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NUMERICAL SIMULATION OF PERFORATION GEOMETRY IN A RECTANGULAR TABBED JET CONTROL

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Abstract:

This paper deals with the optimization of tab perforation to enhance the mixing characteristics of subsonic and correctly expanded sonic axi-symmetric jets issuing from a convergent nozzle. Passive jet control technique involves a set of tabs at the nozzle exit producing a pair of counter-rotating vortices, which can offer considerable reduction of potential core length as well as the noise reduction. Measurements of centerline axial velocity decay and radial velocity distribution were carried out. The effect of various perforation geometries such as Circular, Triangular and Regular Hexagonal cross sections of 2 mm equivalent diameter in the tab are analyzed. In this paper a three dimensional numerical simulation of jet flow with perforated geometries are performed using the FLUENT software. The potential core length for perforation tab at Mach numbers of 0.4, 0.8 and correctly expanded sonic conditions are estimated. The centre line velocity of the jet is found to decay at a faster rate in the case of Hexagonal perforation geometry as compared to other geometries.

Key Words: Potential Core, Axi-Symmetric Jets, Circular Perforation, Triangular Perforation and Hexagonal Perforation & Jet Mixing

Nomenclature:

CFD	Computational fluid dynamics
D	Nozzle exit diameter
M	Mach number
V_j	Centerline jet velocity
V_e	Nozzle exit velocity
P_a	Atmospheric static pressure
P_o	Total pressure
d	Equivalent diameter
x/D	Axial position
y/D	Radial position

Introduction:

High-speed, compressible, turbulent jets feature in many important aerospace applications, notably in jet aircraft and rocket propulsion, gas turbine combustion chambers etc. In many of these applications an understanding of the mixing between the jet and an ambient fluid is critical to their successful design. Specific research areas include jet noise reduction, infra-red signature reduction, etc. Most jet powered aircraft operating in the high subsonic and low supersonic flight regimes will use turbofan engines with convergent propulsive nozzles. In an effort to enhance mixing in jet flows, a passive control method, using vortex generators in the form of mechanical tabs or small protrusions at the exit of a nozzle has been under investigation in the past several years. A tab is kept normal to the flow direction which can produces a pair of counter-rotating stream-wise vortices, which can offer considerable reduction of potential core length as well as the noise reduction. Due to the interference of jet stream with the tabs, thrust losses are inevitable. In order to achieve the reduced potential core length at the cost of minimum thrust loss, perforated tabs can be shown in figure 1. The increasing use of CFD techniques early in the design cycle leads to a requirement for high-quality experimental data with which to validate a particular model. The experimental data have been limited to pitot probe measurements within the jet mixing in the surrounding flow field.

