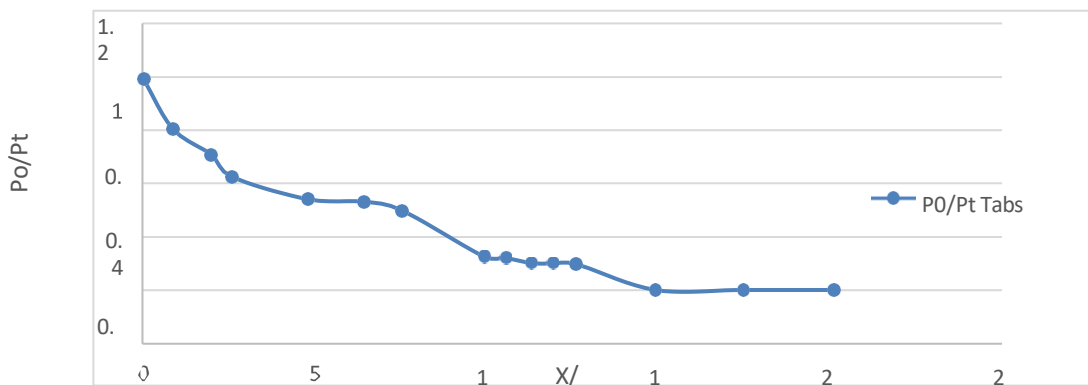


Fig:6.14 : Centerline decay for nozzle with Tabs of AR=16

6.2.7 Comparison of CASE I and CASE IV

- Initial Conditions:

Both datasets start with high pressure ratios at low X/D values, indicating minimal pressure loss or mixing near the nozzle exit. However, the pressure ratios without tabs (second column) generally start slightly higher than those with tabs (first column).

- Transition and Mixing:

As X/D increases, both datasets exhibit a decrease in pressure ratio, indicating the onset of mixing with the surrounding medium. The rate of decrease appears similar in both datasets, suggesting comparable mixing dynamics.

- Effect of Tabs:

The presence of tabs seems to slightly reduce the pressure ratio at each corresponding X/D value compared to the case without tabs. This indicates that the tabs might influence the flow behaviour, potentially causing more efficient mixing or pressure loss.

- Stabilization:

Towards higher X/D values, both datasets stabilize in terms of pressure ratio, although the stabilization levels are slightly lower in the case with tabs compared to without tabs. This suggests that the tabs might influence the flow characteristics even in the fully developed region.

- Boundary Effects:

Both datasets exhibit drops in pressure ratio at specific X/D values, indicating potential boundary effects or interactions with the environment. However, the presence of tabs does not seem to significantly alter these boundary effects.

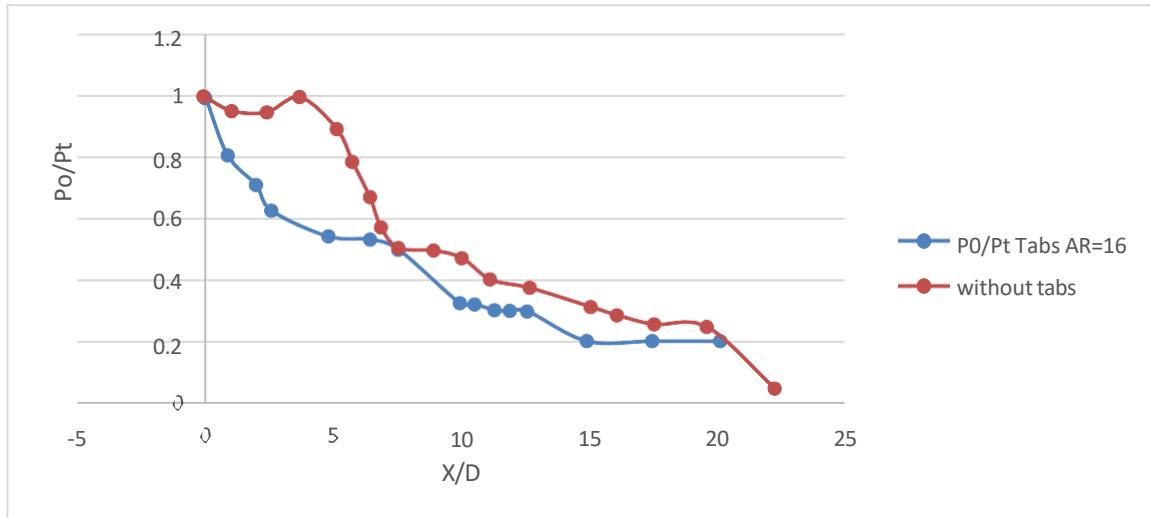


Fig:6.15 : Comparison of Centerline decay for nozzle with Tabs of AR=16 and without tabs

