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Experimental and Computational Investigation of Effect of Jet Control using Rectangular Tabs

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ABSTRACT

In airplanes, majority of noise created in is due to jet issued from the power- plant. There are two methods for jet control for noise reduction like active methods and passive methods which will help in noise reduction. In passive methods mainly chevrons, tabbed nozzles, contoured plugged nozzles are used whereas in active methods micro jets, water injection, piezoelectric strips, etc.Moreover thrust penalties involved in these methods are to be controlled by reducing the blockage before they can be use in the commercial aircraft engines. In this context control of jets is by passive methods in which rectangular tab is used. Here rectangular tab is a passive controlling device. Tabs generate a pair of counter rotating transverse vortices due to the formation of pressure hill behind the tab which will become stream wise vortices after shedding. The investigation focuses on computational and experimental analysis of jet spread characteristics under various Mach numbers.

KEYWORDS

Potential core, Jet decay, Jet spread, turbulence models, vortices, pressure hill, shear layer, Jet mixing

INTRODUCTION

Jet Noise is widely recognized to be one of the most objectionable impacts of aviation and an important environmental issue for those living close to airports as well as further afield under the main arrival and departure tracks. Therefore taking effective measures to control and mitigate the effect of aircraft noise is fundamental to achieving the sustainable development of the aviation industry. Although new jet transport airplanes in today’s fleet are considerably quieter than the first jet transports introduced about 40years ago, airport community noise continues to be an important environmental issue as the no of flights are increasing day by day. Jet noise is a large section of the field of aero acoustics that focuses on the noise generation caused by high-velocity jets and the turbulent eddies generated by shearing flow. Such noise is known as broadband noise and extends well beyond the range of human hearing (100 kHz and higher). Jet noise is also responsible for the loudest sounds ever produced by mankind.

Hence, many researches and studies are going on all around the world to meet the appropriate solutions to reduce the jet noise but still now there are many requirements that have not yet fulfilled. Mostly the requirements are finding ways to limit the exposal of flight deck personnel to areas of high noise, the developments of better procedure to monitor the noise exposal and hearing loss of personnel, further development of noise abatement procedures to minimize the noise foot print around commercial and military air stations and finally more research into the physiological effects of the full spectrum of noise-including low frequency pressure levels on humans. The propagation of aircraft noise and sonic boom from source to receiver is a function of several factors, including relative distance; atmospheric attenuation due to wind, humidity, and temperature; and intervening noise barriers (e.g., large stands of trees and buildings).

From vortex theory, it is known that small vortices are stable than the larger vortices. The vortices shed by the rectangular tabs will actually increase the mass entrainment from the surrounding atmosphere to the jet stream. From the computational results it was found that tabs distort the jet cross section which will increase the jet spread. The objective of this investigation is to study computationally and experimentally compare the effect of tabs on the mixing enhancement of a jet issuing out from a nozzle. The effectiveness of tabs (with 9% blockage) and their relative performance are compared with free jet.

EXPERIMENTAL SETUP

The experiments have been carried out by supersonic free jet. The experiment setup consists of settling chamber, reservoir, compressors, pitot tube and digital manometer. The compressed airwere passed through the settling chamber to the convergent nozzle which is mounted at the rear part of the settling chamber. The diameter of the convergent nozzle is 20mm diameter. The convergent nozzle made up of brass. The free jet from the nozzle is ejected out into the atmospheric condition. The total pressure in the settling chamber were measured using digital manometer. The convergent nozzle was attached on to the settling chamber using the threaded coupling arrangement.

The experiment setup were shown in fig.2, 3, and 4. The solid tabs may be single tab and twin tabs. The tabs are made up of mild steel of 5mm length and 3mm width. The total blockage area of solid tabs 9.55%.The same geometry of solid tabs are fitted together on to the outer surface of the convergent nozzle. The pitot tube was used for measuring the total pressure throughout the nozzle exit. The pitot tube was connected to the digital manometer which is used to measuring the total pressure. The pressure along the radial axis and centerline of jet axis were measured by using the transverse mechanism of pitot tube.

