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# Experimental Study on Mixing Enhancement by Petal Nozzle in Supersonic Flow

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**An experimental study on mixing enhancement in supersonic flow by a radially lobed nozzle, called petal nozzle, has been conducted. The study entails the mixing of a supersonic primary stream and a coflowing sonic secondary stream in cold flow. The radial distribution of momentum flux is characterized by a mixing parameter called the degree of mixing. The loss in stagnation pressure associated with the mixing is also determined. With emphasis on momentum mixing and pressure drop, the petal nozzle and the conventional conical nozzle have been compared so as to assess the suitability of the former. The results show that using an optimum length of the mixing chamber, a compromise can be struck between the mixing enhancement and the associated increase in pressure loss. The contribution of shear area at the nozzle exit to mixing enhancement was found to be marginal.**

## Nomenclature

$L/D$ = length to diameter ratio of the mixing tube
$P_0$ = stagnation pressure
$x$ = axial station along the mixing tube
$\mu$ = momentum flux, N/M$^2$
$\sigma$ = standard deviation
$\phi$ = uniformity factor

*Subscripts*
av = average value
um = unmixed condition

## I. Introduction

MIXING of two high-speed streams in a short mixing chamber is a basic requirement for the efficient and reliable operation of scramjets, air augmented rockets, and supersonic ejectors. Experimental and theoretical studies[1,2] have shown that the growth rate of shear layers that controls the mixing of two coaxial jets, decreases substantially with increase in compressibility of the streams. This reduction in the growth of shear layers renders the mixing of coaxial supersonic streams extremely slow. Hence, methods of achieving enhanced mixing of supersonic jets play an important role in the development of advanced aerospace propulsion systems.

The multilobed forced mixer nozzle has been identified as an efficient tool in promoting enhanced mixing of compressible jets.[3] The mixing mechanism of a lobed nozzle is characteristically different from that of a conventional conical nozzle. In the case of jets from circular nozzles, mixing is dominated by momentum transfer through the action of viscous shear stresses and small-scale turbulence in the mixing layer.[3] Hence, the slow growth rate of supersonic shear layers renders the conical nozzle highly inefficient for applications involving supersonic mixing. A rectangular nozzle provides better mixing than a circular nozzle of the same exit area owing to the distribution of viscous shear stresses over a larger surface area.[3] But the mechanism of mixing is basically the same for both.

In recent years lobed nozzles (or forced mixer nozzles) have been the subject of numerous experimental and computational studies due to their potential in enhancing high-speed mixing. Paterson[4] has reported a benchmark experimental study of a three-dimensional subsonic flowfield in a multilobed forced-mixer nozzle. Based on temperature and velocity contours, he has concluded that the mixing process is dominated by large-scale secondary circulations. Barber et al.[5] formulated a three-dimensional inviscid flow model to analyze the subsonic flow through a turbofan forced mixer. The results of computations confirmed that the mechanism of mixing in the flowfield of a lobed nozzle is basically of an inviscid nature as inferred from the experimental observations in Ref. 4.

In the case of lobed nozzles, the formation of large-scale vortex patterns that are believed to enhance mixing is predicted by Koutmos and McGuirk[6] using a finite volume analysis. The study is confined to subsonic mixing. More recently, Tillman et al.[3] have reported an experimental study on supersonic mixer nozzles in coflowing streams. The jet mixing was characterized by measured distributions of total temperature, total pressure, static pressure, and velocity. The study revealed that the generation of large-scale vortex structures was effective in the mixing of supersonic jets as well.

