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FACTORS WHICH INFLUENCE THE ANALYSIS AND DESIGN OF EJECTOR NOZZLES

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Abstract

A theoretical analysis of the viscous interaction between the primary and secondary streams of ejector nozzles was developed. The analysis accounts for real sonic-line effects and the streamwise variation in stream mixing and boundary layer within the ejector. The aspects of the analysis are explained and illustrated by applying the theory to a variety of ejector configurations including cylindrical shroud, contoured flap and plug nozzles. Extensive comparisons are made between theory and data to show the importance of various analytical assumptions and such design variables as diameter ratio, spacing ratio, total temperature ratio, and primary nozzle geometry.

Introduction

Obtaining enough range out of a supersonic cruise aircraft has always been a fundamental design problem. Critical to this problem is the sensitivity of an aircraft mission to nozzle design. For example, a gain in cruise nozzle efficiency can be three times as effective as improvement in any other component of the propulsion system for a supersonic cruise mission.

The potential of secondary flow to improve the performance of exhaust nozzles has received widespread attention and numerous experimental as well as theoretical investigations have been conducted. Most of the early analytical efforts to analyze ejector nozzles were based on one dimensional concepts.(1,2,3) In these studies of ejector systems, one dimensional isentropic relations were applied to both the primary and secondary flows which were considered to coexist within a cylindrical shroud and allowed to have different average pressures. Realizing that such a treatment has limitations, later analyses constructed the primary flow using the method of characteristics, while assuming one-dimensional isentropic flow for the secondary stream.(4,5,6) The effect of mixing between the primary and secondary streams was treated as a simple perturbation superimposed on the overall inviscid flow field.(4) In spite of these refinements, these analyses did not accurately predict the performance of many ejector nozzles of practical design. Difficulty arose principally because these analyses did not account for physical phenomena which frequently occur within ejector nozzles.

It is therefore the intent of this paper to show to what extent real effects alter ejector nozzle behavior. A computer program has been developed which incorporates several phenomena not previously considered. One factor which will be shown to strongly influence the performance of ejector is the primary nozzle inlet flow conditions. Previous analysis assumed uniform axial flow at the primary nozzle exit, which is not valid for many ejector configurations which have been tested. The problem of compressible flow through choked conical nozzles has been treated in reference 7 and incorporated into the present analysis. In addition, streamwise variation in the mixing process can become important.(8) This has also been incorporated into the computer program and its effect will be demonstrated.

Theoretical Considerations

The flow within an ejector nozzle is based on the mutual interaction between a high-energy stream (primary flow) and a low-energy (secondary flow), Figure (1). These two streams begin to interact at the primary nozzle lip. For the ejector operating in the supersonic regime, the secondary flow is effectively "sealed off" from ambient conditions. When this occurs, the ejector mass flow characteristics become independent of the ambient static pressure. It is this ejector nozzle operating condition that is considered in the theoretical analysis.

When the amount of secondary flow supplied to the ejector is small, the primary flow plumes out and impinges on the shroud wall, Figure (2). This causes an oblique shock to form which effectively "seals off" the secondary flow from ambient conditions. The secondary flow is "dragged" through the recompression zone (oblique shock) by its mixing with the higher velocity primary jet. In this flow regime, all the secondary flow is entrained by the mixing process. Thus equilibrium conditions are satisfied in the analysis when the amount of secondary flow which "leaks" past the recompression zone associated with the oblique shock is equal to the secondary flow supplied to the ejector.

If the secondary flow is increased, the secondary pressure increases and this "pushes" the primary jet away from the shroud wall, Figure (2). The oblique shock can no longer be sustained at the shroud wall and thus the secondary flow accelerates and chokes within the shroud. The viscous interaction between the two streams occurs along the interface (dash-dot line in Fig. (2)). The effect of mixing results (1) in a transfer of energy (shear work) from the primary jet flow to the secondary stream and (2) modification of the pumping characteristics due to the displacement thickness of the mixing zone. These effects are included in the analysis by requiring that at every net point along the interface the amount of secondary flow entrained by the mixing process up to that position, in addition to the unmixed flow, must be equal to the amount supplied to the ejector. The displacement thickness of both the shroud boundary layer and mixing layer are included in the computation of the secondary flow area associated with unmixed flow.

The primary nozzle flow field, Figure (3), is computed using the method of characteristics starting from an initial datum (sonic line) computed using the method described in reference 7. The sonic line therefore depends not only on the primary nozzle geometry but also on "back pressure" under which the nozzle is operating. This dependence is illustrated in Figure (3), where the primary nozzle mass flow ratio (discharge coefficient) is shown as a function of ejector secondary corrected weight flow ratio for both theory and data. The data were obtained for a primary nozzle with a 27 degree inside lip angle operating within an ejector at a Reynolds number of 3.3×10^6.[9] The theoretical line was obtained by integrating the mass flux along the sonic line and correcting for boundary layer effects. The calculations indicate about a 0.4 percent decrease in discharge coefficient when the secondary corrected weight flow ratio was increased from 0 to 10 percent. This was caused by an increase in back pressure under which the primary nozzle was operating. The measured data indicates this variation.