The potential core length, as indicated in the provided data, varies depending on the configuration of the nozzles. Here are some observations and comments on the potential core lengths associated with each configuration:

- Without Cross Wire: The potential core length is reported as 5.7 for the configuration without a cross wire. This suggests that without the cross wire, the jet flow maintains a relatively stable and coherent core over a certain distance downstream from the nozzle exit.
- With Cross Wire: Introducing a cross wire increases the potential core length to 4.1. The presence of the cross wire likely enhances mixing and dispersion within the jet flow, resulting in a longer potential core length compared to the configuration without the cross wire.
- With Tabs (Aspect Ratio = 10): The potential core length decreases to 3.8 when using tabs with an aspect ratio of 10. Tabs are often used to control and stabilize the flow, but in this case, the shorter potential core length suggests that they may contribute to more efficient mixing and dispersion of the jet flow.

- With Tabs (Aspect Ratio = 16): Further reducing the aspect ratio of the tabs to 16 results in the shortest potential core length of 2.6. This indicates that tabs with a higher aspect ratio contribute to even more effective mixing and dispersion of the jet flow, resulting in a shorter potential core length compared to other configurations.

In summary, the potential core length of the jet flow is influenced by various factors, including the presence of cross wires and tabs, as well as their specific configurations such as aspect ratio. The data provided highlights the importance of nozzle design and flow control mechanisms in determining the characteristics of the jet flow, particularly in terms of stability and mixing efficiency.

6.2.8 Experimental studies for different Mach number

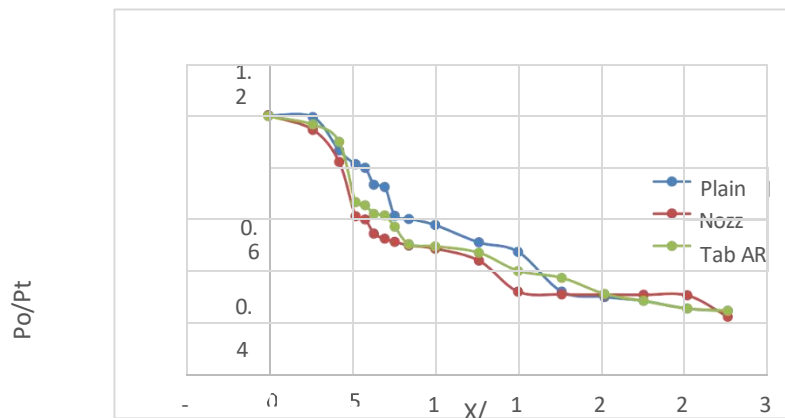


Fig:6.16 : Comparison of three nozzles at $M=0.8$

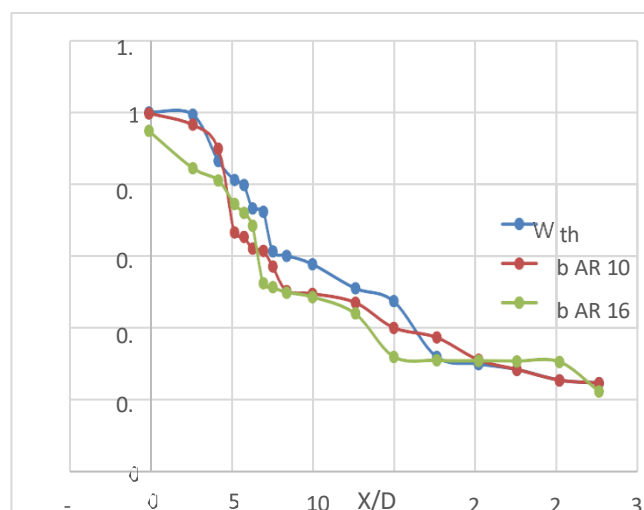


Fig: 6.17 : Comparison of three nozzles at $M=1$

6.3 Comparison of CFD and Experiment results

The comparison between experimental (EXP) and computational fluid dynamics (CFD) results for different nozzle configurations reveals some interesting insights:

