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Thrust Characteristics of a Supersonic Mixer Ejector

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This article describes recent findings relative to the thrust performance of supersonic mixer ejectors. Mixer ejectors are a candidate means to mix out the high-velocity engine exhaust on the High Speed Civil Transport (HSCT) aircraft, thereby reducing jet noise at takeoff and landing. In the present work, data and analyses are presented that demonstrate that mixer ejectors can provide rapid mixing of a supersonic jet for acoustic benefits, all while increasing aircraft system static thrust. Jet engine thrust data is presented that demonstrates that a properly designed choked mixer nozzle has essentially no thrust loss when compared to conventional axisymmetric nozzles and mixer ejector thrust gains are invariant over a range of pressure ratios that choke the lobed nozzle. Model data of higher pressure-ratio mixer ejectors (i.e., consistent with HSCT applications) are analyzed to provide relevant thrust parameters. Comparisons are made with a conventional slot-nozzle ejector. A principal finding of this study is that the mixer ejector thrust performance is particularly sensitive to secondary inlet flowfield conditions and geometry. With proper inlet geometries, mixer ejector thrust performance was found to substantially exceed that of the slot-nozzle ejector.

Nomenclature

A = area, in.^{2}
A_e, A_p = ejector primary area (nozzle exit area), in.^{2}
A_s = ejector secondary area, in.^{2}
A_3 = ejector mixing duct area, in.^{2}
A^* = nozzle throat area, in.^{2}
D_h = ejector shroud exit hydraulic diameter, in.
EPR = engine pressure ratio, P_{TJ}/P_{T_∞}
F_G = ejector gross thrust, lbf
L = length of ejector mixing duct, in.
L_d, L_D = length of ejector shroud, in.
M_J = jet exit Mach number (primary nozzle exit plane)
M_∞, M_0 = forward flight Mach number
m = mass flow rate, slug/s
m_p = primary nozzle mass flow rate, slug/s
NPR = nozzle pressure ratio, P_{TJ}/P_{S_∞}
P = flowfield static pressure, psia
P_{S_∞} = freestream ambient static pressure, psia
P_T = flowfield total pressure, psia
P_{TJ} = jet supply (primary nozzle) total pressure, psia
P_{T_∞}, P_{T0} = freestream total pressure, psia
T_T = flowfield total temperature, °F
T_{TJ} = jet supply (primary nozzle) total temperature, °F
T_{T_∞}, T_{T0} = freestream total temperature, °F
U = axial velocity, ft/s
U_J = jet exit velocity (primary nozzle exit plane) calculated from A_e/A^*, ft/s
V_I = nozzle exit velocity ideally expanded from P_{TJ} to P_{S_∞}
X, x = axial distance, in.
X_p = axial penetration of nozzle exit plane into ejector shroud, in.
Y, y = vertical distance, in.
Z, z = transverse distance, in.
γ = ratio of specific heats
ρ = fluid density, slug/ft^3
ϕ_G = ejector gross thrust coefficient, F_G/m_pV_I

Subscripts
J, P, 1 = primary nozzle exit or jet flow state
S = secondary flow state
∞, 0 = wind-tunnel freestream or ambient flow state

Introduction

THE High Speed Civil Transport (HSCT) aircraft, currently under development in the U.S. and other countries, faces many difficult design challenges. One of these challenges is the development of a quiet engine exhaust system, which is capable of both meeting Federal Aviation Administration (FAA) Stage III noise requirements as well as providing an efficient generation of thrust to power the aircraft. Any noise suppressor that is applied to the current problem must address the issue of thrust. Specifically, thrust penalties associated with the suppressor must be minimized. The objective of the current study was to provide an understanding of potential thrust penalties and sensitivities for the mixer ejector.

The mixer ejector is a candidate exhaust nozzle/noise suppressor for the HSCT engine. The mixer ejector concept involves the introduction of large-scale, low-loss streamwise vortices into an ejector mixing duct that surrounds the primary jet exhaust nozzle. These vortices are introduced at the primary nozzle exit plane by special geometrical contouring of the nozzle surface. Figure 1 shows a diagram of the mixer lobes for a mixer ejector primary nozzle and their generation of axial vortices between two airstreams. The presence of axial vortices has been shown to dramatically enhance the ejector mixing and pumping performance relative to conventional ejectors. In a conventional ejector, large-scale axial vorticity is not present and mixing is accomplished via viscous diffusion

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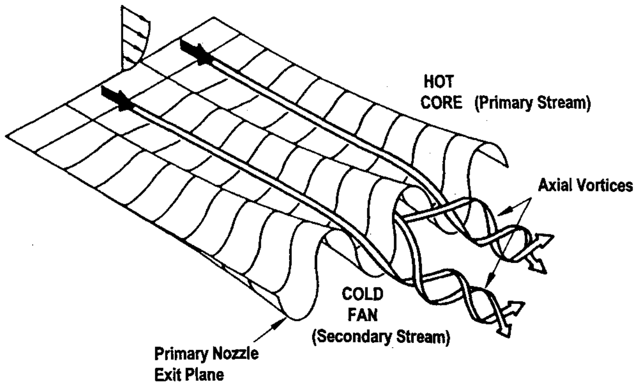

Fig. 1 Lobe contours of mixer ejector primary nozzle.

