CONSIDERATION OF SOME CRITICAL EJECTOR PROBLEMS

by

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INTRODUCTION

Recent research and development related to ejector thrust augmentation for V/STOL applications has been directed towards either a) methods for the achievement of improved mixing, or, b) attempts to minimize ejector size by the design of wide angle diffusers.

While FDRC has been concerned with these areas and has devoted a major portion of its effort to diffuser as well as simple and effective primary nozzle design, there has also been considerable effort to investigate other aspects of ejector design and application, including,

1. Three dimensional effects
2. Cross flow effects
3. Ejector as a propulsion device
   (underwater, subsonic, supersonic).

It has been shown that in a practical ejector, even one as small as the jet diffuser ejector, the mixing process, using a segmented slot nozzle, can provide sufficient mixing to permit performance equivalent to complete mixing, provided the effective diffuser area ratio is increased to compensate for the incomplete mixing. This increase of the effective diffuser area ratio is accomplished by a jet-diffuser.

The design of an efficient jet-diffuser, however, must consider the three-dimensionality of the flow field and provide a flow uniformity around the entire periphery of the ejector exit.

The influence of cross flow due to translation normal to the thrust vector has been investigated in the FDRC wind tunnel. The results indicate a very large increment of thrust (or lift) resulting from the ejector induced flow over the external fairings.

Work on the propulsive ejector, although of great interest, will not be discussed here.

LIST OF SYMBOLS

A_2	Area of ejector throat
a_∞	Area of primary jet after lossless expansion to ambient pressure
a_1	Area of primary jet after expansion to p_1, with loss corresponding to η_N
C_{di}	Inlet drag coefficient = $(P_{oe} - P_{o1})/[(\rho/2)U_1^2]$
C_F	Coefficient of skin friction based on A_2 and $\bar{U}_2$
C_f	Coefficient of skin friction based on two-dimensional wetted surface
C_{fdj}	Coefficient of skin friction for diffuser jet (jet-diffuser ejector)
ℓ_T	Mixing duct + diffuser length
$\dot{m}$	Mass flow rate
P_o	Stagnation pressure (gage) $(P_{op} = P_{od})$
U	Velocity
U'	Perturbation velocity
$\bar{U}$	Average velocity
V	Jet velocity
s_∞	Area of diffuser jet after lossless expansion to ambient pressure
X	Section width of a two-dimensional ejector
$\tilde{X}$	Effective section width of a two-dimensional ejector
α	Inlet area ratio = X_2/a_1
δ	Diffuser area ratio = X_3/X_2
δ^*	Effective diffuser area ratio (solid diffuser ejector) = $\tilde{X}_3/X_2$
η_{dj}	Efficiency of jet diffuser
η_N	Primary nozzle thrust efficiency = $V_{p\infty}/[(V_{p\infty})_{\text{lossless}}]$
λ	Non-dimensional velocity = U/V_{p1}
ρ	Mass density
ϕ	Thrust augmentation

SUBSCRIPTS

c	Core flow
d	Diffuser jet
e	Intake of induced flow
p	Primary jet, or intake of primary flow
∞	Free stream
1,2,3,4,J	Section index, see Figure 1

MIXING

The integration of ejectors with modern airframe designs, particularly for high speed aircraft, demands the development of small ejectors. As ejector size becomes smaller, the adequacy of mixing within the ejector duct becomes questionable. In a solid diffuser ejector, the flow returns to ambient pressure at or before the end of the solid surfaces. Thus mixing must be sufficiently complete within the ejector duct, to avoid performance penalties. The influence of incomplete mixing upon ejector performance is therefore an important area for investigation.

In a jet diffuser ejector, the flow does not return to ambient pressure for a considerable distance downstream of the solid surfaces of the diffuser. Thus the region available for effective mixing is considerably larger than that represented by solid surfaces, but the length of the extension of the flow pattern, beyond the solid surfaces, depends upon the adequacy of the design.

Three-dimensional effects in a jet-diffuser ejector of finite aspect ratio have been shown to limit the extent of the jet diffuser, but recent work in this area (to be discussed later) has improved this three-dimensional limitation.

Returning to the question of "How much mixing is adequate?", we have shown that, under the assumption that with incomplete mixing the velocity distribution at the diffuser exit can be described by the relationship

$$U_3 = \overline{U}_3 + U_3' \qquad (1)$$

where $|U_3'/\overline{U}_3| << 1.0$, (Figure 1).

Other parameters, and loss coefficients utilized in the analysis, are also illustrated on Figure 1.

Then with the assumption of incomplete mixing, the thrust augmentation ϕ of a stationary solid diffuser ejector in an incompressible fluid can be expressed as

$$\phi = \frac{\text{Ejector Thrust}}{\text{Reference Jet Thrust}} \tag{2}$$

$$= \eta_N \frac{\rho \int U_3^2 d\tilde{X}_3}{\text{Primary Jet Thrust at Ambient Pressure}} \tag{3}$$

$$= \eta_N (\dot{m}_c/\dot{m}_p) \left\{ \frac{\bar{U}_3 [1 + \overline{U_3'^2}/\bar{U}_3^2]}{V_{p\infty}} \right\} \tag{4}$$

$$= \eta_N \ (\dot{m}_c/\dot{m}_p)^2 \left\{ \frac{1 + \overline{U_3'^2}/\bar{U}_3^2}{\tilde{X}_3/X_2} \right\} \frac{1}{\alpha \sqrt{1 - (1 + C_{di}) \lambda_1^2}} \tag{5}$$

