Prediction of Performance of Low-Pressure-Ratio Thrust-Augmenter Ejectors

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A description is given of a simple procedure for predicting the static performance of low-pressure-ratio thrust-augmenter ejectors equipped with hypermixing primary nozzles. Such ejectors have been proposed as vertical, and transitional, flight mode thrust augmenters for VTOL aircraft. The analysis is based on incompressible flow concepts employed in such a way that the thrust augmentation ratio is evaluated with negligible error. Results are presented of a parametric computer-generated study showing the sensitivity of the optimized performances of a basic ejector configuration to changes in loss coefficients, area ratio, and operating conditions. It was concluded that it is most important to achieve the highest possible effectiveness of the ejector diffuser and that ejectors with large area ratios are particularly adversely affected by back pressure. Comparisons of predictions made using the analytical procedure with experimental results generated by the U.S. Air Force Aerospace Research Laboratories show good agreement.

Nomenclature

A = cross-sectional area
A_{eff} = effective planform area [see Eq. (15)]
C = nozzle velocity coefficient
D = hydraulic mean diameter of mixing zone $\equiv 4A$/wetted perimeter
f = skin friction factor $\equiv \dfrac{\text{drag}}{(L/D)\,\frac{1}{2}\rho_M u_2^2 A_2}$
F_{ejc} = thrust of ejector
F' = thrust of primary stream alone when expanded reversibly to pressure p_3
L = length of mixing zone
p = static pressure
P = stagnation pressure
q = density ratio ρ_M/ρ_P
r = density ratio ρ_S/ρ_P
S = area ratio A_S/A_P (note: $A_1 = A_2 = A_S + A_P$)
T = temperature
u = fluid velocity
V = velocity ratio u_S/u_P
w = velocity ratio u_2/u_P
α = half-angle of diffuser
β = secondary-to-primary mass flow ratio
γ = ratio of specific heats
η_D = diffuser effectiveness [see Eq. (1)]
η_E = effectiveness of ejector thrust augmenter
θ = angle of sidewall of variable area diffuser
ρ = fluid density
ϕ = thrust augmentation ratio
ϕ_{eff} = effective augmentation ratio [see Eq. (15)]

Subscripts

0 = (second subscript) denotes density or temperature at stagnation conditions
$1,2,3$ = stations within ejector
F = pertaining to fan flow of turbofan
M = completely mixed fluid in ejector
P = ejector primary stream
S = ejector secondary stream
∞ = surroundings (ambient) conditions

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Introduction

THE importance of ejectors as thrust augmenters for VTOL aircraft has recently assumed considerable significance because of the large (static) thrust augmentation ratios, in the region of 2:1, demonstrated experimentally by the Aerospace Research Laboratories (ARL).[1-3] Yet more recently a prototype VTOL aircraft, the Rockwell XFV-12A, has been constructed incorporating, in its lift augmentation system, some of the features of the successful ARL ejectors. A fundamental requirement of any ejector thrust-augmentation system for VTOL is that the augmentation ratio must be sufficiently high to cancel out the weight penalty associated with the ejector system and still yield a net gain in aircraft performance at takeoff or landing.

Previously, some sophisticated and detailed analyses of thrust-augmenter ejectors have been presented, such as that by Salter,[4] in which, for example, the relative merits of slot vs hypermixing primary nozzles were assessed. The analysis due to Nagaraja et al.[5] is based on compressible flow, but lumps together all losses in the system. Overall loss factors were evaluated on the basis of correlations with ARL experimental data obtained from ejector tests.

The purpose of the present work was to analyze the static performance of thrust-augmenter ejectors in a simplified manner, which readily permitted parametric performance studies to be made. These showed the influences on optimum ejector performance of individual sources of internal losses, external influences such as back pressure, and fundamental variations of geometry, such as changes of primary-to-secondary area ratio and diffuser area ratio.

System Modeled

The ejector system modeled in the analysis is shown, together with an analogous turbomachine unit, in Fig. 1. The type of ejector depicted schematically in Fig. 1 is intended to represent, in a general way, the form of large area ratio ejector tested by Quinn et al.[1-3]

Because of the simplified nature of the analytical model the assumption had to be made of complete mixing within the uniform cross-sectional area mixing zone. This assumption appeared to be quite close to, although not identical with, the

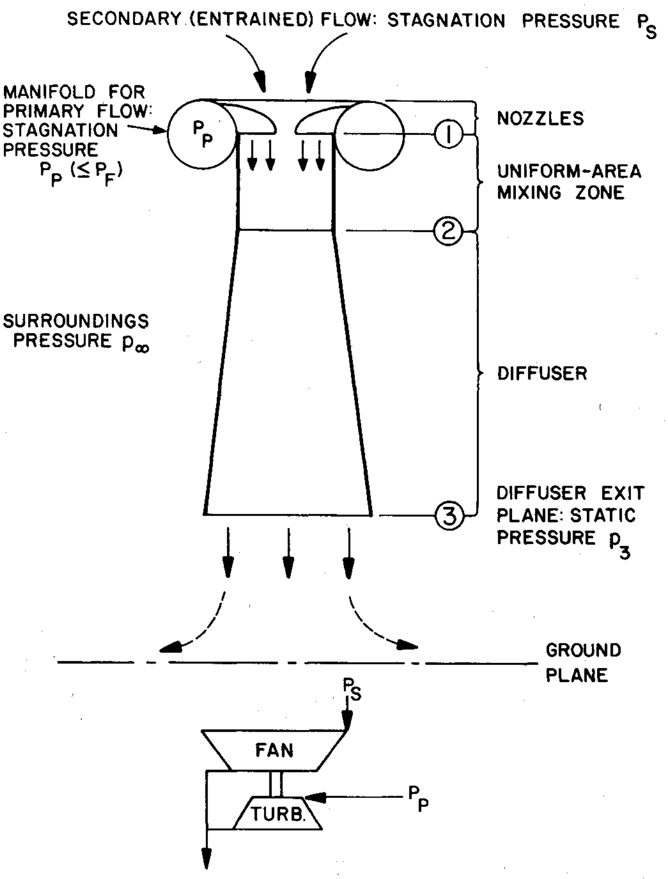

Fig. 1 Basic configuration of ejector; turbo-machine counterpart of the thrust-augmenter ejector shown in the lower portion of the diagram.