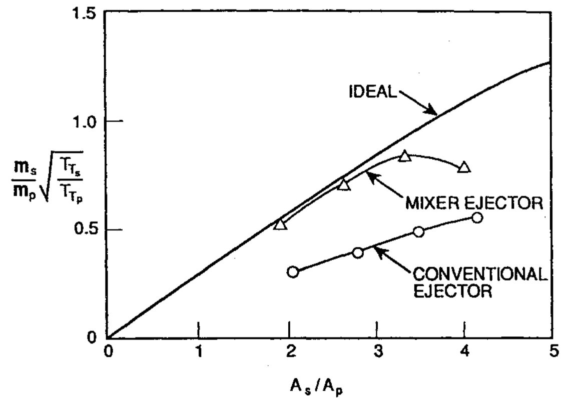

Fig. 2 Supersonic mixer ejector pumping.[4]

and small-scale turbulence transport. Typically, this is a relatively slow mixing process, particularly in the supersonic flow regime. Long mixing duct lengths are required to achieve reasonably well-mixed ejector exit conditions. Properly designed axial vorticity mixer lobes, however, initiate large-scale streamwise vortices that entrain large amounts of secondary fluid and rapidly stir it into the primary stream. It is by this mechanism that the distribution of viscous shear stresses and small-scale turbulence, which occur naturally between the primary and secondary streams (and are ultimately responsible for the mixing), is significantly enhanced.

The mixing and pumping characteristics of mixer ejectors have been well documented by several investigators.[1-5] Operating at low-speed, subsonic conditions and relatively low primary temperatures (less than 200°F), mixer ejectors have displayed static pumping benefits relative to conventional ejectors in excess of 100%.[2,3] Experimental studies of mixer ejectors in the high-temperature (1000°F), supersonic flow (M_j = 1.5) regime indicate similar benefits both for near-static and simulated forward flight operating conditions.[1,4-6] In all of these studies, the mixer ejector exit plane flow was found to be significantly better mixed relative to relevant conventional ejectors.

Due to the presence of axial vorticity, mixer ejectors have demonstrated high pumping levels with significantly reduced shroud lengths. Typically, conventional ejectors require a minimum shroud length of 5–7 mixing duct diameters to achieve good mixing and pumping results. Mixer ejectors, on the other hand, have been shown to be capable of pumping near-ideal levels of secondary flow with shroud lengths on the order of 1–2 mixing duct diameters. This translates into a significant weight and material savings for aircraft implementation. Figure 2 shows experimental mixer ejector pumping data as compared with a conventional ejector, both operating in the high-temperature, supersonic primary flow regime. The conventional ejector employs a nozzle with a single rectangular slot of aspect ratio (AR) 3.7. Near-ideal pumping levels are seen for the mixer ejector. Ejector mixing duct lengths L are between 1.5–2.3 mixing duct hydraulic diameters for the data in this figure. For both ejectors, L/D_h values were around 2.3 at A_s/A_p = 2. When the mixing duct area was increased, it was done so without changing the length of the duct. Thus, the L/D_h values decreased with increasing secondary-to-primary area ratio. At A_s/A_p = 4, the L/D_h values were approximately 1.5 for both ejectors.

The mixer ejector has been proven capable of pumping the increased amounts of secondary flow necessary for mixing out the high-velocity jet core on the HSCT engine.[5] Further, the actual mixing performance of the device is encouraging from a jet noise reduction standpoint. A remaining issue is the question of the mixer ejector thrust performance. Questions have been raised relative to potential thrust penalties associated with a device that vectors some of the nozzle primary flow off-axis in order to create axial vortices. The goal of the present study is to provide insight into the mixer ejector thrust performance, and provide answers to questions concerning potential thrust penalties and sensitivities. This study re-examines experimental data that were acquired to assess supersonic mixer ejector mixing performance.[1] The data are analyzed to provide relevant thrust parameters both for several configurations of a mixer ejector as well as for a conventional slot-nozzle ejector. New experimental results for supersonic axial vorticity mixer nozzles and mixer ejectors are also presented.

A principal finding of this study is that the mixer ejector thrust performance is particularly sensitive to secondary inlet flowfield conditions and geometry. With proper inlet geometries, mixer ejector thrust performance was found to substantially exceed that of the slot-nozzle ejector. In addition, it was found that mixer nozzles that properly produce large-scale, streamwise vorticity incur little thrust penalty relative to conventional nozzles operating at the same conditions.

Results

In order to properly produce axial vorticity to enhance flowfield mixing, a nozzle surface is contoured into a series of lobes. These lobes, shown schematically in Fig. 1, alternately vector the nozzle flow upwards and downwards. When designed correctly, the nozzle flow fills the lobes and follows their contour with minimal loss. The result is a circumferential (or spanwise, in the case of a two-dimensional nozzle) array of axial vortices that are created at the nozzle exit (see Fig. 1). These vortices rapidly stir the nozzle and external flows together, dramatically increasing the interfacial contact area between the streams and therefore providing the mechanism for enhanced mixing to occur.

