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Corrugated Tabs for Subsonic and Sonic Jet Control

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Abstract

Experiments were carried out to study the effect of rectangular tabs of aspect ratio 4, with and without corrugation, on controlling the mixing of subsonic and sonic free jets. The corrugations used in the present investigation were rectangular. The blockage of the tabs without and with corrugation is 4.2% and 3.6%, respectively. The centerline pitot pressure decay for the jets, without control, with plain rectangular tabs, and with corrugated rectangular tabs, revealed that the core length reduction caused by the plain tabs is larger than that by the corrugated tabs, at all the Mach numbers studied. Up to an axial distance of about 22D, the uncontrolled and controlled jets retain their signatures. For the sonic jet, a maximum core length reduction of 32.3% was achieved with the plain tabs, whereas with the corrugated tabs the corresponding reduction was 17.63%.

Keywords: Corrugated; Sonic jet; Subsonic

Introduction

Control of high-speed jets, with passive control in the form of tabs of various shapes has been reported by large number of researchers in open literature. A tab is essentially a small solid strip kept normal to the flow, usually at the nozzle exit. A tab (placed normal to the flow) generates a pair of counterrotating transverse vortices (with the axis of rotation along the tab length), which become streamwise soon after shedding, that can influence the jet flow development significantly. From the vortex theory, it is well known that, the smaller the vortex size the better is its mixing promotion efficiency. Also, small vortices are stable and can travel longer distances compared to large vortices, which are unstable [1]. In the subsonic and sonic jet studies reported so far, tabs of straight edges only have been studied. To exploit the advantage of smaller vortices, rectangular tabs with corrugated edges have been studied in the present investigation. To understand the effectiveness of corrugated rectangular tabs, and their relative performance compared to identical plain rectangular tabs, jets from Mach 0.3 to Mach 1 axisymmetric convergent nozzle without control, controlled with corrugated tabs and plain tabs have been investigated in the present study. Measurements of centerline pitot pressure decay, pitot pressure profiles in the directions along and normal to the tabs, at different axial locations from the nozzle exit, have been carried out. Zaman [2] proposed that, the distortion introduced to a jet controlled by a mechanical tab is due to a pair of streamwise vortices shed by the tab. This distortion might result in significant increase of entrainment of the surround fluid into the jet. Itwas found that, the tabs distort the jet cross-section, leading to a significant increase of jet spread. Subsequent researchers have clearly determined that, the tab produces a pair of counter-rotating streamwise vortices.

Reeder and Samimy [3] found that, the mixing promotion caused by a tab is the best when it is located at the nozzle exit. Singh and Rathakrishnan [4] found that, for the same projected area, the length of the tabs is more effective in enhancing the mixing than its width. Further work was done by Sreejith and Rathakrishnan [5] based on the preceding postulation. Instead of tabs, a wire running across a diameter (cross-wire) was used as passive control to enhance jet mixing. The streamwise vortices introduced by the cross-wire lead to a more rapid decay of the centerline pitot pressure, compared to shorter tabs of the same blockage. The cross-wire was found to be effective at all levels of expansion for sonic jets. The authors proved that, the limiting length for the tab is the nozzle exit radius and not the boundary layer thickness. This limit is termed Rathakrishnan limit [6-8]. Most of the studies on tabs has been conducted experimentally. In addition to these experimental studies, some numerical studies [9,10] also have been reported. Thus, it is evident from the previous discussions that manipulation of the size of the vortices shed by the tabs play a dominant role in promoting the mixing of free jets. Also, it is well known that, smaller the size of vortices better is their mixing. To exploit this advantage of smaller vortices, Phanindra and Rathakrishnan [11] studied the effect of corrugated rectangular tabs on jet mixing. Two rectangular tabs of 4.2% blockage, with corrugations at the edges, located diametrically opposite at the exit of a Mach 1.8 convergent-divergent nozzle were found to be better mixing promoters than identical rectangular tabs without corrugations, at over expanded, correctly expanded, and under expanded states of the jet. Furthermore, the corrugated tabs were found to be more efficient in weakening the shocks in jet core compared with the plain tabs. But this study was for a specific supersonic Mach number.

