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Approximate Similarity Principle for a Full-Scale STOVL Ejector

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Full-scale ejector experiments are expensive and difficult to implement at engine exhaust temperatures. For this reason the utility of using similarity principles, in particular the Munk and Prim principle for isentropic flow, was explored. Static performance test data for a full-scale thrust augmenting ejector were analyzed for primary flow temperatures up to 1560°R. At different primary temperatures, exit pressure contours were compared for similarity. A nondimensional flow parameter is then used to eliminate primary nozzle temperature dependence and verify similarity between the hot and cold flow experiments. Under the assumption that an appropriate similarity principle can be established, properly chosen performance parameters were found to be similar for both hot flow and cold flow model tests.

Nomenclature

A = cross-sectional area
M = Mach number
NPR = nozzle pressure ratio, P_p/P_{ambient}
P = total pressure
p = static pressure
T = total temperature
γ = specific heat ratio
ϕ = thrust augmentation ratio

Subscripts
p = primary
s = secondary
2 = diffuser entrance location
3 = diffuser exit location

Introduction

An ejector is a mechanically simple pumping device consisting of a nozzle exhausting into a diffuser or shroud. Figure 1 highlights the main components and pertinent terminology of a simple ejector. Ejectors operate by inducing large amounts of air from the ambient through the entrainment action of the primary nozzle jet shear layer. Turbulent mixing of the two airstreams accelerates the entrained air, increasing total mass flow and creating a force ($F = ma$) which results in an increase of thrust.

Several possible ejector applications are depicted in Fig. 2. The turbofan forced mixer or mixer ejector (Fig. 2a) is used for noise suppression of a jet engine exit nozzle by mixing the core and fan flow before the nozzle exit. Pumping ejectors such as the turbine engine test installation (Fig. 2b), act as mass flow augmentors to capture and expel free-jet flows. Thrust augmenting ejectors (Fig. 2c) could provide vertical lift for short take-off and vertical landing (STOVL) aircraft. Here, air is ducted to a row of nozzles between the wing and fuselage of the aircraft. It is this third type of ejector application that will be discussed in this article.

Although properly designed ejectors can perform very well with cool primary air, proposed technology results in elevated primary nozzle air temperatures. To examine specific performance effects, a full-scale lift ejector was tested with primary flow temperatures ranging from ambient to 1100°F, and NPR up to 3.0. This unique ejector testing, performed at the NASA Lewis Research Center's Powered Lift Facility (PLF), signifies the first design point (both pressure and temperature) testing of a full-scale thrust augmenting ejector. For experimental purposes, the model was turned on its side, measuring thrust in the axial direction (parallel to the ground plane).

The cost and complexity of testing ejector models could be greatly reduced if one could neglect temperature effects of the primary nozzle when determining ejector performance. Theoretically, this could be accomplished if a suitable jet similarity principle could be established. An approximate technique has been used by Greitzer et al.[1] for viscous heat conducting flows (mixer ejector nozzles). Basically, this technique states that for fixed geometry and inlet total pressure distributions, the Mach number and total pressure along the streamlines are independent of the upstream total temperature distribution. This is an extension of the Munk and Prim

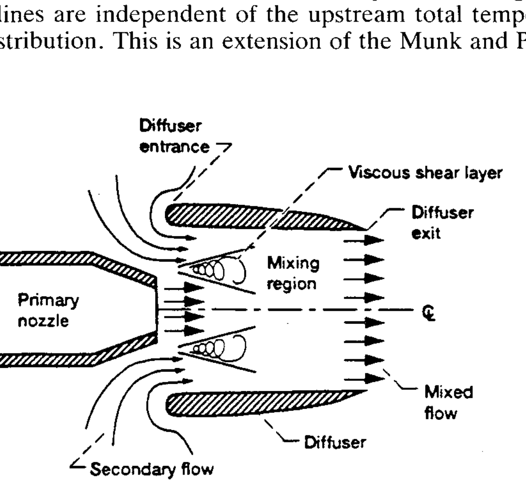

Fig. 1 Main components of a simple ejector.