It is clear that in order to produce axial vorticity in the manner described above, some of the nozzle primary flow must be vectored off-axis. This raises questions regarding potential thrust penalties. Some quantitative answers to these questions are provided from full-scale static engine testing of an axisymmetric, lobed mixer nozzle and a mixer ejector (i.e., this same mixer nozzle contained within a short ejector shroud). As part of this testing, thrust measurements were performed for both the lobed mixer nozzle and a conventional circular nozzle (both unshrouded) operating over a wide range of engine pressure ratios (EPR = 1.05–2.15). The higher pressure ratios caused the nozzle flow to choke. The mixer nozzle was designed to generate good mixing with minimal thrust loss. The primary lobe exit angle was only 6 deg; this generated very low axial momentum loss for the bulk of the flow passing through the nozzle. The secondary lobe exit angle was 20 deg. Such lobe contours not only turn the flow, but also generate static pressure gradients at the primary nozzle exit plane. Thus, the flow exit angularity does not convert directly to a thrust loss. The flow stream thrust in the axial direction (i.e., $mU + [P - P_{s_\infty}]A$) has to be integrated over the entire

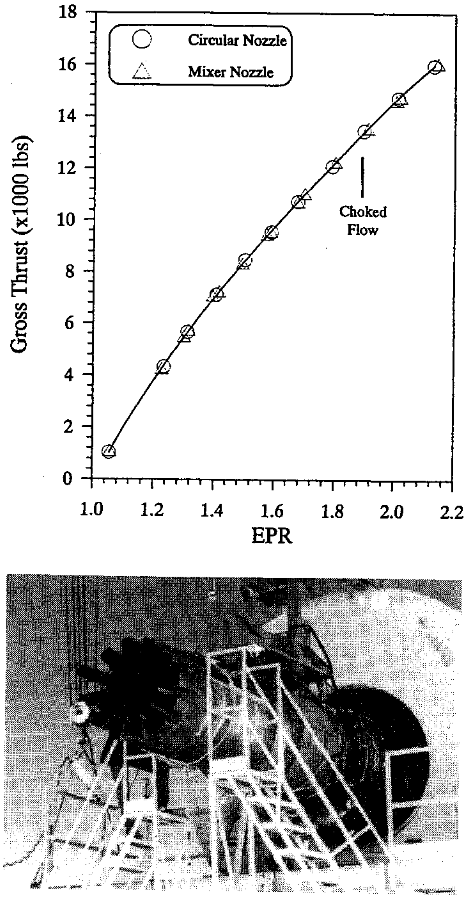

Fig. 3 Axial vorticity mixer nozzle and circular nozzle thrust performance comparison.[7]

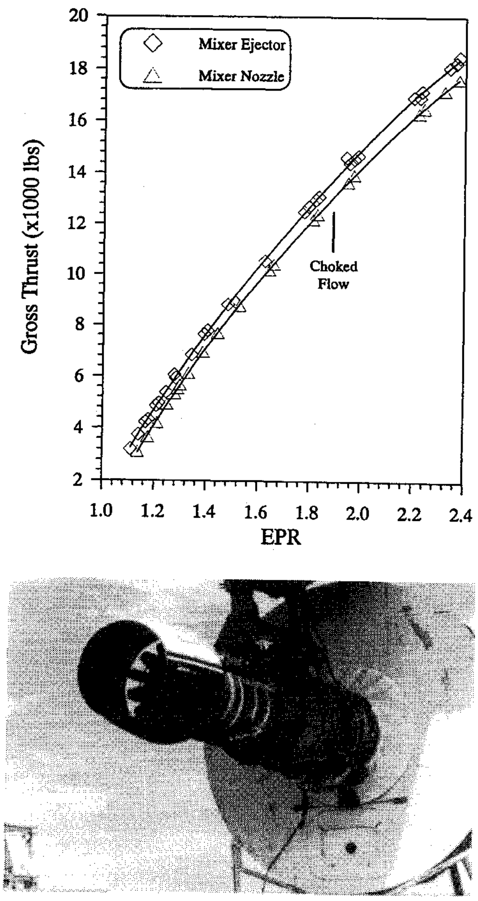

Fig. 4 Mixer ejector static thrust augmentation.[7]

exit plane to determine such angularity losses. Analytical estimates using linearized potential theory indicated that the angularity thrust loss for the mixer nozzle presented in Fig. 3 would be less than 0.1%.

Figure 3 presents a photograph of the axial vorticity lobed nozzle on a JT8D jet engine, and the results of thrust measurements as compared to the conventional circular nozzle.[7] The comparison agrees with the prediction and shows no measurable thrust differences between the two nozzles, even for choked-flow engine pressure ratios. This important result demonstrates that properly designed choked mixer nozzles introduce little thrust loss when compared with conventional circular nozzles. Furthermore, since the losses through a lobed nozzle should not change once the nozzle is choked, this result should be indicative of behavior at higher pressure ratio operation as well.

