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Investigation of Sonic Under-expanded Jets Using Slotted Rectangular Mechanical Tabs

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ABSTRACT

Study on the behavior of jet flows are important for various reasons especially in the fields of aerospace, mechanical engineering, and environmental science. In aerospace engineering, understanding how jets behave can assist in increase / decrease thrust, decrease drag, improve fuel efficiency and reduce jet associated noise in aircraft engines and rockets. The flow control of jets is necessary for faster mixing and spreading, which can lead to much important aspects of noise reduction. Passive flow control of jets for various advantages like noise reduction, better mixing and thrust vector control is achieved by using mechanical slotted tabs. The effects of the slotted rectangular tabs are studied experimentally at different nozzle pressure ratios of 3, 4 and 5. The study involves the usage of three different novel configurations of rectangular slotted tabs for jet flow control. The Tabs A, B and C are designed with a blockage of 7.3% which are placed diametrically opposite to each other at the exit of a converging nozzle of 13 mm exit diameter. The centerline total pressure profiles, radial total pressure profiles and shadowgraph images for the tabbed cases are retrieved from the investigation and the results are compared with the free jet to study and visualize the jet mixing characteristics of the tabs. The results proved that tabs are found to be effective in enhancing the mixing and thereby reducing the acoustical characteristics of the jets. Tab C is seen to perform better in enhancing the mixing compared to other tabs with a percentage reduction of 89 %, 86 % and 84 % for the Nozzle Pressure Ratio (NPR) 3, 4 and 5 respectively.

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1. INTRODUCTION

Jet flow control has been essential in making changes to the existing format of the jet to alter its structure desirably to cater to the existing problems and difficulties. Especially in the aerospace industry, the main focus in the design of aircrafts and rockets lies in the reduction of noise. The past few decades saw the increase in devising technology for the abetment of jet associated noise. In order to improve the jet mixing and to reduce the sound pressure levels, various control techniques have been designed in the past, and those control techniques are classified into the passive and active methods. The passive technique comprises of the mechanical devices fitted to the nozzle and its exit, whereas, the active control technique involves an external power source to control the flow.

Grooved nozzles, cross- wires, splitter plates and mechanical tabs are a few widely used passive control techniques. Many researchers of the past have shown interest in using the simple mechanical tabs as passive control devices to enhance the jet mixing characteristics and noise reduction. Research related to jet flow control and jet noise reduction, using rectangular tabs to manipulate jet flow and turbulence, was started initially by Bradbury and Khadem (1975). A tab is simply a protrusion kept normal to the flow direction (Zaman, 1993). Tabs placed diametrically opposite to each other at the nozzle exit, which creates stream wise mixed size vortices to transport fluid to the core (Reeder & Samimy, 1996). Such fluid transportation into the jet core from the jet periphery is called the entrainment process. The vortices produced are streamwise, counter rotating and in smaller and larger sizes. The streamwise vortices have longer life and tend to extend to many times the exit diameter. Whereas, the azimuthal vortices have shorter life but are highly energetic. The boundary layer thickness of the nozzle or the level of turbulence and convergence are found to be

Nomenclature

NPR	Nozzle Pressure Ratio	p_{oy}	total pressure normal the tab axis
D_e	exit diameter of the nozzle in mm	X	direction along the jet axis
p_o	total pressure at the nozzle inlet	Y	direction normal to the tab axis
p_{ox}	total pressure along the jet axis	Z	direction along the tab axis

insignificant in influencing the jet flow development (Rathakrishnan, 2009).

Bradbury and Khadem (1975), were one of the first researchers to study the development of axisymmetric jets using tabs as vortex generators. The study of tabs for axisymmetric jet distortions by Bradbury and Khadem (1975) limited the recurrence of vortex rings, which in turn reduced jet-associated noise. Two tabs situated in diametrically opposed directions were determined to have the highest efficiency in the study of the jet mixing enhancement employing hot and cold jets (Ahuja, 1990, 1993). This was accomplished by expanding Bradbury and Khadem (1975) research to the supersonic regime. It is reported that there are two stages to the mixing of turbulent jets with the atmosphere (Grinstein et al., 1995). A significant amount of fluid is brought together at the first junction, and vortex production occurs at the second. As a result, the vortices created will eventually have a tendency to hasten the atmosphere's mixing with the main stream jet. An experimental research by Reeder and Samimy (1996) advises positioning the tabs near the nozzle's exit plane to create counter-rotating vortices that are streamwise and lead to the deformation of jets.

The weaker vortices that are created at the tabs are discovered to be in perfect harmony with the horseshoe vortex's structure. Thus, it may be inferred that when the tabs are inserted, the shear forces speed up the mixing of the layers. High-speed jets are explored using a variety of jet mixing approaches, with a focus on reducing infrared signatures (Knowles & Saddington, 2006). Using an atypical jet exhaust nozzle design, the velocity ratio, number of tabs, shape and geometry of the tabs, and orientation angle are examined (Island et al., 1998).

