Technical Notes

TECHNICAL NOTES *are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).*

AIAA 81-4013

Effects of Axisymmetric Sonic Nozzle Geometry on Mach Disk Characteristics

A. L. Addy*
University of Illinois at Urbana-Champaign, Urbana, Ill.

Introduction

THE Mach disk is a distinctive characteristic of the near-field shock wave structure in freejet flows from sonic or supersonic nozzles. In this Note, results are presented from an experimental investigation of the effects of axisymmetric sonic nozzle geometry on the onset, diameter, and location of the Mach disk in moderately underexpanded freejet flows. The axisymmetric nozzle geometries investigated were a contoured converging nozzle, four conically converging sharp-edged nozzles, and a sharp-edged orifice.

Previous experimental investigations of the Mach disk were less conducted for axisymmetric[1-6] and planar[7,8] nozzle geometries which produced uniform sonic or supersonic flows. These investigations established empirical relationships between the stagnation-to-ambient pressure ratio and the Mach disk diameter and location for different gases,[1,2,5,7,8] gas-particle flows,[3,4] and reacting gas flows.[6]

Theoretical models for predicting Mach disk location and diameter range in complexity from postulations concerning the pressure at the Mach disk[2,9] to coupling between the shock-wave structure and the accelerating subsonic flow downstream of the Mach disk.[10-13] While these models have been used primarily to analyze freejet flows from uniform flow sonic or supersonic nozzles, they could, in principle, be extended to analyze freejet flows from nonuniform flow nozzles. Diringer[12] analyzed the freejet flow from a conically converging sharp-edged nozzle with a highly distorted sonic line; the predicted and experimental flowfield shock-wave structure were in good agreement.

Experiments

The experimental apparatus and the geometries of the six axisymmetric sonic nozzles that were used in this investigation are shown in Fig. 1. During the experiments, the stagnation pressure P_0 upstream of the nozzle was varied while the back pressure P_b in the observation chamber was maintained approximately constant. Consequently, the Reynolds number based on nozzle exit diameter varied in the approximate range $10^5 < R_{e,D} < 5 \times 10^6$. The Mach disk diameters and locations were determined from short-duration, 10 μs shadowgraph photographs of the freejet flowfields.

Results

The mass flowrate and choking characteristics of the six sonic nozzles were investigated over the stagnation-to-back pressure ratio range of $1 < P_0/P_b < 10$. The limiting experimental values of the mass flowrate coefficient and the stagnation-to-back pressure ratio for choked flow are tabulated in Table. 1. The deviations of the observed mass flowrate coefficient and the choking pressure ratio from the values of ideal, one-dimensional flow are measures of the distortion of the sonic line and interactions with the sonic line in these nozzles.

The experimental data for the Mach disk diameter and location are compiled and presented in Fig. 2 for the six sonic nozzle geometries investigated. The onset of the Mach disk structure for the different nozzles is indicated by the shaded portion of Fig. 2 for which $D_{md}/D_n \simeq 0$; the pressure ratio for the onset of the Mach disk structure is seen to increase with nozzle convergence angle. If the convergence angle at the nozzle exit plane is taken to define the nozzle geometry, a plot of the stagnation-to-back pressure ratio for the onset of the Mach disk structure can be defined; Fig. 3 is such a plot for the nozzle geometries investigated. The shaded region in Fig. 3 represents the uncertainty band associated with the transition to the Mach disk shock structure; this transition region is accompanied by instabilities in the shock structure near the flow axis.

Near onset of the Mach disk, instability in the shock wave structure made it difficult to determine accurately the location of the Mach disk for the sharp-edged nozzles. As a result, data for the location of the Mach disk in the transitional regime are presented in Fig. 2 for only the converging nozzle. In the well-established Mach disk regime of Fig. 2, the Mach disk location is not significantly affected by the sonic nozzle geometry; the empirical equation, curve 3, proposed by Crist et al.[5] is shown to correlate well the Mach disk location data except for the contoured converging nozzle ($\beta_n = 0$) data at low operating pressure ratios.