Figure 4 shows a photograph of the same lobed nozzle in a mixer ejector configuration installed on the JT8D jet engine. Thrust measurements for the engine with both the mixer ejector system and the unshrouded lobed nozzle are also presented. An ejector thrust gain is seen to occur over the entire range of engine pressure ratios tested. Furthermore, the magnitude of the thrust gain is invariant over the range of pressure ratios that choke the lobed nozzle. Choking the primary nozzle on a mixer ejector does not incur additional losses if the ejector is designed properly. For the configuration shown in Fig. 4, a shroud length equal to 1.1 mixing duct diameters was used. As described earlier, to achieve good mixing and pumping performance, and hence, static thrust augmentation, a conventional nozzle ejector would require much longer duct lengths. It should be noted that the thrust gain for the mixer ejector system shown in Fig. 4 is for a static operating condition. In forward flight, ejectors introduce a thrust penalty for flight speeds in excess of approximately $M = 0.2–0.3$ due to propulsion system ram drag. For most aircraft, jet noise reduction is important primarily at the low Mach number takeoff and approach conditions. Thus, the mixer ejector may be used as a noise suppressor with little or no loss in propulsion system thrust. It may be stowed or bypassed during cruise to avoid the large ram drag penalty associated with high-speed forward flight.

The implications of the results presented in Figs. 3 and 4 are as follows. First, properly designed axial vorticity mixer nozzles do not introduce a significant thrust penalty when compared to circular nozzles operating at the same conditions. This result would appear to be valid for sonic and supersonic engine pressure ratios. In addition, it is possible to achieve static thrust augmentation on an engine by installing a mixer ejector system with a short mixing duct. Thus, while implementing a mixer ejector for the purpose of jet noise reduction via enhanced mixing, engine thrust gains are also possible.

In order to investigate the parameters affecting mixer ejector flowfield mixing, a model scale supersonic mixer ejector experimental study was conducted at United Technologies Research Center. This study is described thoroughly by Tillman and Patrick.[1] Since the focus of the experiment was to assess the mixing, detailed surveys of total pressure, static pressure, and total temperature were performed in the exhaust flowfield. These data were acquired in dense grids at the mixer ejector shroud exit plane and at several downstream planes. Typical measurement grids involved several hundred data points over one quadrant of the symmetrical flowfield. Nozzle and wind-tunnel operating conditions for this experiment were such that an adequate simulation of a generic high-speed exhaust system was achieved. The jet exit (or primary nozzle exit) Mach number was nominally 1.5, the wind-tunnel forward flight Mach number was 0.5, and the primary flow supply total temperature was 1000°F. The secondary flow total temperature was on the order of 50°F.

The supersonic mixer ejector model consisted of a two-dimensional supersonic mixer nozzle, mounted in a flat-plate ejector shroud with a thin-lip inlet designed for forward flight. The mixer ejector model is shown schematically in Fig. 5. The ejector top and bottom walls were adjustable in the vertical direction to provide for a variable ejector area ratio. Ejector secondary-to-primary area ratios in the range of 2.5–4.0 were tested in this study. The degree of nozzle axial penetration into the ejector shroud could be varied by removing one or more of the segmented shroud sections and reinstalling the leading-edge segment as shown in Fig. 5. During the experiment, two values of nozzle axial position within the shroud were studied, corresponding to $X_p/L_D = 0.17$ and 0.28. Ejector mixing duct length-to-diameter ratios L/D_h that were tested ranged from 1.5 to 1.8, corresponding to the range of secondary-to-primary area ratios (2.5–4.0). As described earlier, mixer ejector and slot-nozzle ejector L/D_h values were approximately equal for each area ratio tested. The high value ($L/D_h = 1.8$) corresponds to $A_s/A_p = 2.5$, whereas the lower value ($L/D_h = 1.5$) is associated with $A_s/A_p = 4.0$.

The ejector model was designed such that a conventional supersonic slot nozzle (a rectangular nozzle of AR = 3.7), of the same area ratio (A_e/A^*) as the mixer nozzle, could be installed and tested as well. With the same area ratios for the two nozzles, their major aerodynamic difference was the introduction of axial vorticity into the mixing duct in the case of the lobed mixer nozzle. Figure 6 shows an end-view photograph of the mixer ejector. The lobed primary nozzle is clearly visible. Figure 7 shows a diagram of the conventional slot-nozzle ejector.

Flowfield mixing was assessed using measured total temperature directly and by using the measured static pressures to correct the total pressure measurements for any probe-induced shock losses. Using the measured total temperature

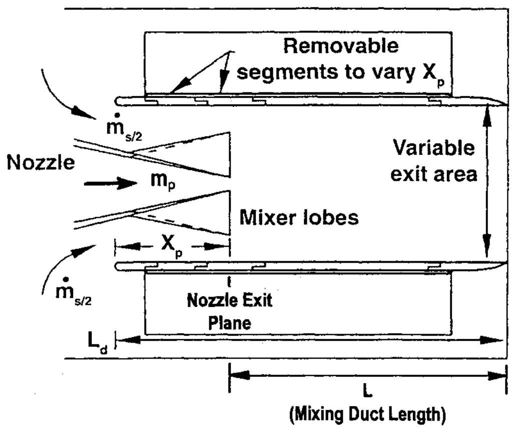

Fig. 5 Mixer ejector model with variable shroud geometry.

