Experimental Investigation of InnovativeVortex Generators in the Mixing Enhancement of Subsonic Jets

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Abstract: *Jet mixing becomes necessary for its wide range of applications from household appliances to modern high technology rockets. Various researchers have studied the enhancement of jet mixing and concluded that the most effective jet mixing is due to the engagement of a vortex generatorat the exit plane of the nozzle, thereby creating vortices of different sizes to enhance the mixing. To intensify the jet mixing, two similar innovative vortex generators with a total blockage ratio of 3.5% are placed diametrically opposite locations of the convergent nozzle. The Aspect Ratio of the convergent nozzle is 1. A numerical investigation is carried out to assess the effectiveness of the vortex generator for Mach numbers of 0.4, 0.5, 0.6, 0.7 and 0.8. The centerline Pitot pressure decay was calculated and found to exhibit the core length reduction due to the introduction of the Vortex generator. To measure the effectiveness of the jet mixing using vortex generators, the results are compared with the uncontrolled jet.*

Key Words: *jet mixing, passive control, subsonic, vortex generator*

1. INTRODUCTION

The present paper continues the theme of the authors' recent research [1-8], by detailing the extensive research procedure on jet mixing characteristics and improvement that has been carried out over the last 50 years. Jet mixing is the process of main jet stream coming out of the nozzle mixing with the ambient air. A solid vortex generator is a small protrusion placed at the jet nozzle exit. A vortex generator (placed normal to the flow) generates a pair of counter-rotating transverse vortices (with the axis of rotation along the vortex generator length). Clearly, if beneficial, one or more vortex generators can be attached to the nozzle exit to enhance the mixing process (e.g., to effect plume signature reduction), although this may also increase the associated drag (thrust loss) penalty. A vortex generator [9-11] appears to be a practical method for jet plume mixing enhancement in the near field, that is, between 2 and 10 diameters from the jet exit. Vortex generators have also been shown to eliminate or substantially reduce screeching noise and noise associated with mixing and shock at low frequencies. From the vortex theory, it is well known that, the smaller the vortex size the

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better is its mixing promotion efficiency. Also, small vortices are stable and can travel longer distances compared to large vortices, which are unstable.

Jet mixing can be achieved by two methods. There are Passive jet mixing and Active jet mixing. The active jet mixing involves energized actuators to dynamically manipulate the flow. Active jet mixing involves the external power source. The passive control is preferable since no external power source is required for its operation. Passive controls are mainly based on the geometrical modification of the nozzle, which generates the jet, or the introduction of a secondary body, which can shed mixing by promoting small-scale vortices. A vortex generator is one such passive control, which generates counter-rotating vortices all along its sides, that become stream-wise immediately after shedding.

2. ANALYSIS OF VORTEX GENERATOR

A. Convergent nozzle

The convergent nozzle design is developed in CATIA V5R21 software. The dimensionof the convergent nozzle is given below.

- Inlet radius = 20 mm
- Inlet area = 1256.36 mm^2
- Exit radius = 10 mm
- Exit Area = 314.15 mm^2

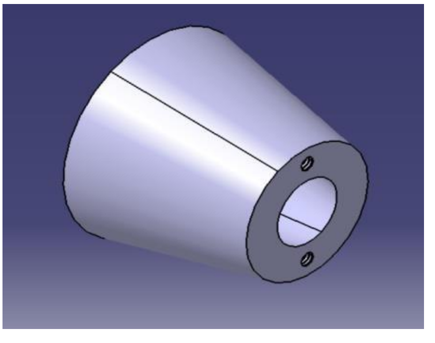


Fig. 1 Design of convergent nozzle

B. Vortex generator calculation

A convergent nozzle with 20 mm exit diameter is used to examine the mixing effectiveness of the rectangular slotted tab.