The development of the jet is significantly impacted by the positioning of tabs around the nozzle's edge in order to prevent jet screeching. The formation of vortex rings around the whole perimeter of the jet is prevented by two tabs placed immediately across from one another, which in turn reduces the noise associated with jets (Pannu & Johanessan, 1976). The addition of grooves and v-notches also significantly reduces noise. They weaken and decrease the shock-cell structure, which lessens the noise caused by shocks. The mixing and shear layers are claimed to be distorted by the tabs, which lessens the phenomena of screech. Ahuja (1990), discuss ten potential noise-suppression theories for round nozzles. A microphone that is mounted on the jet departure plane collects data on jet associated noise. C-D nozzles with holes on the walls are identified as the most promising noise suppressor, according to Ahuja (1990). To roughly reproduce the conditions and patterns of flows with greater temperatures, Papamoschou (2004) measured the noise for coaxial jets made of helium-air mixtures. The authors VG et al. (2021), Krishnaraj & Ganesan (2023), Radha Krishnan et al., (2023) reported the effects of lip thickness on coflow nozzles.

Tabs and ejectors can be utilized for mixing enhancement and jet noise reduction (Ahuja, 1993). The mixing improvements of the jet with that of the atmosphere are investigated using tabs and ejectors. The decay, spread, and noise suppression characteristics of a converging-diverging nozzle with a Mach 1.8 include the impact of internal grooves (Vishnu & Rathakrishnan, 2004). Various designs and analyses of nozzles with various numbers of internal grooves are made possible. The findings demonstrate that where a negative pressure gradient exists at the nozzle exit, the nozzle pressure ratio also has a significant role. For low subsonic and sonic Mach numbers, (Krishnaraj & Ganesan, 2021, 2023) studied the influence of the slotted tabs on the jet flow control, numerically and experimentally to reveal that the slots in the adjacent faces produced better flow control and mass entrainments. Kumar and Chidambaram (2019, 2021) and Kumar et al., (2022) studied the effects of semi-circular corrugation on triangular tabs for the subsonic, sonic and supersonic regime respectively and reported that even the locations of corrugations plays a vital role in improving the mixing characteristics of the jet. Ezhilmaran et al. (2021) investigated the effect of straight and slanted perforations on a rectangular tab to control a Mach 1.8 supersonic jet, with slots connecting the opposing faces of the rectangular tab.

It is hence evident from the literatures that the jet decay characteristics are a priority and have a wide range of applications and the effects of slots on the opposite face of the rectangular tab was studied extensively for the subsonic and supersonic jet flow conditions. It is also very much evident that the effects of rectangular tabs with slot connecting the adjacent faces for sonic under expanded cases is not reported yet in any open literatures and proves to be the novelty of the present study. Hence the present paper deals with the investigation of jet mixing characteristics such as jet core, jet spread and their flow development using slotted rectangular tabs with slots connecting the adjacent face of the tabs.

2. TEST FACILITY AND EXPERIMENTAL MODELS

The experiments were carried out at the aerodynamics laboratory's open jet test facility. Figure 1 displays a schematic of the test facility. A gate valve and a pressure regulating valve are used to control the flow and pressure of the high pressure dry air that is sent to the settling chamber. At the other end of the settling chamber a provision is made to fix the convergent nozzle model. For a flow visualization studies shadowgraph visualization technique was adopted. The shadowgraph apparatus consists of a light source, lens and a screen. The light source and the lens are aligned and positioned in such a

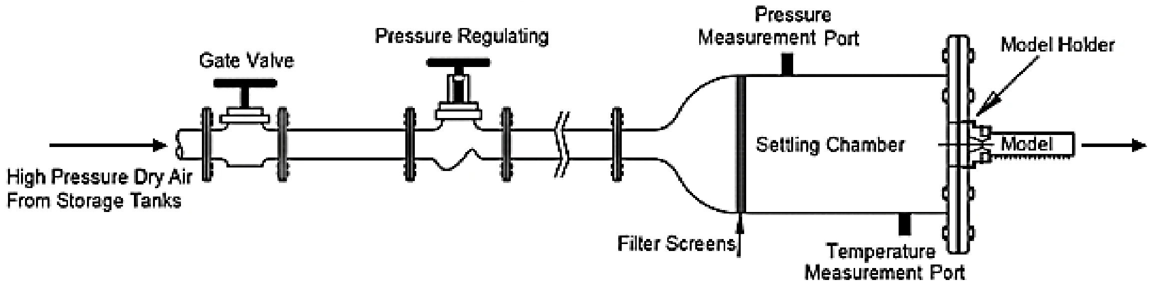


Fig. 1 A schematic of the open jet test facility

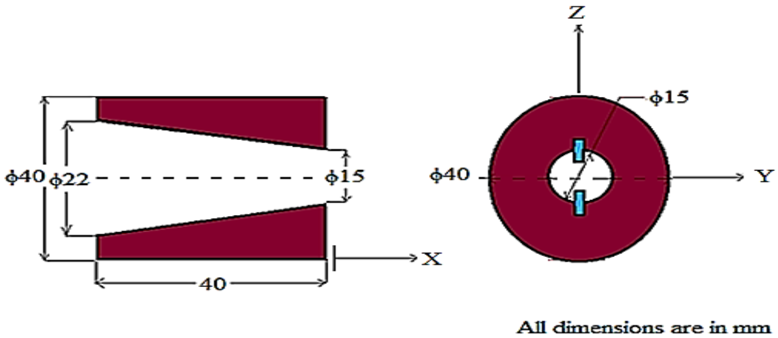


Fig. 2 Schematic of the convergent nozzle and tabs fixed at the exit of the nozzle

