Triangular Tabs for Supersonic Jet Mixing Enhancement

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Abstract The mixing promoting capability of right-angle triangular tab with sharp and truncated vertex has been investigated by placing two identical tabs at the extremities of an exit diameter of a Mach 2 axi-symmetric nozzle. The mixing promoting efficiency of these tabs have been quantified in the presence of adverse and almost zero pressure gradients. It is found that, at all levels of expansion of the present study though the core length reduction caused by both the tabs are appreciable, the mixing caused by the truncated tab is superior. The mixing promoting efficiency of the truncated tab is found to increase with increase of nozzle pressure ratio (that is, decrease of adverse pressure gradient). For all the nozzle pressure ratios of the present study, the core length reduction caused by the truncated tab is more than 95 %, with a maximum of 99 %, at NPRs 7 and 8. The present results clearly show that the mixing promoting capability of the tab is the best when the jet is almost correctly expanded (that is with almost zero pressure gradient).

List of symbols

NPR	Nozzle pressure ratio (p_{0s}/p_a)
p_{0s}	Settling chamber pressure
p_{0t}	Pitot pressure in the jet field
p_e	Nozzle exit pressure
p_a	Atmospheric pressure
p_b	Backpressure (p_a)
R	Distance along the radial direction of the uncontrolled jet
Y	Coordinate normal to the tabs
z	Coordinate along the tabs

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1 Introduction

Jet control with tabs is an active research area, finding a lot of application. A concise compilation of the literature associated with jet control is recently compiled by Rathakrishnan (2010). From this survey it is evident that, for an efficient mixing of the mass entrained by the large scale vortices, at the boundary of a free jet, an appropriate proportion of mixing promoting vortices need to be introduced into the jet flow, to ensure rapid mixing. Indeed rapid mixing of the jet issuing from the engine nozzle with the cool air mass of the atmosphere, to which the jet is discharged, is essential to ensure that the length of the hot plume at the nozzle exit is reduced to as short as possible to minimize the infrared signature, resulting in high stealth capability for missiles. This kind of rapid mixing of the hot gases with the cold ambient air will results in the reduction of base heating, which is highly desirable for launch vehicles. Because of this kind of high-tech applications, large quantum of research has been done on jet mixing. However, until 2009 the school of thought was that the length of the mixing promoting tab should be within the boundary layer. This hypothesis is based on the vortex flow physics, namely that a vortex should have high vorticity and find large residential time to promote mixing efficiently. But in 2009, in his work on experimental studies on the limiting tab (Rathakrishnan 2009), Rathakrishnan demonstrated that the tab need not be within the boundary layer and indeed, the tab length can extend up to the nozzle radius. Following this Chiranjeevi Phanindra and Rathakrishnan (2010) showed that corrugations introduced at the tab edges result in a better mixing, owing to the generation of mixing promoting vortices of mixed size. However, they studied only rectangular tab with and without corrugation. Also, they studied only rectangular corrugation. Combining all these concepts, Arun Kumar and Rathakrishnan (2013a, b, c) studied triangular tabs and found that the triangular tabs shedding vortices of continuous variation in size is a better mixing promoter than tabs of rectangular geometry. But this investigation is with isosceles triangular tabs. Therefore, even though these tabs shed vortices of continuous variation in size, the vortices shed from the opposite edges at a given height from the tab base are of identical size. To improve the mixing process by introducing vortices of continuously varying size, even from the opposite edges at a given height, right-angle triangular tabs are investigated in the present study. In addition to right-angle triangular tabs, with sharp and truncated vertex, rectangular tabs were also studied for comparison.

2 Experimental Details

The experiments were conducted in the open jet facility at the high speed aerodynamics laboratory, Indian Institute of Technology Kanpur, India (Rathakrishnan 2009). The experimental model used in the present investigation is a Mach 2.0

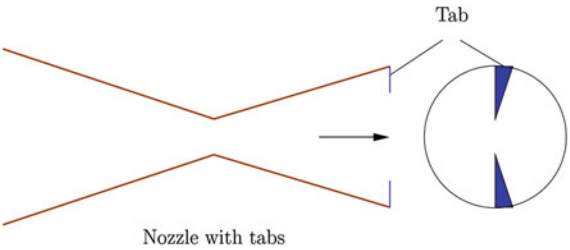

Fig. 1 Schematic representation of nozzle and placement of tabs at the nozzle exit

axi-symmetric convergent-divergent nozzle of semi-divergence angle 7°, made of brass. The throat diameter of the nozzle is 10 mm and the exit diameter is 13 mm. The Reynolds numbers of the Mach 2.0 jet issuing out of the nozzle, based on nozzle exit diameter are 712,300 and 1,660,410, respectively, for the minimum and maximum NPRs of 4 and 8 of the present investigation. Tabs were made of 1 mm thick brass strips. The schematic diagram of the tabs placed at the nozzle exit is shown in Fig. 1.