From the literature it is obvious that the jets studied with controls are mostly in the supersonic regime. Control effectiveness of tabs with and without corrugation has been quantified only in the supersonic regimes and the corrugations were found to be immensely beneficial. But there is no information about the effectiveness of the tabs at the subsonic and sonic Mach numbers. Therefore, it will be of value to investigate the effectiveness of plain and corrugated tabs, in promoting the mixing of subsonic and sonic free jets. With this objective, the present study aims at quantifying the mixing effectiveness of plain and corrugated tabs over a range of subsonic Mach numbers and correctly expanded sonic Mach number. Free jets from a circular nozzle with Mach numbers from 0.3 to 1, in steps of 0.1, have been studied with uncorrugated and corrugated rectangular tabs.

Experimental Setup and Procedure

The experiments were conducted in the open jet facility at the

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high speed aerodynamics laboratory, Indian Institute of Technology Kanpur, India. The facility consists of air supply system (which consists of compressor and storage tanks) and an open jet test facility. The test facility used consists of a settling chamber, with a provision to mount the jet nozzles on its end plate. The settling chamber is fed with compressed dry air at high pressure (up to 300 psi) through a pressure regulating valve, which controls the settling chamber pressure at any desired level before expansion through the jet nozzles. Pressures were measured with a 16 channel Pressure Systems Inc., 9010 transducer, with a range 0 to 300 psi. The software provided by the manufacturer, was used to interface the transducer with a computer. The user-friendly menu-driven software acquires data, and shows the pressure reading from all the 16 channels simultaneously in a window type display on the computer screen. The software can be used to choose the units of pressure from a list of available units, perform a re-zero/full calibration, etc. The transducer also has a facility to choose the number of samples to be averaged, by means of dip-switch settings. The accuracy of the transducer (after re-zero calibration) is specified to be ± 0.15% of full scale. The pitot pressures were the mean values of pressure averaged over 250 samples per second. This is done because the jet is essentially a turbulent flow which is unsteady. However, the frequency and amplitude of the unsteadiness were not measured because the aim of the present investigation is to compare the mixing effectiveness of corrugated tabs with plain tabs of identical blockage. The repeatability of pressure measurements was ± 3%, respectively. The pitot probe used was of outer diameter 0.6 mm and inner diameter 0.4 mm. Thus, the ratio of nozzle exit area to the probe area is $(12.7/0.6)^2=448$, which is well above the limit of 64 for regarding the probe blockage negligible [11]. The pitot probe was mounted on a rigid 3-dimensional traverse, with a resolution of ± 0.1 mm, in linear translation. In all measurements the sensing probe stem was kept normal to the jet axis, with its sensing hole facing the flow. The pitot pressures measured were accurate within ± 2%. The pressures measured by pitot probes are significantly influenced by very low Reynolds numbers based on the probe diameter. However, this effect is seldom a problem in supersonic streams because a probe of reasonable size will usually have a Reynolds number above 500, which is above the range of troublesome Reynolds number. For the present probe of outer diameter 0.6 mm, the Reynolds number at the Mach numbers of the study are well above the troublesome limiting value of 500. Hence, the viscous effect will not cause any error in the pitot pressure measurements. The nozzle used is a convergent nozzle of 12.7 mm exit diameter, made of brass. The tabs were made of 1 mm thick aluminium sheet. The centerline pitot pressure distribution, the pitot pressure variation along the tab direction and normal to the tab direction, for the controlled jet, and along the radial direction, for uncontrolled jet, were measured for Mach numbers 0.3 to 1. In all the three directions, the pitot pressures were measured at intervals of 1 mm, with an accuracy of ± 0.1 mm. During the measurements, the stagnation temperature of the air was approximately 20°C. The variation in stagnation temperature was ± 0.5°C Figure 1.