Theoretical Calculations and Data

The influence of both sonic line and pointwise mixing on the performance of a convergent-divergent conical flap ejector is illustrated in Figure (4). The ejector had a shoulder diameter ratio D_s/D_p of 1.225 and was operated at a Reynolds number of 4.0×10^6. The label "mixing" indicates that mixing between the primary and secondary streams was computed point wise as the flow was constructed, while the "no-mixing" solution is indicative of an inviscid calculation. Computation for the real sonic line with mixing (solid line) was based on a choked conical nozzle with a lip angle of 16 degrees, and compares favorably with data from reference 10. The effect of mixing is seen by comparing the solid line with the dashed line on Figure (4). Higher efficiency computed for the no-mix case was due primarily to larger secondary total pressures. These two calculations were again repeated assuming that the primary nozzle had a plane sonic line. Both of these ejector cases had substantially higher primary and secondary thrust contributions and also larger primary nozzle discharge and velocity coefficients which resulted in greater efficiencies over the real-sonic line cases. Divergence losses in the initial primary nozzle flow field (sonic line) was the principal cause for the lower primary nozzle thrust for the real sonic-line calculations. Consequently, the primary nozzle inlet flow conditions can strongly influence both the pumping and thrust characteristics of ejector nozzles.

Figure (5) represents an attempt to recover some of the divergence losses associated with the primary nozzle thrust by varying the spacing ratio L_s/D_p, for the ejector configurations represented in Figure (4) at a secondary corrected weight flow ratio of 0.04. While increasing the spacing ratio does result in higher secondary pressures, and consequently higher thrust contributions (solid line), this effect is offset by a decreasing integrated pressure force along the shroud wall in the thrust direction. The net result is that the efficiency maximizes at a spacing ratio of about 0.30 inlet diameters downstream of the primary nozzle exit, for an ejector with a shoulder diameter ratio of 1.225.

The plane-sonic line, no-mixing case (dashed-dot line) was repeated since it represents the basic solution of previous analyses. Comparison of the mixing and no-mixing cases for the real sonic line (solid and dashed lines) indicates that mixing between the primary and secondary streams effects nozzle efficiency more at the larger values of spacing ratios than at the lower values, while its contribution to pumping remains nearly constant.

The influence of the primary nozzle lip angle on the performance of the conical flap ejector with a shoulder diameter ratio of 1.225 is shown in Figure (6). Computer results are shown for two types of assumptions regarding primary nozzles: (1) constant primary nozzle exit area and (2) constant primary nozzle mass flow. Constant mass flow was obtained by resizing the primary nozzle exit area to account for loss of mass flow as the lip angle was increased. Thus the shoulder diameter ratio D_s/D_p and spacing ratio L_s/D_p varied in these calculations, while these variables were held fixed for the constant exit area solution. The ejector nozzle performance presented in Figure (6) was generated by increasing the primary nozzle lip angle from 0 to 60 degrees. Computer results for the constant primary nozzle exit area case (solid line) indicate this variation in lip angle results in a 27 percent increase in pumping and about 1.3 percent decrease in nozzle efficiency. This compares with 12 percent variation in pumping and 0.8 percent decrease in efficiency for the constant primary nozzle mass flow solutions (dashed line). Reoptimizing the ejector with the 60 degree primary nozzles by changing the spacing ratio resulted in a 0.25 to 0.30 percent increase in nozzle efficiency. The best performance therefore for the 60 degree primary nozzle was about 1/2 percent lower than for the zero degree nozzle. The results presented on this figure are also indicative of the sensitivity of the pumping and thrust characteristics to distortions in the primary inlet flow.

Computer flow fields for the 10 and 60 degree primary nozzle ejector configuration presented in Figure (6) are shown in Figure (7). The dashed lines represent the velocity vector at each point in the characteristic net. Calculations were performed at a secondary corrected weight flow ratio of 0.04. The variation in sonic line and its effect on the entire flow field is evident from these computer plots. It is also interesting to note that even for the 10 degree primary nozzle, there is a noticeable distortion in the sonic line.

