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Supersonic Jets From Bevelled Rectangular Nozzles

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ABSTRACT

The influence of nozzle exit geometry on jet mixing and noise production was studied experimentally for a series of rectangular nozzles operating at supersonic jet velocities. Both converging (C) and converging-diverging (C-D) nozzles were built with asymmetrical (single bevel) and symmetrical (double bevel) exit chamfers and with conventional straight exits for comparison. About a four decibel reduction of peak mixing noise was observed for the double bevelled C-D nozzle operated at design pressure ratio. All bevelled geometries provided screech noise reduction for under-expanded jets and an upstream mixing noise directivity shift which would be beneficial for improved acoustic treatment performance of a shrouded system.

INTRODUCTION

The objective of this research is to study ways in which the noise of a supersonic rectangular jet can be significantly reduced using excitation or other shear flow control means which could find practical application in a single or multiple jet mixer or ejector device. It is intended that this shear flow control device be a natural source which feeds upon the steady flow for its energy rather than requiring an external power source of any kind. The emphasis of this work was to investigate geometries which would be used internal to a shroud and this has led to the concentration on near-field hydrodynamic and acoustic fields. Two approaches to improving the performance of such devices seem obvious. The first is to increase the mixing rate of the jets to move the jet noise source back toward the nozzle lip and thus provide a longer propagation length for an acoustic lining to reduce the internal mixing noise. The second is to cause the directivity of the internally generated mixing noise to be more normal to the acoustic treatment surface which would make the suppressor much more effective. An attempt to accomplish these objectives led to the single and double-bevelled nozzle tests which are reported here. The oblique nozzle exits were intended to produce oblique modes on the supersonic rectangular jet surfaces for which there is some evidence that instability growth rate may be increased. Also the oblique traveling hydrodynamic waves were suspected to produce acoustic waves travelling at a greater angle to the jet axis. The results of these innovations with the rectangular supersonic jet showed one geometry with significantly improved jet mixing and all of the oblique geometry jets showed potential for significant mixing noise reductions especially if used with properly designed and located acoustic treatment in an internal mixer-ejector system. A high frequency noise component was increased in intensity by up to ten decibels but this noise was directed normal to the jet and could thus be easily intercepted by properly designed acoustic treatment.

Seiner and Krejsa (1989) have discussed the status of supersonic jet noise reduction relative to the supersonic transport. A large reduction in jet noise will be necessary for such an aircraft to meet anticipated noise goals. The work reported in this paper is intended to explore the two approaches mentioned above to help provide an efficient method to achieve some of this required noise reduction. Tam (1991) and Lilley (1991) have provided excellent recent reviews of the fundamentals of jet noise production. The idea that the jet noise is intimately involved with the large coherent structures produced in the jet mixing process is particularly relevant here. This paper reports research based upon the manipulation of these structures to try to increase jet mixing and effect a jet noise reduction.

Seiner et al. (1986) and Ponton et al. (1986) have extensively measured the noise produced by supersonic

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rectangular jets. Norum (1983) tested asymmetric nozzles to reduce screech tones by altering the feedback path between the shocks and the nozzle lip. Wlezien and Kibens (1986) have conducted experiments on the noise generated by supersonic jets formed by round nozzles with unsymmetrical exits. For these round supersonic jets only a modest noise reduction was claimed for a single geometry, the "four tab" configuration. Only flow visualization data was presented from which mixing enhancement was inferred. In this paper, aerodynamic data will be presented to illustrate the changes in the jet mixing due the oblique nozzle exits. Also the studies are performed on rectangular geometries which are more suitable for multiple jet ejectors than are round geometries. Some acoustic data will be shown as a supplement to the aerodynamic data, but details of the acoustic measurements are available in a separate paper (Rice and Raman, 1993b).

EXPERIMENT

Air Flow Facility. A schematic drawing of the flow facility used in this experiment is shown in Fig. 1. The facility was previously described in detail by Rice and Raman (1993a,b), and therefore only a brief description is given here. The high pressure air enters at the left into the 76 cm diameter plenum where it is laterally distributed by a perforated plate and a screen. Two concentric acoustically treated splitter rings remove the upstream valve and entrance noise. The flow is further conditioned by two screens before undergoing two area contractions of 3.5 and 135 for the rectangular nozzles used in this experiment. The final nozzle shown in Fig. 1 is not drawn to scale but is greatly enlarged.