Fig1: Nozzle with and without tabs

Fig2: Open Jet facility with transverse mechanism and side view

The jet facility consists of 5000 litres of capacity with maximum of 20bar storage pressure. There are two compressors (20Hp each) supplying pressurised air to the storage tank. The experimental results obtained by pitot tube connected to pressure transducer with reliable accuracy and sensitivity.

METHODOLOGY

In order to reduce the jet noise, the potential core should be reduced to control the shear noise.The potential core is identified by constant nozzle exit velocity.Pitot tubes are used to capture the positional core in the jet spread by recording the pressure along the center line jet axis and radial tabbed direction and non-tabbed

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direction. Two tabs are placed diametrically opposite to each other providing the same blockage area on the nozzle exit.Reservoir is charged for about 2 hrs by the two 20 hp centrifugal compressor to attain 15 bar pressure (max 20bar).The bottom valve in the reservoir is opened to remove the water condensation during the compression process since humidity will be present in atmosphere.The pitot tube is placed in the transverse mechanism holder and fitted at the center of nozzle exit.And the pitot tube is connected to a digital manometer probe. Then the check wall is opened in the reservoir and the required pressure is minted in the settling chamber recorded by a mechanical gauge.First the centerline pressure decay along the axial is recorded.The radial spread of the jet is then captured at different axial locations (1d, 2d, 5d, 5d) in both tabbed and non-tabbed radial axis.The recorded pressure is then converted into Mach number by the isentropic relation

$$\frac{P_0}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

The obtained Mach number is then non-dimensionalised by dividing the local Mach number (m) by nozzle exit Mach number (Mj) and the plots are drawn for different exit Mach number's(0.8,1)

COMPUTATIONAL SET UP

DOMAIN SPECIFICATON AND BOUNDARY CONDITIONS

The computational domain considered and its boundary conditions are shown in figure. The primary jet is discharged through a straight pipe with a length of 50mm. Because of symmetry only half of the physical domain is modelled. The nozzle diameter D is 20mm. The radius of the domain is set at 50D and the length is set at 200D. This can ensure enough space for the spreading of the jet and keeping the influence of the artificial boundaries to a minimum.

In the figure the plane bounded by z=0 is defined as the symmetry plane. The inflow boundary is gauge total pressure and the outflow boundary is set as gauge pressure. The no-slip boundary condition is defined at the nozzle wall.

GOVERNING EQUATIONS

The governing equations used in the present computations are the continuity, momentum and turbulence equations. These equations were solved with the help of the computational fluid dynamics software ANSYS Fluent 15.0, which is based on the finite volume approach. The computations are treated as steady, incompressible, three dimensional. The governing continuity, momentum equations adopted for the present computation are as follows:

Continuity equation :

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_i$$

Where i, j and k are the unit vectors along coordinate x, y and z directions.

TURBULENCE MODEL

Realizable k-ε turbulence model available within the solver was chosen for the present computations. The governing equations for the turbulent kinetic energy (k) and turbulent dissipation rate (ε) are given below:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{u_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon$$

Turbulent kinetic energy (k):

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{u_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Turbulent dissipation rate (ε):

Where G_K is the rate of generation of the turbulent kinetic energy, while ρε is the destruction rate and $C_{1\varepsilon}$, $C_{2\varepsilon}$ are empirical constants. G_K is expressed by the following equation:

$$G_k = (-\rho\overline{u_i' u_j'})\frac{\partial u_j}{\partial x_i}$$

The Boussinesq hypothesis is normally used in the eddy viscosity models in flows with turbulence, to relate the Reynolds stresses $-\rho\overline{u_i' u_j'}$ to the mean velocity gradients by the equation as given below:

$$-\rho\overline{u_i' u_j'} = \mu\left(\frac{\partial u_i}{\partial \ _j} + \frac{\partial \ _j}{\partial \ _i}\right)$$

The turbulent viscosity term μ_t is to be computed from the turbulence model selected using the following equation:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

COMPUTATIONAL MESH

The mesh for the computational domain is made with tetrahedral cells, as the geometry is complex.The element size settings were used from the grid independency study, and the optimum grid was generated.The pressure based solver, chosen by with implicit and absolute velocity formulation. SIMPLE algorithm is used for coupling the pressure and velocity terms. The first order upwind differencing scheme is used for the turbulence quantities in order to enhance the numerical accuracy of the computational results.

