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Experimental Study on the Effect of Tabs with Asymmetric Projections on the Mixing Characteristics of Subsonic Jets

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ABSTRACT

This study experimentally explores the effect of tabs with asymmetric projections on the mixing effectiveness of jets at different nozzle exit Mach numbers with subsonic ranges of 0.4, 0.6, and 0.8. The results obtained with the tab-controlled jet are compared with those of uncontrolled jets. In this experimental investigation, a pair of identical tabs is deployed along a diameter of a convergent nozzle with inlet and exit cross sections of a circle, where each tab has two triangular projections configured at locations offset to each other at a distance of 1 mm on a plain rectangular stem. The geometrical blockage due to the presence of both tabs is maintained at 5.09% to minimize the thrust loss incurred due to tabs. The counter-rotating vortices generated at different locations of the tabs, caused instability or shear distortions at the nozzle exit, promoting jet mixing and eventually leading to rapid velocity decay along the jet axis and accentuating the reduction of the potential core. Compared to plain jet, reductions in core length of about 70%, 76%, and 81% at Mach 0.4, 0.6, and 0.8, respectively, are observed with the tab-controlled jets. The total pressure decay characteristics in the radial profile along the tab and normal-to-tab orientations have shown significant distortion in the jet structure, making it asymmetrical again owing to the asymmetrical positioning of projections on the tabs. Besides, in comparison with the plain nozzle, the total pressure decay characteristics in the radial profiles of tab-controlled jets are significantly different along the axial locations in the downstream direction due to the same reason of the asymmetrical positioning of triangular projections on the tabs. The primary research goal of this experimental investigation with asymmetrical tabs is to promote jet mixing asymmetrically to achieve thrust vectoring of jets.

Keywords: Experimental aerodynamics; Jet mixing; Convergent nozzle; Subsonic jets; Asymmetric projections; Jet entrainment; Counter-rotating vortices.

NOMENCLATURE

D	nozzle exit diameter	x	coordinate along the centerline
M	Mach number	y	coordinate normal to the centerline
p_t	total pressure at the nozzle exit	z	coordinate normal to the ground plane
p_0	gauge pressure at the nozzle inlet		

1. INTRODUCTION

In many engineering applications involving jet flows, the mixing enhancement of jets plays a significant role. Jet mixing enhancement finds its importance in applications such as noise reduction in commercial aircraft, reduction of infrared signature in military jets, improvement of the combustion cycle's efficiency, and so on. As a result, it has been the focus of continuous and extensive research for several decades. Jet control is broadly classified into active and passive control techniques, adapted for mixing enhancement in jet flows based on the applications and requirements. In the case of the former, jet control is achieved by an external energy source to create disturbances to the flow, whereas, in the latter, modifications at the nozzle exit like vortex generators (tabs), chevrons, and grooves or perforations are used.

Entrainment, an important feature of shear flows, is primarily responsible for the shear layer growth in the downstream direction due to the inward flow of the slower-moving surrounding fluid. It is essentially the result of a mixed layer (free shear layer) forming between the core and the surrounding fluid near the jet exit. The free shear layer grows directly from the nozzle exit due to the instabilities created by the jet control technique, thus creating vortices of different length scales that act as momentum transporters between them. The ensuing stream-wise vortices grow in size due to vortex stretching, and inundate the surrounding fluid from the environment into the jet core, thereby improving jet mixing and hastening jet decay. The interaction of these vortices with the flow structures in the mixed layer traps more surrounding fluid into the jet core. The downstream distance from the jet exit, as well as the velocity gradient across the shear layer, have a significant impact on the potential core length reduction.

The experimental investigation carried out by Bradbury and Khadem (1975) to investigate the effective influence of mechanical tabs (small protrusions at the exit of a nozzle) on low-speed jets showed that the introduction of tabs increased the jet spread rate significantly, thereby reducing the potential core length and also causes bifurcation of the jets. Zaman *et al.* (1991), Zaman (1993) and Zaman *et al.* (1994) experimentally investigated the effects of the distortion created by the mechanical tabs. The tabs shed a pair of stream-wise vortices that was found to be responsible for the entrainment and significant jet spread. Ahuja (1990) found that the mechanical tabs fixed at the nozzle exit render significant jet mixing, particularly at subsonic speeds. In a further study by Ahuja (1993), the mechanical tabs were equally effective in increasing the jet mixing at high speeds. The systematic research by Zaman *et al.* (1992) reported the effectiveness of delta tabs' enhanced mixing performance and discovered that at high temperatures and speeds delta tabs exhibit good mixing enhancement performance. Behrouzi and McGuirk (1998) in their experimental investigation reported that the parameters like a tab's projected area, number, width, shape, and angle of orientation play a significant role in jet decay. Results showed that an increased number of tabs ensued more jet decay. Singh and Rathakrishnan (2002) observed from their experiments that the tabs' width was found to be more effective in the jet mixing enhancement for the same projected area than its length.

