Experimental Investigation of a Novel VTOL Thrust Vectoring Nozzle

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A two-dimensional corner-expansion thrust vectoring nozzle, in which thrust vectoring is achieved by rotation of a single vane, is proposed for high supersonic V/STOL aircraft. A $\frac{1}{10}$ scale model of the configuration has been statically tested with most favorable results. A thrust coefficient in excess of 0.97 was demonstrated in the VTOL mode and throughout transition at nozzle pressure ratios typical of turbojet engines considered for high supersonic V/STOL applications. In addition, a thrust coefficient in excess of 0.96 was attained in the horizontal cruise mode down to a nozzle pressure ratio of 3.5. This is particularly significant when considering that the design pressure ratio of the nozzle was 21. Effective thrust vectoring was also demonstrated, with a 1:1 correspondence between vane mechanical deflection and thrust vector direction. A jet pumping effect was found to exist at very low-pressure ratios at a slightly deflected position of the thrust vectoring vane, and an alternating normal component of the total thrust vector was found to exist at low-pressure ratios in the horizontal cruise mode.

Introduction

COMPARSION of various propulsion schemes for V/STOL aircraft application has been the subject of several recent investigations.[1] These studies have generally shown that thrust vectoring is a favorable scheme for high supersonic V/STOL interceptor missions, thus establishing the need for developing a simple, highly efficient, and reliable thrust vectoring nozzle; in addition to providing the basic V/STOL thrust vectoring and low-pressure ratio cruise performance for subsonic and low supersonic missions, an efficient nozzle is required for the high supersonic cruise condition in which the nozzle pressure ratio may be as high as 30. A simple and efficient thrust vectoring nozzle, fulfilling all the requirements of a high supersonic V/STOL mission, has been conceived and tested at Norair with favorable results. The detailed results of this test are documented in Ref. 2. The basic features of the configuration, which conveniently lends itself to underbody installations, are shown in Figs. 1 and 2.

In the horizontal flight position, the nozzle geometry is that of an isentropic wedge in which a two-dimensional free-jet corner-expansion to the local ambient pressure occurs at the nozzle lip. The upper boundary of the nozzle is defined analytically by a Prandtl-Meyer stream line at the nozzle design pressure ratio. Ideally, an isentropic expansion occurs at the design pressure ratio giving a horizontal free-jet boundary downstream of the nozzle lip, with uniform, parallel, fully expanded flow at the axial location defined by the intercept of the nozzle upper boundary with the design Mach number line emanating from the nozzle lip. At off-design pressure ratios, nozzle losses due to overexpansion and underexpansion of the exhaust gases are minimized by the ability of the lower jet boundary to adjust to the external local pressure as for a conventional plug nozzle. Side plates are provided to contain the jet in the transverse direction in the region of the flow field where jet pressures are greater than ambient. The side plates eliminate end-effect losses by maintaining a constant and maximum pressure across the width of the upper boundary, thus insuring the maximum value of axial thrust. Variable nozzle throat area in the aft position, if desired, can be conveniently provided by rotation of the nozzle lip.

Received August 27, 1964; revision received December 3, 1964.

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In the VTOL and transition modes of operation, an efficient free-jet aerodynamic-throat nozzle is formed by rotation of the thrust vectoring vane and associated extension. In these modes of operation, the flow expands around the sharp corner at the terminal point of the nozzle lip with a free-jet boundary and aerodynamic throat prevailing downstream of the nozzle lip. Ideally, the flow is expanded supersonically and uniformly at the vane trailing edge. In principle, the internal aerodynamic operation of the nozzle in the VTOL and transition modes is much like that of the horizontal cruise configuration, with the essential difference being that the locus of the sonic line in the former modes occurs downstream of the minimum physical internal cross section of the nozzle and, of course, the design pressure ratio is an order of magnitude lower.