Aerodynamic and Acoustic Instrumentation. Since the exiting flow of the nozzles in this experiment is supersonic, this presents considerable measurement problems in using hot wire or hot film anemometry. We have avoided these difficulties by just measuring the total pressure referenced to room pressure using a simple total pressure tube of 0.8 mm outside diameter. We are presenting the data derived from this raw total pressure, often called P_{T2}, which would be the total pressure downstream from the bow-shock which stands ahead of the total pressure tube in supersonic flow. In the subsonic flow regions this data is adequate, but for the supersonic flow regions it is recognized that the data should be used qualitatively for comparison purposes only.

The acoustic data were obtained using a 6.35 mm B&K microphone mounted on a Klinger three-dimensional traversing mechanism. The rectangular nozzles were mounted with the large nozzle dimension in the vertical plane. The emphasis was on acoustic data taken in this plane since this is where the acoustic treatment would be located in a multi-nozzle mixer-ejector, above and below the bank of nozzles. Acoustic data was also taken in the horizontal plane but it will not be reported here. For vertically unsymmetrical nozzles, such as the single bevelled nozzles, the nozzle was rotated 180 degrees and the acoustic data taken again above the nozzle to stay away from the room floor. The room was not anechoic

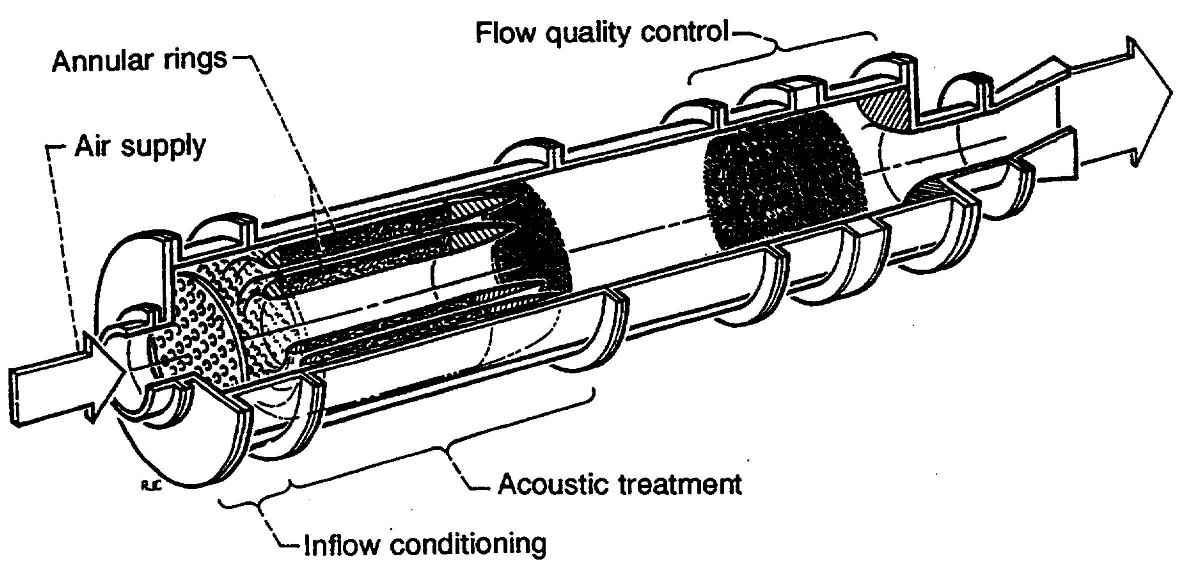

Figure 1. Schematic of supersonic jet flow rig

although it did have extensive ceiling and wall acoustic treatment mainly for the environmental protection of the operators. Surfaces near the nozzle were wrapped with acoustic treatment to reduce reflections. Only near-field acoustic data are of interest here since the emphasis is on shrouded nozzle systems, and thus less than anechoic conditions can be tolerated with the source noise being substantially above the reverberant level in the volume of interest.