The length of the tabs was kept constant at 4 mm, for both triangular and rectangular shapes. Schematic sketch of the tabs are shown in Fig. 2. The blockage offered by the two identical tabs placed at the nozzle exit, intruding the flow, with respect to the nozzle exit area, in the present investigation is 5 %.

The pressure in the jet field was measured using a pitot tube of 0.4 mm inner diameter and 0.6 mm outer diameter, mounted on a rigid three-dimensional traverse, following the same procedure used by Chiranjeevi and Rathakrishnan (2010). The waves prevailing in the supersonic jet core were visualized using a shadowgraph system with a helium spark arc-light source in conjunction with a concave mirror. The shadowgraph images were recorded using a still camera.

The settling chamber pressure during the experiments of present investigation was maintained within ±2 %, for all the NPRs studied. The movement of the pitot probe mounted on the traverse had a resolution of ±0.1 mm, in the linear translation. The repeatability of the pressure measurements was found to be within ±3 %.

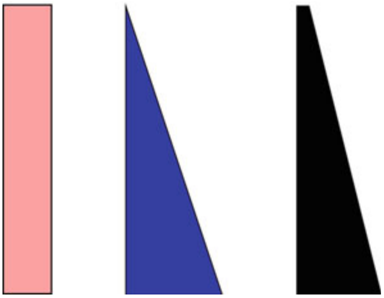

Fig. 2 Schematic representation of *rectangular tab*, *right-angle triangular tab* with *sharp and truncated vertex*

3 Results and Discussion

It is important to note that, in a supersonic flow, the pitot probe measures the total pressure behind the bow shock that stands ahead of the probe nose and not the actual total pressure. If the actual total pressure is required, one has to correct the measured pressure for the pressure loss across the shock. The jet core is wave dominated and the Mach number in the core varies from point to point, and also the waves in different shock cells are of different strength. Therefore, it is difficult to correct the measured pitot pressure for shock loss. Hence, the results in supersonic regions should be considered only as qualitative and are good enough for comparative purposes (Rathakrishnan 2009, 2010).

3.1 Centerline Pitot Pressure Decay

It is well established that the centerline pitot pressure decay is an authentic measure to quantify the jet core length, characteristic decay and far-field decay of free jet (Rathakrishnan 2010). For a supersonic jet, the jet core is the axial extent, from the nozzle exit, up to which the supersonic flow prevails or the axial extent at which the characteristic decay begins. The aim of the present investigation is to quantify the mixing promoting efficiency of right-angled triangular tabs with sharp and truncated vertex. The centerline decay of the jet, (that is, the reduction in core length caused by the tabs) can be taken as a measure, to quantify this feature. That is, fast decay implies better mixing.

The centerline decay of uncontrolled jet, and jet controlled with sharp and truncated triangular tabs, are compared in Fig. 3, for NPR4. The centerline pressure decay caused by rectangular tabs is also shown in this plot. For Mach 2 jet NPR4 is an overexpanded state, with an overexpansion level of about 49 % ($pe/pa = 0.511$). Therefore, at the nozzle exit there will be an oblique shock cone positioned, leading to the compression of the flow at a lower pressure at the nozzle exit to come to an equilibrium with the backpressure, namely the atmospheric pressure to which the jet is discharged. The oblique shocks of opposite family from the extremities of a diameter at the nozzle exit, would intersect at the jet axis and propagate towards the jet boundary. Thus, the maximum deceleration encountered by a overexpanded supersonic jet exiting the nozzle would be along the jet axis. The first pressure minimum in the centerline pressure decay plot is the point just ahead of the first shock cross-over point.