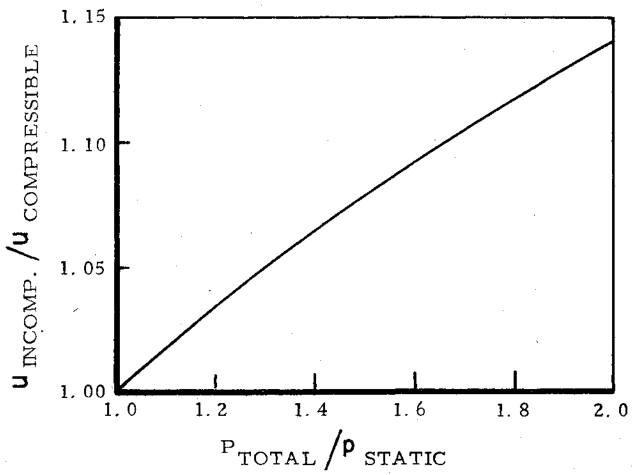

Fig. 2 The ratio of flow velocities, as predicted by incompressible and conventional compressible flow analyses, vs the corresponding stagnation-to-static pressure ratio.

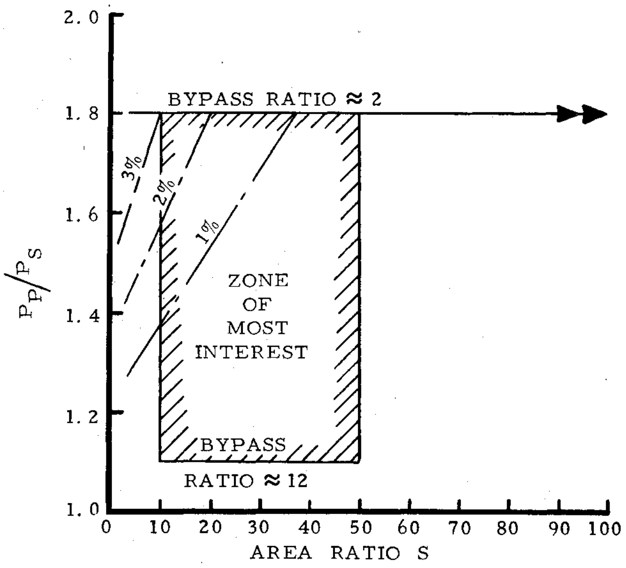

Fig. 3 Region of applicability of the analytical technique and the zone of most practical interest. Lines of constant error, corresponding to overestimates of the true value of ϕ by 1,2, and 3%, are also shown.

system shown by experiment, to give best results in practice.[6] Experiments have also shown that too much, or too little, boundary-layer blowing resulted in performance penalties[3] the implication being that, at least to a first approximation, best results were obtained when mixing was complete a situation closely approached in practice when hypermixing primary nozzles are employed in conjunction with limited boundary-layer blowing.

The other major simplification incorporated in the analytical model concerns the use of an incompressible flow relationship to evaluate the velocity, u_P, of the ejector primary flow based on knowledge of the primary nozzle stagnation-to-static pressure ratio P_P/p_I. Correct compressible flow relations where applied, conventionally, to evaluate the density ratio, ρ_{P0}/ρ_P, corresponding to P_P/p_I. The adoption of this procedure results, as shown in Fig. 2, in overestimating u_P by as much as 14% for a primary-to-static pressure ratio of 2:1. The considerable error in the prediction of thrust augmentation ratio, which could arise due to the use of an incompressible flow relationship to evaluate u_P, is, for large area ratio ejectors, almost totally eliminated by using a similar incompressible flow relationship in the evaluation of the thrust ideally obtainable by expanding the primary stream from the source pressure to pressure p_3. The thrust obtained in this way constitutes the denominator of the expression for augmentation ratio ϕ.

This cancellation of errors occurs because, in large area ratio ejectors, the static pressure within the ejector at station 1 is quite close to the static pressure p_3 at the diffuser outlet. The effectiveness of the error cancellation is shown quantitatively in Fig. 3 where approximate contours of constant overestimation of ϕ by 1, 2, and 3% are shown. The shaded rectangle in Fig. 3 marks the approximate zone of interest in the study of large area ratio ejectors using as the source of their primary stream the fan-flow of turbofan engines. The cutoff, in Fig. 3, at area ratio $S=50$ is somewhat arbitrary and is intended to identify the largest area ratio likely to be of practical interest. There is no reason, provided low Reynolds number effects do not become dominant, why the analysis cannot be extended to values of S greater than 50. The restriction of $P_P/P_S \leq 1.8$ is to eliminate from the analysis conditions where significant pressure wave action could occur within the ejector; wave phenomena are not accounted for in the model.

The analysis, which was arranged in terms of prescribed, easily identifiable, and physically meaningful parameters governing the operating conditions and geometry of ejectors is, for all practical purposes, comparable in accuracy to an analysis based on conventional compressible flow considerations. The use of a primarily incompressible flow analysis results in considerable simplification.

Analysis

Since one-dimensional flow was assumed for both the primary and secondary streams entering the ejector, and it was further assumed that the flow passing into the diffuser is fully mixed, the analysis was carried out quite simply by manipulating algebraic equations without the need to perform cross-stream, or streamwise, integration. The physical principles involved are, of course, the familiar ones of continuity and conservation of momentum. The ejectors studied were all of the constant-area-mixing type. The primary purpose of the analysis was to set up equations which allowed ϕ, V, and β to be evaluated for prescribed ejector geometry and operating conditions.

For the ejector diffuser

$$\eta_D = \frac{p_3 - p_2}{(\rho_M/2)(u_2^2 - u_3^2)} \tag{1}$$

Since the exit-plane pressure of the diffuser will normally be that of the local pressure in the field around the ejector, the thrust produced by the ejector, F_{ejc}, is given by

$$F_{\text{ejc}} = \rho_M u_3^2 A_3 \tag{2}$$

It can be shown by invoking Eq. (1), after rearrangement to take into account continuity and the constancy of area in the mixing zone, that Eq. (2) can be rewritten as

$$F_{\text{ejc}} = \frac{A_3(p_3 - p_2)}{(\eta_D/2)[(A_3/A_1)^2 - 1]} \tag{3}$$

With wall friction in the mixing zone considered on the basis of the *mixed* flow conditions (*not* on the basis of a linear distribution between the secondary and mixed flow conditions as by Kentfield and Barnes[7]) Eq. (19) of Kentfield and Barnes[7] modified appropriately then gives

$$p_2 = p_1 + [2C_p^2/(1+S)](P_P - p_1)[1 + \beta V - (1+\beta)w]$$
$$- f(L/D)qw^2 C_P^2 (P_P - p_1) \tag{4}$$

for ejectors with constant-area mixing zones.

