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Impact of Vortex Generators' Location on Supersonic Asymmetric Jet Control

T. Paramesh[1], T. Jana [2†], and M. Kaushik[3]

[1] *Department of Aerospace Engineering, JAIN (Deemed-to-be University), Bengaluru, 560069, India*
[2] *Department of Aerospace Engineering, B.M.S. College of Engineering, Bengaluru, 560019, India*
[3]*Department of Aerospace Engineering, Indian Institute of Technology, Kharagpur, 721302, India*

†Corresponding Author Email: tamaljana.aer@bmsce.ac.in

ABSTRACT

The usefulness of the supersonic jet is inhabitable in the Aerospace industry. However, control of the supersonic jet is important for efficient mixing and noise attenuation. Particularly, asymmetric jets are better than axisymmetric jets in rapid mixing. Considering this, the experimental investigation has been carried out for the vortex generators or tab-controlled Mach 1.6 elliptic jet. To compare the impact of the locations of the vortex generators, they are deployed at the diametrically opposite locations of the nozzle outlet along the major or longest axis and the minor or shortest axis, respectively. The investigations have been carried out using the centerline pressure distributions employing the Pitot probe and the Schlieren flow visualizations. A maximum of 66.43% reduction in supersonic length has been observed from the centerline pressure distributions for the vortex generator placed along the shortest axis. In addition, the Schlieren flow visualizations confirm substantial distortions in the shock cell structures when the vortex generators are placed along the shortest axis which results in noise mitigation. The study concluded that the impact of the vortex generator, placed along the shortest axis, is superior in the manipulation of shock cell structure, efficient mixing, and thereby noise mitigation than those placed along the longest axis.

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1. INTRODUCTION

The implications of supersonic jets are evident in the aerospace industry, particularly in Convergent-divergent nozzles, supersonic ejectors, air-augmented rockets, and scramjets for supersonic combustion and to obtain adequate thrust (Srikrishnan et al., 1996; Mahulikar et al., 2005). However, the limitations of supersonic jets are significantly low mixing rates and intense noise emissions (Papamoschou & Roshko, 1988; Samimy &Elliott, 1990). Also, a longer high-temperature exhaust plume leads to a higher infrared signature (IR) for stealth aircraft (Knowles & Saddington, 2006). An important consideration for the efficient mixing of supersonic jets is the transformation of the axisymmetric nozzle geometry to the asymmetric one (Ho & Gutmark, 1987; Quin, 1989; Zaman, 1995; Kumar & Rathakrishnan, 2016). The investigation of Quin (1989) shows that the supersonic jet ejected from the elliptic or rectangular convergent-divergent nozzle has the rapid mixing characteristics than that of the circular convergent-divergent nozzle. Moreover, Quin (1989) demonstrated that the asymmetric jet works better than the axisymmetric jets due to the variations in the azimuthal curvatures. Particularly, the mixing characteristics of the rectangular jet are a little lower due to the flat sides and corners it has. Essentially, the asymmetric coherent structure leads to azimuthal alterations which result in the entrainment of the large mass of surrounding fluids into the jet (Ho & Gutmark, 1987). Moreover, the near-field mixing of the elliptic jet is substantially improved due to the axis-switching phenomenon (Kumar & Rathakrishnan 2016). Later, the studies of Kumar & Rathakrishnan (2017) revealed that the elliptic jet with Aspect Ratio 4 demonstrates superior mixing than the jets with aspect ratios 2 and 3. Mohanta et al. (2021) also confirmed the fact that the supersonic length decreases for both elliptic and rectangular jets as the Aspect Ratio increases. In addition to nozzle modifications, the implementations of vortex generators have also been studied extensively in the last few decades. The vortex-generator used to control jets are flat metal strip located at the nozzle outlet plane (Bradbury & Khadem 1975; Ahuja & Brown, 1989; Zaman et al., 1991, 1993; Kaushik, 2012; Kaushik & Rathakrishnan, 2015). Essentially vortex generator produces

NOMENCLATURE

CD	Convergent Divergent	*P*	pitot pressure
NPR	Nozzle Pressure Ratio	P_o	settling chamber pressure
AR	Aspect Ratio	*X*	axial distance
D	nozzle outlet diameter	*Y*	radial distance along major or longest axis
Z	radial distance along minor or shortest axis		

streamwise vortices into the flow field, required for efficient mixing. Since the size and shape of the vertex generator essentially control the size of the mixing-promoting vortices, several vortex generator configurations have already been studied to characterize the jet mixing behavior (Kaushik, 2012). It has been found that the implementation of the corrugation shapes has a substantial impact on the jet control. The square, semicircular, triangular shape has been investigated by Thillaikumar et al. (2020), and Jana and Kaushik (2021) for Mach 1.73 axisymmetric jet. It has been observed that the triangular tab behaves in a better way for a lower aspect ratio of 1.5 whereas the semicircular tab is superior at a higher aspect ratio of 2. On the other hand, as asymmetric jet performs better than symmetric jet due to the well-known axis-switching phenomenon, studies have been specifically concentrated on vortex generator-controlled asymmetric jets, particularly elliptic jets (Akram & Rathakrishnan, 2019). The results confirmed that the introduction of vortex generators significantly decreases the supersonic length of the elliptic jet.

Defining the location of the vortex generator is important for the asymmetric jet as the turbulent properties are very different along the longest and the shortest axis (Ho & Gutmark, 1987). A few investigations have been conducted on vortex generators of different shapes, such as triangular and rectangular, along the longest axis and shortest axis in controlling supersonic jets (Kumar & Rathakrishnan, 2016). The results revealed that the mixing has been substantially enhanced when the vortex generators are placed along the shortest axis at Mach 2. Though the investigations have been conducted on placements of vortex generators along the longest and shortest axes of the elliptic jets, vortex generators operating at varied Mach numbers may bring significant differences in flow field characteristics. Since the impact of vortex generators might be significantly dependent on the strength of shock cell structures. The motivation is to understand the impact of the interactions of the vortices, generated from the vortex generators, and the shock cells of sufficiently weaker strength that prevail inside the supersonic jet. Considering this in mind, the study has concentrated on the specific behavior of uncontrolled and controlled elliptical jets at a slightly lower Mach number of 1.6. On the other hand, Mach 1.6 represents a supersonic flow regime that is commonly encountered in various engineering applications, including aerospace propulsion systems. Therefore, the current study aims to experimentally evaluate the impact of vortex generators when it is particularly placed along the longest and the shortest axis in diametrically opposite locations at the nozzle exit plane at Mach 1.6.

