Numerical Study on the Effect of Innovative Vortex Generators in the Mixing Enhancement of Subsonic Jets

S. Thanigaiarasu, S. B. Jabez Richards, V. Karthikeyan, A. Muthuram, Surendra Kumar Yadav, and T. Vijaya Raj

Abstract Numerical analysis of subsonic jets with and without tabs (vortex generators with exit area blockage of 4.84%) has been done in the present research paper. Two tabs has been fixed at nozzle exit diametrically opposite. ANSYS CFX software was used for analysis purpose and to understand the flow characteristics at four different Mach numbers 0.4, 0.6, 0.8 and 1.0. The main objective of the present study is to analyze the effect of innovative vortex generators in the form of solid tabs with triangular fins on either side offset to each other on the performance characteristics. Due to counter rotating streamwise vortices, there is large engulfment of masses from ambient air into the core jet, resulting in the reduction of potential core length.

Keywords Subsonic jets · Tabs · Asymmetric · Innovative vortex generators · Mixing enhancement · Stream-wise vortices · Mass entrainment

S. Thanigaiarasu · S. B. Jabez Richards (✉) · V. Karthikeyan
Madras Institute of Technology Campus, Anna University, Chennai, India
e-mail: jabez3011@gmail.com

S. Thanigaiarasu
e-mail: sthanigaiarasu@mitindia.edu

V. Karthikeyan
e-mail: aerokarthi21@gmail.com

A. Muthuram
St. Peter's College of Engineering and Technology, Chennai, India
e-mail: masrimuthu@gmail.com

S. K. Yadav · T. Vijaya Raj
Prince Shri Venkateshwara Padmavathi Engineering College, Chennai, India
e-mail: aero.surendra@gmail.com

T. Vijaya Raj
e-mail: jaywinvijay@gmail.com

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Nomenclature

D	Diameter of nozzle exit
M	Mach number
P_0	Gauge inlet total pressure
P_{0e}	Total pressure at nozzle exit
x	Axial distance along the jet
RT	Right-angled triangular projection

1 Introduction

Jet mixing enhancements of both low and high-speed flows are widely used in numerous applications such as noise suppression in airplanes, improvement of efficiency in combustors, pollutant dispersal to the environment and in reducing infrared radiance of plumes in the case of military jets. The jet noise is minimum when the jet stream mixes with the ambient fluid at the earliest. In the case of gas turbine engines, for better combustion characteristics, the mixing of fuel should be in the proper proportion with the air. The main combustion problem which is generally encountered in the gas turbine engines is the minimal time available for the fuel to mix with the air and ignite to produce the required thrust due to the faster moving air into the core. Therefore, jet exit at the fuel injector should reach the optimal pressure required for better combustion at the earliest. Enhancing the mixing in that regime helps in designing a combustor of shorter length, which is an important aspect in the design gas turbine engines. Another application of jet control is reduction of plume length in the nozzle exit, which serves for military purposes making aircraft to minimal exposure to the enemy radars by reducing its IR signature. For such applications, jet control using both passive and active techniques are in practice. Active control techniques are moderately used due to its complex phenomenon. As far as passive control technique is concerned, it is quite simple and as much effective as active control techniques. Thus, passive control methods are widely preferred for jet control applications, which uses geometrical modifications such as tabs, grooves, vanes, notches, cross wires etc. for controlling the jet stream.

Many researchers have carried out extensive researches on various passive methods of jet controls. An early study by Bradbury and Khadem [1] found that two tabs placed 180° apart at the exit of an axisymmetric jet caused it to bifurcate, causing significant increment in the overall mass entrainment of the fluids. With the obtained results as reference several studies were made by various researchers and the results were reported taking into account the variations in flow field conditions, tab shape, size, number and angle. Behrouzi and McGuirk [2] observed the jet decay as function of tab projected area, tab width, number of tabs, tab orientation angle and tab shape. From the observations, it was found that jet centreline decay weakly dependent on tab orientation angle and tab shape but the effects are quite significant with increase in the number of tabs. Zaman [3] studied experimentally the effect of vortex generators, in the form of small tabs at the nozzle exit over various Mach number ranges. The effects of increasing the number of tabs has been studied in comparison with the corresponding case without a tab. Bifurcations were observed when two tabs were placed diametrically opposite at the nozzle exit.