In their experimental study, Sreejith and Rathakrishnan (2002) used a cross-wire at the exit of a convergent nozzle operating at subsonic speeds and reported that the cross-wires created stream-wise vortices that aids in the decay of the centerline Pitot pressure more swiftly. Lovaraju and Rathakrishnan (2006) compared the cross-wire effectiveness of subsonic and sonic axisymmetric jets. The jet mixing obtained was quite effective right from the nozzle exit in the presence of cross-wires at all Mach numbers. Thanigaiarasu *et al.* (2008) investigated experimentally the geometrical effects of fixing tabs at the exit plane of a convergent nozzle on underexpanded sonic jet conditions at different tab orientations. The configuration with arc-tab facing-in used by them at all blockage levels proved to be more effective when compared with the other two configurations of arc-tab facing-out and rectangular tabs. With the former configuration, the core length reduction observed was 80%, and for the latter case i.e. jets with arc-tab facing-out and rectangular tabs, the corresponding reduction was only 40%.

Phanindra and Rathakrishnan (2010) experimentally investigated the effect of rectangular tabs with corrugations in the mixing enhancement of convergent-divergent axisymmetric jets with a design Mach number of 1.8. From their experimental investigation, the reduction in core length achieved was about 78% for NPR 7 in the case of corrugated rectangular tabs when compared to the plain rectangular tabs. Chand *et al.* (2011) in their experimental study reported the effectiveness of arc tabs with perforations fixed at a convergent nozzle exit plane on the mixing improvement of axisymmetric jets at subsonic and sonic conditions. The results showed that the arc tabs with perforations enhanced the mixing of jets for both subsonic and sonic conditions significantly. The potential core length decreases significantly for various Mach numbers.

Ahmed *et al.* (2013) in their experimental study compared the jet mixing effectiveness of tabs with and without perforations (solid tabs) on the jet at different subsonic Mach numbers. The results revealed that the influence of tabs without perforations (solid tabs) dominates in the far downstream directions when compared to perforated tabs. An increment in centreline decay at Mach 0.4 was observed compared to other Mach numbers. Despite being less effective on pressure decay, the perforated tabs significantly improved the thrust loss reduction. Maruthupandian and Rathakrishnan (2018) experimentally studied the effect of tab location on supersonic jet mixing and revealed that the aerodynamic mixing of supersonic free jets was modified by the shifting of limiting tabs. The jet core length reduction achieved by the introduction of tabs was better in the presence of an adverse pressure gradient of about 55%. The core length reduction caused by the shifting of the tab at 0.25D, 0.5D, and 0.75D were 35%, 15%, and 31%, respectively, whereas, for the tab at 0D, the core length reduction was only 6%.

Thanigaiarasu *et al.* (2020) in their numerical analysis reported the effectiveness of two configurations of solid rectangular tabs with right-angled triangular projections on the effectiveness of jet mixing of subsonic jets. In comparison to the tab configuration with right-angled triangular projections separated with a distance of 0 mm between them on either side, the configuration with a separated distance of 1 mm between the triangular projections was found to be more effective for all the Mach numbers analyzed.

The above discussions reveal that by controlling thevortex size owing to the presence of the tabs, promotion in the mixing rate could be achieved, as a result of which more ambient fluid gets entrained into the jet core. Also, it is a proven fact that as the size of the vortices gets smaller, the mixing efficiency becomes better since the smaller-sized vortices have a comparatively longer life than the larger ones. In addition, the smaller vortices tend to pair with each other, growing in size, thereby entraining more surrounding fluid into the core effectively.

Most of the research on jet control largely focused on using symmetric configurations of vortex generators for flow manipulation. Only limited studies were carried out on the asymmetric configuration of vortex generators. In this present study, asymmetric tabs with triangular protrusions at offset locations are used since they shed vortices at different locations, which is expected to affect the flow characteristics. Two asymmetric tabs are used in this present study. Each tab consists of a stem on which two triangular protrusions are fixed, one on either side offset from the other at a distance of 1 mm. At the exit of a convergent nozzle that discharges the flow at subsonic jet Mach numbers of 0.4, 0.6, and 0.8, respectively, two of such tabs are fixed. The triangular projections shed vortices of different sizes and scales in the jet's transverse and azimuthal directions, thereby accentuating the entrainment of the surrounding fluid into the jet core.

2. EXPERIMENTAL METHODOLOGY

2.1 Experimental Models Used

An exit diameter of 20 mm and an inlet diameter of 40 mm were used as the dimensions for the convergent nozzle used in this experimental study. The nozzle and the base plate for attachment to the settling chamber flange have been grouped into one unit. The overall length of the nozzle, including the base plate thickness, is kept at 50 mm and the convergence angle of the nozzle is 11.3 degrees. The base plate diameter is around 97 mm concerning the size of the mounting flange. The nozzle was made of brass material and was attached to the exit of the settling chamber using a flange assembly.