$$= \eta_N \ [1+(\alpha-1)\lambda_1] \sqrt{\frac{1}{[1-(1+C_{di})\lambda_1^2]} \left\{ \frac{1-\lambda_1^2}{\alpha^2} \left[1 + \frac{2(\alpha-1)}{1+\lambda_1} \right] - C_{di}\lambda_1^2 - C_F \left[\frac{1+(\alpha-1)\lambda_1}{\alpha} \right]^2 \right\}} \tag{6}$$

where

$$\lambda_1 = U_1/V_{p1} = \frac{-B + \sqrt{B^2 - AC}}{A} \tag{7}$$

and

$$A = (\alpha - 1)^2 + D^2 + \alpha^2 D^2 \ [C_{di} + (\frac{\alpha - 1}{\alpha})^2 C_F] \tag{8}$$

$$B = (\alpha - 1) \ [D^2 (1 + C_F) + 1] \tag{9}$$

$$C = 1 - D^2 \ [(2\alpha - 1) - C_F] \tag{10}$$

$$D = \frac{\tilde{X}_3/X_2}{1 + (\overline{U_3'^2}/\bar{U}_3^2)} \tag{11}$$

$$\alpha = X_2/a_1 \tag{12}$$

$$C_F = 2C_f \times [(\text{Mixing Duct + Diffuser Length})/\text{Throat Width } (X_2)] \tag{13}$$

Reference Jet Thrust = Thrust of lossless free jet having mass flow and power equal to those of ejector's primary jet.

It is well known that in a non-separating uniform flow analysis, the thrust augmentation increases with increasing values of X_3/X_2.

As a result of the above analysis, it is shown that the parameter $[\tilde{X}_3/X_2]/[1 + (\overline{U_3'^2}/\bar{U}_3^2)]$ can replace the diffuser area ratio (X_3/X_2) and $[\bar{U}_3/V_{pl}][1 + (\overline{U_3'^2}/\bar{U}_3^2)]$ replaces U_3/V_{pl}. With these substitutions, the thrust augmentation for the non-uniform case is identical to the thrust augmentation for the uniform flow analysis. Therefore, if the mixing is incomplete $(\overline{U_3'^2}/\bar{U}_3^2) > 0$, the parameter $[\tilde{X}_3/X_2]/[1 + (\overline{U_3'^2}/\bar{U}_3^2)]$ can be increased by increasing $\tilde{X}_3$. In other words, an increase in the effective diffuser area ratio can compensate for the lack of complete mixing Detailed analyses are presented in a forthcoming report on work sponsored by ONR (Reference 1).

One simple method for evaluation of the non-uniformity parameter $\overline{U_3'^2}/\bar{U}_3^2$ consists of the use of ejector tests where no separation exists in the diffuser. Then $\delta^* = \delta$ and the parameter $\delta^*/[1 + (\overline{U_3'^2}/\bar{U}_3^2)]$ and C_F can be determined from Equations 5 and 6 with the knowledge of ϕ, α, λ_1, η_N, and C_{di}, for a stationary ejector, since $\dot{m}_c/\dot{m}_p = 1 + (\alpha - 1)\lambda_1$. Since $\delta^* = \delta$, for non-separating ejectors, the non-uniformity parameter can be evaluated from the identity

$$\overline{U_3'^2}/\bar{U}_3^2 = \left[\frac{1 + \overline{U_3'^2}/\bar{U}_3^2}{\delta^*}\right] \cdot \delta - 1$$

where

δ = geometric diffuser area ratio X_3/X_2

δ^* = effective diffuser area ratio $\tilde{X}_3/X_2$

However, λ_1 $(= U_1/V_{pl})$ is a quantity which is difficult to measure accurately, but can be determined from Equation 6 if C_f, and thus C_F, are assumed.

Using Quinn's data (Reference 2), and his estimates of the loss coefficients, it was determined that for all the ARL ejectors reported in Reference 2, there is a maximum value of C_f which satisfies the physical restriction that

$$(\delta/\delta^*)[1 + (\overline{U_3'^2}/\bar{U}_3^2)] \geq 1$$

This value of C_f ia about 0.0057. (After correcting for the aspect ratio effect, the coefficient of skin friction based on the wetted surface area becomes 0.0049, which is the typical value for a flat plate turbulent boundary layer over a wide range of Reynolds Number near 10^6). Using the value of $C_f = 0.0057$, the quantitiy $(\delta/\delta^*)[1 + (\overline{U_3'^2}/\overline{U}_3^2)]$ of the ARL ejectors are calculated and summarized on the upper chart of Figure 2. The average value of $(\delta/\delta^*)[1 + (\overline{U_3'^2}/\overline{U}_3^2)]$ for Configuration F is about 1.05. This value appears to be adequate for the low diffuser area ratio range of all other Configurations under consideration. Therefore, for non-separating ARL ejectors, $(\delta = \delta^*)$, the non-uniformity parameter, $\overline{U_3'^2}/\overline{U}_3^2$, is about 0.05.

Using this value, the theory and experiments agree very closely, as illustrated on Figure 2. However, the assumption that $\delta^* = \delta$ breaks down for Configuration D near $\delta = 1.4$, which indicates that flow separation occurred at diffuser area ratios larger than 1.4 and that $\delta^* < \delta$.

These considerations indicate that for fixed values of the loss coefficients, an increase of the effective diffuser area ratio can compensate for the degradation due to incomplete mixing. Attempts to improve the mixing of primary and induced flows frequently involve an increase in other losses and therefore do not result in improved performance. For example, as shown by Equation 6, a decrease in nozzle efficiency (η_N) or an increase in C_{di} or C_F (or ejector length) always results in smaller thrust augmentation as might be expected. An increase of δ^* however, can result in improved performance as indicated by Bevilaqua (Reference 3) for the Hypermixing Nozzle.