Bradbury and Khadem [1] were the first to study the effect of mechanical tabs on jet flows in detail. They reported that, at low jet speeds, mechanical tabs or small protrusions into the jet flow at the exit of nozzle can increase the jet spreading rate significantly, reduce the potential core length (from 6D for the conventional jet to 3D) and even bifurcate the jet flow. Clement and Rathakrishnan [2] investigated jet from a sonic nozzle with and without tabs operated at nozzle pressure ratio from 2 to 7They found that the potential core length was reduced up to 75% at NPR 7compared to uncontrolled jet. The shock cell structure was weakened drastically. The distortions produced by the two tabs grow with downstream distance and result essentially in bifurcation of the jet. Zaman et al [3] conducted an experimental investigation on the effect of small tabs at the nozzle exit on evolution of a jet. Primarily tabs of triangular shaped are considered, and the effect is studiedupto a Mach number of 1.8. A triangular shaped with its apex leaning downstream 45^0 referred as a delta tab, is found to be most effective in producing such vortices. Two delta tabs, spaced 180^0 apart completely bifurcate the jet. Four delta tabs stretch the mixing layer into four "finger" resulting in a significant increase in the jet mixing downstream. The pressure gradients produced by the tabs are the main two sources of stream wise vorticity are identical. One is due to "pressure hill" and the other is due to vortex filament shed from the sides of the tab and re-oriented downstream by the mean velocity gradient. Saddingtonetal [4] carried out numerical and experimental study of mixing in under expanded, super sonicturbulent jets issuing from axisymmetric and castellated nozzles into quiescent conditions. Experimental studies used laser Doppler velocimetry (LDV) and Pitotprobe measurements along the jet centerline at a nozzle pressure ratio (NPR) of 4. A computational fluid dynamics (CFD) model using the FLUENT commercial code (v5.5) and the RNG (k- two-equation turbulence model was developed. When compared with a plain axisymmetric jet, an increase of up to 13% in mixing, based on mass flow rate, was predicted for jets emanating from the castellated nozzles. The increased mixing rate of these jets appears to be due to differential expansion of the jet fluid in the gap and tooth regions as it leaves the nozzle exit. Lovaraju and Rathakrishnan [5] investigated the effect of cross-wire placed at a convergent nozzle exit running across a diameter and found that the cross-wire is efficient in enhancing the mixing at all subsonic and sonic Mach numbers. The waves in the potential core were altered drastically. Further, it was found that jet core length reduction of about 46–50% was achieved with cross-wire across the nozzle diameter. Chiranjeevi and Rathakrishnan [7] carried out an experimental investigation of rectangular tab with and without corrugation operated at Mach number 1.8. As high as 78% of reduction in core length was achieved with corrugated tabs for the jet operated at nozzle pressure ratio (NPR) of 7, the corresponding reduction with the plain tabs is only 54%. The mixing effectiveness of corrugated tabs increases progressively with increase of NPR whereas, the maximum mixing effectiveness of the plain tabs is found to be at the correctly expanded state. Thanigaiarasuetal [8] found experimentally that the jet decays at faster rate in the case of arc-tab facing in configuration at all blockage levels as compared to arc-tab facing out and rectangular tab configurations. With arc-tab facing in, the core length was reduced by 80% and the corresponding reduction was 40% for the jet with arc-tab facing out and rectangular tabs. Dharmahinderetal [9] found that the jet control with circular perforation tabs at the nozzle exit. It shows the velocity decay is faster and the core length is reduced drastically as compared to uncontrolled jets at all subsonic and sonic correctly expanded conditions. The tabs so far used by the previous researchers were rectangular, triangular, cross wire, corrugated tab, arc-in, arc-out, solid tabs for controlling high-speed jets. These tabs are better mixing promotes but it causes considerable thrust loss due to blockage of nozzle exit area. The aim of present study is to investigate and analyse tabs with various equivalent diameters of perforation, which offers lesser blockage than a plain tab.

2. Numerical Methodology:

The computational domain was modeled and meshed in GAMBIT. It consisted of a convergent nozzle of length 40mm with inlet diameter of 40mm and exit diameter of20mm followed by a rectangular domain. The flow is assumed to be axi-symmetric, compressible and turbulent. The computational domain consisted of an axi-symmetric of tetrahedral mesh with approximately 410000 cells. The simulation has been carried out by the realizable k-ε (epsilon) two equations turbulence model in the FLUENT software.

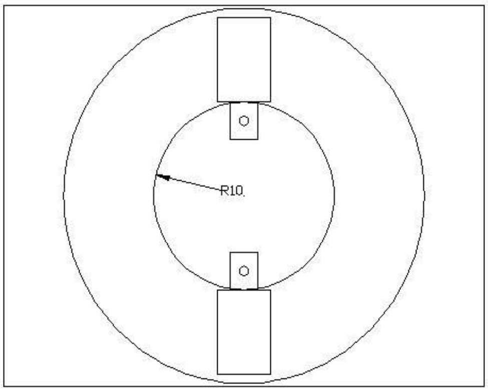

Figure 1: Perforation tab (Circular) arrangement at the Nozzle Exit

The boundary condition for the nozzle was set as a pressure inlet with a prescribed total pressure, static pressure, total temperature and turbulence intensity. The far-field and outlet boundary was set as a pressure outlet with a prescribed static pressure and static temperature.