This study employs a passive jet control method. At the exit of a convergent nozzle, two rectangular tabs with two isosceles triangular projections (resembling fins) on each tab are fixed diametrically opposite. The tabs used in the experiment were made of mild steel. The length of the rectangular stem was limited to 4 mm and the height of the triangular fins to 1.8 mm to minimize the geometric blockage to the flow. To minimize the thrust loss, the total geometric blockage due to tabs is limited to about 5.09%. Both fins were mounted at an offset distance of 1 mm. The additional sharp corners of the triangular fins also shed the counter-rotating vortex pairs. As a result, these additional vortices, along with those produced by the main stem of the tabs, engulf more surrounding fluid into the jet core, thereby improving the jet mixing characteristics and also resulting in a significant reduction of potential core length. The geometry of the convergent nozzle and the tab configuration used is shown in Figs. 1.a, 1.b shows the photographic view of the tab mounted at the nozzle exit.

The percentage of Blockage ratio with the presence of tabs at the nozzle exit was calculated using equation (1).

$$\%\ of\ Blockage\ ratio = \frac{tab\ area}{nozzle\ exit\ area} \times 100$$

2.2 Experimental Setup

The experiments were carried out in the high-speed jet laboratory at MIT Campus of Anna University, Chennai. The schematic layout of the experimental setup is shown in Fig. 2.a. Two compressors were used to compress the atmospheric air and the compressed air was stored in two large reservoirs (storage tanks), and the compressed air from the tanks was allowed to expand through a settling chamber with flow conditioning units. The

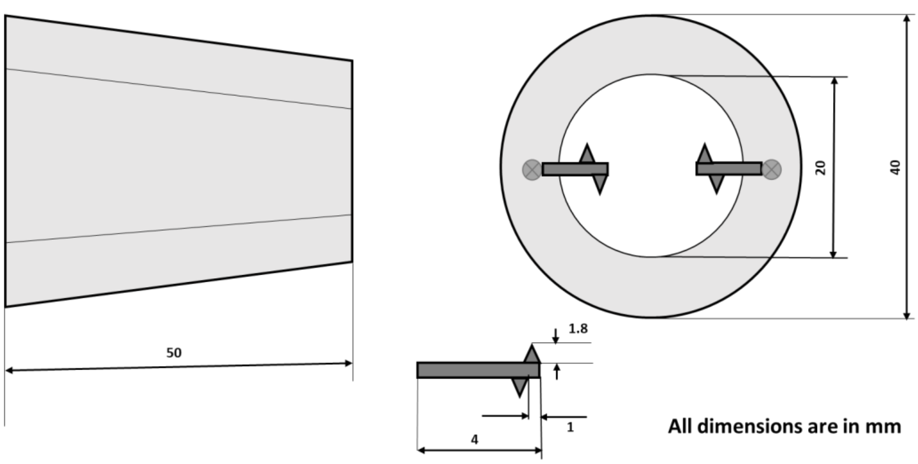
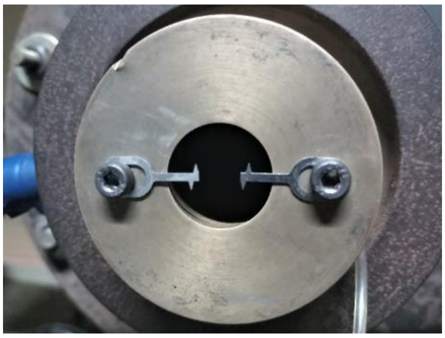


Fig. 1.a. Schematic diagrams of the convergent nozzle and the tab.



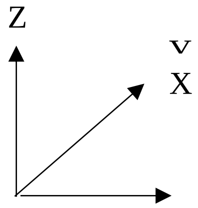


Fig. 1.b. Photographic view of the tab mounted at the nozzle exit.

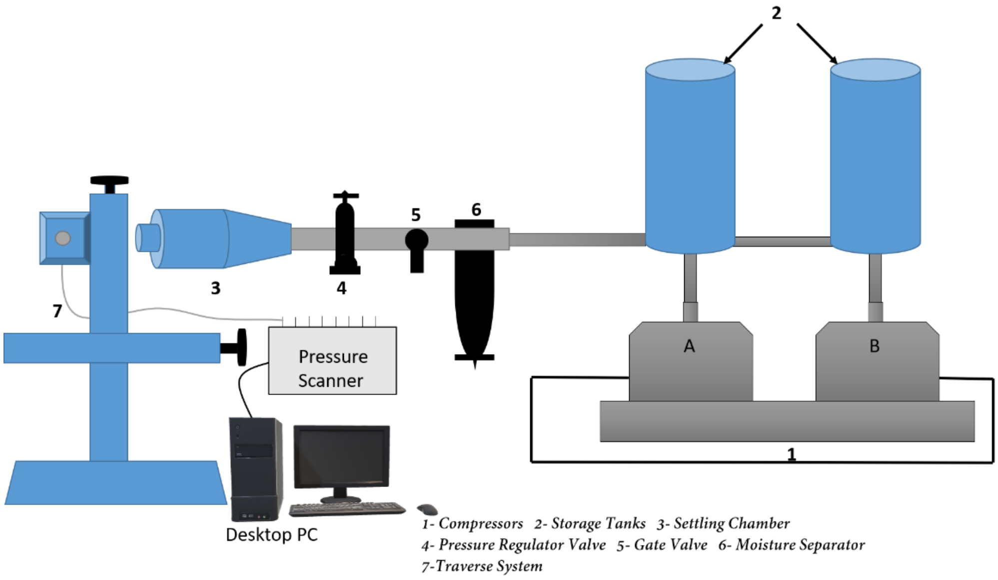


Fig. 2.a. Schematic layout of the experimental facility.

