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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Studies on the Effect of Notches on Circular Sonic Jet Mixing

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Nomenclature

D = exit diameter of ungrooved nozzle
NPR = nozzle pressure ratio p_0/p_a
P = pitot pressure in the jet field
P_a = atmospheric pressure
p_c = pitot pressure along jet centerline
P_0 = settling chamber pressure
X = jet axis
Y = axis along the grooves
Z = axis normal to the grooves

I. Introduction

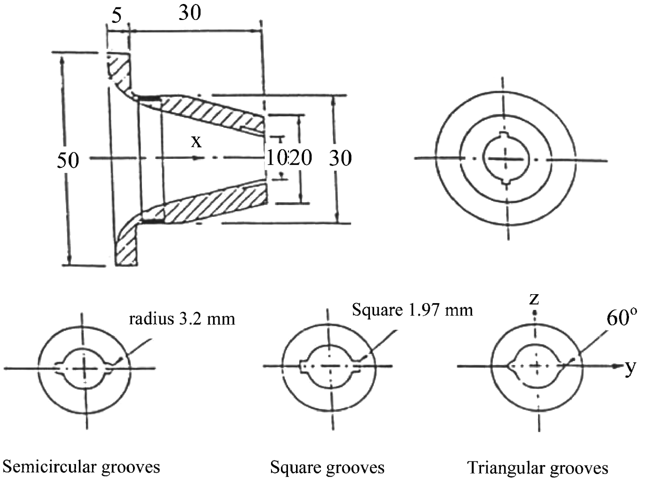
MIXING enhancement and noise attenuation are two primary objectives of high-speed jet research. Many studies were made to achieve these with unconventional exit geometries.[1–6] Jet control techniques are broadly divided into passive or active. Passive control can be permanent or deployable, but might no moving parts during operation.[6] In contrast, active controls use energized actuators to dynamically manipulate flow phenomena. For example, pulsed jets[7] use piezoelectric actuators for active mixing enhancement. Both tabs and vortex generators introduce streamwise vortices to entrain low-speed fluid while forcing out higher-speed core fluid. A tab produces a pair of counter-rotating vortices, whereas a half-delta-wing vortex generator produces only a simple vortex. Navin Kumar Singh and Rathakrishnan[6] reported 80% core reduction for underexpanded sonic jets using two rectangular tabs at the nozzle exit. But the introduction of tabs resulted in significant thrust loss.

Two tabs in symmetry lead to more rapid jet development as compared to when placed in an asymmetric manner.[8] Samimy and Reeder[9] observed tabs to be ineffective in overexpanded jets, and in underexpanded flow the tab width has a more profound effect on jet decay for the same blockage area ratio. Navin Kumar Singh and Rathakrishnan[6] found that the tab length is more effective in enhancing the jet mixing than its width, for same blockage. A passive control limit, namely, Rathakrishnan limit, has been reported recently by Sreejith and Rathakrishnan.[10] They demonstrated that tabs can extend up to the radius of any axisymmetric nozzle, and also there is no need for the existence of favorable gradient for the control effectiveness. The control effectiveness is dictated by a combination of both flow and geometrical parameters. But in all of these controls, the nozzle suffers a significant thrust loss.

For the notched nozzle, these studies were made by complete removal of material from nozzle wall at specific locations.[4,11] These notches are effective in increasing the spread and reducing the noise, but lead to considerable pressure loss. Hence, a modified form of notch was considered, which can prove efficient while keeping the pressure loss minimum. The notches in the present study were made by partial removal of material from nozzle inner surface, in the form of grooves (Fig. 1). This can be expected to prevent the lateral dissipation of the pressure energy through the notches, thereby minimizing the loss of pressure. These nozzles are better described as nozzles with internally grooved exit.[12] Recently, Jayant Vishnu and Rathakrishnan[13] reported the advantages derived from grooved nozzles on both jet mixing enhancement and noise attenuation. Even though they studied semicircular and square grooves, the study was for a specific supersonic Mach number. Jets from nozzles with semicircular, square, and triangular grooves were investigated in the present study. Attention was focused on jet mixing characteristics.