Ejector pumping characteristics are strongly influenced by the shroud diameter ratio D_s/D_p as illustrated in Figure (8). The calculations were performed on a family of cylindrical shroud ejectors having diameter ratios of 1.06, 1.11, 1.21, and 1.41, all with an 8 degree conical primary nozzle. Results of the experimental investigation are presented in reference 11. A comparison of the computed performance and model data generally indicates good agreement except for the low diameter ratio ejector operating at high secondary mass flows. Under these conditions, the secondary inlet Mach number ranged from 0.30 to 0.60. In an attempt to account for the disagreement at this low diameter ratio, the secondary inlet flow blockage was increased by changing the initial shroud boundary layer displacement thickness (δ^*/D_p) from 0 to 0.0025. The results of this latter calculation are shown as the dashed line in Figure (8) and show better agreement with data. Consequently, secondary inlet flow blockage can influence the pumping characteristics particularly when the secondary inlet Mach number is high.

If the performance of the four ejector nozzles are examined in sequence at zero secondary corrected weight flow ratio, it can also be seen that agreement between predicted pumping and experimentally measured pumping gets poorer as the shroud diameter ratio approaches unity. However, it should be noted that agreement at 1 percent secondary weight flow was very good.

In order to investigate the ability to predict the performance of ejector nozzles at higher primary total temperatures, a series of solutions was obtained for the cylindrical shroud ejector whose test results are presented in reference 12. These ejector nozzles were tested with an afterburning turbojet engine mounted in an altitude facility. Power settings were varied from part power to maximum afterburning yielding exhaust primary gas temperatures between 1600° and 3500° R. In order to accommodate the flow, the primary nozzle angle was varied from 5 to 15 degrees. Therefore, as the power setting was varied, both the nozzle lip angle and shroud diameter ratio changed. The secondary inlet temperature used in the calculation presented in Figure (9) was based on experimental measured results. In general, the theory was able to predict fairly well both the pumping and thrust characteristics that were measured. The stream thrust (or vacuum thrust) parameter used to compare theory and data was defined in terms of the sonic throat area of the primary nozzle (A_p^*) and the primary total pressure (P_p).

An aspect of the problem of predicting ejector nozzle pumping and thrust characteristics which has not received much attention is the effect of the heat transfer phenomena between the secondary and primary nozzles flow fields. To examine this problem, a series of computer cases were run on a convergent-divergent conical flap ejector with a shoulder diameter ratio (D_s/D_p) of 1.265. The base case (solid line), Figure (10), was run as a cold flow condition at a secondary weight flow ratio of 0.06 and compared to the cold flow data presented in reference 10 over a range of spacing ratios. Agreement between theory and data is generally very good. Computed results for hot flow conditions were performed for two types of assumptions regarding the mixing process (1) no-mixing of the two-streams (dashed line) and (2) complete mixing of the primary and secondary flows; i.e., bringing the total temperature of the secondary flow instantaneously up to the temperature of the primary jet. The results indicate that primary total temperature strongly influences the ejector pumping characteristics regardless of the heat transfer process. The differences in ejector thrust performance for the cold flow (solid line) and hot flow with complete heat transfer (dash-dot line) were due to underexpansion losses. The maximum computed nozzle thrust efficiency was the same for both these cases but occurred at different nozzle pressure ratio (P_p/p_0). For spacing ratio L_s/D_p up to and including optimum, the difference between the "no-heat transfer" and "complete heat transfer" was about 0.25 percent. However, as the spacing ratio was increased beyond optimum, the difference in efficiencies between these cases increased sharply to about 1.0 percent. The heat-transfer process alone, however, should not be regarded exclusively as causing these effects since this study did not account for the effects of secondary inlet temperature independent of the heat transfer process. However, it is evident that heating the secondary inlet flow would result in a decrease in nozzle efficiency.

It can be concluded that there could be gains in thrust efficiency in going from "cold flow" to "hot flow" testing provided the secondary inlet temperature is kept as low as possible and that losses in the primary nozzle inlet flow remain about the same. These gains, however, would not be very large if the ejector is operating at optimum conditions and could be easily offset by losses in the primary nozzle inlet flow. It may also be concluded that there are ejector nozzle conditions when the heat transfer process between the primary and secondary flows could noticeably affect nozzle performance.

One type of ejector that has not received wide spread analytical attention is the plug nozzle. It was pointed out in reference 13 that good performance could be achieved with a plug nozzle which incorporates a translating shroud and variable geometry primary nozzle. In order to investigate the question of effectiveness of this type of ejector nozzle, the "afterburner on" configuration discussed in reference 13 was run using the current computer program. The results are presented in Figure (11). The present analysis computed a primary inlet flow sonic line by assuming conical flow in the vicinity of the primary nozzle exit, i.e., the primary inlet flow satisfies the Taylor-Maccoll equation. Computed results using the geometric primary nozzle exit area (dash-dot line) unpredicted ejector pumping and over predicted nozzle efficiency. By matching the primary nozzle mass flow, i.e., using an effective or sonic area (A_p^*), better agreement with data resulted. Thus the assumption that the primary nozzle inlet flow satisfies the Taylor-Maccoll equation (conical flow) is equivalent to the plane sonic line assumption previously discussed. This partially accounts for the higher computed efficiencies. Although fair agreement can be achieved in computing nozzle performance, ultimately the real primary nozzle inlet flow must be used in the computations.