Two slotted rectangular tabs were kept on diametrically opposite sides in the exit plane of the converging nozzle. The blockage ration can by calculated by using the nozzle and tab dimensions.

$$\text{Blockage Ratio} = \frac{2 \times (Vortex\ Generator)}{Nozzle\ exit\ area} \times 100\%$$

- Rectangular area = 3×1 = 3 mm^2
- Triangular Area 1 = 0.5×2×1 = 1 mm^2
- Triangular Area 2 = 0.5×1.8×1.8 = 1.62 mm^2
- Tab Area = 3+1+1.62 = 5.62 mm^2

The blockage ratio of the vortex generator with convergent nozzle is 3.57%. The design of the vortex generator with dimensions is shown in Fig. 2

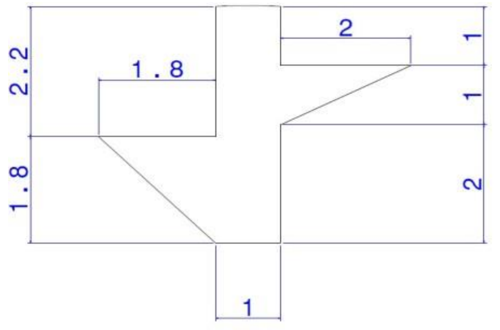


Fig. 2 Vortex generator with dimensions

C. Design

The vortex generator design is developed in CATIA V5R21 software. The design of the vortex generator is shown in Fig. 3

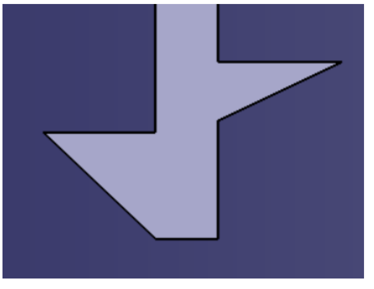


Fig. 3 Design of the vortex generator

The assembly design with convergent nozzle and vortex generator using CATIA V5R21 software is shown in Fig. 4.

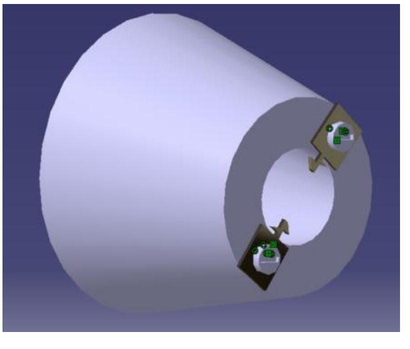


Fig. 4 Assembly design

3. COMPUTATIONAL DOMAIN AND SETTING PARAMETERS

To computationally investigate the jet mixing and jet spread characteristics, ANSYS CFX software is used for generating the grid and for solution solving, respectively. The boundary conditions are initially fixed. The domain of diameter 8 *D*e (exit diameter) and length 22.5 *D*e is used for the study. For the inlet, the boundary condition is the velocity inlet corresponding to Mach 0.6 and, for the domain, a pressure outlet with the ambient condition is chosen. The temperature is set to 300 K for the air fluid material. For the nozzle and tabs wall with the adiabatic, no-slip condition is specified. The turbulent wall function for the fluid domain is set to automatic. The Figure below shows the boundary details of the free jet configuration. The convergence criteria for the variables for solving the solution algorithm is set to 10^{-4}.

