Proceedings of the
International Conference on Mechanical Engineering 2005
(ICME2005) 28- 30 December 2005, Dhaka, Bangladesh

ICME05-FL-15

# SUPERSONIC JET CONTROL WITH INTERNAL GROOVES

**Shafiqur Rehman[1], M. Jamil Ahmad[2], Ahamed Saleel C.[3] and S. A. Khan[3]**

[1] KFUPM, DAHARAN, S A
[2] Mechanical Engineering Department, A.M.U., Aligarh, U.P., India
[3] Mechanical Engineering.Department, PA College of Engg, Mangalore, Karnataka

## ABSTRACT

The effect of vortex generators, in the form of internal grooves cut along the inner surface of the diverging portion of the converging-diverging nozzle and parallel to the flow, on the characteristics of an axi-symmetric jet is investigated experimentally at jet Mach number of 1.8. The performance of such passive control is important in missile and launch vehicle engine application for jet mixing enhancement and noise suppression. Information on decay, growth and noise suppression characteristics of supersonic jets from three nozzle configurations, namely plain nozzle, nozzle with two semicircular grooves and nozzle with two square grooves, are presented. It is found that the grooves act as effective passive controls resulting in significant enhancement of jet mixing. The shock cell structure from grooved nozzle appeared to be weaker than that of plain nozzle. These observations suggest that they are due to the significant stream wise vortices generated by the grooves. Further, the present results authenticate that Nozzle Pressure Ratio (NPR) plays an important role in the case where an adverse pressure gradient exists near the nozzle exit. The results of present studies agree well with the experimental and theoretical results of previous studies.

**Keywords:** Super sonic jet, Nozzle pressure ratio, Jet Mac number.

## 1. INTRODUCTION

Jets are free shear flows driven by the momentum introduced at the exit of, usually, a nozzle or an orifice. Jets flow plays a central role in research aimed at improving our understanding of the fundamental physics of turbulent shear flows. The diverse nature of applicability of jets demand that they made suitable for their specific applications by controlling them. Control may be defined as the ability to modify the flow characteristics in such a way to achieve better engineering efficiency, technological ease, economy, adherence to standards etc. Jet controls may be broadly classified into active and passive controls. In active control, an auxiliary power source (like micro jets, acoustic excitation) is used to control the jet characteristics. The other method, termed passive control does not require any additional energy for achieving control. Both active and passive control mainly aim at modifying the flow and acoustic characteristics of jets to result in enhanced mixing and reduce noise.

The first review of supersonic jet was done by Tam [1]. In his inspiring review, Tam discusses the noise sources in supersonic jets, methods, and models developed for predicting them. Tam and Chen [2] proposed a stochastic wave model theory for the turbulent mixing noise from supersonic jets.

Tam et. al. [3] examined the relationship between the broadband shock associated noise and screech tones. Based on their analysis they concluded that the screech tone frequency is dictated by the weakest link of the feedback loop. It is the weakest link that relates the spectral characteristics of screech tone to those of broadband shock-associated noise.

Pannu and Johannesen [5] investigated under expanded jets issuing from notched nozzles. The centerline pitot pressure data indicated that the shock cell structure was modified and the jet decayed faster than the unnotched nozzle flow beyond the core region.

Smith and Hughes [6] presented experimental results obtained in jets from notched nozzles in a co-flowing free stream. The results showed that even at low jet velocities and with slowly tapering nozzles produced quite distinct vortices, which persisted well down stream. It was also observed that the introduction of a free stream had little effect on the development in the region of the vortices, though it reduced the rate of decay of the centerline velocity in the main part of the jet.

Elangovan and Rathakrishnan [7] evaluated the effect of vortex generators in the form of grooves on the penetration and spreading of jets from circular nozzles. In their experiment they found that the grooves weakened the shock cell structure of the under expanded jets. The jet flow field was found to be strongly influenced by the groove length.

