Studies on high speed jets from nozzles with internal grooves

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ABSTRACT

Experiments were carried out on jets issuing from circular nozzles with grooved exits and the results compared with those of the plain nozzle. The plain nozzle had an exit diameter of 10mm. Because of the introduction of semi-circular grooves at the exit, the effective or equivalent diameter of the grooved nozzles was 10·44mm. The groove lengths were varied as 3, 5 and 8mm. The nozzles were operated at fully expanded sonic and underexpanded exit conditions. The corresponding fully expanded Mach numbers were 1·0 and 1·41. The shock cell structure of the underexpanded jets from grooved nozzles appeared to be weaker than that of the plain nozzle, as indicated by lesser amplitudes of the cyclic variation of the Pitot pressure. The iso-Mach contours indicate that the jet spread along the grooved plane is significantly higher than that along the ungrooved plane. Off-centre peaks were observed in the mean pressure profile of underexpanded jets from grooved nozzles. They were probably due to the streamwise vortices shed from the grooves.

NOMENCLATURE

D	nozzle exit diameter
D_e	equivalent diameter
M_j	fully expanded exit Mach number (sonic and underexpanded jets)
P_a	ambient pressure
P_c	pitot pressure along jet centreline
P_t	pitot pressure in the jet flow field
P_0	stagnation pressure in the settling chamber
X	co-ordinate perpendicular to nozzle exit plane (streamwise direction)
Y	axis normal to the grooved plane (normal direction)
Z	axis along the grooved plane (transverse direction)

1.0 INTRODUCTION

It has been well established that the growth rate and turbulence levels in high speed mixing layers are significantly reduced as the compressibility level is increased[1]. The problem becomes all the more complicated when the nozzles are operated under off-design conditions, i.e. when the static pressure at the nozzle exit is different from the ambient pressure. It is well known that an underexpanded jet leads to expansion waves at the exit of the nozzle which extend to the free pressure jet boundary and reflect as weak compression waves. These compression waves coalesce to form the intercepting shock in the interior of the jet and thus, the core of the underexpanded jet is dominated by periodic shock cell structures. The presence of these shock cell structures results in additional noise. The shock-associated noise is clearly divided into two categories, a narrow band tone referred to as jet screech and a broad band tone referred to as broad band shock-associated noise. The screech tone has been found to have a profound effect on the initial shear layer development leading to drastic changes in jet spread rate with varying underexpansion levels. The complexities in the shock-shear layer interaction make theoretical studies of underexpanded jet flow fields very difficult. Hence, for proper understanding of such flow fields experimental studies have become indispensable. Notches and cut-outs have been found to enhance mixing in the case of non-circular slot jets[2,3]. But in many practical situations well contoured nozzles may be appropriate and fabrication of such nozzles with non-circular exit geometry poses manufacturing difficulties. Circular nozzles with notches and slots may be expected to combine advantages of easier fabrication and enhanced mixing. Studies made earlier on notched circular nozzle jets were based on the modification of the boundary layer growing along the nozzle inner walls achieved through notches and slots. Similar studies have been conducted earlier by many researchers[4-9]. The notched nozzles used for their studies were made by completely removing the material from the wall of the nozzle at specific locations (in the form of V-shaped notches[4], or in the form of fingers[6] as shown in Fig. 1). These notches may be effective in increasing the spread and reducing the noise of the jet, but they may also lead to considerable total pressure loss. Hence, a modified form of notch was thought of, which might prove effective while keeping the pressure loss at a minimum unlike passive control in the form of tabs[10]. The notches in the present study were made by partial removal of material, in the form of grooves as shown in the figure. This may be

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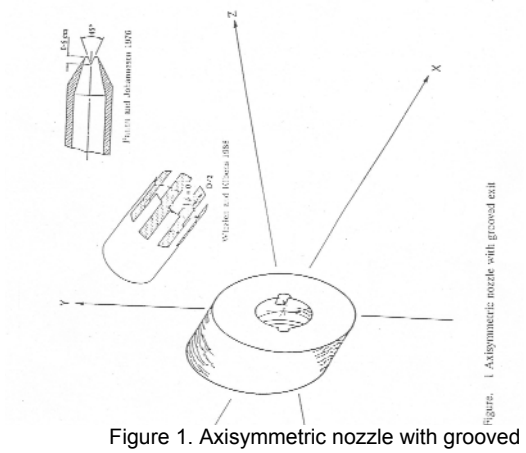


Figure 1. Axisymmetric nozzle with grooved exit.

expected to prevent the lateral dissipation of the pressure energy through the notches, thereby minimising the loss of pressure. These nozzles are better described as nozzles with internally grooved exit.

2.0 EXPERIMENTAL SETUP AND PROCEDURE

A schematic diagram of the experimental rig is shown in Fig. 2. The test models were axisymmetric plain and notched nozzles. Single axisymmetric nozzles of 10mm exit diameter (D) were made out of brass. The single nozzle models primarily consisted of a common base nozzle brazed on to a circular plate of mild steel (dimensions and details given in Fig. 3). The parallel portion or the end attachment of the base nozzle was made as a separate part which could be threaded on to the base nozzle. Two half circular notches (at 180 degrees to each other as shown in the figure) were cut at the exit of the parallel portion which extended up to a certain distance along its length. In other words, these notches were in the form of grooves cut along the inner surface of the end attachment. Three such end attachments were made with different groove lengths. The lengths of the grooves or notches studied were 3, 5 and 8mm. Due to the presence of grooves the exit area of the nozzles increased by 9% and the equivalent diameter (D_e) of the grooved or notched nozzles was found to be 10·44mm.