Results and Discussion

Centerline pressure decay

The measured pitot pressure P_c distribution along the jet centerline was made non-dimensional with the settling chamber stagnation pressure P_0. The axial distance X is nondimensionalized with the nozzle exit diameter D. The centerline pitot pressure variation with X/D for Mach numbers 0.3 to 1, in steps of 0.1, are given in Figures 2-9.

The centerline pressure decay for Mach 0.3, given in Figure 2, shows that, the core for the uncontrolled jet extends to about 5D.

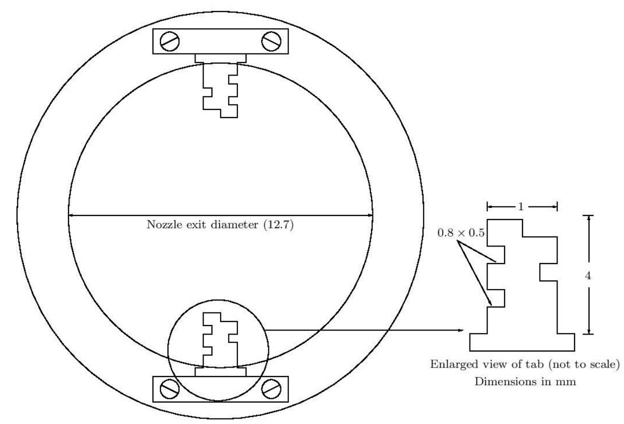


Figure 1: Schematic of nozzle exit with corrugated tabs.

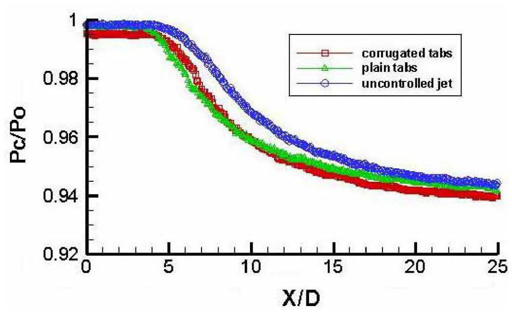


Figure 2: Centerline pitot pressure variation of Mach 0.3 jet.

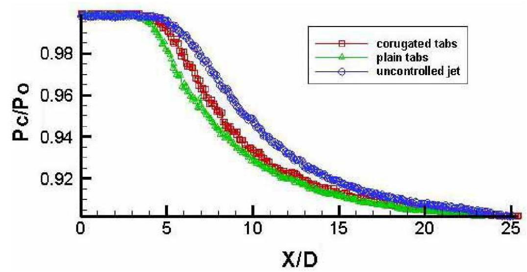


Figure 3: Centerline pitot pressure variation of Mach 0.4 jet.

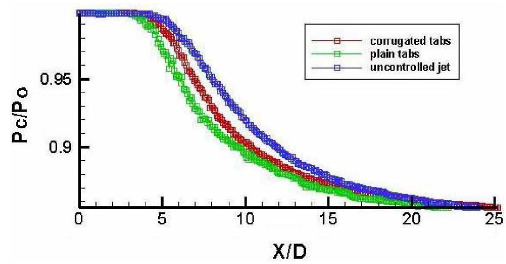


Figure 4: Centerline pitot pressure variation of Mach 0.5 jet.

When two plain tabs were placed at the nozzle exit, the core length comes down to about 4D. For the corrugated tabs the core length is

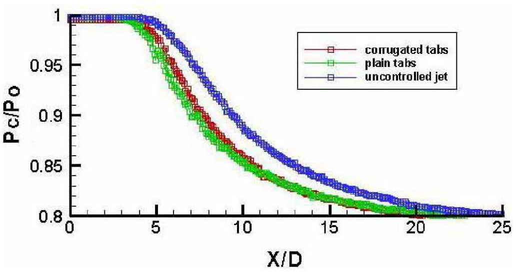


Figure 5: Centerline pitot pressure variation of Mach 0.6 jet.