Test Objective

The primary objective of the static test conducted at Norair was to demonstrate performance feasibility of the free-jet aerodynamic-throat nozzle configurations of the VTOL and transition mode and to determine the propulsive performance of the horizontal cruise configuration at low (off-design) pressure ratios. It was not an objective of the test to determine performance of the horizontal cruise configuration at, or near, the design condition as this is rather well established. Based on experimental data of a slightly non-isentropic wedge nozzle of design pressure ratio 24[3] and on experimental data of various axisymmetric isentropic plug nozzles, it is estimated that the horizontal cruise mode thrust

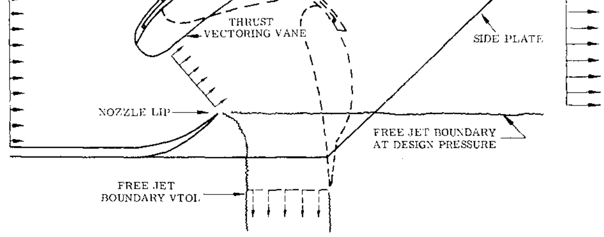

Fig. 1 VTOL corner-expansion nozzle.

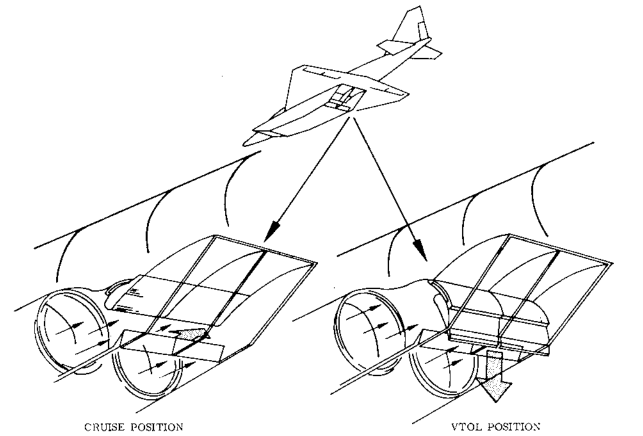

Fig. 2 VTOL corner-expansion nozzle installation.

coefficient of the subject nozzle is approximately 0.98 at the design pressure ratio.

Model and Procedure

The model tested is shown in Fig. 3. The model was $\frac{1}{10}$ scale based on a prototype nozzle sized for a Mach 3 V/STOL interceptor aircraft. This scale gave a characteristic model throat dimension of 1.2 in. Seven discrete orientations of the thrust vectoring vane were provided as shown in Fig. 3. In the horizontal cruise mode (−26°), the nozzle contour conformed to a streamline of a two-dimensional isentropic Prandtl-Meyer expansion based on a design pressure ratio of 21 and sonic flow at the nozzle throat. At vane orientations greater than 50° below the horizontal, a filler was provided to close off the space between the vane leading edge and the Prandtl-Meyer contour.

Instrumentation included measurements of the horizontal and vertical components of thrust, airflow rate, nozzle supply pressure and temperature, internal static-pressure distributions, and nozzle total pressure recovery. The horizontal and vertical components of thrust were taken from Leeds and Northrup digital read-out instruments. Nozzle supply pressure and nozzle total pressure recovery were measured with rakes as shown in Fig. 3.

Airflow was supplied to the model through a faired entrance from a settling chamber. The Reynolds number of the model with air, using any model dimension as a characteristic dimension, was approximately 0.6 that of the full scale prototype with hot gas. Data were taken at pressure ratios from 2.0 to 5.0 at vane orientations from VTOL to 0°, and pressure ratios from 2.0 to 7.0 in the horizontal cruise mode (−26° vane orientation). From these measurements, nozzle thrust coefficients, nozzle discharge coefficients, thrust vector direction, static-pressure distributions, and nozzle pressure recovery were determined as functions of nozzle pressure ratio and vane orientation.

Discussion

Thrust Coefficients

Experimental thrust coefficients are shown in Fig. 4 as a function of nozzle pressure ratio for the VTOL mode and the horizontal cruise mode. The thrust coefficient of the test nozzle in the VTOL mode (Fig. 4a) is in excess of 0.97 at pressure ratios from 2.6 to 4.6. (Typical turbojet engines considered for high supersonic V/STOL aircraft applications operate at a pressure ratio of about 3 during takeoff.) For comparative purposes, the thrust performance of a simple convergent turbojet nozzle, without thrust vectoring capability, is also shown. The thrust coefficient of the test nozzle is seen to be comparable to that of the nonthrust-vectoring convergent nozzle at a pressure ratio of 3.0. As the pressure ratio increases, the inherent advantage of minimum thrust loss due to the minimum underexpansion characteristics of the free-jet boundary nozzle compared to the simple convergent nozzle becomes increasingly apparent.