II. Experimental Setup

The experiments were conducted in an open-jet facility.[13] Semicircular, square, and triangular notches (Fig. 1) were cut along the inner wall and extended to 5.6 mm from nozzle exit. The grooves increased the exit area by 9%. A pitot tube of 0.7 mm outer diameter, mounted on a traverse and a PSI 9010 pressure transducer, was used for pressure measurement.[13] The transducer (after rezero calibration) is specified to be accurate up to ±0.15% full scale. Transducer pressure measurements are accurate within ±1.8%. The nozzle pressure ratios (NPRs) of present study were from 2 to 6. The centerline pressure was measured at 2 mm intervals upto $6D$ and at 5 mm intervals upto $25D$. Pitot pressure P_c along the axis passing through the grooves and the axis normal to it were also measured to have an insight into the additional mixing process introduced by



Semicircular grooves Square grooves Triangular grooves

Fig. 1 Experimental model.

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the vortices generated by the grooves. The shock cells in the jet core were visualized by shadowgraph. The length dimensions measured were accurate up to 0.1 mm. Measurements were repeatable within ±3%. The maximum uncertainty of pitot pressure was ±2.5%.

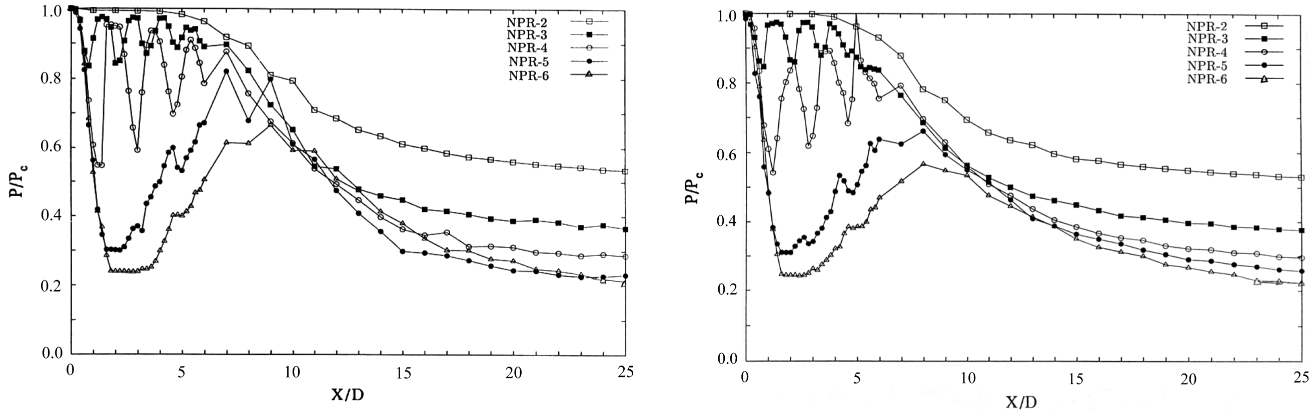
III. Results and Discussion

In a supersonic flow, measured pitot pressure corresponds to total pressure behind the bow shock at the probe nose. Pitot-pressure oscillations in the core are caused by the stationary shock structure in the jet. Because of probe interference with shock structure, there could be some measurement error, and hence the results represent the qualitative nature of flow in the jet. Nevertheless the data are accurate enough to capture the overall features, that is, the number of shocks and the spacing between them etc.[1] In a steady supersonic flow with a single normal shock ahead of the pitot tube, a sharp drop in total pressure followed by a rise signifies the presence of a strong shock wave.