Powell [10] was the first to study the under expanded jet noise. Powell found that the shock-associated noise is related to acoustic feed back loops. According to Powell, as the disturbances created at the nozzle lip passed through the third or fourth shock-cell, strong interaction takes place with the oblique shocks resulting in the emission of intense acoustic waves. When the jet exit pressure is less than the ambient pressure the jet is said to over expanded. The flow tries to attain the ambient pressure; this takes place across an oblique shock attached to the nozzle exit outside the duct.

Noise is an inevitable consequence of jets, and in general all turbulent flows. Whenever there is relative motion between fluids, or between a fluid and a solid, noise is generated. Noise in jets depends on the speed of the jet, temperature, and turbulence level; shear layer dynamics, observer angle, etc. Jet noise can be classified into the following major types:

1. Turbulent Mixing Noise.
2. Broadband shock associated Noise.
3. Screech Tones.

## 2. TURBULENT MIXING NOISE

As discussed earlier, the large-scale structures grow in size as they move forward, thus setting up intense activity in the circumferential region of the jet. Thus, the kinetic energy of the main flow is continuously extracted by the large structures and converted into “turbulence energy”. It is these shear stresses of the fluctuating velocities, which is the source of sound. Since the noise is produced due to the exchange of momentum of the jet and the ambient fluid (i.e., mixing) by turbulent action, it is termed as turbulent mixing noise.

### Shock-Associated Noise

Jet noise receives additional component in the form of shock-associated noise, when the jet plume contains shocks. The noise component with discrete frequencies is commonly called the *Screech tone,* and the other component is broadband, usually termed as the broadband shock-associated noise.

### Screech

The jet screech noise is a result of the large-scale coherent structures in the jet shear layer interacting with the shock cells, generating fluctuating pressures that propagate upstream. As they travel upstream, they couple with the shear layer causing amplification of the coherent structure in the shear layer and resulting in a feed back process. When the phase relationship between the downstream traveling coherent structures in the shear layer and the upstream traveling pressure waves is matched, high amplitude tones of discrete frequency are generated. These are called screech tones. When a jet emits strong screech tones, the jet undergoes strong oscillations.

Hence, a modified form of notch was thought of, which can prove effective while keeping the pressure loss at minimum. The notches in the present study were made by partial removal of material i.e., in the form of grooves as shown in Fig. 1. This may be expected to prevent the lateral dissipation of the pressure energy through the notches, thereby minimizing the loss of pressure.

Convergent-divergent nozzles made of brass were used for the present study. For Mach 1.8, the nozzle exit diameter was 12 mm. The nozzle model primarily consisted of a common base nozzle fitted on to a circular base plate of aluminum. The divergent portion (with grooves) or the end attachment of the base nozzle was made as a separate insert, which can be threaded on the base nozzle. Two half semi-circular notches were cut at the exit of the diverging portion which extended up to half the distance along its length. In other words, these notches were in the form of grooves cut along the inner surface of the end attachment. Similar insert was made for square shaped grooves. Due to the presence of grooves the exit area of the nozzles increased by 10 %.

The flow measurements include pitot pressure survey along the (geometric) centerline of the jet for the Mach number 1.8, at correct, over and under expanded flow conditions.

The pitot pressure probe is mounted on a three-dimensional traverse, for the pitot pressure surveys conducted over the entire flow field. The traverse has a spatial resolution of 0.1 mm in all the three dimensions. The pitot probe used, had an inner diameter of 0.4 mm and outer diameter of 6 mm. The pressure was measured by PSI model 9010.

## 3. RESULTS AND DISCUSSION

The principal parameters governing the flow of a free under expanded/over expanded are the following: the nozzle pressure ratio (NPR), the jet Mach number, and the condition of the nozzle exit. In the present investigation, nozzle pressure ratios (NPRs) studied are 4, 5.75, and 7. For the nozzles studied NPR = 5.75 corresponds to the correct expansion case, NPR = 4 corresponds to the over expansion case and NPR = 7 is the under expanded case. The nozzle jet Mach number studied is 1.8. Experiments were conducted for the above-mentioned NPRs using plain nozzle, nozzle with semi-circular grooves and nozzle with square grooves.