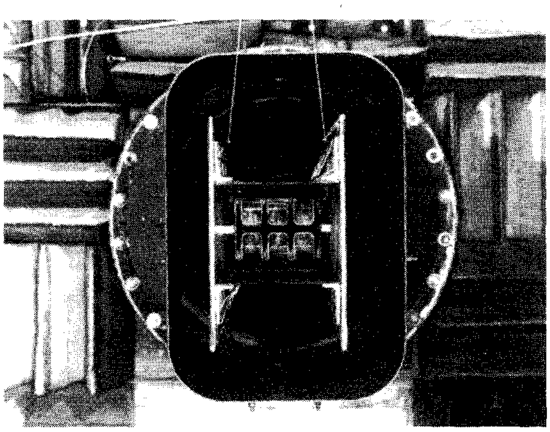

Fig. 6 Mixer ejector model, end view.

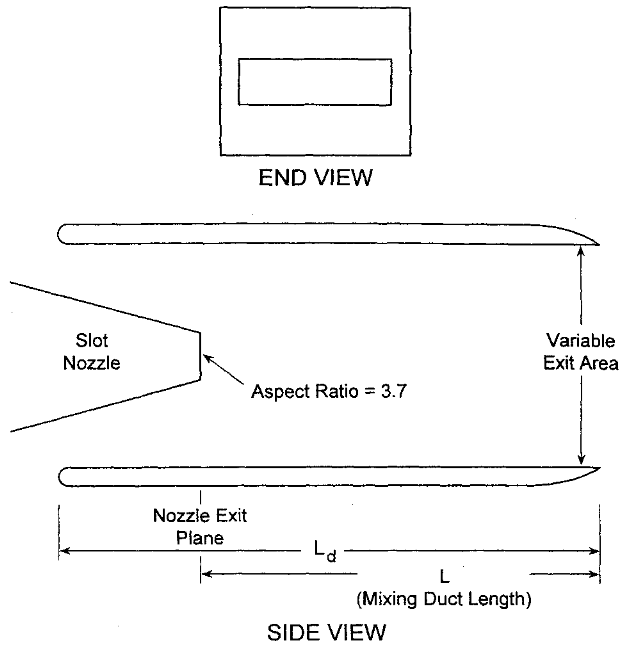

Fig. 7 Conventional slot-nozzle ejector.

and static pressure values, together with the total pressure, other compressible flow variables such as axial velocity and Mach number were calculated. Thus, with dense measurement grids of mixer ejector shroud exit plane axial velocity and static pressure, a gross thrust term could be integrated for each configuration. This was done, both for mixer ejector as well as conventional ejector configurations. The estimated uncertainty in the measurement of typical values of the flowfield variables was $\pm 0.3\%$ for total pressure, $\pm 0.2\%$ for static pressure, and $\pm 0.8\%$ for total temperature. The estimated uncertainty in the measurement of gross thrust was approximately $\pm 1.5\%$.

The superior mixing performance of the mixer ejector relative to the slot-nozzle ejector is shown in Fig. 8. This figure shows contour plots of the axial velocity just downstream of the ejector shroud exit plane for the two configurations. Again, several hundred data points were obtained over one quadrant of the flowfield, and then symmetrically projected into the other quadrants to create the complete picture. This resulted in a very dense spacing of data points, and hence, good resolution of the spatial gradients shown in the figure. The data is presented in nondimensional form, with values of 1.0 corresponding to the primary nozzle jet exit velocity (calculated using the isentropic relation for A_e/A^*) and values of zero corresponding to the wind-tunnel freestream velocity. From a jet noise reduction standpoint, the benefits of a mixer ejector are evident. While in the case of the slot-nozzle ejector a large high-velocity jet core still exists at the shroud exit, this core has been significantly mixed-out with the mixer ejector. The flowfield of the mixer ejector is more spatially uniform as well.

While the mixing enhancement, and hence, jet noise reduction potential of the mixer ejector is clear, it is desirable to obtain an understanding of its thrust characteristics as well. The present experiment is well suited to supply this information, since several mixer ejector geometries were tested in forward flight at supersonic nozzle pressure ratios. Furthermore, the ejector shroud exit plane flowfield surveys were dense enough to allow meaningful integration of the thrust terms. The ejector gross thrust was calculated for each configuration by integrating $mU + (P - P_{s_\infty})A$ over the shroud exit. The gross thrust was defined as