In the light of the above discussion and Bevilaqua, it is apparent that the Hypermixing Nozzle, developed in the Air Force Aerospace Research Laboratories, achieved its performance improvement at large values of the diffuser area ratio as a result of improved diffuser performance as well as a result of improved mixing. This is made apparent by the fact, reported in Reference 3, that the performance improvement was achieved at large diffuser area ratios.

At smaller diffuser area ratios (where the diffuser was efficient), hypermixing resulted in a performance degradation, due to increased inlet drag and decreased nozzle efficiency.

It must therefore be concluded that the search for improvement in mixing must be directed towards those methods which decrease the loss parameters, and that the development of a high performance, short, wide angle diffuser is of greater significance than the recent emphasis on improved mixing.

The jet-diffuser ejector is an example of an ejector designed with major emphasis on the diffusion process, and its large performance/size ratio indicates the practicality of the above remarks.

JET-DIFFUSION CONCEPT

The concept of jet-diffusion is basically an extension of the concepts of boundary layer control by the use of blowing jets and of the jet flap to provide additional diffusion beyond that of the solid surfaces. Blowing jets have been used to delay separation in large area ratio solid diffusers with some degree of success. By blowing a jet having a higher stagnation pressure than the ambient pressure in the diffuser, separation can be delayed to the point where the effective diffuser area ratio is almost as large as the geometric area ratio of the solid surface.

Using energized fluid for the avoidance of separation is a costly process, since the momentum of the boundary layer control fluid must be considered in the evaluation of ejector performance. Thus, unless extreme care is exercised in the design of the blowing jet system, the net effect can be more detrimental than that of the use of a smaller diffuser area ratio without boundary layer control.

Jet diffusion has the advantage over conventional blowing jet systems in that it has the potential for providing a diffuser area ratio larger than the geometric area ratio of the solid surfaces in addition to its capability for avoiding separation despite extremely large divergence angles of the solid surfaces.

A typical jet diffuser ejector developed under the U.S. Navy/Marine Corps STAMP (Small Tactical Aerial Mobility Platform) Program and tested at the Naval Air Propulsion Center is illustrated on Figure 3. This ejector was the result of an intensive development program aimed at its eventual use as the lifting, thrusting and controlling element of an apterous vehicle and details of its development program and its performance are described in Reference 4. It is of particular interest to note that, as shown on Figure 3, the ends of the ejector are flat, with a semi-circular end plate protruding beyond the solid diffuser surfaces at the ends of the ejector as a means of providing two-dimensional flow in the diffuser. This protruding end plate, although somewhat undesirable from the viewpoint of ejector integration and drag characteristics was essential for the avoidance of some performance degradation associated with the use of flat ends within the diffuser.

Attempts to utilize diverging end bells resulted in local flow separation and performance penalties not acceptable under the STAMP Program and the design illustrated on Figure 3 was utilized as a quick-fix alternative, the advantage of which is best illustrated by perusal of the data presented on Figures 4 and 5.

To illustrate the characteristics of the flow within the region of jet diffusion, the pressure distribution in that region is plotted on Figure 4 with a large end plate extending from the end of the solid diffuser to a distance of 27.4 cm, 0.9 of the exit dimension. Obviously, the recovery of kinetic energy attributable to the jet diffuser is directly related to the pressure recovery in the region illustrated by the isobars. Removal or reduction in size of the end plate would seriously collapse the isobar pattern and cause a pressure increase throughout the ejector, with an accompanying reduction in secondary/primary flow ratio and thrust augmentation.

The influence of end plate size on the thrust augmentation of the ejector, with a diffuser area ratio of 3, is plotted on Figure 5. The semi-circular end plate (labelled STAMP) is shown to produce a thrust augmentation factor of 2.12 with the illustrated ejector and end plate configuration. Increasing the end plate to a 27.4 cm x 61 cm shape similar to that used in Figure 4 resulted in an increase of 3% or a thrust augmentation of 2.18. Decreasing the end plate size resulted in a more serious performance degradation, equivalent to a reduction of 14% in the thrust augmentation, to a value of 1.82. Thus it appears that the three-dimensional effects resulting from the requirement for finite ejector aspect ratio contribute significantly to the degradation of performance and that some effort to avoid the peripheral discontinuity of flow properties is required.

THREE-DIMENSIONAL EFFECTS

In an ideal jet-diffuser ejector, the mixing process can proceed for a considerable distance downstream of the end of the solid surfaces, since the core flow pressure remains below ambient. The extent of this region of sub-ambient pressure is limited, in a real three-dimensional ejector if the uniformity of the peripheral distribution of the diffuser jet properties are interrupted, as in the case of the STAMP ejector which had flat ends.

Recent work under NADC sponsorship (Reference 5) resulted in a method for diffuser design, using potential flow theory, which provided better continuity of the peripheral distribution of flow properties in the diffuser and eliminated the requirement for protruding end plates. The method utilized a three-dimensional closed (ring) vortex distribution of constant circulation whose shape could be adjusted to vary the maximum pressure gradient and/or length of the diffuser. The influence of various ring vortex shape parameters upon maximum pressure gradient distribution, diffuser length, and other practical limitations has been determined and a selection based upon these parameters was made.

The ejector designed by this method is illustrated on Figure 6, (designated as Model 0232) and as shown, the end plates required by the flat end design of the STAMP ejector have been eliminated.

The performance of this ejector whose diffuser is designed by the methods of potential flow is described in comparison to the performance of the STAMP ejector, in the following section.