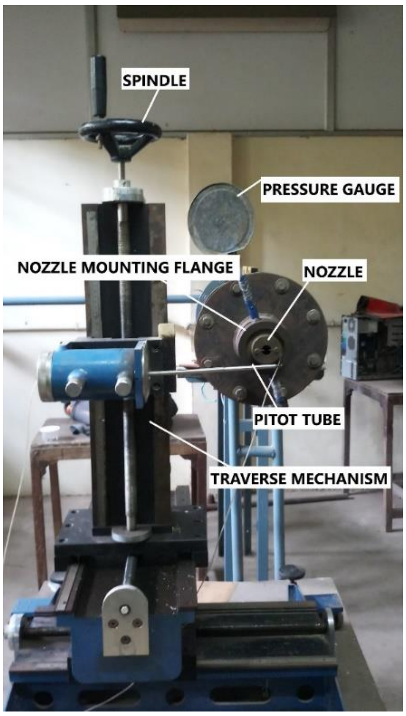


Fig. 2.b. Photographic view of the experimental facility.

convergent nozzle was mounted in the flange of the settling chamber exit using suitable mounting provisions. Standard atmospheric conditions were assumed during the experiments. Compressed air from the storage tanks was filtered via wire mesh screens in the settling chamber to reduce air turbulence at the nozzle inlet. The convergent nozzle, which was fixed to the end of the settling chamber, discharged the jet into the laboratory under stagnant conditions. A pressure regulating unit was fitted along with a moisture separator to adjust the parametric variation of pressure values corresponding to various jet Mach numbers during the experiments. The moisture separator unit removes any moisture content in the compressed air formed due to the condensing effect. Experiments were conducted for three different Mach numbers of 0.4, 0.6, and 0.8. The photographic view of the experimental facility is shown in Fig. 2.b.

2.3 Instrumentation

2.3.1 Pitot Probe

A Pitot probe mounted on a 3-D traverse system was used to measure the pressure. The probe was positioned so that it was aimed straight into the jet stream issuing out from the nozzle exit. A Pitot

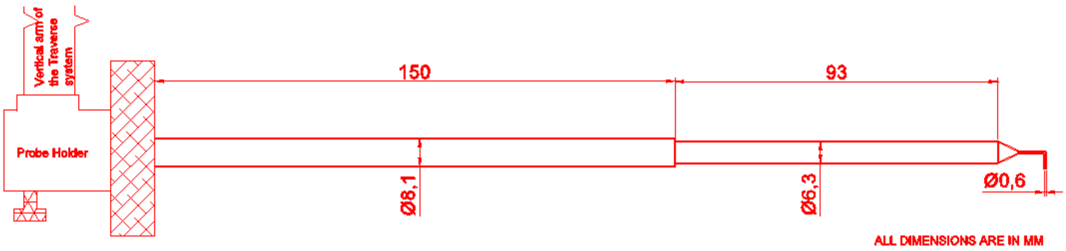


Fig. 2.c Schematic diagram of the Pitot probe

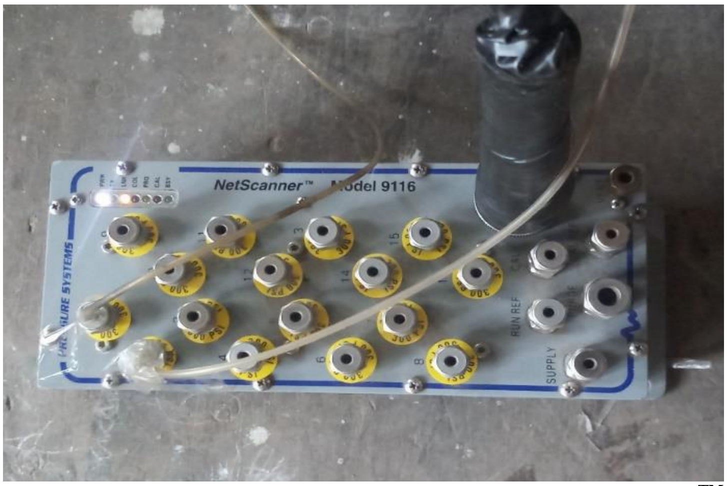


Fig. 2.d Photographic view of a 16-Channel pressure transducer (NETSCANNER^{TM} Model 9116).