GRID INDEPENDANCY TEST

Table 1: List of nodes and elements

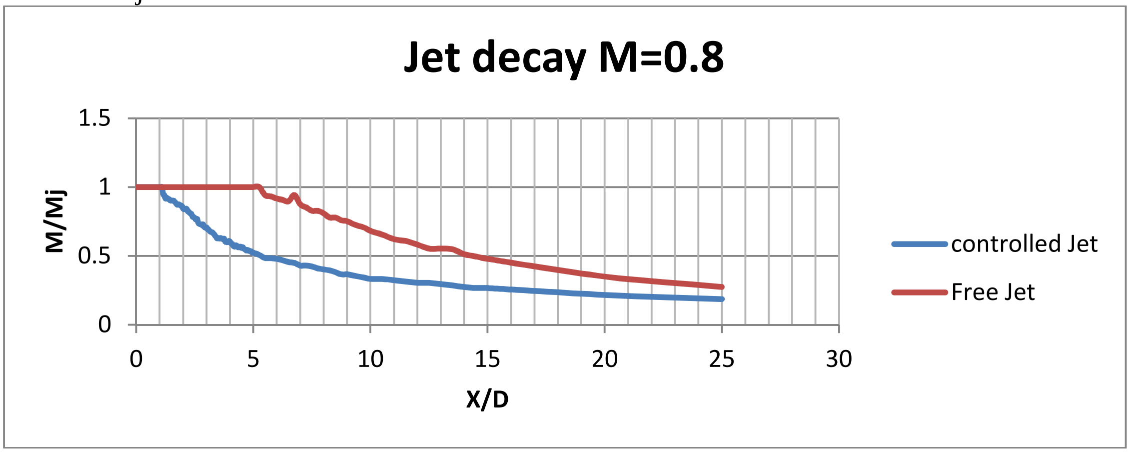
NODES	ELEMENTS	MAX.FACE SIZE (mm)
14395	69993	30
461834	2453316	8
641646	3530922	7
888160	5007353	6

Maximum face size of 6mm was chosen for meshing .

Results and discussion

Experimental Results

The jet decay characteristics investigation is carried out using centreline jet Mach number plot with the axial locations from the jet exit.