2. EXPERIMENTAL METHODOLOGY

The experimental investigation was conducted in a supersonic jet test facility. The schematic drawing of the facility is shown in Fig. 1. In addition, the photograph of the Pitot probe, placed downstream of the nozzle exit, is shown in Fig. 2. The experimental model employed in this study (Fig. 3a) is an asymmetric, Convergent-Divergent (CD) nozzle.

The CD Nozzle is designed for isentropic flow expansion where the exit pressure matches the ambient pressure and as a result, a shock-free supersonic jet is generated (Munday et al., 2011). To achieve the desired exit Mach number of 1.6, the exit area of the nozzle to the throat area is kept at 1.25. Based on the experimental run time of 15 minutes, the supersonic nozzle throat area is calculated to be 63.6 mm^2. This nozzle is designed with an aspect ratio of 2 for which the longest and shortest length at the throat is found to be 12.74 mm and 6.36 mm, respectively. Similarly, at the exit, the maximum and minimum lengths are 14.22 mm and 7.12 mm, respectively. The divergent length is considered to be 20.25 mm. The convergence angle is maintained at 5 degrees along the longest axis and the divergence angle is kept at 3 degrees along the shortest axis to achieve a more gradual expansion of the exhaust gases and to minimize flow separation within the nozzle (Hashim & Dharmalingam, 2023).

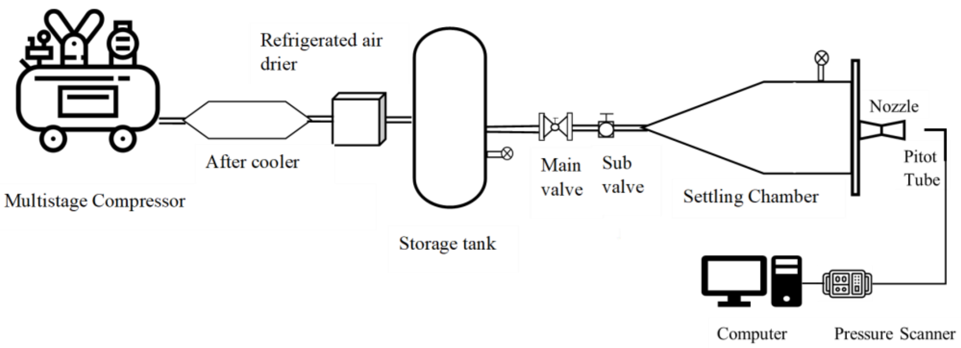


Fig. 1 Schematic representations of the supersonic open jet test facility

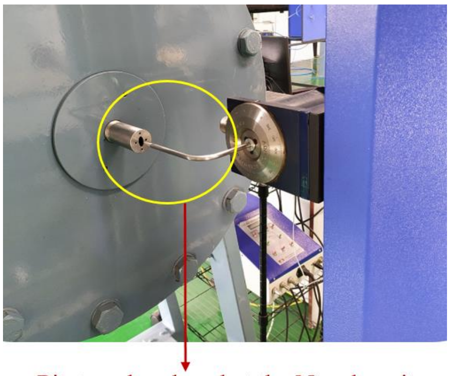


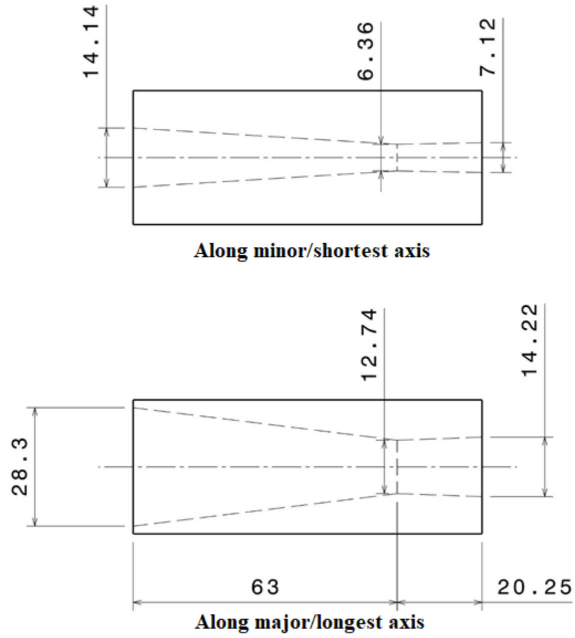
Fig. 2 Photograph of the Pitot probe deployed in front of the elliptic nozzle

The nozzle design Condition is the flow state where an exit pressure matches ambient pressure and thereby produces a shock-free supersonic jet. In jet studies, NPR is the common pressure ratio used to define the various flow states. Essentially, the Nozzle Pressure ratio (NPR) is the ratio of settling chamber pressure to the pressure of the surrounding environment to which is jet is released. The design NPR for the present study is 4.25. Note that, NPR 2.5 is considered as an overexpansion and NPR 6 is considered an underexpansion for this study.

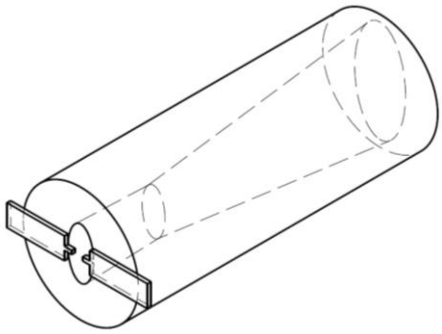
The pitot probe is employed to measure the total pressure. The outer diameter and the inner diameter of the probe are 0.8 mm and 0.6 mm, respectively. The software controlled three axes traverse mechanism is used to move the Pitot probe to measure the pressure in the desired location. The Pitot tube is connected to the 16-channel pressure scanner via a 1 mm transparent PVC tube. The three-dimensional traverse mechanism has a positional accuracy of +/- 0.5 mm in all three directions. The software-controlled window is used to collect the data and has a sampling rate of 175 samples per second. The data is saved in a .dat file format. The M3256-00000E-010BG with a range of 0-10 bar is used as a transducer with an accuracy of ±0.25% on Full Scale Operation. The repeatability in the pressure measurement is 2% (Moffat, 1988).

The Schlieren flow setup is used for flow visualization. To have sufficient illumination, the Halogen bulb of 1000 watts is used as a light source for the Schlieren flow visualization. The power is supplied through a power regulator with a current rating of 0-6 Amps and a voltage of 0-220 Volts. The 200 mm parabolic mirror with a focal length of 1.5 meters is used as the present experimental setup. A knife edge is used to block a portion of refracted light that leads to an image of varied light intensity on the camera lens.