A. Jet Decay

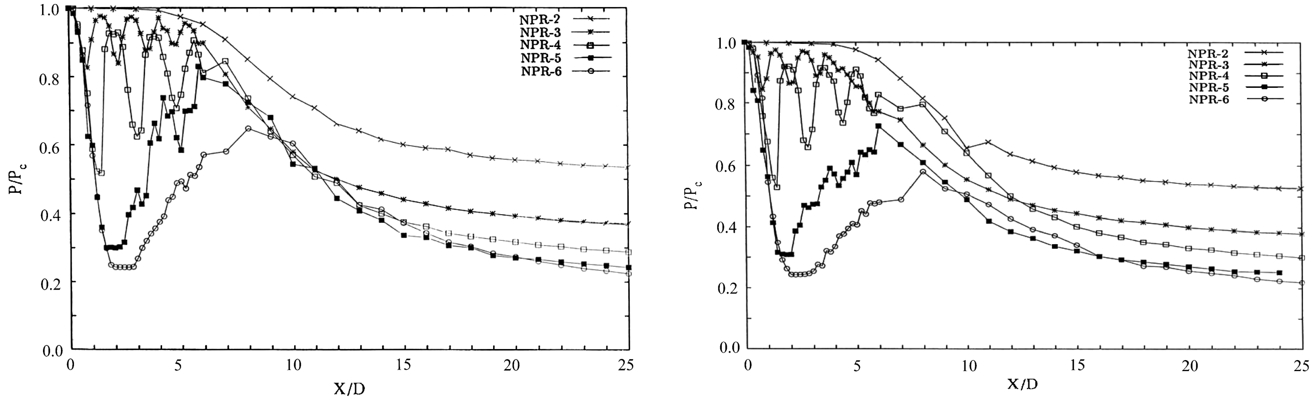
The centerline pressure decay for jets from plain and grooved nozzles, is given in Figs. 2a–2d. Figure 2a shows the decay for the plain (without grooves) nozzle. It is seen that the NPR influences the shock cells in the jet core (axial extent of shock presence) as well as the jet decay very strongly. This is because as NPR increases the first shock strength increases as a result of the higher Mach number encountered in the vicinity of nozzle exit owing to the expansion fan at the nozzle exit for underexpanded jets. The expansion fan and first shock become progressively stronger with increase of NPR. This process is required in a bid to equalize the nozzle-exit pressure and ambient pressure when the underexpansion level is high. As a result, the strength of the successive shocks gets relatively reduced. Because of this, the number of shock cells appearing in the core region decreases. Also, the core at NPR 2 is much shorter than higher NPRs. Further, there are only mild shocks present in the core. This is because NPR 2 is just above the isentropic NPR limit of 1.89 required for choking. But as NPR increases, the core becomes shock dominated, and the first shock becomes progressively stronger with increase of NPR. This is typical of freejets. Because of increased shock strength, even though there are fewer shock cells at NPR 4 compared to NPR 3, the flow exiting the core (i.e., the end of super sonic region) experiences a lower subsonic Mach number for NPR 4 than NPR 3. This is clearly reflected as faster characteristic decay for NPR 4 than NPR 3. Jet decay as a function of axial distance and NPR, for nozzle with triangular grooves, is shown in Fig. 2b. Grooves' effect on jet mixing promotion is clearly seen from the comparison of results in Figs. 2a and 2b. At NPR 2, the mild shocks observed in the core of plain nozzle jet are diffused in the jet from the nozzle with triangular grooves. Another interesting feature of notch effect is that the shock cell lengths decrease with increase of NPR. Centerline pressure decay for square and semicircular grooves is shown in Figs. 2c and 2d, respectively. Here again it is seen that the vortices generated by the grooves influence the shocks in the jet core strongly and cause core length reduction.