Plot 1 : Jet decay comparison along the centre line for Mach 0.8

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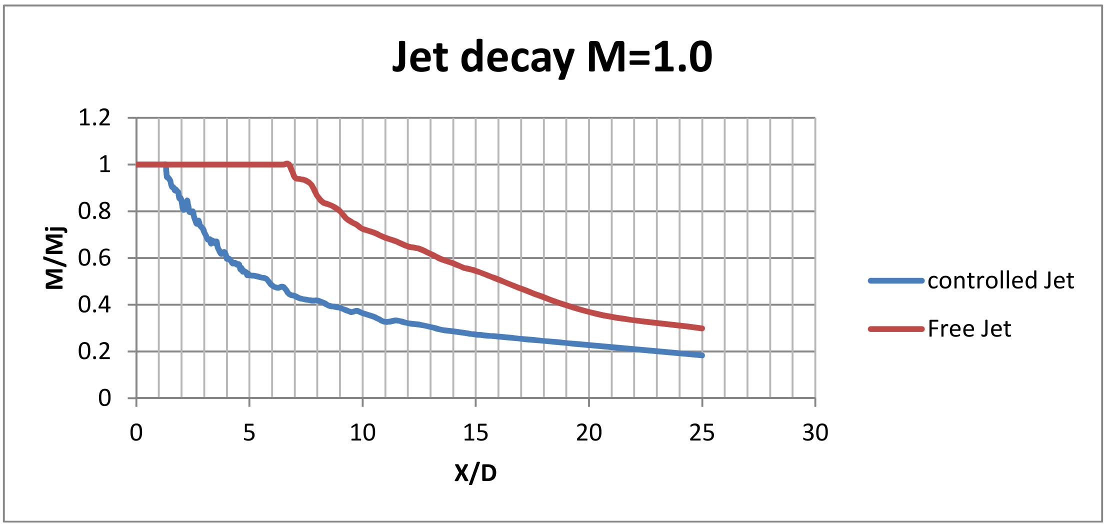
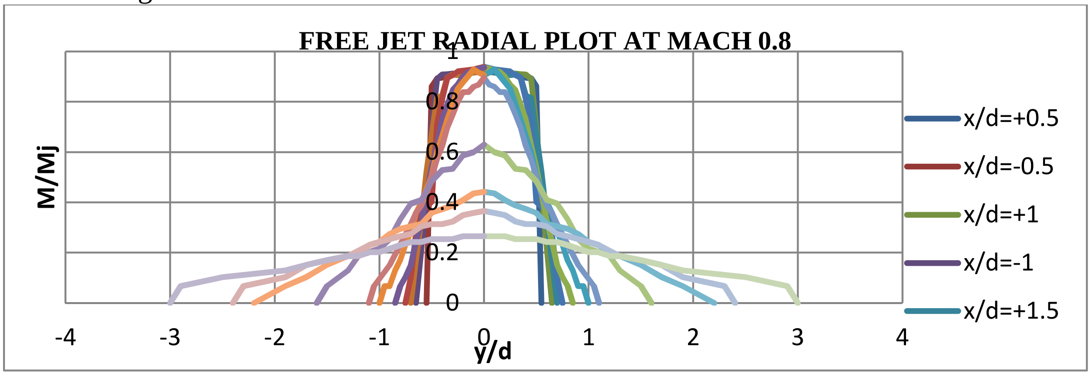
The plot1 can be analysed to have considerable reduction in the potential core length of the jet. The free jet potential core length was extending upto 5.5X/D where the controlled jet using tabs was around 1.1X/D. The reduction of potential core can be due to generation of pair vortices generated by the tabs. The vortices generated enhances the mass entrainment in the flow bringing in more amount of external air and thereby it increases the jet mixing.