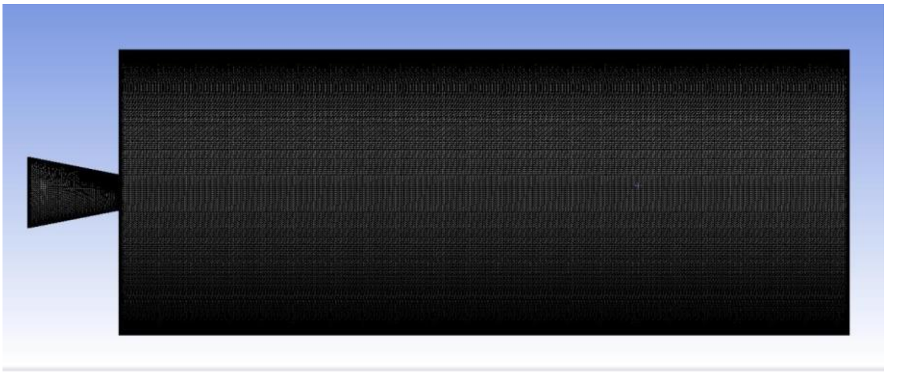


Fig. 5 Mesh

4. EXPERIMENTAL SETUP AND PROCEDURE

The experiments were conducted in the open jet facility at the aerodynamics laboratory, Rajalakshmi Engineering College, Chennai, 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 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 an 8 port pressure transducers with DAS. The Direct-Attached Storage (DAS) is digital storage directly attached to the computer accessing it, as opposed to storage accessed over a computer network.

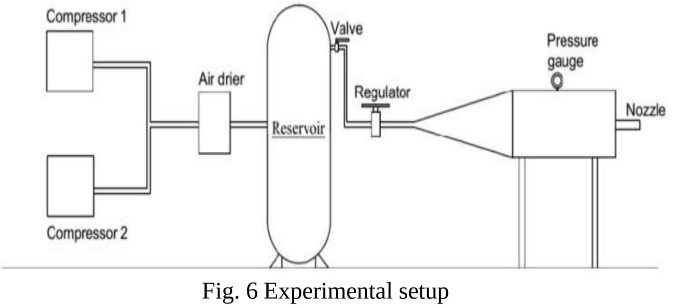


Fig. 6 Experimental setup

5. DISCUSSIONS

A. Velocity Contours in XY Plane

The Figure below shows the velocity contours in the XY plane free jet. The Figure shows the velocity contours in the XY plane innovative vortex enabled jet. It is seen that the core of the free jet is larger compared to the innovative vortex generator. When compared to the free jet, the core of the innovative vortex generator employed jet is smaller. Along the y-direction, the jet spread distance for the innovative vortex generator configuration is larger than the free jet. This ensures that the innovative vortex generator decays faster and enhances the jet mixing process when compared to the free jet.

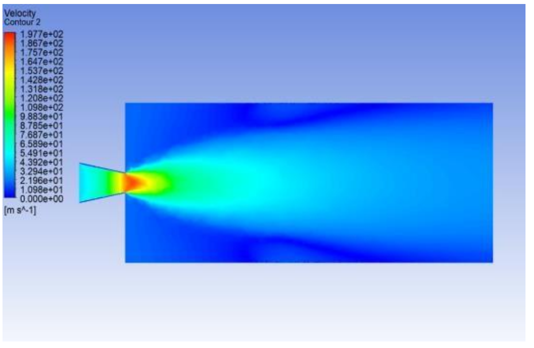


Fig. 7 Velocity Contour for Uncontrolled jet

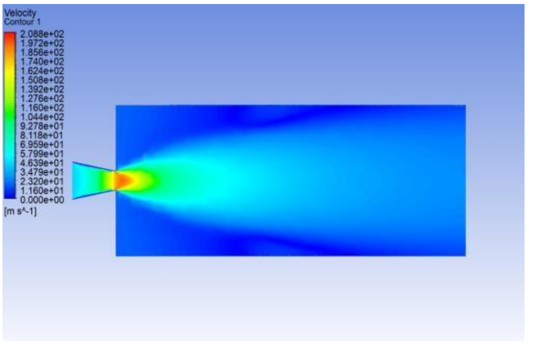


Fig. 8 Velocity Contour for controlled jet

B. Centreline Pressure Decay

The jet centerline velocity/ Mach number/ total pressure decay is a reliable measure of jet mixing (Rathakrishnan 2009), i.e., the faster the decay, the faster is the jet mixing with the entrained fluid mass. The centerline velocity decay can clearly state the jet core. The jet core is the distance from the nozzle exit along the centerline, until which the velocity or Mach number or total pressure is unaffected.

The total pressure from the exit of the nozzle (P) is measured along the jet centreline for a length of 22.5 De.