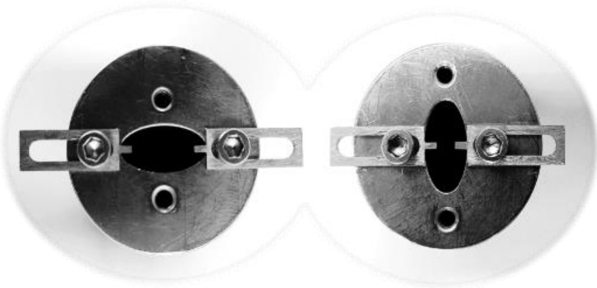
The asymmetric jet flow from the elliptical nozzle is controlled with the tabs that were made of 1 mm thick steel strips. Two similar tabs, positioned opposite to each other at the nozzle outlet plane were used in the investigation (Fig. 3b). Each tab has a width of 1 mm and a length of 2 mm, which leads to an aspect ratio of 2, resulting in a tab blockage (tab area to the nozzle exit area) of 5%. The photographic view of the placements of the tabs along the



a)



b)



c)

Fig. 3 Elliptical nozzle and tabs. a) Schematic diagram of the elliptical nozzle. b) Isometric view of the elliptical nozzle with tabs. c) Photographic view of the exit of the elliptical nozzle with tabs positioned on the longest and shortest axes

longest and shortest axes at the outlet of the elliptic nozzle is shown in Fig. 3c.

3. RESULTS AND DISCUSSIONS

The prime aim of the study is to examine the impact of the locations of vortex generators in encouraging the mixing of the asymmetric jet at Mach 1.6 at three different nozzle pressure conditions (underexpanded, correctly

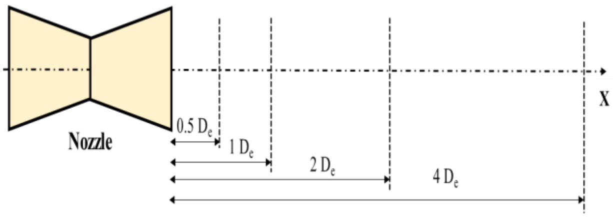


Fig. 4 Representation of the various axial locations having different X/D values

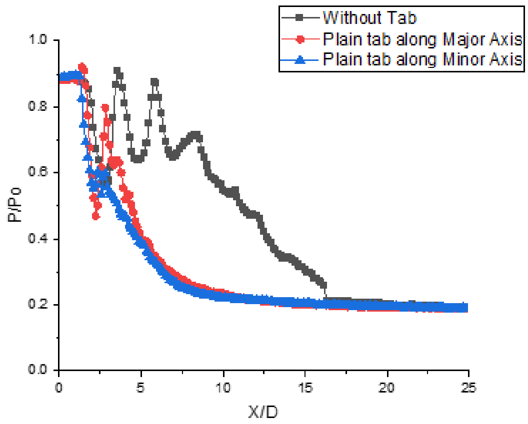


Fig. 5 Pressure reduction along the central axis of the jet at Nozzle Pressure Ratio 6.

expanded, and overexpanded). The effectiveness of the tabs as vortex generators is examined using both quantitative and qualitative methods. The quantitative observation has been carried out using centerline pressure decay measured by a pitot probe. The qualitative observations are achieved using Schlieren flow visualization.

3.1 Pressure Decay

In supersonic jet flow where the core is dominated by complex shock and expansion wave structures, it is difficult to convert measured pitot pressure to actual stagnation pressure prevailing inside the supersonic core. Therefore, to analyze supersonic length, the measured pitot pressure is commonly used. The key features of the jet, such as the supersonic length and its decay over distance, can be understood by looking at the pressure variation along the jet centerline. When the mingling of the jet with surrounding air is fast, the supersonic length becomes shorter, the pressure decreases quickly, and the fully developed jet is formed downstream to the nozzle outlet. Additionally, the amplitude of the pressure oscillations in the supersonic length can demonstrate the presence of shock cell structures.

To analyze the jet, the measured pitot pressure (P) data along the jet axis is made non-dimensional by using the settling chamber pressure (Po). This data is then plotted against the non-dimensional axial distance (X/D) for flow without and with tabs placed on the longest and shortest axis of the elliptical nozzle. The axial distances at different nozzle exit locations are shown in Fig. 4.

The non-dimensional pressure distributions along the central axis against axial locations are plotted in Fig. 5 which is associated with underexpanded conditions with a Nozzle Pressure Ratio (NPR) of 6. The analysis specifically looks at changes in centerline pressure for jets without any tab and with plain tabs placed on the longest and shortest axes of the elliptical Nozzle.

In the case of the jet without any tab, a visible supersonic length is observed, extending up to an axial distance of X/D = 8.4. Introducing the plain tabs on the longest axis at the nozzle outlet, the jet's supersonic length is notably reduced to X/D = 4.26. Likewise, the incorporation of a tab on the shortest axis at the nozzle outlet decreases the supersonic length to about X/D = 2.82. The supersonic length reductions in terms of percentages were evaluated using Eq. 1.

$$\text{Supersonic length reduction \% } (\Delta L) = \frac{L_{\text{Jet without tab}} - L_{\text{Jet controlled with plain tab}}}{L_{(\text{Jet without tab})}} \times 100 \tag{1}$$

Note that the supersonic length is decreased by 49.3% and 66.43% due to plain tabs placed on the longest axis and the shortest axis, respectively. The improved mixing associated with plain tabs on the shortest axis is attributed to the introduction of breaking down the large-size vortices into small-scale vortices along the axis. Analyzing the characteristic decay, it is observed that the jet without tabs experiences a greater amplitude of pressure fluctuation. In Fig. 5, it can be seen that introducing plain tabs on the longest axis causes a reduction in the amplitude of pressure fluctuations. Notably, the situation improves even further when tabs are deployed along the shortest axis, where the pressure fluctuates with a much lesser amplitude compared to both the uncontrolled jet and the jet with plain tabs on the longest axis.

Examining the centerline pressure reduction for the correct expansion condition at NPR 4.25 from Fig. 6, in the absence of a plain tab, a noticeable supersonic length is observed, extending up to an axial distance of X/D = 5. Placing the plain tabs on the longest axis at the nozzle outlet significantly reduces the jet's supersonic length to X/D = 2.46. Similarly, incorporating a tab on the shortest axis at the nozzle outlet further decreases the supersonic length to X/D = 1.9. This represents a substantial reduction of 50.8% in supersonic length due to plain tabs placed on the longest axis and an even greater reduction of 62% due to plain tabs placed on the shortest axis. In the characteristic decay, the pressure fluctuations observed without tabs are noticeably reduced when they are introduced on the longest axis. Furthermore, the reduction becomes even more pronounced when tabs are placed on the shortest axis. Additionally, there is a sharp decrease in pressure within a short distance, indicating a rapid transition into the fully developed region. This suggests that the incorporation of tabs, particularly on the shortest axis, contributes to a significant reduction in pressure fluctuations and facilitates a quicker transition to the fully developed state.