The results in Figs. 2a to 2d reveal that for NPR 2 the jet decays smoothly for both plain and grooved nozzles and grooves influence on core reduction is insignificant. But at NPR 3 there is a significant influence of grooves on jet propagation. The core length of $7D$ for the plain nozzle jet has come down to about $5D$ with the introduction of triangular grooves. For square and semicircular grooves the core drastically comes down to $3.5D$. That is the core length is reduced to 50% of its value for the plain nozzle. Even though this reduction in jet core length is far below the 80% reduction achieved with tabs,[6] the present control has two specific advantages compared to tabs. One is that the thrust loss with tabs is more than 6%, whereas the thrust loss with grooves, even though not quantified, can be envisaged from the exit plane pressure profiles (Fig. 3) to be much less than that for tabs. Secondly, positioning thin tabs in a high inertial hot gas stream is a technological challenge, whereas partial removal of material at the nozzle inner wall to form the grooves is very simple.



a) Nozzle without grooves

c) Nozzle with square grooves



b) Nozzle with triangular grooves

d) Nozzle with semicircular grooves

Fig. 2 Centerline pressure decay.

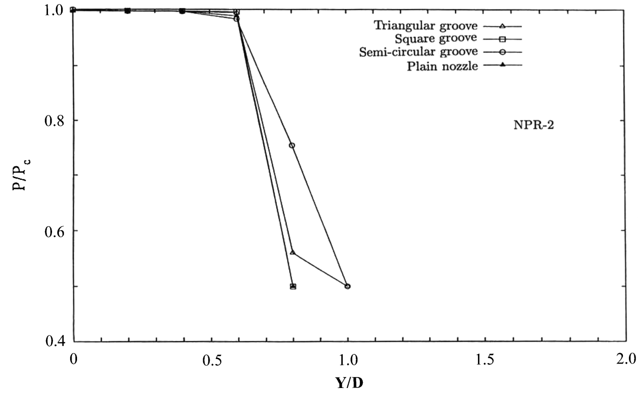


Fig. 3a ***Y* profile at *X/D* = 0 (grooved plane).**

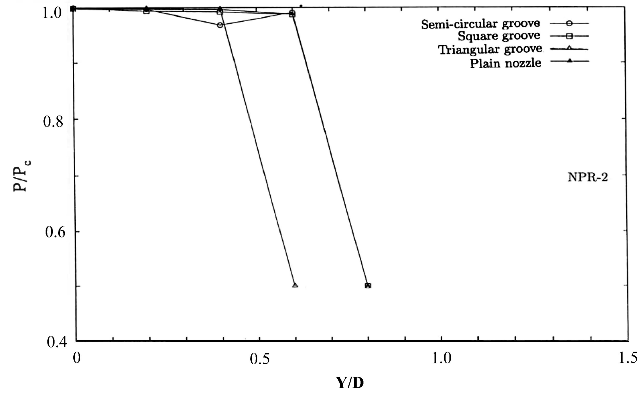


Fig. 3b ***Z* profile at *X/D* = 0 (ungrooved plane).**

At NPR 4 also the effect of grooves on jet decay is significant. For plain nozzle the core is about $7D$, whereas for triangular, square, and semicircular grooved nozzles the core assumes lengths of $6.5D$, $5.5D$, and $6D$, respectively. That is, the core is reduced by 7.1, 21.4, and 14.3% for triangular, square, and semicircular grooved nozzles, respectively. At NPR 5 the jets from plain and grooved nozzles experience a strong shock between $2D$ and $2.5D$ (Fig. 2d) and then recovers energy gradually. For this case the core length is $9D$ for plain nozzle and $8D$, $6.5D$, and $6.3D$, respectively, for triangular, square, and semicircular grooved nozzles. At NPR 6, the core lengths are $11D$, $10D$, $8D$, and $8D$ for plain, triangular, square, and semicircular grooved nozzles, respectively.