Substitution in Eq. (3) from Eqs. (1) and (4), the definitions of q, w, V, and S, the continuity condition, and the constancy of cross-sectional area in the mixing zone allows the following expression to be established after some algebra:

$$F_{\text{ejc}} = 2A_3\left(\frac{A_1}{A_3}\right)^2 C_P^2 (P_P - p_1)\frac{(1+SrV)(SV+1)}{(1+S)^2} \tag{5}$$

The unkown pressure p_1 can be eliminated from Eq. (5) after rearranging Eq. (11) of Ref. 7 and hence substituting for p_1 in Eq. (5). This yields the result:

$$F_{\text{ejc}} = 2A_3\left(\frac{A_1}{A_3}\right)^2 C_P^2\left(\frac{P_P - P_S}{1 - r(VC_P/C_S)^2}\right)\frac{(1+SrV)(SV+1)}{(1+S)^2} \tag{6}$$

To evaluate the augmentation ratio ϕ ($\equiv F_{\text{ejc}}/F'$), the ratio of the ejector thrust to that (F') which would be produced by the primary stream alone if it were expanded under *ideal* conditions to p_3, it is first necessary to establish F' in terms of known parameters, where

$$F' = \rho_F A_F u_F^2 \tag{7}$$

and from continuity:

$$A_F = \frac{\rho_P}{\rho_F}\frac{u_P}{u_F}A_P \tag{8}$$

Substitution for A_F from Eq. (8) in Eq. (7), after expressing u_P/u_F as the ratio of two incompressible flow velocities and subsequently invoking the classical isentropic relations between pressure ratio and density ratio, allows the following expression for F' to be derived after some algebra:

$$F' = 2C_P\left(P_P\left\{\frac{P_F}{p_3}\left[\frac{(P_S/P_P) - r(VC_P/C_S)^2}{1 - r(VC_P/C_S)^2}\right]\right\}^{1/\gamma}\right.$$
$$\left.\times\left(1 - \frac{p_3}{P_F}\right)\frac{(P_P - P_S)}{[1 - r(VC_p/C_S)^2]}\right)^{1/2} A_P \tag{9}$$

Division of Eq. (6) by Eq. (9) results in the following expression for ϕ:

$$\phi = \frac{\left[\frac{A_1}{A_3}\right]C_P\left[\frac{1 - P_S/P_P}{1 - r(VC_P/C_S)^2}\right]^{1/2}\frac{(1+SrV)(SV+1)}{(1+S)}}{\left\{\left[\frac{P_F}{p_3}\left(\frac{(P_S/P_P) - r(VC_P/C_S)^2}{1 - r(VC_P/C_S)^2}\right)\right]^{1/\gamma}\left(1 - \frac{p_3}{P_F}\right)\right\}^{1/2}} \tag{10}$$

It now remains to derive an expression which, for known values of η_D, f, and also the area and pressure ratios relating to the ejector, allows V to be established for use in Eq. (10). It can be shown that the required result can be obtained by setting up an appropriate expression for $(p_3 - p_1)$ and substituting for p_1 from a rearranged version of Eq. (11) of Ref. 7. The final form, after appropriate simplification, is

$$1 + \frac{f}{2}\left(\frac{L}{D}\right) - \frac{\eta_D}{2}\left[1 - \left(\frac{A_1}{A_3}\right)^2\right]$$
$$= \frac{(1+S)}{(1+SrV)(SV+1)}\left\{(1 + SrV^2)\right.$$
$$\left. - \frac{(1+S)}{2}\left[\frac{(p_3/P_S) - 1}{C_P^2[(P_P/P_S) - 1]} + r\left(\frac{V}{C_S}\right)^2\right]\right\} \tag{11}$$

For any prescribed situation the only unknown in Eq. (11) is V. The value of V obtained from Eq. (11) can then be substituted in Eq. (10) thereby allowing ϕ to be evaluated.

Although not required for the evaluation of ϕ, it can also be helpful to know the ratio, ρ_{F0}/ρ_P, of the density, at stagnation conditions, of the fan flow so that, at static conditions, of the ejector primary stream. It can be shown that the appropriate expression is

$$\frac{\rho_{F0}}{\rho_P} = \frac{P_F}{P_P}\left\{\frac{1 - r(VC_P/C_S)^2}{(P_S/P_P) - r(VC_P/C_S)^2}\right\}^{1/\gamma} \tag{12}$$

Similarly it can also be helpful to know the ratio, T_{S0}/T_{F0}, of the stagnation temperatures of the secondary-to-primary flows in the ejector. For adiabatic operation the stagnation temperature of the primary stream equals that of the fan discharge. It can be shown that

$$\frac{T_{S0}}{T_{F0}} = \frac{1}{r}\frac{P_S}{P_P}\left\{\frac{1 - r(VC_P/C_S)^2}{(P_S/P_P) - r(VC_P/C_S)^2}\right\}^{1/\gamma} \tag{13}$$

Application of the continuity condition with substitutions based on the definitions of r, S, and V gives the expression for the mass flow ratio β:

$$\beta = rSV \tag{14}$$

Computer Program

A computer program was written to allow, for prescribed conditions, the optimum value of the thrust augmentation ratio ϕ to be evaluated as a function of the ejector area ratio S. Essentially the routine was, for prescribed S, to put $A_1/A_3 = 1.0$ and solve Eq. (11) iteratively to establish velocity ratio V. Using the value of V obtained from Eq. (11), and the other known parameters, Eq. (10) was solved to establish ϕ. Maintaining the same value of S, A_l/A_3 was incremented and new values of V and ϕ were computed from Eqs. (11) and (10). This process was repeated until ϕ had been maximized. This value of ϕ was the optimum value obtainable for the prescribed parameters and the particular value of S under consideration.

A new value of S was then selected and the entire sequence repeated to establish the optimum ϕ value applicable to the new S value, and so on, until the preselected range of S values had been explored. Although not needed explicitly for the optimization procedure, obtaining solutions to Eqs. (12) and (13) for conditions corresponding to optimum values of ϕ, permitted, respectively, the density ratio ρ_{F0}/ρ_P and the temperature ratio T_{S0}/T_{F0}, to be established. The mass flow ratio β was evaluated from Eq. (14).