The length of the supersonic core in a high-speed jet is a direct measure of the mixing and spreading characteristics of the jet. The axial point farthest downstream at which there exists a supersonic Mach number determines the core length. Hence, centerline pitot surveys were conducted, for all the nozzle configurations and NPRs, to determine the extent of the core of the jets. In the supersonic regions of the flow, the measured stagnation pressure corresponds to the stagnation pressure behind the standing bow shock in front of the Pitot tube.

A typical variation of the pitot pressure $P_c$ along the centerline of the jet for a pressure ratio of 5.75 is shown in Fig. 4.1(a). The absolute values of $P_c$ are divided by the settling chamber pressure $P_0$ and plotted against the non-dimensional axial distance along the jet axis. These results cannot be converted directly into velocity or Mach number because of the unknown entropy increase that has occurred. In a steady supersonic flow with single normal shock wave ahead of the Pitot tube, a large pitot pressure corresponds to low Mach number, and vise versa. For the case of the plain nozzle, near the nozzle exit, a sharp drop in the pitot pressure followed by a rise is observed, which signifies the presence of the normal shock wave commonly referred to as the Mach disc. For X/D > 13, the total pressure decays monotonically and has a variation similar to subsonic jet.

The oscillations in the plotted stagnation pressure data, Fig. 2(a), plain nozzle, in the upstream regions (X/D ≈ 12) are due to the stationary shock structure in the jet. It is to be noted here that due to probe interference with the shock, structure there is some measurement error and the amplitudes in the supersonic region should be considered only qualitative. Fig. 2 (a) indicates a drastic reduction in the length of the jet core under the action of the grooves, for correctly expanded case. The variation of the total pressure along the centerline of the jet exiting from grooved nozzle suggests that the shock cell structure is significantly weakened by the presence of the grooves. This is mainly seen from the significantly reduced amplitudes of the pressure data oscillations in the core region.

As mentioned in the literature that the correctly expanded jets is wave free. This statement is incorrect because the jets from the correctly expanded nozzle are highly wave prone. The only difference between correctly and under expanded jets since the expansion fan at the nozzle lip for correct expansion is weaker than that for under expansion. This is explicitly evident from the first Mach disc strength seen in Figs. 2(a) and (e).

For the over expanded condition the centerline decay is given in Figs. 2(a) and (d). It is a general feeling among researcher working in the area of jet control that the passive control will not be effective when there is an adverse pressure gradient. In the present investigation, Mach 1.8 jet operating at pressure ratio (NPR) of 4 is a jet with adverse pressure gradient, but it is seen that the passive control in the form of grooves act as effective mixing promoters. An important point to be noted here is that with the semi-circular grooves, the first two shock cells are behaving identically similar to those from plain nozzle. The second and third cells become very weak but once again, the shocks in the subsequent cells show increased strength. In addition, the plain nozzle jets show only marginal decay up to fourth cell, even though the decay after the fourth cell is rapid. However, when the grooves are introduced, the rapid decay in the supersonic zone begins from the second cell onwards. This may be due to penetration of the vortices introduced by the grooves towards the jet centerline. The process of this penetration is found to curtail the energy flow into the cells as reflected from significantly reduced peaks after the shocks. In addition, because of this additional mixing activities introduced by the grooves the span of expansion fan activity is increased especially for the shock cells beyond the second cell, as evident from the spread out peaks.

The effect of square grooves on the centerline decay is shown in Fig. 2 (d). It is interesting to note the difference between the influence of semicircular and square grooves on jet mixing. Unlike the semicircular groove, the square groove influences the mixing right from the first cell. All the cells have been weakened in the near field; however, the cells beyond the fourth exhibit an increase in strength compared to the plain nozzle. A closer look into the vortex generation mechanism in these grooves will explain the reason behind the above results. For semicircular grooves, the vortex generated is free from any corner effect and hence does not have any inner mixing in it. It comes out of the groove as an axial vortex and introduces mixing along the path of its propagation. In the process, it promotes mixing of the jet field and spends its energy to get dissipated. This activity seems to be hectic around the third and fourth cell. Since the field is with an adverse pressure gradient the expected long life of axial vortex is reduced in overcoming this adverse pressure gradient, hence cells beyond the fourth one are able to gain energy from the surrounding high-speed fluid without being significantly inhibited by the axial vortices.