GROUND EFFECTS

The influence of ground plane proximity to the ejector's exit plane on thrust augmentation is of importance for V/STOL applications of ejector thrusters. Since it appears likely that the influence of the ground plane is related to its influence upon the flow pattern within and around the ejector, and the effectiveness of the diffuser in particular, some limited investigations were conducted. This test set-up utilized a large 2.74 m x 3.05 m flat plate which could be moved with respect to the ejector, to vary its distance from the exit plane of the ejector.

The thrust augmentation of the STAMP and Model 0232 ejectors were measured over a range of distances from 0.5 to more than 5 meters between ejector exit plane and ground plane.

As indicated on Figure 7, the thrust augmentation of Model 0232 decreased less than 2% over most of the range of distances until the ejector was within 0.75 m from the ground plane. As the distance decreased to values smaller than 0.75 m, the mean thrust dropped rapidly. Preliminary observation of the Model 0232 ejector when the ground plane is at 0.56 m from its exit indicates that the flow within the ejector duct and near the diffuser exit is free from abnormality while violent unstable flow is developed on and near the ground plane.

The thrust augmentation of the STAMP ejector decreased by about 4% over most of the range of distances, compared to about 2% for Model 0232, as indicated on Figure 7. The decrease in thrust augmentation with distances smaller than 0.75 m was more pronounced for the equivalent STAMP Ejector with semi-circular end plates than for the Model 0232 ejector, as shown on Figure 7. This indicates that the Model 0232 is a more stable ejector than the STAMP ejector. This effect may depend upon the ejector's stagnation pressure and upon its geometric arrangement; more detailed tests are required for further understanding of this subject.

CROSS FLOW

V/STOL ejector applications require that the ejector provide a lift force varying from the all-up gross weight of the aircraft at take-off decreasing to zero at cruise.

When the ejector is producing thrust in a direction normal to the flight direction, there is no thrust decrement due to ram drag. The translational motion normal to the thrust vector may result in some drag and moment, due to the external influence of the jet on the aircraft surface pressure distribution. However, the momentum increment resulting from the ejector process is unaffected by the motion normal to the thrust, except for the indirect influence of inlet or diffuser flow distortion resulting from the cross flow.

Careful design of ejector external fairings can result in large additional thrust (or lift) forces on these fairings, attributable to the ejector. For example, tests on the STAMP ejector, reported in Reference 4, and shown on Figure 8, indicated large increases in thrust resulting from motion normal to the thrust. Thrust augmentation in excess of 2.6 were achieved at speeds of 60 ft/sec, with a small fairing.

As indicated, the phenomenon is related to the stagnation pressure of the ejector jets, and tests were performed at relatively low pressure. Increasing stagnation pressure delays the stall (as indicated) and further effort is required to determine the continuity of the trend indicated.

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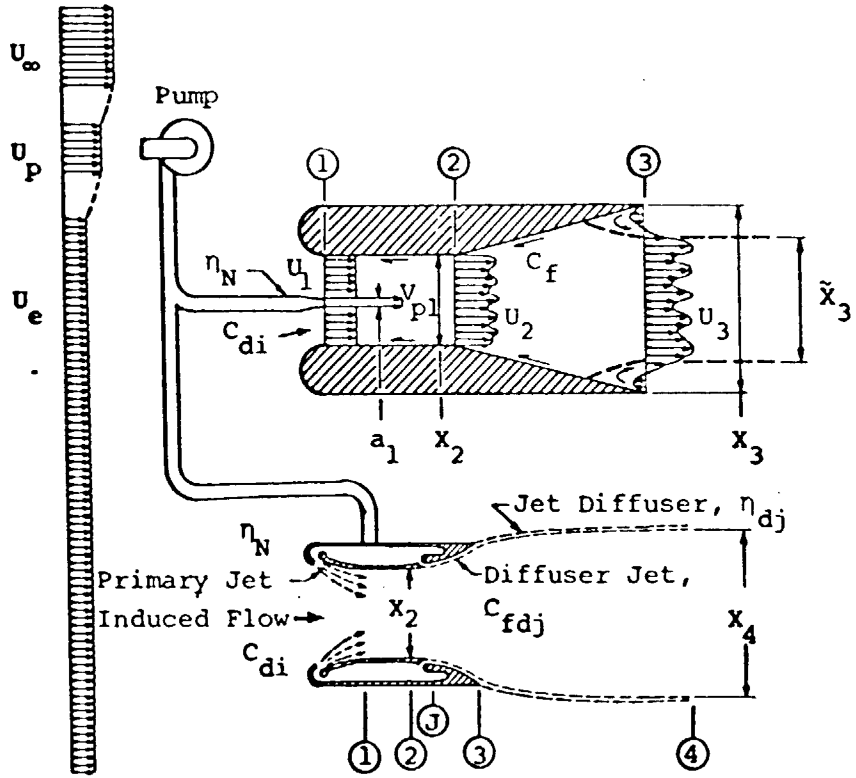
3. Bevilaqua, P.M., "Evaluation of Hypermixing for Thrust Augmenting Ejectors", Journal of Aircraft, June 1974.

4. Alperin, M., Wu, J.J., and Smith, Ch.A., "The Alperin Jet-Diffuser Ejector (AJDE) Development, Testing and Performance Verification Report", Feb. 1976, Flight Dynamics Research Corporation, NWC Report No. 5853.

5. Alperin, M., and Wu, J.J., "End Wall and Corner Flow Improvements of the Rectangular Alperin Jet Diffuser Ejector", Flight Dynamics Research Corporation, NADC-77050-30, May 1978.