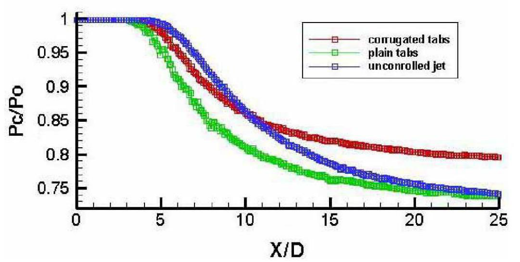


Figure 6: Centerline pitot pressure variation of Mach 0.7 jet.

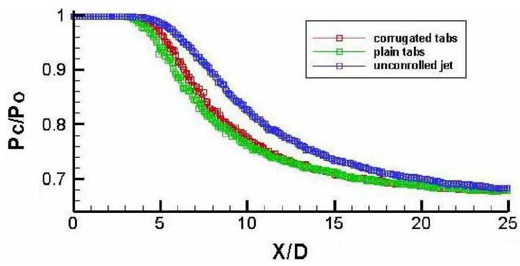


Figure 7: Centerline pitot pressure variation of Mach 0.8 jet.

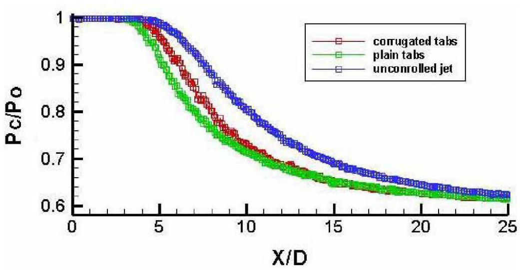


Figure 8: Centerline pitot pressure variation of Mach 0.9 jet.

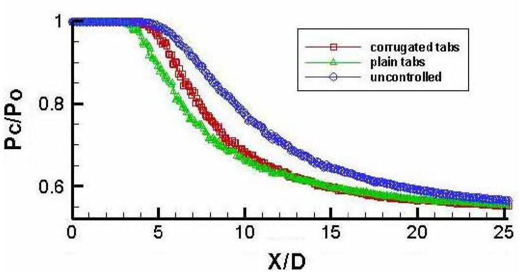


Figure 9: Centerline pitot pressure variation of Mach 1.0 jet.

almost the same as that for the plain tab. In the characteristic decay zone, the pressure decay for both plain and corrugated tabs is faster compared to the uncontrolled jet. The enhancement of mixing due to the tabs is because of the mixing promoting vortices shed by the tabs into the jet right at the nozzle exit. It is well known that the vortices shed by the tabs are transverse vortices while leaving the tabs, and become streamwise vortices soon after leaving the tabs, because of the high inertia of the jet flow. Further, the a plain tab sheds vortices of uniform size all along its edges, and at the sharp corners at the tip of the tab, the vortices shed from the side and bottom edges would interact. But for the corrugated tabs there are additional sharp corners at the corrugation location, and the tab becomes narrower at the corrugation locations. Due to this the vortices shed by the corrugated tabs are of mixed size. This is because. As demonstrated by Takama et al. [12], the size of the vortex shed by an object is proportional to the half-width of the geometry. Thus, for the plain tab, the vortex size is proportional to semi-width of the tab. For the corrugated tabs, at the corrugation location the half-width is much smaller than that at the location without corrugation. Due to this at corrugated positions, the vortices shed are smaller than those shed at the uncorrugated locations. Because of the mixed size, soon after shedding, the vortices interact intensely among themselves and spend some of their energy. This may be the reason that the mixing efficiency of the corrugated tabs is less than that of the plain tabs, as seen in Figure 2. Another aspect of Mach 0.3 jet is that, the compressibility effect in the jet field is negligible. Therefore, to gain an understanding about the mixing efficiency of the uncontrolled jet and corrugated tabs in the presence of increasing compressibility, the mixing of the jets were investigated at different compressible subsonic Mach numbers.