As these models were made in two parts, great care was taken to ensure concentricity of the two parts, *viz*, the base nozzle and the end attachments. Care was also taken to see that the inner surfaces of the

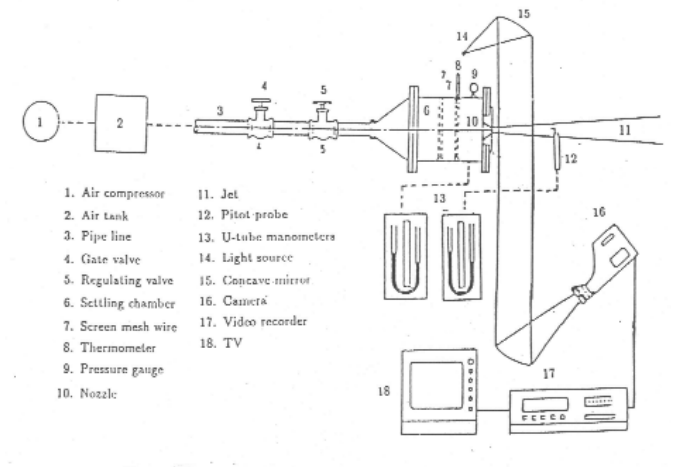


Figure 2. Schematic diagram of the jet flow test facility.

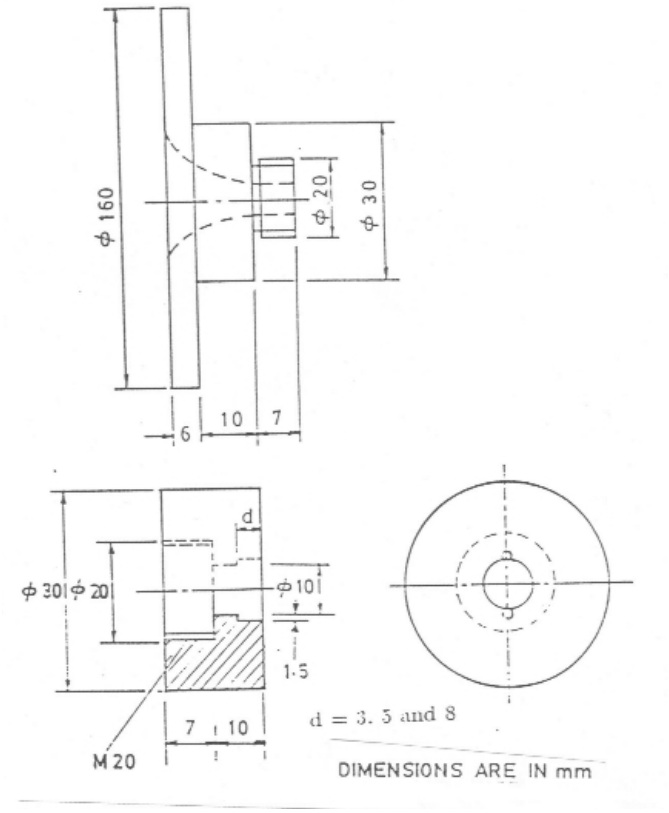


Figure 3. Details of circular nozzle with grooves and tabs.

two parts merged smoothly. This was achieved by polishing the inner surfaces with brasso until a smooth finish was realized. All the end attachments had a lip thickness of 10mm. The lip thickness had to be maintained the same for all the models because studies by Ponton and Seiner[11] and Norum[5] have shown that the lip thickness has a marked effect on the feed back loop of, particularly, the imperfectly expanded jets.

The stagnation pressure in the settling chamber was measured by a long column U-tube mercury manometer (to start with and then changed over to PSI pressure transducers). The temperature in the settling chamber was measured by a sensitive thermometer.

In sonic and underexpanded jets, due to the fluctuating nature of the flow field and also due to the fact that the core region of the underexpanded jets is shock-dominated (where a five-hole or a three-hole probe cannot be used), only a single hole Pitot probe designed in accordance with the recommendations of Nagai[12] was used. Rice and Raman[13] have noted in their report that, as the flow exiting from their rectangular nozzle was supersonic, it presented considerable measurement problems in using hot wire or hot film anemometry. They avoided these difficulties by just measuring the total pressure ($P_{t_{gauge}}$) referenced to the room pressure (P_a) using a simple total pressure tube. They presented the data derived from this raw total pressure, which would be the total pressure downstream of the bow-shock, ahead of the total pressure tube in supersonic flow. The Mach numbers were obtained from the measured pitot (gauge) pressures using the following relation:

$$M = \sqrt{5\left[\left(\frac{P_a}{P_t}\right)^{-0.2857} - 1\right]} \qquad \ldots (1)$$

For the sake of convenience, the grooved nozzles are referred to as N 1, N 2, N 3 Nozzles which correspond to a groove length of 3, 5, and 8mm, respectively.

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The grooved nozzles were operated under two exit conditions:

- Fully expanded, with sonic exit velocity
- Underexpanded, corresponding to a fully expanded Mach number of 1·41.

This particular underexpansion level was chosen in order to compare the results with that of Pannu and Johannesen[4].

The Reynolds number based on the equivalent diameter D_e was varied from $2{\cdot}17 \times 10^5$ to $3{\cdot}06 \times 10^5$ for plain and grooved nozzle jets. While operating the grooved nozzles, it was observed that the N 3 nozzle showed maximum total pressure loss of around 4·3%. For the N 1 nozzle it was around 2%, and for the N 2 nozzle it was around 3·1%.

2.1 Data accuracy

The room temperature was almost constant with a maximum variation of ±0·5° during one experimental run. The stagnation pressure was maintained with an accuracy of ±0·1%. The uncertainty in the measurement of Pitot pressure was estimated to be ±1·8% and that of probe position was ±1·2%. The nozzle dimensions were accurate within ±1·5%. The two nozzles in a block were identical within the maximum variation of ±0·6%. All the measurements were found to be repeatable within ±3%. The maximum uncertainty involved in the calculation of local Mach number M was estimated to be ±3·5 %.

3.0 RESULTS AND DISCUSSION

The results are presented after normalizing the spatial coordinates *X, Y, Z* with the equivalent diameter D_e. For the grooved nozzle results, the Pitot pressure data have been nondimensionalised with the ambient pressure P_a so as to compare with the results of Pannu and Johannesen[4].