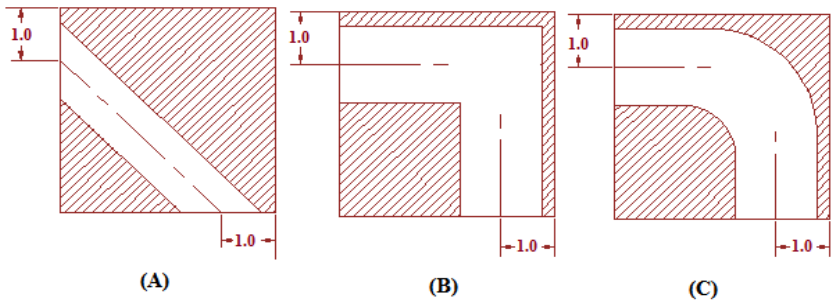


Fig. 3 Tab dimensions: (A) Tab A- Slant Slotted Tab, (B) Tab B - L Bent Slotted Tab, (C) Tab C- Filleted Tab

way that the beam of light passes through the jet and falls on the screen. The settling chamber is then operated at the required pressure and the wave patterns and shock cells can be visualized. The shock cells are captured with a high definition camera.

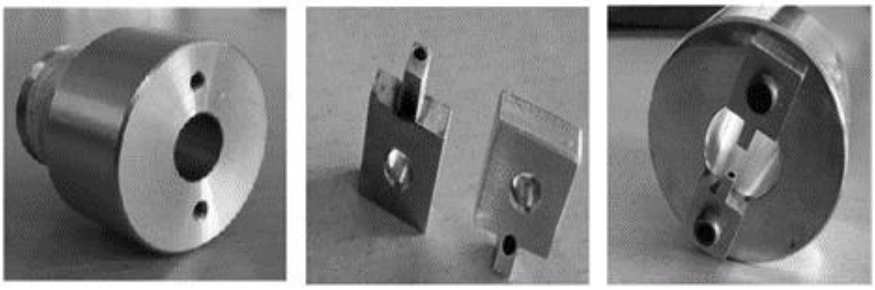
A convergent nozzle with a 15 mm exit diameter and a length of 40 mm is used for the investigation. Figure 2 shows the nozzle's cross-sectional and side views, respectively. The setup is then run at different NPRs of 3, 4 and 5 without tabs and with tabs placed diametrically opposite to each other and were fixed at the exit of the nozzle. The Pitot probe fixed with a 3D traverse mechanism, was used to measure the total pressure of the jet. The centerline total pressures are measured in the direction of the jet axis, whereas the radial total pressures are measured in normal and along the tab axis. The probe is attached to a temperature compensated pressure scanner having an accuracy of 0.25%, which reads the necessary data and digitally transfers it to a computer for processing.

In this study, set of three slotted rectangular tabs (Fig. 3): Tab A, Tab B, and Tab C are used. The slots in the current study are designed to join the two neighboring faces of the solid rectangular tab. The blockage of the each tab set is about 7 %. The blockage ratio was calculated using the formula:

$$\text{Blockage ratio, BR} = \frac{2 \times \text{Tab Area}}{Exit\ Area\ of\ the\ Nozzle}$$

Where, the tab area equals 6.23 mm and the exit area of the nozzle equals 176.63 mm.

The tabs are effectively designed so that the jet flow from the slots intersects the main stream flow at right angles in each of the three configurations. Figure 4 shows the actual images of the nozzle, tabs and the nozzle-tab assembly used in the present study. The pressure measurements and the shadowgraph images were taken after the jet reaches the steady state flow condition for the fixed NPR which is considered as stable flow.



(a) (b) (c)

Fig. 4 Actual images of (a) Convergent nozzle used for the experiment, (b) A pair of slotted tabs, (c) Tabs fixed at the exit of the nozzle

3. RESULTS AND DISCUSSION

3.1 Centerline Total Pressure Decay Profiles

The investigations were carried out for three different nozzle pressure ratio of 3, 4 and 5 comparing the free jet and tabbed jet cases. The under-expanded sonic jet's potential core prevails up to the length where supersonic flow is present or the extent to which the shock waves are dominant. The percentage reduction in the core length for the jet was calculated using the formula:

$$\% \, Reduction = \frac{CL \; for \; the \; FJ - CL \; for \; the \; TJ}{CL \; for \; the \; FJ}$$

Where, CL is the Core Length, FJ is the Free Jet and TJ is the tabbed jet respectively.

For NPR 3 (Fig. 5), the core for the free jet extends up to 11.57D_e, whereas, it is X/D_e = 1.87, X/De = 1.6 and X/D_e = 1.33 for the Tab A, Tab B and Tab C jet respectively. They provide a substantial percentage reduction in the core of about 84% for Tab A, 86% for Tab B and 89% for Tab C. For NPR4 (Fig. 6), the core length for the free jet is extended upto X/D_e = 9.76 and for the Tab A enabled jet it is 1.73. There is also a great reduction in the core for Tab B and Tab C with X/D_e = 1.47 and X/D_e = 1.33 respectively. The percentage reduction in core lengths is about 82 %, 85 % and 86 % for Tabs A, B and C. For NPR 5 (Fig. 7), the core extends up to X/D_e = 9.49 and it is X/D_e = 1.93 for Tab A, X/D_e = 1.67 for Tab B and X/D_e = 1.53 for Tab C enabled jet. The tabbed cases have a percentage reduction of 80% for Tab A, 82% for Tab B and 84% for Tab C respectively.