Concluding Remarks

An analysis has been presented which incorporates real sonic line computations and streamwise variations in both mixing and boundary layer growth and shows very good agreement with measured pumping and thrust performance. Extensive comparisons were made between theory and data to indicate the importance of factors which have not previously been considered. It can be concluded that both primary nozzle inlet flow conditions (sonic-line) and pointwise mixing between the two streams strongly influence the pumping and thrust characteristics of ejector nozzles. When the secondary inlet Mach number becomes high, the pumping characteristics can be noticeably affected by boundary layer flow blockage. Reasonable agreement can be achieved in predicting ejector performance with primary inlet temperatures up to 3500° R provided the secondary inlet temperature is known. High primary nozzle inlet temperatures strongly effect ejector pumping characteristics, while giving only marginal gains in thrust efficiency if the ejector is operating at optimum conditions. The heat transfer process associated with the turbulent mixing zone within ejector nozzles could noticeably affect ejector performance and therefore should be included in future analyses.

Symbols

A area

C_v nozzle efficiency, $(F - p_0A_e)$ (Fip + Fis)

D diameter

F thrust

Fip ideal thrust based on measured primary flow

Fis ideal thrust based on measured secondary flow

L_s distance from primary nozzle exit to shroud shoulder point

P total pressure

p static pressure

Re Reynolds number based on primary nozzle exit diameter

T total temperature

W weight flow

W_p measured primary weight flow

W_{ip} ideal primary weight flow

α angle

δ^* displacement thickness

$\omega\sqrt{t}$ corrected secondary weight flow ratio, $\frac{W_s}{W_p}\sqrt{\frac{T_s}{T_p}}$

Subscripts:

e exit

i ideal

p primary

s secondary

0 free stream

* sonic conditions

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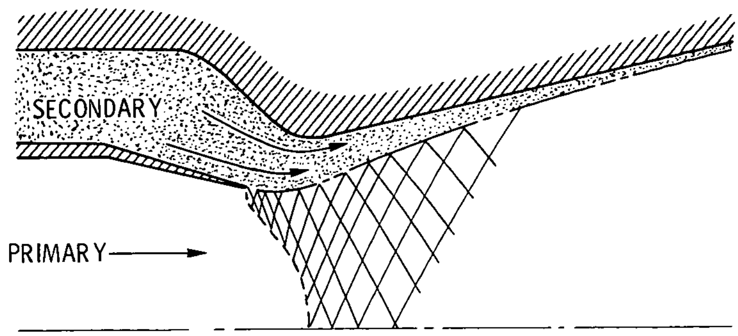

Figure 1. - Supersonic ejector system.

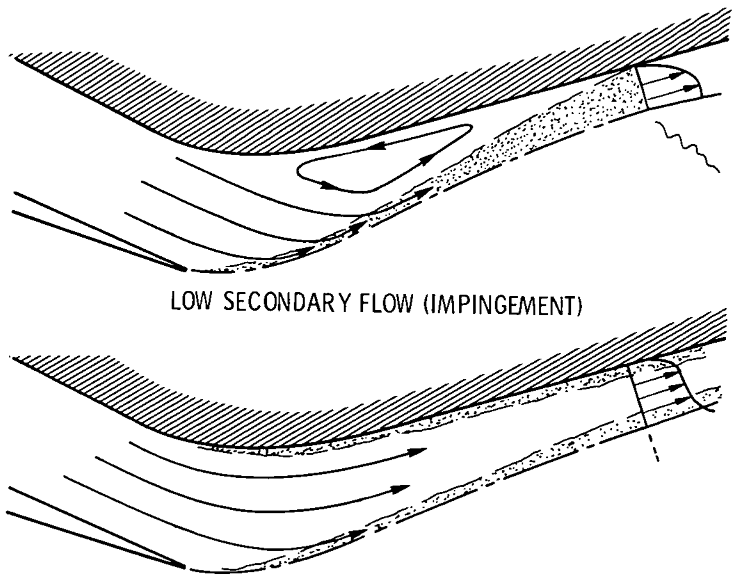

Figure 2. - Ejector flow regimes.