3.1 Pressure profiles

The variation of Pitot pressure along the grooved (*XZ*) and the ungrooved (*XY*) plane at various axial locations are presented in Figs 4(a-f) for all the grooved nozzles, for sonic exit velocity. It can be easily seen from the figures that the grooved nozzle causes the jet to spread asymmetrically, being wider in the grooved plane as expected. Similar profiles for N 1 and N 2 Nozzles are plotted in Figs 4(g-j) for underexpanded jets. The 'dips' close to the centerline at axial locations less than $4D_e$ are due to the shock cells in the jet core. One may notice, at axial locations $X/D_e = 2$ and 3, a sudden increase in pressure almost near the jet boundary, then decreasing to approach the value of ambient pressure. This is observed only in the grooved plane suggesting that this phenomenon is related to the grooves. As these peaks are noticed very close to the outer edge of the jet where the flow is clearly subsonic, a possible explanation may be found from earlier studies on subsonic jets. Hussain and Husain[14] observed off-centre peaks or humps in the velocity profiles of the elliptic jet (*AR* = 4:1) studied by them. They noted that these peaks were caused by two vortex cores produced by the bifurcation of the initially elliptic vortex structures. They surmised that the peaks were due to the velocities induced by these vortex cores superimposed on the basic velocity distribution. Quinn and Militzer[15] also observed off-centre peaks in the mean velocity profile of the square jet they studied and attributed that to the presence of vortex structures close to the nozzle exit. The pressure profiles shown in the report of Pannu and Johannesen[4] are also characterised by similar (not so well marked) humps. In the case of grooved nozzles of the present study also, the peaks are, possibly, due to the streamwise vortices shed from the grooves. Comparing the profiles at $X/D_e = 2$ and 3, one may notice that the peaks are shifted away from the centerline, which

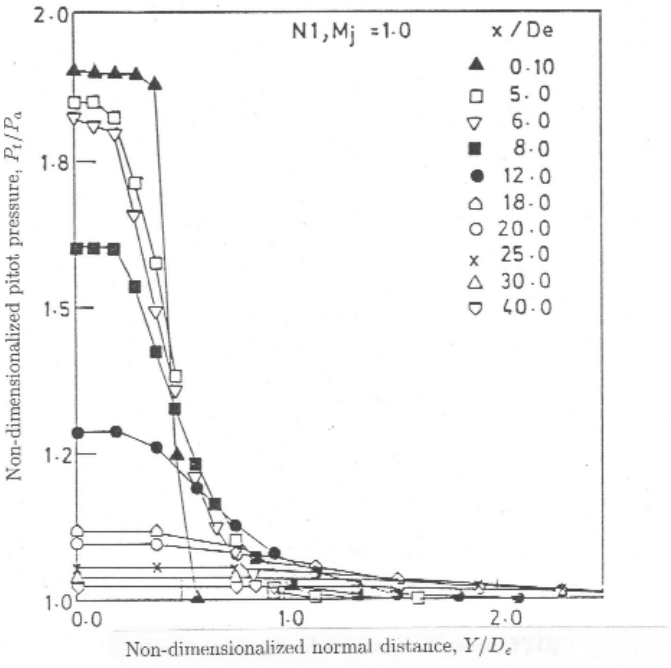


Figure 4(a). Pressure profile (N 1 nozzle, M_j = 1·0, ungrooved plane).

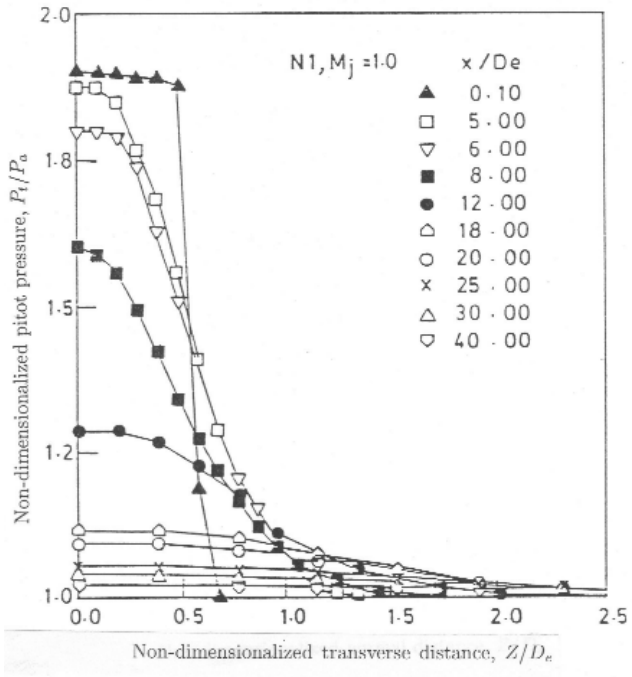


Figure 4(b). Pressure profile (N 1 nozzle, M_j = 1·0, grooved plane).

suggests that the vortices move away from the nozzle axis as they propagate downstream. The absence of peaks at an axial location beyond[4] indicates that the vortices have got dissipated beyond that. It is surprising that similar peaks are not present in the case of sonic jets. It is possible that when sonic exit conditions (full expansion) prevail, the vortices are not strong enough to leave their mark on the mean pressure profile. But a deeper study is needed to give a proper explanation for this phenomenon.

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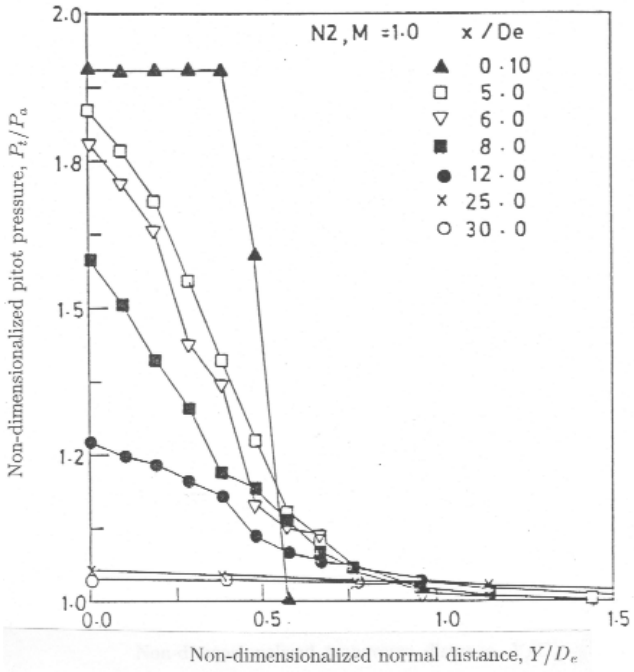


Figure 4(c). Pressure profile (N 2 nozzle, M_j = 1·0, ungrooved plane).