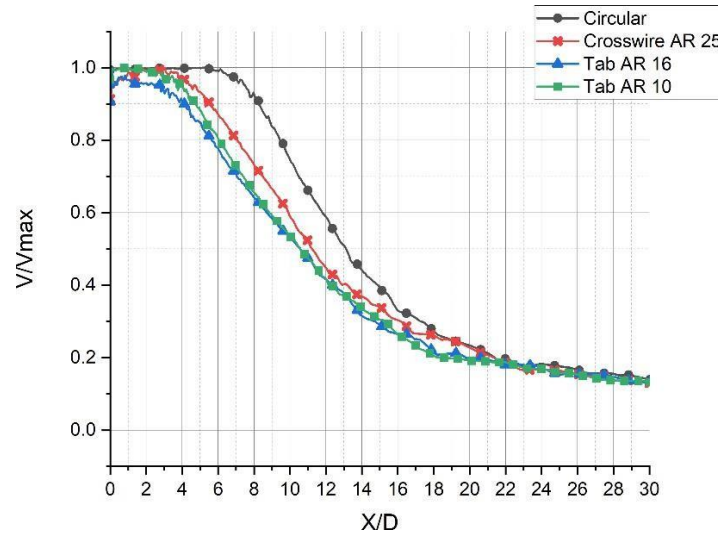


Fig: 6.18 : CFD Result of Circular Nozzle

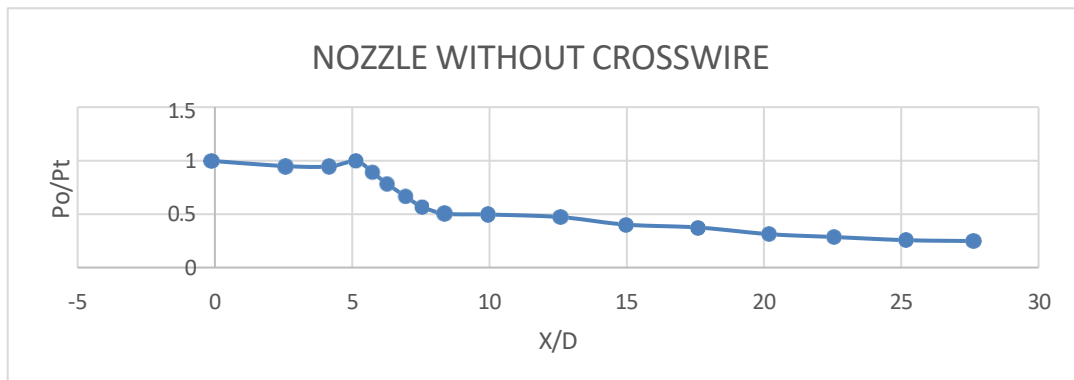


Fig: 6.19 : Experimental Result of Circular Nozzle

- Circular Nozzle:

Experimental potential core length: 5.7

CFD predicted potential core length: 7

Comment: There is a notable discrepancy between the experimental and CFD results for the circular nozzle configuration. The CFD simulation overestimates the potential core length compared to the experimental data, indicating potential limitations or inaccuracies in the simulation model or assumptions.

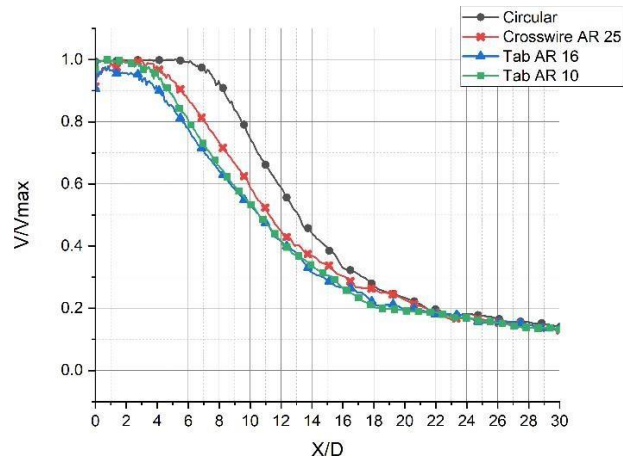


Fig:6.20 : CFD Result Of Crosswire AR (25)