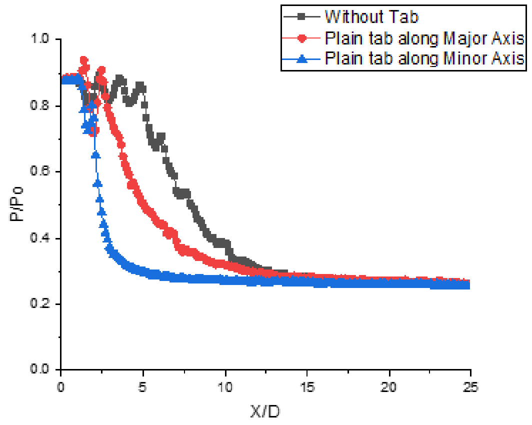


Fig. 6 Pressure reduction along the central axis of the jet at Nozzle Pressure Ratio 4.25

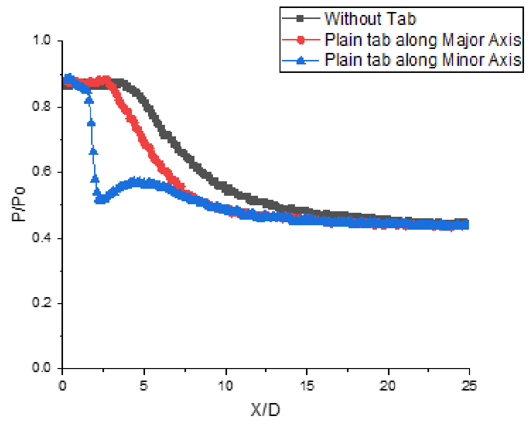


Fig. 7 Pressure reduction along the central axis of the jet at Nozzle Pressure Ratio 2.5

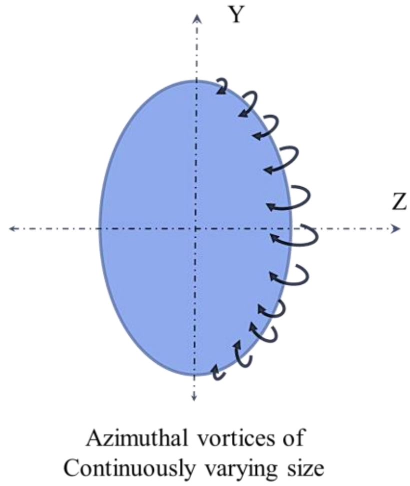


Fig. 8 Generation of varying-size vortices due to the Azimuthal asymmetry of the Elliptical nozzle

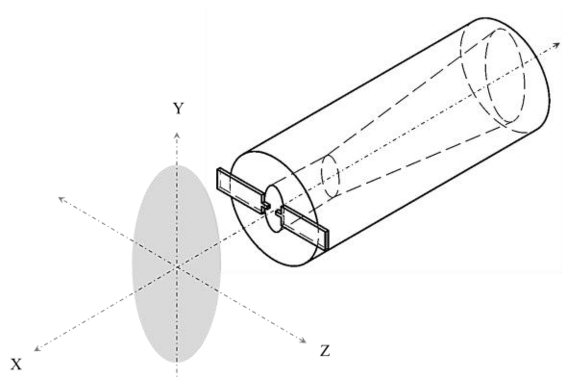


Fig. 9 Representation of X, Y, and Z directions of an elliptical Nozzle

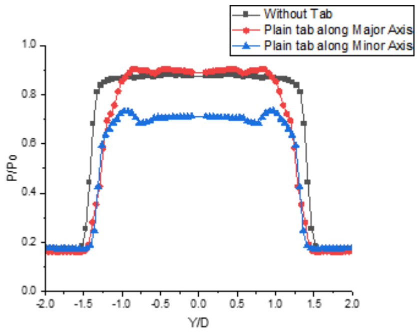
Figure 7 reveals notable changes in centerline pressure in overexpansion conditions at NPR 2.5. In the absence of plain tabs, a distinct supersonic length emerges, reaching X/D = 4. However, the introduction of plain tabs along the longest axis at the nozzle outlet considerably shortens the supersonic length, limiting it to X/D = 2.7. Similarly, the inclusion of a tab on the shortest axis further reduces the supersonic length to X/D = 1.52. This indicates a substantial 32.5% reduction in supersonic length with plain tabs on the longest axis and an even more significant 62% reduction with plain tabs on the shortest axis. Also, the characteristic decay is more rapid within a short region when the tabs are placed on the shortest axis.

When the jets are released from the nozzle, the vortices form due to kelvin Helmholtz instability. The size of the vortices defines the rate of jet mixing. A suitable proportion of small and large size vortices is essential for effective jet mixing (Kaushik, 2012). Figure 8 is a schematic representation of the formation of mixed-size vortices over azimuthal asymmetry at the exit plane of an elliptical nozzle. The figure highlights a direct correlation between the size of these vortices and the radius of curvature of the geometry.

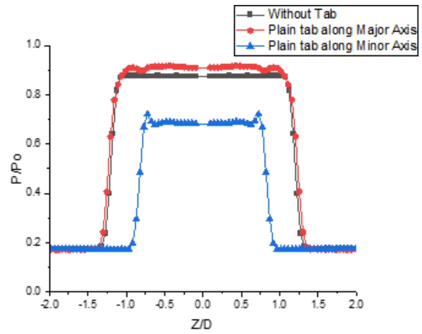
In an elliptical nozzle, the size of the vortices varies continuously at the boundary of the elliptical outlet, extending from the shortest axis to the longest axis. The largest vortices form at the shortest axis, while the smallest vortices form at the longest axis. This size variation is due to the fact that the radius of curvature of the nozzle boundary dictates the size of the vortices. As a result, the elliptical nozzle produces continuously varying vortices that promote mixing more effectively than an equivalent axisymmetric nozzle. Placing a tab on the shortest axis breaks the larger vortices into smaller ones. This advantage is compromised when the tab is deployed along the longest axis, where the vortices are already small. Thus, positioning the tab on the shortest axis enhances jet mixing and reduces the supersonic length.

To get more insight on jet flow characteristics the radial pressures are also plotted in Y and Z directions. The experiments are conducted keeping the longest axis as the vertical axis. The representation of X, Y, and Z directions are shown in Fig. 9.