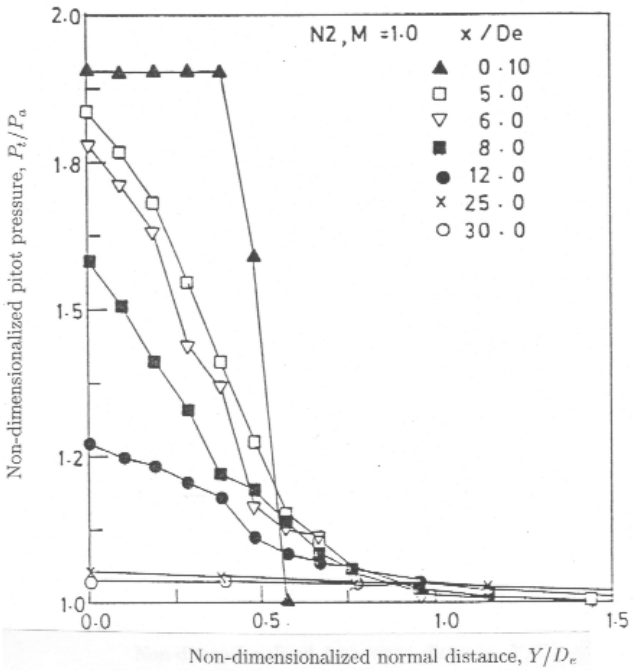


Figure 4(e). Pressure profile (N 2 nozzle, M_j = 1·0, grooved plane).

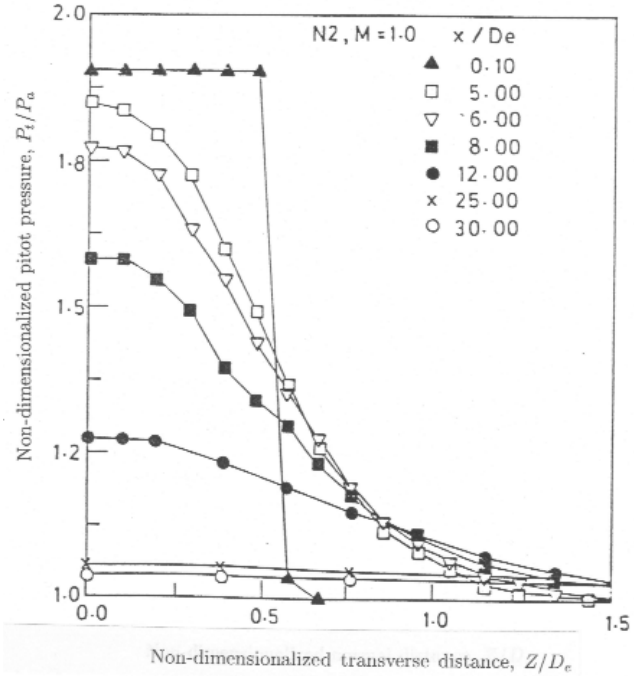


Figure 4(d). Pressure profile (N 2 nozzle, M_j = 1·0, grooved plane).

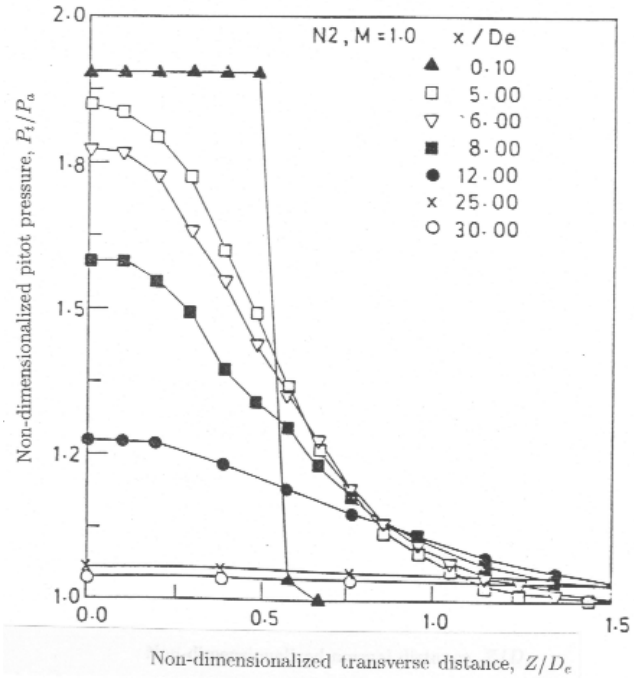


Figure 4(f). Pressure profile (N 2 nozzle, M_j = 1·0, grooved plane).

3.2 Mean jet flow field

The jet mean flow fields, as represented by the constant Mach fraction contours, for the plain and grooved nozzles are shown in Figs 5(a-e). In the figures, the outermost contour line represents the fraction M/M_j = 0·01 where M is the local Mach number. In other words, it is the locus of points at various axial locations (X/D_e), where the local Mach number is 1% of the fully expanded Mach number M_j. As mentioned already, M_j is calculated assuming that the jet expands to ambient pressure. The local Mach number M is calculated assuming the local static pressure to be equal to ambient pressure. It is noted here that only the overall properties of the jet flow fields should be inferred from the Mach fraction contours shown in these figures. But these figures help us to visualise the jet flow field. The values of the fraction M/M_j for other contour lines are given in Fig. 5(a) which is applicable to other figures also. It can be clearly seen that the grooved nozzle jets have a higher spread along the grooved plane compared to the ungrooved plane. In the case of underexpanded jets (M_j = 1·41, N 2 nozzle) as seen from the Figs 5(a), (b), the transverse pressure relief is pronounced in the grooved plane. The spread in the