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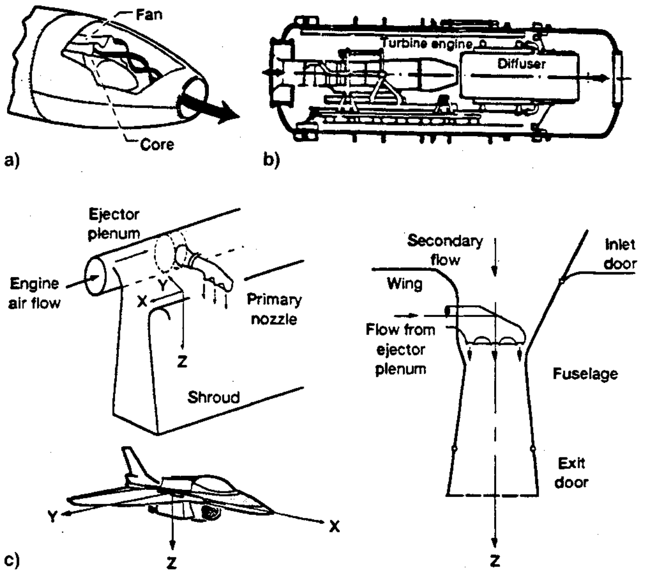

Fig. 2 Different ejector applications: a) turbofan forced mixer, b) typical turbine engine test installation, and c) vertical lift aircraft configuration.

principle[2] for steady isentropic flows, where the current approach includes the nonisentropic (viscous) effects.

The purpose of this article is to examine the cold and hot experimental ejector data and assess the validity of an approximate similarity principle (Munk and Prim) for this application. Results presented will include thrust augmentation, normalized pumping, Mach number, and total pressure profiles. The degree of dependence of the normalized ejector performance on the primary nozzle total temperature is examined.

Experimental Apparatus and Procedure

Facility

The Powered Lift Facility is a triangular-shaped thrust frame, multidirectional force measuring system, and dry air supply. The three sides of the thrust stand are 30 ft long and 15 ft above ground level. There are six load cells capable of measuring thrust levels in the lateral (0–5000 lbf), vertical (0–25,000 lbf), and axial (0–5000 lbf) directions, as well as the moments of roll, pitch, and yaw.

Air enters the test section at a maximum pressure of 150 psig, and can be supplied to the test hardware at ambient temperatures, to simulate fan jet airflow, or heated to 1200°F by means of a J-58 burner supplied with JP5 fuel, to simulate engine exhaust conditions. Flow measurement is accurate to within ±0.5%, including both scatter and systematic errors. The maximum allowable line pressure and flow rate at the test section is 90 psig and 150 pps, respectively. Ground effects of the exhaust flow are negligible.

Model

The ejector model is an array of 10 notched-cone nozzles (primary flow) placed chordwise (the x direction in Fig. 2c) along the throat of a converging/diverging nozzle shroud. Each of these primary nozzles has three spanwise (the y direction in Fig. 2c) convergent nozzle exits. Figure 3 is a cross-sectional view of the ejector showing the three spanwise nozzles and the diffuser walls. Also shown in the figure is the leading edge and root fairing of the nozzles to optimize the ejector performance.[3] Figure 4 shows a sketch of the ejector plan view. The figure shows the 10 notched-cone nozzles and the ejector primary nozzle plenum which is attached between the second and third nozzle (plenum anchor plane). Diffuser exit plane data collection was obtained spanwise with a single pressure/temperature rake traversed in the chordwise direction. During the experiment, several model configuration changes were

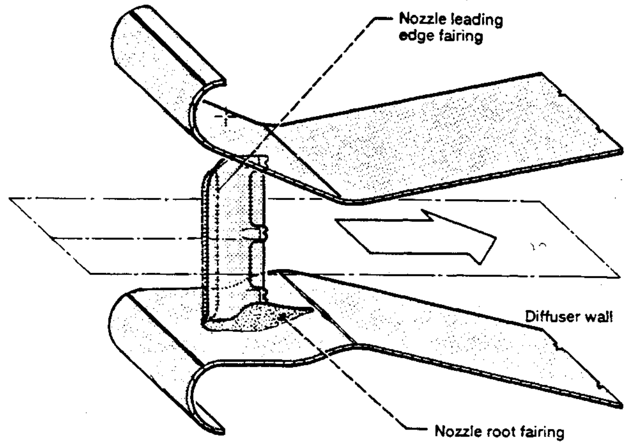

Fig. 3 Cross-sectional view of an ejector.