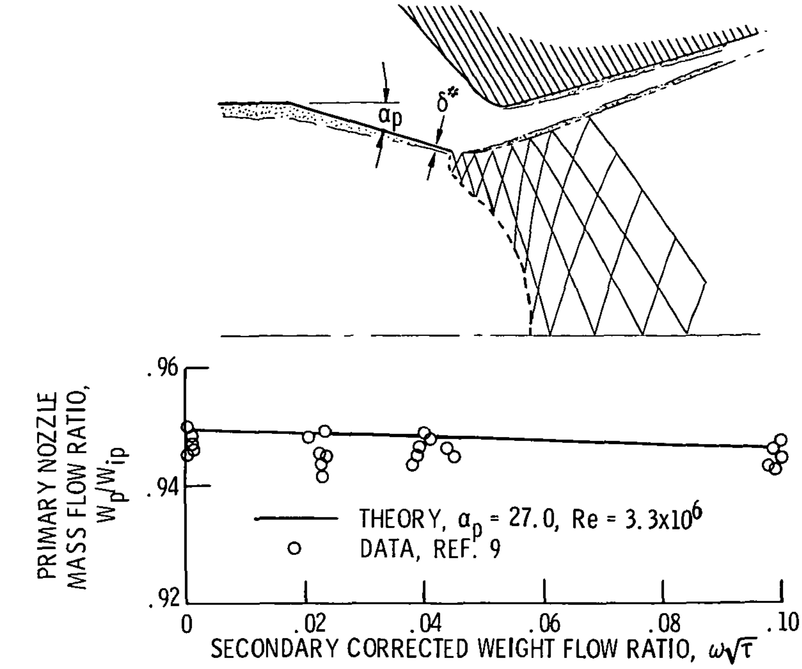

Figure 3. - Primary nozzle.

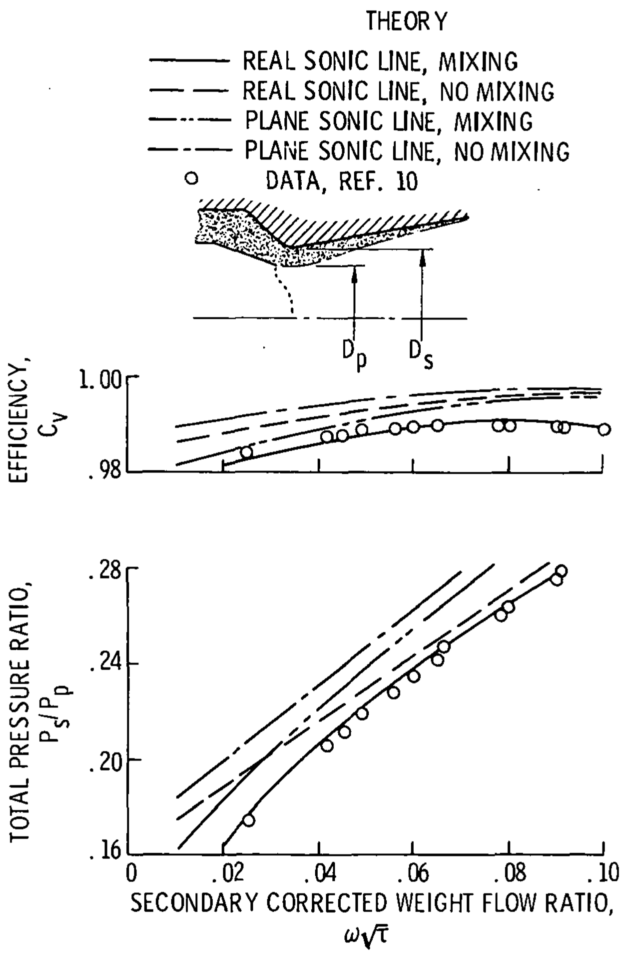

Figure 4. - Influence of sonic line and mixing, D_s/D_p = 1.225, Re = 4.0x10^6, P_p/p_0 = 14.0.