Venkatramanan and Thanigaiarasu [4] made an experimental and computational study for different jet spread regimes in the nozzle exit. From their investigation they found that the jet decay and the jet spread characteristics have increased substantially using the rectangular tabs. The controlled jet has about 79.04% of potential core length reduction for Mach 0.8 and 80.74% for Mach 1.0. Berrueta and Rathakrishnan [5] studied experimentally the mixing caused by the limiting tab with and without corrugations at the nozzle exit at various downstream distances. It was observed that the presence of tab at the nozzle exit gives positive results than at downstream locations.

Lovaraju and Rathakrishnan [6] investigated the cross-wire effectiveness for subsonic and sonic jet control for axisymmetric jets for various Mach numbers. The cross-wires were found to be effective in promoting jet mixing right from the nozzle exit, at all Mach numbers. Dharmahinder et al. [7] studied the effect of perforated arc tabs in the mixing enhancement of axi-symmetric subsonic and sonic jets. Centerline velocity decay profiles and radial velocity decay profiles of the controlled jet gave a clear insight on the effect of perforated arc tabs.

Asad Ahmed et al. [8] studied the effect of perforated tabs and solid tabs in the jet flow at Mach numbers 0.4, 0.6, 0.8 and 1.0. From their investigation, they found that the effect of solid tabs dominates in far downstream locations compared to perforated tabs. Rathakrishnan [9] studied the effect of rectangular tabs of different aspect ratios, with and without corrugation, in the mixing of subsonic and sonic free jets. For the sonic jet, a maximum core length reduction of 32.3% was achieved with the plain tabs, whereas with the corrugated tabs the core length reduction obtained was 17.63%.

Zaman [10] experimentally investigated the jet spreading characteristics of several nozzles with circular, rectangular and elliptic cross-sections. Jets from the rectangular nozzle fitted with two tabs on the narrow edges and the circular nozzle fitted with four equally spaced tabs were also included in the comparative study over various ranges of Mach numbers. In comparison with the axisymmetric jet, the asymmetric jets spread only slightly faster at subsonic condition than at the supersonic regime. Zaman [11] investigated the effect of triangular tabs, placed at the nozzle exit, on the evolution of free jets. The effect, a large distortion of the jet cross section and a resultant increase in mixing downstream, has been inferred before as a result of a pair of stream wise vortices originating from each tab.

In the present study, tabs are used to create instabilities, which modifies the jet flow structure in the proximity of the nozzle exit. Instead of normal tab configuration used in previous researches for jet control, this paper presents innovative tabs with sharp cornered right-angled triangular fin like projections on solid rectangular tabs with certain offset distance between them on either side.

2 Nozzle Geometry and Tab Placement

In this paper, plain nozzle and nozzle with two different tab investigations are carried out. Plain nozzle is simply a convergent circular nozzle with 40 mm inlet diameter and 20 mm exit diameter with nozzle lip thickness of 5 mm throughout the length of the nozzle. Jet is controlled by placing the tabs (Vortex Generators) at the exit plane of the circular nozzle on both sides of the jet centreline. Tabs used here have a rectangular shaped stem (4 mm × 1 mm × 1 mm) with triangular projections placed at both sides offset to each other asymmetric to the jet centreline. Asymmetry mentioned in this paper is not with respect to the placement of tabs, but due to the extended triangular projections about the jet centreline. Area blockage by the tabs accounts for 15.2 mm^2 which are 4.84% of exit area of plain circular nozzle. Nozzle is designed using SOLIDWORKS 2015 software (Figs. 1 and 2).

Tabs are categorized into two types based on the distance between triangular projections and named as mentioned below:

- RT_0 mm: Tabs with Right angled triangular projection where distance between projections is 0 mm.
- RT_1 mm: Tabs with Right angled triangular projection where distance between projections is 1 mm.