Comparing the Fig. 5, 6 and 7, the jet enabled with tabs are more efficient in enhancing the jet mixing with the ambient than the free jet due to the fact that the tabbed jet always sheds mixed size vortices. The tabs placed diametrically opposite emit vortices that move in the direction of the jet axis and have the ability to upset the area surrounding the potential core. Also for lower NPR the number of shock cells were higher than the high NPR jet. But the strength of the shock cells were high for high NPR jets. It is observed that Tab C enabled jet having higher core reduction percentage compared with other two configurations. Table 1, summarizes the core length (X/D) and percentage reduction in core length for the tabbed jet cases for various NPRs.

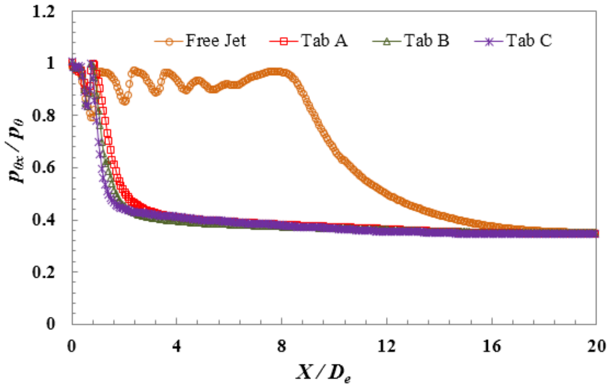


Fig. 5 Centerline total pressure decay profiles for NPR 3

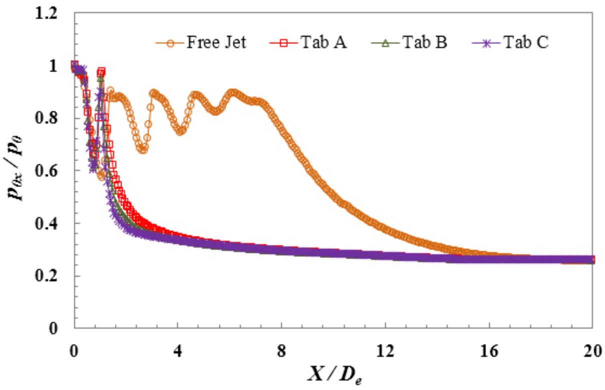


Fig. 6 Centerline total pressure decay profiles for NPR 4

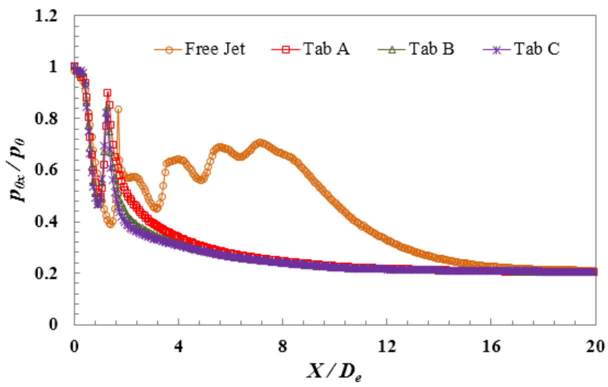


Fig. 7 Centerline total pressure decay profiles for NPR 5

Table 1 Core length (X/D_e) for the jet at different NPRs

Jet Case	CL for NPR			% Reduction in CL for NPR		
	3	4	5	3	4	5
Free Jet	11.57	9.76	9.49	-	-	-
Tab A	1.87	1.73	1.93	84	82	80
Tab B	1.6	1.47	1.67	86	85	82
Tab C	1.33	1.33	1.53	89	86	84

3.2 Radial Total Pressure Profiles

The pressure profiles were investigated normal to the tab axis to gain a thorough understanding of the characteristics of jet spread. At varied axial distances of 0.5, 0.8, 1.0, 2.0, 4.0, and 8.0 the radial pressure profile experiments were performed for NPR 3, 4 and 5. The Figs 8, 9 and 10 represents the comparison between the radial pressure profiles of the free jet and the jet controlled by the tabs A, B and C for NPR 3, 4 and 5 at different axial locations of the jet.

From Fig. 8 (c) for X/De = 1.0, the pressure ratio at Y/De = 0 is 0.96, 0.94, 0.83 and 0.72 for free jet, Tab A, Tab B and Tab C respectively. From Fig. 8 (d) for X/De = 2.0, the pressure ratio for free jet, Tab A, Tab B and Tab C at Y/De = 0 is 0.85, 0.51, 0.48 and 0.51 for respectively. Similarly from Fig. 8 (e) for X/De = 4.0, the pressure ratio for free jet, Tab A, Tab B and Tab C at Y/De = 0 is 0.94, 0.55, 0.64 and 0.6 for respectively. From Fig. 8 (e), it is also evident that the Tab C enabled jet losing its strength faster when compared to other cases. Comparing the Fig. 8, it is observed that the jet spread is more for the tabbed cases than the free jet. The raise and drop in the profiles represents the occurrence of the waves produced in the jet.