Solid Diffuser Ejector:

η_N = Primary Nozzle Thrust Efficiency

C_{di} = Inlet Drag Coefficient

C_f = Coefficient of Skin Friction

$$\frac{\tilde{X}_3/X_2}{1 + (\overline{U_3'^2}/\bar{U}_3^2)} \quad \text{(Generalized Diffuser Area Ratio)}$$

Jet-Diffuser Ejector:

η_N = Primary Nozzle Thrust Efficiency

C_{di} = Inlet Drag Coefficient

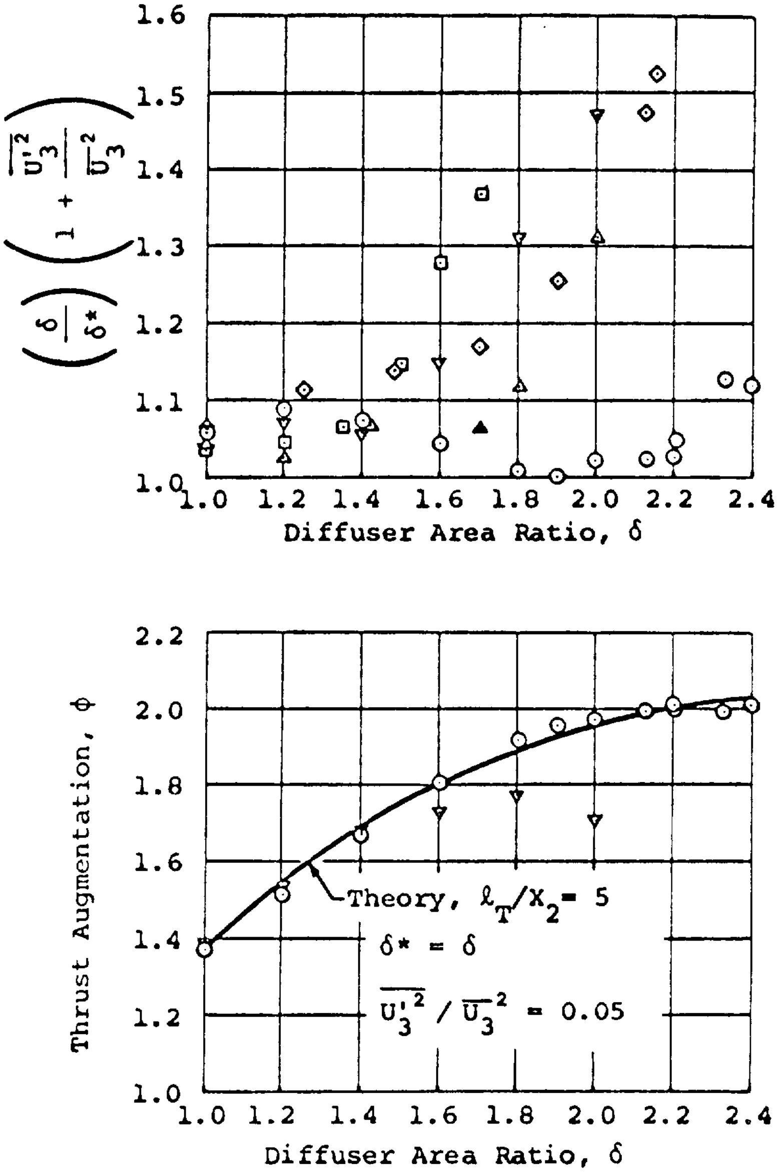
C_{fdj} = Coefficient of Skin Friction (Diffuser Jet)

η_{dj} = Efficiency of Jet Diffuser

$$= \frac{X_4/X_{4,\text{ideal}}}{1 + (\overline{U_4'^2}/\bar{U}_4^2)}$$

$\dot{m}_d/\dot{m}_p$ = Diffuser Jet/Primary Jet Mass Flow Ratio

Figure 1.- Basic parameters.



$\alpha = 25.3$; $\eta_N = 0.96$; $C_{di} = 0.025$

$C_f = 0.0057$ (assumed)

Configuration	Symbol	ℓ_T/X_2
A	▲	4.525
B	▣	2.825
C	◇	2.8
D	▼	5
F	⊙	5

Figure 2.- Comparison of theory to ARL ejector experiments.

