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ORIGINAL ARTICLE

Effect of cross-wire and tabs on sonic jet structure

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Abstract An experimental study has been conducted to investigate the effectiveness of passive controls in the form of small tabs and a cross-wire projecting normally into the flow at the nozzle exit, on the characteristics of an axisymmetric sonic jet operated at three underexpansion levels. In this investigation, NPR 3, 5 and 7 were studied. The cross-wire and tabs were found to reduce the amplitude and axial extent of Pitot pressure oscillations and also the supersonic core length. Both cross-wire and tabs were found to be effective in modifying the jet structure significantly, resulting in faster characteristic decay of the jet at all the NPRs. Shadowgraph pictures captured the widening of the supersonic zone in the direction normal to the tabs/cross-wire.

Keywords Underexpanded jets · Passive control · Tabs · Shock–cell · Mixing · Streamwise vortices

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1 Introduction

It has been recognized for many years that the noise radiated from an underexpanded jet displays features that are different from that of a shock-free jet. The underlying cause being the presence of a stationary shock-cell pattern, which results in a shock shear-layer interaction and, hence, an additional noise known as the shock-associated noise. This noise continues to be a major environmental concern. In an effort to attenuate noise and increase mixing in jet flows, passive control methods, such as vortex generators at the nozzle exit have been under investigation in the past several years. Vortex generators introduce streamwise vortices to entrain low-speed fluid into the jet, while forcing out high-speed core fluid. Many studies on vortex generators like notches and grooves were being carried out by many researchers to achieve mixing enhancement and noise attenuation. Elangovan and Rathakrishnan [1] studied jets from circular sonic nozzles with grooved exits and found the shock-cell structure of the underexpanded jets from grooved nozzles to be weaker than that of the plain nozzle, as indicated by lesser amplitudes of the cyclic variation of the Pitot pressure. Further, they identified that, the jet spread along the grooved plane is significantly higher than that along the ungrooved plane. Vishnu and Rathakrishnan [2] investigated the aerodynamic and acoustic characteristics of jets from Mach 1.8 converging-diverging nozzle with internal grooves. The grooved nozzles show better mixing characteristics than the plain nozzle, manifested by shorter core lengths and faster jet decay both in near and far fields. Mrinal Kaushik et al. [3] reported that, square and semicircular grooves are more efficient mixing promoters than the triangular grooves. As high as 50% reduction in the jet core length was achieved with square and semicircular grooves.

Bradbury and Khadam [4] studied axi-symmetric subsonic jets under the influence of rectangular tabs and observed potential core length reduction of about $2D$, followed by a significant increase in the jet centerline velocity decay when two tabs were located 180 degrees apart at the nozzle exit. Samimy et al. [5] carried out a systematic study to gain an

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understanding of the flow mechanisms with regard to the influence of tabs and found that the tabs can distort the jet cross-section and increase the jet spread rate significantly. The distortion produced is essentially the same at subsonic and underexpanded sonic conditions. They conjectured that, a tab with a height as small as 2% of the jet diameter, bit larger than the efflux boundary layer thickness produces a significant effect. They identified that, variation of tab length for a given width did not seem to make much difference as long as the length was larger than the boundary layer thickness. Singh and Rathakrishnan [6] investigated on the argument that the projection of tabs beyond the boundary layer thickness is effective. They identified that, for the same projected area, length of the tab is more effective in enhancing the mixing than its width. Further, they postulated that, when the streamwise vortices are introduced right upto the jet centerline, it may prove to be an advantage in enhancing the mixing. Therefore, it can be justifiably stated that, the limit for tab length is the nozzle radius and not the boundary layer thickness. This limit of tab length is termed as *Rathakrishnan limit*. Sreejith and Rathakrishnan [7] investigated, instead of tabs, a wire running across a diameter (cross-wire) as a passive control to enhance the jet mixing. The streamwise vortices introduced by the cross-wire lead to a more rapid decay of the centerline pressure. The cross-wire was found to be effective at all levels of expansion. As high as 50% reduction in core length was achieved for Mach 1.79 at NPR 5.66. Clement and Rathakrishnan [8] investigated tabs of various combinations of length to width ratio on sonic jets, by keeping the blockage area constant. To gain an insight into the jet spread rate and the distortion of the tabbed jets, a surface flow visualization method was developed and employed. They demonstrated that, the mechanical tabs generate a pair of counter-rotating vortices, resulting in enhanced mixing. Presence of two pairs of streamwise vortices in the vicinity of nozzle exit and the bifurcation of the jet field at the downstream for the tabbed jets were also captured by the surface coating technique. Vandsburger and Ding [9] reported that, a self excited wire was possible to control the directional evolution of the mixing layer. Perturbation and control of the evolution of the two-stream turbulent, planar, mixing was achieved through the use of a flow excited wire mounted in front of the trailing edge of the splitter plate.

In a continuing study on the effectiveness of passive controls on the sonic jet structure, cross-wire and tabs have been studied in the present investigation. Effectiveness of cross-wire and tabs on the jet structure is assessed. Cross-wire of circular cross-section and tabs of rectangular geometry with different blockage areas were considered. Main idea of the present work is to analyze impact of the two kinds of passive controls on jet mixing and their effect on the shock-cells present in the jet core.

2 Experimental setup and procedure

The experiments were conducted in the jet facility at the High Speed Aerodynamics Laboratory, Indian Institute of Technology Kanpur. The layout of the jet facility is shown in Fig. 1. High pressure air enters the settling chamber through a tunnel section with a gate valve followed by a pressure regulating valve and a mixing length. The settling chamber is connected to the mixing length by a wide angle diffuser. The flow is further conditioned inside the settling chamber by closely meshed wire screens. The settling chamber temperature was the same as the ambient temperature and the back pressure was the ambient pressure of the atmosphere to which the jets were discharged. A convergent circular nozzle of exit diameter (D) 10 mm was used in the present investigation. A 0.5 mm diameter stainless steel wire was used as the cross-wire. The wire was fixed at the nozzle exit. Two tabs of 1 mm length and 2 mm width were used for the present study. Photographs of the experimental models are shown in Fig. 2. Pressure measurements were made using a 9016 model pressure scanner. It has sixteen DH200 transducers. These DH200 transducers are with full scale pressure range from 2.5 to 5,200 kPa. Application software was developed using Lab View to interface the transducer with a computer. A Pitot probe of 0.4 mm ID (inner diameter) and 0.6 mm OD (outer diameter) mounted on a rigid traverse measured pressures along the jet axis (X), at 1 mm