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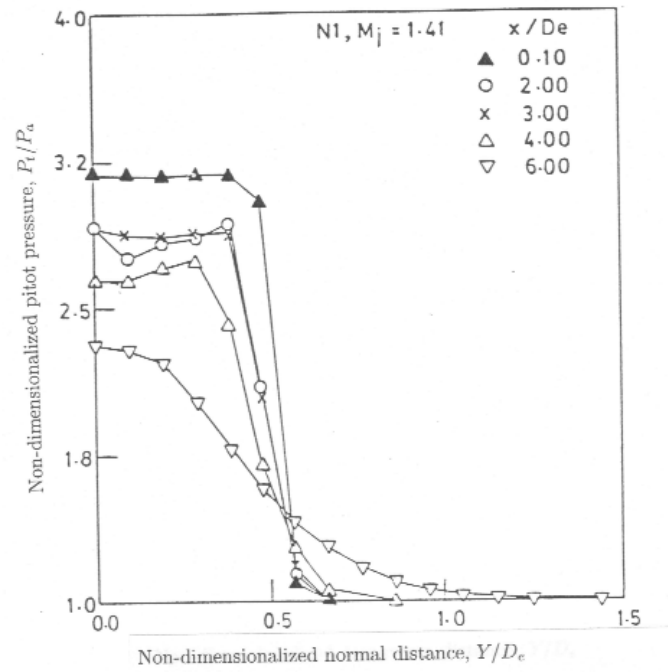


Figure 4(g). Pressure profile (N 2 nozzle, M_j = 1·41, ungrooved plane).

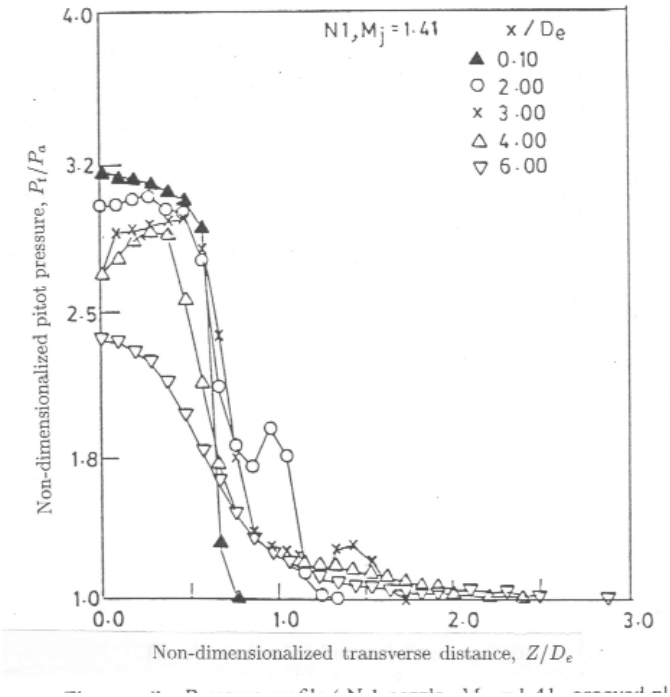


Figure 4(h). Pressure profile (N 2 nozzle, M_j = 1·41, grooved plane).

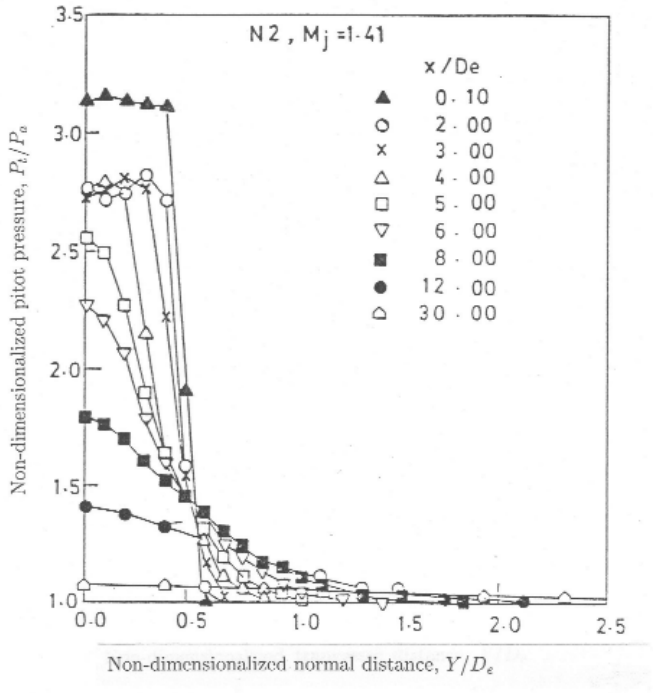


Figure 4(i). Pressure profile (N 2 nozzle, M_j = 1·41, ungrooved plane).

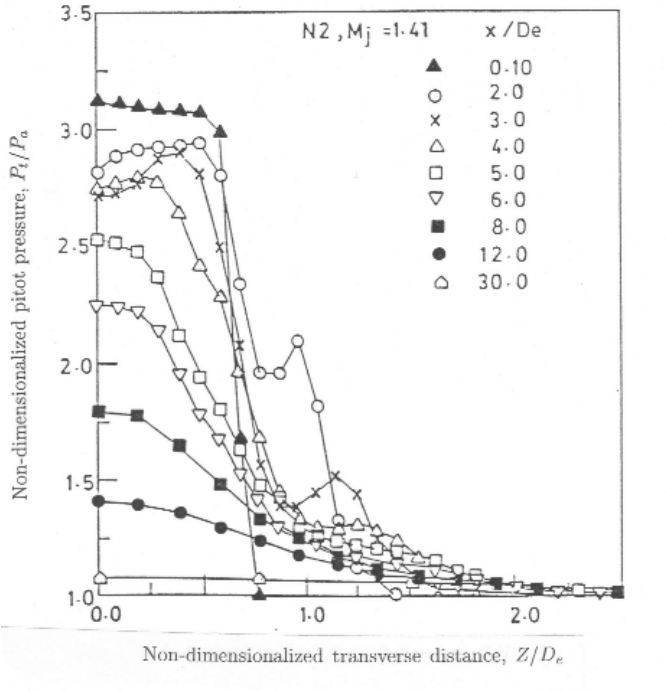


Figure 4(j). Pressure profile (N 2 nozzle, M_j = 1·41, grooved plane).

ungrooved plane is not much different from that of the plain nozzle jet (Fig. 5).