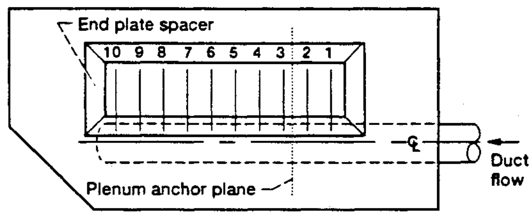

Fig. 4 Sketch of ejector plan view.

made to increase performance.[3] For simplicity, data from only one configuration was analyzed with the similarity principle.

Procedure

Steady-state performance testing consisted of pressure, temperature, and thrust measurements over a NPR range of 1.6–3.0. These runs were conducted with primary flow temperatures of 1560, 1360, and 1160°R, and a cold flow of approximately 530°R (temperature of facility air supply without the burner ignited). For the hot temperatures, the steady-state max-to-min temperature variation was approximately ±20°R, based on the burner system capability. The cold flow primary temperature did not vary as much during each test run; however, since the PLF is an outdoor facility, primary and secondary air temperatures are lower for the tests conducted in the winter months than in the summer. For more detailed information regarding the experiment and model, see Ref. 3.

Munk and Prim Similarity Principle

In the prediction of hot ejector flow, a similarity principle that could eliminate the primary nozzle temperature effect on performance, would reduce testing costs and complexity by eliminating the need to conduct experiments at elevated temperatures. If the energy exchange due to viscous stresses could be neglected and the flow therefore considered isentropic, the Munk and Prim similarity principle would apply.[2] This principle is valid for steady, adiabatic, inviscid flow of a perfect gas with constant specific heats.

Simply stated, the Munk and Prim principle is a guiding philosophy which says that for a fixed geometry and upstream total pressure profile, any change in the upstream total temperature profile does not alter the streamline shapes, Mach number, or total pressure distributions (and therefore, momentum) in the device. This can be seen by inspection of the governing equations for isentropic, compressible flow written in terms of the Mach number and pressure[1]:

Continuity

$$\nabla \cdot M \left[1 + \frac{(\gamma - 1)}{2} M^2\right]^{-(\gamma+1)/2(\gamma-1)} = 0 \qquad (1)$$

Momentum

$$(M \cdot \nabla)M - \frac{\gamma - 1}{\gamma + 1} M(\nabla \cdot M) + \frac{1}{\gamma} \nabla \ln(p) = 0 \qquad (2)$$

Momentum expressed in terms of total pressure

$$(M \cdot \nabla)M - \left(\frac{\gamma - 1}{\gamma + 1}\right) M(\nabla \cdot M) - \left(\frac{1}{\gamma - 1}\right) \times \nabla \left[\ln\left(1 + \frac{\gamma - 1}{2} M^2\right)\right] + \frac{1}{\gamma} \nabla \ln(P) = 0 \qquad (3)$$

Because continuity and momentum are decoupled from the energy equation (total enthalpy or total temperature does not appear), the Mach number and static and total pressure fields are unchanged with respect to changes in upstream total temperature. The streamline pattern is also unchanged. In other words, a change in total temperature affects only the local velocity, such that the relative distributions remain constant.

The limitation in applying the Munk and Prim principle to an ejector is that mixing in an ejector is not isentropic; energy is exchanged by both heat exchange and momentum transfer in the viscous shear layer. This violates the inviscid flow assumption, so in a strict sense the original Munk and Prim analysis is not applicable. However, studies by Greitzer[1] and Presz[4] have shown that the heat exchange and viscous interaction approximately counteract each other over a wide range of flow conditions, so expanding the similarity principle to include ejector problems would be an appropriate first approximation.