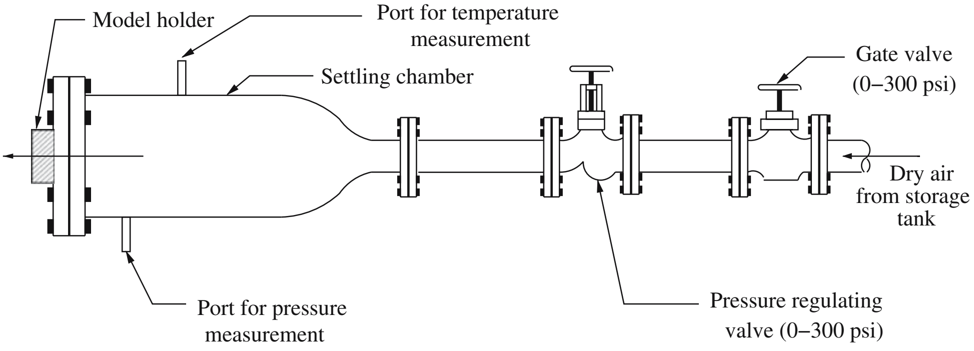

Fig. 1 Layout of the jet facility

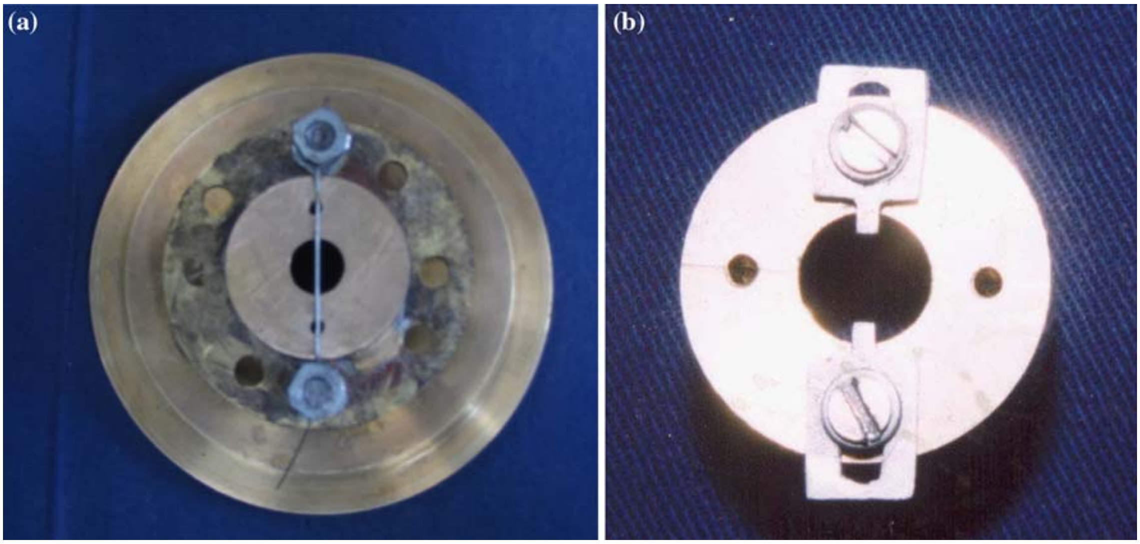

Fig. 2 Experimental models. **a** nozzle with cross-wire; **b** nozzle with tabs

interval. Pitot pressures along Y and Z directions were also measured to quantify the jet growth in these directions. The pressures measured were accurate within $\pm 2\%$. The nozzle was operated at nozzle pressure ratios (NPR) of 3, 5 and 7. To gain an insight into the physics of the wave structure with and without control, the flow was visualized by shadowgraph technique. The jet flow field for the controlled nozzles was visualized in the directions normal to the control and along the control.

3 Discussion of results

In the supersonic region of the jet flow, the measured Pitot pressure, P_t, corresponds to the total pressure behind the standing bow shock in front of the Pitot probe. Since the supersonic jet core contains both supersonic and subsonic zones, probe interference with supersonic zones measures the stagnation pressure behind the standing bow shock. The bow shock wave near the probe centerline, however, is almost normal to the probe axis, so that the Pitot probe measures the total pressure behind the normal shock wave. The pressure oscillations in the core region of the supersonic flow are due to the formation of shock-cells in the jet. Due to probe interference with the shock structure, there could be some measurement error and hence, the results represent only the qualitative nature of the flow. Nevertheless, the Pitot pressure distributions along the jet centerline are accurate enough to capture the overall features, such as the extent of the supersonic core region, the number of shock cells, the spacing between them and the rate of pressure decay after the core region, etc. The Pitot pressure (P_t) distribution along the jet centerline is non-dimensionalized with the settling chamber pressure (P_0). The axial distance from the nozzle exit is non-dimensionalized with the nozzle exit diameter D.

3.1 Centerline Pitot pressure characteristics of cross-wire and tabbed jets

Centerline Pitot pressure distribution of the controlled and uncontrolled jets are compared in Fig. 3. When the pressure ratio P_e/P_a becomes more than one, the jet delivered from a convergent nozzle is said to be underexpanded. The underexpansion level is the ratio of nozzle exit pressure (P_e) to the ambient pressure (P_a) which varies with the NPR (P_0/P_a). The underexpansion level for sonic nozzle operated at NPR 3, 5 and 7 are 1.58, 2.64 and 3.7, respectively. A flow process is required in a bid to equalize the nozzle exit pressure and ambient pressure at the underexpansion state of a jet. Since the back pressure is lesser than the nozzle exit pressure, wedge shaped expansion waves occur at the edge of the nozzle, expanding the flow to the ambient pressure at the jet boundary. Then the condition of constant pressure along the jet boundary causes this boundary to be bent back toward the axis of the flow. As the flow changes direction along this boundary, many compression waves formed at the intersection of the expansion waves with the jet boundary, are sent back into the flow; these waves coalesce to form intercepting shock. For slightly underexpansion states (P_e/P_a less than 2.0), these intercepting shocks meet at the axis forming the familiar diamond configuration, NPR 3 in the present study. For highly underexpanded sates (P_e/P_a more than 2, i.e, NPR 5 and 7 in the present study), the form of the shock structure in the initial cell begins to change. Along the centerline, where the expansion is maximum, the pressure becomes so low relative to the ambient pressure that the recompression in the remainder of the cell reaches the limiting value

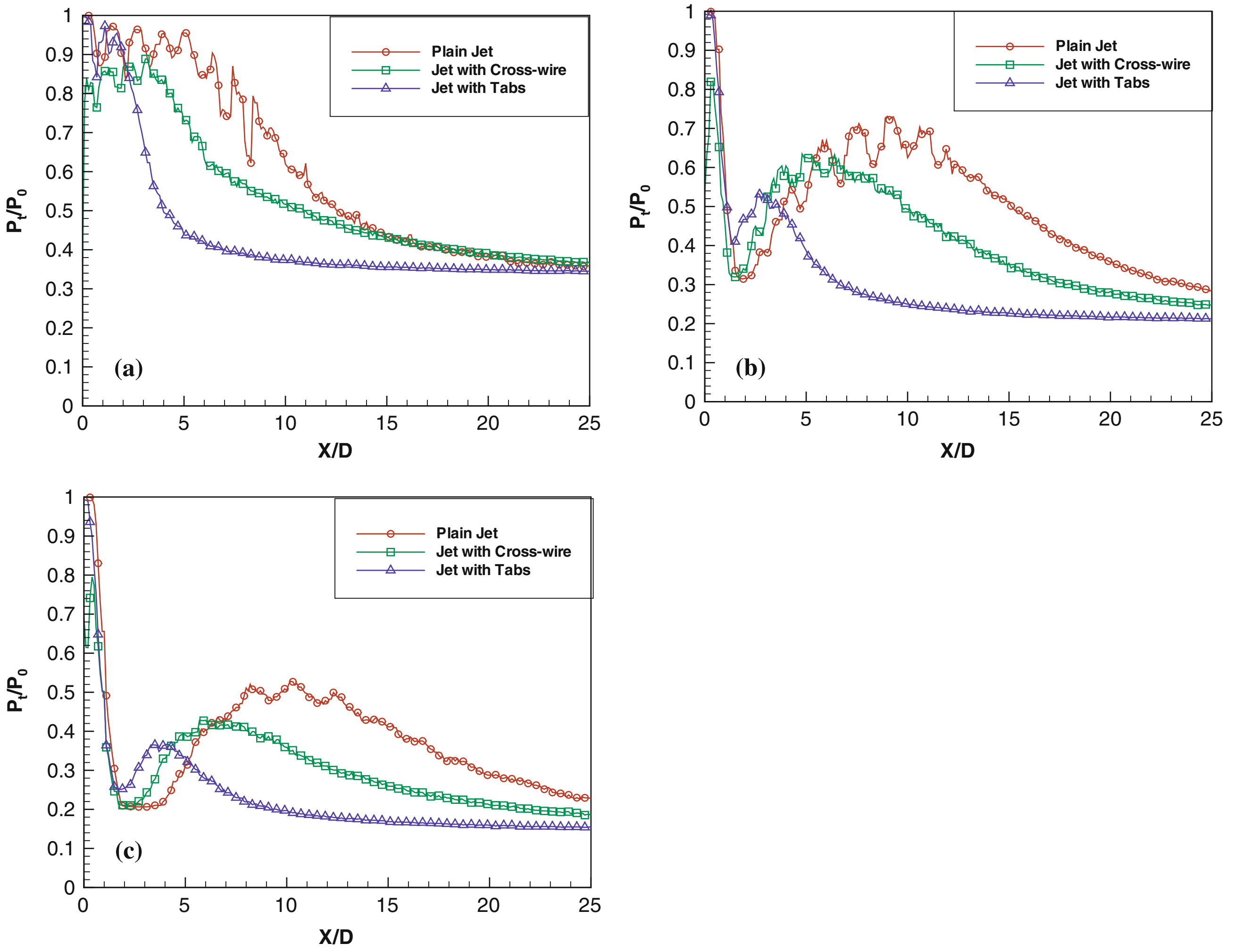

Fig. 3 Centerline Pitot pressure distribution. **a** NPR 3; **b** NPR 5;**c** NPR 7

for conical shocks, and the required compression takes place through an observable normal shock or Mach disc. In both the slightly and highly underexpansion states, reflected shocks are formed which intersect with the jet boundary reflecting as expansion waves, and the whole process is repeated. The centerline Pitot pressure distributions presented in Fig. 3, show the oscillations in the measured Pitot pressures up to some axial distances. With the increase of NPR, i.e., for NPR 5 and 7, a severe pressure drop, followed by rise for the plain jets is observed as shown in Fig. 3b and c. This is because the expansion fan and the first shock-cell become progressively stronger with increase of NPR. The Pitot pressure when measured along the centerline at these operating conditions, decreases as the axial distance from the nozzle exit increases up to a certain location (where Mach disc forms), due to the increase in the flow Mach number, since for the same upstream stagnation pressure, the total pressure measured by the Pitot probe in the supersonic regime reduces for the increased Mach number.