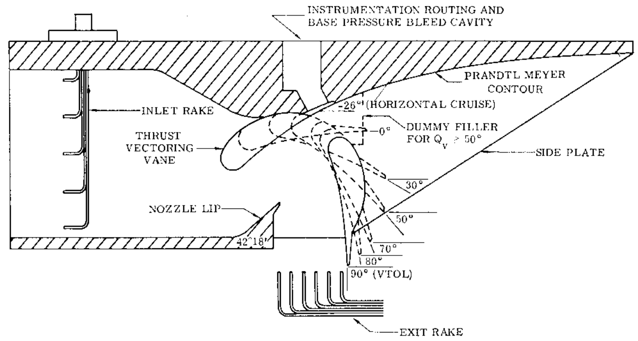

Fig. 3 Test article.

The performance of the nozzle in the supersonic cruise mode (Fig. 4b) shows the thrust coefficient to be in excess of 0.96 down to a nozzle pressure ratio of 3.5. This is particularly significant when considering that the design pressure ratio of the test nozzle was 21 in this mode of operation. Since gross overexpansion characteristics are avoided with the free-jet boundary nozzle, the only significant losses occurring are the pressure losses associated with an alternate expansion-compression cyclic flow pattern occuring at low values of nozzle pressure ratio.

Although it was not the objective of this test to ascertain the nozzle performance at the design pressure ratio in the full aft mode for this particular test nozzle, the thrust coefficient is estimated to approach 0.98 at the design pressure ratio based on design point performance of similar free-jet boundary nozzles. This is substantially in agreement with test data obtained by NASA[3] for a slightly nonisentropic length wedge nozzle designed for a pressure ratio of 24 which provided a thrust coefficient of 0.97 at the design pressure ratio.

Thrust coefficients as a function of vane deflection angle are shown in Fig. 5 for pressure ratios of 3 and 5. The high level of thrust performance demonstrated in the VTOL mode and cruise mode is maintained at all vane positions at the pressure ratio 5, and from 90° to approximately 5° below horizontal at the pressure ratio 3. The nozzle performance at the pressure ratio 5 is higher than that of a conventional nonthrust-vectoring convergent nozzle at all vane positions. The thrust coefficient is insensitive to nozzle pressure ratio as the vane is rotated from the VTOL mode toward the cruise mode until the 0° vane position is approached. Near the 0° vane position, a sudden reduction in thrust coefficient is ob-

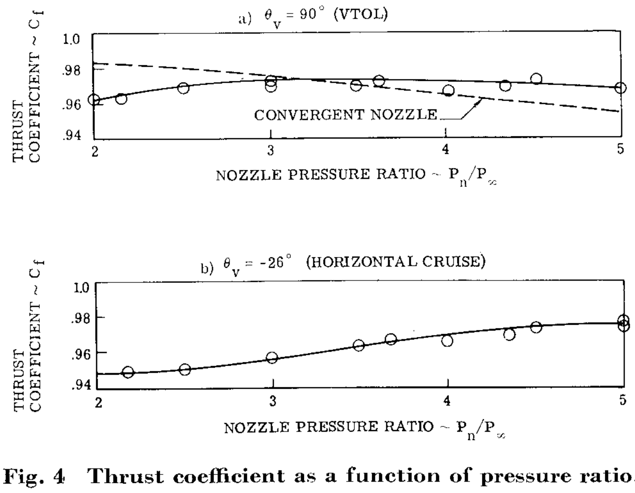

Fig. 4 Thrust coefficient as a function of pressure ratio.