Parametric Study

The parametric study was based on a datum specification, shown in Table 1, which was based mainly on experimental results.[1,2] This specification was maintained constant for the entire investigation of ejector optimum performance with the exception of the particular parameter the perturbation of which was being investigated. For example in Fig. 4 the ejector analyzed was in accordance with the specification given in Table 1 with the exception of the overall pressure ratio P_P/P_S which was 1.2 (chain-dotted curves) or 1.8 (solid curves). The implication is, therefore, that the optimum performances of ejectors of the type described are very insensitive to the primary-to-secondary pressure ratio P_P/P_S. This finding is consistent with that of Salter[4] who showed that for one value of S (=23.4) and a diffuser area ratio $A_3/A_2 = 1.8$, ϕ was substantially constant for nozzle pressure ratios ranging up to the critical value.

In Fig. 5 the effect is investigated of variation of the secondary-to-primary stream density ratio r at station 1. Assuming that the primary and secondary streams have the properties of air, r is the ratio of the static temperature, at station 1, of the primary stream divided by that of the secondary stream. Over the relatively small temperature range investigated ϕ was found, for presecribed S, to decrease very slightly with increasing r while the corresponding optimum value of A_3/A_2 also decreased slightly. These findings agree, in trend, with those predicted by Salter,[4] although Salter's investigation was carried out for a fixed diffuser area ratio A_3/A_2. It is also worth noting, from Fig. 5, that β increases and V decreases as r increases.

Figure 6 shows the effect, on thrust augmentation ratio, of back pressure. As might be expected, for a prescribed back pressure ratio, p_3/p_∞, the influence of back pressure is more dramatic at a low ejector primary-to-secondary pressure ratio than at a high one. Figure 6 should be interpreted with caution as the affect of the back pressure acting over the exit area of the ejector, and over the (smaller) exit of the hypothetical

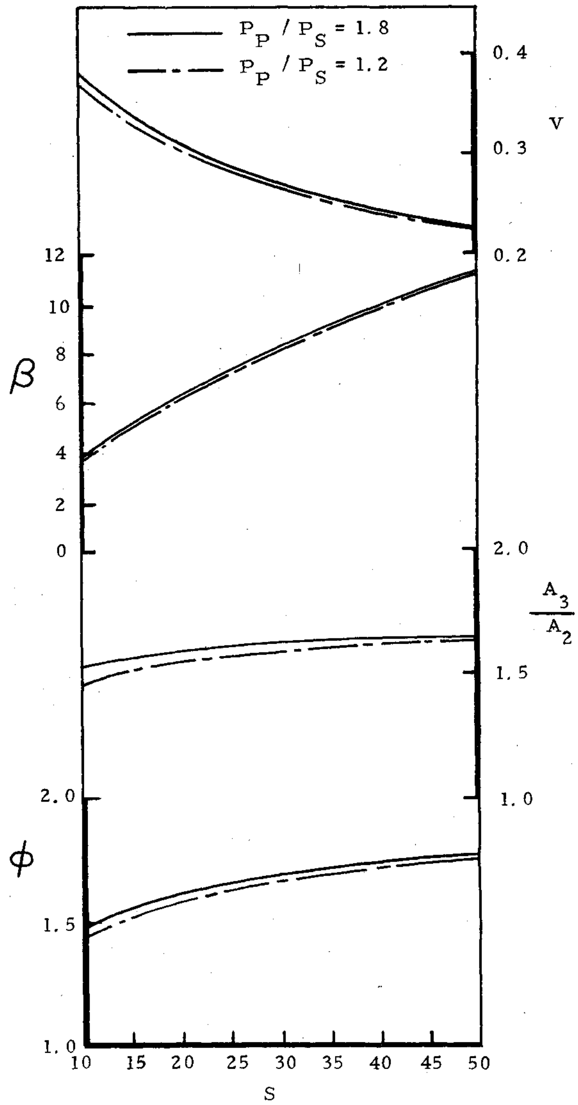

Fig. 4 The influence, on ejector performance, of primary-to-secondary nozzle pressure ratio.

nozzle implicit in the denominator of ϕ, has been omitted. Presumably, in practice, the net back pressure, $p_3 - p_\infty$, will act over an effective vehicle under surface area, A_{eff}, much larger than the exit area and this surface area will include, but be independent of, the exit area of the ejector; hence since $\phi \equiv F_{\text{ejc}}/F'$, when the back pressure is taken into account, the effective augmentation ratio, ϕ_{eff}, is given by

$$\phi_{\text{eff}} = \frac{F_{\text{ejc}} + A_{\text{eff}}(p_3 - p_\infty)}{F' + A_{\text{eff}}(p_3 - p_\infty)}$$

thus,

$$\phi_{\text{eff}} = \frac{\phi + A_{\text{eff}}(p_3 - p_\infty)/F'}{1 + A_{\text{eff}}(p_3 - p_\infty)/F'} \tag{15}$$

The value of ϕ appearing in Eq. (15) is that presented as the ordinate in Fig. 6.

The influence of duct pressure losses between the turbofan engine and the ejector primary nozzles is displayed in Fig. 7. It can be seen that the effect of duct pressure losses decreases in significance as the primary-to-secondary pressure ratio P_P/P_S increases.

The dependence of ejector performance on diffuser effectiveness is displayed in Figs. 8 – 10. Figure 8 shows that the

Table 1 Basic input data used in analysis

Definition	Symbol	Value
Diffuser effectiveness	η_D	0.800
Friction factor in mixing zone	f	0.020
Dimensionless length of mixing zone	L/D	0.500
Density ratio	r	1.000
Primary nozzle velocity coefficient	C_P	0.960
Secondary nozzle velocity coefficient	C_S	0.988
Ratio of fan-delivery to primary-nozzle pressure	P_F/P_P	1.000
Ratio of primary-to-secondary nozzle pressure	P_P/P_S	1.300
Ratio of secondary inlet to ambient pressure	P_S/p_∞	1.000
Ratio of static pressure at diffuser exit to ambient pressure	p_3/p_∞	1.000

