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).

Performance Characteristics of an Underexpanded Multiple Jet Ejector

M. S. Chandrasekhara*
Naval Postgraduate School, Monterey, California 93943
A. Krothapalli†
Florida State University, Tallahassee, Florida 32301
and
D. Baganoff‡
Stanford University, Stanford, California 94305

Nomenclature

A = cross-sectional area of the mixing duct
$\overline{C_{P_t}}$ = average throat static pressure coefficient
D = nozzle exit width
P_0 = nozzle pressure
p_a = atmospheric pressure
$\overline{p_t}$ = average throat static pressure
R = nozzle pressure ratio
$\bar{U}$ = longitudinal mean velocity
X, Y, Z = Cartesian coordinate system
Φ = thrust augmentation ratio
Ψ = mass augmentation ratio
ρ = density

I. Introduction

SEVERAL experimental studies have been reported[1-5] on thrust augmenting ejectors using a single jet. The necessary theoretical framework for this was provided by Von Karman[6] and Keenan et al.[7] One of the main observations from earlier work on ejectors is that the ejector performance can be greatly improved, if the primary and secondary flows mix completely inside the ejector duct. Consequently, several mixing ideas such as the hypermixing nozzles (Bevilaqua[8]) and use of screech tones (Hsia,[4] Krothapalli et al.[9]) have been tried out successfully in ejectors with a single primary jet.

In many practical applications, such as in an augmentor wing for V/STOL aircraft,[10] it is common to use a linear array of nozzles as shown in Fig. 1. These multiple jets (MJ) are generally believed to have superior mixing characteristics, and hence a multiple jet ejector can be expected to deliver a better performance than the single jet ejector. Ejectors used in such applications typically employ a large area ratio of about 20–30. They operate quietly even under supersonic discharge conditions and hence offer some advantages. But, the available data on such large area ratio multiple jet ejectors is scant, at best. The present study was aimed at providing this vital information.

To evaluate and ascertain the possible superior performance of a multiple jet ejector, it is necessary to obtain results on an "equivalent" single jet (ESJ) ejector. A complete definition of the equivalent single jet is not possible because such a jet should be able to generate the effects and flowfields of a multiple jet system in totality. This includes the pressure field set up by the merging jets, the appropriate length scales for the developing as well as the resulting flow, the effect of jet spacing, etc. With these limitations in mind, the equivalent single jet is defined here as *a jet having the same total area (momentum) and aspect ratio as that of the multiple jet system* tested. Identical tests under identical conditions were carried out on both jet assemblies and their performances were compared. The performance characteristics of an ejector are a function of the following: nozzle pressure ratio, ejector area to jet area ratio, distance from the nozzle exit plane to the throat of the ejector shroud, the number of jets, the spacing between the jets, and the mixing shroud length/diameter ratio. The experiments were carried out to study the effects of these parameters.

II. Experimental Apparatus and Procedure

A high-pressure blow-down type air supply stream was used to provide the airflow to a settling chamber 1.75 m long and 0.6 m in diameter. The settling chamber temperature was maintained constant at room conditions, to within 0.5°C over the duration of each test. The flow passed through an adapter containing six flow control screens set 5 cm apart before exhausting through the nozzles.

Two sonic nozzle assemblies were used in the experiment. The multilobe nozzle, shown in Fig. 1a, consisted of five rectangular lobes, spaced 2.4 cm apart, each 0.3 cm wide and 5 cm long, placed on a wedge of 70-deg included angle. Most of the experiments were performed by using the central three lobes. A Cartesian coordinate system defined in Figs. 1 was used for defining the flow.

Data on the equivalent single jet were obtained using the nozzle shown in Fig. 1b. Its exit dimensions were determined to be 0.52 × 8.66 cm, with a 70-deg included angle, by stipulating that its aspect ratio and total flow be the same as that of the multiple jets. However, its longer dimension was chosen to be along the wedge so that the same settling chamber and ejector shroud as was used for the multiple jet system could be used.