At NPR4 this point is found to be around 1.3D, downstream of the shock cross-over point the flow is forced to become subsonic, owing to the added strength of two oblique shocks, even though individual shocks are weak in nature. The subsonic flow downstream of the first shock cross-over point accelerates due to the flow of momentum from the higher momentum zone around the jet axis, where the flow continues to be supersonic even after passing through the weaker oblique

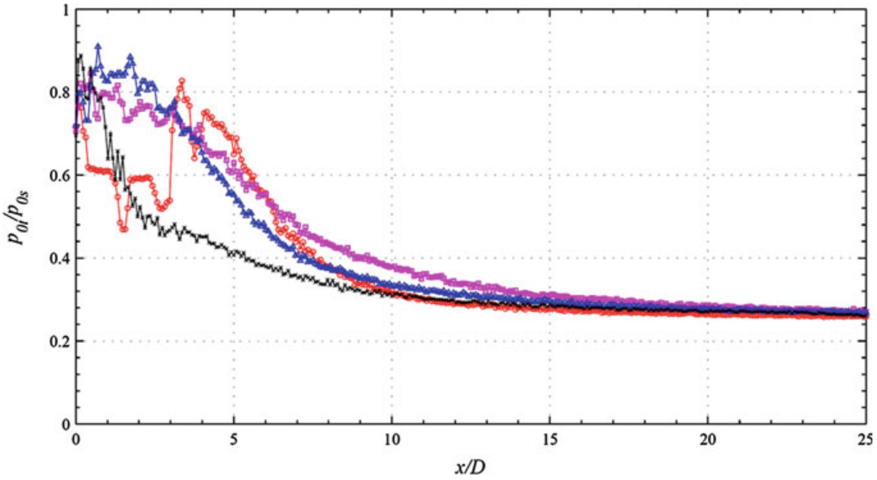

Fig. 3 Centerline pressure decay of Mach 2.0 jet at NPR4 (overexpanded). *Red circle* uncontrolled jet, *pink rectangle* jet controlled with rectangular tabs, *blue triangle* jet controlled with right-triangular tabs, and *asterisk* jet controlled with truncated right-triangular tabs

shock. The accelerated subsonic flow downstream of the shock cross-over point, after reaching sonic speed (indicated by the pitot pressure maximum), accelerates further to supersonic level up to the second shock cross-over point. This process continues up to the end of the supersonic core, which is found to be around 4D, for the uncontrolled jet. The characteristic decay of the uncontrolled jet continues up to around 20D, for NPR4. For the rectangular tab, the core length is only marginally shorter than the uncontrolled jet core. But for the sharp vertex triangular tabs, the core length comes down to 3D, also the jet becomes fully developed as early as 15D. When the vertex of the triangular tab is truncated, the core length drastically comes down to about 0.5D, which corresponds to a reduction of about 87 %. Further, the characteristic decay for the truncated triangular tab is the steepest and the jet becomes fully developed as early as 10D. From these results it is obvious that, the mixing promoting performance of truncated triangular tab is the best among the tabs considered. A closer look into the flow physics of the momentum transfer process associated with the small scale vortices shed by the truncated tab would explain the reason for its mixing promoting superiority. It is well known that the vortices shed from an object is proportional to the half-width of the object normal to the stream direction (Rathakrishnan 2010).

For the rectangular tab the half-width is uniform all along the tab length, therefore the tab would shed mixing promoting vortices of only uniform size all along its edges, excepting the tip where there are two sharp corners and the vortices shed from the flat tip end and side wall are of different size and interact intensely. Also, the vortices shed from the tip would be of transverse type, whereas those shed from the edges are normal type. Therefore, the uniform vortices shed by the rectangular tab would travel some downstream distance before becoming active in promoting mixing. Whereas, the triangular tab owing to its geometry would shed vortices of continuously varying size from its edges. An important feature to be noted is that the geometry of right-angle triangular tab is totally different from that of an isosceles triangular tab, recently studied by Arun Kumar and Rathakrishnan (2013a). The isosceles triangular tab, though capable of shedding vortices of continuously varying size along its edges, at every height from the base would be of identical size, though of opposite family. But, the mixing promoting vortices shed from the right-angle triangular tab would be of different size at all height, in addition to being of opposite family. This might be the primary reason for the intense interaction of vortices shed by the right-angle triangular tab leading to greatly enhanced mixing. Another important feature to be noted is that, near the sharp vertex tip, though the vortices shed are of different size and opposite family, their closer proximity would make them to interact intensely leading to loss of vorticity content. This might be the reason for lesser mixing promoting efficiency of the sharp vertex triangular tab compared to the truncated triangular tab. However, the mixing promoting efficiency of sharp triangular tab is higher than the rectangular tab due to the mixed size of vortices shed from the triangular tab. When the vertex is truncated, even at the tip, vortices of opposite family do not interact among themselves. This might be an advantage because almost entire vorticity content available with the mixing promoting vortices would be used for mixing promotion. This can be regarded as the primary reason for the better efficiency of the triangular tab with truncated vertex than the sharp vertex.