$$F_G = \int_A [\rho U^2 + (P - P_{s_\infty})] \, dA \qquad (1)$$

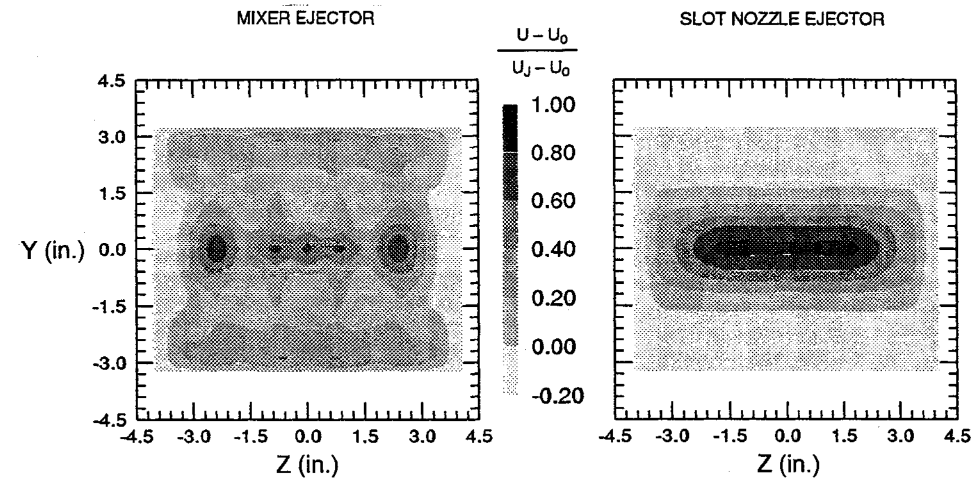

Fig. 8 Comparison of mixer ejector and slot-nozzle ejector shroud exit plane axial velocity mixing (X_p/L_d = 0.17, M_0 = 0.5, A_s/A_p = 4.0).

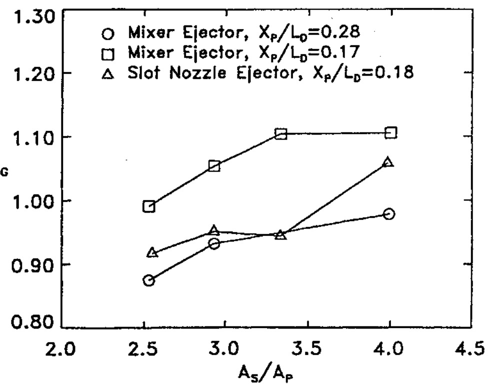

Fig. 9 Mixer ejector gross thrust coefficient [defined by Eq. (2)].

and the corresponding gross thrust coefficient as

$$\phi_G = F_G/m_p V_I \qquad (2)$$

where m_p is the measured primary (nozzle) flow, and V_I is the velocity obtained by ideally expanding the measured nozzle supply pressure to freestream ambient conditions. The primary flow was measured using an ASME standard venturi and associated measurement technique.

It should be noted that the definition of the gross thrust coefficient in Eq. (2) does not contain a correction for the ram drag. The coefficient is presented in this form so that it may provide an indication of the thrust augmentation that would be possible for a static operating condition. Statically, the ram drag would be equal to zero and the gross thrust produced by the nozzle/ejector system would be somewhat lower than, but on the same order as, that produced at M_0 = 0.5. Ram drag corrections were applied to the gross thrust coefficients for both the mixer ejector and the conventional slot-nozzle ejector. It was found that the thrust coefficients were reduced (as expected), but relative differences were essentially unchanged. The emphasis of the current study was on identifying the reasons for thrust differences between the various configurations and not on measuring absolute thrust levels. Thus, the gross thrust coefficient definition of Eq. (2) should be adequate, and as described earlier also provides an indication of achievable static thrust augmentation levels.

The thrust data for both the conventional and mixer ejector systems are presented in Fig. 9. The gross thrust coefficient is plotted vs secondary-to-primary area ratio. The most striking feature of this figure is the wide difference in the thrust data between the two mixer ejector configurations, X_p/L_D = 0.17 and 0.28 (see Fig. 5). It is clear that by choosing the appropriate values of nozzle penetration, mixer ejector thrust gains between 5–15% are possible relative to the conventional ejector. However, this figure also shows that it is possible to select a nozzle penetration value such that the mixer ejector thrust performance is actually worse than that of the conventional ejector. A second noteworthy feature of Fig. 9 is the sensitivity of ejector gross thrust to the area ratio. Both the conventional and mixer ejector systems possess similar trends of increasing thrust performance with increasing area ratio.

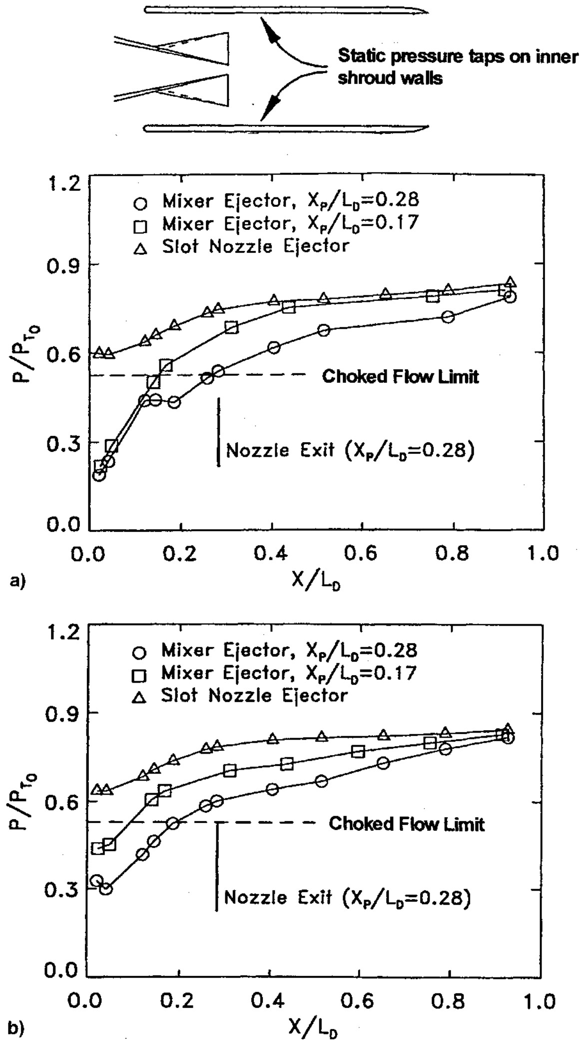

Fig. 10 Ejector static pressure distribution showing choked secondary flow, A_s/A_p = a) 2.5 and b) 3.3.