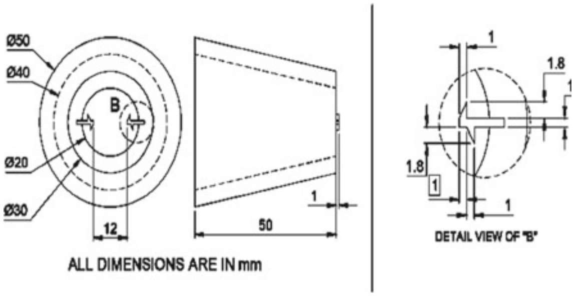

Fig. 1 Nozzle with RT_0 mm tab

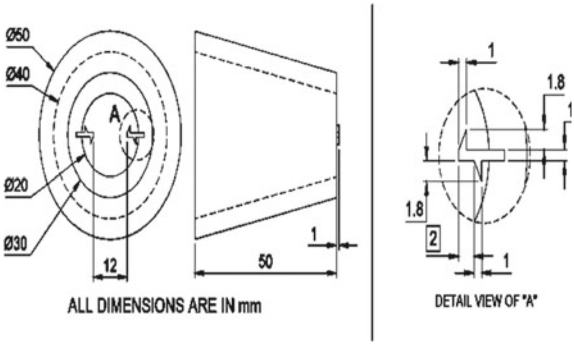

Fig. 2 Nozzle with RT_1 mm tab

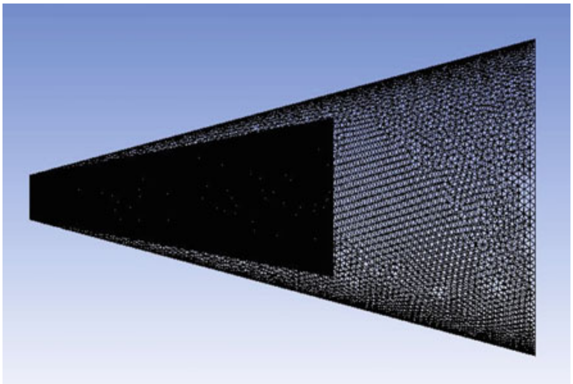

Fig. 3 Unstructured mesh of nozzle with domain

3 Computational Details

3.1 Geometry and Domain

Convergent Nozzle with inlet diameter 40 mm, exit diameter 20 mm and length 50 mm with a lip thickness of 5 mm. Domain for capturing the jet mixing characteristics is designed up to 35 times the exit diameter. Two domains are created such that first domain is up to 20 x/D and next domain up to 35 x/D with a domain interface.

Grid Generation Grids are generated using the ANSYS 16.0 meshing software. Generated grids are unstructured tetrahedrons, where finer meshing with minimum element size of 2 mm is achieved in first domain. In second domain, element size increased by a factor of 1.2. Mesh adaption is done until there are finite number of nodes at required points and thereby grid independency is studied (Fig. 3).

3.2 Boundary Conditions

Defining boundary conditions involves identifying the location of the boundaries and applying information at the boundaries. The data required at a boundary depends upon the boundary condition type and the physical model employed. Poorly defined boundary conditions can have a significant impact on the solution. Inlet of the nozzle is given as pressure inlet, Exit of domain as pressure outlet; sides of the domain are pressure farfield (Opening), nozzle is chosen as wall as shown in Fig. 4.

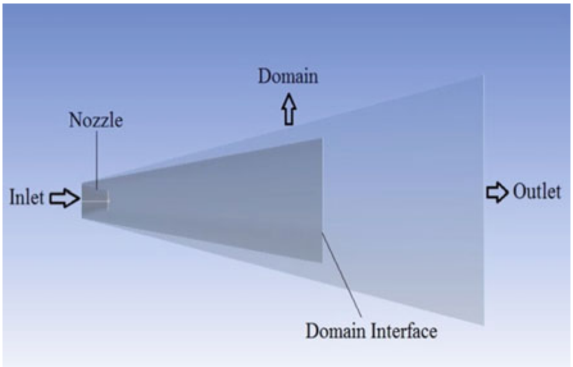

Fig. 4 Boundary details of the model analyzed

3.3 Solver and Turbulence Model

CFX 16.0 is used as solver to perform the numerical simulation, in which the finite difference method is used for solving the governing equations. Selecting the turbulence model is most important criteria in performing the numerical simulation. That defines how close the numerical data are matching with the experimental results. In most cases, K-ε turbulence model is used for defining the turbulence characteristics in the jet flow due to its accuracy. But in current study, there is limitation of using K-ε turbulence model (i.e.) tabs which are placed at the exit plane of the nozzle creates a strong adverse pressure gradient which makes the solver unstable using that turbulence model. So, for current study SST K-ω turbulence model is used, since the model has an advantage being stable at the strong adverse pressure gradient regimes. The SST model accounts for cross-diffusion with the K-epsilon and K-omega models. In other words, SST K-ω turbulence model works like K-epsilon in the far field and K-omega near the target geometry. This criterion fulfills flow requirement of the current study and thus SST K-ω is preferred over the standard K-ε turbulence model used in previous research papers.