The centerline decay results for NPR5 are shown in Fig. 4. At NPR5 also Mach 2 jet is overexpanded, but with a reduced overexpansion level of only about 36 %. Therefore, the oblique shocks at the nozzle exit would be weaker than those for

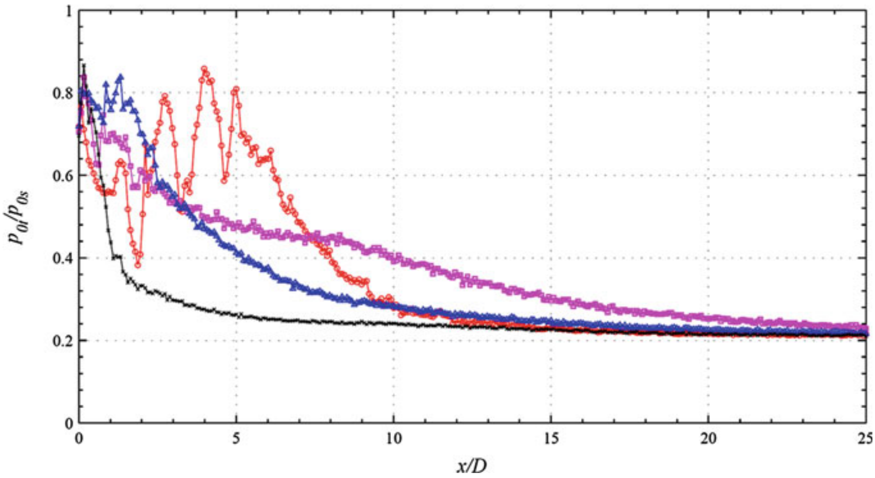

Fig. 4 Centerline pressure decay of Mach 2.0 jet at NPR5 (overexpanded). *Red circle* uncontrolled jet, *pink rectangle* jet controlled with rectangular tabs, *blue triangle* jet controlled with right-triangular tabs, and *asterisk* jet controlled with truncated right-triangular tabs

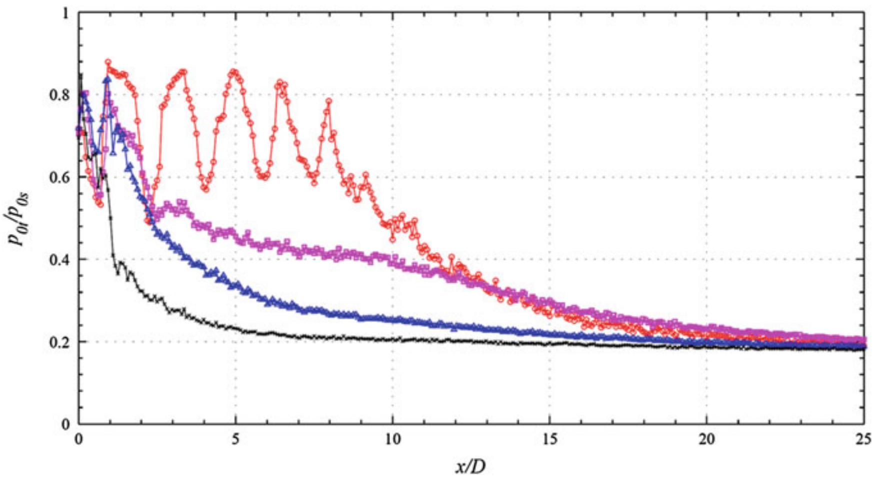

Fig. 5 Centerline pressure decay of Mach 2.0 jet at NPR6 (overexpanded). *Red circle* uncontrolled jet, *pink rectangle* jet controlled with rectangular tabs, *blue triangle* jet controlled with right-triangular tabs, and *asterisk* jet controlled with truncated right-triangular tabs