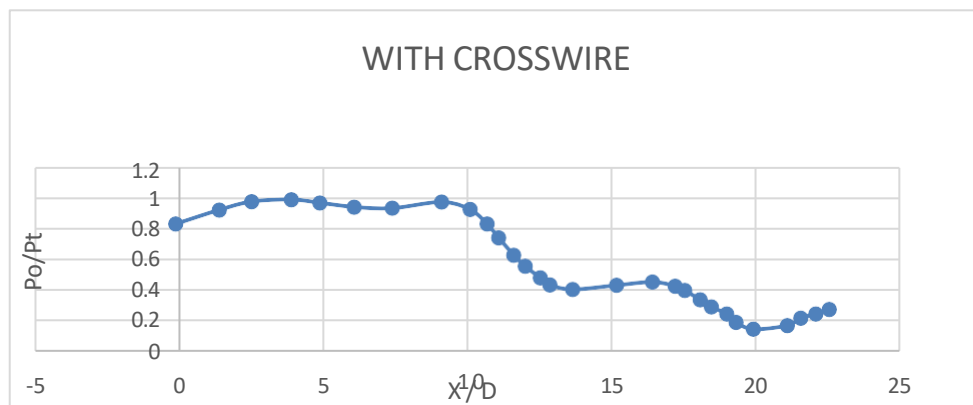


Fig : 6.21 : Experimental Result of Crosswire AR (25)

- With Cross Wire:

Experimental potential core length: 4.1

CFD predicted potential core length: 5

Comment: The CFD simulation provides a closer match to the experimental data for the configuration with a cross wire. However, there is still a slight discrepancy between the two results, suggesting some room for improvement in the simulation model.

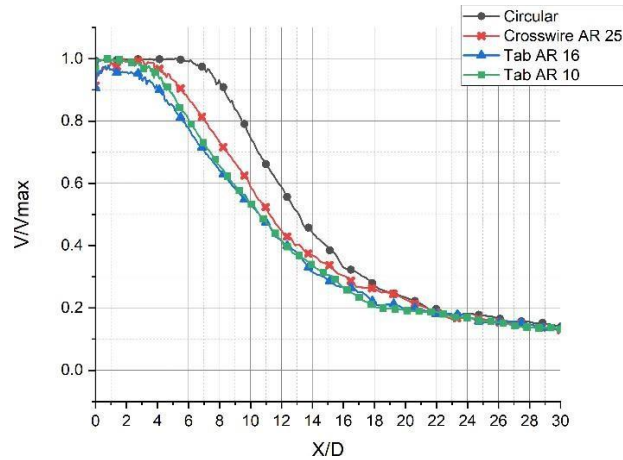


Fig: 6.22 : CFD Result of Tab AR (10)