An investigation into pressure measurements of jet flow in both Y and Z directions across various configurations, including plain tabs on longest and shortest axes, as well as uncontrolled jets, reveals

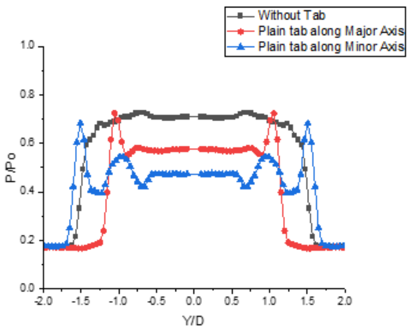


Pressure profile in Y direction

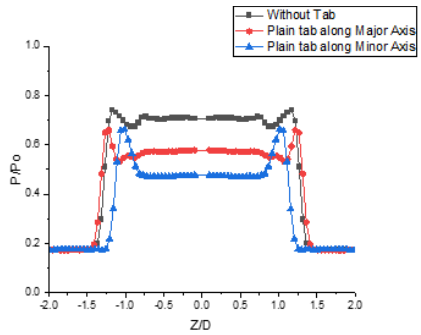


Pressure profile in Z direction

a) X/D=0.5

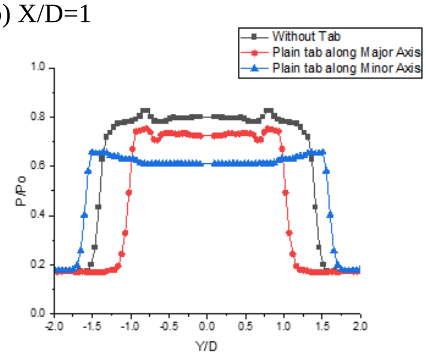


Pressure profile in Y direction

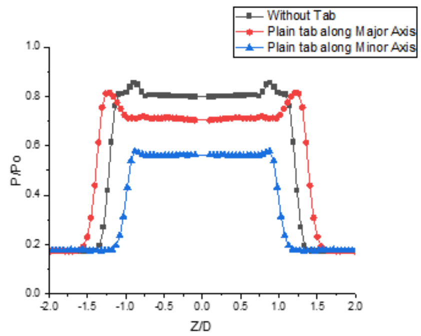


Pressure profile in Z direction

b) X/D=1

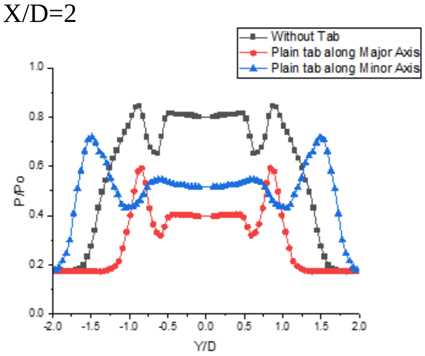


Pressure profile in Y direction

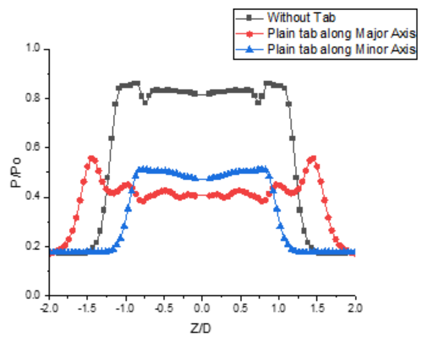


Pressure profile in Z direction

c) X/D=2



Pressure profile in Y direction

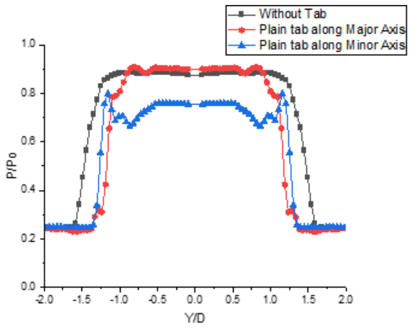


Pressure profile in Z direction

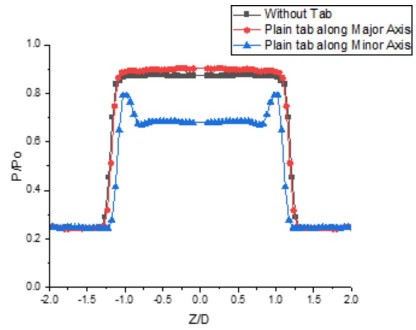
d) X/D=4

Fig. 10 Pressure profile comparison for the jet without and with tab placed on the longest and shortest axis at Nozzle Pressure Ratio 6

noticeable behaviors for each case. Figure 10 demonstrates the radial pressure profile for an underexpansion case at NPR 6. The ratio of pitot pressure to the settling chamber is plotted against the radial distances Y and Z. Focusing on an axial distance of X=0.5D, the plain tab on the shortest axis exhibits lower pitot pressure in both the Y and Z directions compared to the plain tab on the longest axis. At x=1D and 4D, the presence of two pressure peaks with low pressure at the center distinctly indicates jet bifurcation, promoting effective jet mixing. Similar patterns are observed for tabs placed on the longest axis.