NPR4. Due to the presence of weaker shocks, the pressure loss encountered by the flow in the near-field at NPR5 will be considerably less than that at NPR4. It is seen that the core length of the uncontrolled jet is 6D. At NPR5, the mixing caused by rectangular tab is significantly higher than at NPR4. The core length of the rectangular tab is about 2.5D. For the sharp triangular tab the core length is about 0.5D, whereas for the truncated triangular tab the core length is as short as about 0.2D. Further, for the truncated triangular tab, the flow is fully developed at around 6D itself. The characteristic decay is also much faster than that at NPR4. Thus, at NPR5 also the truncated triangular tab performance is the best among the tabs studied in the present investigation.

At NPR6, as seen from Fig. 5, the core length for the uncontrolled jet is about 10D. Whereas the core length for the rectangular, sharp vertex triangular and truncated vertex triangular tabs, respectively, are 3.5D, 1.2D and 1D. For NPR6 also the jet has become fully-developed at 6D, for the truncated triangular tab.

With increase of NPR to 7, the number of shock-cells is found to increase considerably, which is typical for a free jet. The core length has increased to about 14D, as seen in Fig. 6. At NPR7 the Mach 2 jet is with a marginal overexpansion level of about 10 %. For this overexpansion level also, the mixing promoting efficiency of all the tabs are found to be appreciable. But among the tabs, the mixing caused by truncated triangular tab is the best, reducing the core length to 0.2D, which is about 98.6 % reduction in core length. The mixing caused by the truncated triangular tab is found to be the best in both characteristics decay and fully-developed zones.

At NPR8, which is marginally underexpanded or almost correctly expanded state for Mach 2 jet, the core length for the uncontrolled jet extends up to about

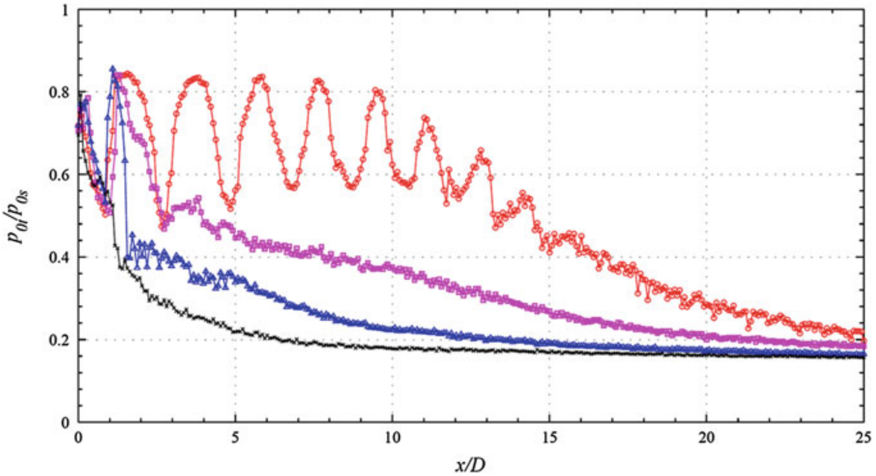

Fig. 6 Centerline pressure decay of Mach 2.0 jet at NPR7 (overexpanded). *Red circle* uncontrolled jet, *pink rectangle* jet controlled with rectangular tabs, *blue triangle* jet controlled with right-triangular tabs, and *asterisk* jet controlled with truncated right-triangular tabs

15.5D, as seen in Fig. 7. The core length for the sharp and truncated vertex triangular tabs respectively are 0.3D and 0.2D. That is, core length reductions of about 98 and 99 % are achieved with the sharp and truncated tabs. These reductions are greatly higher than the reduction of 83 and 87 % (at NPR7 and NPR8) reported for isosceles triangular tabs (Arun Kumar and Rathakrishnan 2013a). In the presence of almost zero pressure gradient also, the tabs are found to perform