3.3 Shock structure

In order to have a close look at the near field shock cell structure, a typical variation of the centerline Pitot pressure P_c along the centre-line of the jet, up to an axial distance of eight equivalent diameters only, is shown in Figs 6(a-d), for the grooved nozzles. The results of Pannu and Johannesen[4] are given for comparison. Four shock cells are clearly identified by the cyclic behavior of the Pitot pressure for X/D_e less than 4, and beyond $4D_e$ one can observe faster diffusion of shock cells, in the case of grooved nozzles of the present study. Compared to this, one can observe greater number of shock cells in the jet core of the notched nozzle studied by Pannu and Johannesen[4]. Another interesting point is that, in the case of all grooved nozzles in the present study, there is a considerable decrease in the

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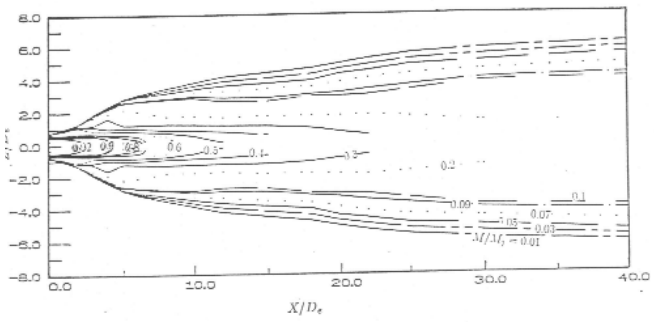


Figure 5(a). Constant Mach fraction contours (N 2 nozzle, M_j = 1·41, grooved plane).

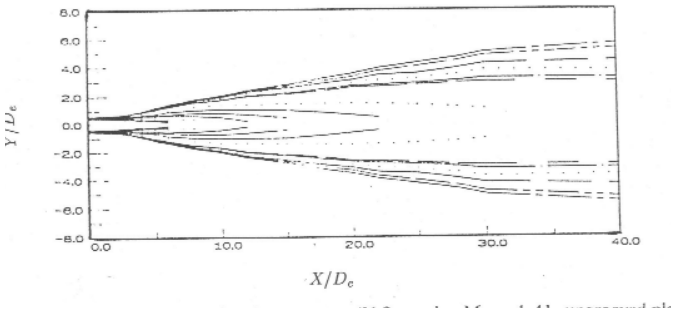


Figure 5(b). Constant Mach fraction contours (N 2 nozzle, M_j = 1·41, ungrooved plane).

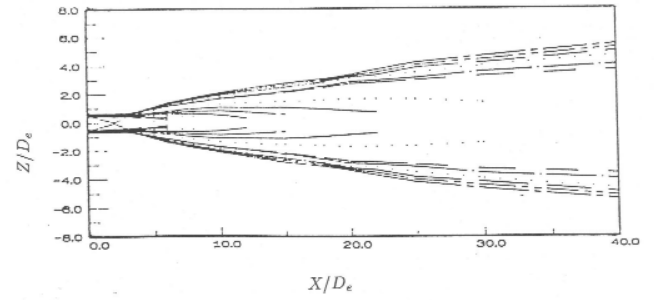


Figure 5(c). Constant Mach fraction contours (plain nozzle, M_j = 1·41).

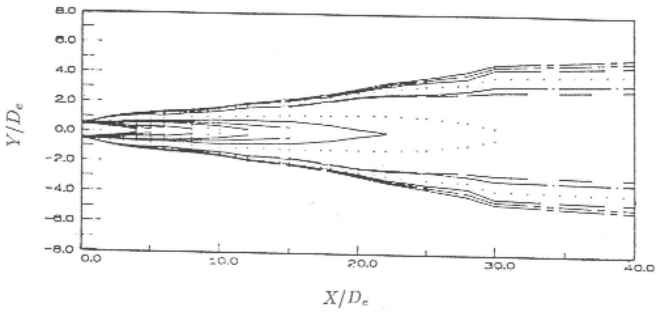


Figure 5(d). Constant Mach fraction contours (N 3 nozzle, M_j = 1·0, ungrooved plane).

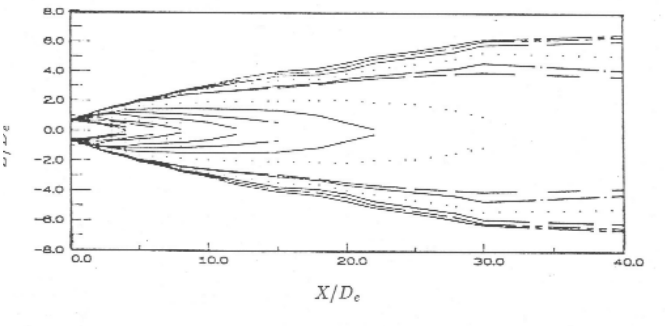


Figure 5(e). Constant Mach fraction contours (N 3 nozzle, M_j = 1·0, grooved plane).

length of the first shock cell when compared with that of Pannu and Johannesen[4]. Moreover, the first shock appears to be much stronger as indicated by the greater 'dip' in the Pitot pressure. This feature is common for all the grooved nozzles of the present study. This may be due to the relief experienced by the flow owing to the presence of the grooves. This relief effect appears to depend on the groove length. The relief due to the grooves were found to modify the shocks strength and the shock cell length in the core. Also, from the second shock cell onwards, one can notice a weakened shock structure, marked by lesser amplitudes of oscillation of Pitot pressure when compared with the plot of Pannu and Johannesen[4]. Raman[16] observed that the third and fourth shock cells determined the screech amplitude and the unsteadiness of screech of the rectangular jet he studied. Extending this to circular nozzles also, one may view shocks three and four as having special significance with regard to screech suppression. It is easily seen from the figures, that the strengths of the third and fourth shock cells are very much reduced which can prove beneficial from the point of view of minimising screech tone amplitudes. Another significant observation is that all the grooved nozzles of present study have a shorter core length, around $5D_e$, whereas, that of Pannu and Johannesen[4] is around 6·5 diameters. Thus, the grooved nozzles under study appear to have better near field mixing characteristics than that of Pannu and Johannesen[4].