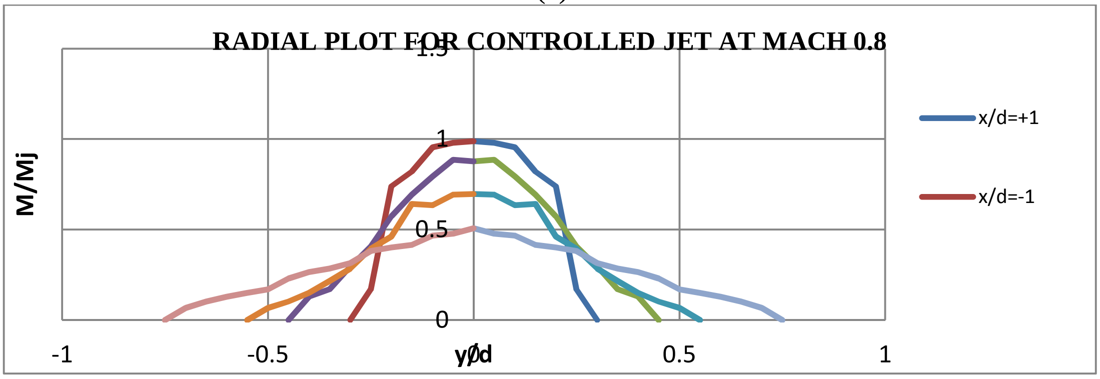


Plot 2 : Jet decay comparison along the centre line for Mach 1.0

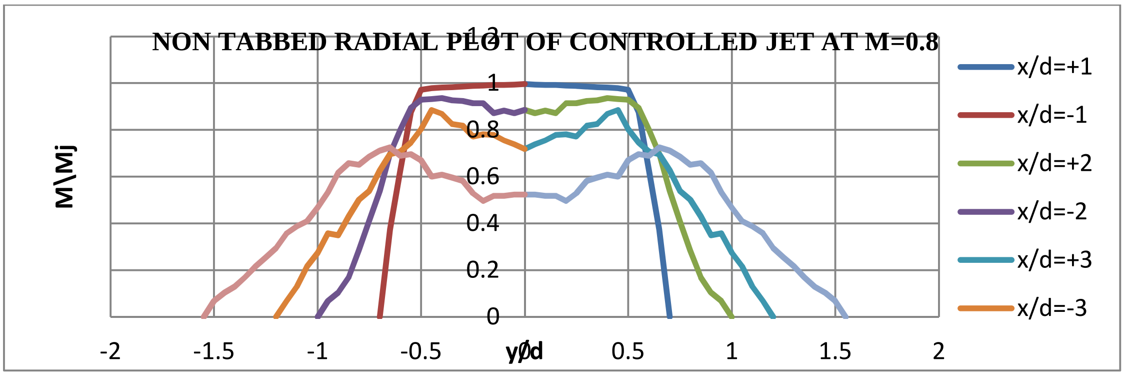
Similar to the plot 1, the plot2shows reduction in the potential core length of the jet using tabs. The free jet potential core length was extending up to 7.0X/D where the controlled jet using tabs was around 1.4X/D. The reduction of potential core with increase in the exit Mach number is observed in comparing M=0.8 and M=1.0. This observation justifies that the tabs effectiveness increases with increase in Mach numbers, which reduces the noise to great extent.



(a)



(b)



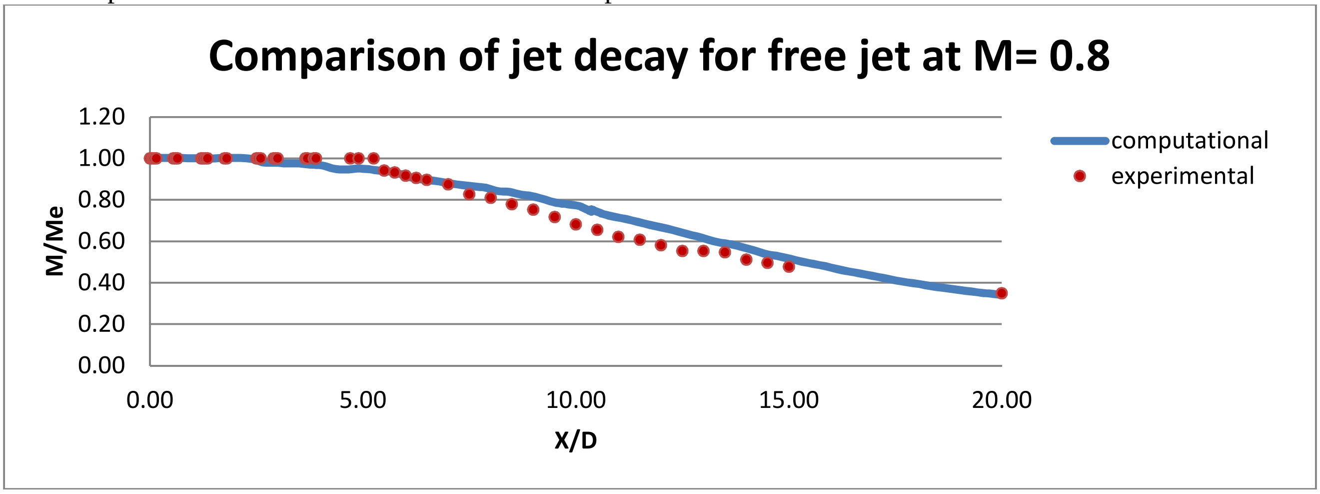
(c)

Plot 3 Radial plots of free jet and controlled jet in tabbed and non-tabbed directions