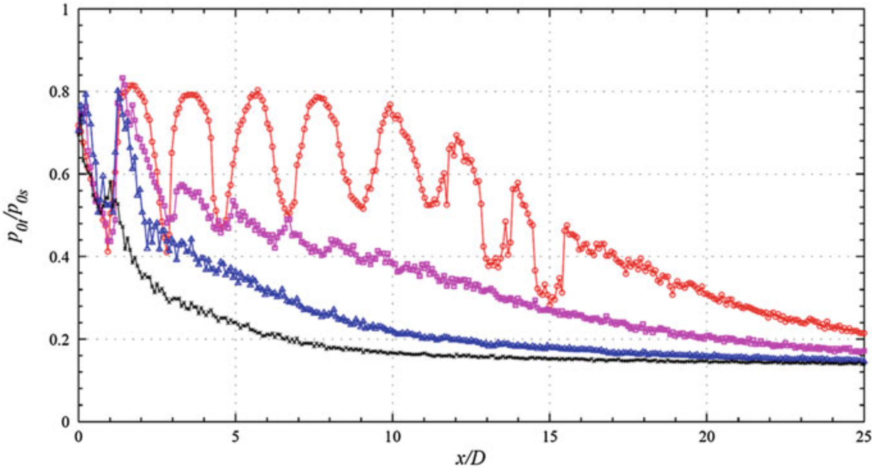

Fig. 7 Centerline pressure decay of Mach 2.0 jet at NPR8 (almost correctly expanded). *Red circle* uncontrolled jet, *pink rectangle* jet controlled with rectangular tabs, *blue triangle* jet controlled with right-triangular tabs, and *asterisk* jet controlled with truncated right-triangular tabs

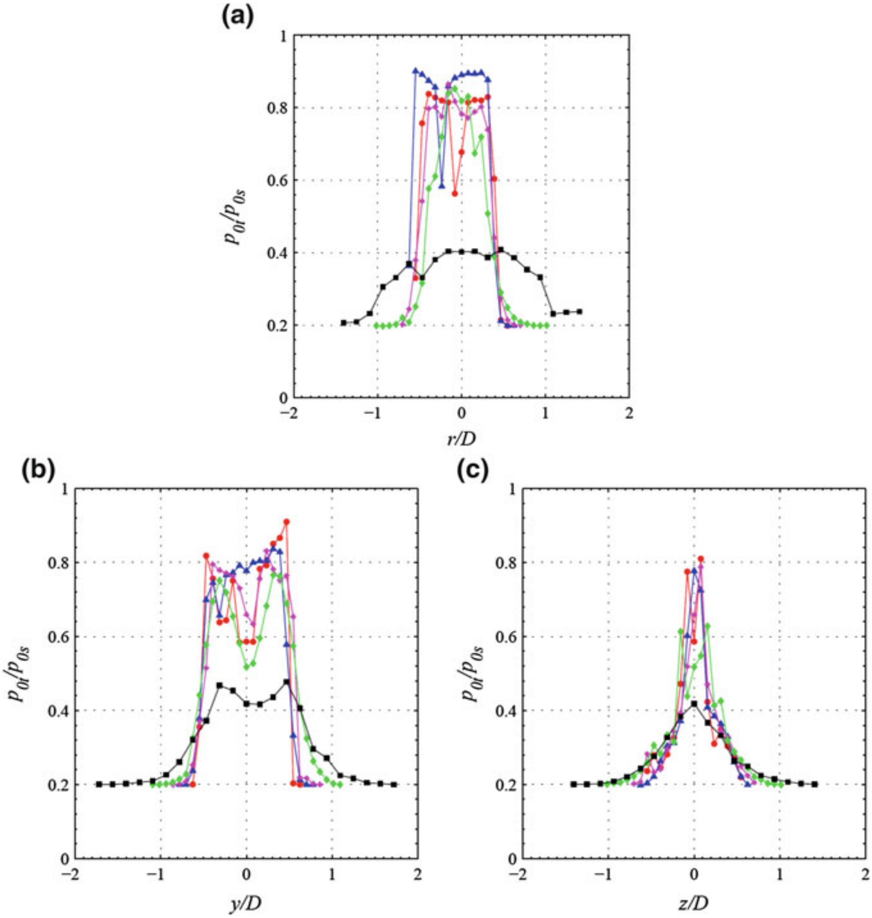

Fig. 8 Radial pressure profiles of Mach 2.0 jet at NPR5 (overexpanded). *Filled red circle x/D* = 0.5, *filled blue triangle x/D* = 1, *asterisk x/D* = 2, *filled green diamond x/D* = 4 and *filled black rectangle x/D* = 8. **a** Uncontrolled jet *r*-direction. **b** Rectangular tabs *y*-direction. **c** Rectangular tabs *z*-direction. **d** Triangular tabs; *y*-direction. **e** Triangular tabs; *z*-direction. **f** Truncated triangular tabs; *y*-direction. **g** Truncated triangular tabs; *z*-direction

well. Among them, the performance of truncated triangular tab is once again the best leading to a core length reduction of about 0.2D, which is about 99 %.