The measured pressure is made dimensionless using the inlet pressure (P0) and is plotted as a function of the axial distance (*X*/*D*e) to investigate the effect of tabson jet mixing. In Fig. 9, it is observed that the potential core region lies at 4.08 and 2.61 *D*e for the free jet and innovative vortex generator, respectively.

Thus, the percentage reduction in the jet core for the innovative vortex generator when compared to the free jet is 35.97%. In Fig. 10, it is observed that the potential core region lies at 3.81 and 2.37 *D*e for the free jet and innovative vortex generator, respectively. Thus, the percentage reduction in thejet core for the innovative vortex generator when compared to the free jet is 37.65%.

In Fig. 11, it is observed that the potential core region lies at 4.15 and 2.25 *D*e for the free jet and innovative vortex generator, respectively.

Thus, the percentage reduction in the jetcore for the innovative vortex generator when compared to the free jet is 45.75%.

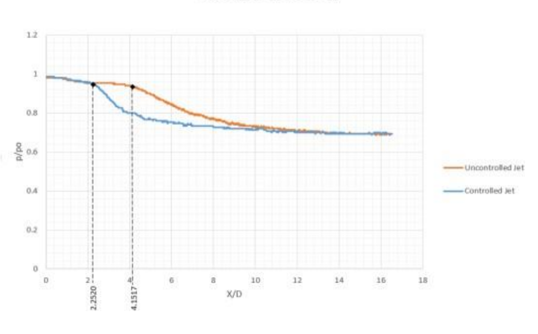


Fig. 9 Centreline Pressure Decay Profile forMach number. 0.5

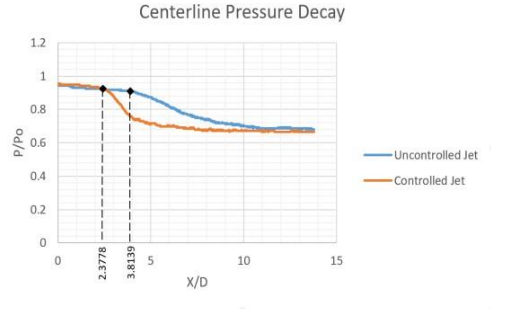


Fig. 10 Centreline Pressure Decay Profile for Mach number 0.7

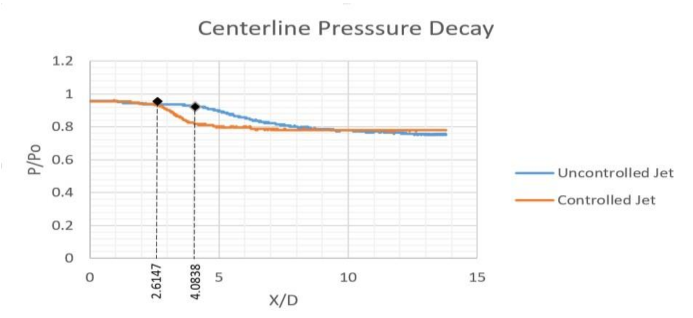


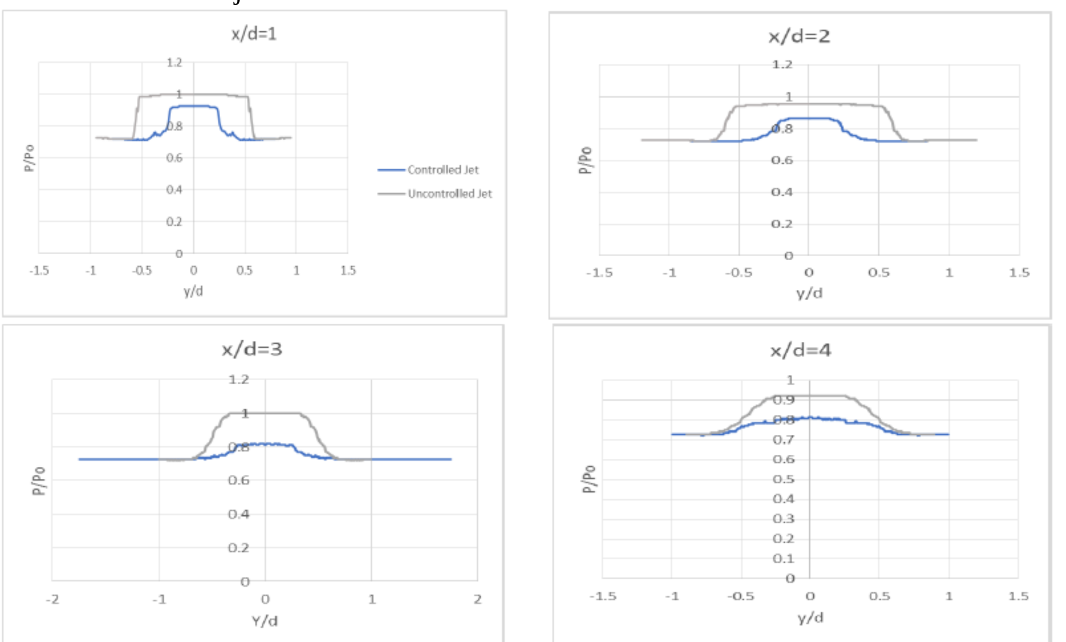
Fig. 11 Centreline Pressure Decay Profile for Mach number 0.8