The ejector shroud was a 50-cm-long constant area duct with a rounded bell mouth inlet (sealed at the corners) to permit gradual acceleration of the entrained air; it is shown schematically in Fig. 1c. The inside flow area could be varied by moving these four walls continuously in the X-Y plane and discretely in the X-Z plane. The shroud could be moved relative to the nozzle exit plane. Accordingly, the throat position, defined to be the plane where the bell mouth meets the straight walls, could also be varied.

Static pressure measurements and velocity measurements with a hot wire were obtained at stagnation pressures ranging from 1.36 to 3.4 kg/cm^2 ($R = 1.36$–3.4) for ejector area to

---

Presented as Paper 87-0248 at the AIAA 25th Aerospace Sciences Meeting, Reno, NV, Jan. 12–15, 1987; received May 4, 1989; revision received May 9, 1990; accepted for publication May 15, 1990.

*Adjunct Research Professor and Assistant Director, Navy-NASA Joint Institute for Aeronautics, Department of Aeronautics and Astronautics, M.S. 260-1, NASA Ames Research Center, Moffett Field, CA 94035. Associate Fellow AIAA.

†Professor and Chairman, Department of Mechanical Engineering, FAMU/FSU College of Engineering. Senior Member AIAA.

‡Professor, Department of Aeronautics and Astronautics. Member AIAA.

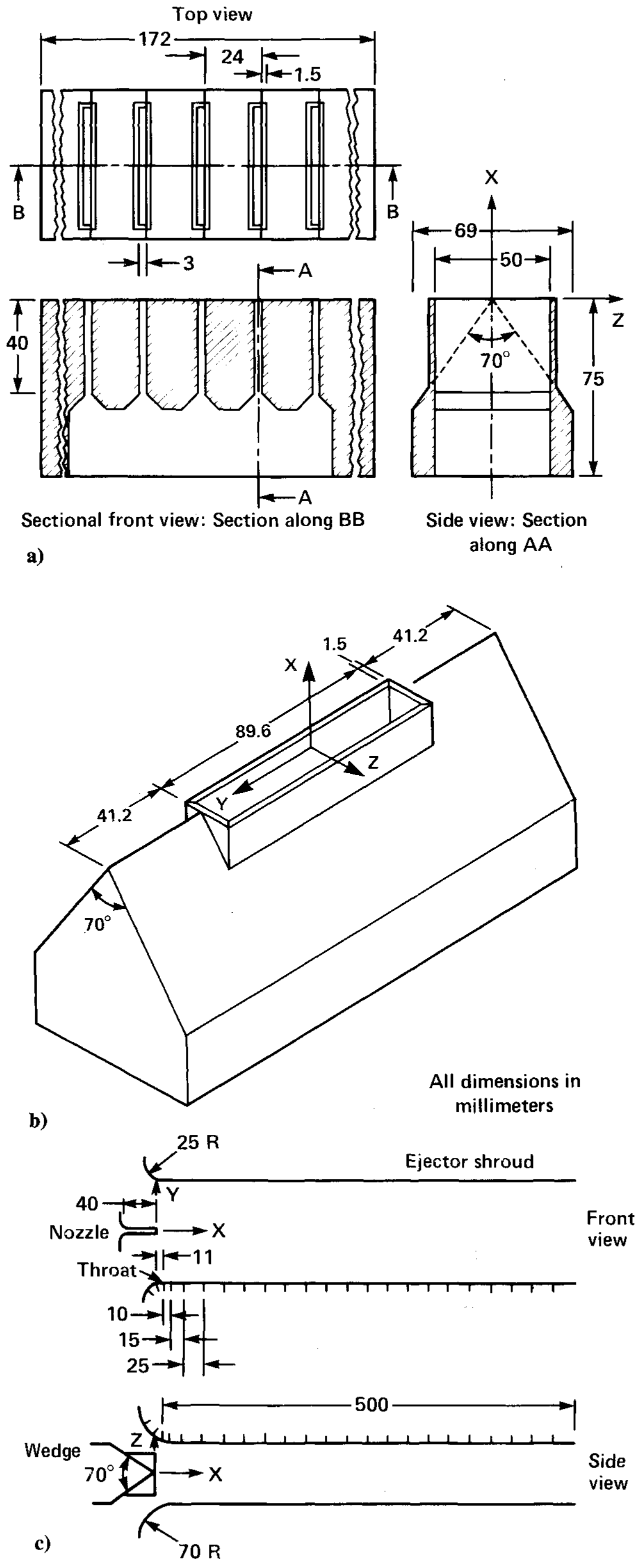

Fig. 1 Schematic of the ejectors studied: a) multiple jet system; b) equivalent single jet; c) details of the ejector shroud and wall pressure taps.