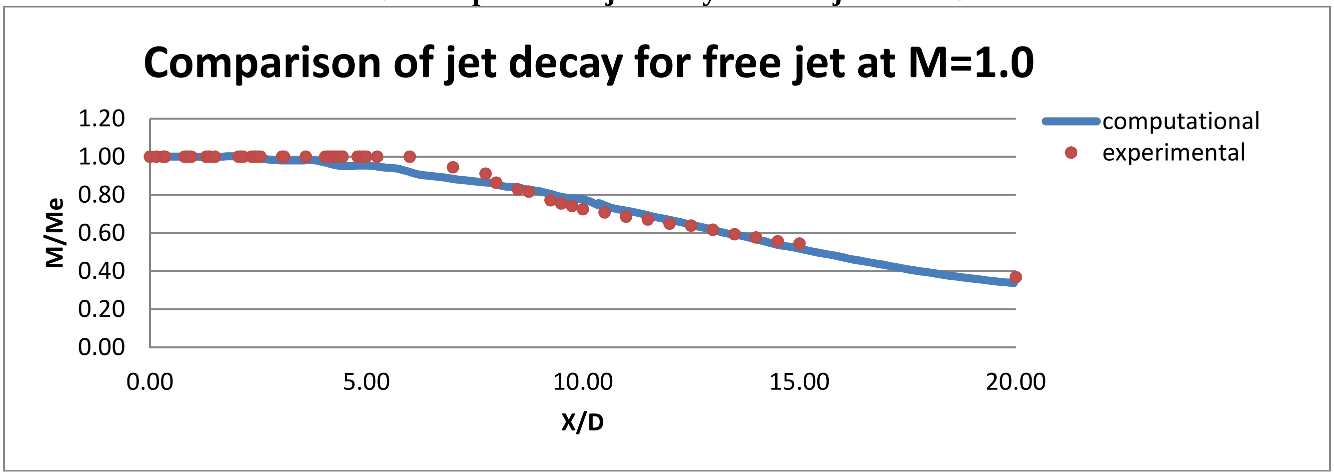
The radial plot describes the jet spread in different directions, for free jet the spread is symmetric since the jet is axi-symmetric. But for the jet with tabs the jet is non-symmetric, therefore the radial plots are drawn in two directions (Tabbed and non-tabbed). The radial plots can be observed that the controlled jet is expanding in the radial directions which helps in the reduction of potential core length in plot1.

Computational results

The computational results are validated with the experimental results obntainned for M=0.8 and M=1.0.



Plot:4 Comparison of jet decay for free jet atM=0.8



Plot:5 Comparison of jet decay for free jet at M=1.0

The results have shown thet the variation of computation and experimental results were below 8% (max). Hence the computational results can fairly be used for the study of flow behaviours.

Velocity magnitude contours for Axial jet decay

In the below contours, velocity along the axial flow direction of the jet are displayed for free jet and controlled jet for Mach number 0.8 and 1.0.