Hence from Fig. 8.(c), 8.(d) and 8. (e), it is very much evident that the pressure ratio of the tabbed jet is reduced compared to the free jet, indicating that the loss of momentum of the jet due to effecting mixing and Tab C performs better in enhancing the mixing process.

From Fig. 9, it is observed that the strength of the waves is higher when compared to Fig. 8 which is due to the higher expansion pressure and the jet spread is more for the tabbed cases compared to free jet. From Fig. 9. (b) and 9. (c), the strength of the shocks waves produced in the jet is clearly varying for all the cases of the jet. From Fig. 9.(d), for X/De = 2.0, the pressure ratio for free jet, Tab A, Tab B and Tab C at Y/De = 0 is 0.87, 0.47, 0.41 and 0.38 respectively, indicating that Tab C performs better than other cases. In Fig. 9.(e), all the tabbed cases has the pressure ratio of 0.35 at Y/De = 0 and the variation is seen in the raising peak and the Tab C jets strength is less compared with other cases, indicating that Tab C performing better.

From Fig. 10, it is evident that for the higher NPR the wave strength and length of the waves in the jet seems to be more when compared with lower NPR. Comparing the profiles of NPR 3, 4 and 5, for NPR 5, the variation between the tabbed cases is clearly seen in the near field i.e, at X/De = 0.8. The jet spread for Tab C jet is more than other cases of the jet. At X/De = 0.8, the pressure ratio for free jet, Tab A, Tab B and Tab C at Y/De = 0 is 0.63, 0.55, 0.51 and 0.49 respectively, indicating that Tab C performs better than other cases. At X/De = 2.0, the waves are more predominant in nature and the pressure ratio at Y/De = 0, for the free jet, Tab A, Tab B and Tab C jet are 0.6, 0.51, 0.43 and 0.39 respectively, indicating Tab C performs better.

3.3 Shadowgraph Pictures

Figure 11 (a), 11 (b) and 11 (c) shows the shadowgraph pictures normal to the jet axis for free jet, Tab A, Tab B and Tab C enabled jet at NPR 3, 4 and 5 respectively. For the convergent sonic nozzle used the NPR 3, 4 and 5 are under expanded pressures. Referring to Fig. 11 (a) at NPR 3 , the jet exiting from this sonic under expanded pressures experiences the expansion to attain the ambient conditions, resulting in formation of expansion fans at the exit of the nozzle. These expansion fans from the nozzle exit moves up to free boundary of the jet and reflects as compression waves. The reflected compression waves moves to the axis of the jet and converted in to oblique shocks. When the oblique shocks from both directions meets at the axis of the jet, expansion fans are produced. When this oblique shock of higher strength meets (Fig. 11. (b) and 11. (c), at NPR 4 and 5 respectively), a compression front same as normal shock will be formed referred to as Mach disk. The waves from either direction after striking the Mach disk reflected back as expansion fan. This phenomenon continues till the flow reaches subsonic levels and then the decay begins.

For the free jet case at NPR 3, 4 and 5, there are four notable shock cells were present. For the tabbed jet, few shock cells with weaker strength were present in the near field. For the Tab C enabled jet, waves observed at the near field are weaker compared with the Tab A and Tab B. Also the shock cells are shorter and fewer in number. Even though the jet acoustic characteristics were not studied for the free and tabbed cases, the reduction in shock cell length and weak waves in the core for the tabbed cases of jet, can be taken as a measure of reduction in jet noise. Therefore it is righteous to state that the use of slotted tabs will reduce the jet associated noise

4. CONCLUSION

(1) Investigations using various configurations of mechanical slotted tabs for different NPRs of 3, 4 and 5 were done by studying the centerline total pressure decay and radial pressure profiles and their corresponding flow development were visualized using shadowgraph technique.

(2) The centerline total pressure profiles extracted gives a clear image of tabs performing better in comparison to the free jet. The reduction in the core for the Tab C