From the centerline pressure decay results it is evident that, the mixing promotion caused by right-angle triangular tabs are significantly higher than that of isosceles triangular tab. Truncating the vertex of the tab is found to be of immense benefit in mixing promotion at all the three zones. Furthermore, the best efficiency of the tabs is around the correct expansion with almost zero pressure gradient at the nozzle exit. This aspect agrees with the findings of Rathakrishnan for limiting tab (Rathakrishnan 2009).

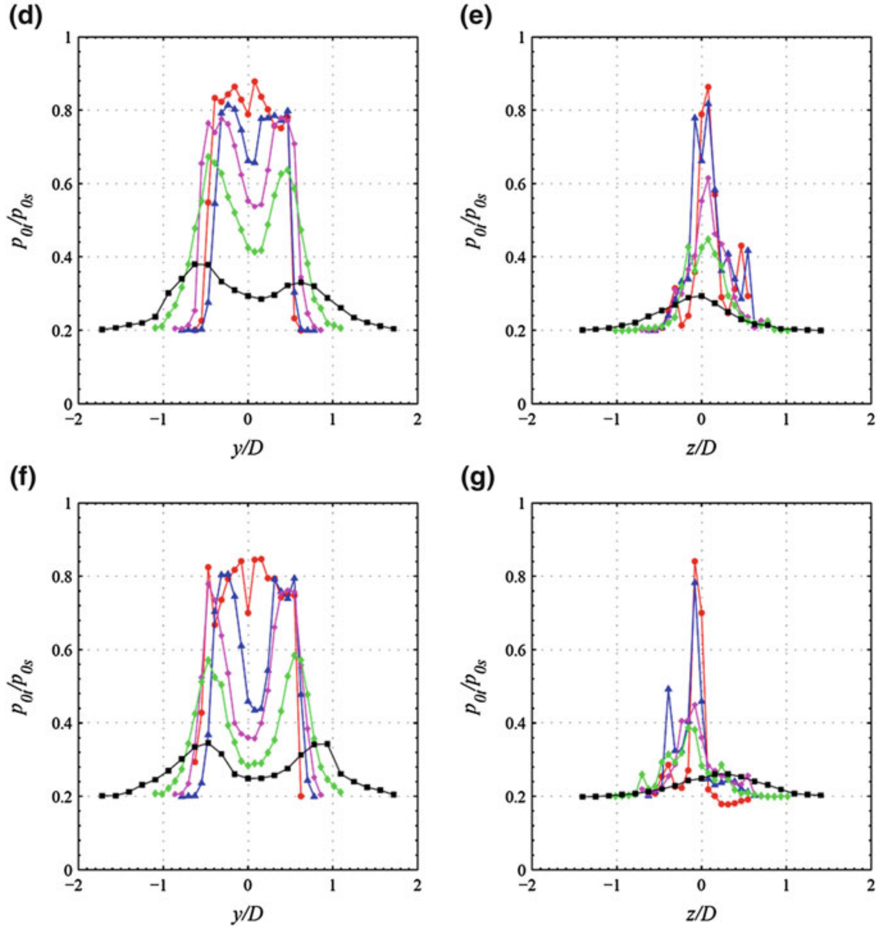

Fig. 8 continued

3.2 Pressure Profiles

It is desirable to ensure that the tabs cause appreciable mixing enhancement without making the jet highly unsymmetrical. To investigate this feature, the pressure profiles for the controlled jets, in the direction along the tabs (*z*-direction) and normal to the tabs (*y*-direction), were measured for the all possible combination of the flow and geometrical parameters of the present study. A representative set of pressure profile for the uncontrolled and controlled jet at NPR5 are given in Fig. 8. It is seen that, the triangular tabs do not introduce any asymmetry in the direction normal to the tab (*y*-direction). Whereas, in the direction along the tabs (*z*-direction) there is considerable level of asymmetry, especially at $x/D = 1$. This may because, the triangular tab used in the present study is right-angle