For square grooves, the vortices generated by the grooves experience an inbuilt mixing mechanism due to the sharp corners. Therefore, they may be fragmented when they come out of the grooves. This proves to be an advantage for mixing enhancement in the near field, however, because of the reduced strength compared to the vortices from the semicircular grooves, the decay achieved is not much in the near field. Above discussion can be quantified from the fact, as seen from Fig. 2(c) and (d), the rapid decay begins right from nearly X/D = 2.5 for semicircular groove case, whereas for the square groove rapid decay begins only from X/D = 5.

It should be realized that whatever be the nature of the groove shape, the additional vortices introduced by the grooves will provide some shielding to the jet noise radiation at least in the plane of the grooves. This can be regarded as an advantage.

The centerline decay for under expansion condition at NPR = 7 is given in Figs. 2(e) and (f). This is the field with favorable pressure gradient. Because of this, the groove effect is felt up to the end of the core. The semicircular groove is effective in promoting the jet mixing. The shocks have become weaker compared to the plain nozzle case. Especially, after the fourth cell the shocks have diffused significantly. However, for the square grooves, though the effect of groove is felt in the core there is no significant reduction in the shock strength. This is because, as discussed above, a part of the vortex strength is consumed in overcoming sharp corner effects and hence they could influence the jet only marginally when favorable pressure gradient is present.

## 4. CONCLUSIONS

The aerodynamic and acoustic characteristics of jets from nozzles with internal grooves were investigated. The far field noise characteristics of the grooved jets in the grooved plane show definite gains in noise reduction. However, such reduction, observed in the grooved plane is not seen in the plane normal to the grooved plane. Any reduction in the mixing noise observed in the far field seems to be associated with the orientation of the grooved plane with respect to the measurement plane. This observation demonstrates the shielding effect offered by the stream wise vortices generated by the grooves. Also, for the over expanded case of jet flow it was seen that the effectiveness of stream wise vortices on jet control is strongly influenced by the NPR