3. Results and Discussion:

Centerline Velocity Decay: Potential core region in subsonic and sonic jet is the region where the centerline velocity is same as the velocity at the exit of the nozzle. The velocity along the centerline was calculated from the total pressure and static pressure, assuming the static pressure across the jet to be surrounding environment pressure for subsonic jets. For sonic jet, this assumption is valid only when it is correctly expanded condition. The nozzle exit velocity V_e, distribution along the jet centre line is non-dimensionalized with the jet velocity V_j. The axial distance (x) from the nozzle exit is non-dimensionalized with the nozzle exit diameter (D).

Effect of Perforation Geometry of Tab on Jet Decay: The comparison plots of centerline velocity decay for the uncontrolled jet, controlled jet with plain tabs and perforated tabs are given in figures 2-4.The potential core length of 2 mm equivalent diameter of perforated geometries of 0.4 Mach number is shown in Fig. 2. For uncontrolled jet, the core length is more than 6.84D and plain tabs the core length reduces to about 4.1D.Fromthe Fig. 2, the circular perforation velocity decay starts from x/D = 5.4location. For hexagonal perforation, the potential core length is about x/D = 5.4 whereas the triangular perforation is about x/D = 5.9. Hence, it can be regarded that hexagonal perforation acts as an effective mixing promoter as the tab shortens the potential core more effectively than the other perforated tabs. Because of the formation of small sizes vortices produced along the edges of hexagonal perforation which gives better mixing characteristics of jet stream. The region of the interaction between the primary jet and the secondary jet is dominated by shear which causes the formation of vortices and these vortices will take part in enhance entrainment of the primary jet.

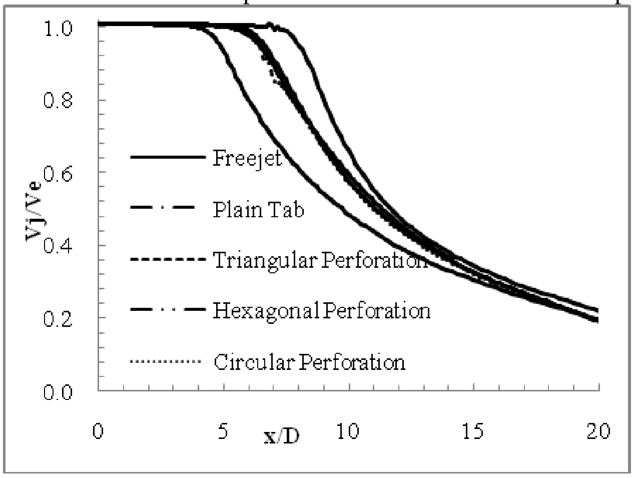

Figure 2: Centerline velocity decay for M=0.4

Figure 3 compares the potential core length of 2 mm equivalent diameter of perforated geometries of 0.8 Mach number. For uncontrolled jet the core length is more than 8.3D and plain tabs the core length reduces to about 4.9D. The circular perforation velocity decay starts from x/D = 6.4 location. For hexagonal perforation, the potential core length is about x/D = 6.0 whereas for the triangular perforation is about x/D = 6.6.

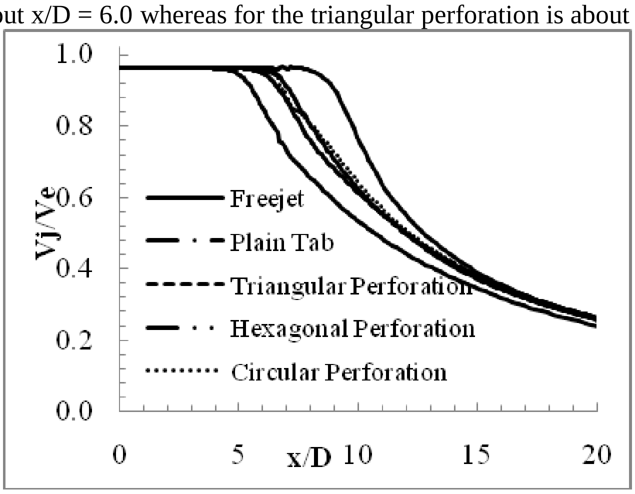

Figure 3: Centerline velocity decay for M= 0.8

The centerline velocity decay of correctly expanded sonic jets conditions are shown in Fig. 4. For uncontrolled jet the core length is more than 8.2D and for plain tabs the core length reduces to about 4.9D of correctly expanded sonic jets conditions. From the Fig. 4, the circular perforation velocity decay starts from x/D = 6.8 location. For hexagonal perforation, the potential core length is about x/D = 6.2 whereas for the triangular perforation it is about x/D = 6.9.