4 Results and Discussions

4.1 Centreline Pressure Decay

Centreline pressure decay profile is a significant measure of jet mixing. The faster the decay, the faster is the jet mixing rate with the entrained ambient fluid mass and so on, which clearly indicates that the core of the jet gets better mixing due to the entrainment of the ambient fluid from the surrounding. The centreline pressure decay clearly shows the extent of the potential core of the jet, which is defined as the axial distance up to which the nozzle-exit velocity remains uniform for subsonic jets. P_{oe} is the gauge total pressure along the jet axis which is non-dimensionalized with the gauge inlet total pressure P_o supplied to the nozzle inlet. Axial distance x is non-dimensionalized with nozzle exit diameter D. Thus, the graph is plotted between x/D in x-axis and P_{oe}/P_o in y-axis to observe the jet decay characteristics in axial direction.

Figures 5, 6, 7 and 8 shows the centreline pressure decay for the jet with Mach numbers of 0.4, 0.6, 0.8 and 1.0 respectively. Base represents the centreline decay of uncontrolled jet whereas RT_0 mm and RT_1 mm represent centreline decay of controlled jet with corresponding tab configurations. Potential core region for uncontrolled jet increases slightly as Mach number increases which may be due to the high kinetic energy possessed by the jet with the supplied inlet pressure to achieve the desired Mach number. Percentage reduction in potential core length for tabbed jet is increasing with increase in Mach number. This is because the mixing efficiency of the vortices generated due to the tabs depends on its vortices strength and also the residual time for the interaction with the ambient fluid.