probe is a tube with a blunt-nosed, open end that is pointed in the direction of the airflow. The Pitot probe has an inner diameter of 0.4 mm and an outer diameter of 0.6 mm. Based on the formula, Blockage ratio = Nozzle exit area/Probe area, the blockage ratio as a result of the probe's presence was calculated to be 1111.11. The tolerable probe blockage value of 64 established by Kaushik (2012) is very mush lesser than this value; therefore the probe blockage doesn't radically affect the pressure reading. Also, since the Reynolds number for the jet Mach numbers considered in this investigation are comparatively greater than 500, the effects of viscosity are deemed negligible on the pressure measurements. The pressure measured by the Pitot probe is the total pressure from which the flow velocity can be determined using the isentropic relation because the studied Mach numbers are subsonic. The schematic diagram of a Pitot probe is shown in Fig. 2.c.

2.3.2 Traverse Mechanism

A 3-D traverse system was used in this experimental study in which the Pitot probe was fixed. The 3-D traverse system employed has 6 degrees of freedom and a Probe-yawing mechanism for moving the probe. Measurements can be taken along the X, Y, and Z axes via the traverse mechanism in all three directions. The probe has a positioning accuracy of ±0.1 mm. The linear resolution of the traverse system was about 0.1 mm. The Pitot tube, mounted on the traversing mechanism, could move up to 800 mm in all three directions.

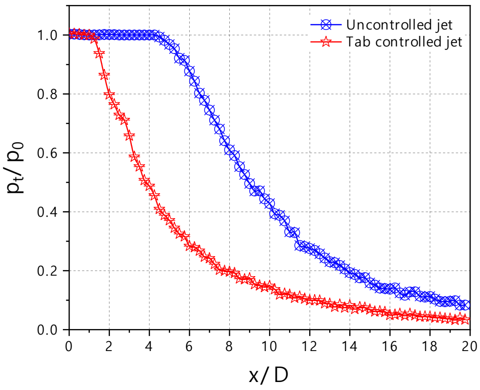
2.3.3 Pressure Scanner

A 16-channel pressure transducer unit was used in this experiment to measure the pressure values in the jet field (NETSCANNER^{TM} Model 9116). A pressure transducer is an electronic device that converts the pressure input into electrical signals that a processing unit can capture. The 16-channel pressure transducer was connected to a computer via a software interface, which helped the data acquisition and processing. The pressure transducer was capable of measuring 300 psi (approximately 20 atm). The pressure transducer sampling rate was approximately 500 readings per channel per second. Figure 2.d illustrates the photographic view of the 16-channel pressure transducer used in this investigation.

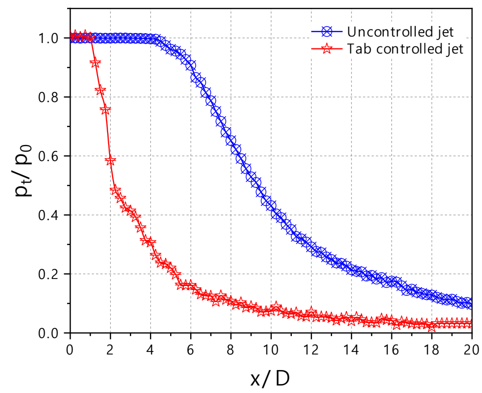
3. RESULTS AND DISCUSSION

3.1 Centerline Total Pressure Decay

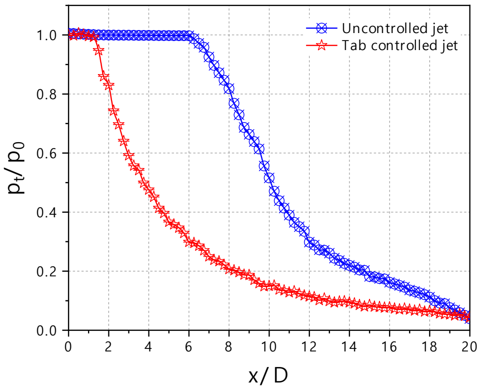
The jet entrainment is a measure of total pressure decay along the centerline. The most accurate way to assess jet propagation is the centerline total pressure decay, which is well-known. The rate at which the jet mixes with the surrounding fluid is proportional to the increase in jet decay rate, which shows that the jet mixing gets better when the centerline decay is instantaneous. According to