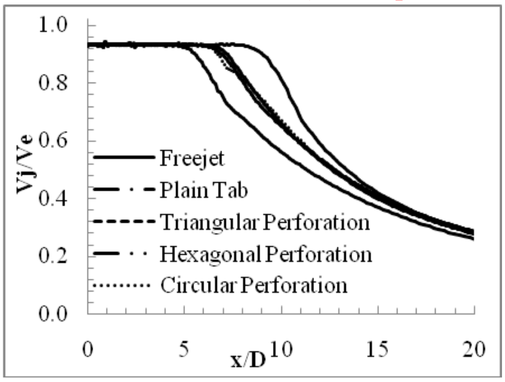

Figure 4: Centerline velocity decay for correctly expanded sonic Mach number

Those results clearly demonstrate that the hexagonal perforation gives better mixing efficiency compared to other perforation geometries of 2 mm equivalent diameter for all Mach numbers. A tab kept normal to the flow direction generates counter-rotating transverse vortices. The mass entrained by the large size vortices formed at the jet boundary, due to differential shear is transported towards the jet centerline by the mixing and hence promoting small size vortices shed by the tabs.

Radial Velocity Profile:

The comparison plots of radial velocity profile in the direction normal to the perforated tabs are shown in Figures 5 to 7 for different Mach numbers. The variation of radial velocity along 2mm equivalent diameter of various perforation tabs geometry at various axial downstream locations for 0.4 Mach number is shown in figure 5. It is seen that the core width is greatly reduced by the perforated tabs compared to uncontrolled jet. For uncontrolled jet, at x/D = 0.15 the potential core extends up to y/D = 0.43, whereas the plain tabs is about y/D = 0.18. At x/D = 0.15, all the perforated tabs having potential core extends up to y/D = 0.21. But at y/D = 0.3 to 0.4, the mass flow through the perforation greatly affects the radial velocity profile, as shown in Fig. 5, which cause sudden rise in velocity at y/D = 0.4 locations.