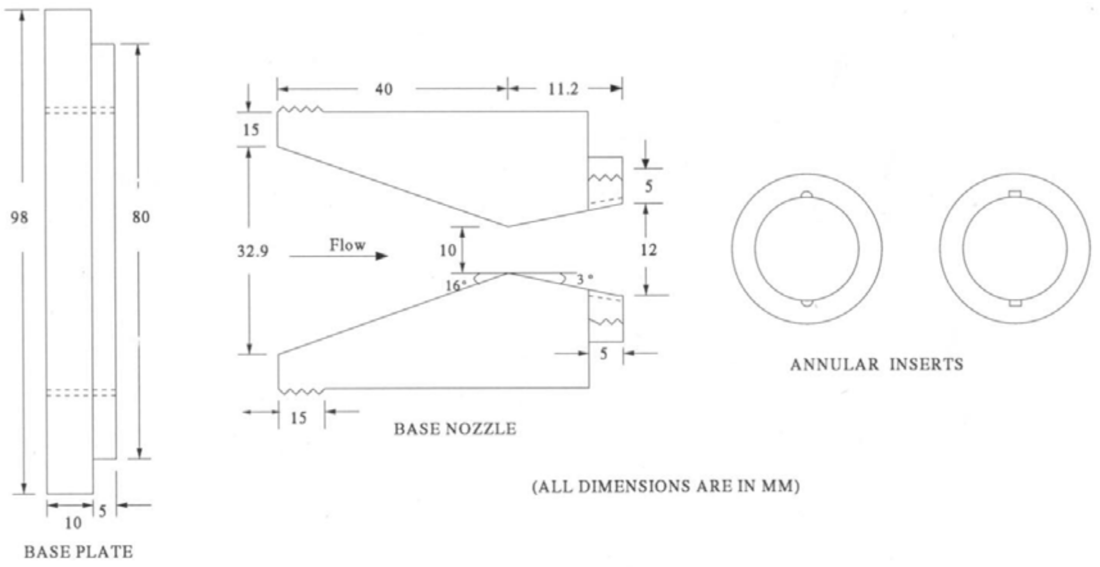

Fig 1. Model Drawing

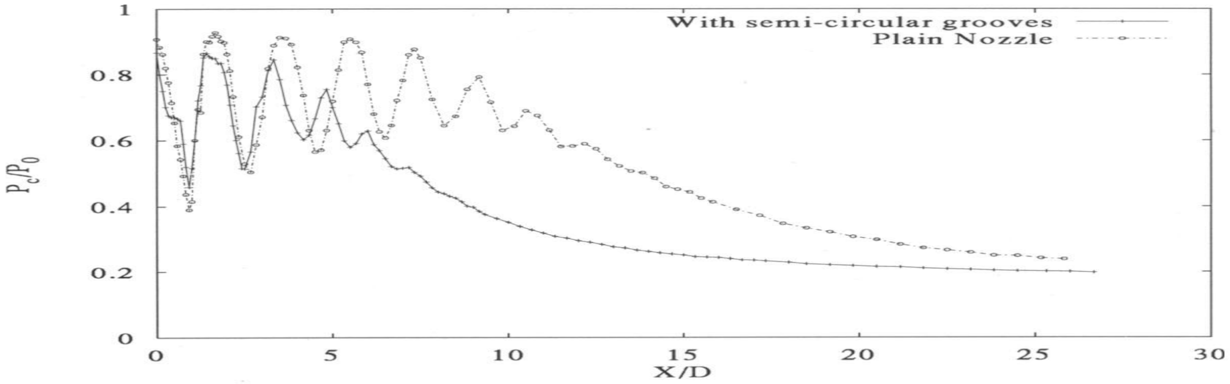

Fig. 2 (a): Centerline pressure decay for M = 1.8, NPR=5.75

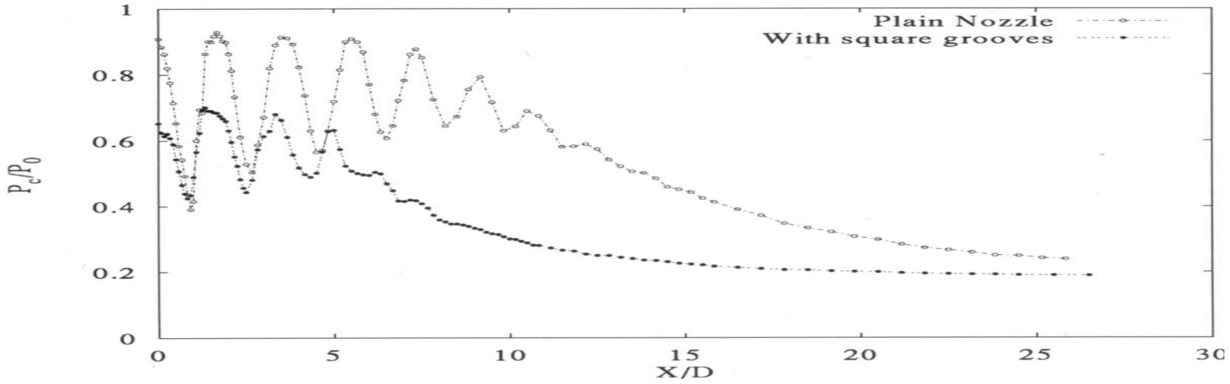

Fig. 2 (b): Centerline pressure decay for M = 1.8, NPR=5.75

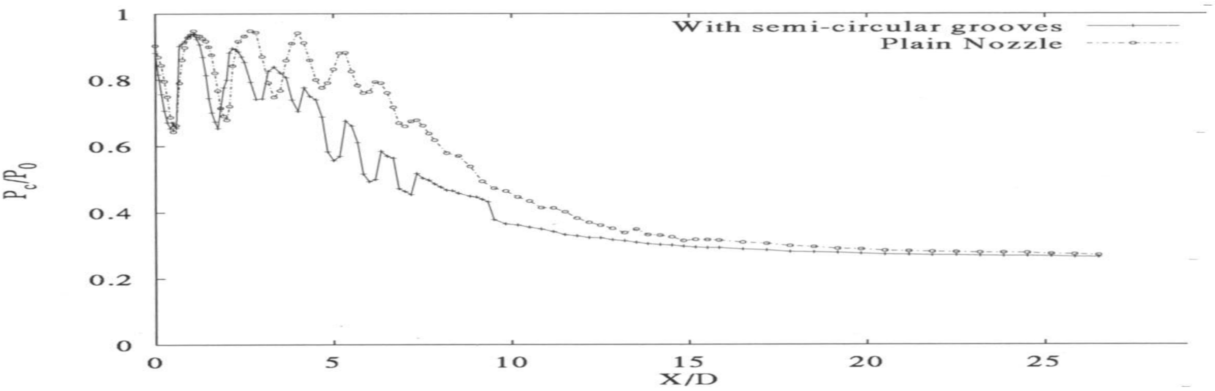

Fig. 2 (c): Centerline pressure decay for M = 1.8, NPR=4

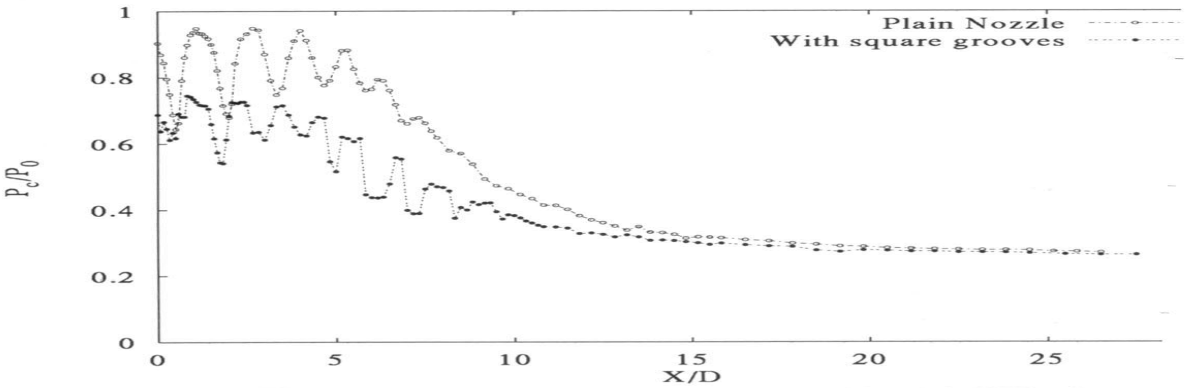

Fig. 2 (d): Centerline pressure decay for M = 1.8, NPR=4

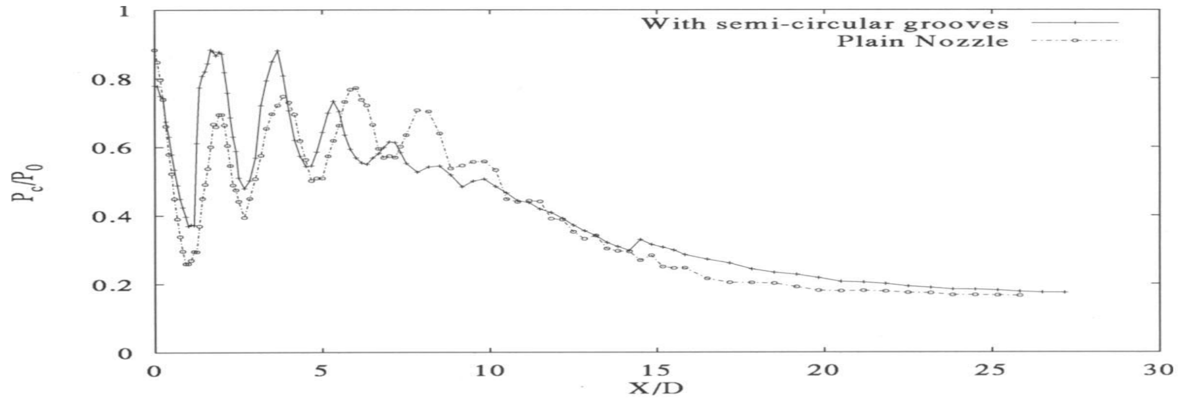

Fig. 2 (e): Centerline pressure decay for M = 1.8, NPR=7

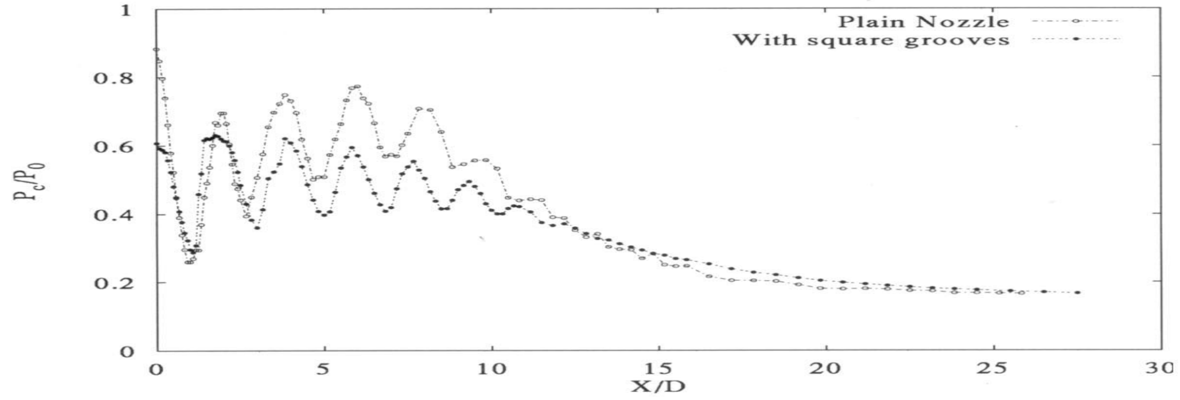

Fig. 2 (f): Centerline pressure decay for M = 1.8, NPR=7