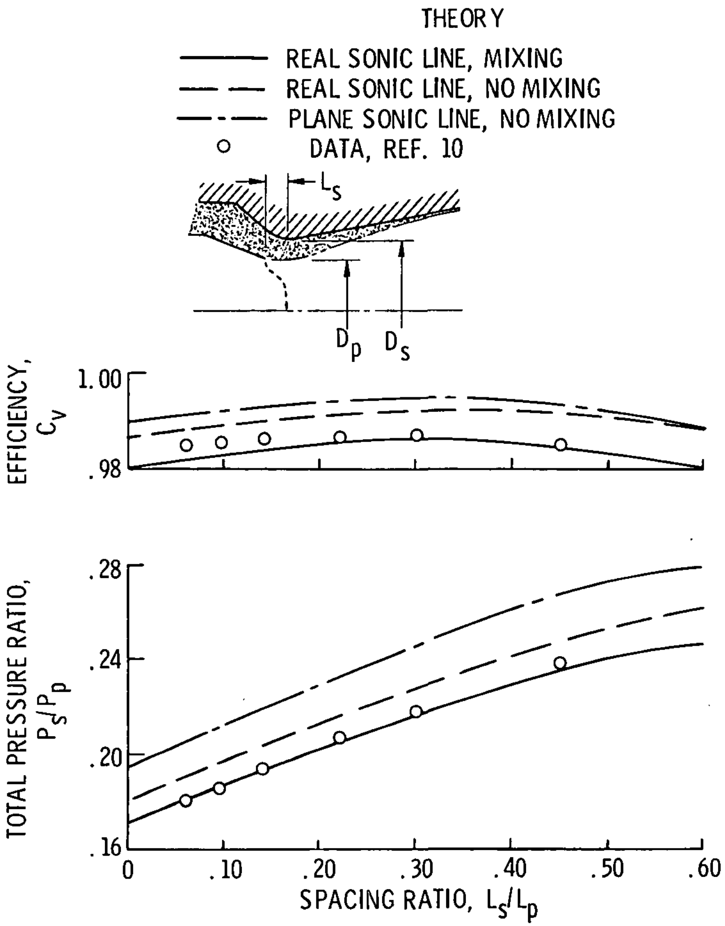

Figure 5. - Effect of spacing ratio, $D_s/D_p = 1.225$, $\omega\sqrt{\tau} = 0.04$, $P_p/p_o = 14.0$.

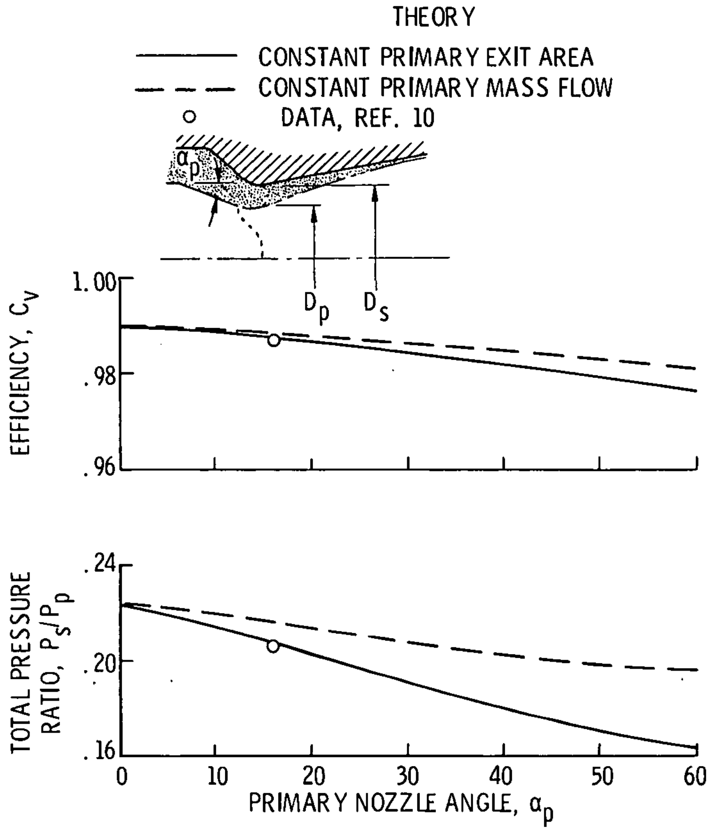

Figure 6. - Effect of primary nozzle angle, $D_s/D_p = 1.225$, $\omega\sqrt{\tau} = 0.04$, $P_p/p_o = 18.0$.