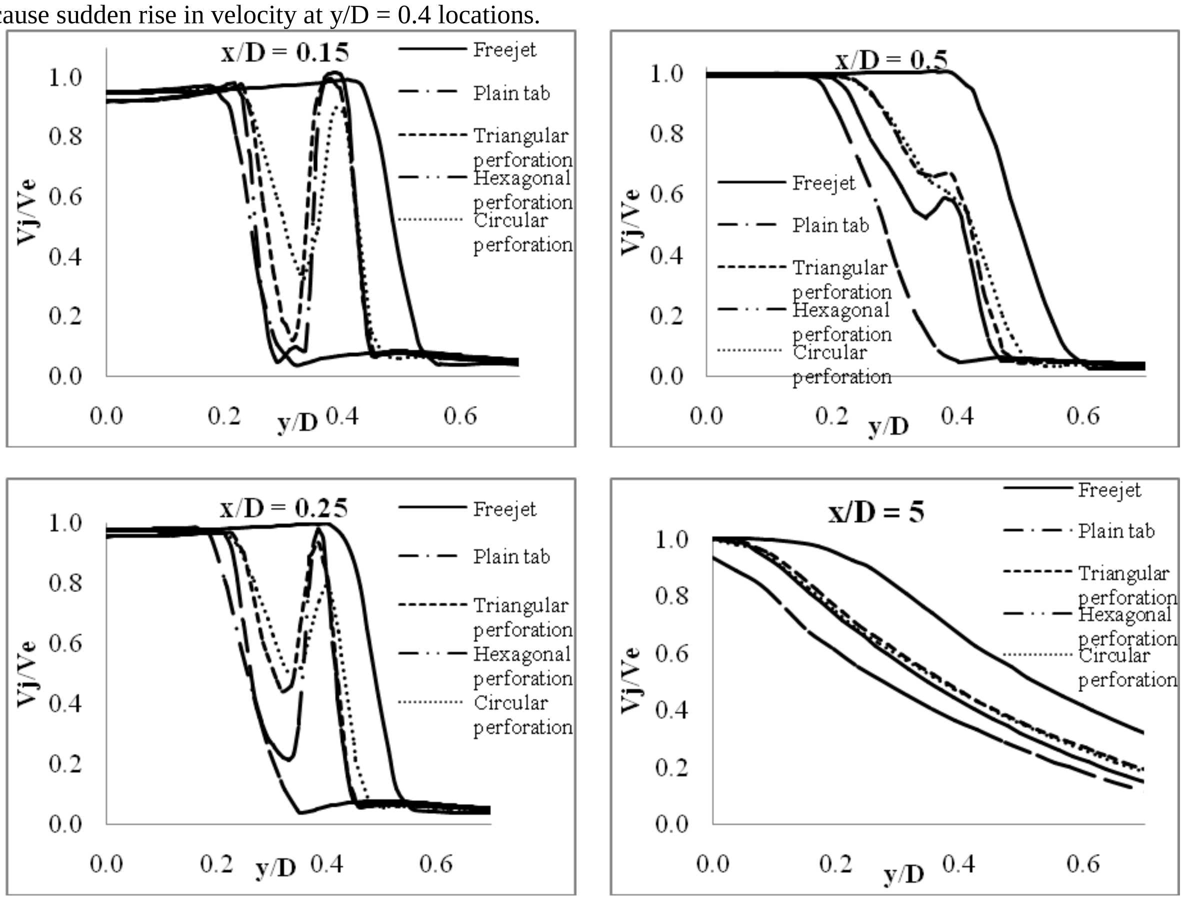

Figure 5: Radial velocity profile of perforation (circular, hexagonal and triangular) diameter at M = 0.4

The perforation effect in radial direction vanishes at x/D=0.6 for hexagonal perforation tabs whereas for other perforated tabs the influence of perforation vanishes beyond x/D=0.6.From Fig. 5, at x/D = 5 and beyond the jet has encountered the characteristic decay and at some axial downstream location, the flow becomes fully developed. From the results, the hexagonal perforation tab has more mass entrainment than the circular and square perforation tabs.