The supersonic core is the axial extent upto which waves (compression and expansion waves) prevail [10]. The axial extent upto which measured centerline Pitot pressures show oscillatory trend, represents the supersonic core. The core length of the supersonic jet can be taken as a direct measure of mixing and spreading characteristics of the jet [2]. Large amplitudes of the Pitot pressure oscillation denote the presence of strong shocks in the supersonic core. The amplitudes of Pitot pressure oscillation are reduced at all the operating conditions for the cross-wire and tabbed jets compared to their uncontrolled counterpart. The axial extent of supersonic core is reduced significantly at all the operating conditions for both the controlled jets. From Fig. 3a, it is evident that, the supersonic core extends up to $X/D = 8.4$ for uncontrolled jet, whereas for cross-wire controlled jet the supersonic core extends only up to around $X/D = 3.2$ and for tabbed jets, it is around $X/D = 2.0$. From Fig. 3b, it is seen that, the supersonic core at NPR 5 extends up to $X/D = 11.9$ for uncontrolled jet, and for cross-wire and tabbed control jets

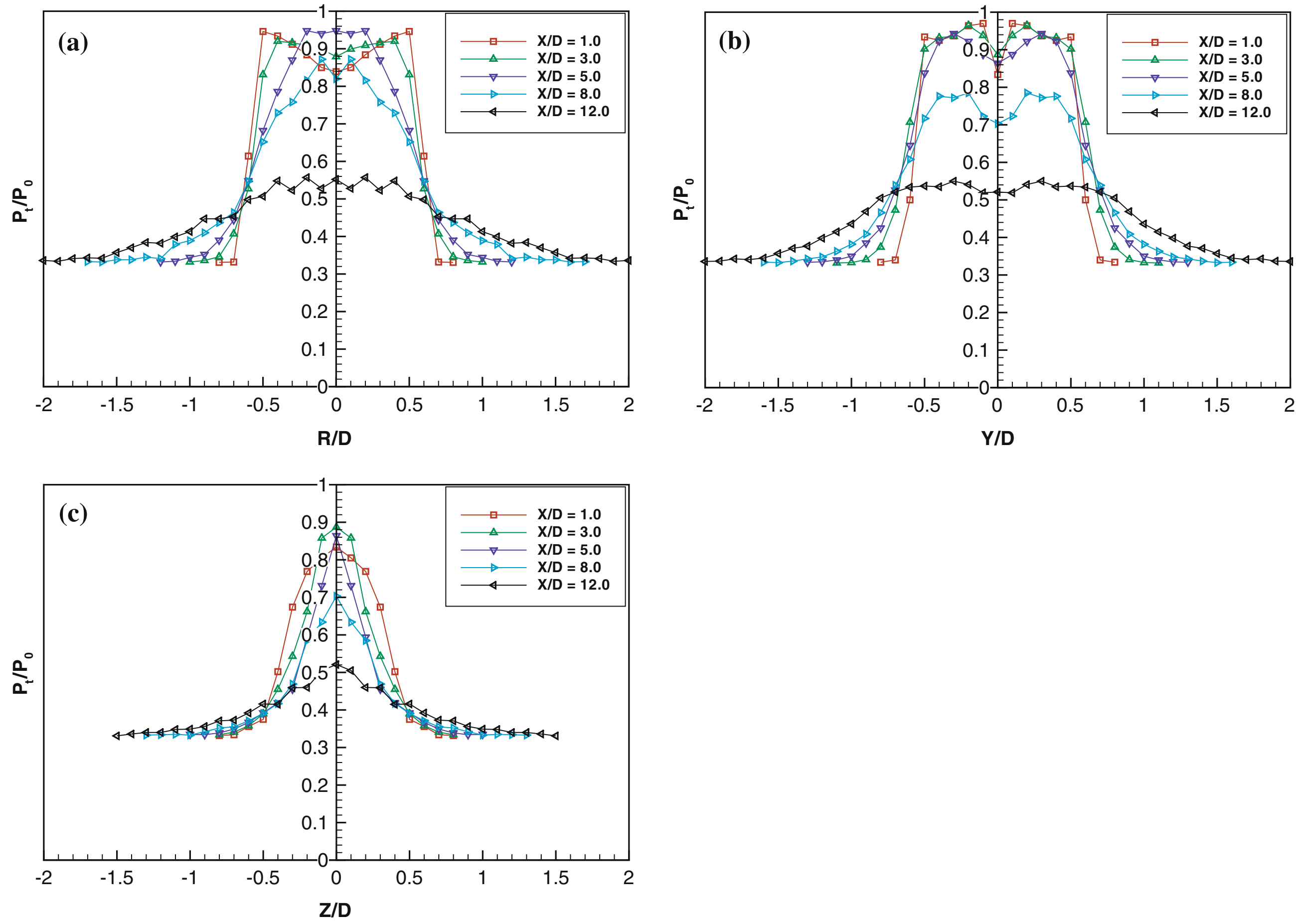

Fig. 4 Pitot pressure profiles for sonic jet with and without cross-wire at NPR 3. **a** plain jet; **b** Y-profiles for jet with cross-wire; **c** Z-profiles for jet with cross-wire

it is around 6.4 and 3.0, respectively. For NPR 7 case, both cross-wire and tab controlled jets possess core only up to $X/D = 6.0$ and 4.0, respectively, whereas for uncontrolled jet it is around $X/D = 12.0$ (Fig. 3c). The centerline pressures vary asymptotically in the axial direction at all the operating conditions for tab controlled jets from $X/D = 6.0$. The decay of the centerline total pressure of the cross-wire and tab controlled jets is rapid in the subsonic zone at all the operating conditions, which implies faster jet spread.

3.2 Effect of cross-wire on the jet structure

The Pitot pressure distributions for the plain jet and jet with cross-wire in the direction perpendicular to the cross-wire (Y), and along the cross-wire (Z) at various axial locations are presented in Figs. 4, 5 and 6 for the sonic nozzle operated at NPR 3, 5 and 7, respectively. From these profiles, it is evident that the cross-wire is effective in influencing the shock-cell structure right from the nozzle exit onwards and in both the planes. By employing the cross-wire, the Pitot pressure distribution is made greatly asymmetric at all the operating conditions, which implies that, the shock structure and the jet growth is unsymmetrical in both the planes. The cross-wire controlled jet grows as an unsymmetrical jet right from the nozzle exit. Just behind the cross-wire, the flow experiences a low pressure region over a short distance because of the wake caused by the wire. Because of the low momentum in the wake of the wire, the surrounding fluid at higher momentum is deflected towards the lower momentum zone. This results in an active transverse exchange of momentum. It should be noted that though the above physics of momentum exchange between the wake zone and the surrounding can be inferred intutively, the size of the Pitot tube was too large to capture precisely the characteristics of wake developing downstream of the cross-wire. At NPR 3 (Fig. 4), the cross-wire alters the Pitot pressure profile from the beginning in both the planes. The Y-direction profiles possess off-center peaks right from $X/D = 1.0$ and the Z-profiles possess single peak pressure profiles at all the axial stations presented, which implies the distinct nature of the shock and vortex structure of cross-wire controlled jets. The single peak profiles in the direction along the cross-wire (Z-profile) imply