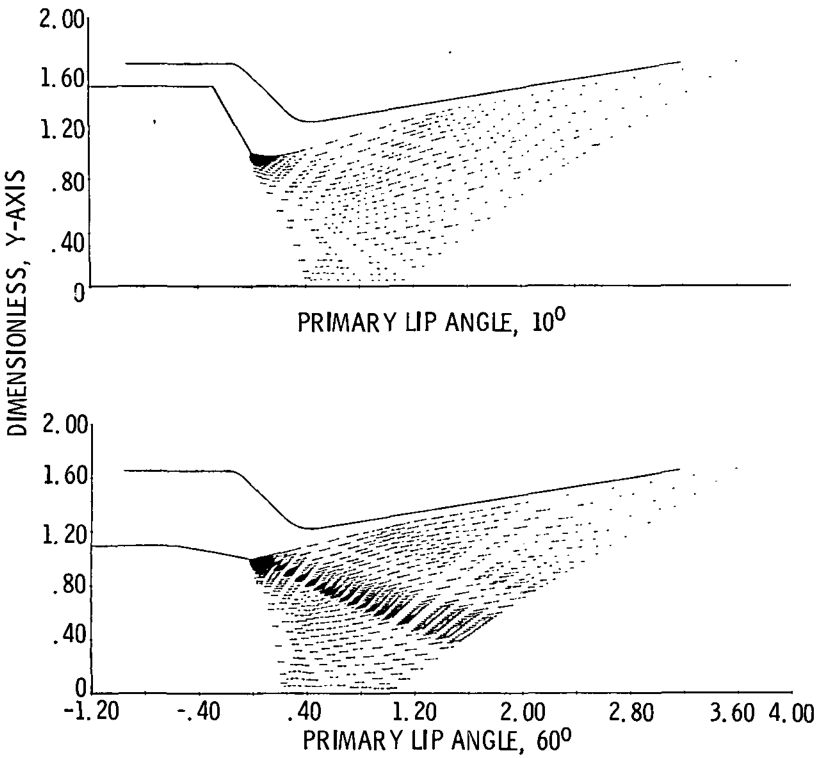

Figure 7. - Computer flow field solution $D_s/D_p = 1.225$, $\omega\sqrt{\tau} = .04$.

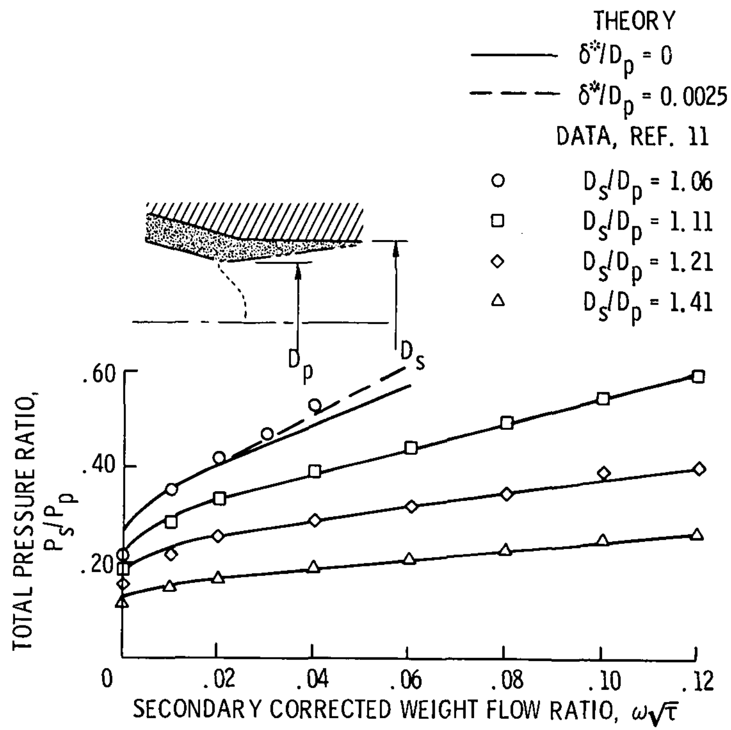

Figure 8. - Effect of shroud diameter ratio, $Re = 3.5\times10^{6}$.

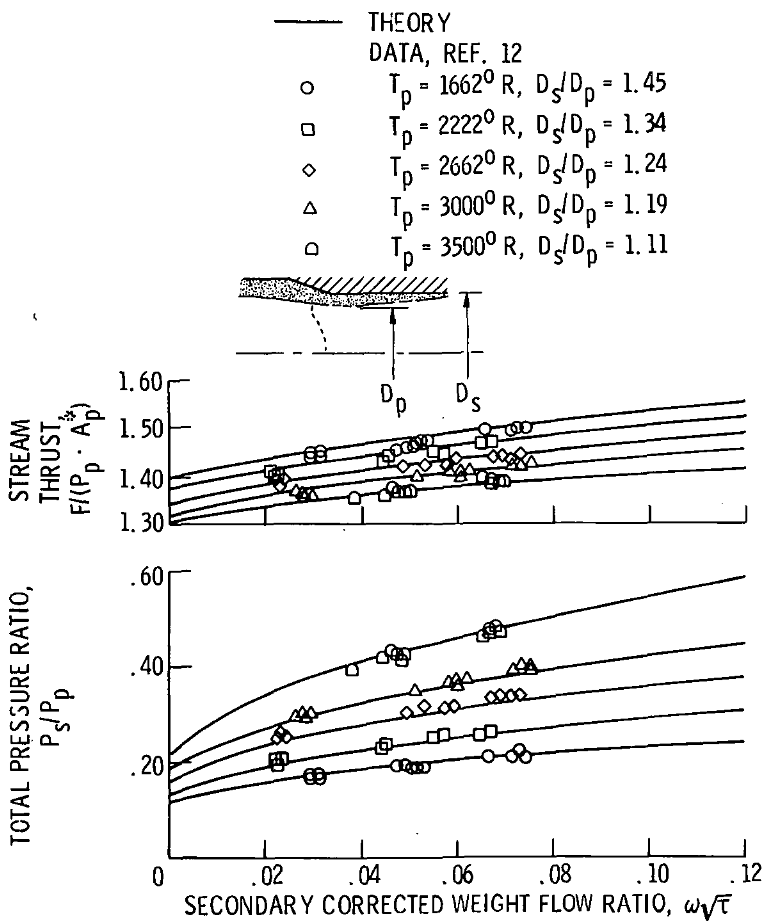

Figure 9. - Effect of primary temperature.