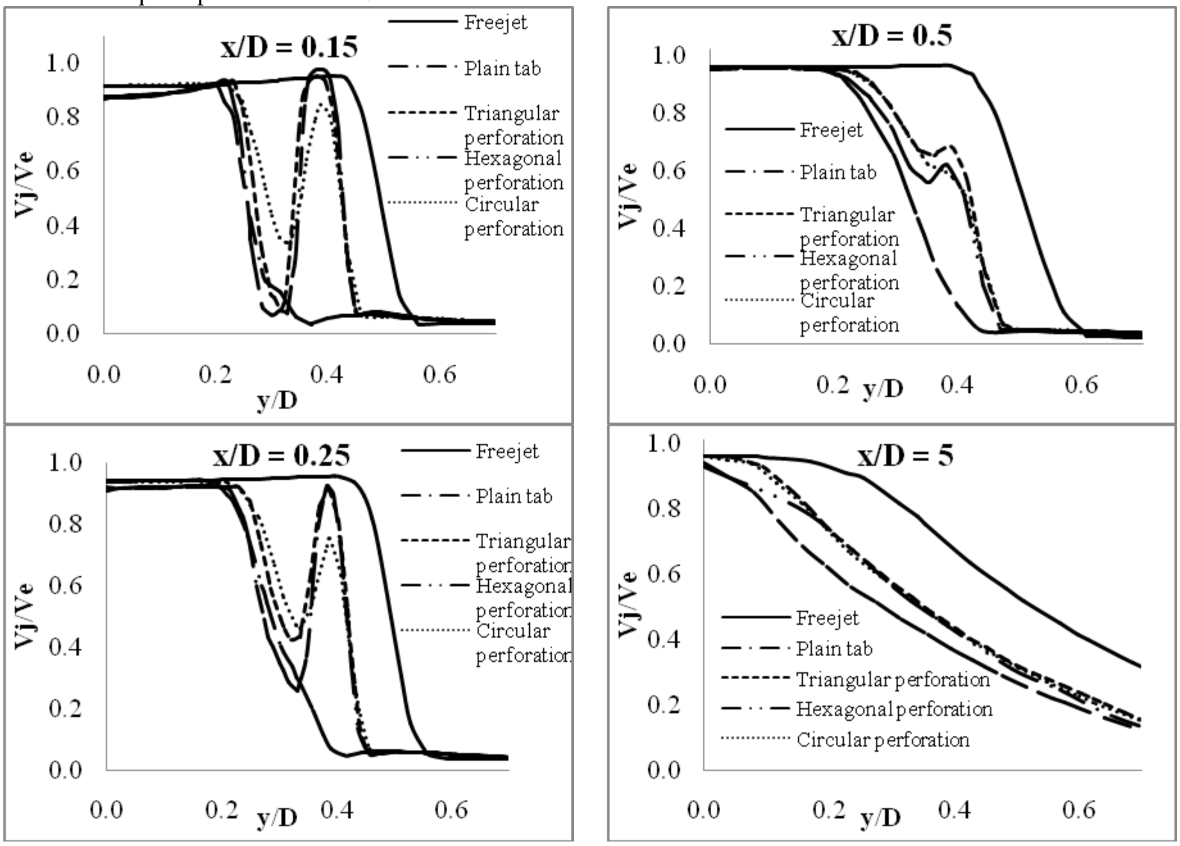

Figure 6: Radial velocity profile of perforation (circular, hexagonal and triangular) diameter at M = 0.8

From figure 6 of 2 mm equivalent diameter and M = 0.8, the perforation effect in radial direction vanishes at x/D = 0.65 for hexagon perforation tabs whereas for other perforated tabs the influence of perforation vanishes beyond x/D = 0.65.