Anil[7] has experimentally established the efficacy of a six-lobed petal nozzle (this term will be used in this article to denote the radially lobed nozzle) in providing an appreciable enhancement of momentum mixing in supersonic flow. Anil and Damodaran[8] used the petal nozzle as the primary nozzle in an experimental arrangement to simulate the air augmented rocket and obtained a fairly uniform temperature profile at the exit of a relatively short length of mixing chamber of $L/D = 4.25$. The role of petal nozzle in supersonic combustion becomes clear when this result is compared with that of the theoretical analysis of Schetz et al.,[9] in which even a 2-m-long combustor resulted in an exit flow with substantial nonuniformity. The suitability of the petal nozzle for various applications like supersonic ejector was also established, with emphasis on the mixing performance.[7] Detailed studies, both theoretical and experimental, have emphasized the utility of the two-dimensional lobed nozzles in supersonic ejectors.[10,11] However, quantitative information available on various aspects of mixing enhancement in supersonic flow through the radially lobed nozzle (petal nozzle) is limited. Also, within the knowledge of the authors, the concomitant increase in stagnation pressure drop has not been studied at all.

The present experimental study addresses the following issues associated with the flowfield inside the mixing chamber of a radially lobed petal nozzle. First, due to the axial asymmetry of the petal nozzle, the mixing chamber flowfield may

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not follow an axisymmetric pattern, even though the mixing tube is of circular cross section. Hence, to ascertain whether there is complete momentum mixing in the flowfield it is necessary to analyze both the radial and the transverse distribution of momentum. In Ref. 7 radial distribution of momentum flux is used to study the progress of mixing. In this article results of an angular survey of momentum distribution are presented so as to understand the mixing enhancement better.

Secondly, considering the practical application of petal nozzles in scramjets, air augmented rockets, or supersonic ejectors, it is of extreme importance to estimate the additional losses in stagnation pressure. Any method of mixing enhancement in supersonic flow will be accompanied by an increased drop in stagnation pressure. The petal nozzle is not an exception to this. Hence, the improvement in mixing gained over a conical nozzle has to be assessed in the perspective of increased stagnation pressure loss associated with the petal nozzle. The ultimate choice can be made only after considering the improvement in mixing, reduction in the required length of mixing chamber, and the increase in stagnation pressure loss. The present study examines the advantage of petal nozzle as far as the mixing performance is concerned, and also highlights the disadvantageous part of it, namely, the increased stagnation pressure loss. A factor called degree of mixing is defined on the basis of the uniformity of momentum profile so as to compare the mixing performance of the two types of nozzles. The stagnation pressure loss, in terms of a pressure drop factor, and the length requirement of mixing tube are also compared for the two nozzles.

Finally, an attempt has been made to throw light on the mechanism of mixing enhancement in a lobed nozzle. The lobed geometry provides a larger shear area compared to a circular one of the same cross-sectional area. This increase in shear area can be a contributing factor for the mixing enhancement. However, this alone cannot explain the remarkable increase in mixing produced by the lobed mixer.[3] Paterson[4] and Tillman et al.[3] suggest the formation of large-scale streamwise vortices as responsible for the enhanced mixing.

Broadly, it may be stated that the improved mixing that a lobed nozzle achieves as compared to a conical nozzle of the same exit area can be attributed to two distinct factors: 1) the formation of large-scale vortices in the mixing chamber flowfield and 2) the increase in shear area between the two jets owing to the larger perimeter at the nozzle exit. In the present study an attempt is made to compare the individual contribution of these two factors. Though mainly a qualitative assessment, such information will be useful in arriving at an optimum geometry of the petal nozzle. To isolate the influence of factors like streamwise vorticity from that of the increase in shear area, the mixing performance of a three-lobed petal nozzle is compared with that of a conical nozzle both having the same exit perimeter. Hence, the shear area at nozzle exit remains the same in both cases and whatever improvement results in mixing could be attributed to other factors.

## II. Description of the Experiment

### A. Experimental Setup

A schematic diagram of the experimental setup is shown in Fig. 1. The test nozzle (petal or conical as the case may be) is in the primary line and the secondary jet is introduced through the passage around the primary nozzle. Both the primary and secondary air lines are provided with pressure gauges and control valves. The primary line ends in a contraction piece to which the nozzle can be screwed on. The secondary air is supplied to the annular nozzle through a settling chamber. The primary flow issuing through the nozzle mixes with the annular secondary flow within the cylindrical mixing chamber attached to the exit of the two nozzles.