nozzle area ratios of 14, 20, 26, and 33. Sufficient care was taken to insure that the experimental conditions were steady and that the temperature was the same as that during calibration of the hot wire. Further details can be found in Chandrasekhara et al.[11]

In addition to the previously mentioned quantitative measurements, schlieren flow visualization studies were also conducted. These studies showed no screech tones and indicated that acoustic interaction was not a significant factor in the multiple jet flow. These studies have been presented in detail in Refs. 11 and 12.

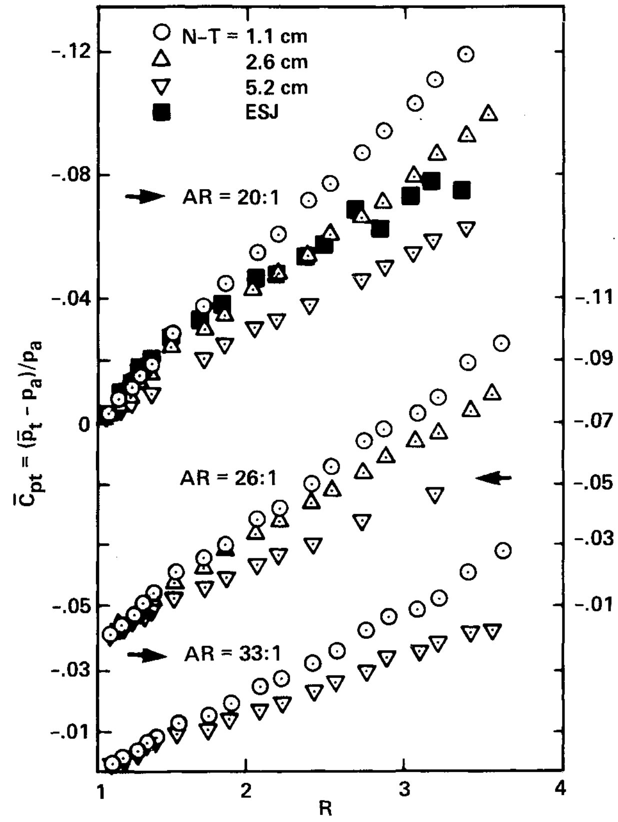

Fig. 2 Effect of nozzle-throat distance on throat static pressure coefficient for different area ratios: open symbols—multiple jets; filled symbols—equivalent single jet.

III. Results and Discussion

A. Surface Pressure Measurements

The thrust contributed by the ejector shroud with a curved wall is equal to the integration of the force due to the wall pressure in the projection plane perpendicular to the ejector axis. (See Ref. 6 for a description of augmentation based on energy transfer between the primary and secondary streams.) For an ejector with a constant area mixing duct, the excess thrust is produced mainly from the inlet section. This being the case, the magnitude of surface pressure in the inlet region can determine the thrust augmentation of an ejector. Figure 2 is a plot of the average of the measured throat pressures in a plane, $\overline{C_{P_t}}$, vs the pressure ratio for different area ratios and nozzle-throat distances (N-T). As indicated by the one-dimensional, inviscid, compressible flow analysis of Keenan et al.,[7] it was found that the throat pressure varied linearly with increasing nozzle-throat distance. An increase in the value of $\overline{C_{P_t}}$ generally means less entrainment of the ambient fluid and, hence, a degradation of the total performance. At larger area ratios, at 33, for example the sensitivity of $\overline{C_{P_t}}$ to changes in nozzle-throat distance is relatively less. For the equivalent single jet ejector, it was observed[11] that the variation of $\overline{C_{P_t}}$ with R was insensitive to changes in nozzle-throat distance in the range tested.