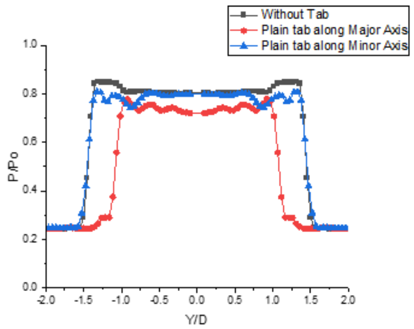


Pressure profile in Y direction

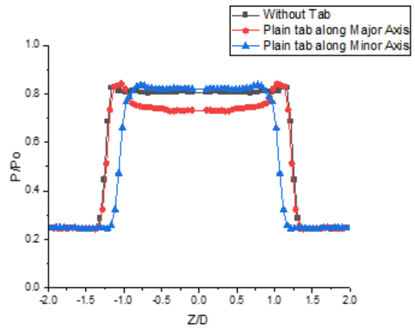


Pressure profile in Z direction

a) X/D=0.5

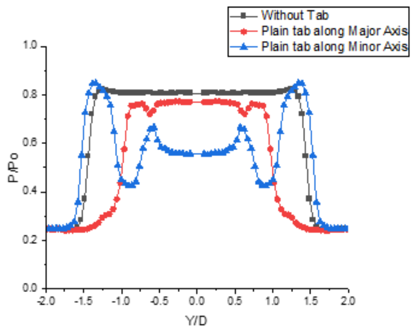


Pressure profile in Y direction

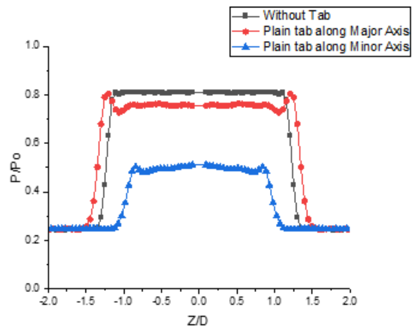


Pressure profile in Z direction

b) X/D=1

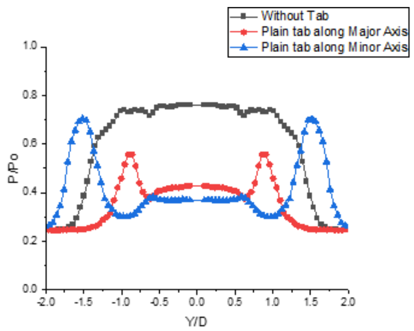


Pressure profile in Y direction

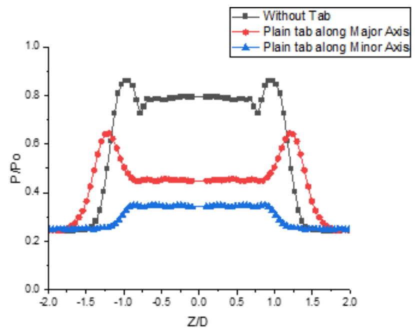


Pressure profile in Z direction

c) X/D=2



Pressure profile in Y direction



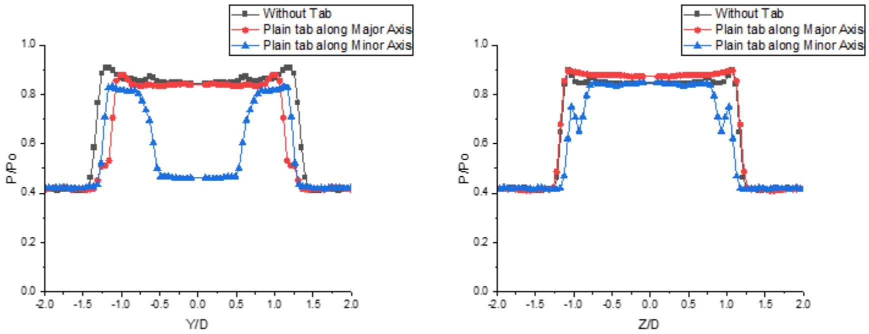
Pressure profile in Z direction

d) X/D=4

Fig. 11 Pressure profile comparison for the jet without and with tab placed on the longest and shortest axis at Nozzle Pressure Ratio 4.25

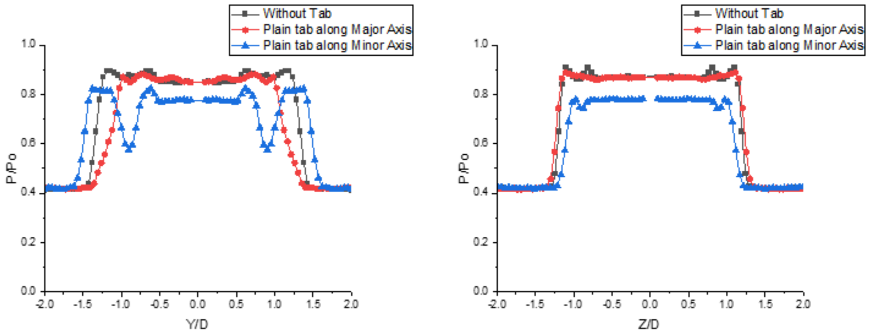
In Fig. 11, which illustrates the radial pressure profile for a correct expansion case at NPR 4.25, similar trends are observed as observed for NPR 6. At axial distances of 0.5D, 2D, and 4D, the plain tab on the shortest axis displays lower Pitot pressure in both Y and Z directions compared to the plain tab on the longest axis, signifying effective jet mixing. However, at an axial distance of 1D, the pressure recorded is slightly higher when plain tabs are placed on the shortest axis compared to the longest axis, attributed to the stronger daughter stream jet.

Finally, Fig. 12 depicts the radial pressure profile for an overexpansion case at NPR 2.5. Interestingly,



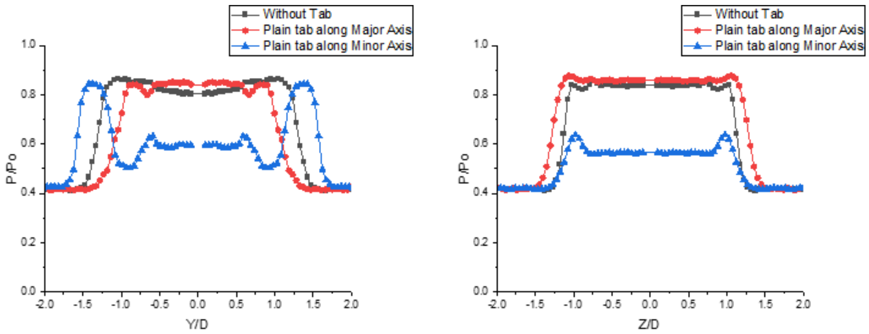
Pressure profile in Y direction | Pressure profile in Z direction

a) X/D=0.5



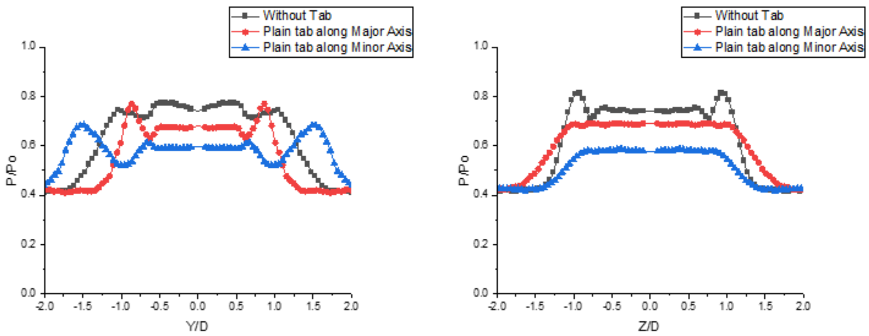
Pressure profile in Y direction | Pressure profile in Z direction

b) X/D=1



Pressure profile in Y direction | Pressure profile in Z direction

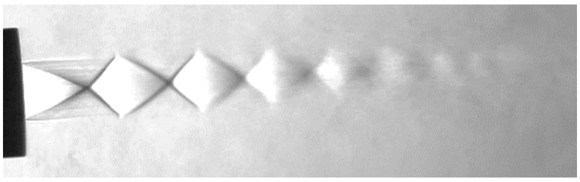
c) X/D=2



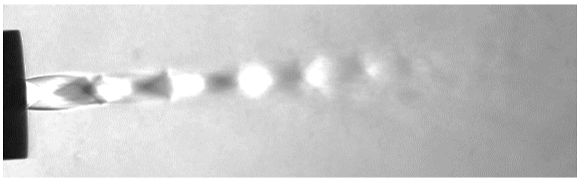
Pressure profile in Y direction | Pressure profile in Z direction

d) X/D=4

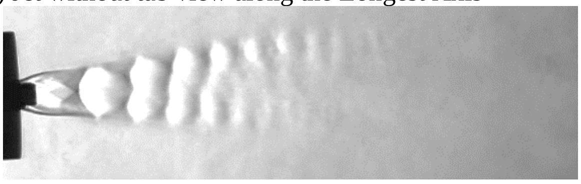
Fig. 12 Pressure profile comparison for the jet without and with tab placed on the longest and shortest axis at Nozzle Pressure Ratio 2.5



