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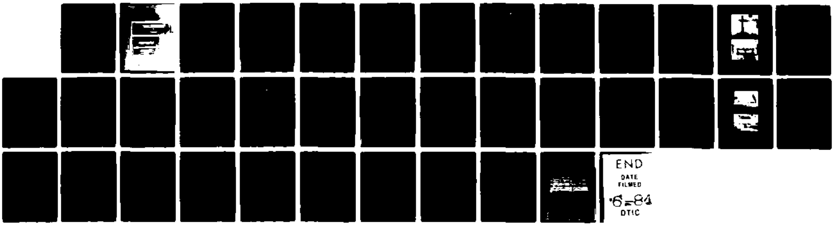

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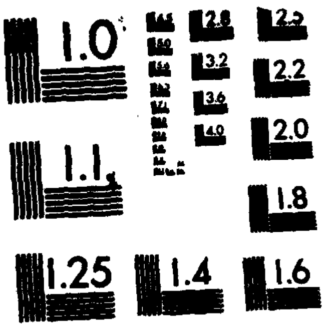

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A pneumatic thrust deflector has been developed in which the thick slipstream from a turbojet is deflected by blowing a thin jet sheet tangentially over a deflecting surface adjacent to the slipstream. In developing this concept, three geometries have been evaluated for the thrust deflecting surface. The three deflecting surfaces are cylindrical with a semicircular, a quarter-circular, or a semielliptical cross section. The

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range of thrust deflection achievable with each deflecting surface was determined by using each surface to deflect the slipstream of a small turbojet simulator. In the cold gas investigation, a thrust deflection of 20 deg or more was achieved with this mechanically simple system. The cold gas performance is compared to the range of thrust deflection achieved by pneumatically deflecting the hot gas of a small turbojet. Results of the hot gas investigation are also presented.

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NOTATION

A	Measured axial force, lb
F_N	Average measured thrust, lb
$\dot{m}$	Measured tangential blowing mass flow, slug/sec
$\dot{m}V_{slot}$	Tangential blowing jet momentum, lb
N	Measured normal force, lb
V_{slot}	Calculated tangential blowing jet velocity, ft/sec
θ	Thrust deflection angle, deg

ABSTRACT

A pneumatic thrust deflector has been developed in which the thick slipstream from a turbojet is deflected by blowing a thin jet sheet tangentially over a deflecting surface adjacent to the slipstream. In developing this concept, three geometries have been evaluated for the thrust deflecting surface. The three deflecting surfaces are cylindrical with a semicircular, a quarter-circular, or a semielliptical cross section. The range of thrust deflection achievable with each deflecting surface was determined by using each surface to deflect the slipstream of a small turbojet simulator. In the cold gas investigation, a thrust deflection of 20 deg or more was achieved with this mechanically simple system. The cold gas performance is compared to the range of thrust deflection achieved by pneumatically deflecting the hot gas of a small turbojet. Results of the hot gas investigation are also presented.

ADMINISTRATIVE INFORMATION

The cold gas investigation using the turbojet simulator was funded by the Air Force Wright Aeronautical Laboratories (AFWAL) under program element 62201F, reference MIPR FY1456-83-N0026. This investigation was conducted during August 1983 at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC).

The hot gas investigation with the small turbojet was conducted during July through September 1982. This investigation, funded jointly by the Naval Air Systems Command (NAVAIR-310D) and the Air Force Wright Aeronautical Laboratories, is documented in detail in Reference 1.*

INTRODUCTION

The pneumatic thrust deflector concept is a mechanically simple system capable of a wide range of thrust deflection without requiring moving surfaces. This system can provide increased maneuverability, heavy lift, or short takeoff and landing (STOL) capability. A schematic of a pneumatic thrust deflector is presented in Figure 1.

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*A complete list of references is given on page 31.