Figure 2 also compares the $\overline{C_{P_t}}$ variation with R for both single and multiple jet ejectors at an area ratio of 20 for a nozzle-throat distance of 1.1 cm. For this area ratio and for underexpanded conditions, the $\overline{C_{P_t}}$ values for the multiple jet ejector are lower, indicating a better performance. The irregular behavior of $\overline{C_{P_t}}$ for a single jet ejector is a result of acoustic interactions inside the duct, the details of which are described by Hsia et al.[2] It was also found that, for subsonic conditions, i.e., for $R \leq 1.9$, the difference in the data for single and multiple jet ejectors at corresponding conditions are insignificant. Similar observations were also made at other area ratios greater than 20.

B. Performance Characteristics

The performance characteristics of an ejector are measured in terms of the mass augmentation ratio Ψ and thrust augmentation ratio Φ. These are defined here as

$$\Psi = \frac{\text{total mass flow at the duct exit (primary + secondary)}}{\text{primary jet mass flow}}$$

$$\Phi = \frac{\text{actual thrust produced by the ejector}}{\text{thrust produced by isentropically expanding the primary jet}}$$

The actual thrust produced was not directly measured. It was estimated by integrating the measured exit velocity profiles and obtaining a mass averaged velocity. This method of performance computation depends on the accuracy of the hot-wire data and the distribution of data points across a profile. However, Φ and Ψ values computed for the two jets studied involve the same uncertainties, and so the comparison may still be valid.

The mass augmentation characteristics of the two ejectors are shown in Fig. 3a for an area ratio of 20. It can be seen that, under identical subsonic conditions of operation, the equivalent single jet ejector entrains about 5% more ambient air than a multiple jet ejector. However, for the case of the underexpanded multiple jet, the mass augmentation is higher than that of the corresponding single jet by about 10%.

The calculated thrust augmentation ratio Φ is plotted in Fig. 3b for different pressure ratios for an area ratio of 20. As before, it is observed that, for $R \leq 1.9$, the equivalent single jet ejector produces better augmentation than a corresponding multiple jet ejector. But, for $R \geq 1.9$, the multiple jet ejector provides about 10% augmentation in thrust. The reason for the drop in performance in the transonic region ($R \approx 2$) is not clear.

In order to better understand this observed effect, exit velocity profiles from the two ejector systems were compared for an area ratio of 20:1. These and additional results can be found in Ref. 11. It was found that, for $R = 1.7$ (subsonic conditions), the equivalent single jet system showed better mixing, as evidenced by the overlapping of the velocity distributions at different cross sections. On the other hand, for the supersonic discharge condition of $R = 3.38$, the multiple jet system showed better mixing. This is probably due to the stronger pressure field set up in the initial developing region for the underexpanded jet, creating a stronger interaction between the jets resulting in enhanced mixing. However, the flow in this region is very complex and needs to be studied in great detail before definitive explanations can be offered. Nevertheless, it is clear that better performance is always related to better mixing.