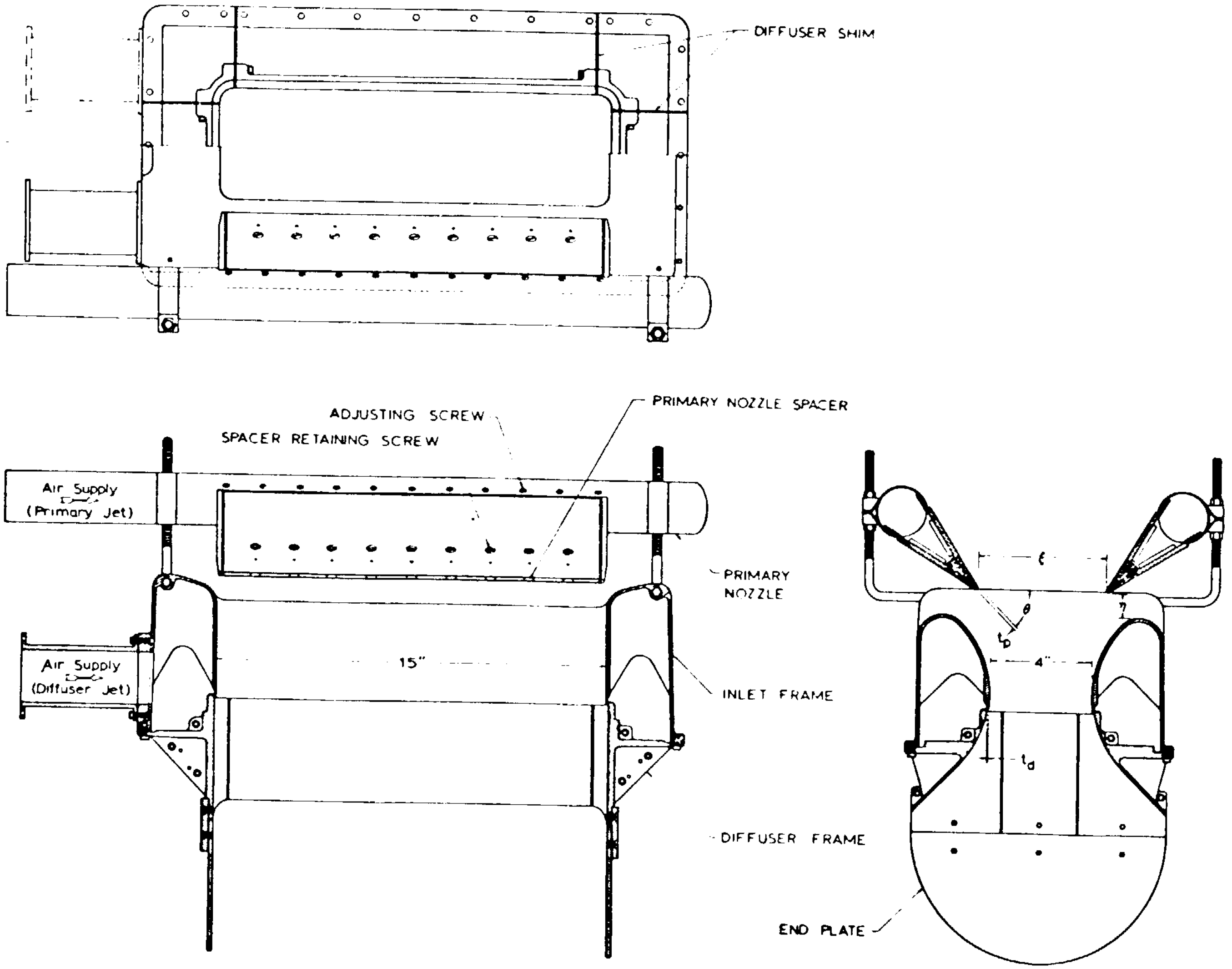


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Figure 3.- Alperin jet-diffuser ejector, model 0542, 1976.

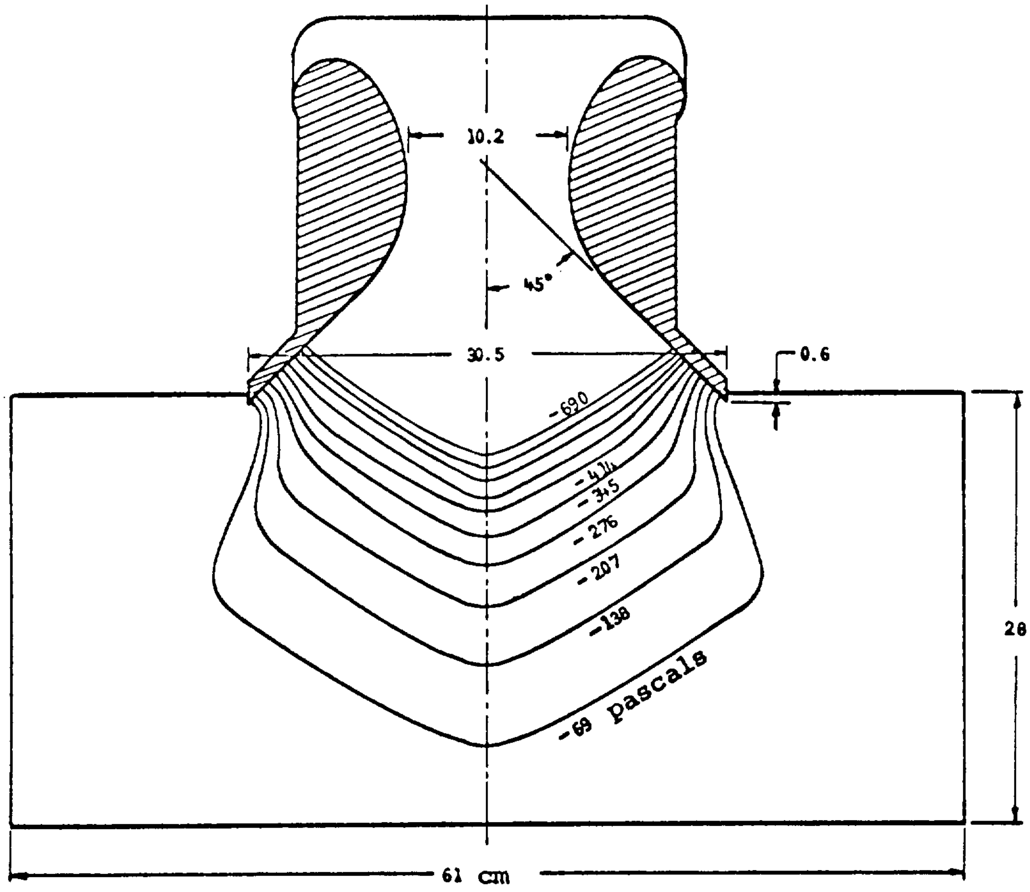

Figure 4.- Isobars on end plate of stamp AJDE ejector; P_o = 24.3 kilopascals, $A_2/(s_\infty + a_\infty)$ = 21.6, s_∞/a_∞ = 0.62.