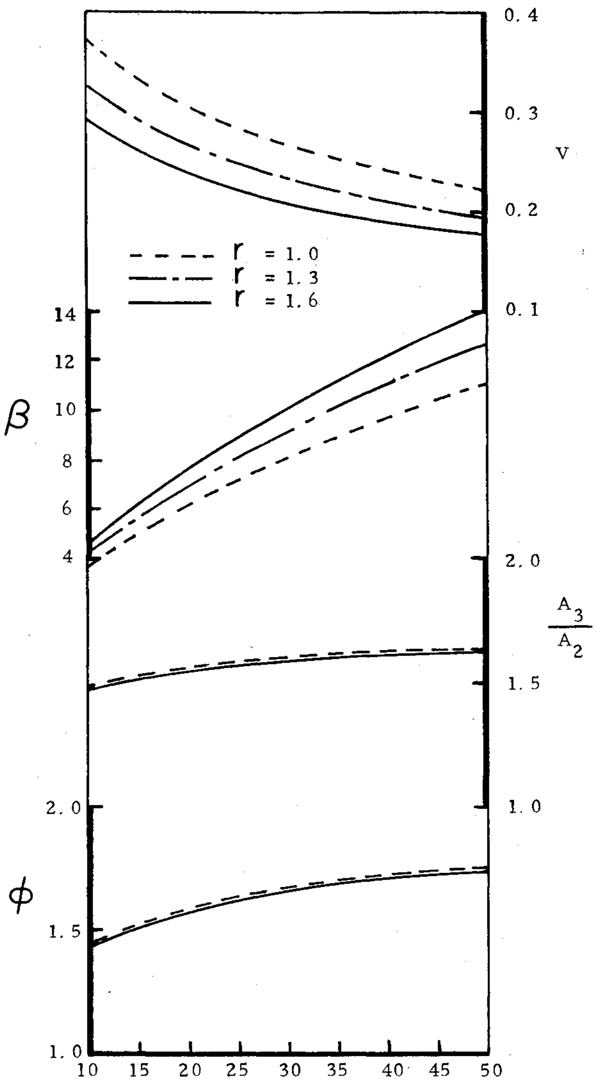

Fig. 5 The influence of density ratio, *r*, on ejector performance.

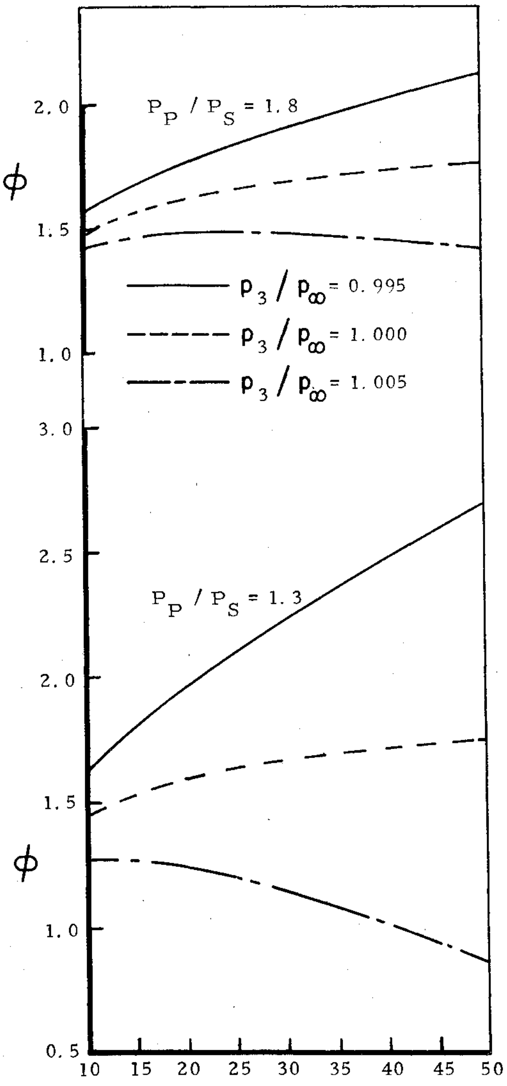

Fig. 6 The influence, on ejector performance, of the ratio of the static pressure at the diffuser exit to the surroundings pressure.

value of ϕ at $S=25$ can range between approximately 1.5 when $\eta_D=0.7$ to $\phi\simeq 2$ when $\eta_D=0.92$. This diagram emphasizes the extreme importance of achieving the highest possible diffuser effectiveness. Figure 9 shows the very significant ranges of diffuser area ratio and mass flow ratio β corresponding to Fig. 8. It can be seen from Fig. 8 that the higher the diffuser effectiveness the greater is the optimum diffuser area ratio. According to the work of Sajben et al.[8] and also McDonald et al.,[9] the effectiveness of a diffuser, defined as in Eq. (1), falls with increasing area ratio. According to Sajben et al.[8] values of η_D established experimentally with a laminar boundary layer at entry to the diffuser and an inlet Reynolds number of 0.15×10^6 varied from 0.965 for an area ratio $A_3/A_2=1.5$ to 0.915 for $A_3/A_2=2.0$ falling to 0.885 for $A_3/A_2=2.5$. These results, which are in line with the best diffuser effectiveness value of $\eta_D\simeq 0.92$ implied in the ARL test results for $A_3/A_2=2.1$,[3] indicate the practical difficulties of achieving high η_D at large values of A_3/A_2.

Figure 10 shows ϕ and A_3/A_2 for $\eta_D=0.7$, 0.8, and 0.9 over the range $20\le S\le 180$. With $\eta_D=0.9$ ($A_3/A_2=2.35$) a value of $\phi=2.3$ should be obtainable for $S=180$. A value of S of this magnitude is not feasible for a configuration in which the ejectors are buried within the wings of an aircraft of conventional proportions.

The curves of η_E appearing at the top of Fig. 10 represent the values of ϕ of the optimized ejector divided by the thrust augmentation ratio of an idealized, isentropic, turbine-driven fan corresponding to the ejector. The idealized turbine-driven fan has a fan-to-turbine mass flow ratio equal to the secondary-to-primary mass flow ratio β of the ejector. The stagnation temperature of the fan flow equals that of the secondary flow entering the ejector. The stagnation temperature of the flow entering the turbine equals that of the ejector primary flow. It can be seen, from Fig. 10, that η_E decreases with increasing S, implying that the irreversibilities of optimized thrust-augmenter ejectors increase with S.

The influence on performance of the secondary flow inlet-nozzle velocity coefficient is shown in Fig. 11. The consequences of reducing C_S progressively, in two equal steps of 0.025, from a value of 0.988 (Table 1) are significant particularly with respect to a reduction in ϕ. This result appears to indicate the importance of preventing adjacent ejectors from starving each other, mutually, of secondary flow and also the penalties which may arise if the folding sheet metal work of an ejector does not approximate well to a good secondary flow inlet when the ejector is operational.