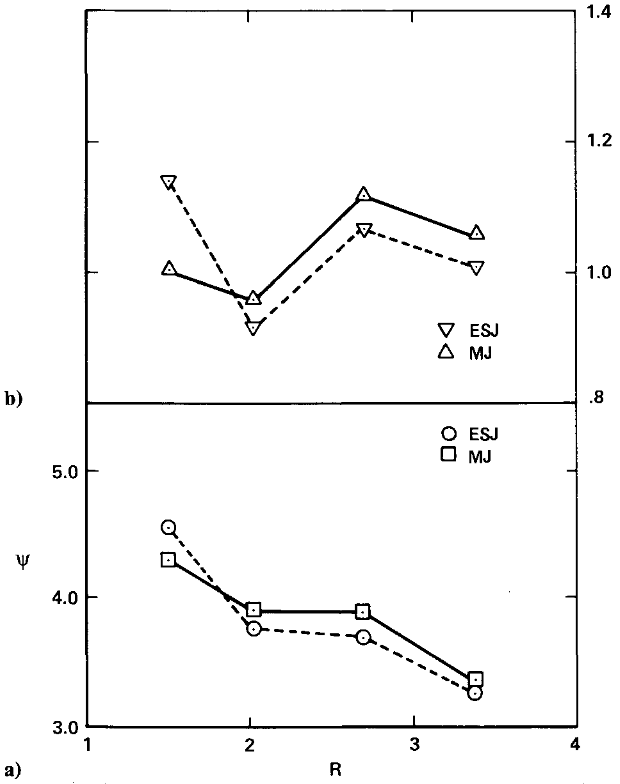

Fig. 3 Comparison of performance characteristics of the ejectors: a) mass augmentation Ψ; b) thrust augmentation Φ.

IV. Conclusions

This work was aimed at determining the performance of a supersonic multiple jet ejector. In so doing, it was realized that a proper base for comparison of the results was not available. The study was expanded to establish this base by defining an equivalent single jet ejector and conducting identical tests on an ejector using such a jet.

The following major conclusions can be drawn from this study:

1) The location of the ejector throat relative to the nozzle exit plane has a large effect on the ability of the ejector to entrain the ambient fluid and deliver a better performance. The performance deteriorates monotonically as the throat moves farther.

2) A multiple jet ejector is superior to a single jet ejector from a performance point of view because of enhanced mixing under supersonic conditions. For subsonic conditions, a single jet ejector seems to be better.

Acknowledgment

This work was supported by the Air Force Office of Scientific Research under Contract F 49620-79-0189.

References

[1] Hsia, Y. C., "An Experimental Investigation of an Underexpanded Rectangular Jet Ejector," Ph.D. Dissertation, Stanford University, Stanford, CA, March 1984.

[2] Hsia, Y. C., Krothapalli, A., and Baganoff, D., "Some Observations on the Mixing of an Underexpanded Rectangular Jet Ejector," *Journal of Propulsion and Power*, Vol. 4, No. 2, 1988, pp. 256-262.

[3] Bernal, L., and Sarohia, V. K., "Entrainment and Mixing in Thrust Augmenting Ejectors," Jet Propulsion Laboratory, California Inst. of Tech., Pasadena, CA, Rept. D-66, Feb. 1982.

[4] Viets, H., "Thrust Augmenting Ejectors," Aeronautical Research Lab., Wright Patterson Air Force Base, OH, Rept. 75-0224, Aug. 1975.

[5] Quinn, B., "Interaction Between Screech Tones and Ejector Performance," *Journal of Aircraft*, Vol. 14, No. 5, 1977, pp. 467-473.

[6] Von Karman, T., "Theoretical Remarks on Thrust Augmentation," Reissner Anniversary Volume, *Contributions to Applied Mechanics,* 1949.

[7] Keenan, J. H., Neumann, E. P., and Lustwerk, F., "An Investigation of Ejector Design by Analysis and Experiment," *Journal of Applied Mechanics*, Vol. 17, No. 3, 1950, pp. 299-309.

[8] Bevilaqua, P. M., "Evaluation of Hyper-Mixing for Thrust Augmenting Ejectors," *Journal of Aircraft*, Vol. 11, No. 6, 1974, pp. 348-354.

[9] Krothapalli, A., Hsia, Y. C., Baganoff, D., and Karamacheti, K., "The Role of Screech Tones in Mixing of an Underexpanded Rectangular Jet," *Journal of Sound and Vibration*, Vol. 106, No. 1, 1986, pp. 119-143.

[10] Aiken, T. N., "Aerodynamic and Noise Measurements on a Quasi-Two Dimensional Augmentor Wing Type Model with Lobe-Type Nozzles," NASA TMX-62237, Sept. 1973.

[11] Chandrasekhara, M. S., Krothapalli, A., and Baganoff, D., "Mixing Characteristics of an Unexpected Multiple Jet Ejector," Stanford University, Stanford, CA, JIAA TR-55, June 1984.

[12] Chandrasekhara, M. S., Krothapalli, A., and Baganoff, D., "Mixing Characteristics of a Supersonic Multiple Jet Ejector," AIAA Paper 87-0248, Jan. 1987.