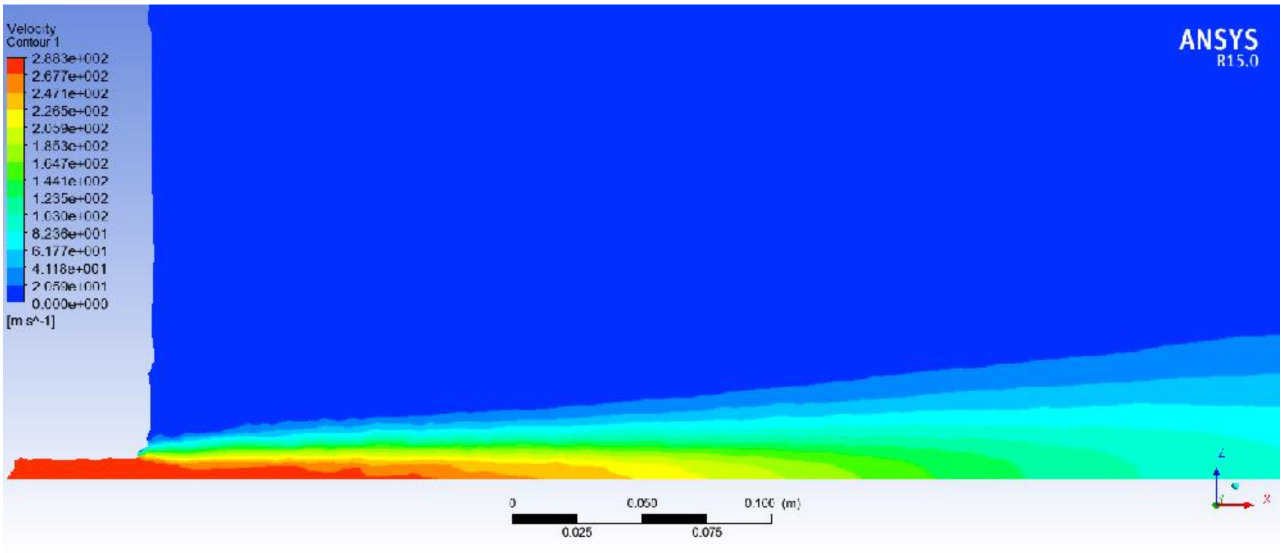


Fig. 3 Axial velocity magnitude contour for free jet at Mach number 0.8

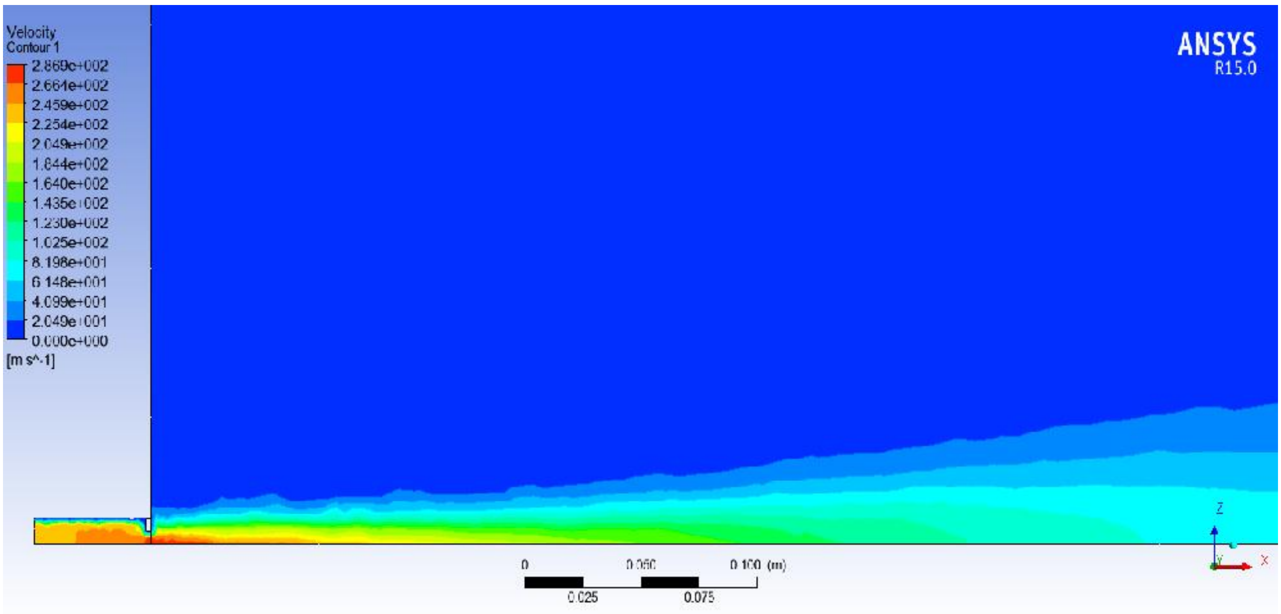


Fig. 4 Axial velocity magnitude contour for single tab at Mach number 0.8

The velocity contours generated from the computation explains the jet spread characteristics and the region of potential core. Its observed qualitatively from the contours that the potential core length was reduced considerably.

Conclusion

An experimental and computational study has been presented for different types of jet speed regimes from the nozzle. The computational results was also validated with the experimental results. The investigation shows that the jet decay and the jet spread characteristics have increased using the rectangular tabs. The controlled jet has created **79.04%** of potential core reduction for Mach 0.8 and **80.74%**of potential core reduction for Mach 1.0. The results also states that the tab efficiency increases with the increase the exit Mach number. The computation using Ansys - fluent has been carried out for Mach number 0.8 and 1.0. Passive control using solid tab was investigated for jet control. The jet spread characteristics were also compared which has shown considerable increase in the jet spread in which the maximum radial spread in tabbed and non-tabbed directions. The rectangular tab was found effective than the free jet in all aspects of the jet.

Future work:

The investigation can be carried out for higher NPR's of about NPR3, NPR4 etc to create underexpanded jet condition. The computation can also be done for various other tabs. The jet control and jet spread characteristics of the above cases can be compared to justify the effective tab in those conditions.

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