(3.a) At M = 0.4



(3.b) At M = 0.6

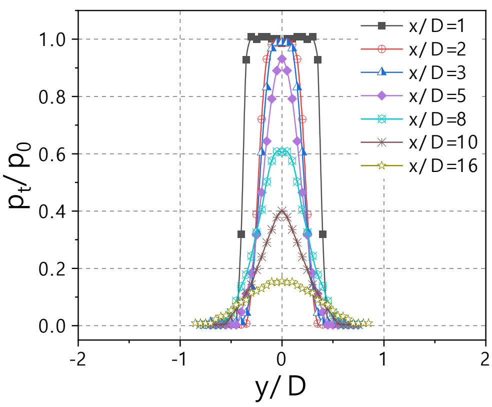


(3.c) At M = 0.8

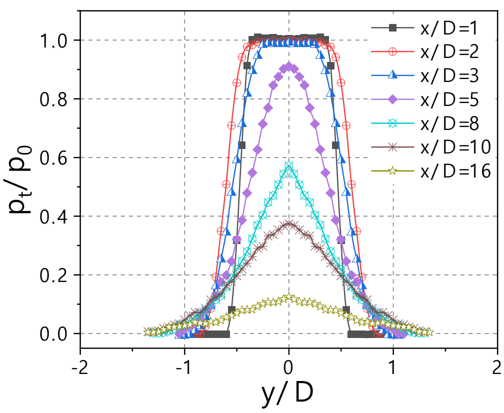
Fig. 3.a–3.c. Centerline total pressure decay for uncontrolled and tab-controlled jets at different Mach numbers.

Kaushik (2019), the centerline pressure decay reveals the length of the potential core region, which is generally perceived as the axial distance up to which the velocity along the axis is unaffected. Comparisons are made between both the uncontrolled and tab-controlled jets' centerline pressure decay characteristics at Mach 0.4, 0.6, and 0.8. The comparative graphs provide insights into the superiority of tabs in the mixing enhancement over the uncontrolled jet. The centerline total pressure decay trends of both the uncontrolled and tab-controlled jets at various jet Mach numbers are shown in Figs. 3.a – 3.c. Figure 3.a depicts the centerline total pressure decay of tab-controlled and uncontrolled jets at Mach 0.4. The potential core length is about 4.3D for the uncontrolled jet, which gets reduced to about 1.2D for the tab-controlled jet. Figures 3.b and 3.c show similar trends for Mach 0.6 and 0.8 jets, where the potential core length reduces from 5D to 1.2D and 6.5D to 1.25D, respectively. The jet core length reduction achieved is due to the entrainment of surrounding fluid into the core, as reported by Kaushik (2012). The reduction in core length achieved with the introduction of tabs shows that the asymmetric projections in the tabs substantially affect the mixing characteristics. This is due to counter-rotating stream-wise vortex pairs of various length scales generated at the main stem's sharp corners and projections, which start merging at specific downstream locations and expanding as ambient fluid is engulfed in the jet.

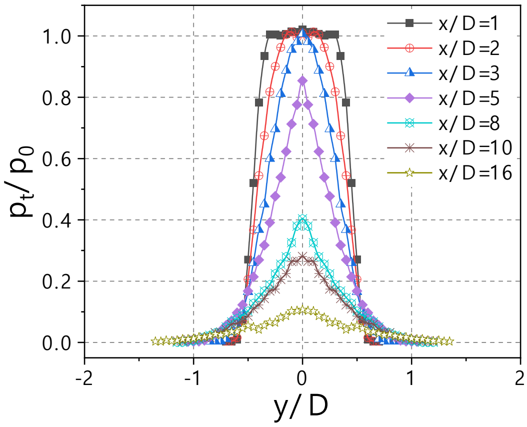
In comparison to the uncontrolled jet, the Mach 0.4 jet controlled with the tabs experiences a core length reduction of around 70%. With the increase of Mach number from 0.6 to 0.8, the percentage core length reduction also increases to 76% and 81% respectively. These results imply that when the jet Mach number rises, momentum transfer between the surrounding fluid and the jet during entrainment is more efficiently promoted by the counter-rotating vortices shed at the asymmetric locations of protrusions on the tabs, especially at higher subsonic velocities. The potential reduction in core length may be due to the vortices' increased mixing efficiency (since they are now mixed size for tab-controlled jets) and their residual time to interact with the surrounding fluid (Rathakrishnan 2013). For Mach 0.6 and 0.8 jets, the residual time available for vortices is less than that available for the Mach 0.4 jet. Another reason for this improved performance may be the larger compressibility effects associated with jets at higher Mach numbers. The efficiency of the tabs is further substantiated by the comparison of the three cases, which revealed that the tab-controlled jets accomplish a significantly faster decay than the uncontrolled jets. Since the tabs used in this experimental investigation is having protrusions along the y and z-axes of the flow, two sets of vortices are formed.



(3.d) At M = 0.4



(3.e) At M = 0.6



(3.f) At M = 0.8

Fig. 3.d – 3.f. Total pressure decay profiles for the uncontrolled jet in the radial direction at different Mach numbers

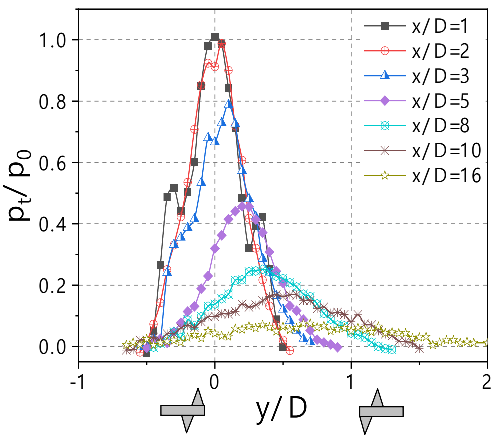
Transverse vortices are generated along the y-axis by the rectangular stem of the tabs and azimuthal vortices are formed by the presence of two triangular projections on either side of the main stem. These sets of vortices move along the jet axis downstream and become stream-wise and entrain more surrounding fluid into the core thereby promoting jet mixing.