It is believed that the large differences in thrust between the two mixer ejector configurations are due to differences in secondary inlet/duct losses. It was found that the mixer ejector secondary inlet flow was choked for the case of high nozzle penetration into the shroud ($X_p/L_D = 0.28$, see Fig. 5). The mixer lobe blockage of the inlet area, and the proximity of the shroud to the nozzle external surface, resulted in a nonoptimized and reduced inlet area. Figure 10 shows ejector shroud internal axial static pressure distributions. Figure 10a shows both of the mixer ejector configurations along with the slot-nozzle ejector for $A_s/A_p = 2.5$. The static pressure values are normalized by the wind-tunnel freestream total pressure, which gives an indication of Mach number since this total pressure is essentially that of the secondary inlet. Note the extremely low values of static pressure in the secondary inlet region, for both of the mixer ejector configurations. These pressure values indicate choked secondary flow.

Figure 10b shows the static pressure distributions for $A_s/A_p = 3.3$. Here, the mixer ejector with $X_p/L_D = 0.28$ still shows strong evidence of choked secondary flow. The $X_p/L_D = 0.17$ configuration possesses minimum pressure ratios that would indicate that the secondary flow is just choked. However, since there will likely be some losses in total pressure as the wind-tunnel flow enters the ejector inlet, the local inlet pressure ratios may be somewhat higher than the P/P_{T0} values. Thus, the mixer ejector secondary inlet flow for the case of $X_p/L_D = 0.17$, $A_s/A_p = 3.3$ is most likely very near the choking limit. Note that for the conventional ejector, which pumps reduced levels of secondary flow, the pressure ratios are far from the choking limit for all area ratios.

The presence of choked flow in the mixer ejector secondary inlet is significant for two reasons. First, choking of the secondary inlet flow limits the system pumping. A further increase in secondary flow pumping is not possible for fixed upstream secondary flow conditions. Second, the supersonic flow in the secondary stream can result in high losses. Frictional losses in ducts are proportional to flow velocity squared, so that regions of higher flow speed can produce increased losses. In addition, choked or supersonic flow can produce shock waves that can add significantly to the total pressure losses. Duct wall boundary-layer separation, another loss mechanism, is also possible in the presence of shock waves.

Quantitative evidence of the difference in total pressure losses for the two mixer ejector configurations is shown in Fig. 11. This figure presents a contour plot of the ejector shroud exit plane total pressure distribution. The total pressure values are nondimensionalized such that a value of zero corresponds to P_{T0} (wind-tunnel freestream condition), and a value of 1.0 corresponds to P_{TJ} (jet supply condition). The comparison is made between the $X_p/L_D = 0.28$ and 0.17 configurations, for an area ratio $A_s/A_p = 4.0$. For this area ratio, the $X_p/L_D = 0.17$ configuration possesses a secondary inlet that is unchoked. The $X_p/L_D = 0.28$ configuration still has a choked secondary inlet.

Figure 11 clearly shows lower total pressure values (i.e., higher losses) for the $X_p/L_D = 0.28$ case. The lower and upper duct wall regions in particular show higher losses. There is an additional area partway between the upper/lower wall surfaces and the center of the shroud that shows higher losses as well. As shown in Fig. 9 there is approximately a 12% difference in gross thrust coefficient for these two mixer ejector configurations. Since the secondary-to-primary area ratio is large (4.0), the flow limiting aspect of the secondary inlet is minimized at this operating condition. That is, the severity of the secondary flow choking is reduced for $X_p/L_D = 0.28$ and choked secondary flow is eliminated for $X_p/L_D = 0.17$. This means that the differences in thrust coefficient at this area ratio are primarily due to differences in the loss characteristics of the two configurations, and not to differences in secondary inlet area.

Differences in ejector secondary inlet area could limit the amount of pumped secondary flow, particularly for cases of a choked inlet. For this reason, the difference in thrust between the two mixer ejector configurations ($X_p/L_D = 0.17$ and 0.28), which could be attributed purely to pumping was calculated. For an ideal augmenter,[8] thrust augmentation is given by

$$\Phi = \sqrt{1 + (m_s/m_p)} \tag{3}$$

Secondary mass flow was calculated from the current experimental data by integrating the flow at the ejector shroud exit plane, and subtracting off the measured primary flow. Equation (3) was then used to estimate ideal augmenter thrust augmentation levels. It was found that for area ratios of ≈3–4, the thrust differences between the two mixer ejector configurations calculated in this fashion (and thus, attributable solely to differences in pumping) were less than 5%. As seen from Fig. 9, actual thrust differences were found to be on the order of 10–12% for these area ratios. This provides evidence that the thrust differences between the two mixer ejector configurations are due in large part to a loss mechanism, and not simply to differences in secondary flow pumping.