The centerline pressure decay results for Mach 0.4 jet, shown in Figure 3, shows that, the core length reduction caused by the plain tabs is 1.5D, whereas for the corrugated tabs it is 0.7D. This may be because the mixing efficiency of the vortex is governed by its vorticity content and the residence time it finds for interaction with the surrounding fluid. The interaction time available for vortices at Mach 0.4 is less than that at Mach 0.3, therefore, the vortices are convected away faster, thus leading to reduced mixing in the near field of Mach 0.4 jet. However, since the faster convection causes less loss of vorticity, at the axial location where the jet velocity is reduced to a level which is suitable for the vortices to cause significant mixing, their performance increases considerably for Mach 0.4 jet. This environment appears to be in the characteristic decay zone. The mixing caused by the plain tabs is larger than the corrugated tabs in the characteristic decay zone, as seen as the larger gap between the uncontrolled jet decay and controlled jet decay.

Mach 0.5 offers high compressibility than Mach 0.4. The results for Mach 0.5, shown in Figure 4, once again demonstrates that, the mixing caused by the plain tab is significantly larger than that of the corrugated tabs, in the core as well as characteristic decay zones. Even in the fully developed zone the pressure levels for the corrugated tabs is found to be marginally higher than those for the plain tabs.

The results for Mach 0.6 jet, shown in Figure 5, shows that, the mixing efficiency of the plain and corrugated tabs approach each other even in the characteristic decay zone. This clearly demonstrates the role of compressibility of the mixing promoting efficiency of the tabs.

The centerline decay results shown in Figure 6 shows that, at Mach 0.7, the behavior of the centerline pressure decay for plain tabs and corrugated tabs are distinctly different even in the far field. This may be because the convective velocity at Mach 0.7 may be such that the vortices of less vorticity content are convected away before they could able to induce mixing. For the plain tabs, the mixing efficiency has gone up compared to Mach 0.6 in the characteristic decay zone as well as in the fully developed zone. The decay shows that in the fully developed zone the pressure level for corrugated tabs significantly higher than the uncontrolled tabs. This clearly demonstrates that the corrugations results in reduced mixing compared to the uncontrolled jet.

At Mach 0.8 the characteristic decays of plain tabs and corrugated tabs, shown in Figure 7, demonstrate that the mixing promotion caused by both the tabs is considerable in the characteristic decay zone. From the results of Mach 0.7 and Mach 0.8 jets it is evident that the compressibility associated with the Jet Mach number has a strong role in dictating the mixing promotion caused by the tab.

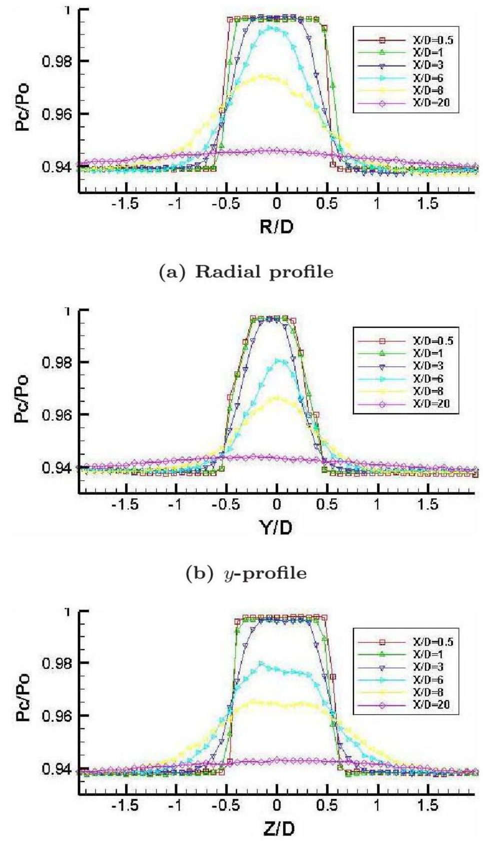
At Mach 0.9, as shown in Figure 8, the mixing caused by the corrugated tab is significantly lower than the plain tab, in the core and characteristic decay zones. But in the fully developed region, the mixing promoting capability of the tabs is almost the same.