Figure 6(e) shows the shock structure of N 1 Nozzle compared with that of the plain nozzle of the present study. One may observe four clear shock cells in the core region of the plain nozzle also, but it may be noticed that the shock cell length is a little higher than that of the N 1 Nozzle. The cyclic variation of the Pitot pressure shows much higher amplitude than that of the N 1 Nozzle, indicating that the shock structure of the plain nozzle is stronger than that of the latter. Particularly, the third and fourth shock cells are marked by higher 'dips' than the corresponding cells of N 1 Nozzle. Thus, it may be expected that the acoustic characteristics of the plain nozzle might be substantially modified by the introduction of grooves. Further, it is seen that for the plain nozzle the pitot pressure remains constant for about first half-diameter downstream of nozzle exit, in similar fashion to the results from Ref. 4. Whereas, for the grooved nozzle the total pressure falls off immediately. This is because, for the plain nozzle the flow at the nozzle exit is not influenced by the vortices formed at the jet periphery, since the vortices are of uniform size owing to uniform radius of curvature of the nozzle exit plane and they move some distance before interacting with the core fluid. In deed they protect the core near the nozzle exit. But for the grooved nozzle the grooves make a sudden change in the radius of curvature of the nozzle exit and hence vortices of different sizes are generated at the nozzle exit. Also, the grooves themselves generate vortices. These vortices interact, introducing rapid mixing right from the exit. Also, the grooves offer a relief to the exiting fluid. Due this relief the vortices where pushed away from the centerline. Because of this the supersonic flow experiences an acceleration. Owing to this the pitot pressure falls continuously up to the Mach disc.

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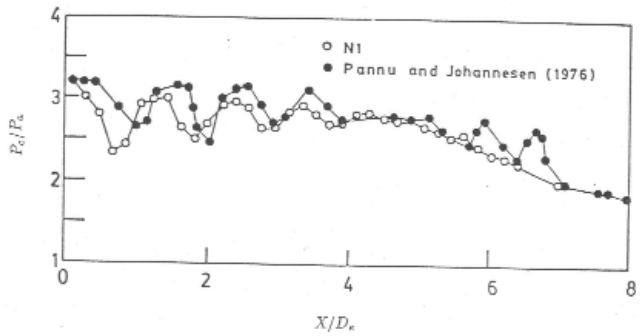


Figure 6(a). Jet core shock structure of N 1 nozzle (M_j = 1·41).

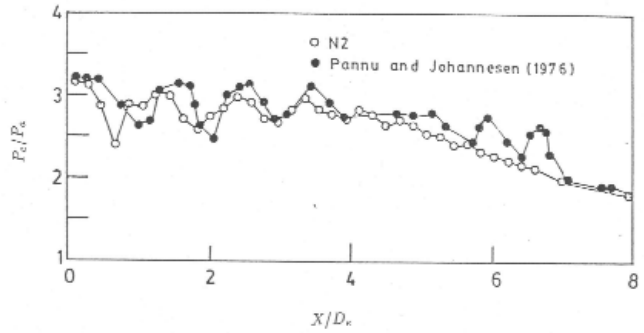


Figure 6(b). Jet core shock structure of N 2 nozzle (M_j = 1·41).

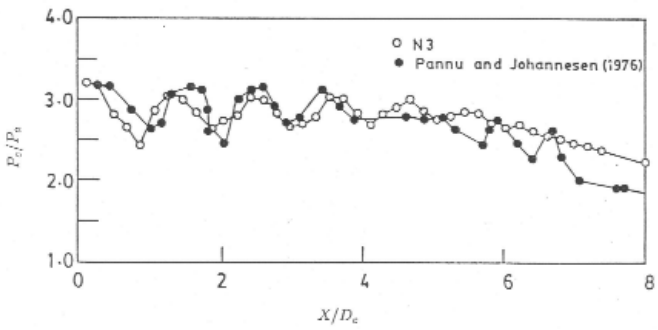


Figure 6(c). Jet core shock structure of N 3 nozzle (M_j = 1·41).

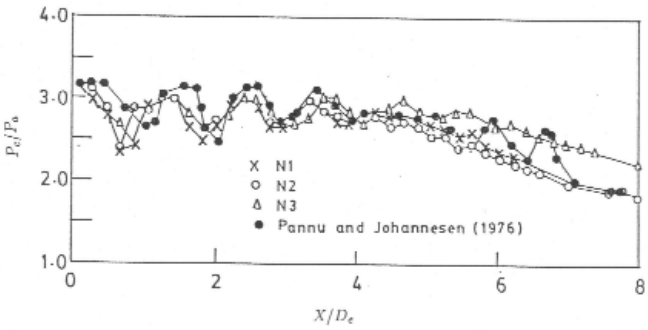


Figure 6(d). Jet core shock structure of all grooved nozzles (M_j = 1·41).

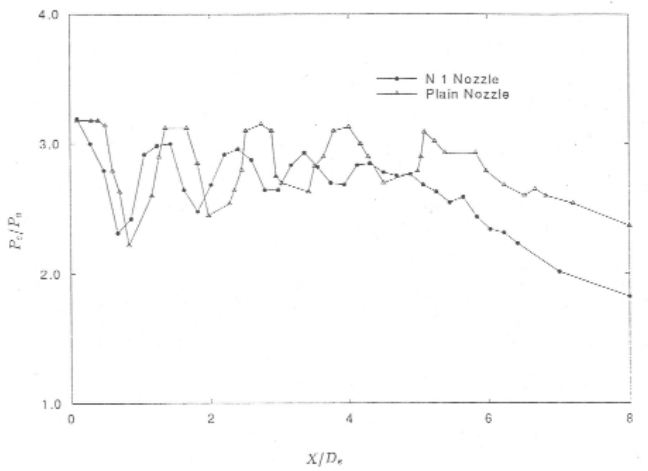


Figure 6(e). Comparsion of core structure of plain and N 1 nozzle.