Results and Discussion

In this discussion, ejector performance is measured by the thrust augmentation ratio

$$\phi = \frac{\text{total thrust}}{\text{primary-nozzle ideal thrust}} = \frac{\text{load cell measurement}}{\text{isentropic thrust}} \qquad (4)$$

where isentropic thrust is computed from internal nozzle static pressure taps and the supply pipe mass flow rate.

Constant pressure performance curves of the present data (Fig. 5) show a thrust augmentation loss as the primary nozzle temperature increases. The augmentation levels of the two curves—representing different ambient temperatures—differ by approximately 2%. It is interesting to note that similar amounts of reduction in the augmentation ratio can take place by 1) decreasing the secondary flow temperature by about 30°R, or 2) increasing the primary nozzle temperature by about 500°R. Supporting this result is Fig. 6, which includes the experimental results of eight different ejectors.[5] All the data from the literature show a slight temperature dependence of the ejector, and although all the data—except that of Lockheed—included a scale or configuration change, the trend is consistent.

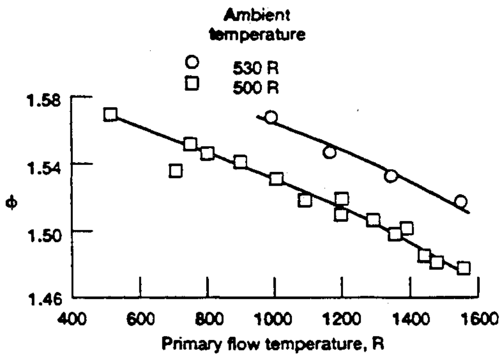

Fig. 5 Thrust augmentation ratio vs primary nozzle temperature at NPR = 2.7.

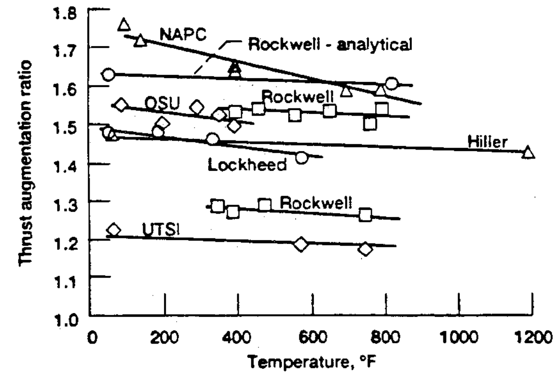

Fig. 6 Comparison of different thrust augmentation experimental data. Source: Ref. 5.

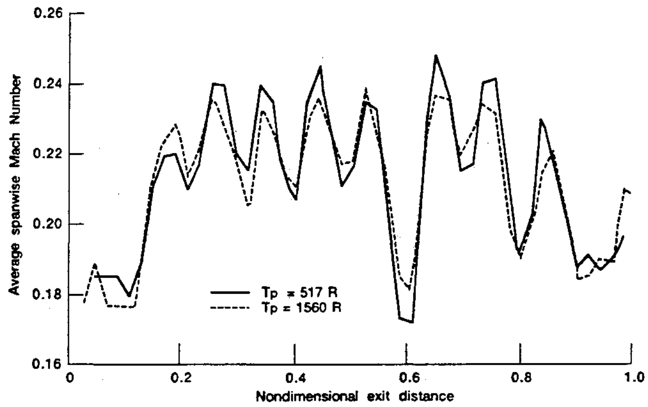

Fig. 7 Chordwise Mach number distribution at the ejector exit plane.

The consistency in the data trends indicates that no major problems occurred in the experimental data acquisition. Therefore, the first step in the Munk and Prim analysis involved comparing exit plane Mach number and total pressure profiles of the cold and hot primary flow experiments. For inviscid flow these profiles should stay constant when changing the primary nozzle total temperature. Since Mach number and total pressure exit plane distributions are quite similar, redundant plots will not be presented.

The chordwise Mach number distribution (Fig. 7) was calculated at each location as the average of the spanwise exit rake values. Although end effects are present, similarity between the two different primary nozzle total temperature data sets can be seen. Other than lowering the local peak values, the change in primary nozzle total temperature did not significantly change the Mach number distribution.