The centerline decay of correctly expanded controlled and uncontrolled sonic jets is compared in Figure 9. It is seen that, the mixing promoting efficiency of the plain tab is better than the corrugated tab, both in the core and characteristic decay zones. But, as in the case of Mach 0.8 and 0.9 jets, both the tabs perform identical in the fully developed region.

From the above discussions, it is evident that the control effectiveness of the tabs is considerably influenced by the compressibility effect. However, at all levels of compressibility it appears to be beneficial to introduce vortices of uniform size than mixed size. This is in contrast to the observations of Phanindra and Rathakrishnan [11], who found that introduction of vortices of mixed size promotes the mixing of a supersonic jet better than a plain tab shedding vortices of uniform size. They reported that, for Mach 1.8 jet, the core length reduction achieved in plain tabs is less than the corrugated tabs. Thus, it may be summarized that, for supersonic jet mixing corrugation may prove to be beneficial. But for the mixing of subsonic and sonic jet vortices of uniform size, shed by plain rectangular tabs is found to be better than the vortices of mixed size shed by corrugated rectangular tabs.

M	Jet	L	ΔL%
0.3	Without tabs	4.43D	
	Plain tab	3.56D	19.6%
	Corrugated tab	4.06D	8.35%
0.4	Without tabs	4.63D	
	Plain tab	3.47D	25.05%
	Corrugated tab	3.94	14.9%
0.5	Without tabs	4.24D	
	Plain tab	3.26D	23.11%
	Corrugated tab	3.77D	11.08%
0.6	Without tabs	4.02D	
	Plain tab	3.05D	24.12%
	Corrugated tab	3.51D	12.68%
0.7	Without tabs	4.22D	
	Plain tab	3.06D	27.48%
	Corrugated tab	3.43D	18.72%
0.8	Without tabs	4.50D	
	Plain tab	3.36D	25.33%
	Corrugated tab	3.93D	12.67%
0.9	Without tabs	4.6D	
	Plain tab	3.31D	28.04%
	Corrugated tab	3.82D	16.9%
1.0	Without tabs	4.48D	
	Plain tab	3.03D	32.3%
	Corrugated tab	3.69D	17.63%

Table 1: Core lengths of jets and ΔL caused by the tabs.



(a) Radial profile

(b) y-profile

(c) z-profile

Figure 10: Pressure profiles for (a) uncontrolled jet and (b), (c) jet with plain tabs, at Mach 0.3.

The core lengths of uncontrolled and controlled jets of different subsonic and sonic Mach numbers are listed in Table 1. The percentage reduction defined as

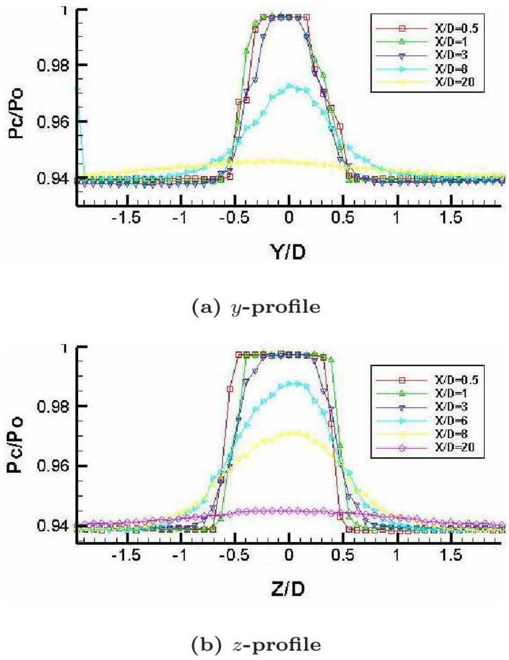
$$\%reduction = \frac{\Delta L_{without\ tabs} - \Delta L_{with\ tabs}}{\Delta L_{without\ tabs}} \times 100$$