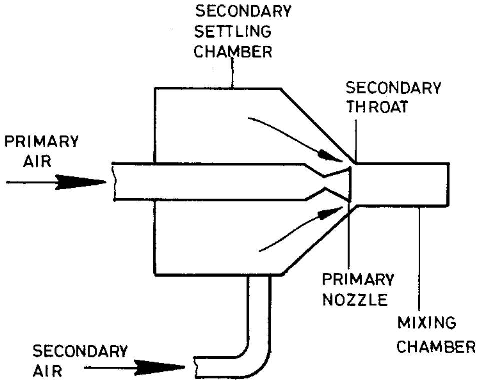


**Fig. 1 Schematic of the experimental arrangement.**

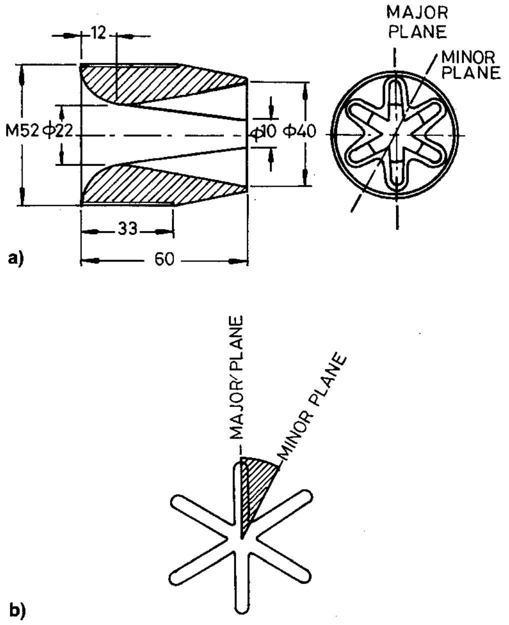


**Fig. 2 a) Six-lobed petal nozzle and b) 30-deg angular segment between major and minor planes.**

The instrumentation includes pressure gauges and a three-dimensional traversing mechanism that is employed to move the pressure probes (total and static) axially and radially. A diaphragm type pressure transducer is used for measuring pressure.

### B. Nozzles

A six-lobed petal nozzle (Fig. 2a) and a conical nozzle are used for comparative studies on mixing and pressure drop. Both of the nozzles have the same exit areas and the same area ratio corresponding to an exit Mach number of 1.67. The ratio of exit areas of primary and secondary nozzles is also maintained the same in both cases. For the study of equal shear area nozzles, a three-lobed petal nozzle is compared with a conical nozzle of the same exit perimeter and area ratio. The three-lobed nozzle has an area ratio of 1.68, which corresponds to an exit Mach number 2. The conical nozzle that is made with the same exit perimeter as the three-lobed nozzle, is also designed for Mach 2. In all cases the secondary nozzle issues the jet at sonic velocity into the mixing tube.

For the petal nozzle (Fig. 2a), the plane that contains the middle of the lobed region is referred to as the major plane. Similarly a minor plane is identified as the one that contains the middle of the interlobe region. For a six-lobed nozzle the angle between the major and minor planes is 30 deg.