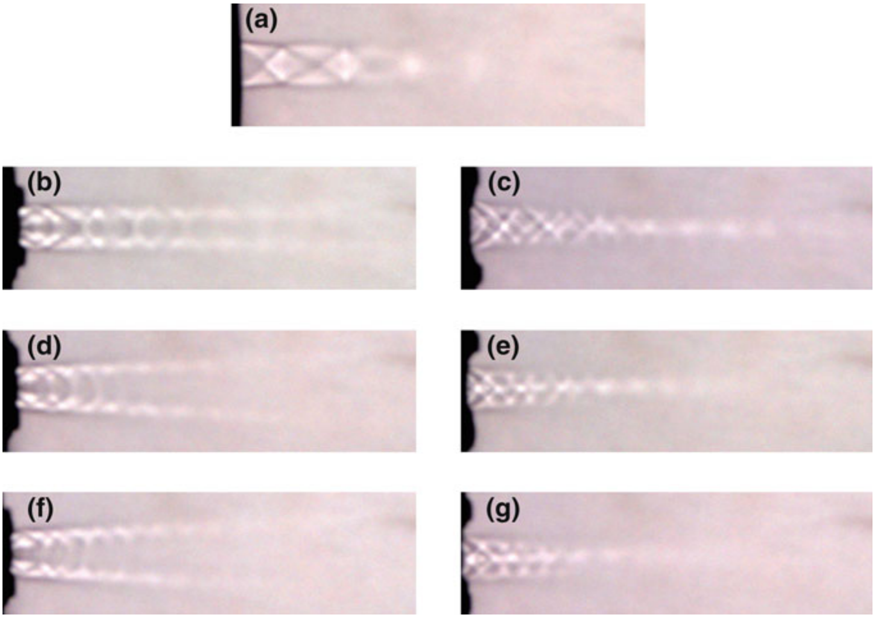

Fig. 9 Shadowgraph pictures for Mach 2 jet at NPR5 (overexpanded). **a** Uncontrolled jet. **b** Jet controlled with rectangular tabs. **c** Jet controlled with rectangular tabs. **d** Jet controlled with right-triangular tabs. **e** Jet controlled with truncated right-triangular tabs. **f** Jet controlled with right-triangular tabs. **g** Jet controlled with right-triangular tabs

triangle and hence it is bound to cause asymmetry in the near-field, owing to the differential size of vortices shed at every height from the base. However, with increase in downstream distance the level of asymmetry gradually decreases forcing the jet to become symmetry, identical to the uncontrolled jet.

3.3 Flow Visualization

The waves prevailing in the controlled and uncontrolled jet fields, at NPR5, are presented in Fig. 9. For the controlled jet the visualization was done viewing along and normal to the tabs. It is seen that there are three prominent shock-cells in the uncontrolled jet, that is exhibiting the shock cone at the nozzle exit, shock cross-over point at the nozzle axis and the reflection of expansion fans from just inside the inner boundary of the jet. With rectangular tabs, the waves in the shock-cells are perturbed, as seen in Fig. 9b and c. With sharp vertex triangular tabs (Fig. 9d and e), the wave spread is found to be larger than the rectangular tabs, and with truncated triangular tabs (Figs. 9f and g) the spread is found to be the highest and the complexity of a waves in the jet field is the maximum. This could cause increased entropy production, leading to greatly enhanced mixing for the truncated triangular tabs (Rathakrishnan 2009).

4 Conclusions

The results of the present investigation clearly demonstrates that the mixing caused by right-angle triangular tab with truncated vertex is superior than the identical tab with sharp vertex and rectangular tab of equivalent blockage. The mixing promoting efficiency of the tab is found to increase with increase of NPR. The best performance of the tab is found to around correct expansion. At almost correctly expanded state, core length reduction of about 99 % is achieved with truncated triangular tab, which is much higher than the core length reduction of 87 %, reported for isosceles triangular tab of identical blockage at same Mach number (Arun and Rathakrishnan 2013a). It is found that, in-spite of the intense action of the mixing promoting vortices of continuously varying size shed by the triangular tabs, the jet does not become unduly asymmetry. The waves present in the jet field controlled by truncated triangular tab is found to be significantly weaker than the waves prevailing in the jet controlled by sharp triangular tab and rectangular tab.

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