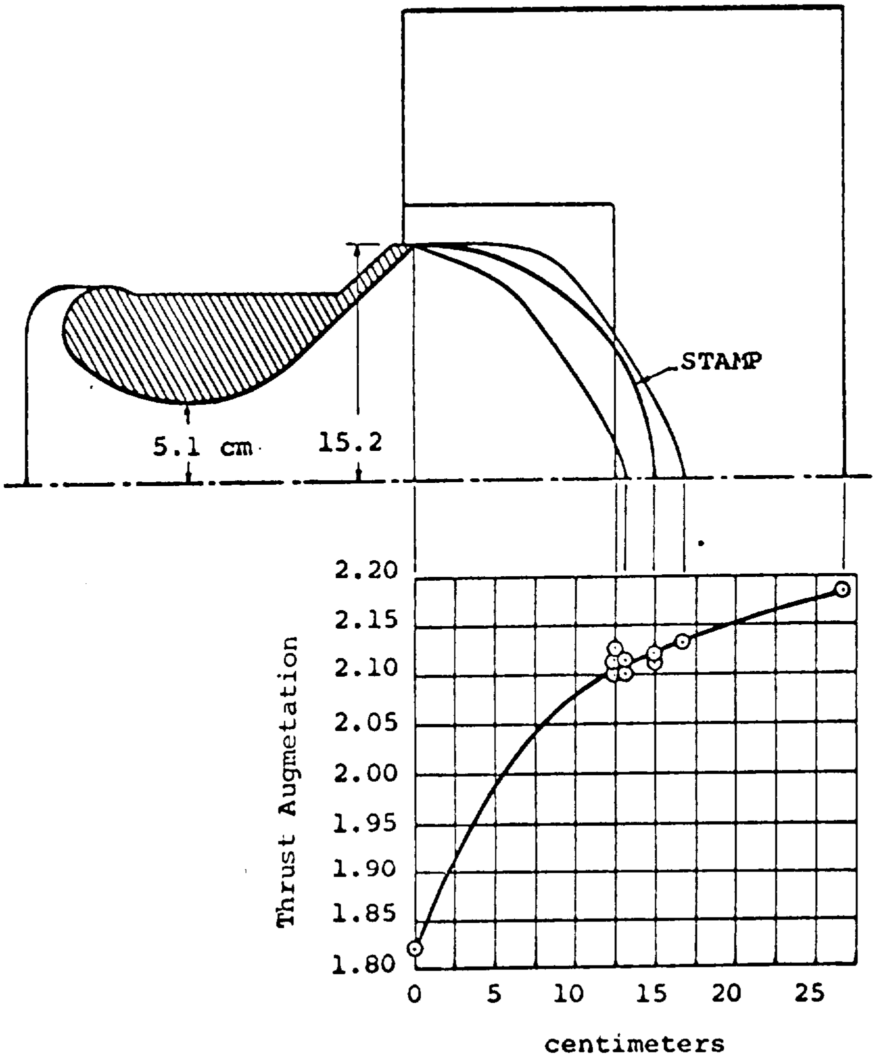

Figure 5.- End plate configuration and performance; P_O = 24.3 kilopascals, $A_2/(s_\infty + a_\infty)$ = 21.6, s_∞/a_∞ = 0.62.