From the profile for the innovative vortex generator, it is observed that the characteristic decay and the self-similar regions were occurring faster than the free jet. Thisis due to the vortices induced by the innovative vortex generator geometry. It is evident that the innovative vortex generator changes the jet structure to a more substantial amount to enhance the jet mixing. Further downstream the mixing happens much faster for the controlled jet. The Percentage of core reduction defined as

$$\%\ reduction = \left(\frac{\Delta L_{without\ vortex\ generator} - \Delta L_{with\ vortex\ generator}}{\Delta L_{without\ vortex\ generator}}\right) \times \%$$

C. Radial line Pressure Decay

To get a clear insight into jet spread characteristics, the pressure profiles are studied at locations normal to the innovative vortex generator axis and along the innovative vortex generator axis. The velocity profiles were taken at various axial distances of 1, 2, 3, 4 and 5 respectively. The pressure profiles were made dimensionless with reference values of the jet. This following section discusses the radial pressure profiles normal to the innovative vortex axis. Figures represents the radial velocity profiles at various X/De locations 1, 2, 3, 4 and 5 for Mach 0.7 and 0.8 jet.



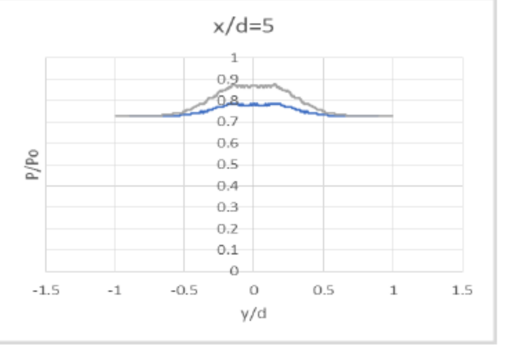


Fig. 12 Radial line Pressure Decay for Mach number 0.7 at different X/De locations