3.2 Total Pressure Decay in Radial Direction (Along the Tab)

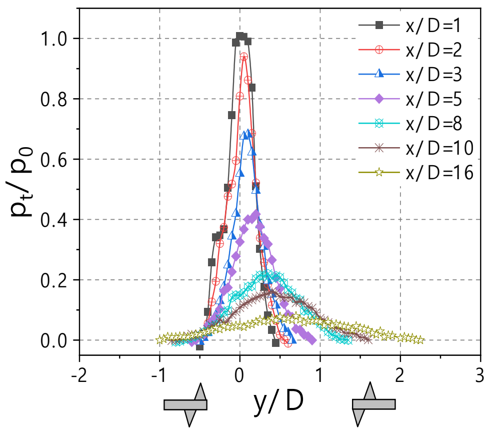
For each of the investigated Mach numbers, Pitot pressure profiles were taken at various axial locations along and normal to the tab orientations for the uncontrolled and tab-controlled jets to gain a deeper comprehension of the development of the jet flow. The total pressure decay profiles of the uncontrolled and tab-controlled jets at three jet Mach numbers of 0.4, 0.6, and 0.8 in the y and z directions are shown in Figs. 3.d – 3.i.

A comprehensive understanding of the effect of asymmetric projections in the tabs at different x/D positions may be gained by comparing the radial pressure decay profiles of the uncontrolled jet and the tab-controlled jets at various Mach numbers. At x/D = 1, the total pressure profile is flat along the radial direction and exhibits a classic top-hat structure, as shown in Fig. 3.d, which represents the radial pressure decay profile of the uncontrolled jet at Mach 0.4. It shows that the pressure profile is nearly constant around the jet axis up to around y/D = 0.5, after which the Pitot pressure drops sharply. As the downstream distance grows, the pressure homogeneity gradually decreases as a result of the development of vortices at the jet periphery along the axial direction, which results in the jet spreading phenomena. At x/D = 5, the pressure profile displays a single peak. At x/D = 8, the pressure value drops to pt/p0 = 0.6, showing the characteristic decay of the jet. Due to the velocity drop at the centerline, the pressure profile is almost flat at x/D = 16, suggesting a fully developed jet and resembling a self-similar profile.

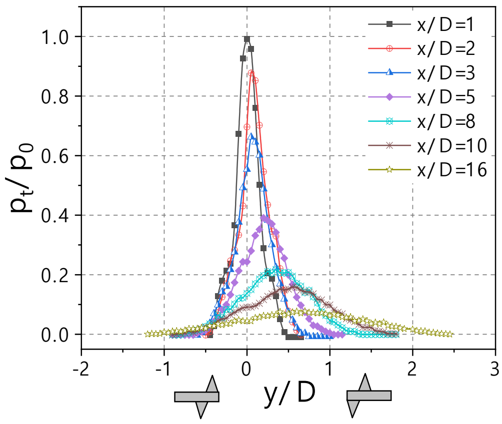
Fig. 3.g shows the radial pressure profile for the tab-controlled jet at Mach 0.4. The pressure decay is comparatively faster than the uncontrolled jet, both in the vicinity of the nozzle exit and in the far downstream locations. The asymmetricity observed in the pressure profile is due to the effect of triangular projections kept offset to each other, facilitating the generation of stream-wise vortices of different scales at various radial locations and thus



(3.g) At M = 0.4



(3.h) At M = 0.6



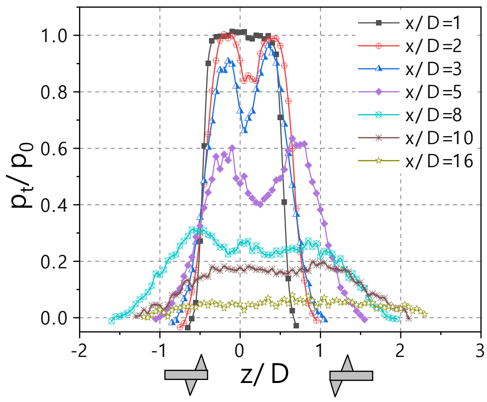
(3.i) At M = 0.8

Fig. 3.g – 3.i. Total pressure decay profiles for the tab-controlled jet at M = 0.6 along the Y-axis (along the tab).