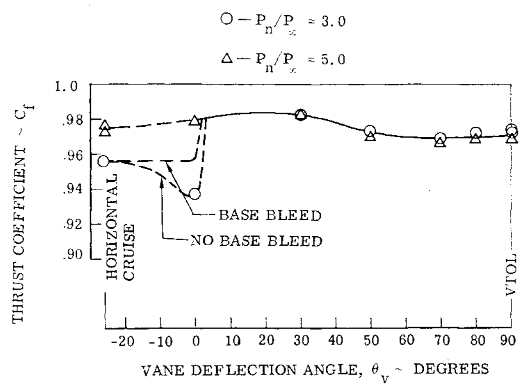

Fig. 5 Thrust coefficient as a function of vane deflection angle.

served at the pressure ratio of 3 for further rotation of the vane.

The reduction in thrust coefficient at the pressure ratio 3 is the result of an interaction of the exhaust jet with the Prandtl-Meyer contour. This interaction occurs as the vane approaches 0° position, and the exhaust jet leaving the trailing edge of the vane comes into the proximity of the Prandtl-Meyer contour, thereby causing a jet pumping action. Still further rotation of the vane toward the cruise position results in attachment of the exhaust jet to the Prandtl-Meyer contour. This jet pumping action and jet attachment result in a negative (subambient) pressure field along the Prandtl-Meyer contour in the vicinity of the vane trailing edge. The negative pressure field results in a reduction in the thrust coefficient and produces a component of thrust in the downward direction (discussed later) by deflecting the jet toward the Prandtl-Meyer contour. The reduction in thrust coefficient caused by the jet pumping action diminishes as the pressure ratio is increased, and at a nozzle pressure ratio of approximately four, the effect of the jet pumping action on thrust coefficient suddenly ceases as indicated by the data of Fig. 6 which show the variation of thrust coefficient with pressure ratio at the 0° vane position.

Figures 5 and 6 also show the effect of bleeding ambient air into the aspirated region. The bleed air was provided by venting the Prandtl-Meyer contour to ambient pressure in the region above the vane trailing edge. This increased the thrust performance approximately 2% over the no-bleed condition at pressure ratios less than approximately four. At pressure ratios greater than four, venting the upper reaction surface in the region of the vane trailing edge produced no discernible effect in the nozzle thrust coefficient or thrust vector direction.

The thrust coefficient profile corresponding to a hypothetical climb-to-cruise mission for a Mach 3 VTOL aircraft is shown in Fig. 7 based on the static nozzle performance of this test. In the VTOL mode, throughout the transition mode, and over the entire range of horizontal flight Mach

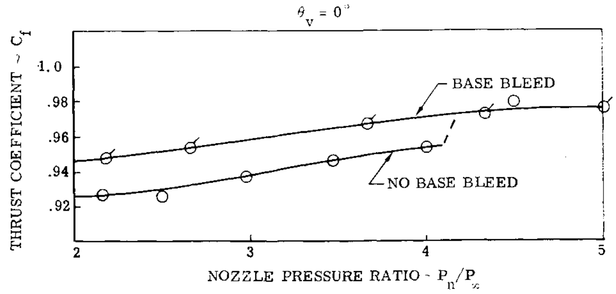

Fig. 6 Thrust coefficient as a function of pressure ratio.

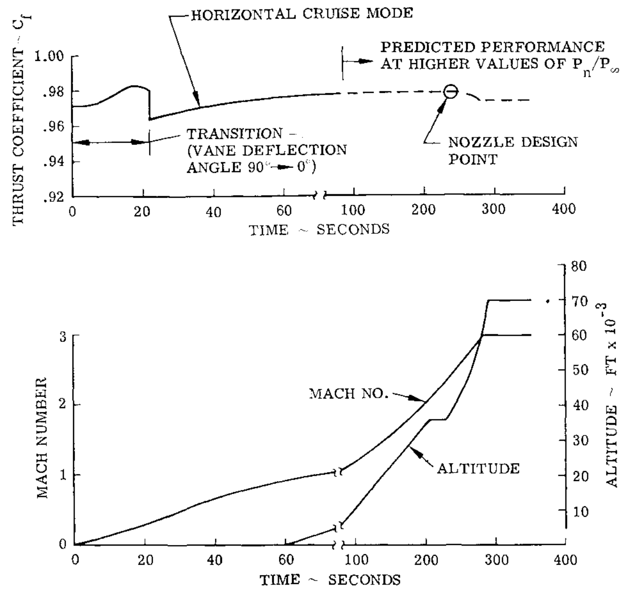

Fig. 7 Thrust coefficient during typical transient to cruise condition.

numbers from 0.3 to 3.0, the thrust coefficient is seen to be in excess of 0.96 approaching a predicted maximum of 0.98 at Mach 2.7.