From the preceding discussions, it is evident that grooves' influence on jet decay is well pronounced because of the additional mixing caused by the streamwise vortices introduced by the notches. This results in a rapid cross-stream mixing and hence significantly thickens the mixing region of the jet. Owing to this mixing enhancement, the shocks in the core get diffused faster, resulting in weaker shocks and hence a faster decay thereafter. Weakening the shocks in the core region can be taken as a great advantage from jet acoustic point of view.[1] It is well known that reduced shock strength will result in reduction of shock associated noise, which constitutes a significant portion of overall sound pressure level of supersonic jets.

The grooves dominate the jet mixing process in the characteristic decay region more prominently than in the core, for NPRs 2 and 3. In the far field all of the jets decay almost alike. But for NPRs 4, 5, and 6, the streamwise vortices generated by the grooves dominate the mixing process throughout the field, starting from end of first shock cell to the far field. The groove effectiveness in promoting mixing increases with increase of NPR. This is in accordance with results of Navin Kumar Singh and Rathakrishnan,[6] for sonic jets from nozzle with tabs. The control effectiveness increases with increase of underexpansion level. In other words, the presence of favorable pressure gradient augments the performance of the controls. Semicircular and square grooves are found to be more effective than the triangular grooves in enhancing the jet mixing, especially at NPRs 5 and 6.

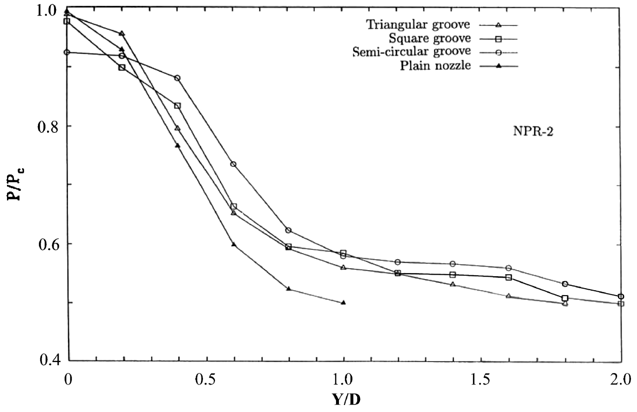


Fig. 4a ***Y* profile at *X/D* = 5 (grooved plane).**

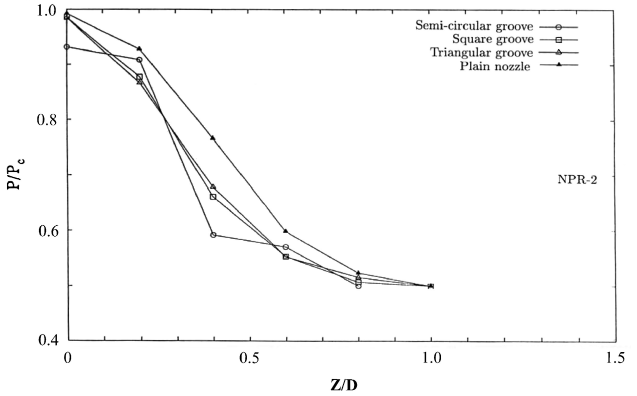


Fig. 4b ***Z* profile at *X/D* = 5 (ungrooved plane).**

B. Pressure Profile

Pressure variation along the grooved Y and ungrooved Z axes were also measured to assess the jet growth in the grooved and ungrooved planes. As expected, it was found that the grooves made the jets to spread asymmetrically, exhibiting larger width in the grooved plane.

For all grooves the pressure variation along the grooved plane and ungrooved plane was almost identical to that of the plain nozzle jet at $X/D = 0$, as seen in Fig. 3, for NPR 2. This implies that the thrust loss as a result of the disturbances caused by the grooves is only marginal. As the jet propagates downstream, the jet width in the grooved plane becomes much larger than that in the identical plane for the jet from the plain nozzle, as seen in Fig. 4. The reason for this width enhancement when grooves are introduced was that the streamwise vortices, when exiting the nozzle, form a secondary jet, and the combination of the secondary jet with the primary jet from the nozzle results in significant enhancement of jet growth in the grooved YX plane. The groove geometry influences this growth process very strongly.