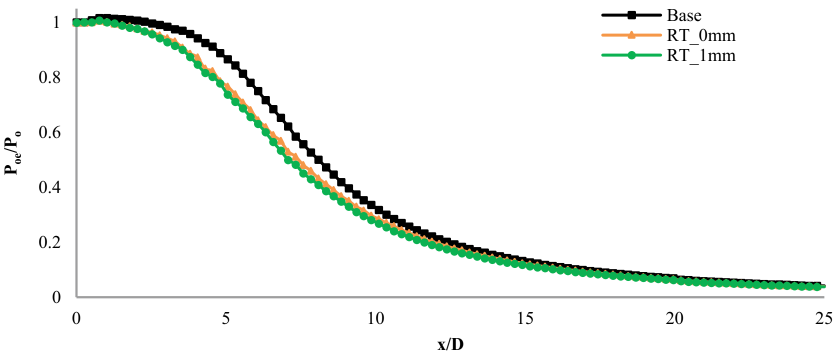

Fig. 5 Centreline pressure decay for M = 0.4

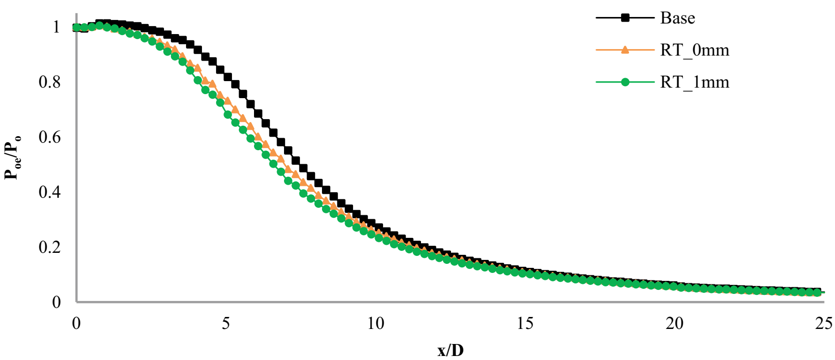

Fig. 6 Centreline pressure decay for M = 0.6

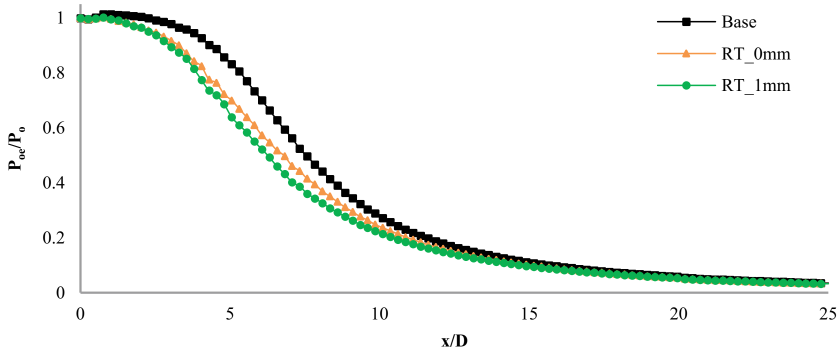

Fig. 7 Centreline pressure decay for M = 0.8

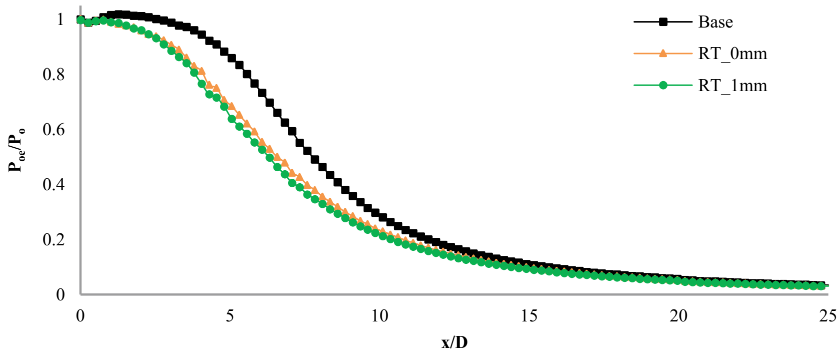

Fig. 8 Centreline pressure decay for M = 1.0

For instance, when comparing Mach numbers 0.4 and 0.6 for present study, the interaction time available for vortices at Mach 0.6 is less than that at Mach 0.4, which depicts that the vortices are transported away faster, since the faster transportation causes lesser vorticity loss, these vortices are helpful in engulfing the ambient fluid into the core region. So, the performance of the tabs in reducing the potential core length increases proportionally with the Mach number. The other factors include, the mass flow accumulation which is more at higher Mach numbers making more pressure gradients and causing the vortices' convective Mach number to be large causing strong eddy formation in the shear layer of the jet stream.

The concept of using the tabs with projections instead of a plain rectangular tab is to promote generation of more vortices from the sharp corners which in turn results in the engulfment of more ambient fluid into the jet core. When the tab configurations RT_0 mm and RT_1 mm are separately compared for centreline pressure decay, nozzle with RT_1 mm shows more characteristic decay. This is because the vortices which are produced at the sharp corners of the projections are counter-rotating type which becomes streamwise vortices due to high kinetic energy of the jet. So, when the projections are placed at a distance of 1 mm, the interaction between the streamwise vortices produced by those sharp corners gets delayed, thereby ensuing minimal loss in vorticity content when compared to RT_0 mm tab configuration.

Thus, observed centreline pressure decay is more for RT_1 mm tab configuration in potential core regime as well as transition regime of the jet. It is also observed that compressibility effect has a role to play in the jet decay characteristics due to the presence of the tabs (i.e.) when Mach number increases, reduction percentage increases. From the above plots the potential core length is maximum for Mach 1.0 which extends to about 4.54 D for uncontrolled jet, whereas potential core length is reduced to 1.37 D for same Mach number of controlled jets with tab RT_1 mm configuration which is a significant reduction.

5 Conclusions

In this paper numerical analysis of base nozzle and nozzle with tabs (2 configurations) has been presented for four Mach numbers. Due to the effect of tabs, the reduction in potential core length is observed because of the enhanced mixing produced by the counter rotating vortices from the sharp corners of tabs. From the numerical results, it is found that the core length was reduced significantly with increase in Mach number along the jet axis centreline. Even the vortex generators enhance the slope of the centreline pressure decay in the transition region when compared to base nozzle's centreline pressure decay. Nozzle with tab named RT_1 mm for Mach number 1.0 shows maximum percentage reduction of potential core about 69.82% when compared with free jet.

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