In Fig. 2 the Mach disk diameter varies significantly between the contoured converging and sharp-edged nozzles. All sharp-edged nozzle data have consistently smaller values of the diameter ratio, D_{md}/D_n; after the Mach disk structure is well established, the D_{md}/D_n data are clustered for all the sharp-edged nozzles. Crist et al.[5] and Davidor and Penner[6] proposed an empirical correlation for large pressure ratios that the Mach disk diameter and location are linearly related; from Fig. 2 it is evident that a linear relationship does not hold for moderately underexpanded pressure ratios. Rather, the Mach disk diameter data are better correlated for the smooth converging nozzle ($\beta_n = 0$) by the empirical equation, curve 1,

$$D_{md}/D_n = 0.36(P_0/P_b - 3.9)^{1/2} \tag{1}$$

Table 1 Experimentally determined sonic nozzle performance characteristics

Nozzle geometry, β_n, deg	Mass flowrate coefficient,[a] C_f	Observed choking pressure ratio,[b] $(P_0/P_b)_{\text{choked}}$
0 (contoured)	0.975	1.92
30	0.927	2.78
45	0.898	3.85
60	0.869	5.00
75	0.839	5.56
90 (orifice)	0.812	5.88

[a] For these experiments, $R_{e,D} > 10^6$. [b] For air flow, the ideal choking pressure ratio is $P_0/P_b = 1.894$.

Received Jan. 14, 1980; revision received May 5, 1980.

*Professor of Mechanical Engineering, Department of Mechanical and Industrial Engineering. Associate Fellow AIAA.

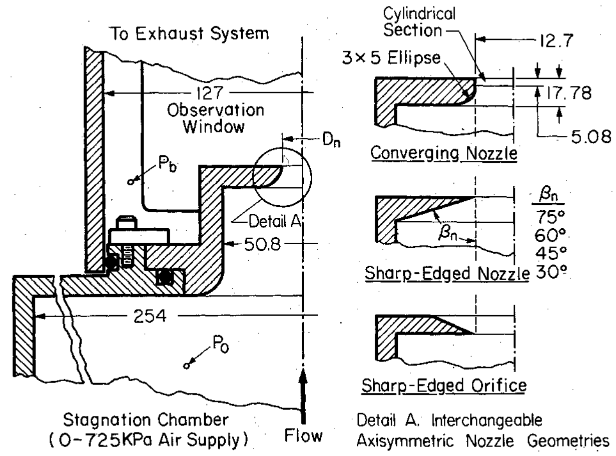

Fig. 1 Experimental apparatus and soniz nozzle geometries for Mach disk investigation. (All dimensions are in millimeters.)

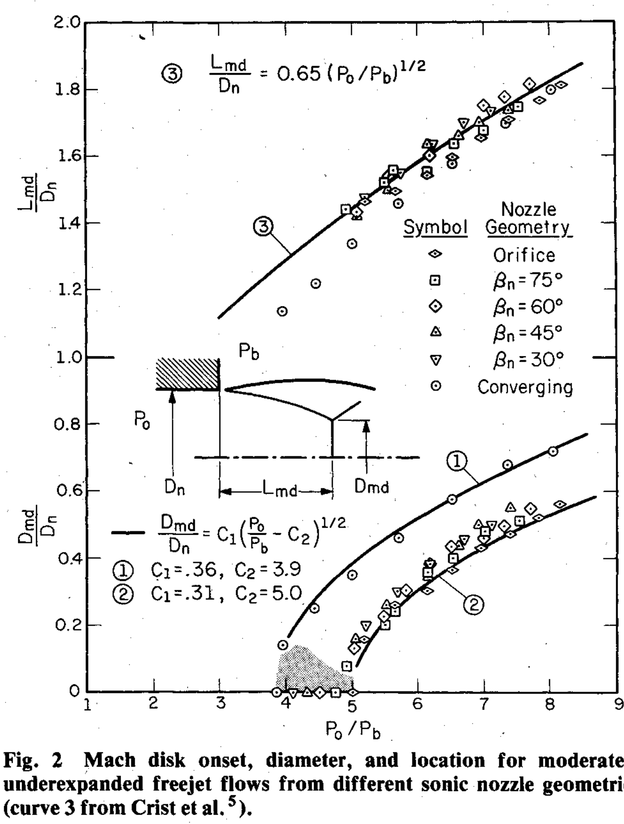

Fig. 2 Mach disk onset, diameter, and location for moderately underexpanded freejet flows from different sonic nozzle geometries (curve 3 from Crist et al.[5]).

and for the sharp-edged orifice ($\beta_n = 90$ deg) by the empirical equation, curve 2,

$$D_{md}/D_n = 0.31\,(P_0/P_b - 5.0)^{1/2} \tag{2}$$

All Mach disk diameter data are bounded by Eqs. (1) and (2); the data for the five sharp-edged nozzles are, for the most part, clustered near curve 2 corresponding to Eq. (2).