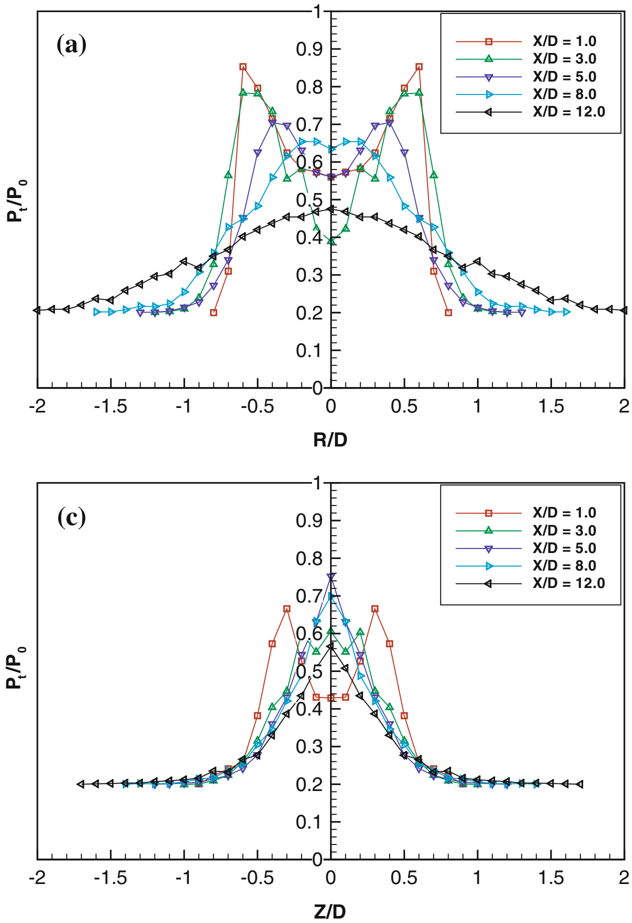

Fig. 5 Pitot pressure profiles for sonic jet with and without cross-wire at NPR 5. **a** plain jet; **b** Y-profiles for jet with cross-wire; **c** Z-profiles for jet with cross-wire

that, the shock-cells diffuse slowly in that direction and shear layer merges at the jet axis. The shock-cells diffusion in this plane is seen in Fig. 7c. With the increase of NPR, the jet core is dominated by the strong shock-cells in the near field and relatively weak shock-cells in the downstream direction. The repetitive shock-cell structure is shown in Figs. 8a and 9a for NPR 5 and 7, respectively, for plain jets. This shock structure gradually gets diffused in the downstream direction by the turbulence arising from the shear layer spreading towards the jet centerline and the surroundings. The weakening of shocks in the jet core depends primarily on the discontinuities to the azimuthal radius of curvature introduced at the exit plane of a nozzle, which generates turbulence as close to the jet exit. For the plain jet at NPR 5 (Fig. 5a) and NPR 7 (Fig. 6a), there is a central dip in the pressure profile followed by a rise in the supersonic core. This is due to the presence of shock-cells in the core region. The profiles assume single peak beyond the core and the pressure decays gradually. By employing the cross-wire, a dip at the center followed by a sharp rise in the pressure is seen at $X/D = 1.0$ for NPR 5 and these off-center peak profiles continue in the downstream locations, without experiencing sharp rise in the pressure profile in the direction normal to the cross-wire (Fig. 5b). This implies that, the shock structure is made weak by the cross-wire. In the plane of the cross-wire (Fig. 5c), the profiles assume single peak beyond $X/D = 3.0$ and profiles become narrower compared to the Y-direction profile. This suggests that, the jets from the cross-wire controlled jets grow wider in the direction normal to the cross-wire. Same is the case with NPRs 3 and 7 (Fig. 4c and Fig. 6c). From the Pitot pressure profiles of NPR 7 (Fig. 6b) it is evident that, from $X/D = 8.0$ onwards, flow is in the range of where the shock expansion train had already decayed, and the flow became subsonic. From these pressure profiles, it is evident that the symmetric shock-cell structures are made unsymmetrical and weaker all along supersonic core. It is well established that, destruction/weakening of shocks in the supersonic zone will result in reduction of shock associated noise and hence, the overall jet noise [2]. Therefore, weakening of shocks in the supersonic zone by the presence of cross-wire is likely to result in jet noise reduction. To understand the nature of the waves in the controlled and uncontrolled jets, the flow was visualized

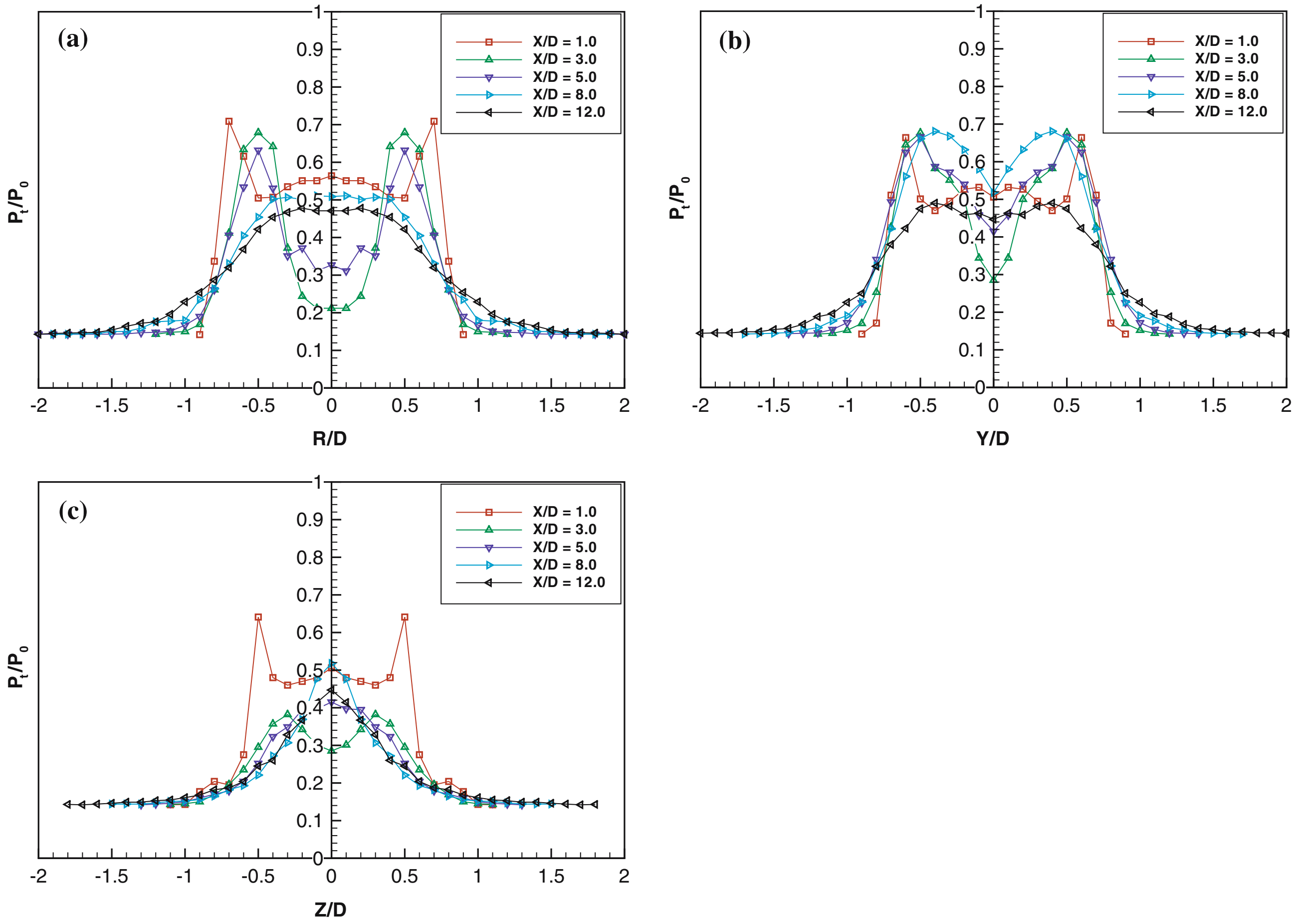

Fig. 6 Pitot pressure profiles for sonic jet with and without cross-wire at NPR 7. **a** plain jet; **b** Y-profiles for jet with cross-wire; **c** Z-profiles for jet with cross-wire

by shadowgraph technique. The jet flow of controlled nozzle was visualized by viewing in the directions normal to the cross-wire and along the cross-wire. The waves prevailing in the controlled and uncontrolled jet field, at NPR 3, 5 and 7 are shown in Figs. 7, 8 and 9, respectively. It is seen that there are organized shock-cells in the uncontrolled jet. But when the cross-wire is introduced, the waves are made weaker and also the shock-cells become shorter, both along and normal to the wire.