### C. Experimental Procedure

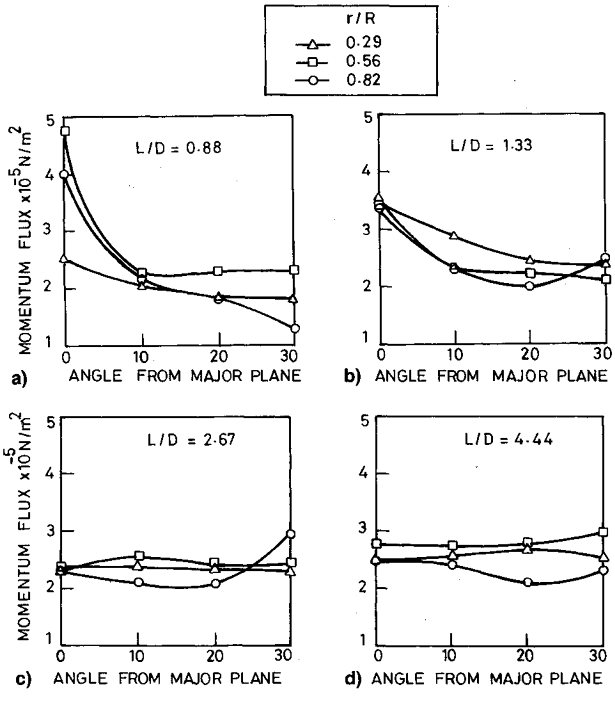
During each run, the upstream stagnation pressures of the primary and the secondary streams are set and maintained at the predetermined values by means of pressure regulating valves. Surveys of static and stagnation pressures are done using a three-dimensional traversing mechanism. The probes were carefully positioned at the desired radial and axial locations. To study the extent of mixing and the drop in stagnation pressure at various axial locations, mixing tubes of different lengths are used. For each mixing tube, the pressure readings are taken close to the downstream end of the tube. The movement of the probe holder in the radial direction is controlled by a stepper motor.

## III. Results and Discussion

### A. Momentum Mixing in the Azimuthal Plane

As the geometry of petal nozzle is not axisymmetric, the uniformity of momentum flux in radial direction[7] need not imply mixing in the azimuthal direction. To check the extent of mixing in the transverse planes, measurements are done along radial lines in four angular locations spread over 30 deg. This angular segment is bounded by the major and minor planes (Fig. 2b) and from the geometry of the six-lobed nozzle it is clear that the flow pattern in the other segments should be similar.

Figure 3 shows the angular distributions of momentum flux at four axial locations characterized by the $L/D$ ratio of the mixing tube. The results are plotted for three radial locations ($r/R$ denotes the nondimensional radial distance from the axis of the mixing tube). In the abscissa of the plots, 0 deg corresponds to the major plane and 30 deg to the minor plane. At $L/D = 0.88$, a clear distinction exists between the momenta in the two planes. The primary stream that possesses higher momentum, issues along the major plane, through the lobe region. The secondary stream, having a lower momentum, issues through the interlobe region that is centered around the minor plane. Hence, the high value of momentum flux near 0 deg (major plane) and much lower value near 30 deg (minor plane) show that at $L/D = 0.88$ the two streams still retain their identity and there is no appreciable mixing between the two.



a) ANGLE FROM MAJOR PLANE b) ANGLE FROM MAJOR PLANE

c) ANGLE FROM MAJOR PLANE d) ANGLE FROM MAJOR PLANE

**Fig. 3 Distribution of momentum flux in angular planes (petal nozzle).**

In contrast to this, at $L/D = 2.67$ (Fig. 3c), it is seen that the momentum profile becomes more or less uniform in the azimuthal plane. The distribution highlights the striking difference in momentum profiles at $L/D = 0.88$ and $L/D = 2.67$. In the latter case it can be seen that the high primary momentum has diffused in the angular direction, the conclusion being that a fair amount of momentum mixing has taken place between $L/D = 0.88$ and 2.67. This rapid mixing can be attributed to the generation of large-scale vortices as discussed in Refs. 3 and 4. Further downstream at $L/D = 4.44$, the distribution of momentum flux is still better as shown in Fig. 3d. This shows that good momentum mixing has taken place over this length of the mixing tube.

The previous results conclusively show that the petal nozzle produces rapid mixing not only in the radial direction, but in the lateral azimuthal planes as well.

### B. Mixing and Pressure Drop with Petal and Conical Nozzles

The loss of stagnation pressure encountered in the flow system employing a petal nozzle is also determined. Using those results a compromise between the mixing enhancement and the associated pressure loss has been made. The first step is to make a comparison between the mixing performances of the petal and the conical nozzles based on a quantitative assessment of the level of mixing achieved. For this purpose a dimensionless parameter called uniformity factor $\phi$ is defined as

$$\phi = 1 - [\sigma_\mu(x)/\mu_{\mathrm{av}}(x)]$$

where $\sigma_\mu$ denotes the standard deviations of the radial distributions of momentum at a given axial location along the mixing tube. The denominator is the average of momentum flux along a radial line at the location considered.