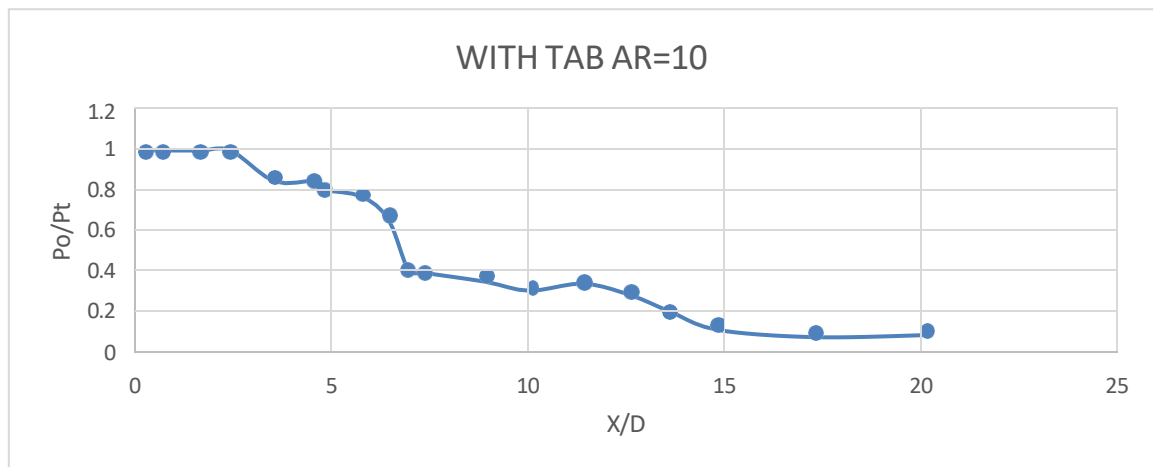


Fig: 6.23 : Experimental Result of Tab AR (10)

- With Tabs (AR=10):

Experimental potential core length: 3.8

CFD predicted potential core length: 4

Comment: The CFD simulation closely matches the experimental data for the configuration with tabs of aspect ratio 10. This indicates good agreement between the simulation and experimental results, suggesting that the simulation captures the flow characteristics accurately for this configuration.

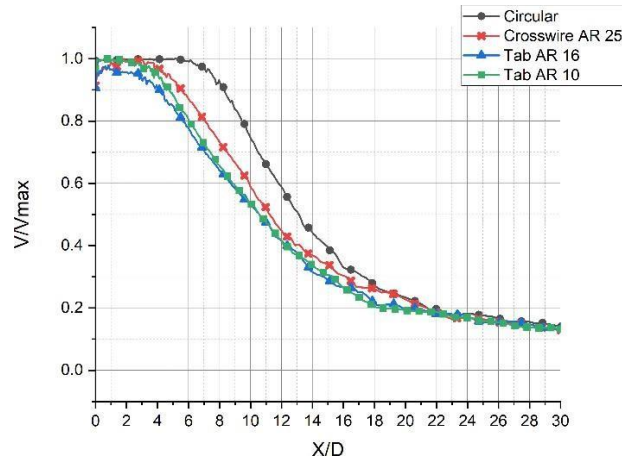


Fig: 6.24: CFD Result of Tab AR (16)

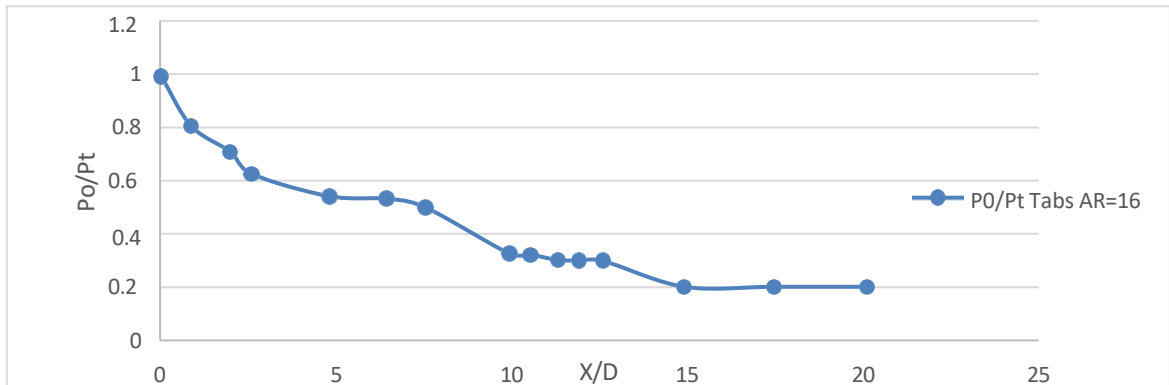


Fig: 6.25 : Experimental Result of Tab AR (16)

- With Tabs (AR=16):

Experimental potential core length: 2.6

CFD predicted potential core length: 4

Comment: The CFD simulation again overestimates the potential core length compared to the experimental data for the configuration with tabs of aspect ratio 16. This suggests that the simulation model may not fully capture the effects of higher aspect ratio tabs on the flow characteristics.

In summary, while the CFD simulation generally provides reasonable predictions for the potential core length of the jet flow for some configurations, there are discrepancies compared to the experimental results, particularly for the circular nozzle and the configuration with tabs of aspect ratio 16. This highlights the importance of validating simulation results with experimental data and further refining the simulation model to improve accuracy and reliability.