When the cross-wire is placed at the nozzle exit, the azimuthal radius of curvature of the exit is altered, also four sharp corners are formed on either side of the cross-wire. Therefore, the vortices get fragmented when come out of the controlled nozzle. When the wire is placed in a subsonic flow it will shed vortices alternatively. These vortices become streamwise in nature soon after shedding and can travel long distance compared to spanwise or azimuthal vortices. Therefore, the streamwise vortices could efficiently serve as mixing enhancement mechanism for jets. But in the underexpanded sonic jets, the core consists of a mixture of subsonic and supersonic Mach number zones. These streamwise vortices shed by the cross-wire have to pass through different Mach number zones in the jet field before loosing their identity. This process would also result in mixing enhancement. The mixing level will vary from place to place in the supersonic jet because of the presence of the mixed subsonic and supersonic zones. Nevertheless, the mixing initiated by these streamwise vortices will result in significantly enhanced mixing of the supersonic jets, especially in the core region. This is the main cause for the shocks in the core to become weaker compared to the plain nozzle jet. This can be regarded as a great advantage from shock associated noise point of view.

3.3 Effect of tabs on the jet structure

Studies on Pitot pressure distributions in the direction normal to the tabs (XY plane) and along the tabs (XZ plane) were carried out to gain an insight into the influence of the tabs on the shock-cells in the core and flow structure and to substantiate the flow physics interpreted from the shadowgraph pictures. Figures 10, 11 and 12 give the the measured Pitot pressure distribution for plain jet in radial

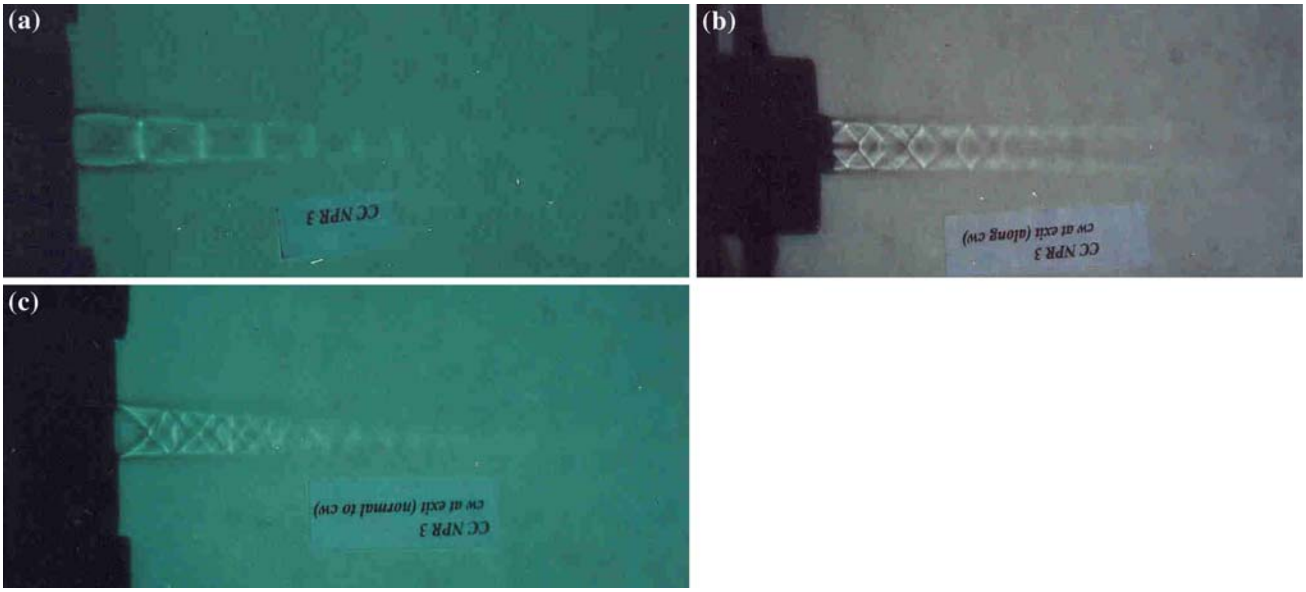

Fig. 7 Shadowgraph pictures for jet with and without cross-wire at NPR 3. **a** plain jet; **b** viewed along the cross-wire; **c** viewed normal to the cross-wire

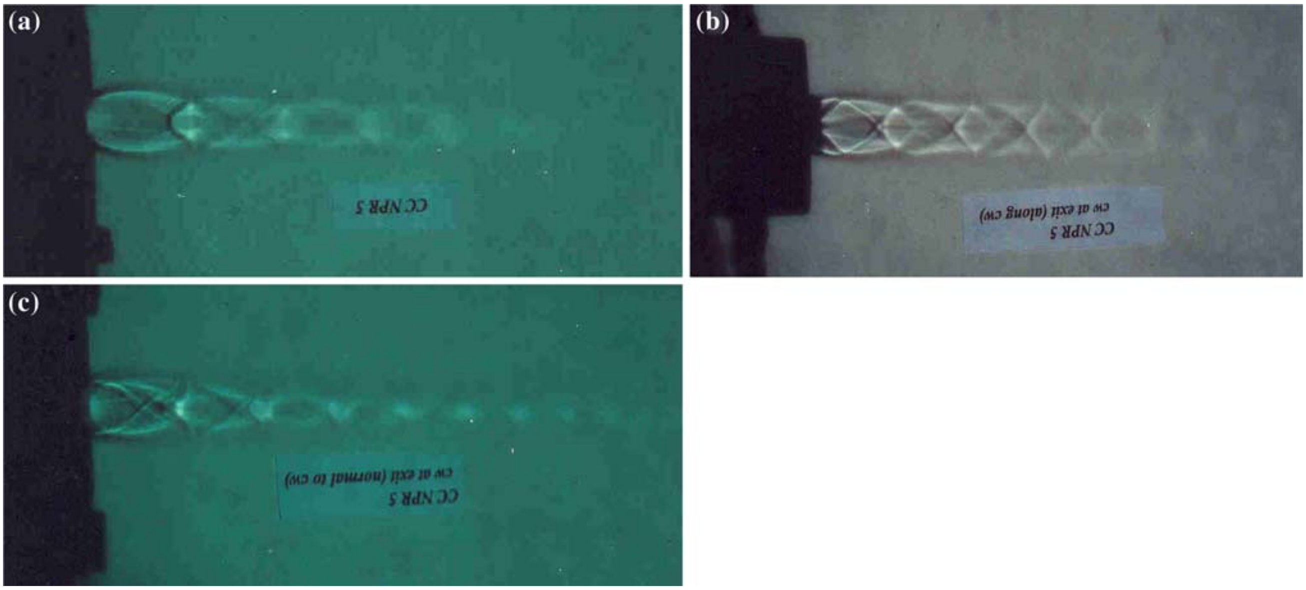

Fig. 8 Shadowgraph pictures for jet with and without cross-wire at NPR 5. **a** plain jet; **b** viewed along the cross-wire; **c** viewed normal to the cross-wire

direction and for the controlled jet in the directions perpendicular to the tabs (Y-direction) and along the tabs (Z-direction), at various axial locations, for NPR 3, 5 and 7, respectively. By employing the tabs, the Pitot pressures are distributed unsymmetrically in both the planes, however, the jet occupies larger space in the XY plane compared to the XZ plane for all the operating conditions presented in this paper. From Fig. 10b, it is inferred that, the influence of tab is significant beyond $X/D = 1.5$, as the pressure variation from $X/D = 2.5$ is completely different from the plain jet profiles at NPR 3. However, the tabbed jet grows norrower in XZ plane right from the nozzle exit, exhibiting single peak from the $X/D = 1.0$, which implies the dissipation of vortices in the direction along the tabs, as shown in Fig. 10c. From the Y-profiles, it is evident that the tabbed jet posseses off-center peaks from $X/D = 2.5$ onwards. These off-center peaks are the indication of the presence of vortices shed by the tabs. These vortices move away from the jet axis in the downstream direction, which suggests fast growth of the jet. Figure 13a and b show shadowgraph pictures of the flow