Figure 12 shows the effect on ϕ of doubling the friction factor in the mixing zone and also of reducing by 0.025 the velocity coefficient of the hypermixing primary nozzles. Provided a "square" velocity profile can be maintained at the downstream end of the mixing zone, thereby preventing a degradation in diffuser effectiveness occuring concurrently

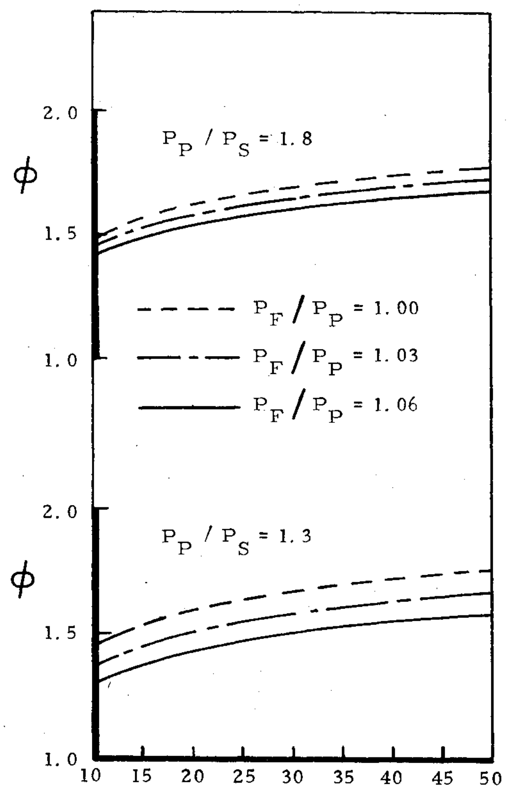

Fig. 7 The influence, on ejector performance, of pressure losses occurring between the pressure generator (turbofan) and the primary flow nozzles.

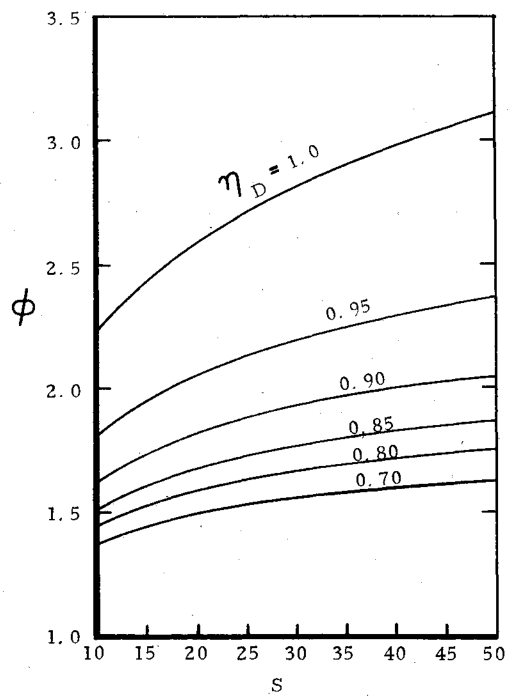

Fig. 8 The influence, on ejector thrust augmentation ratio, of diffuser efficiency.

with the increased friction factor, the increase of friction factor considered in isolation has little influence on ϕ. This implies that the appoximations made in computing wall friction in the mixing zone presumably had but minor affect on the accuracy with which ejector performance was predicted. A reduction of C_P by 0.025 had about half the adverse effect on performance of a decrease in C_S of equal

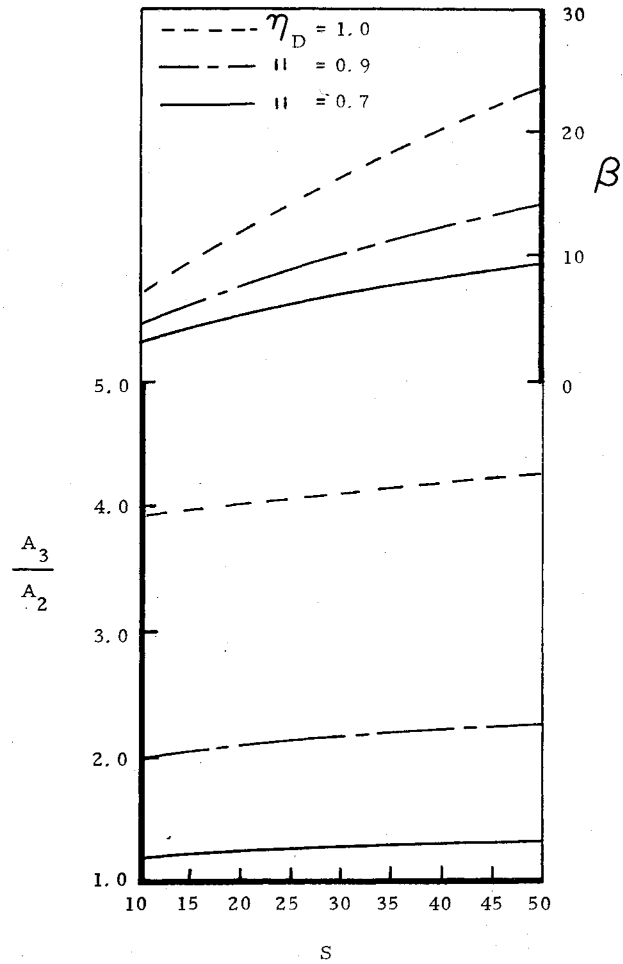

Fig. 9 Optimum diffuser area ratios, and ejector mass flow ratios, corresponding to the augmentation ratio relations displayed in Fig. 8.

magnitude. Consequently the achievement of a high C_P is less important than achieving a high C_S.

Comparison of Analytical and Experimental Results

Ejector performance predictions made using the analytical procedure were compared with experimental results.[1-3] Since the experimental results were obtained using ejectors with variable area diffusers, over a range of diffuser area ratios not merely at optimum diffuser area ratios, the computer program was adapted to this situation. Two adaptations were required; one to model the variable area (approximately) constant overall length diffuser, the other to arrange the computer program to print out ϕ for each area ratio A_3/A_2 investigated.

The provision of a movable sidewall (variable θ) diffuser, used in the experiments, was modeled as shown in Fig. 13. In the analytical model the diffuser with movable sidewalls was replaced by a diffuser of constant divergence angle α but of variable length. The overall length of the ejector was maintained constant by interposing a parallel section of adjustable length, in effect, an extension of the mixing zone, between the end of the mixing zone and the upstream end of the diffuser. The value of the friction factor f in the adjustable length extension of the mixing zone was taken to be the same as that in mixing zone.