Figures 9–11 indicate that total pressure losses, likely originating in the secondary inlet region, can be responsible for significant reductions in mixer ejector thrust. In fact, it is possible to produce mixer ejector configurations that possess a lower thrust performance than that of a conventional ejector (see Fig. 9). However, when the inlet is sized such that secondary flow losses are reduced, it is possible to produce con-

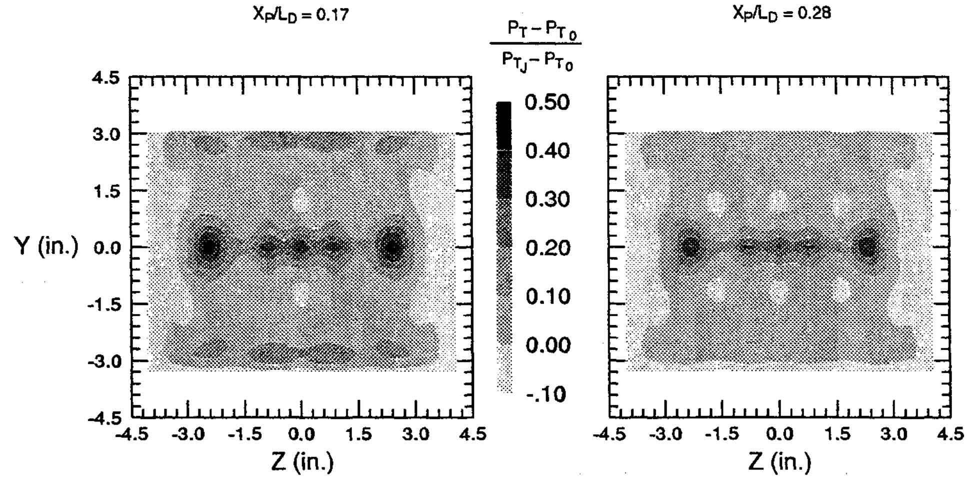

Fig. 11 Mixer ejector total pressure mixing characteristics ($M_0 = 0.5$, $A_s/A_p = 4.0$).

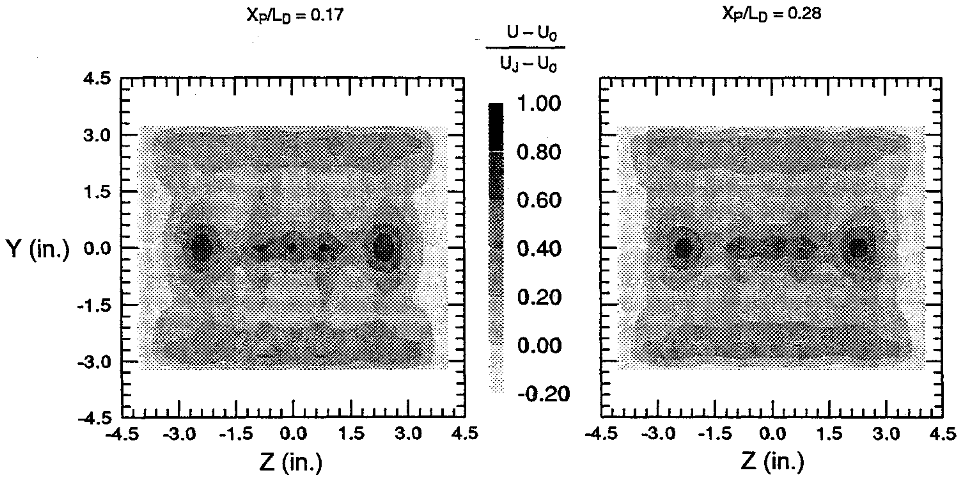

Fig. 12 Mixer ejector axial velocity mixing characteristics (M_0 = 0.5, A_s/A_p = 4.0).

figurations that significantly outperform conventional ejectors.

An interesting feature of mixer ejectors is the thrust sensitivity to secondary flow conditions and losses, combined with a mixing performance that is relatively insensitive to such parameters. Figure 12 shows the shroud exit plane axial velocity mixing characteristics for the two mixer ejector configurations described above (X_p/L_D = 0.28 and 0.17, for A_s/A_p = 4.0). Note that there is very little difference in the global mixing, even though there is approximately a 12% thrust difference between the two configurations. This is an important finding. It implies that while enhanced mixing for jet noise reduction may be accomplished with this device, careful attention must be paid to inlet losses if the resulting thrust performance is to be acceptable.

Conclusions

Across a broad range of pressure ratios, properly designed lobed nozzles that employ axial vorticity can provide a rapid mixing mechanism, with thrust levels that are comparable to conventional axisymmetric nozzles. This is true even for nozzles that are operating at choked pressure ratios. The amount of mixing at the shroud exit plane of a mixer ejector system is not a good indicator of how well the system is producing thrust. It is possible to produce mixer ejector configurations that possess a wide range of thrust performance levels, both above and below the levels associated with conventional ejectors. Good mixing results may be obtained across the range of thrust performance. Mixer ejector thrust levels are shown to be particularly sensitive to secondary inlet geometry and its associated influence on the secondary flow. When secondary inlets are properly designed, mixer ejectors are seen to provide levels of thrust that substantially exceed those of conventional nozzle ejectors.

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