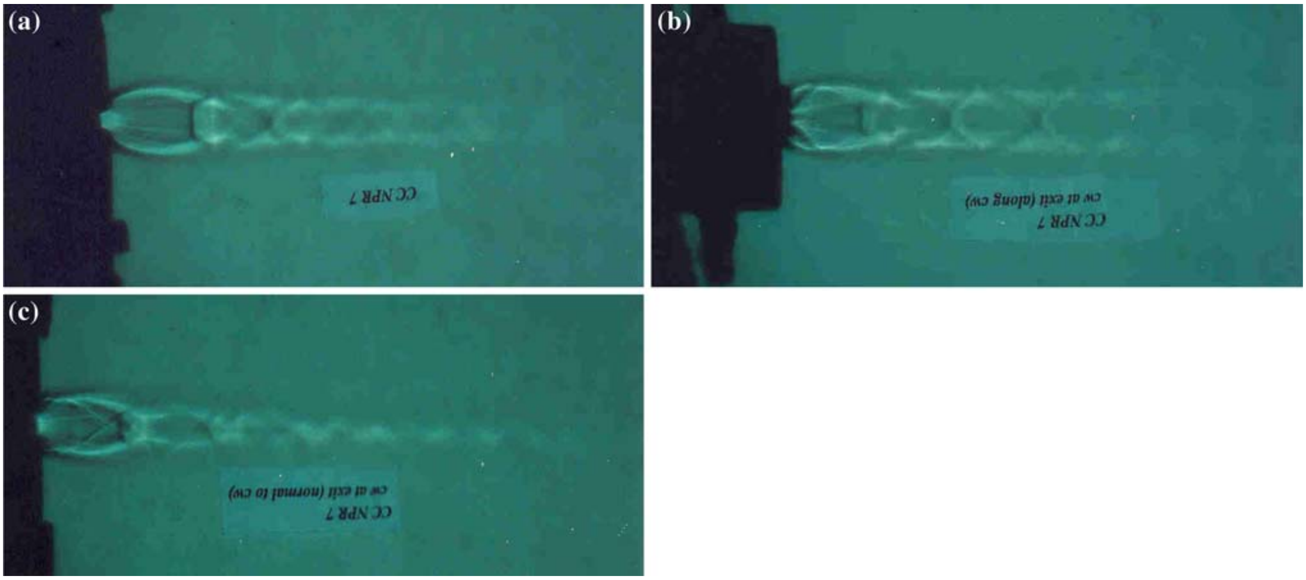

Fig. 9 Shadowgraph pictures for jet with and without cross-wire at NPR 7. **a** plain jet; **b** viewed along the cross-wire; **c** viewed normal to the cross-wire

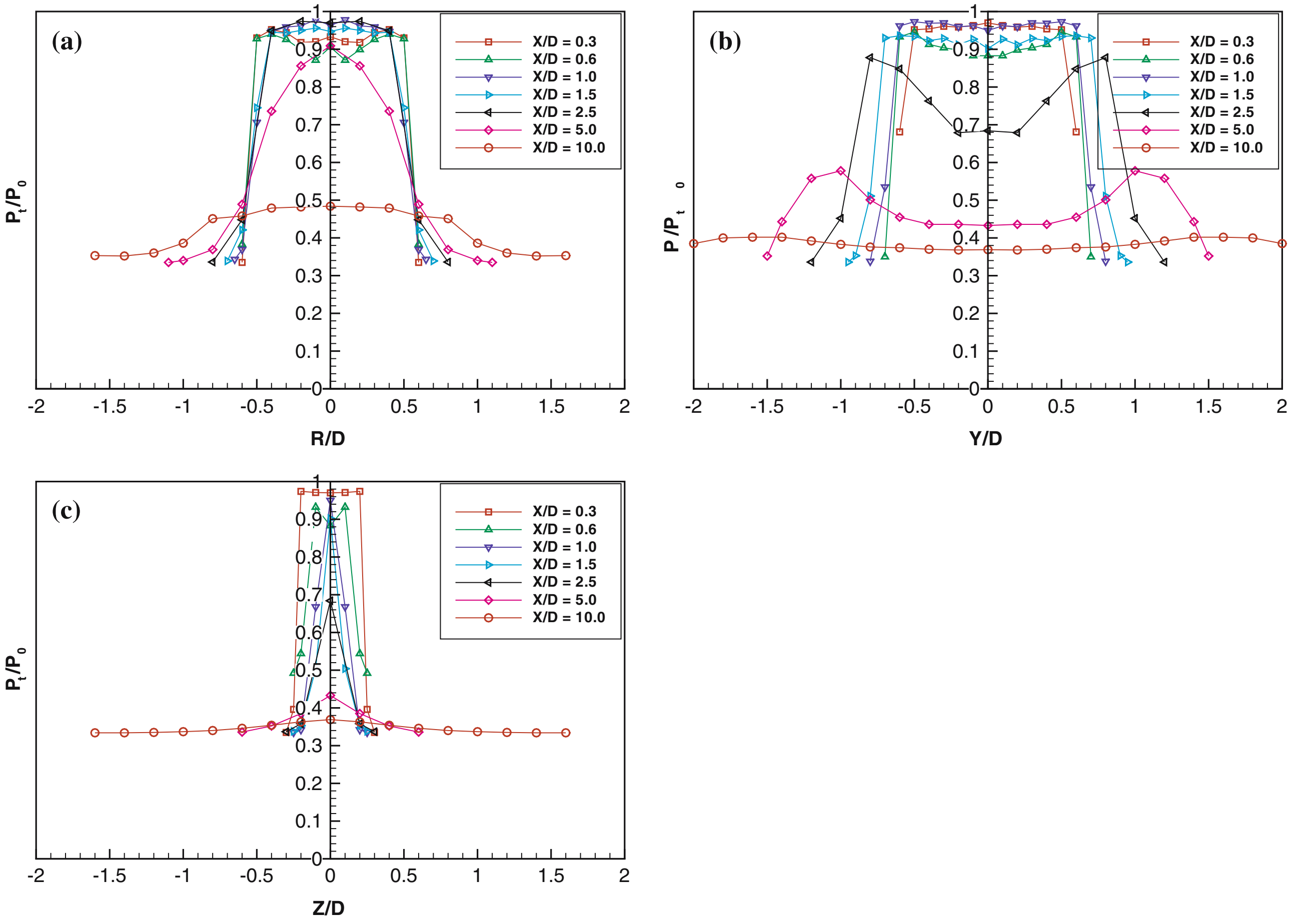

Fig. 10 Pitot pressure profiles for sonic jet with and without tabs at NPR 3. **a** plain jet; **b** Y-profiles for jet with tabs; **c** Z-profiles for jet with tabs