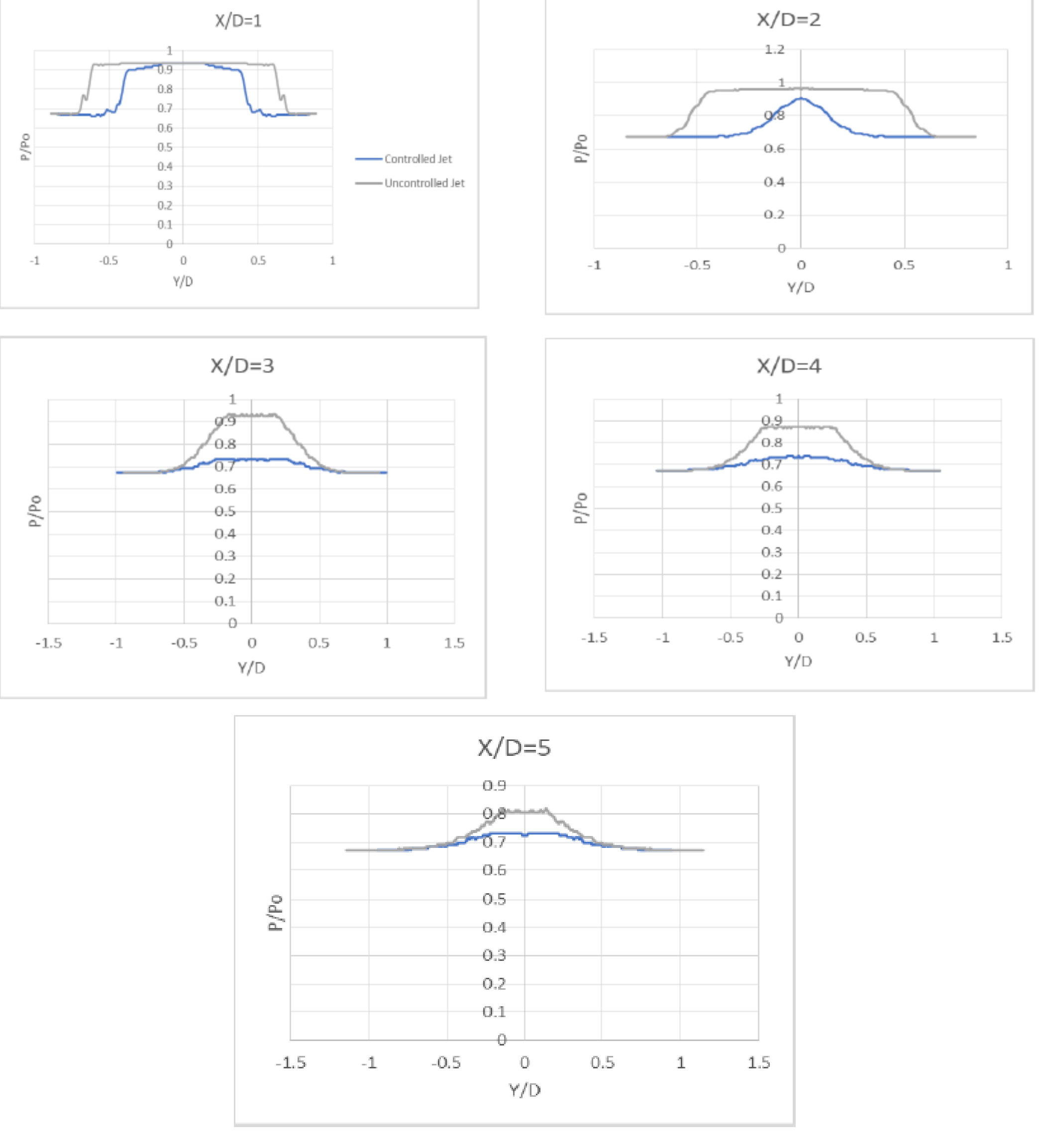


Fig. 13 Radial line Pressure Decay for Mach number 0.8 at different X/De locations

6. CONCLUSIONS

The effectiveness of the innovative vortex generator is studied for the jet exit Mach number 0.5, 0.7, 0.8 and is compared to the free jet. The centerline decay profile shows that the jet with an innovative vortex generator enhances the jet mixing process more than the free jet.The velocity contours extracted by cutting out various planes of the jet gives a brief insight about the jet flow development and its structure at various *X*/*D*e locations of the jet. Hence from the results of the centreline total pressure profiles, it is strongly concluded that the innovative vortex generator proves to be more effective in distorting the jet at the near field and enhances the jet mixing process. The results of the pressure study show that, at 10Dethe pressure at the centreline becomes equal to atmospheric pressure and the pressure becomes almost flat along the jet, showing the fully developed jet. It is observed that the potential core length has been reduced to a considerable amount caused by the mixing promoting vortices shed by the Innovative vortex generator. Further downstream the mixing happens much faster than the controlled jet.

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