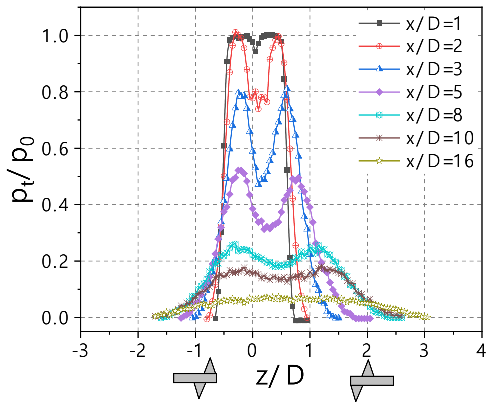
substantially promoting the mixing of ambient fluid with the jet core. In the radial profile plot along the tab orientation, the mixing is faster even in the near field, which shows that the vortices produced by the tabs are very effective due to the asymmetrical location of the projections. This result is in line with the studies of Maruthupandian and Rathakrishnan (2018). Compared to the uncontrolled jet, the half-center pressure peak observed at x/D = 1 is asymmetrical, showing that the sharp projections shed counter-rotating vortex pairs. The pressure profile almost leans to one side at x/D = 3, indicating the effectiveness of the asymmetric arrangement of projections. Similar trends are observed for Mach 0.6 jets, as in Fig. 3.e and Fig. 3.h for the uncontrolled and tab-controlled cases, which reflects that the velocity increment doesn't affect the effectiveness of asymmetrical projections in the tabs, again vindicating the predictions. The radial pressure profiles are symmetric for the uncontrolled jet along the y-axis, whereas, for the tab-controlled jet, the y-profile is shifted away from the centerline, as shown in Figs. 3.g–3i. The shifting of profiles is again due to the peculiar geometry of the tabs. Since the tabs are asymmetric in their configuration, the instability created by them makes the jet asymmetric.

3.3 Total Pressure Decay in Radial Direction (Normal to Tab)

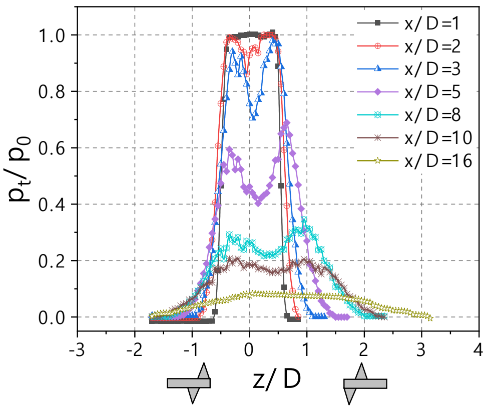
The total pressure profiles along the z-direction (normal to the tab) are shown in Figs. 3.j-3.l. Figures show the bifurcation of the jet in a slightly asymmetric fashion, again providing an insight into the effects of the asymmetric projections on the tabs. The occurrence of varying half-center peaks in the radial profile (normal to the tab orientation) confirms the asymmetric arrangement of projections on the tabs. It is due to the vortex pairs shed at different locations, which spread and propagate with some velocity differences, aiding the engulfment process and forming M-shaped profiles at different axial locations. At x/D = 1, there isn't much difference observed in the radial profiles of the uncontrolled and the controlled jets. However, at locations corresponding to x/D =3 and x/D =5, the tabs cause significant jet spread and also the bifurcation along the jet centerline. At further downstream locations, the jet spreads faster than the uncontrolled jet, as evident from the plots. The jet spreading attains a self-similar profile much earlier than the uncontrolled jet. Fig. 3.k shows the Z-profiles for the Mach 0.6 jet, which also exhibits almost the same characteristics as of Mach 0.4 jet. Further increasing the jet velocity corresponding to



(3.j) At M = 0.4



(3.k) At M = 0.6



(3.l) At M = 0.8

Fig. 3.j - 3.l Total pressure decay profile for the tab-controlled jet at M = 0.8 along the Z-axis (normal to tab).

Mach 0.8, as shown in Fig. 3.l, the effect of the tab is quite significant compared to the previous two cases. For the tab-controlled jets, an increase in the jet spread is observed at x/D = 3 and x/D = 5.

4. Conclusion

The experimental results obtained show that the effect of asymmetric projections in the tabs is quite pronounced compared to the uncontrolled jet. The Mach 0.8 jet achieves a potential core length reduction of about 80%, which is significantly higher than the Mach 0.4 and 0.6 cases. This shows that the mixing effectiveness rises as the jet Mach number increases. The decay rate achieved for the tab-controlled case is much faster than the uncontrolled jet, which shows the effectiveness of the asymmetric configuration of the tabs. The radial pressure profiles also show significant jet spread even in the vicinity of the jet exit in a slightly asymmetric pattern which again vindicates the effect of asymmetric projections in the tab. The results also demonstrate that the jet Mach numbers have a significant impact on the jet mixing characteristics. Off-centered peaks observed in the radial profiles show the jet's distortion due to the tabs' configuration. Thrust vectoring of jets can be achieved with this kind of tabs used in this experimental investigation owing to the asymmetrical arrangement of protrusions in the tabs with slight modifications.

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