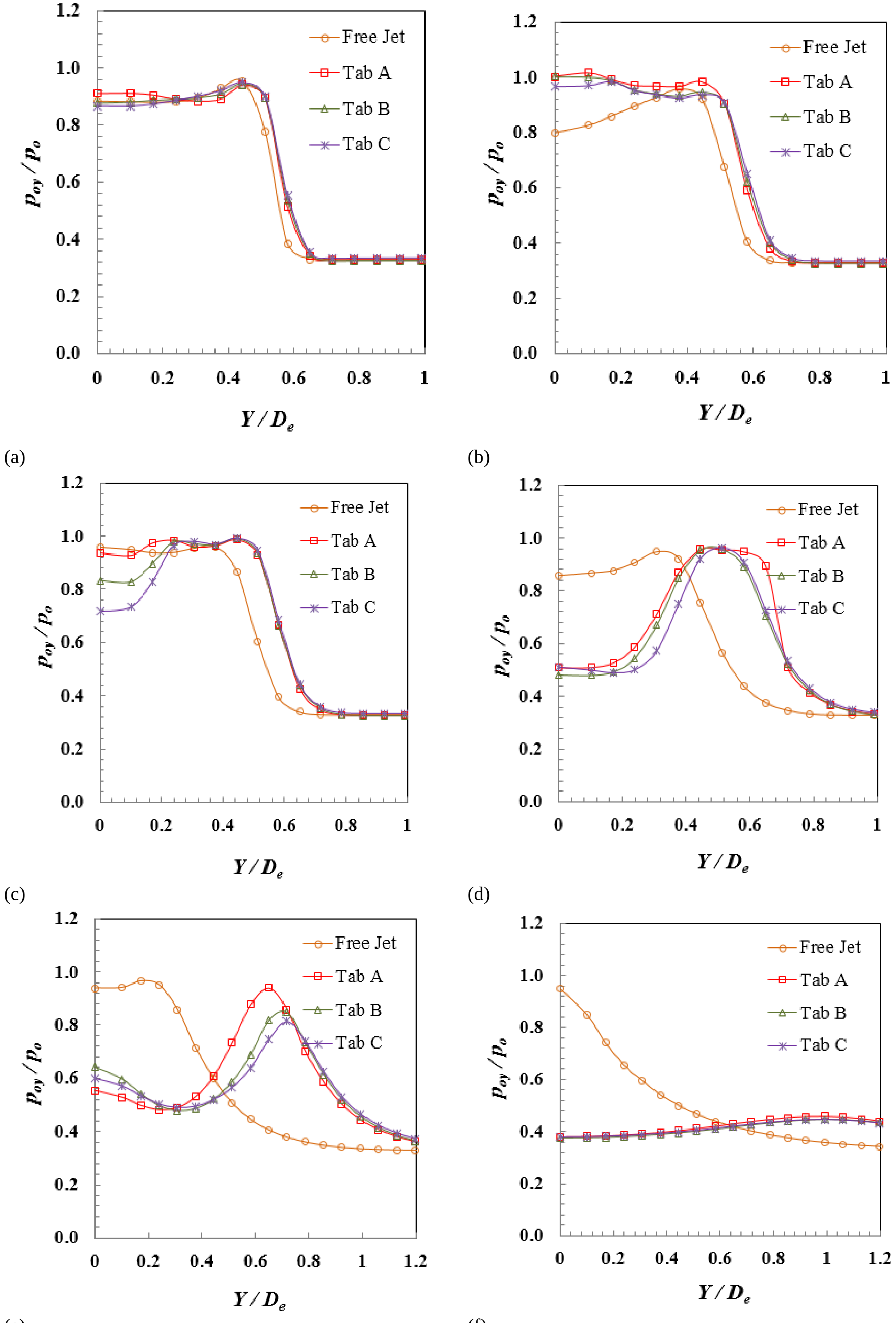


Fig. 8 Radial total pressure profiles in Y-Direction for NPR 3: (a) X/De=0.5, (b) X/De=0.8, (c) X/De=1.0, (d) X/De=2.0, (e) X/De=4.0, (f) X/De=8.0