3.3.1 *Flow visualisation of the shock structure*

The shock cell structure of the underexpanded jets as visualised from the schlieren pictures is shown in Figs 7(a-d). The views of the N 2 nozzle jet core structure at M_j = 1·41, along the grooved and ungrooved planes, are shown. The shock cell structure of the plain nozzle jet and that of the N 3 nozzle jet along the grooved plane at the same exit Mach number are also included for comparison. The effect of the grooves on the shock structure is clearly seen from the pictures. Introduction of grooves results in drastic changes in the cell structure. A modified expansion and compression wave pattern is very much evident from a comparison of the pictures of grooved and plain nozzle jets. This, perhaps leads to weakening of the cell structure in the case of grooved nozzles. Comparing the views of core of N 2 and N 3 nozzles along the grooved plane, the effect of groove length on the cell structure may be noticed.

4.0 CONCLUSIONS

The mean flow field and shock cell structure in the core of jets from nozzles with internally grooved exits have been investigated experimentally. The performances of the grooved nozzles of the present study are compared with that of the notched nozzle studied by Pannu and Johannesen[4].

1. The constant Mach contour plots indicate that the jet spread along the grooved plane is larger than that along the ungrooved plane. The propagation of the jet along the ungrooved plane is comparable to that of a plain nozzle jet.
2. The shock cell structures of the underexpanded jets from the grooved nozzles appear to be weaker than that of the plain nozzle, as indicated by lesser amplitudes of the cyclic variation of the Pitot pressure.
3. Comparison with the core structure of the underexpanded jet from the notched nozzle studied by Pannu and Johannesen shows that all the grooved nozzles exhibit, relatively, shorter core length and more rapid decay in the near field.
4. The comparatively faster diffusion of the cellular wave structure beyond the second cell, observed in the core of grooved nozzle jets, has potential application to the suppression of jet screech.
5. The off-centre peaks seen in the mean pressure profile of underexpanded jets are, probably, due to the streamwise vortices shed from the grooves. The absence of such peaks in the case of sonic jets calls for a deeper study, since the off-centre peaks could lead to increased broad-band jet mixing noise. The authors propose to carry out noise measurement on the present nozzles to answer this.

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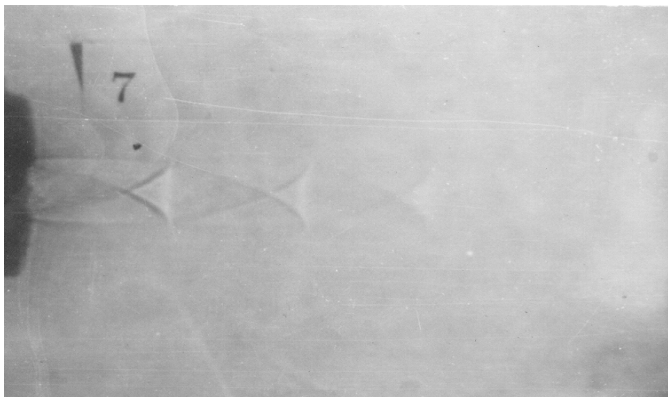


Figure 7(a). Plain nozzle, M_j = 1·41.

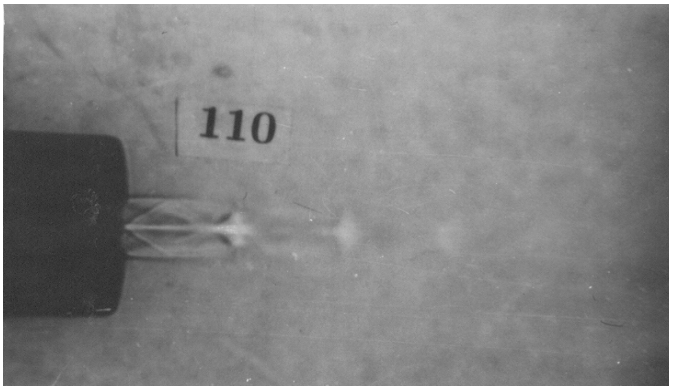


Figure 7(b). N 2 nozzle, M_j = 1·41, ungrooved plane.

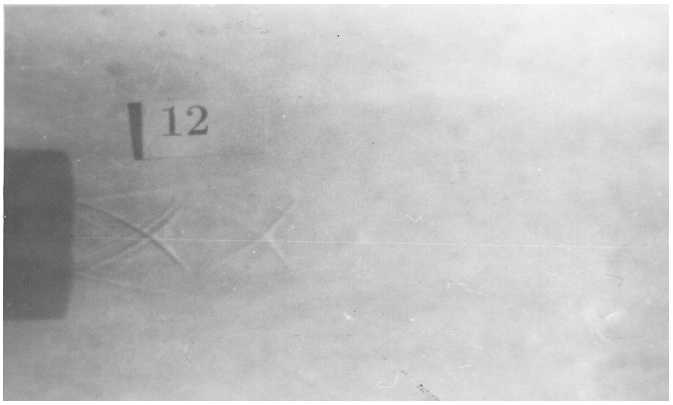


Figure 7(c). N 2 nozzle, M_j = 1·41, grooved plane.

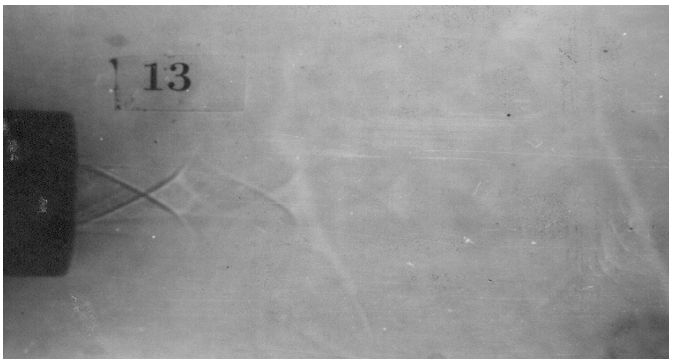


Figure 7(d). N 3 nozzle, M_j = 1·41, grooved plane.

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