Thrust Vector Direction

The thrust vector angle is presented as a function of nozzle pressure ratio in Fig. 8 for the VTOL mode and the supersonic cruise mode. The thrust vector is straight down in the VTOL mode for a pressure ratio of 3 (Fig. 8a) and changes only slightly in the pressure ratio range of interest. At the full aft vane position (Fig. 8b), an alternating thrust vector angle with pressure ratio is observed. This alternation results in a maximum value of normal force of approximately ± 5% of the total thrust vector within the range of pressure ratios shown. These data are in fair quantitative agreement with the data of Ref. 4 that presents data of a similar characteristic for a "penshape" nozzle whose operating principle is similar to that of the subject test nozzle in the supersonic cruise mode.

The alternating normal component of the total thrust vector at low-pressure ratios in the cruise mode is inherent to the configuration and is caused by a cyclical overexpansion and recompression of the flow along the nozzle. The wave length of this expansion-compression cycle is a function of the nozzle pressure ratio, or more directly, the angle of the last

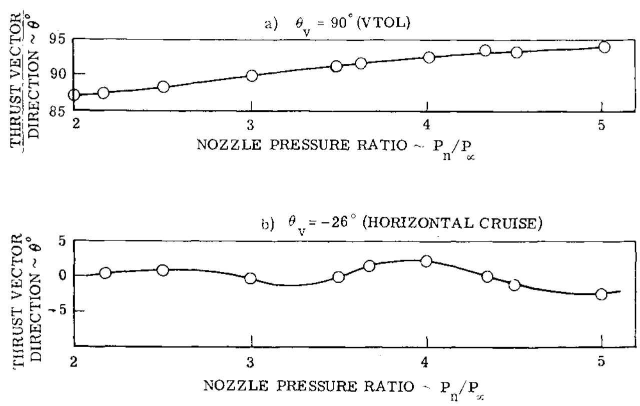

Fig. 8 Thrust vector direction as a function of pressure ratio.

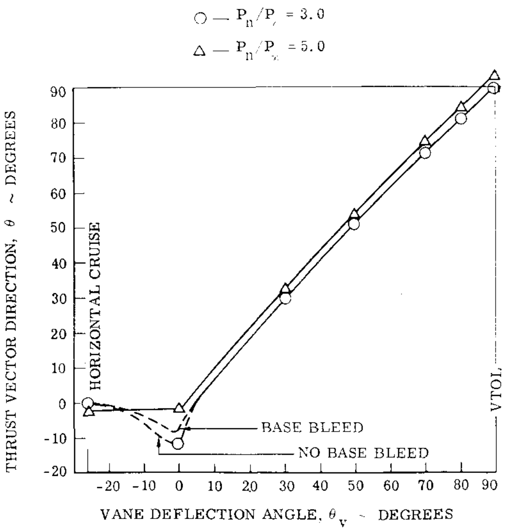

Fig. 9 Thrust vector direction as a function of vane deflection angle.