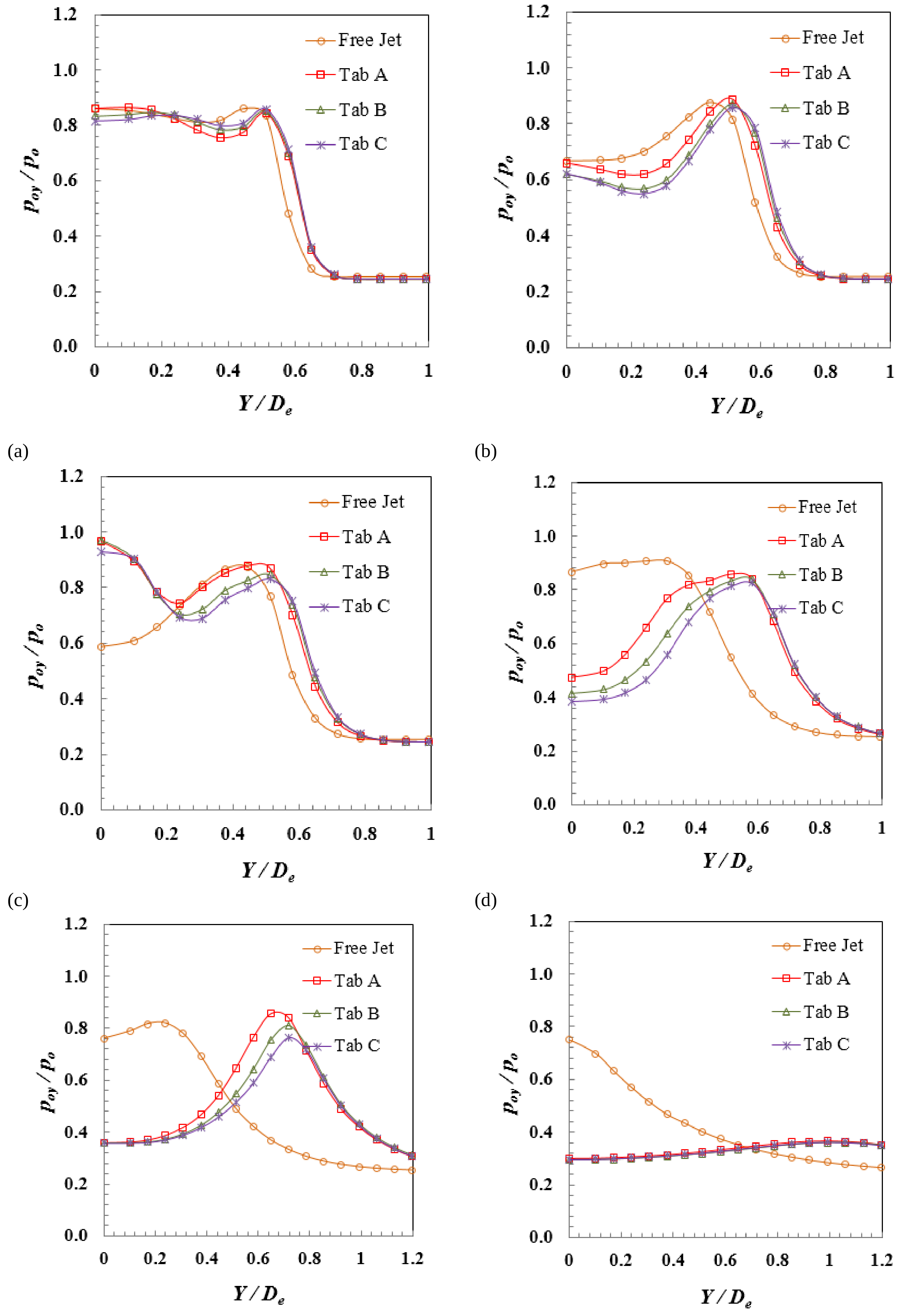


Fig. 9 Radial total pressure profiles in Y-Direction for NPR 4: (a) X/De=0.5, (b) X/De=0.8, (c) X/De=1.0, (d) X/De=2.0, (e) X/De=4.0, (f) X/De=8.0

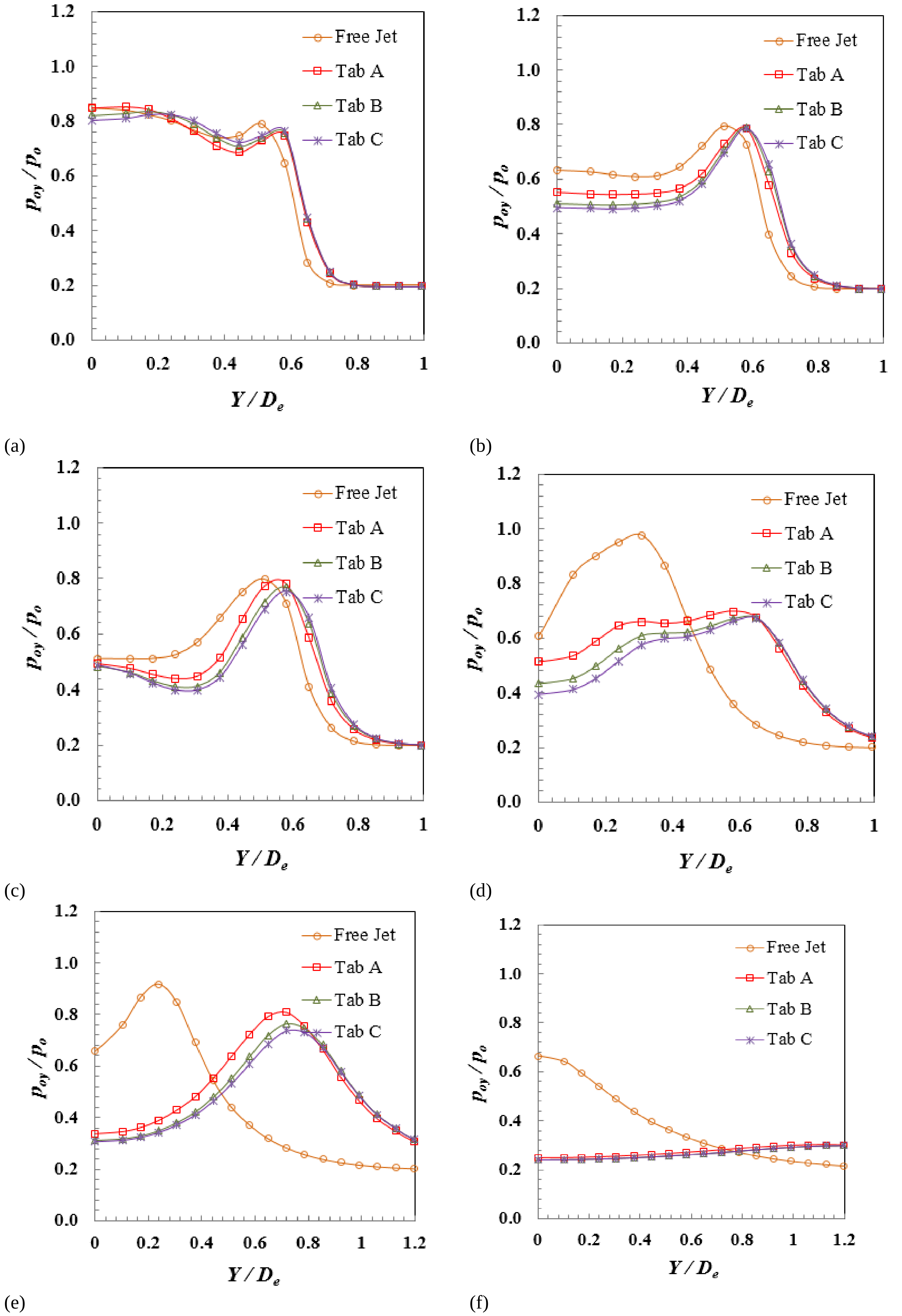
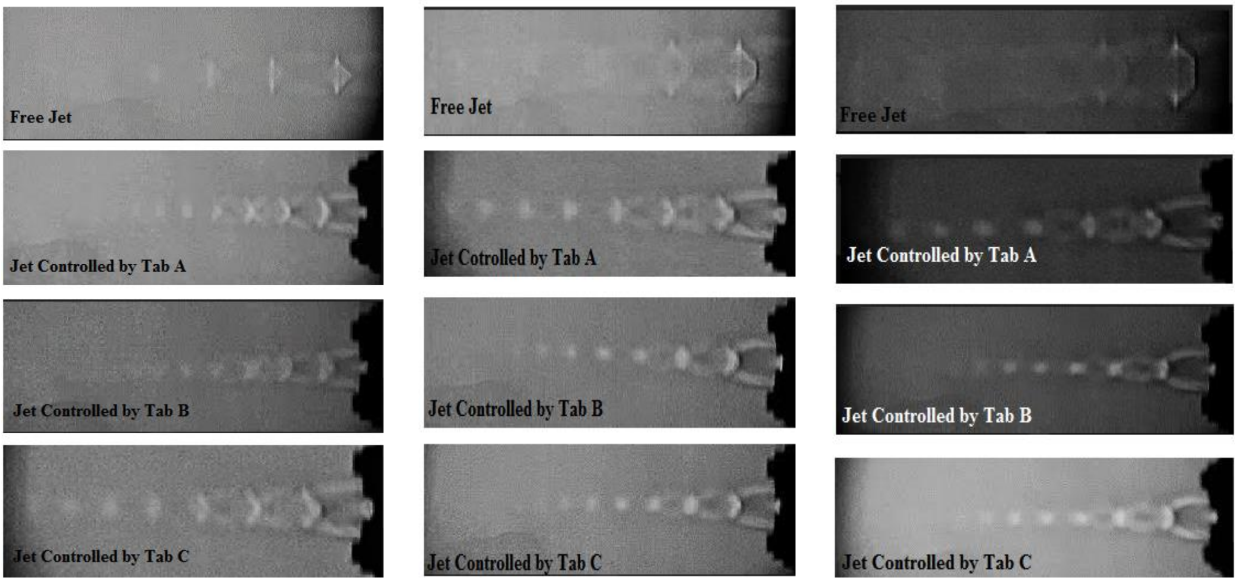