Conclusions

Empirical correlations and bounds were established from these experiments for the Mach disk diameter and location for moderately underexpanded pressure ratios and extremes in sonic nozzle geometry. It was observed that the pressure ratio at the onset of the Mach disk increased smoothly and continuously with the convergence angle of the nozzle and that the Mach disk structure was stable and well established for all nozzles when $P_0/P_b > 5$. In this regime, the Mach disk location was relatively independent of the nozzle geometry

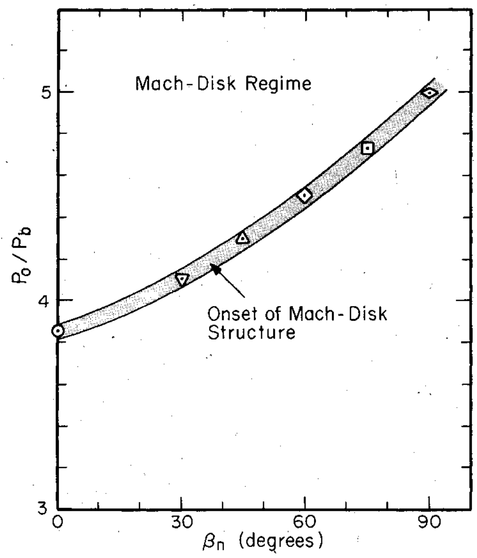

Fig. 3 Onset of Mach disk structure from different sonic nozzle geometries.

and convergence angle and was well correlated by the empirical expression developed by Crist et al.[5] from their high-pressure experiments. In contrast, the Mach disk diameter in this regime was affected strongly by the nozzle geometry and was affected weakly by the convergence angle of the sharp-edged nozzles.

These experimentally observed effects are attributed primarily to the distortion of the sonic line due to nozzle geometry and to local interaction between waves in the flowfield and the sonic line. However, the extent and coupling of these phenomena are not well understood and require further investigation. Of particular interest are: the onset of the Mach disk, intermittent jet screech, instability of the shock structure to small and large disturbances, and their coupling.

References

[1] Hartmann, J. and Lazarus, F., "The Air-Jet with a Velocity Exceeding that of Sound," *Philosophical Magazine and Journal of Science*, Vol. XXXI, 7th Series, No. 204, Jan. 1941, pp. 35-50.

[2] Adamson, T. C., Jr. and Nicholls, J. A., "On the Structure of Jets from Highly Underexpanded Nozzles into Still Air," *Journal of the Aerospace Sciences*, Vol. 26, Jan. 1959, pp. 16-24.

[3] Lewis, C. H., Jr. and Carlson, D. J., "Normal Shock Location in Underexpanded Gas and Gas-Particle Jets," *AIAA Journal*, Vol. 2, April 1964, pp. 776-777.

[4] Bauer, A. B., "Normal Shock Location of Underexpanded Gas-Particle Jets, *AIAA Journal*, Vol. 3, June 1965, pp. 1187-1189.

[5] Crist, S., Sherman, P. M., and Glass, D. R., "Study of the Highly Underexpanded Sonic Jet," *AIAA Journal*, Vol. 4, Jan. 1966, pp. 68-71.

[6] Davidor, W. and Penner, S. S., "Shock Standoff Distances and Mach Disk Diameters in Underexpanded Sonic Jets," *AIAA Journal*, Vol. 9, Aug. 1971, pp. 1651-1653.

[7] Sheeran, W. J., and Dosanjh, S., "Observations on Jet Flows from a Two-Dimensional, Underexpanded, Sonic Nozzle," *AIAA Journal*, Vol. 6, March 1968, pp. 540-542.

[8] Werle, M. J., Shaffer, D. G., and Driftmyer, R. T., "Freejet Terminal Shocks," *AIAA Journal*, Vol. 8, Dec. 1970, pp. 2295-2297.

[9] Eastman, D. W., and Radtke, L. P., "Location of the Normal Shock Wave in the Exhaust Plume of a Jet," *AIAA Journal*, Vol. 1, April 1963, pp. 918-919.

[10] Abdelhamid, A. N. and Dosanjh, D. S., "Mach Disk and Riemann Wave in Underexpanded Jet Flows," AIAA Paper, 69-665, San Francisco, Calif., June 1969.

[11] Abbett, M., "The Mach Disk in Underexpanded Exhaust Plumes," *AIAA Journal*, Vol. 9, March 1971, pp. 512-514.

[12] Diringer, P., "Reflexions Regulieres et Singulieres d'Ondes de Choc Applications aux entrees d'Air et au Probleme due Disque de Mach," Office National d'Etudes et de Recherches Aerospatiales, Note Technique 183, 1971.

[13] Fox, J. H., "On the Structure of Jet Plumes," *AIAA Journal*, Vol. 12, Jan. 1974, pp. 105-107.