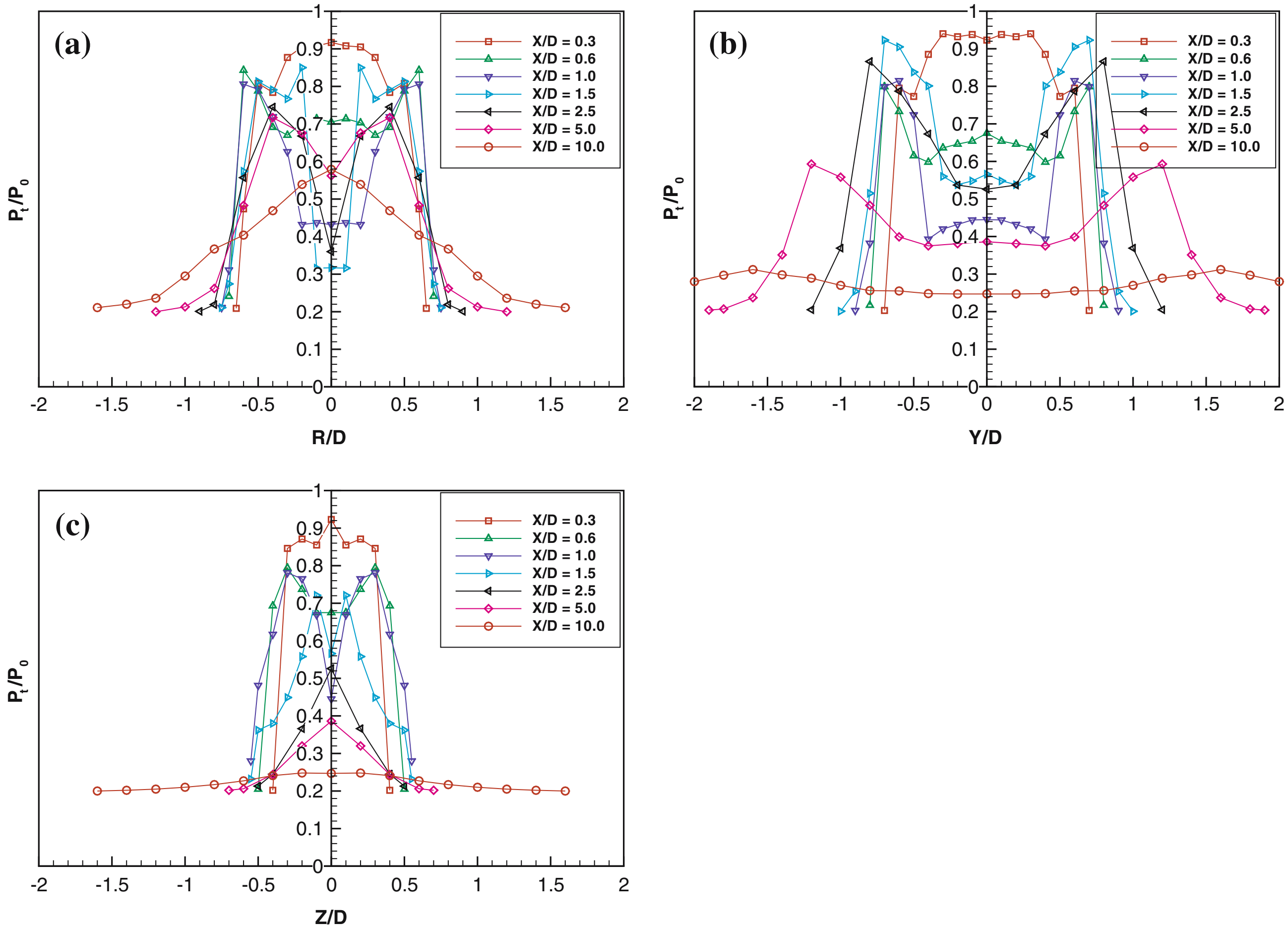

Fig. 11 Pitot pressure profiles for sonic jet with and without tabs at NPR 5. **a** plain jet; **b** Y-profiles for jet with tabs; **c** Z-profiles for jet with tabs

field viewed in the directions along the tabs (Z) and normal to the tabs (Y), respectively, at NPR 3. By the introduction of tabs, the shock-cells in the jet field are made weaker and unsymmetrical in both the directions. The shadowgraph pictures of the flow field viewed along the tabs reveal that, the tabs disperse the supersonic zone of the flow, forcing it to occupy a greater zone of the flow field compared to the plain jet nozzle, this causes the waves to become weaker and the jet to spread faster in this plane. Figure 11 shows the Pitot pressure profiles for the plain and tabbed jets at NPR 5. From the Y-profiles, it is inferred that, the effect of tabs is prominent from $X/D = 1.0$ onwards and from Z-profiles it is inferred that, the tabs begin to influence the jet field from the nozzle exit onwards. Hence, from these profiles at NPR 5, it is evident that, the influence of tabs on the shock-cell structure and the jet structure is distinctly different in the direction normal to the tabs and in the direction along the tabs. The classic single peak profile is observed for tabs at $X/D = 2.5$ from the Z-profile (Fig. 11c), whereas the jet grows wider in the direction normal to the tabs, possessing off-center peaks in the pressure profiles. The modification of the shock structure for the tabbed jet operated at NPR 5 is shown in Fig. 14. The shock-cells are completely perturbed by the tabs in both the planes. The pressure profiles for NPR 7 are shown in Fig. 12. The tabs begin to influence the near field profile in the Y-direction from $X/D = 0.6$ onwards and their effect becomes profound in the downstream direction. The single peak profile location varies with NPR in the Z-direction, which implies that the vortex nature in the Z-direction also changes with NPR. From these profiles it is evident that, the tabs are effective in altering the jet development and its shock nature and vortex nature completely in both the planes. From the shadowgraph pictures of NPR 7, it is seen that the shock-cells occupy a larger space in the direction normal to the tabs (Fig. 15a) and the signature of the shock-cell becomes unidentifiable in the direction along the tabs (Fig. 15b), as the jet propagates downstream. At all the NPRs for tabbed jets, the pressure variation in both the planes, at $X/D = 10.0$ has become almost asymptotic to the corresponding axes, which implies the complete decay of the jet. From the shadowgraph pictures of the plain jets, it is evident that NPR influences the shock-cells in the supersonic core significantly. As the NPR increases the strength of the first shock-cell increases as a result of the higher expan-

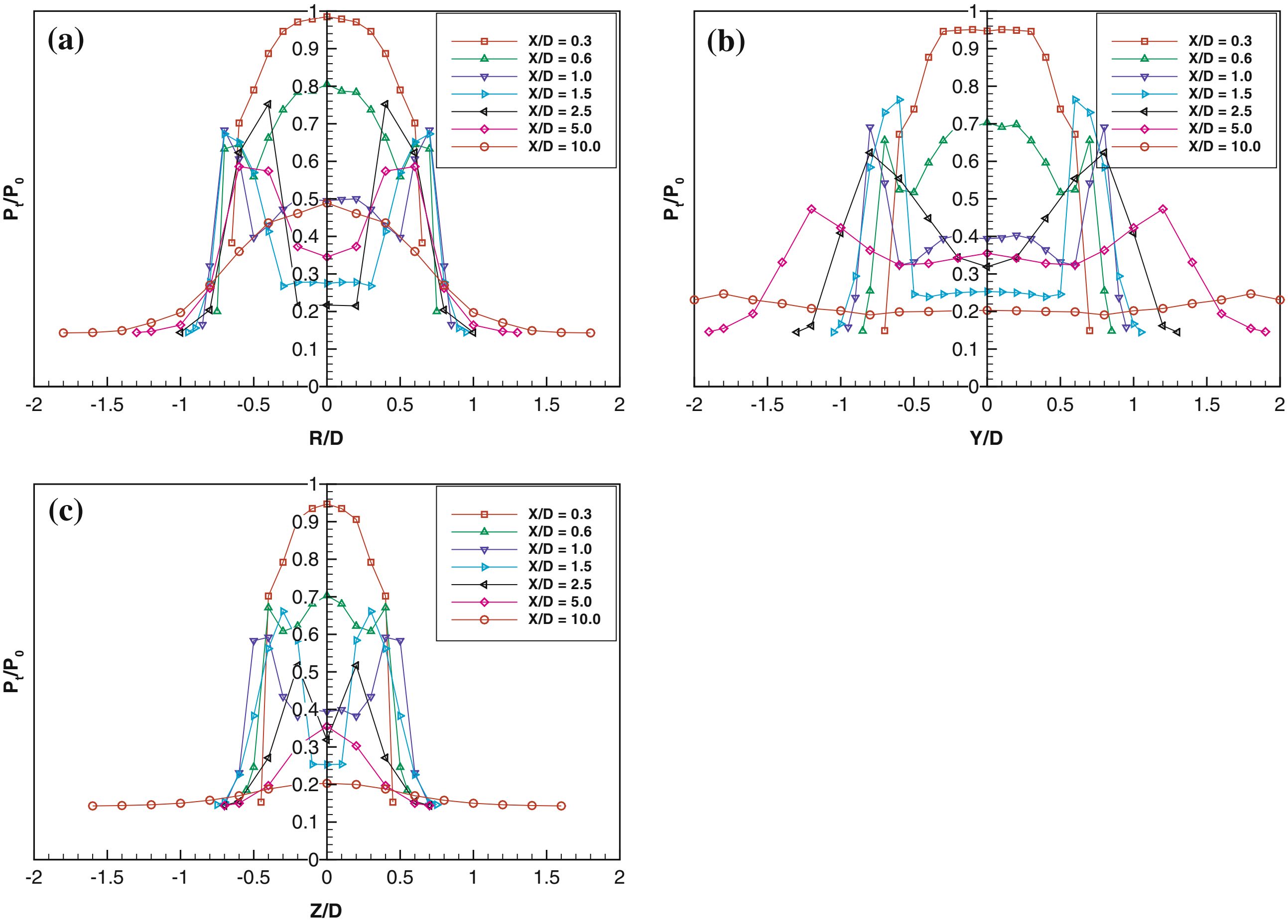

Fig. 12 Pitot pressure profiles for sonic jet with and without tabs at NPR 7. **a** plain jet; **b** Y-profiles for jet with tabs; **c** Z-profiles for jet with tabs

sion for the underexpanded jets. As a result, the strength of the successive shocks gets relatively reduced. When the tabs are introduced, the first shock-cell becomes shorter and the expansion fans are perturbed. The tabs tend to generate a non-symmetric structure of shock-cells. This is attributed to the angles of oblique shocks and expansion fans being different in the two planes of the jet due to which the flow changes direction in non-symmetric pattern. The dispersion of shocks in the direction normal to the tabs is evident from the Pitot pressure profiles. This leads to the weakening of the shock cell structure in the case of jets delivered from nozzle with tabs.