Fig. 10 Radial total pressure profiles in Y-Direction for NPR 5: (a) X/De=0.5, (b) X/De=0.8, (c) X/De=1.0, (d) X/De=2.0, (e) X/De=4.0, (f) X/De=8.0



(a) NPR 3 (b) NPR 4 (c) NPR 5

Fig. 11 Shadowgraph image of free jet in comparison with the controlled jets

enabled jet is about 89%, 86% and 84% for NPR 3, NPR 4 and NPR 5 respectively, which is higher when compared to Tab A and Tab C, indicating Tab C, performs better in enhancing the jet mixing.

(3) From the radial pressure profiles, it is also evident that the Tab C performs well reinforcing the centerline decay study.

(4) The shadowgraph images taken shows the jet development and gives a clear portrayal of the shock train formed. The boundaries of the developed jet is formed with the reflection of shocks and each shock cell can be clearly viewed at different NPRs. The pattern of formation of Mach discs and shock cross over points are also observed.

(5) Therefore, to conclude, the slotted rectangular tabs used in the present study is seen to be effective in reducing the jet core length and also helps in reducing the jet associated noise.

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CONFLICT OF INTEREST

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

AUTHORS CONTRIBUTION

Conceptualization: **Anusindhiya K.** and **G. Vinayagamurthy**; Data Curation: **Anusindhiya K.**; Formal Analysis: **Anusindhiya K.** and **Vinayagamurthy G.**; Funding acquisition: NIL.; Investigation: **Anusindhiya K.** and **Vinayagamurthy G.**; Methodology: **Anusindhiya K.**; Project Administration: **Anusindhiya K.** and **Vinayagamurthy G.**; Software: **Anusindhiya K.** and **Sathish Kumar K.**; Resources: **Vinayagamurthy G.** and **Sathish Kumar K.**; Supervision: **Vinayagamurthy G.** and **Sathish Kumar K.**; Validation: **Vinayagamurthy G.**, **Sathish Kumar K.** and **Anusindhiya K.**; Visualization: **Anusindhiya K.** and **Sathish Kumar K.**; Writing- Original Draft: **Anusindhiya K.**; Writing-Review and editing: **Anusindhiya K.** and **Sathish Kumar K.**

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