The acoustic data were analyzed using a B&K 2532 dual channel instrument. This was used with a frequency span to 25.6 Khz and a bin band width of 32 Hz. The narrow band spectrum was observed to pick out tones but the data presented is one-third octave data calculated from the narrow band data using a standard B&K software package.

Nozzle Geometries Tested. The six nozzle geometries tested in this program are shown in the table below. Note there are three main nozzle types: single-bevelled (3C, 3CD), straight (4C, 6CD), and double-bevelled (9C, 9CD). All bevel cuts were made at thirty (30) degrees from the exit lip. Each type has both a converging version which was operated under-expanded and a converging-diverging version which was run at design pressure ratio. All of the nozzles were made from 50 mm copper pipe. Internal forms were forced into the pipe as the exterior was hammered until the form proceeded to the proper axial location. A separate internal form with a 2.5 degree half angle was used to shape the diverging portion of the C-D nozzles. Nozzles 4C and 6CD had final mill cuts applied to the internal surface at the exit to provide more accurate dimensions. The throat and exit dimensions were accurate and uniform to about 0.1 mm. It should be noticed from the above description of the nozzles that these are not precision polished specimens. It was felt that this level of sophistication was sufficient for the first cut screening reported here and that any phenomenon requiring extreme accuracy and polished surfaces could not be maintained in practice in an actual engine.

RESULTS

The results of the experiments will now be presented. The aerodynamic data showing the overall flow field of the six nozzles and the jet mixing data will be discussed first. This will be followed by a brief presentation of some sample acoustic data to show the general effect of the oblique nozzle exit cutbacks on the acoustic performance. As mentioned earlier, the detailed presentation of the acoustic data for these jets were presented by Rice and Raman (1993b).

Jet Flow fields. The flow fields, as represented by the constant Mach number contours, for the two reference nozzles are shown in Figs. 2 and 3. Nozzle 4C is a converging nozzle (design Mach number $M_D = 1$) which is operated under-expanded at the pressure ratio to provide a fully expanded Mach number, $M_{exp} = 1.40$. The Mach number was calculated assuming the jet expands to ambient pressure. The jet exhibits an over-expansion and then a contraction in the plane of the large nozzle dimension. This jet expands very rapidly in the other dimension, as shown by Rice and Raman (1993a), due to a high amplitude screech tone and the related flapping instability mode. Nozzle 6CD, Fig. 3, is a converging-diverging rectangular nozzle with M_D = 1.398 as determined by the minimum screech condition. This jet flow gently flares out in the large nozzle dimension in

TABLE 1. NOZZLE CONFIGURATIONS TESTED

NOZZLE	CONFIGURATION	L, mm	H_{exit},mm	H_{thrt},mm	ASPECT RATIO
3C	Single-Bevel, Converg.	66.0	13.5	13.5	4.893
3CD	Single-Bevel, C-D	68.0	13.5	11.7	5.051
4C	Straight Exit, Converg.	65.8	13.2	13.2	4.969
6CD	Straight Exit, C-D	68.1	14.1	12.5	4.817
9C	Double-Bevel, Converg.	64.8	13.7	13.7	4.728
9CD	Double-Bevel, C-D	69.3	13.3	11.7	5.200

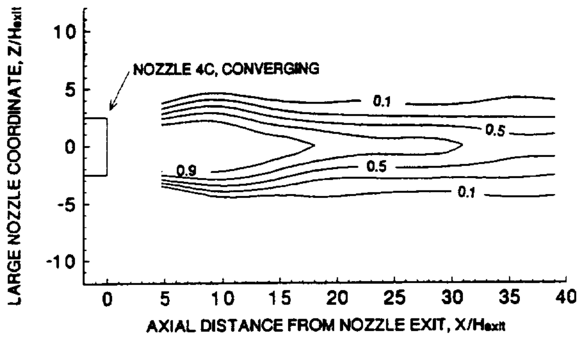

Figure 2. Mach number contours for nozzle 4C, M_{exp} = 1.40

contrast to the flow of nozzle 4C. Detailed jet mixing results for nozzle 6CD were also provided by Rice and Raman (1993a). It is noted here that only the overall properties of the jet flow fields should be inferred from