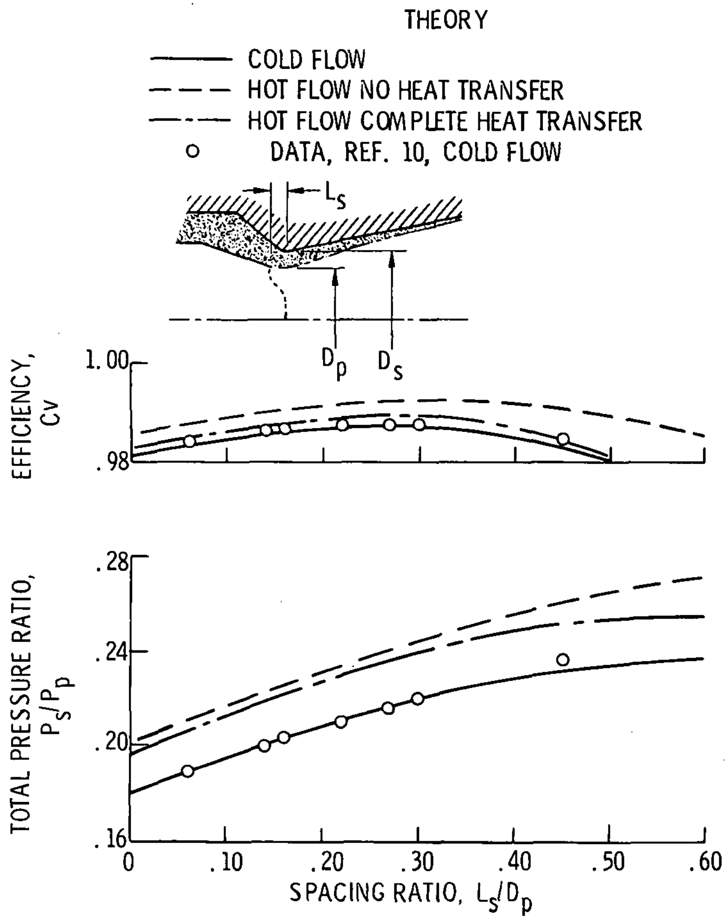

Figure 10. - Effect of heat transfer. D_s/D_p = 1.265, $\omega\sqrt{\tau}$ = 0.06, P_p/p_0 = 14.0

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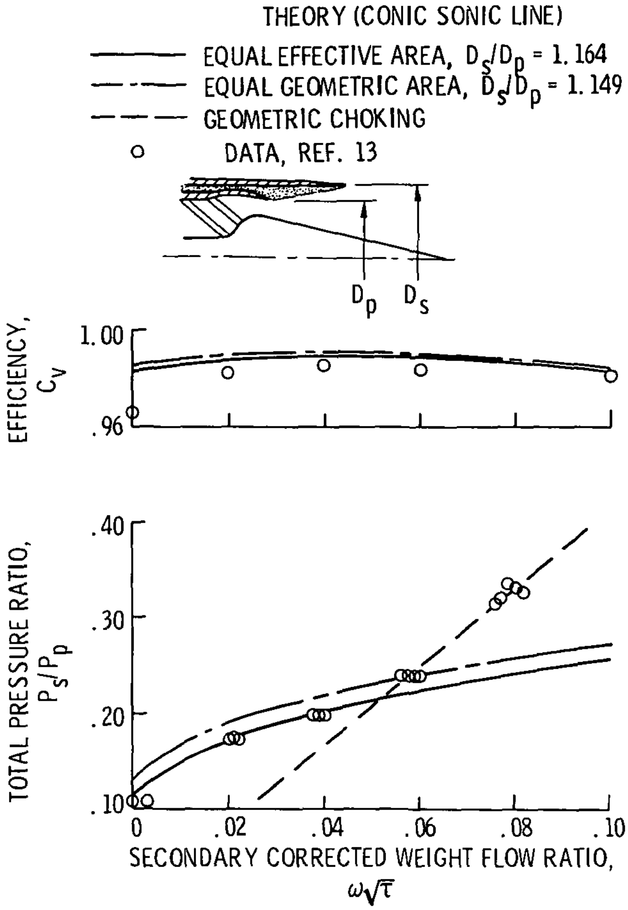

Figure 11. - Performance of a plug nozzle, Re = 3.5×10^6, P_p/p_0 = 15.0.