A typical contour plot obtained from the exit rake data is shown in Fig. 8. Here the cold flow total pressure distribution is plotted across the entire exit plane (NPR = 2.7). The contour shows the overall trends and locations of each nozzle exit, however, the plotting routine's interpolation scheme could not accurately capture the flow details at this scale. To smooth the contours and eliminate any end effects/boundary-layer effects, we then looked at the center third of the duct.

Figure 9 shows the hot and cold primary nozzle pressure comparison for the center portion of the duct (NPR = 2.7), where approximately three and a half nozzle plumes are visible across the chord length. As expected, the contours are definitely similar, however, there are a few discrepancies due to experimental error and duct thermal expansion. The qualitative similarity of the pressure distributions suggests that the approximate Munk and Prim principle may be applicable for the thermal scaling of this ejector's performance characteristics.

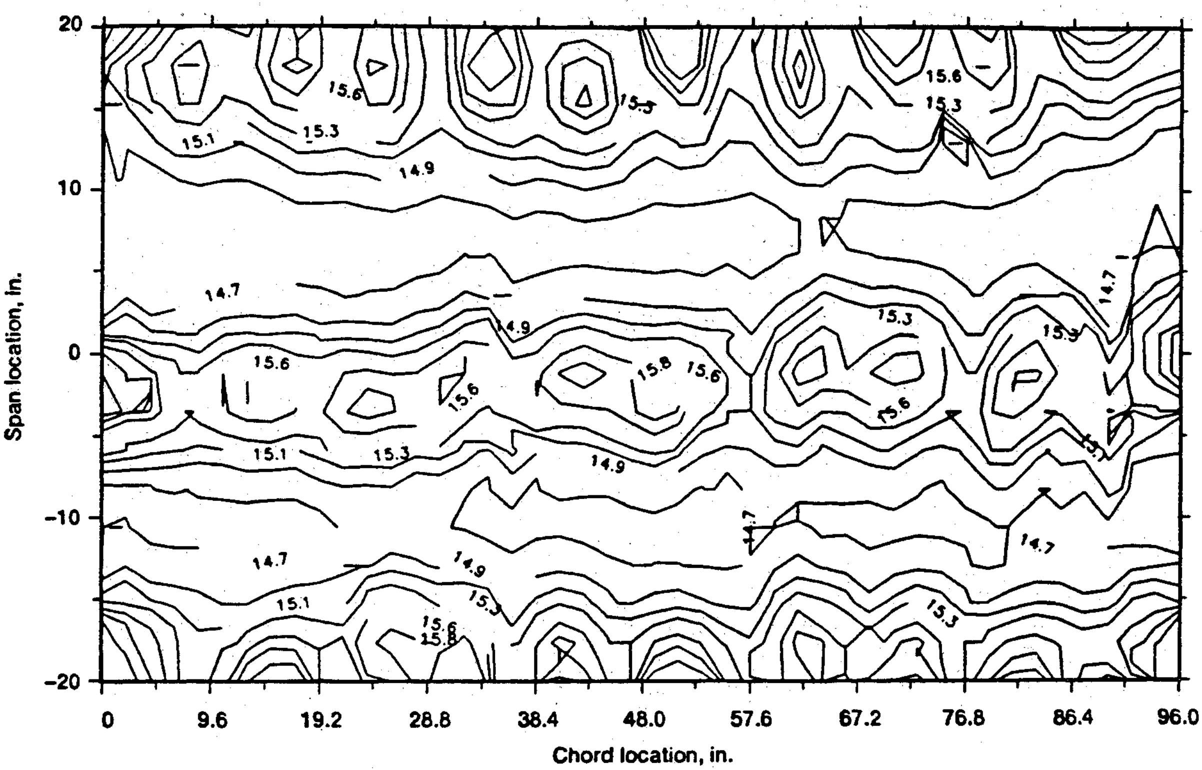

Fig. 8 Total pressure contours at the ejector exit plane (T_p = 517°R).