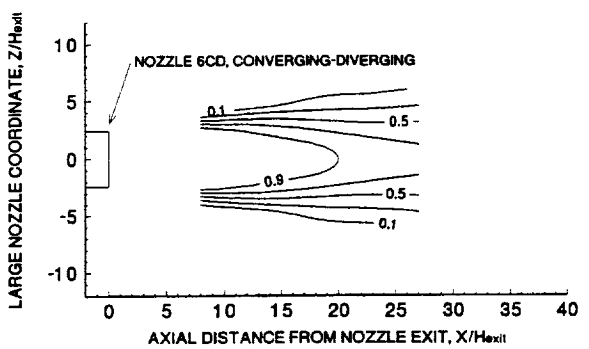

Figure 3. Mach number contours for nozzle 6CD, M_{exp} = 1.398

the Mach number contours shown in Figs. 2 to 7. There is some damping present in the spline fits of the contour plotting routine and some of the detail is washed out to provide reasonably smooth curves. Also, a fairly coarse grid is used in the Z direction (typically 11 points) and in the X direction (5 to 8 points). Also in the Y direction (traverse across nozzle small dimension) 11 to 18 points are used, but this is not relevant to these figures and is involved only in the mass flow data presented later.

The deflected flow fields for the two single bevelled nozzles, 3C and 3CD are shown in Figs. 4 and 5. Nozzle 3C is a converging nozzle operating with an under-expanded jet. Due to transverse pressure relief, the jet is deflected just like the round jets tested by Wlezien and Kibens (1986). In an attempt to minimize this jet deflection the converging-diverging single bevelled nozzle number 3CD was built. It would seem that with supersonic flow at the nozzle exit, the pressure relief could not be transmitted upstream. Although the idea will be seen to work for the double-bevelled nozzle, it did not work here. In fact the high speed core flow seems to be deflected more for the C-D nozzle than for the converging nozzle. Perhaps nozzle 3CD was running separated beyond the throat. Some evidence for this exists since the screech tone was higher than anticipated and did not have an obvious minimum at any Mach number.

The very unusual jet flow field for nozzle 9C, the double bevelled converging nozzle, is shown in Fig. 6. The transverse pressure relief is felt in both directions and the jet appears to diverge into two high velocity streams. The transverse deflection of this jet appears to be larger than those of the single bevelled nozzles 3C and 3CD. It will be shown later that this nozzle geometry provides significant jet mixing increase for both supersonic and subsonic jets. When the double bevelled nozzle was constructed as a converging-diverging nozzle, the elimination of the effects of transverse pressure relief as mentioned relative to nozzle 3CD seemed to work quite well. The flow field for the double bevelled, convergent-divergent rectangular nozzle 9CD is seen in Fig. 7. The transverse extent of the Mach contours are seen to be very similar to those of the C-D baseline nozzle 6CD seen in