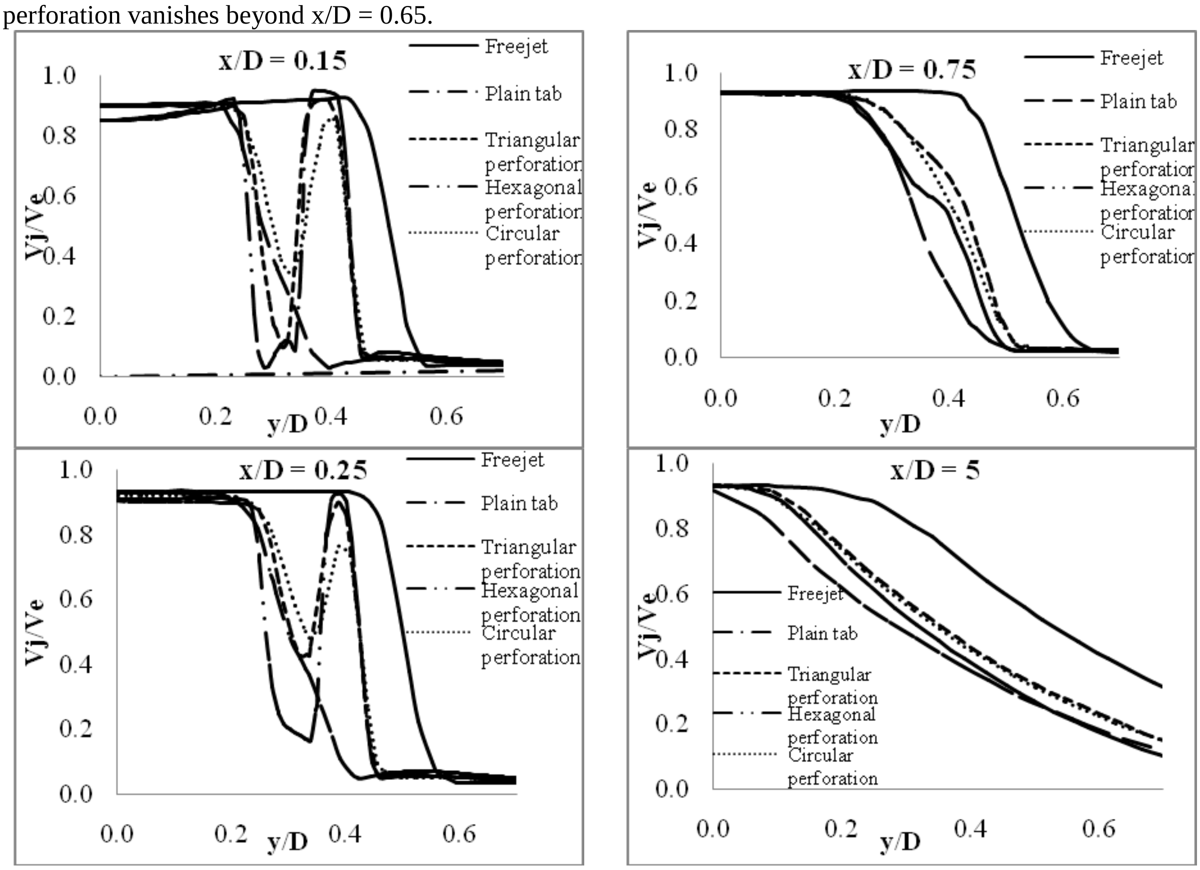

Figure 7: Radial velocity profile of perforation (circular, hexagonal and triangular) diameter at M = 1(correctly expanded)

From figure 7 the perforation effect in radial direction vanishes beyond x/D = 0.75 for all perforation tabs. Among these results clearly demonstrate the hexagonal perforation gives better mixing characteristics of the jets. At X/D = 5, the velocity peak value comes down to 0.6 and also the decrease of velocity shows relatively a gradual variation than the near field profiles upstream of this location. Therefore, the jet has encountered the characteristic decay at some axial downstream location; the flow becomes fully developed region. This clearly shows the effectiveness of the perforated tabs in promoting the mixing of subsonic and correctly expanded sonic jet in the presence of zero pressure gradients at the nozzle exit. For uncontrolled jet, the vortices generated at the nozzle exit are of uniform size due to constant radius of curvature along the azimuth [2]. When the two tabs are introduced, two pairs of counter-rotating stream wise vortices are shed all along the edges of the tabs. Thus, there are two pairs of such vortices shed by the two tabs. These vortices initiate mixing right at the tabs, thereby enhancing mixing significantly. Therefore, the mixing capability of uncontrolled jet is very less compared to that of perforated tabs. It is observed that there is a dip in the radial velocity profile for all perforation circular, hexagonal and triangular perforation tabs in the near field (x/D = 0.25 to 0.5) for all Mach numbers (0.4, 0.8 and correctly expanded sonic condition). This is due to the presence of perforation in the tabs. It disappears after x/D = 0.75 because the energy possessed by the secondary jet is not sufficient to penetrate in the primary jet. Hence perforation effect is dictated by the size of the perforation and geometry of the perforation and also energy possessed by the secondary jet. When the secondary (perforation) jet penetrates into the primary jet, the interactions of the primary and secondary jets take place when they meet each other. The interaction is approximately taking place constant in the centerline velocity since it is straight perforation. These interaction causes dip in the radial velocity profiles in the near field and creates more turbulent dominated in the primary jet. These interaction leads to the formation of vortices which are responsible for mixing enhancement.

4. Conclusion:

Perforated tabs are found to be effective in enhancing the mixing at all subsonic and correctly expanded sonic jet. The perforated tabs influence the potential core length significantly and the core disappears completely within a short distance from the nozzle exit, followed by a rapid decay of the centerline jet velocity. Three dimensional numerical simulation were performed for perforated tabs with equivalent diameter 2mm. Though all the tabs are efficient in mixing promotion, among them hexagonal perforated tab is found to be more efficient. The interaction of the primary and secondary jets take place constant in the centerline velocity since it is straight perforation. But these interaction causes dip in the radial velocity profiles in the near field and creates more turbulent dominated in the primary jet. These interaction leads to the formation of vortices which are responsible for mixing enhancement. Thus, the capable of mixing promoting vortices of mixed size shed by the perforated tabs.

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