Figure 14 shows a comparison of the predicted performance, for $\eta_D = 0.86$, using values of r, L/D, and P_P/P_S taken to correspond to the experiments of Campbell and Quinn.[2] As can be seen, the predicted curve agrees quite closely with the test points representing the experimental results. The most significant departures occur at high values

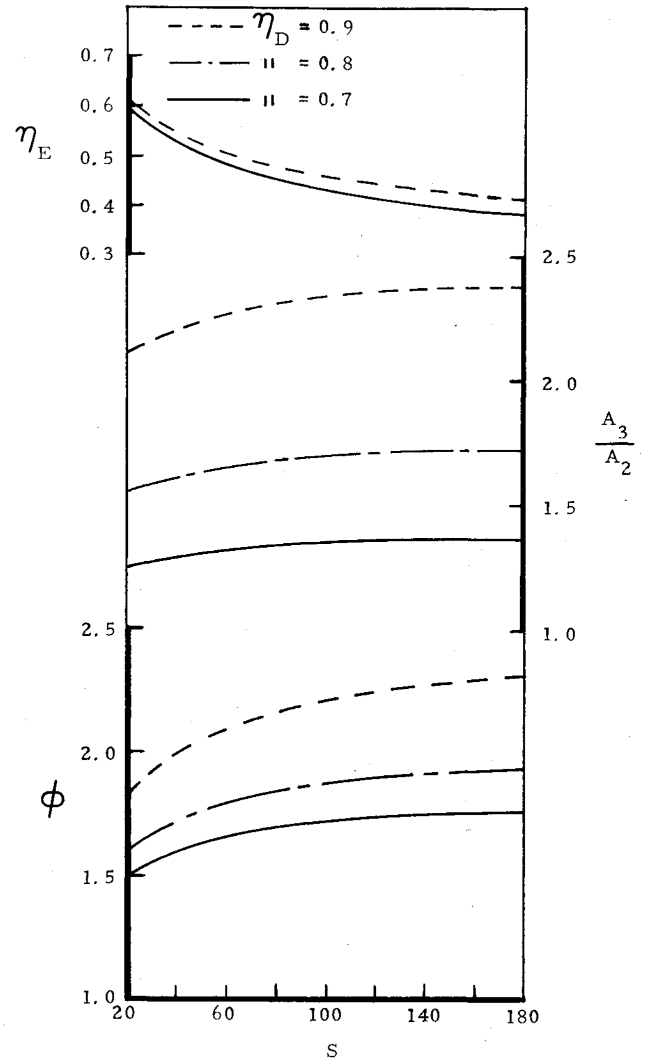

Fig. 10 The influence, over a wide range of area ratio, of diffuser efficiency on ejector thrust augmentation performance. Curves showing the effectiveness of the ejector, as a thrust augmenter, are also presented.

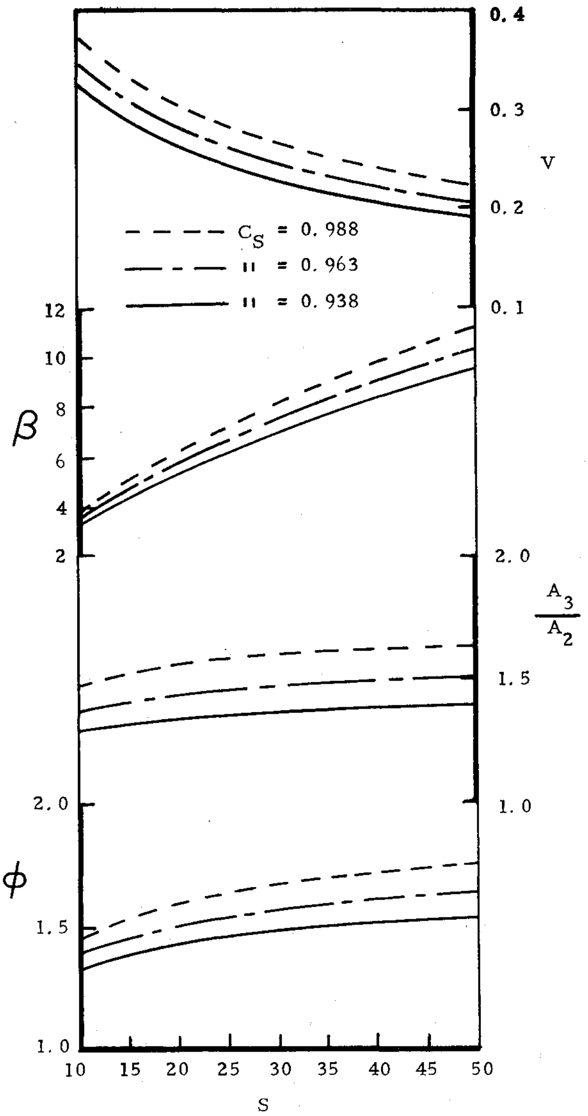

Fig. 11 The influence, on ejector performance, of the secondary flow inlet nozzle velocity coefficient.

of A_3/A_2 where, presumably, separation, or at least serious boundary-layer thickening, was beginning to occur in the diffuser. There was no provision for modeling such affects in the analytical prediction procedure.

Improved results reported by Quinn[1] and results due to Bevilaqua[3] using a modified hypermixing nozzle are compared with a corresponding theoretical prediction in Fig. 15. As can be seen from Fig. 15 the ϕ vs A_3/A_2 relationship obtained analytically is in close agreement with that obtained experimentally.

Conclusions

It was concluded that the simplified analytical procedure presented here is satisfactory for purposes of illustrating quantitatively the influences of the various geometric, internal, and external factors affecting the optimum performance of low-pressure-ratio thrust-augmenter ejectors.

Parametric studies showed that ejectors of the type considered are most sensitive to back pressure, as indicated in Fig. 6 and by Eq. (15). Losses which have particularly significant adverse effects were found to be those occuring in the secondary flow inlet (Fig. 11) and pressure losses in the ducts connecting the primary flow source to the ejector primary nozzles (Fig. 7). Thrust augmentation ratio ϕ was found to be fairly insensitive to the primary to secondary steam pressure ratio P_P/P_S (Fig. 4). Augmentation ratio ϕ

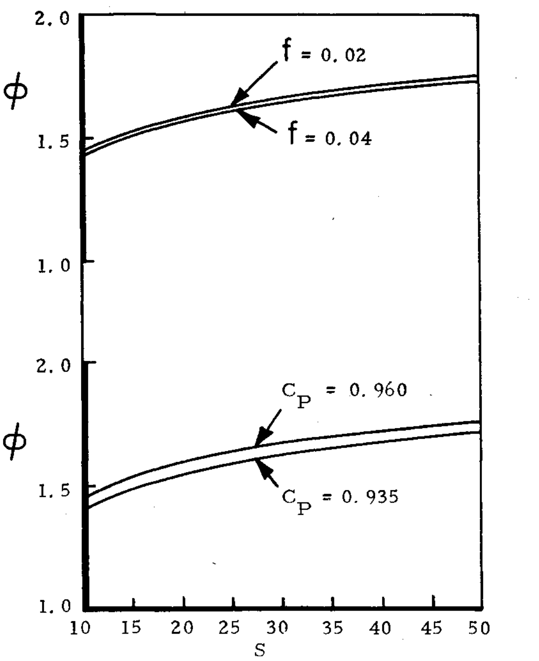

Fig. 12 The influences, on ejector performance, of the primary nozzle velocity coefficient and the mixing zone friction factor.