CHAPTER 7

SUMMARY AND CONCLUSION

From the results obtained it is clear that both the cross-wire (AR 25) and tabs (AR 16) and (AR 10) has greater impact on core length reduction and as Nozzle Pressure Ratio (NPR) increases the effectiveness of both crosswire and tabs. At NPR 1.5 potential decay begins at 7D but as the NPR increased to 2.5 and 3 the characteristic decay started to begin at 7.5D and 8D respectively, this is due to the formation of shockwaves due to the under-expanded condition. The crosswire and tab both are found to have significant effect on core length reduction but compared to crosswire tab (AR 16) found to decay rapidly but the shockcell were found to be diffused by crosswire (AR 25) and the bifurcation (separated into two region) of jet was found in crosswire.

The pressure ratio (P_0/P_t) varies along the jet flow path, indicating changes in mixing efficiency and interactions with the surrounding medium. The non-dimensional parameter X/D , representing the position from the nozzle exit relative to the diameter of the nozzle, plays a crucial role in determining the behavior of the jet flow. Nozzle configurations, including circular nozzles, those with cross wires, and those with tabs of different aspect ratios, influence the potential core length and mixing efficiency of the jet flow. Introduction of cross wires or tabs alters the flow characteristics, affecting mixing efficiency and potential core length. Comparisons between experimental and computational fluid dynamics (CFD) results highlight the importance of validation and accuracy assessment of simulation models

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NUMERICAL AND EXPERIMENTAL ANALYSIS ON MIXING CHARACTERISTICS OF A CIRCULAR FREE JET USING TABS

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ABSTRACT

The main objective of the paper is to study the effectiveness of crosswire for different aspect ratios such as AR 25, AR 16, AR 10 in circular convergent nozzle at under expanded condition. In this study, the effects of different tab aspect ratios on the mixing characteristics of a circular free jet were investigated under Nozzle Pressure Ratios (NPR) of 1.5, 2.5 and 3 by keeping the blockage ratio 5% as constant. The mixing process was evaluated by measuring the jet velocity decay, rapid decay of velocity represents better entrainment. The study found that the aspect ratio of the tab of aspect ratio 16 has a significant effect on the mixing process, compared to other aspect ratios leading to improved mixing characteristics. The study showed that as the NPR increases the shock structure formation increases leading to longer core region and the effectiveness of tab increases with the increase in the NPR. This finding can have important implications for the design and optimization of mixing processes involving circular free jets with tabs

Received: Aug 30, 2023; Accepted: Sep 14, 2023; Published: Sep 28, 2023; Paper Id: IJAERDDEC20234

INTRODUCTION

Jets

Generally speaking, a jet is a pressure-driven shear flow that keeps a consistent width-to-axial distance while decreasing as the Mach number rises. Appropriate jet mixing at the right ratio is critical to lowering noise and increasing performance in current aircraft applications. In order to control the size of the combustion chamber and raise the vehicle's overall efficiency, effective mixing is required in airbreathing engines.

Characteristics of Jets

In the case of a subsonic jet, the potential core usually extends up to six times the diameter of the nozzle exit (D_e) downstream from the exit point.

This is because the mixing process that starts at the jet's edge hasn't yet extended to the whole flow field, resulting in an area with a constant axial velocity. This is the point where the jet's centerline velocity begins to decrease. A notable characteristic is the decay zone, which stretches from around $5D_e$ to $10D_e$ downstream and represents the transition of the turbulence distribution from an annular to a slightly pseudo cylindrical structure. As a result, the shear forces that keep the jet's vortical rings in place are weakened because there is a decrease in the velocity differential between the high-speed core area and the surrounding fluid. As the jet moves forward, the velocity profiles become smoother. The wave instability of the vortex rings cores causes a surge in three-dimensional flow, which is indicative of the transition zone. Large eddies that can stay coherent around the possible jet core are produced when these warped vortices coalesce. After the transition area is passed, the jet's appearance resembles a fluid flow coming from a source that is incredibly thin. The source is a point in an axially symmetric configuration and a straight line perpendicular to the jet's flow plane in a parallel plane configuration. In actuality, though, the jet's velocity starts to decrease sharply after about $30D_e$.



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