The previous definition of the uniformity parameter may be explained as follows. This factor is basically a measure of the uniformity of the momentum flux distribution in the radial direction, at a given axial station. For a perfectly mixed flow, the distribution has to be uniform across the section (neglecting the thin viscous layer). As there exists a momentum gradient between the primary and the secondary streams in the minor plane, an unmixed flowfield will be severely nonuniform in the radial direction, showing a higher momentum across the primary region and lower momentum across the secondary.[7] The standard deviation term in the definition of $\phi$ represents the nonuniformity. This is normalized by the average value of momentum flux and subtracted from unity so that the resulting parameter would represent the degree of uniformity at the given section. For a perfectly flat momentum profile ($\sigma_\mu = 0$), $\phi$ will be equal to unity, as is clear from the definition. The uniformity factor is used to define a mixing parameter called the degree of mixing (DOM). The latter is defined as

$$\mathrm{DOM} = (\phi - \phi_{\mathrm{um}})/(1 - \phi_{\mathrm{um}})$$

where $\phi_{\mathrm{um}}$ represents the value of $\phi$ when the two streams are totally unmixed. This parameter (DOM) gives a direct measure of the mixedness of the combined stream. It can be seen that when the two streams are completely mixed (as it would be in the ideal case), DOM will be equal to unity (as $\phi = 1$), and when they are totally unmixed ($\phi = \phi_{\mathrm{um}}$), DOM will be equal to zero. This parameter is used for comparing the extent of mixing achieved by the two types of nozzles.

Figure 4 compares the variation of DOM for petal and conical nozzles. For conical nozzle the parameter asymptotes to a value of nearly 0.3 rather quickly and repeated tests confirm this trend. The values for petal nozzle are appreciably higher than those for conical nozzle. At $L/D = 4.44$, the petal nozzle attains nearly 60% more uniformity than the

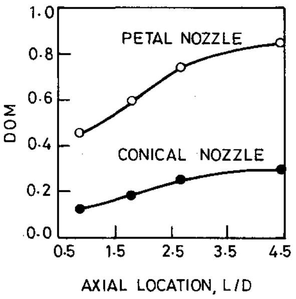


**Fig. 4 Comparison of mixing parameter for petal and conical nozzles.**

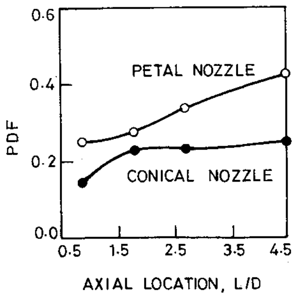


**Fig. 5 Comparison of pressure drop for the two types of nozzles.**

conical nozzle. It can be seen that DOM for the petal nozzle comes closer to the ideal value of unity. Another notable feature is that with a petal nozzle a practically complete mixing in radial direction can be obtained within an $L/D$ of 2.67. This, in conjunction with the observation on momentum flux profiles in angular plane discussed in the previous section, proves that a petal nozzle achieves nearly complete momentum mixing in a three-dimensional flowfield, within a short mixing chamber. In practical applications a reduction in the length of mixing chamber is expedient as it implies a reduction in the overall bulk and weight of the propulsion system. The enhancement of momentum mixing is of particular importance in acoustics and in applications like supersonic ejectors. Results of the present study can also give guidelines for further research on the application of radially lobed nozzles in scramjets, air augmented rockets, etc., despite the fact that in such applications the convective and diffusive mixing of the fuel and air is the dominant issue. Since it has been observed that in lobed nozzles the transport of axial momentum is a result of large-scale circulations,[4] the momentum mixedness can be used as a direct indication of the degree of convective mixing.