## 5. REFERENCES

1. Tam C K W, 1995, "Supersonic Jet Noise," Annual Review of Fluid Mechanics, Vol. 27, pp. 17-43.
2. Tam C K W and Chen P, 1994, "Turbulent Mixing Noise from Supersonic Jets", AIAA Journal, Vol. 32, No. 9, pp. 1774-1780.
3. Tam C K W, Chen P, and Seiner J M, 1992,"Relationship Between Instability waves and Noise of High Speed Jets", AIAA J., Vol. 30, No. 7, pp. 1747-1752.
4. Tam C K W, Chen P, Seiner J M, and Yu J C, 1986, "Proposed Relationship Between Broadband Shock Associated Noise and Screech Tones", Journal of Sound and Vibration, Vol. 110, pp. 309-321.
5. Pannu S and Johannesen N H, 1976, "The Structure of Jets from Notched Nozzles", Journal of Fluid Mechanics, Vol. 74, pp. 515-528.
6. Smith D J and Hughes T, 1984, "The flow from Notched Nozzles in the presence of a Free stream", The Aeronautical Journal, Vol. 88, pp. 77-85.
7. Elangovan S and Rathakrishnan E, 1998, " Passive Control of Sonic and Supersonic Jets", *Proceedings of the 21st International Symposium on Space Technology and Science*, Vol. 1, Omiya, Japan.
8. Gutmark E, Schadow K C, Parr T P, Hanson-Parr D M and Wilson K J, 1989, "Non-circular Jets in Combustion Systems", Experiments in Fluids, Vol. 7, pp. 248-258.
9. Hussain F and Hussain H S, 1991, "Elliptic Jets. Part-I: Characteristics of Unexcited and Excited Jets", Journal of Fluid Mechanics, Vol. 233, pp. 439-482.
10. Powell A, 1953, "On the Mechanism of Choked Jet Noise",Vol. 66, pp. 1039-1056.