is also shown in Table 1. It is seen that, at all Mach numbers of the present study, the plain tabs cause larger core length reduction than the corrugated tabs. It is interesting to note that the difference in the core length reduction caused by the plain and corrugated tabs are comparable (between 11 to 12%), at all subsonic Mach numbers and correctly expanded sonic Mach number.

Pressure Profiles

To gain an insight into the jet flow development, with and without control, the pitot pressure profiles along the radial direction, for the uncontrolled jet, and along the tabs and normal to the tabs, for controlled jets, were taken at different axial locations, for all the Mach numbers of the present study. The pitot pressure profiles for Mach 0.3 jet without control is shown in Figure 10a.

It is seen that, at X/D=0.5, the velocity profile is flat along the radial



(a) y-profile

(b) z-profile

Figure 11: Pressure profiles for jet with corrugated tabs, at Mach 0.3.

direction exhibiting typical top hat profile. The extent of radial distance up to which uniform pressure prevails decreases progressively with axial distance. At 12 X/D=6 the pressure profile exhibits a single peak. This shows that, the mixing initiated by the vortices at the jet periphery has reached the jet centerline at this axial distance. At X/D=20, the velocity at the centerline has become very small and the pressure profile has become almost flat all along the width of the jet, exhibiting that the jet is fully developed. The pressure profiles for Mach 0.3, jet with plain tab, along the tab is shown in Figure 10b. It is seen that, because of the active near field mixing, caused by the mixing promoting vortices shed by the tabs, the pressure decay is faster than the uncontrolled jet in the near field, but the additional vortices due to the tab made the jet field asymmetrical, as clearly indicated by half center pressure peak at X/D=8. The pressure profiles for the plain tabs, in Figure 10c, show that, the spread normal to the tabs is faster than along the jet. Also, the asymmetry due to the tab action is explicit at X/D=8.

The pressure profiles for Mach 0.3 jet, controlled by corrugated tabs, are shown in Figures 11a and b.

Figure 11a shows the pressure profile along the tab. It is seen that, the pressure decay caused by the corrugated tabs is inferior than the plain tab.

Because of this, the pressure profiles for the corrugated tabs are wider than the plain tabs but the asymmetry caused by the corrugated tab is not that significant compared to the plain tab. Thus, it can be stated that, the corrugated tabs promote mixing with less asymmetry than the plain tabs. Further, the pressure profile at X/D=20 shows that, the jet retains significant momentum even at X/D=20. The pressure profiles normal to the corrugated tabs are shown in Figure 11b. It is interesting to see that, in this direction also there is no significant asymmetry. Also, compared to the plain tab, the momentum at X/D=8 for the corrugated tab is higher than the plain tab.