To characterize the drop in stagnation pressure a pressure drop factor (PDF) is defined. The primary and secondary streams enter the mixing tube with different stagnation pressures. Hence, PDF is defined as the difference between the weighted average stagnation pressures at inlet and at the axial station considered, normalized by the weighted average of the inlet stagnation pressures. Inlet here means inlet to the primary and secondary nozzles. The weighted-averaging of any quantity in the axisymmetric flowfield produced by the conical nozzle is trivial, but it is not so in the case of the nonaxisymmetric flowfield in the mixing chamber of the petal nozzle. This problem is handled as follows: the exit plane of the six-lobed nozzle can be considered to be symmetric with respect to an angular segment covering 30 deg (Fig. 2b). Hence, such a segment bounded by adjacent major and minor planes is subdivided into four sections and the radial survey of pressures is conducted along each section at the mixing tube end. The weighted averaging of data corresponding to each radial location is first done over the 30-deg angle and the resulting average value is used to compute the weighted average over the entire section.

The PDF is shown plotted for the two nozzles in Fig. 5. The increase in pressure drop in the case of petal nozzle is clearly seen. This additional pressure loss is more predominant at larger $L/D$. It can be seen that for $L/D = 4.44$, the total pressure drop for the petal nozzle is nearly 100% more than that for conical nozzle. The additional stagnation pressure drop in the case of petal nozzle can be attributed to the following factors:

1) The probable increased shock losses due to a complex shock-infested flowfield as reported in the shadowgraph study of Ref. 7.

2) The losses due to the enhanced mixing.

3) Increased viscous losses inside the nozzle due to increased surface area compared to the conical nozzle (note that the pressure drop factor as defined here includes the pressure drop inside the nozzles also).

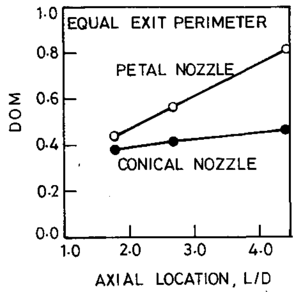


**Fig. 6 Mixing parameter for nozzles with equal shear area at exit.**

Comparing the improvement in mixing and increase in stagnation pressure loss associated with petal nozzle as shown in Figs. 4 and 5, an important conclusion of practical interest can be drawn. For an $L/D$ of 2.67, petal nozzle gives nearly complete mixing and the pressure loss over this length is only 50% over that for the conical nozzle. For $L/D = 4.44$, mixing is nearly uniform, but the associated total pressure drop is 100% more than that of conical nozzle. Hence, it appears that an $L/D$ in the range of 2.5–2.8 can be a practically viable compromise between the gain and the loss. In retrospect, an $L/D$ of 2.5–2.8 corresponds to an optimum length of mixing chamber for the given conditions. To further assess quantitatively the validity of this conclusion in the case of scramjet application, experiments have to be conducted with supersonic combustion in the mixing chamber and the achievable specific impulse values should be compared.

### C. Petal and Conical Nozzle with Equal Shear Area

For the same exit area, a petal nozzle has more shear area than a conical nozzle, owing to the larger perimeter at exit. This can be one of the contributing factors to the enhanced mixing. To gain an insight into the relative contribution of this increased shear area, a three-lobed petal nozzle and a conical nozzle, both having the same exit perimeter, are compared for their mixing performance. The results are shown in Fig. 6. From the values of DOM it is clear that even with equal shear area, the conical nozzle cannot match the performance of the petal nozzle. However, comparing the difference in DOM between the two types of nozzles in this equiperimeter case with that in the earlier case, Fig. 4 (where the conical nozzle has a smaller perimeter than the petal nozzle), it can be seen that there is a slight improvement in the relative performance of the conical nozzle. But it is not comparable with the high degree of momentum mixing achieved with the petal nozzle. The major inference from this comparative study is that the contribution of the increased shear area to mixing is comparatively marginal and any study to optimize nozzle geometry should focus on methods to promote the other contributing factors, discussed in Ref. 3.