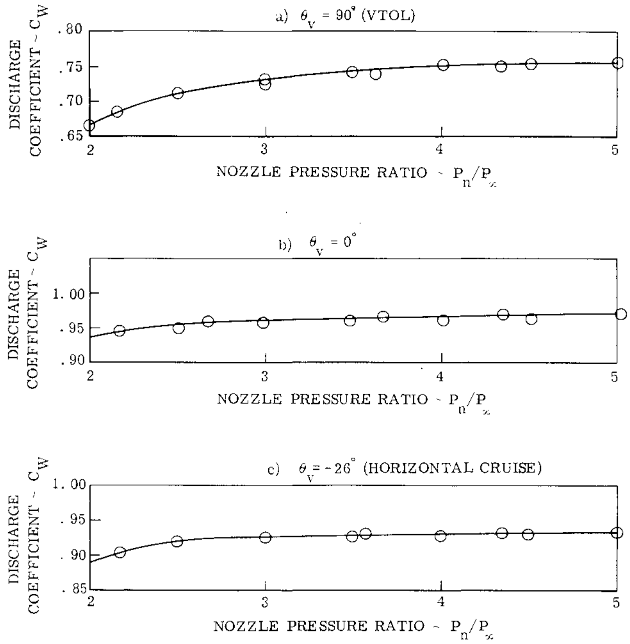

Fig. 11 Discharge coefficient as a function of pressure ratio.

expansion wave emanating from the nozzle lip. The result is a variation in the sense of the wall static pressure at the nozzle exit with nozzle pressure ratio and an associated variation in the exit angle of the exhaust jet, which is a direct measure of the component of normal force. As the nozzle pressure ratio increases, this wavelength increases until at the design pressure (or greater than the design pressure ratio) the wavelength is equal to (or greater than) twice the length of the nozzle, so that only expansion of the flow occurs along the entire length of the nozzle. Further experimental and analytical investigation of this phenomenon is desirable.

The variation in thrust vector direction with vane deflection angle is shown in Fig. 9 for pressure ratios of 3 and 5. At the nominal pressure ratio of 3, the thrust vector direction is seen to be virtually equal to the vane deflection angle in the interval between 90° and approximately 5° below horizontal. At vane positions less than approximately 5°, the jet pumping action previously described with respect to thrust coefficient is seen to also affect the thrust vector direction at the pressure ratio 3. A linear correspondence of thrust vector direction and vane mechanical deflection is observed at the pressure ratio 5.0 all the way to the 0° vane position. The observed linearity of the curve for a nozzle pressure ratio of 5.0 in extending to the 0° vane position confirms that the exhaust jet is not affected by a jet pumping action at this pressure ratio.

The thrust vector direction as a function of pressure ratio is shown in Fig. 10 at the 0° vane position. The effect of bleeding ambient air into the aspirated region is also shown. The thrust vector direction is seen to be sensitive to bleed flow below a pressure ratio of approximately 4 as was the thrust coefficient. At pressure ratios greater than four, the bleed flow produced no discernible effect in thrust vector direction.

Nozzle Discharge Coefficients

The nozzle discharge coefficients as a function of nozzle pressure ratio and vane deflection are shown in Figs. 11 and 12. The nozzle discharge coefficient, although not a measure of nozzle thrust efficiency, is required in sizing the nozzle to provide proper engine matching. As would be expected, this discharge coefficient is observed to increase as the vane position is rotated from the VTOL toward the 0° position and to increase as the nozzle pressure ratio is increased. The effect of vane orientation on nozzle discharge coefficient could have been predicted qualitatively from the model schematic shown in Fig. 3, whereas the effect of pressure ratio is fundamental to all nozzles and orifices.

Jet Plume

Photographs of the jet plume issuing from the nozzle with the thrust vectoring vane in the VTOL and 50° vane positions are shown in Figs. 13 and 14 at a nozzle pressure ratio of 3.0. The photographs were taken with a conventional camera in a darkened test cell with the jet illuminated from behind with a spotlight. Although the jet was virtually invisible under normal daylight conditions, condensation effects within the jet were sufficient to result in a well-defined bluish plume under the foregoing conditions of illumination.

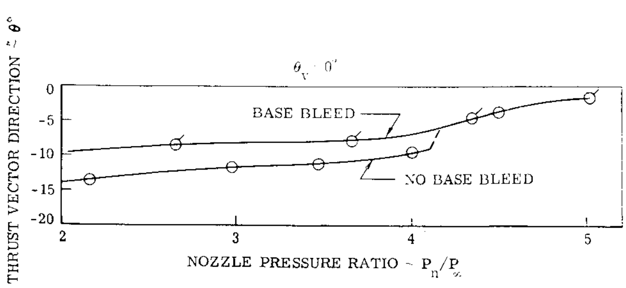

Fig. 10 Thrust vector direction as a function of pressure ratio.