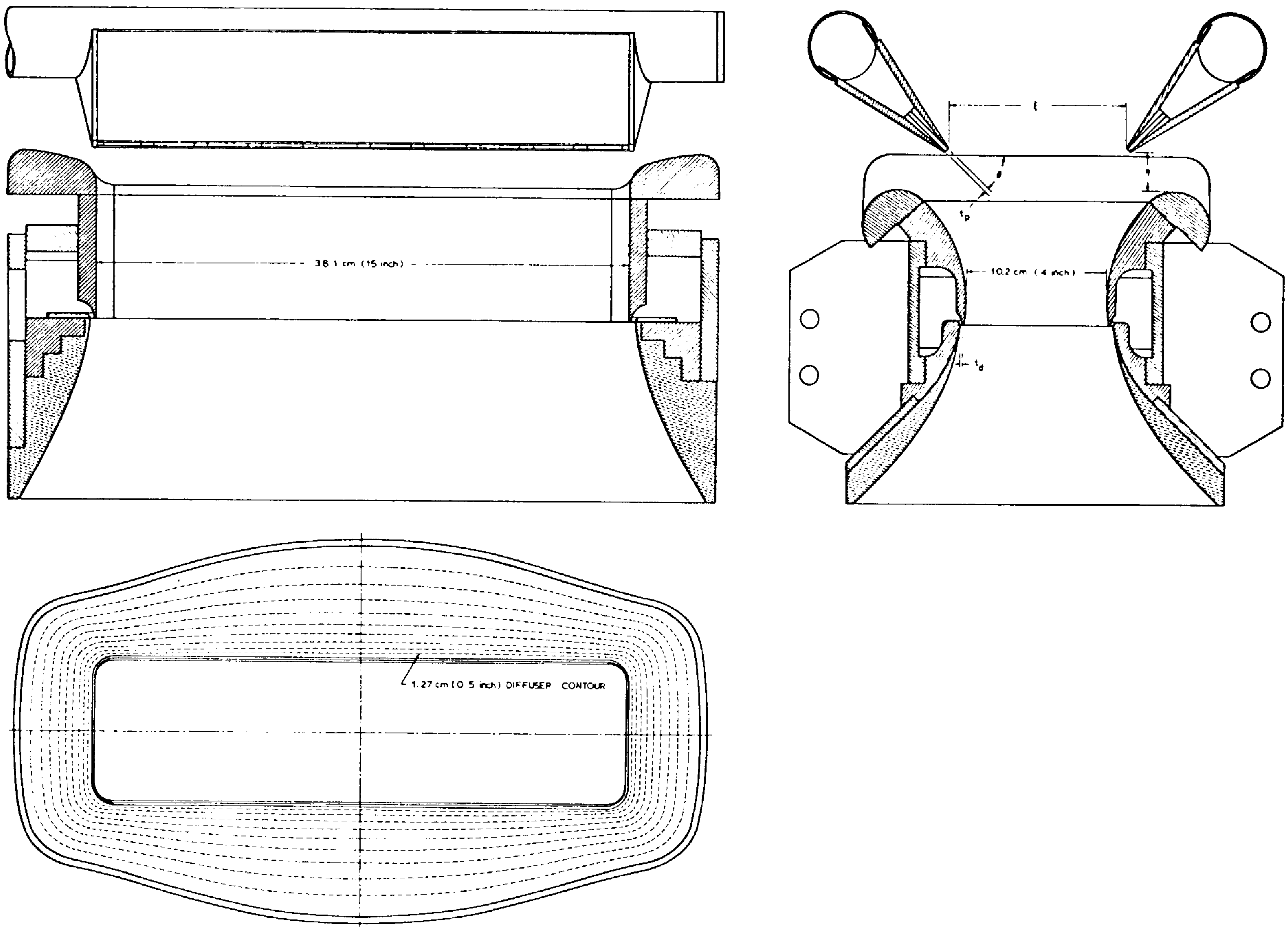

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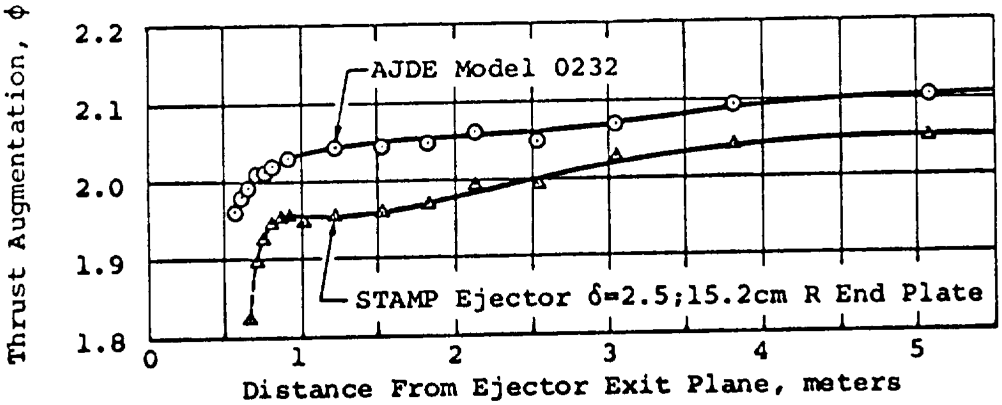
Figure 6.- Alperin jet-diffuser ejector, model 0232, 1978.



P_o = 24.1 kilopascals (gage); $A_2/(s_\infty + a_\infty) = 22$; $s_\infty / a_\infty = 0.8$

Figure 7.- Influence of ground plane on ejector performance.

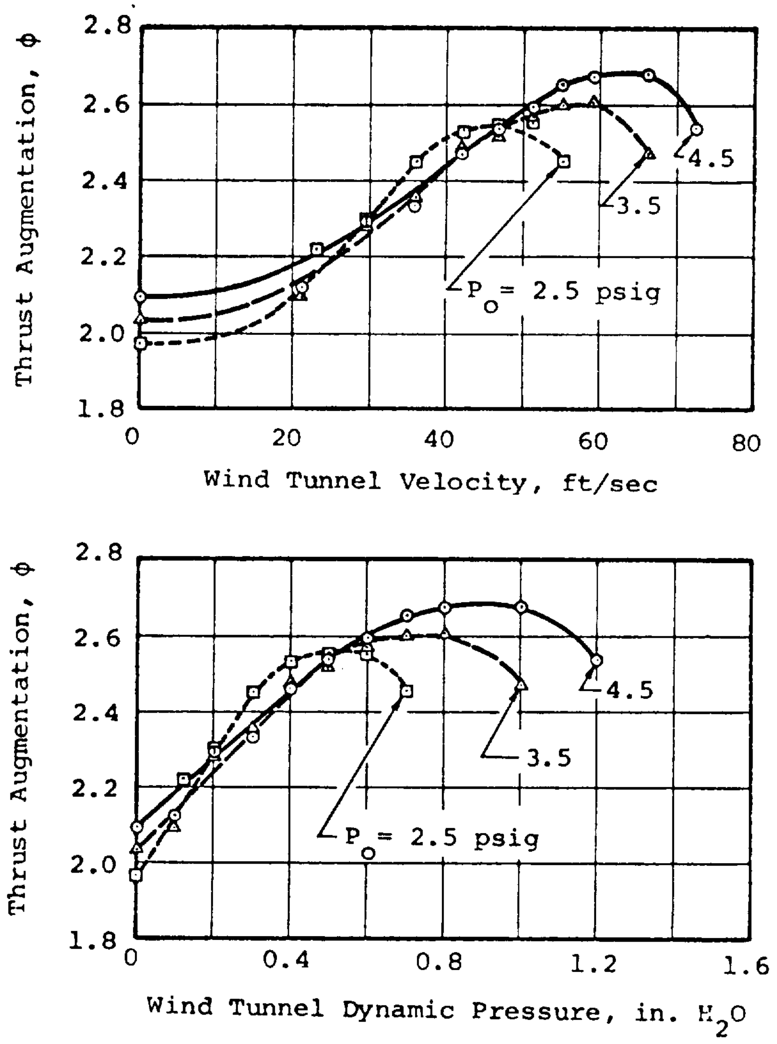


Figure 8.- Influence of translational motion and plenum pressure on AJDE performance.