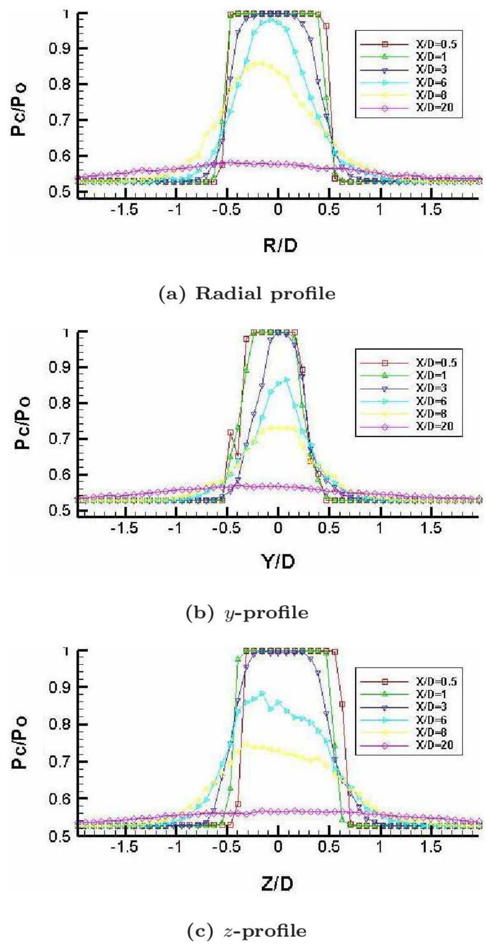
The pressure profiles for Mach 1 uncontrolled jet is shown in Figure 12a. For this Mach number also at X/D=0.5, the top hat profile is seen. At about X/D=6, the pressure profile shows single peak, as in the case of Mach 0.3 jet.

For the plain tabs, the pressure profiles along the tab, shown in Figure 12b, show that, the jet becomes asymmetric. The spread in the direction normal to the tab (Figure 12c) is larger than along the tab but the asymmetry in the direction normal to the tab is more pronounced than along the tab. The pressure profiles along and normal to the corrugated tabs are shown in Figures 13a and b, respectively.

It is seen that, the asymmetry for the corrugated tab is only marginal in both along and normal to the tabs, unlike the plain tab. Therefore, even at higher Mach numbers, the corrugated tabs could able to promote mixing without introducing significant asymmetry. However, the mixing caused by the corrugated tabs is found to be less than that of the plain tabs at all the Mach numbers studied.

Conclusions

The results of the present study show that, the jet core length



(a) Radial profile

(b) y-profile

(c) z-profile

Figure 12: Pressure profiles for (a) uncontrolled jet and (b), (c) jet with plain tabs, at Mach 1.

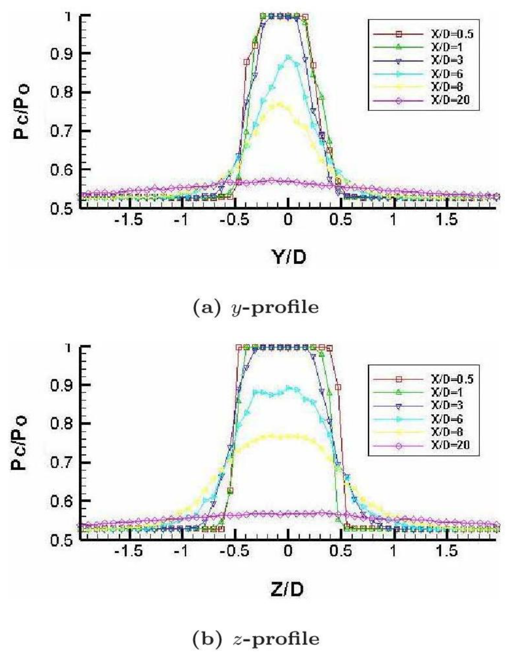


Figure 13: Pressure profiles for Mach 1 jet with corrugated tabs.

reduction caused by the plain tabs is larger than that by the corrugated tabs, at all the Mach numbers studied. Up to an axial distance of about 22D, the uncontrolled and controlled jets retain their signatures. For the sonic jet, a maximum core length reduction of 32.3% is achieved with the plain tabs, whereas with the corrugated tabs the core length reduction is 17.63%. At all subsonic Mach number and sonic Mach number of the present study, the difference between the core length reduction caused by the corrugated and plain tabs is found to be almost the same, that is, independent of the jet Mach number.

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