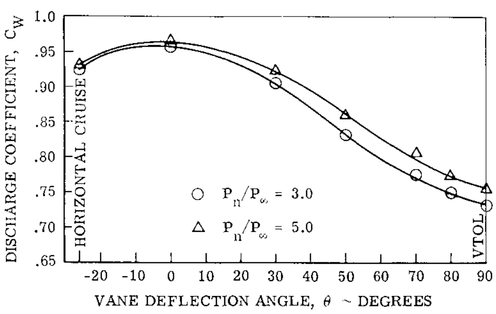

Fig. 12 Discharge coefficient as a function of vane deflection angle.

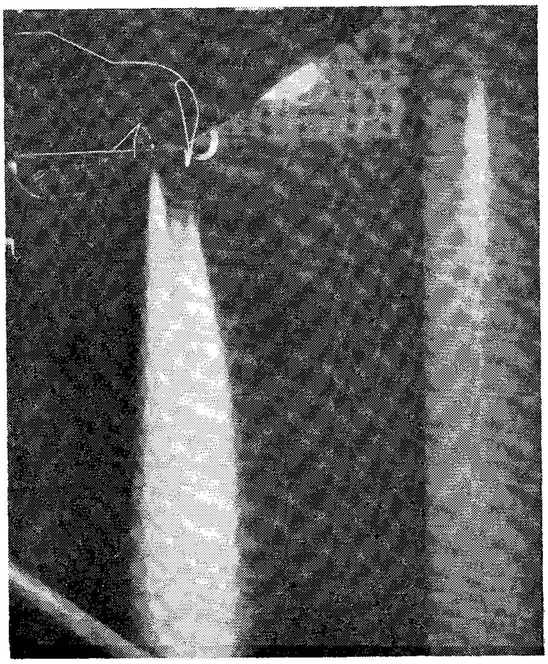

Fig. 13 Exhaust plume: θ_v = 90° (VTOL), P_n/P_∞ = 3.0.

External Aerodynamic Effects

Although the results of the present experimental investigation have demonstrated favorable propulsive performance under static conditions, superimposing the effects of external aerodynamics can cause a significant compromise in the net propulsive performance of the nozzle.[5] However, the degrading effects of external aerodynamics can be minimized by judicious selection of the nozzle afterbody geometry (i.e., the nozzle lip), taking into consideration the effects of base drag, boattail drag, and direct interference of the freestream with the expanding exhaust jet. The aerodynamic drag of the external configuration, if excessive for totally external supersonic expansion, can be reduced by providing an internal configuration that allows some internal supersonic expansion rather than total external supersonic expansion as for the configuration tested.[6,7] Partial internal expansion would reduce the nozzle lip angle thereby reducing the combined external base-boattail area and associated drag. For a given application, it might be desirable to control the external pressure by providing bleed flow through the base. The base bleed would serve in reducing the base drag as well as in reducing the effective range of nozzle pressure ratios. Cooling air required for structural conditioning would be available for base bleed, thereby eliminating any additional drag penalties associated with taking aboard external air.

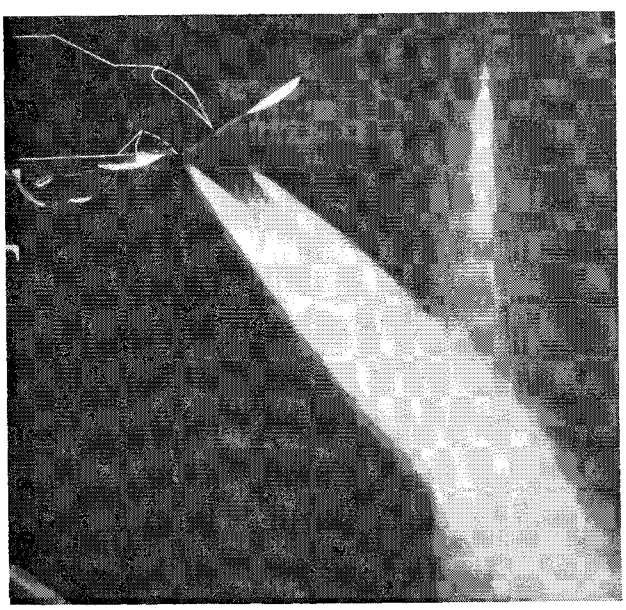

Fig. 14 Exhaust plume: θ_v = 50°, P_n/P_∞ = 3.0.