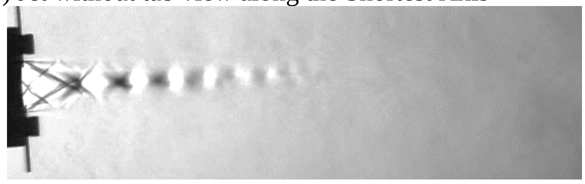
a) Jet without tab view along the Longest Axis



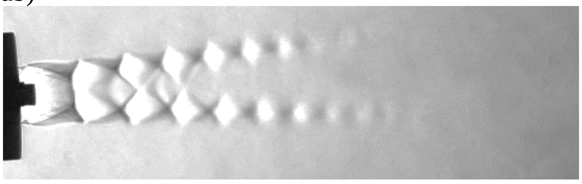
b) Jet without tab view along the Shortest Axis



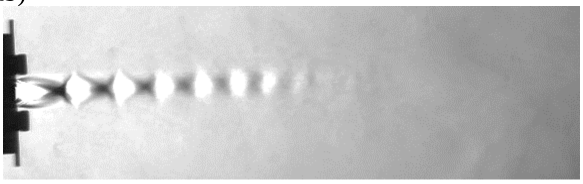
c) Jet with Plain Tab on longest axis (view along the Tab)



d) Jet with Plain Tab on longest axis (view normal to tab)

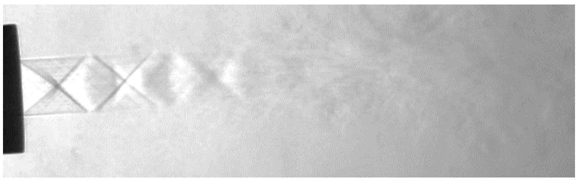


e) Jet with Plain Tab on shortest axis (view along the Tab)

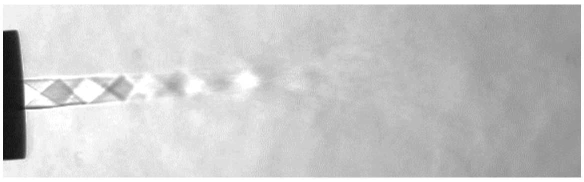


f) Jet with Plain Tab on shortest axis (view normal to Tab)

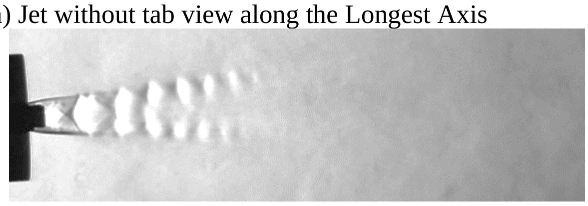
Fig. 13 Schlieren images of jet with and without a plain tab on longest and shortest Axis at Nozzle Pressure Ratio 6



a) Jet without tab view along the Longest Axis

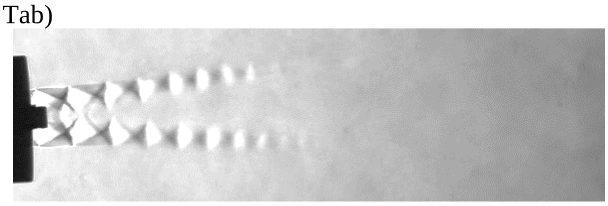


b) Jet without tab view along the Shortest Axis

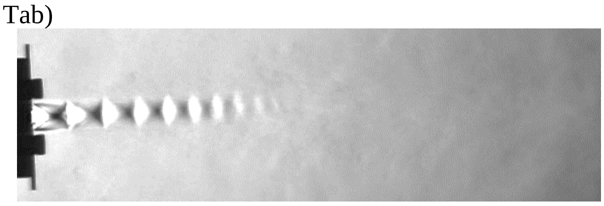


c) Jet with Plain Tab on longest axis (view along the Tab)

d) Jet with Plain Tab on longest axis (view normal to Tab)



e) Jet with Plain Tab on shortest axis (view along the Tab)



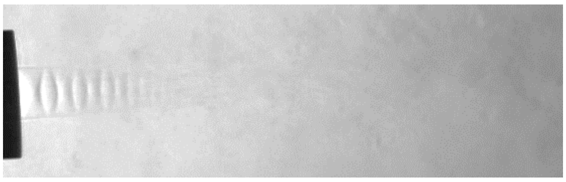
f) Jet with Plain Tab on shortest axis (view normal to Tab)

Fig. 14 Schlieren images of jet with and without a plain tab on longest and shortest Axis at Nozzle Pressure Ratio 4.25

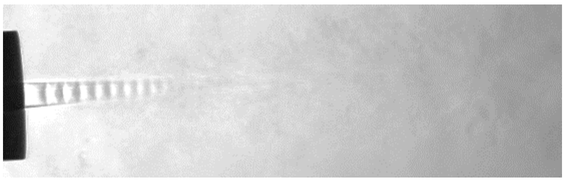
consistent with previous findings, the plain tab on the shortest axis exhibits lower pitot pressure in both Y and Z directions compared to the plain tab on the longest axis at axial distances of 0.5D, 1D, 2D, and 4D. This once again indicates effective jet mixing when the plain tab is placed on the shortest axis.