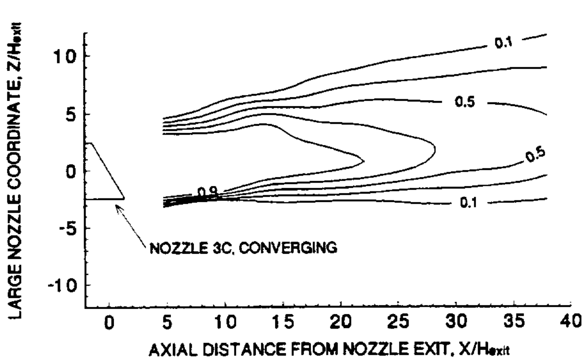

Figure 4. Mach number contours for nozzle 3C, M_{exp} = 1.40

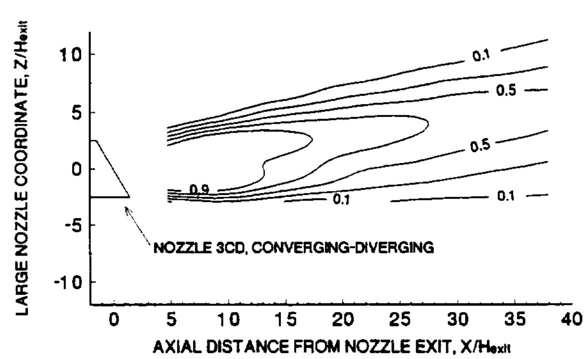

Figure 5. Mach number contours for nozzle 3CD, M_{exp} = 1.40

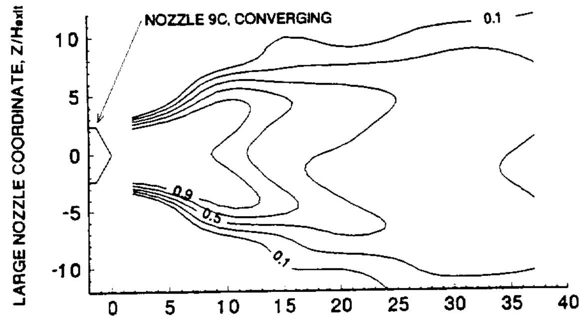

Figure 6. Mach number contours for nozzle 9C, Mexp = 1.40

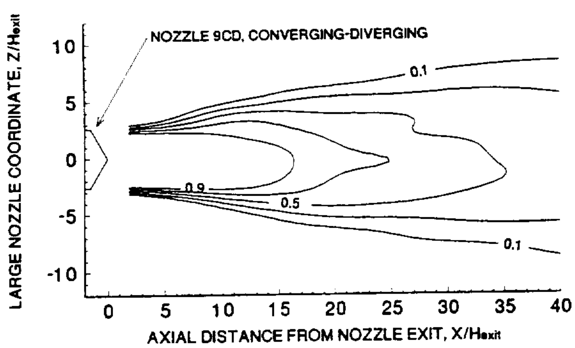

Figure 7. Mach number contours for nozzle 9CD, Mexp = 1.423

Fig. 3. The flow field for nozzle 9CD is seen to be not quite symmetric which may be due to the inaccuracies in the construction technique.

Jet Mixing - Mass Flow Measurements. Mass flow data were calculated from total pressure data assuming isentropic flow without shocks. The static pressure was assumed to be the room static pressure. These assumptions are not valid near the nozzle for the supersonic flows encountered here since the static pressure is below ambient due to flow entrainment, and the total pressure tube has a bow shock which produces a total pressure loss. However, as measurements proceed downstream the Mach number drops and the static pressure approaches room static and the calculated mass flow becomes more accurate. For each cross section (5 to 8) of the jet, at least 121 measurement points were recorded over the area occupied by the jet flow.

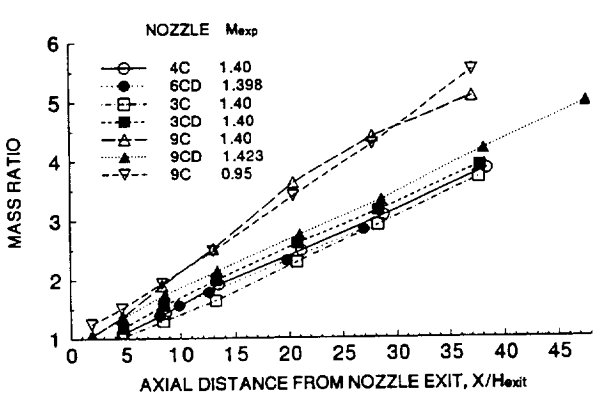

Figure 8. Ratio of measured mass flow to nozzle flow

The calculated mass flows for all of the jet flows reported in this paper are shown in Fig. 8. In spite of the questions raised above about the data near the nozzle, the mass flows approach the nozzle flow near the nozzle exit. The legend shows the nozzle numbers and the fully expanded Mach numbers for the measured flows. The filled symbols represent converging-diverging nozzles and the open symbols the converging nozzles. Notice that the mass flows of all of the nozzles cluster together except for two of the flows. Within the cluster, nozzle 9CD (double bevelled C-D) may have some advantage in mixing but it is modest. The significant increase in mixing was provided by nozzle 9C (double bevelled converging). Recall that this nozzle had the rapid transverse flow divergence or splitting shown in Fig. 6. The subsonic flow data for this nozzle is also shown in Fig. 8 to provide additional evidence of this mixing improvement.