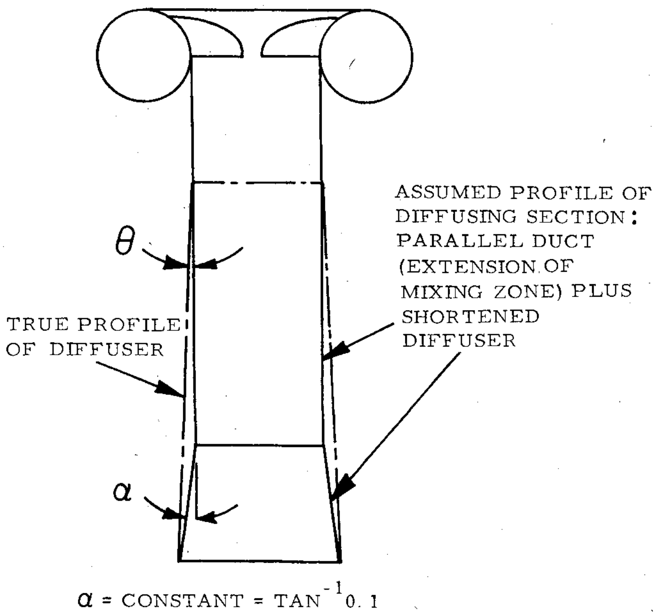

Fig. 13 Analytical model of a moveable sidewall, variable exit area, diffuser.

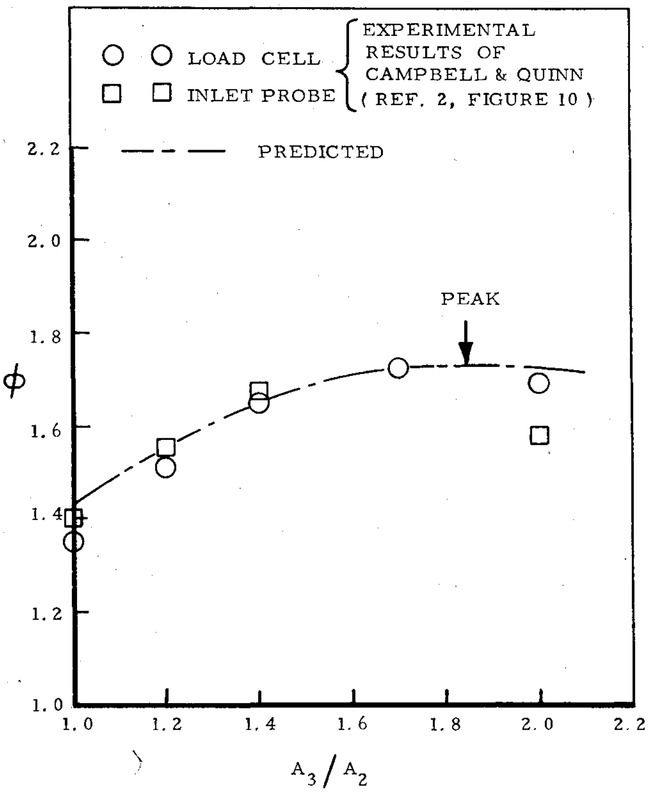

Fig. 14 Comparison of predicted and experimentally obtained ejector performances. For the predicted case: $\eta_D = 0.86$, $L/D = 0.58$, $r = 1.030$, $P_P/P_S = 1.26$; all other parameters are as listed in Table 1. The area ratio $S = 23.4$ for both the predicted and experimental results.

was also relatively insensitive to the secondary-to-primary density ratio r within a range of r sufficient to take into account variations in fan efficiency and operating conditions for ejectors where the primary flow is drawn from the bypass stream of a turbofan (Fig. 5).

Comparisons of predictions made using the analytical procedure with test results obtained experimentally by other workers[1-3] revealed the high values of η_D made possible in

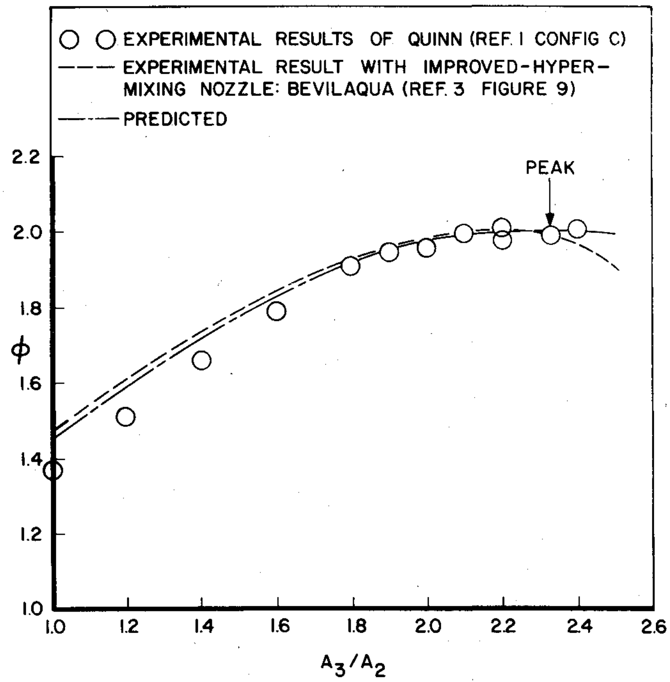

Fig. 15 Comparison of Quinn's best experimental results with the corresponding theoretically evaluated performance. For the theoretical case: $\eta_D = 0.92$, $L/D = 0.29$, $r = 1.030$, $C_P = 0.978$, $P_P/P_S = 1.26$; all other parameters are as listed in Table 1. The area ratio $S = 23.4$ for both the predicted and experimental cases.

practice by the judicious use of boundary-layer (corner) blowing and by the very effective mixing, in very short distances, resulting from the use of hypermixing primary nozzles. The experimental work of ARL[1-3] appears to represent a very significant advance in the ejector thrust augmentation field.

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