Design Considerations

For a practical application of the nozzle, an effort would be made to eliminate the effects of jet pumping which occur in and about the 0° vane position at pressure ratios less than about 4. Although this effect could be considered as a relatively unimportant transient in passing through this mode (or might be entirely avoided altogether with a high-pressure ratio turbojet engine), the versatility of the nozzle would be enhanced by allowing quasi-steady horizontal subsonic acceleration of the aircraft in this mode of operation with precise control of the thrust vector direction. The optimum thrust vector angle, which is a function of the lift to drag L/D ratio of the aircraft and is a positive angle, could then be maintained through the subsonic acceleration regime. In addition, the undesirable alternating normal thrust component observed at low-pressure ratios in the cruise mode of operation could be avoided by subsonic acceleration of the aircraft with the nozzle thrust vectoring vane in the partially deflected mode.

The jet pumping that occurs in the horizontal mode at pressure ratios less than approximately 4 could be virtually eliminated by shortening the upper reaction surface, or, as seen in the data of this report, by bleed flow (exhaust gas or air) into the aspirated region. The length of the upper reaction surface of the test article was that of the full isentropic length (i.e., Prandtl-Meyer contour) for a design pressure ratio of 21. From practical length and weight considerations, without consideration of the jet pumping effect, the nozzle length of an actual aircraft design would probably be shortened to considerably less than the full isentropic length with a rather minor thrust performance decrement (less than 1%) at the design pressure ratio.[6,8] This is common practice in the case of truncated method of characteristics *C-D* nozzles and nonisentropic plug nozzles. The effect on jet pumping of shortening the upper reaction surface of the subject configuration would be similar to that of reducing the spacing ratio of a conventional axisymmetric ejector. At the pressure ratios of concern, the jet pumping characteristics would be considerably reduced. Further detailed experimental investigation of the flow phenomena occurring at vane orientations from approximately 10° below the horizontal to the supersonic cruise position for various upper reaction surface lengths and contours is desirable.

For a practical application, the importance of the alternating normal thrust component observed at low-pressure ratios in cruise mode of operation is not obvious without a parallel systems analysis. In any case, the effect would presumably induce no appreciable pitching moments into an aircraft since the location of the line of action of the normal component of thrust would be very near the aircraft center of gravity. If the vertical acceleration of the aircraft caused by the normal force oscillation were significant, it could easily be avoided as suggested previously by subsonic and low supersonic acceleration of the aircraft at (or slightly below) the nozzle 0° vane position. In fact, in the fully developed configuration, the potential thrust coefficient of the nozzle at (or slightly below) the 0° vane position would be greater than that of the full aft mode at low-pressure ratios, so that this nozzle mode appears desirable for subsonic acceleration.

Conclusions

1) The internal aerodynamic feasibility of a simple corner-

expansion thrust vectoring nozzle applicable to high supersonic V/STOL aircraft has been demonstrated.

2) A thrust coefficient in excess of 0.97 has been demonstrated in the VTOL mode and throughout the transition modes at nozzle pressure ratios typical of turbojet engines considered for high supersonic VTOL aircraft applications ($P_n/P_\infty = 3$ at VTOL).

3) A thrust coefficient in excess of 0.96 has been demonstrated in the horizontal cruise mode of operation down to a pressure ratio of 3.5 for a nozzle designed for a pressure ratio of 21 in this mode of operation.

4) A 1:1 linear correspondence between vane mechanical deflection and thrust vector direction was demonstrated.

5) A jet pumping action, which had an adverse effect on nozzle thrust coefficients and thrust vector direction, was found to exist at pressure ratios less than approximately 4 at and about the 0° vane position.

6) An alternating normal component of the total thrust vector was found to exist at low-pressure ratios in the full aft vane position.

7) Investigation of the effects of external aerodynamics on the nozzle net propulsive performance is warranted.

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