To investigate the Munk and Prim concept further, it is necessary to obtain a nondimensional parameter that would collapse both the hot and cold flow performance curves into one. Since the Munk and Prim principle is only an interpretation of the governing equations, a specific parameter to use for ejector applications must be obtained by other means. As derived by Presz and Greitzer,[4] a control volume analysis for ejector performance under ideal conditions (incompressible, isentropic) yields

$$\frac{T_s}{T_p}\left(\frac{\dot{m}_s}{\dot{m}_p}\right)^2\left[\left(\frac{A_p}{A_s}\right)^2+\left(\frac{A_2}{A_3}\right)^2\right]+2\sqrt{\frac{T_s}{T_p}}\left(\frac{\dot{m}_s}{\dot{m}_p}\right)$$
$$\times\left[1+\left(\frac{A_2}{A_3}\right)^2\right]+\left[\left(\frac{A_2}{A_3}\right)^2-1-2\left(\frac{A_s}{A_p}\right)\right]=0 \quad (5)$$

which is nothing more than a quadratic equation. The variable is the nondimensional ejector pumping ratio

$$\frac{\dot{m}_s}{\dot{m}_p}\sqrt{\frac{T_s}{T_p}} \quad (6)$$

which is only a function of ejector geometry. Since we seek a parameter that is invariant with temperature, it is clear that an appropriate nondimensional parameter is the ejector pumping ratio. Although this equation has been derived for low speed flow, compressible flow would follow the same trend.

Figure 10 demonstrates the usefulness of the nondimensional pumping parameter. Here, part a) of the figure shows the mass flow ratio as a function of the primary to secondary pressure ratio for different primary total temperatures at a constant flow area ratio (A_s/A_p). Note, as expected from the control volume analysis, the pumping parameter is fairly constant with respect to changes in the total pressure ratio. The slight variation with the pressure ratio is due to the compressibility effects that were assumed negligible in the control volume formulation. Part b) of the figure shows that the normalized pumping parameter collapses the results such that the temperature effects drop out. Again, there is a slight compressibility effect present. Also note that if the flow was actually isentropic, the temperature curves should completely collapse with the pumping ratio. The slight difference in the temperature curves is due to the inviscid assumption imposed on the ejector. Since the normalized pumping parameter "washes out" the jet temperature effects, it seems an appropriate factor to use in characterizing ejector performance.

For ideal flow the thrust augmentation ratio can be expressed as

$$\phi = 1 + \left(\frac{M_s}{M_p}\right)\left(\frac{\dot{m}_s}{\dot{m}_p}\sqrt{\frac{T_s}{T_p}}\right) \quad (7)$$

Basically, this is a control volume equation where the pressure-area terms were neglected (first-order approximation). At first glance it may appear that the ideal flow thrust augmentation ratio varies with the normalized pumping parameter. However, the Mach number ratio is constant through the Munk and Prim principle, and the normalized pumping parameter is only a function of ejector geometry. This implies that for the same geometry and inflow total pressure distribution, the normalized ejector performance (thrust augmentation ratio) should be invariant with the normalized pumping parameter. Momentum and energy effects are contained in the normalization.

In Fig. 11 the thrust augmentation ratio was plotted against the normalized pumping parameter. The data reflects a very weak dependency between these two parameters, and therefore this data supports the fundamental premise of the approximate Munk and Prim similarity principle. It should be noted that we are able to plot Fig. 11 because of the viscous and thermal nonidealistic mixing of the ejector. In other words, violation of the basic assumptions used to invoke the Munk and Prim principle. The excursion of the data from the proposed ideal slope (Fig. 11) has a consistent trend for both cold and hot temperatures. There is slight scatter in the data and it shows only a small dependence on the pumping pa-