Acoustic Data. The example data shown here to illustrate the acoustic influence of the bevelled nozzle will be that of nozzle 6CD (baseline C-D) and 9CD (double bevelled C-D). Since both of these nozzles are converging-diverging, the shocks are minimized and the screech tones are of low enough amplitude so that they do not have much effect on the 1/3 octave data representation.

The evaluation of the acoustic benefit of bevelled nozzles is quite a complex process since the benefit is situation or hardware dependent. For example, a bevelled nozzle operated out in the open is noisier than its baseline counterpart because it produces about an additional ten decibels of very high frequency broadband noise near the plane of the nozzle exit. However if this nozzle is enclosed in a properly designed acoustically treated shroud as in a mixer ejector, this excess noise does not present a problem. We will attempt to show here that the bevelled nozzle provides a noise directivity and spectrum shift that can be used to advantage in a properly designed system. The noise directivity shift is precisely the property mentioned in the Introduction which has been sought to render the mixing noise more amenable to attenuation by acoustic liners. A complete analysis of the

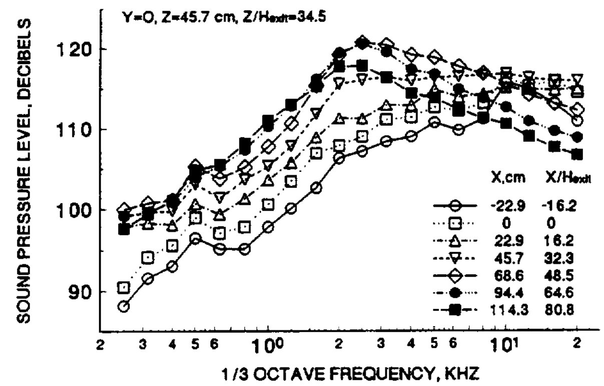

Figure 9. Noise spectra for nozzle 6CD, M_{exp} = 1.395, sideline plane of large nozzle dimension, 45.7 cm from axis

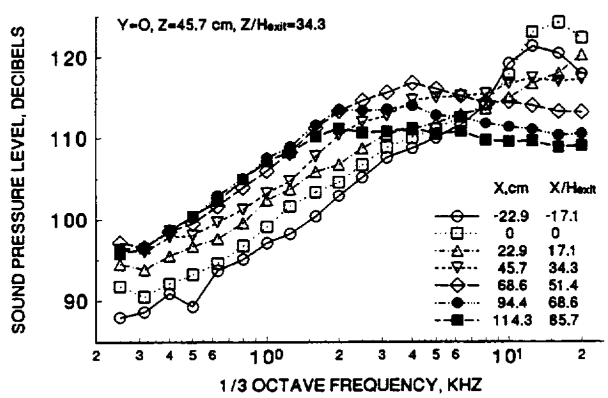

Figure 10. Noise spectra for nozzle 9CD, M_{exp} = 1.425, sideline plane of large nozzle dimension, 45.7 cm from axis

acoustic benefits of the bevelled nozzle is beyond the scope of this paper, but some of the acoustic elements which must be considered in such an analysis will be discussed.

The measured noise spectra for the baseline C-D nozzle 6CD are shown in Fig. 9. All of the data are for a constant distance sideline of 45.7 cm from the nozzle axis in the plane of the large nozzle dimension. Seven equally spaced axial positions are shown from behind the nozzle plane (-22.9 cm) to quite far downstream from the nozzle (114.3 cm). For later more detailed analysis, twenty positions spaced at 7.6 cm are available but they would unnecessarily clutter the graph. As would be expected, near the nozzle exit plane the noise spectra is dominated by very high frequency noise. As the microphone is moved downstream, the mixing noise centered at 2.5 Khz becomes dominant and is seen to peak somewhere between 68 and 94 cm (actually 84 cm) at a level of 121.1 dB.