For all groove shapes, at $X/D = 2$, 3, and 4 a sudden increase of pressure at almost near the jet boundary, followed by a sharp decrease approaching the ambient pressure, was found. The magnitude of these pressure peaks and the gradient of pressure fall thereafter were found to strongly depend on the groove shape. The pressure peaks disappeared for $X/D > 5$. Shadowgraph pictures, in the direction normal to the grooved plane, clearly showed the presence of additional waves caused by the relaxation experienced by the jet as a result of the grooves, causing mixing enhancement.

Conclusions

Grooves were found to be effective mixing promoters. Their effectiveness improves with increase of underexpansion level. Grooves perform better in the presence of favorable pressure gradient. Square and semicircular grooves are more efficient promoters than the triangular grooves. As high as 50% reduction in jet core length was achieved with square and semicircular grooves. The grooves were also found to be effective in weakening the shocks in the jet core.

References

[1] Elangovan, S., and Rathakrishnan, E., "Effect of Cut-outs on Underexpanded Rectangular Jets," *Aeronautical Journal*, Vol. 108, No. 1079, May 1998, pp. 267–275.

[2] Morris, P. J., Bhat, T. R. S., and Chen, G., "A Linear Shock Cell Model for Jets of Arbitrary Exit Geometries," *Journal of Sound and Vibration*, Vol. 132, No. 64, 1989, pp. 199–211.

[3] Quinn, W. R., and Marsters, G. F., "Upstream Influence on Turbulent Jet Flows from Cruciform Nozzles," *Aeronautical Journal*, No. 882, Feb. 1985, pp. 515–528.

[4] Pannu, S. S., and Johannesen, N. H., "The Structure of Jets from Notched Nozzles," *Journal of Fluid Mechanics*, Vol. 74, 1976, pp. 515–528.

[5] Wlezien, R. W., and Kibens, V., "Influence of Nozzle Asymmetry on Supersonic Jets," *AIAA Journal*, Vol. 26, No. 1, 1988, pp. 27–33.

[6] Navin Kumar Singh, and Rathakrishnan, E., "Sonic Jet Control with Tabs," *Journal of Turbo and Jet Engines*, Vol. 19, No. 1–2, 2002, pp. 107–118.

[7] Parekh, D. E., Kibens, V., Glezer, A., Wiltse, J. M., and Smith, D. M., "Innovative Jet Flow Control: Mixing Enhancement Experiments," AIAA Paper No. 96–0308, 1996.

[8] Krothapalli, A., and Wishart, D. P., "Supersonic Jet Control via Point Disturbance Inside the Nozzle," *AIAA Journal*, Vol. 31, No. 7, 1993, pp. 1340–1341.

[9] Samimy, M., and Reeder, M. M., "Effect of Tabs on the Flow and Noise Field of an Axi-Symmetric Jet," *AIAA Journal*, Vol. 31, No. 4, 1993, pp. 609–619.

[10] Sreejith, R. B., and Rathakrishnan, E., "Cross-Wire as Passive Device for Supersonic Jet Control," AIAA Paper 2002-4059, 2002.

[11] Smith, D. J., and Hughes, T., "The Flow from Notched Nozzles in the Presence of a Free Stream," *Aeronautical Journal*, Vol. 88, No. 873, 1984, pp. 77–85.

[12] Elangovan, S., and Rathakrishnan, E., "Studies on High Speed Jets from Nozzles with Internal Grooves," *Aeronautical Journal*, Vol. 108, No. 1079, Jan. 2004, pp. 43–50.

[13] Jayant Vishnu, and Rathakrishnan, E., "Acoustic Characteristics of Jets from Grooved Nozzles," *Journal of Propulsion and Power*, Vol. 20, No. 3, 2004, pp. 520–526.