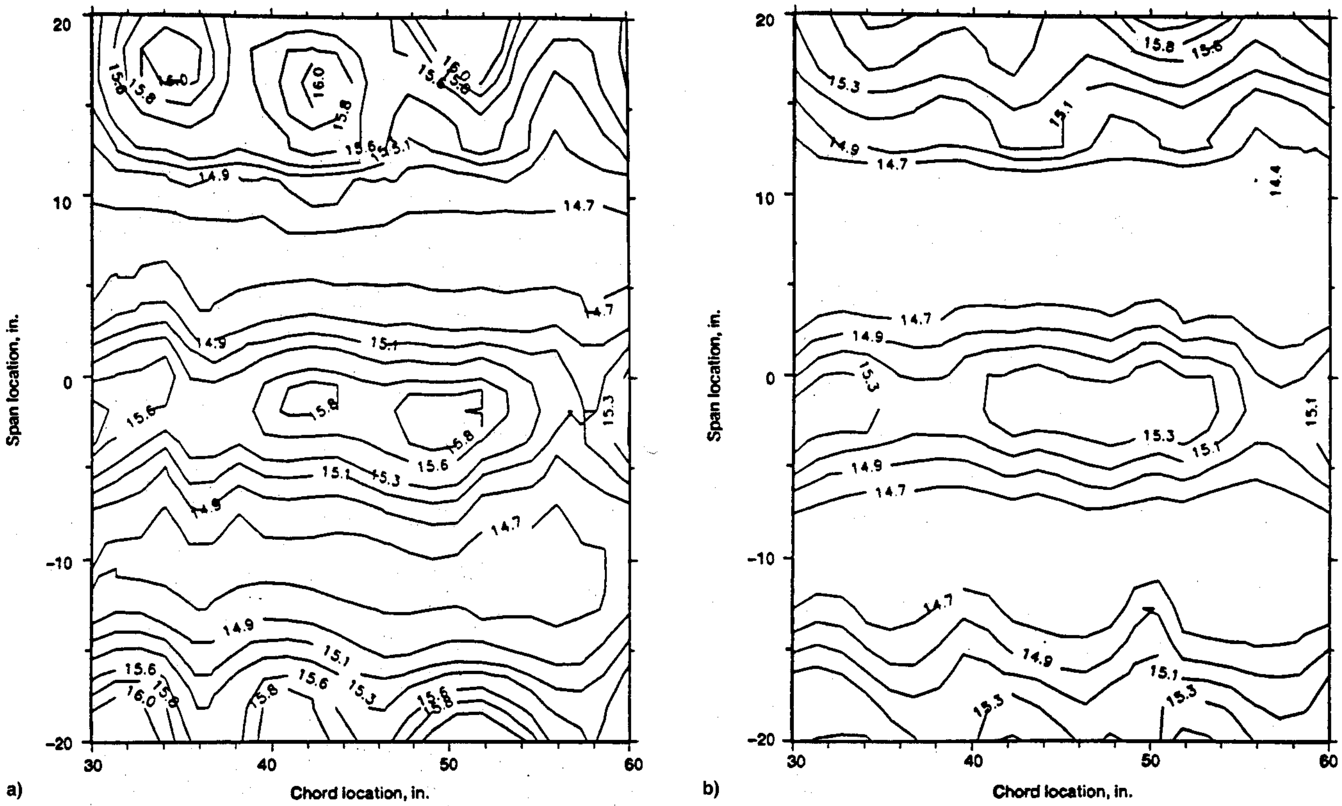

Fig. 9 Total pressure contours at the center nozzles: a) T_p = 517°R and b) T_p = 1560°R.

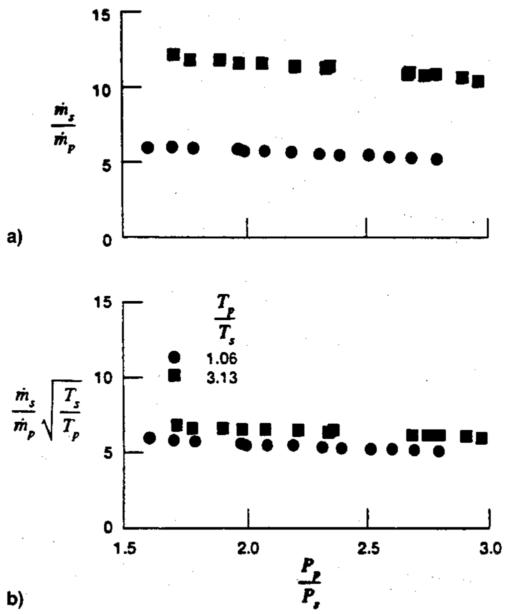

Fig. 10 Normalized pumping parameter at constant ejector area ratio: a) nondimensional mass flow vs pressure and b) normalized pumping parameter vs pressure.