3.2 Schlieren Flow Visualizations

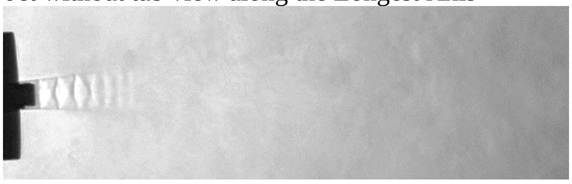
Figures 13, 14, and 15 depict the Schlieren images of a jet without tabs and with tabs positioned along the longest and shortest axes at NPR (Nozzle Pressure Ratios) of 6, 4.25, and 2.5. In the absence of tabs, stronger shocks form due to compression and expansion waves. Note that, the Mach Disks are the distinct patterns of standing wave formations within the supersonic jet, resulting from complex interactions of compression waves and expansion fans. One crucial determinant of Mach Disk placement is the degree of expansion of the supersonic exhaust flow from the nozzle. When the exhaust is slightly over-expanded, Mach Disks tend to form closer to the nozzle exit. Conversely, in cases of under-expansion, where the exit pressure is higher than ambient, Mach Disks form further downstream.



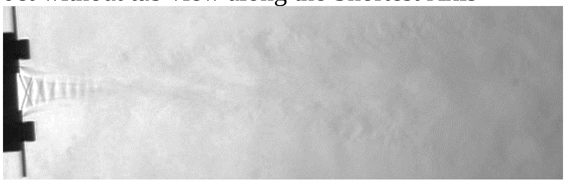
a) Jet without tab view along the Longest Axis



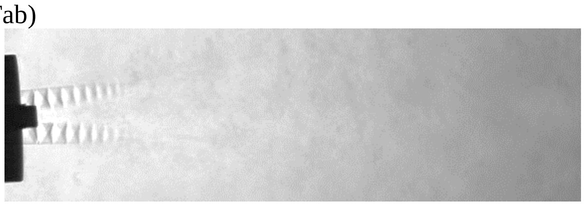
b) Jet without tab view along the Shortest Axis



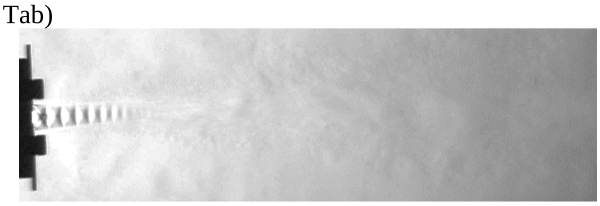
c) Jet with Plain Tab on longest axis (view along the Tab)



d) Jet with Plain Tab on longest axis (view normal to Tab)



e) Jet with Plain Tab on shortest axis (view along the Tab)



f) Jet with Plain Tab on shortest axis (view normal to Tab)

Fig. 15 Schlieren images of jet with and without a plain tab on longest and shortest Axis at Nozzle Pressure Ratio 2.5

It can be observed from the visualization pictures that the uncontrolled jet exhibits stronger waves than the tab-controlled jets. When plain tabs are introduced, along the longest or shortest axis, they bifurcate the elliptic jet along with prominent shock cell distortion which is more noticeable at NPR 6.

Figures 13 depict Schlieren images comparing a jet's behavior both with and without tabs, positioned along the longest and shortest axes, at NPR 6. In the uncontrolled jet, the jet displays stronger shocks due to compression and expansion waves. Conversely, the introduction of plain tabs, regardless of axis orientation, results in the bifurcation of the elliptic jet and noticeable distortion of shock cells. Daughter streams of circular shape emerge as a result. Notably, the jet controlled by tabs along the shortest axis exhibits a reduced supersonic length compared with the jet without tabs and tabs placed on the longest axis which supports the pressure decay study, observed in Fig. 3. The weaker waves are more noticeable with tabs placed on the shortest axis compared to its longest axis. Moreover, distinct diamond-shaped daughter streams are formed, with the dissipation of the jet being more pronounced when tabs are placed along the shortest axis.

Figures 14 and 15 extend this analysis to NPR 4.25 and NPR 2.5, respectively, revealing a consistent trend in shock formation with reduced strength as the NPR decreases. At NPR 2.5, tabs placed along the longest axis failed to induce prominent bifurcation, while those on the shortest axis clearly define the bifurcated jet, resulting in higher jet cross-sectional area and thereby higher mixing. This configuration results in a significant reduction in core length, by 62% compared to the uncontrolled jet that supports the pressure decay, as observed in Fig. 6 and Fig. 7, highlighting the importance of tab placement along the shortest axis in effectively altering jet characteristics.

Among the controlled jets, the tab along the shortest axis results in a shorter supersonic length with weaker waves compared to the tab along the longest axis. Additionally, the strength of expansion and compression waves and the supersonic length increase with higher NPR. However, the supersonic length of the manipulated jets remains smaller across all NPRs.

The Schlieren images support findings from centerline pressure decay. Characteristics such as the shorter supersonic length and weaker waves are visible for controlled jets when compared to the uncontrolled jet. Specifically, the jet with tabs along the shortest axis, depicted in Fig. 13, Fig. 14, and Fig. 15, consistently demonstrates significant jet bifurcation at all NPRs.

Notably, the jet controlled by tabs along the shortest axis exhibits a reduced supersonic length of 66.43% compared with the jet without tabs and tabs placed on the longest axis which supports the pressure decay study as shown in Fig 3. Essentially, the weaker waves are more noticeable with tabs placed on the shortest axis compared to its longest axis. Moreover, distinct diamond-shaped daughter streams are formed, with more pronounced jet dissipations when tabs are placed along the shortest axis.

4. CONCLUSION

The study of Mach 1.6 elliptic jets demonstrates that the introduction of plain vortex generators or plain tabs has a profound influence on the mixing behavior of supersonic jets. It is observed that the deployment of plain tabs along the shortest axis of the jet significantly enhances mixing compared to the placement of tabs on the longest axis of the jet and uncontrolled jet. Specifically, at a Nozzle pressure ratio of 6, plain tabs along the shortest axis of the jet demonstrate superior jet mixing with a 66.43% reduction in supersonic length. Tabs deployed along the longest axis reduce the supersonic length to

49.3% and mitigate pressure fluctuations. Shadowgraph results indicate that tabs along the shortest axis consistently induce jet bifurcation at all Nozzle pressure ratios, leading to improved mixing compared to tabs along the longest axis. Also, the features such as a shorter supersonic length and weaker waves in the presence of tabs, align with the quantitative measurements. This result is consistent across different nozzle pressure conditions, highlighting the superiority of the observed phenomenon. Essentially, the plain tabs induce jet bifurcation when placed in both the longest and shortest axes. The increased mixing is noticeable with tabs along the shortest axis due to the effective jet bifurcation, and generation of smaller-size vortices.

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CONFLICT OF INTEREST

The authors have no conflicts to disclose.

AUTHORS CONTRIBUTION

T. Paramesh performed the experiments and wrote the first draft. **Tamal Jana** supervised the study and edited the manuscript. **Mrinal Kaushik** edited and reviewed the final manuscript.

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