From Figs. 4 and 6, the difference in performance characteristics of six- and three-lobed nozzles can be noted. The three-lobed nozzle seems to give a less rapid mixing initially, but produces good mixing over an $L/D$ of 4.44. Detailed studies on the optimization of number of lobes can give very useful information to the designer.

## IV. Conclusions

The following are the conclusions drawn from the present study:

1) A six-lobed petal nozzle provides complete lateral mixing of supersonic streams in a comparatively short length of the mixing chamber. For the present case, when the two streams are of Mach number 1.7 and 1, respectively, the mixing was fairly complete within an $L/D$ of 2.67. $L/D = 4.44$ gives a nearly flat momentum profile.

2) Superiority of mixing performance of the petal nozzle over that of the conventional conical nozzle has been quantitatively assessed based on a comparative study of uniformity of the momentum distribution in radial direction at the end of mixing tubes of various lengths. The values of mixing parameter showed that the mixing achieved by petal nozzle is close to the ideal case of complete mixing, whereas the performance of the conical nozzle is very poor.

3) The stagnation pressure loss associated with petal nozzle is more than that for conical nozzle. However, for the given conditions there seems to be an optimum value of $L/D$, such that the enhanced mixing of petal nozzle can be achieved without an excessive increase in pressure loss.

4) As far as mixing enhancement is concerned, the contribution of increased perimeter at the nozzle exit is relatively marginal as compared to that of the large-scale vortices induced by the lobed geometry.

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## References

[1] Papamoschou, D., and Roshko, A., "The Compressible Turbulent Shear Layer: An Experimental Study," *Journal of Fluid Mechanics*, Vol. 197, Dec. 1988, pp. 453–477.

[2] Elliott, G. S., and Samimy, M., "Compressibility Effects in Free Shear Layers," *Physics of Fluids A*, Vol. 2, No. 7, 1990, pp. 1231–1240.

[3] Tillman, T. G., Patrick, W. P., and Paterson, R. W., "Enhanced Mixing of Supersonic Jets," *Journal of Propulsion and Power*, Vol. 7, No. 6, 1991, pp. 1006–1114.

[4] Paterson, R. W., "Turbofan Mixer Nozzle Flowfield—A Benchmark Experimental Study," *Journal of Engineering for Gas Turbines and Power*, Vol. 106, July 1984, pp. 692–698.

[5] Barber, T. J., Muller, G. L., Ramsay, S. M., and Murmann, E. M., "Three-Dimensional Inviscid Flow in Mixers, Part II: Analysis of Turbofan Forced Mixers," *Journal of Propulsion and Power*, Vol. 2, No. 4, 1986, pp. 339–344.

[6] Koutmos, P., and McGuirk, J. J., "Turbofan Forced Mixer/Nozzle Temperature and Flow Field Modelling," *International Journal of Heat and Mass Transfer*, Vol. 32, No. 6, 1989, pp. 1141–1153.

[7] Anil, K. N., "An Experimental Study on the Mixing of Two High Speed Co-Axial Streams," Ph.D. Dissertation, Dept. of Aerospace Engineering, Indian Inst. of Technology, Madras, India, 1992.

[8] Anil, K. N., and Damodaran, K. A., "Preliminary Investigations on Improving Air-Augmented Rocket Performance," *Journal of Propulsion and Power*, Vol. 10, No. 3, 1994, pp. 432–434.

[9] Shetz, J. A., Billig, F. S., and Favin, S., "Flowfield Analysis of a Scramjet Combustor with a Coaxial Fuel Jet," *AIAA Journal*, Vol. 20, No. 9, 1982, pp. 1268–1274.

[10] Barber, T. J., and Anderson, O. L., "Computational Study of a Supersonic Mixer-Ejector Exhaust System," *Journal of Propulsion and Power*, Vol. 8, No. 5, 1992, pp. 927–934.

[11] Tillman, E. G., Paterson, R. W., and Presz, W. M., Jr., "Supersonic Nozzle Mixer Ejector," *Journal of Propulsion and Power*, Vol. 8, No. 2, 1992, pp. 513–519.