rameter. A linear least squares regression was invoked on both the hot and cold data. The correlation is as follows:

$$\phi = 1.813 - (0.052) \frac{\dot{m}_s}{\dot{m}_p} \sqrt{\frac{T_s}{T_p}} \tag{8}$$

Therefore, for this ejector, hot flow performance can be approximated by cold flow data according to the approximate Munk and Prim principle, with only a slight overprediction.

Although Eq. (8) is valid for this ejector only, this type of correlation could be useful in experimental research on other

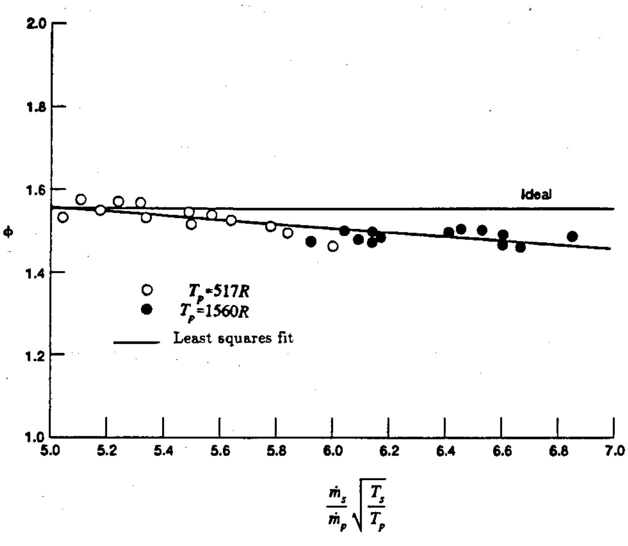

Fig. 11 Thrust augmentation ratio vs the normalized pumping parameter.

ejectors. Remember that the original purpose of using a similarity principle was to eliminate the primary nozzle temperature effect on ejector performance, and subsequently reduce both model and testing costs. If one was not satisfied with a first cut approximation of the Munk and Prim principle (no performance difference between hot and cold), then cold flow data could be taken, the curve fit drawn, and hot flow data extrapolated at considerably less experimental expense.

Concluding Remarks

The similarity between hot and cold flow experiments was confirmed for the full-scale thrust augmenting ejector data. The present experimental data showed a 4% decrease in augmentation ratio for a primary nozzle temperature increase of 1000°R, while supporting data from the literature showed that cold air jets may overpredict the thrust augmentation ratio by approximately 2–3%. Consistent with the Munk and Prim similarity principle, the total pressure and Mach number distributions for different primary nozzle total temperatures were found to be quite similar. Thus, for a first cut approximation, the Munk and Prim similarity principle holds for this ejector configuration and shows that temperature effects are relatively small and compensating, even when there is substantial viscous and heat transfer effects. An ejector pumping parameter was used to significantly reduce the temperature dependence in the performance curves by plotting the pumping parameter vs primary nozzle pressure for constant geometry. The end result is that cold flow tests can be used to obtain a rough prediction of hot flow results at reduced time, cost, and complexity.

References

[1]Greitzer, E. M., Patterson, R. W., and Tan, C. S., "An Approximate Substitution Principle for Viscous Heat Conducting Flows," *Proceedings of the Royal Society of London*, A401, 1985, pp. 163–193.

[2]Munk, M., and Prim, R. C., *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 33, 1947, pp. 137–141.

[3]Barankiewicz, W. S., "A Full-Scale STOVL Ejector Experiment," NASA TM-106019, Feb. 1993.

[4]Presz, W. M., and Greitzer, E. M., "A Useful Similarity Principle for Jet Engine Exhaust System Performance," AIAA Paper 88-3001, July 1988.

[5]Bevilaqua, P. M., "Advances in Ejector Thrust Augmentation," AIAA Paper 84-2425, Oct. 1984.