The noise spectra for the double bevelled C-D nozzle 9CD measured at the same sideline positions are shown in Fig. 10. The very noticeable difference in these spectra is the nearly ten decibel increase in the very high frequency noise mainly near the plane of the nozzle. It is tempting to attribute this high frequency noise increase to shock associated broadband noise as presented by Tam and Tanna (1982) and Tam et al. (1986) since the frequency relationship to mixing noise is about correct. However, this jet is properly expanded and does not have sufficiently strong shocks to sustain a significant screech tone even near the nozzle lip (about 138 dB). It is possible that the oblique bevel of this nozzle exit has promoted the dominance of oblique instability modes which was the reasoning behind trying such a nozzle. The source of this high frequency noise is unknown at present. As mentioned earlier, this high level noise dominates the spectrum only near the plane of the nozzle where it would experience nearly normal incidence onto an acoustic liner in a properly designed shrouded mixer-ejector. It is thus of no consequence for the purposes of this study but could pose a problem for other configurations.

Other characteristics of the nozzle 9CD noise spectra can be seen in Fig.10. The mixing noise peak has shifted to a higher frequency of 4 kHz. The peak occurs at X = 68.6 cm at a level of 116.9 dB. The reduction in the peak mixing noise level from 121.1 to 116.9 dB represents an obvious advantage for the bevelled nozzle. However, the shift in the location of this peak from 84 cm to 69 cm represents another advantage for the bevelled nozzle which is not quite so obvious. The upstream location of the peak means that the noise is propagating at a larger angle to the jet axis (also depends on jet noise source location which must yet be quantified). If used in conjunction with a properly designed and located acoustic liner in a shrouded configuration, the more normal angle of incidence of the noise on an acoustic liner will provide improved acoustic suppression for a given liner length.

The other bevelled nozzles gave acoustic results similar to those discussed above. High frequency noise was always increased near the plane of the nozzle exit. The mixing noise peak was shifted to higher frequency and upstream position. The 4.2 dB drop in peak mixing noise level was not matched by the other configurations. Also the potential benefits of the unsymmetrical nature of the noise field for the single bevelled nozzles has not been sufficiently explored at this time.

CONCLUDING REMARKS

The potential benefits of bevelled rectangular nozzles operated with supersonic jets has been explored. The aerodynamic results showed that a double bevelled rectangular converging-diverging nozzle could be operated at its design Mach number without the flow deflection that would occur due to the transverse pressure relief normally occurring with an oblique exit. The elimination of this deflection or flaring of the flow would reduce the thrust loss associated with the flow deflection. However, in some cases the flaring of the flow may be desirable since it was shown that the jet mixing can be increased for some geometries.

The bevelled nozzle exits were shown to shift the mixing noise peak to higher frequency and to shift this noise directivity lobe toward the upstream direction. This shift in noise directivity toward more normal to the jet axis by encouraging oblique shear layer instabilities and coherent structures has been the main objective of this research effort. The physical effect has been demonstrated although the reason for the phenomenon has yet to be confirmed.

The acoustic benefits of the bevelled nozzles have been discussed. The benefits are system dependent and can not be completely determined from these simple experiments. It appears that the bevelled nozzles can produce significant acoustic benefits in a shrouded system such as an acoustically lined mixer-ejector. The shift in mixing noise directivity toward normal to the acoustic lining surface will provide increased noise attenuation. The double bevelled C-D nozzle provided a 4.2 dB reduction in the peak mixing noise level which is an obvious benefit. However, about a ten decibel increase in high frequency noise (perhaps due to the oblique instability modes) occurred in the exit plane of the nozzle. This normally directed noise component would not be a significant detriment for properly designed and located acoustic treatment on a shroud wall, but it is easy to see that this situation may not be desirable for some applications with an unconfined jet.

The work presented here and by Rice and Raman (1993b) is far from finished. The influence of multiple closely packed jets, high entrainment velocities, proximity of confining walls, and high temperature primary jets are some examples of work that must be completed. Even for the simple single jet substantial additional research would be beneficial. The thirty degree bevel on these nozzles has no great significance. It is possible that other angles and nozzle internal contours may be much more effective than the nozzles tested here. If oblique mode generation is shown to be significant, there may be better methods to provide this excitation than bevelling the exits.

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13. ABSTRACT ***(Maximum 200 words)***

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