A pair of counter-rotating streamwise vortices are generated when a tab is placed in the flow field. Thus, two tabs will shed four rows of counter rotating vortices all along their edges. Even though these vortices are spanwise while shed from the tabs, become streamwise soon after shedding, due to the inertia of the jet flow. These vortices being small, have a long life span and once introduced in the flow, tend to persist over tens of nozzle exit diameter downstream. Therefore, they act as effective mixing promoters and enhance the jet mixing. This faster mixing results in rapid decay of tabbed jets compared to a jet from plain nozzle. For the jet from the nozzle without tabs, the vortices shed at the nozzle exit are azimuthal in nature. Also, these azimuthal vortices are of uniform size due to the uniform azimuthal radius of curvature of the nozzle exit. Therefore, they travel some distance before interacting with the mass entraining vortices formed at the free jet boundary, owing to differential shear. For the tabbed jet, in addition to the counter rotating vortices along their edges, the tabs shed smaller vortices along their bottom edge too. In addition, there are two sharp corners formed at the root end of each tab. At these corners one more set of counter rotating vortices will be generated. Further, these vortices shed along the long edges, bottom edges, and root corners of the tabs are of different size. Thus, for tabbed jet there is a mixture of azimuthal and small vortices of three sizes acting right from the nozzle exit. It is well known that, for efficient mixing mass entraining large vortices and mass transporting small eddies must be present in the jet field. This situation is automatically established for the tabbed jet. However, identifying a proper combination of these large and small eddies is a hard task, since the performance of these vortices is dictated by the jet Mach number, the level of

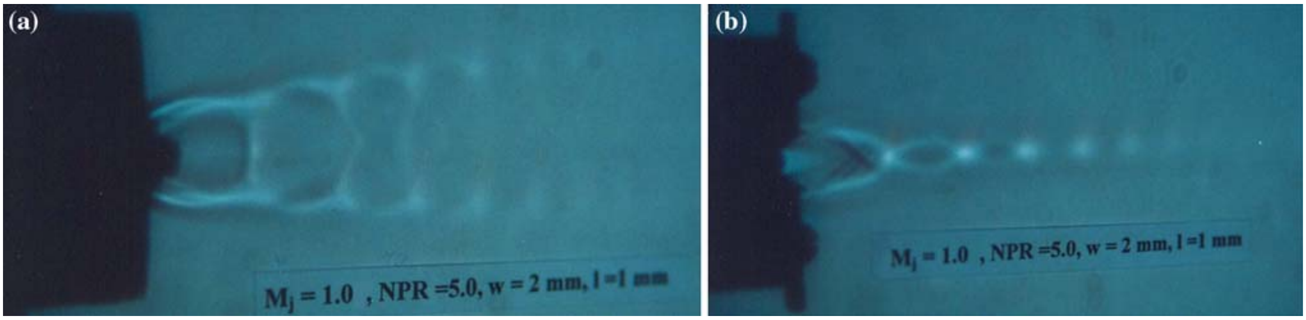

Fig. 13 Shadowgraph pictures for jet with tabs at NPR 3. **a** viewed along the tabs; **b** viewed normal to the tabs

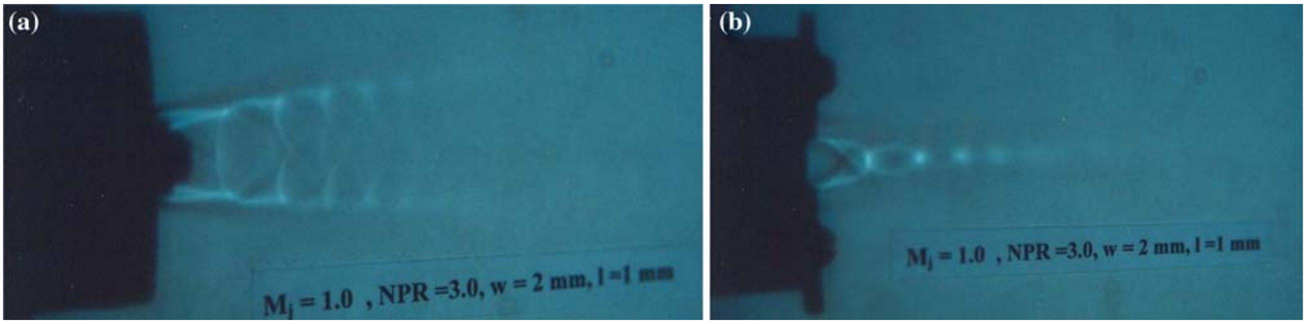

Fig. 14 Shadowgraph pictures for jet with tabs at NPR 5. **a** viewed along the tabs; **b** viewed normal to the tabs

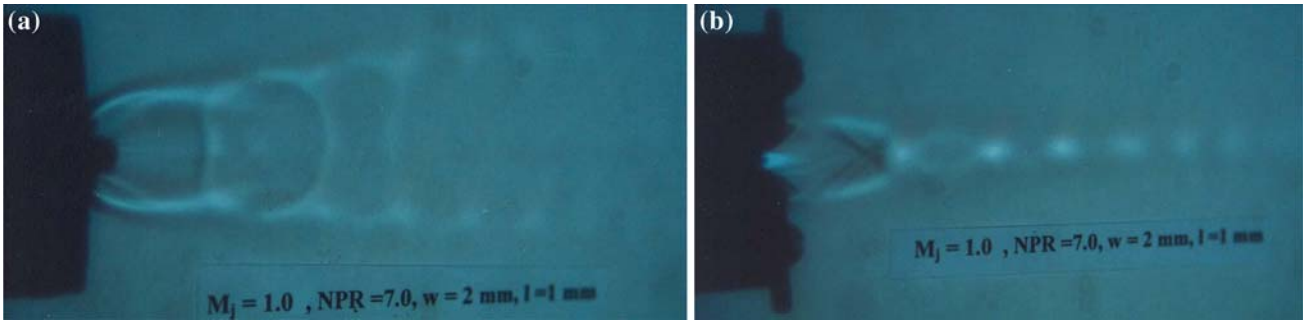

Fig. 15 Shadowgraph pictures for jet with tabs at NPR 7. **a** viewed along the tabs; **b** viewed normal to the tabs

expansion at the nozzle exit, and the proximity of the vortex structure in addition to their size proportion.

Conclusions

The present investigation on the effectiveness of cross-wire and tabs on the underexpanded sonic jets shows that, both the passive controls are effective in reducing the axial extent of supersonic core significantly. Also, both the controls render the symmetric shock-cell structures unsymmetrical and weaker, all along supersonic core. The cross-wire/tab controlled jets grow wider in the direction normal to the cross-wire/tab at all the operating conditions. However, the tabbed jets grow much wider compared to the cross-wire controlled jets. From the Pitot pressure profiles it is inferred that, the tabbed jets decay completely at an axial distance of about $X/D = 10$, whereas the cross-wire controlled jets still posesses definite pressure distribution even beyond $X/D = 10$, which suggests that the jet is yet to decay completely. The influence of tabs and cross-wire on the jet development is distinctly different and their mechanisms to causing the jet modification are also different. The effectiveness of both the controls is profound with the increase of NPR. With increase of NPR, these controls become more effective in diffusing the shock-cells in the plane in which they are located.

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