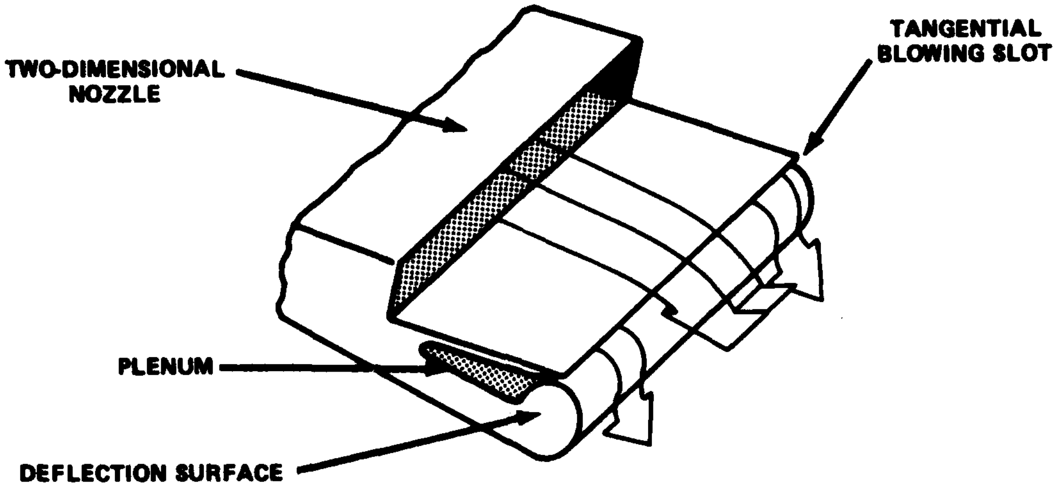

Figure 1 - Pneumatic Thrust Deflector

Pneumatic thrust deflection is an extension of circulation control technology developed at DTNSRDC.[2] In the circulation control wing (CCW), a small tangentially blown curved surface replaces a larger conventional trailing edge flap. A jet sheet is expelled tangentially over the curved trailing edge from a thin spanwise slot in the aft upper surface of the airfoil; see Figure 2. The jet sheet adheres to the curved trailing edge, entraining ambient air as it flows around this surface. This is due to a balance between centrifugal force in the jet sheet and reduced static pressure across the jet sheet. This effect, commonly known as the Coanda effect, provides boundary layer control and lift augmentation, or supercirculation.[3]

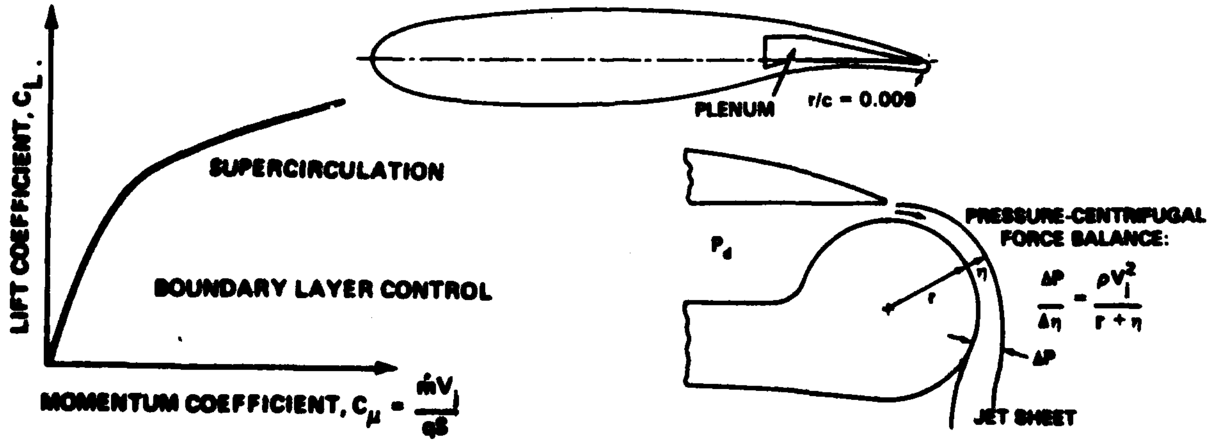

Figure 2 - Circulation Control

Mounting a turbofan or turboprop over a circulation control wing so the slipstream scrubs the upper surface of the airfoil produces a highly effective upper surface blowing system (CCW/USB).[4] The slipstream from the turbofan is entrained by the jet sheet blown tangentially over the small curved trailing edge. The slipstream is deflected downward around the trailing edge, enhancing the lift produced by the wing. The capability of the circulation control wing to deflect the slipstream of a turbofan was demonstrated statically on the NASA quiet short-haul research aircraft (QSRA).[5]

The pneumatic thrust deflector uses the entrainment properties of a thin jet sheet blown tangentially over a curved deflecting surface for thrust recovery. Gas from a turbojet is expelled through a two-dimensional nozzle producing thrust. This gas, or slipstream, flows aft and is entrained by a thin jet sheet. Both the slipstream and jet sheet adhere to the curved deflecting surface and flow around it due to the Coanda effect. A force, or thrust, is recovered along the deflecting surface scrubbed by the slipstream before it separates from this surface. The net deflected thrust is the sum of the nozzle thrust and the force recovered along the deflecting surface.

The angle of thrust deflection is controlled pneumatically. This requires no moving surfaces. The distance both the slipstream and jet sheet flow around the deflecting surface before separating is controlled by varying the momentum of the tangentially blown jet sheet. The farther around the deflecting surface the slipstream flows before separating, the greater the force recovered on this surface and the greater the angle of thrust deflection.

COLD GAS INVESTIGATION

To determine the most suitable geometry for the thrust deflecting surface in the pneumatic thrust deflector concept, a semicircular, quarter-circular and semielliptical cylinder were evaluated as deflecting surfaces. Geometries for the three surfaces are defined in Figure 3.

In previous investigations of the pneumatic thrust deflector, a semicircular cylinder was used as a thrust deflecting surface. A semicircular deflecting surface provide the widest range of thrust deflection, 90 deg or more; however, this surface must be retracted during cruise flight due to its higher base drag. Also, most applications for the pneumatic thrust deflector

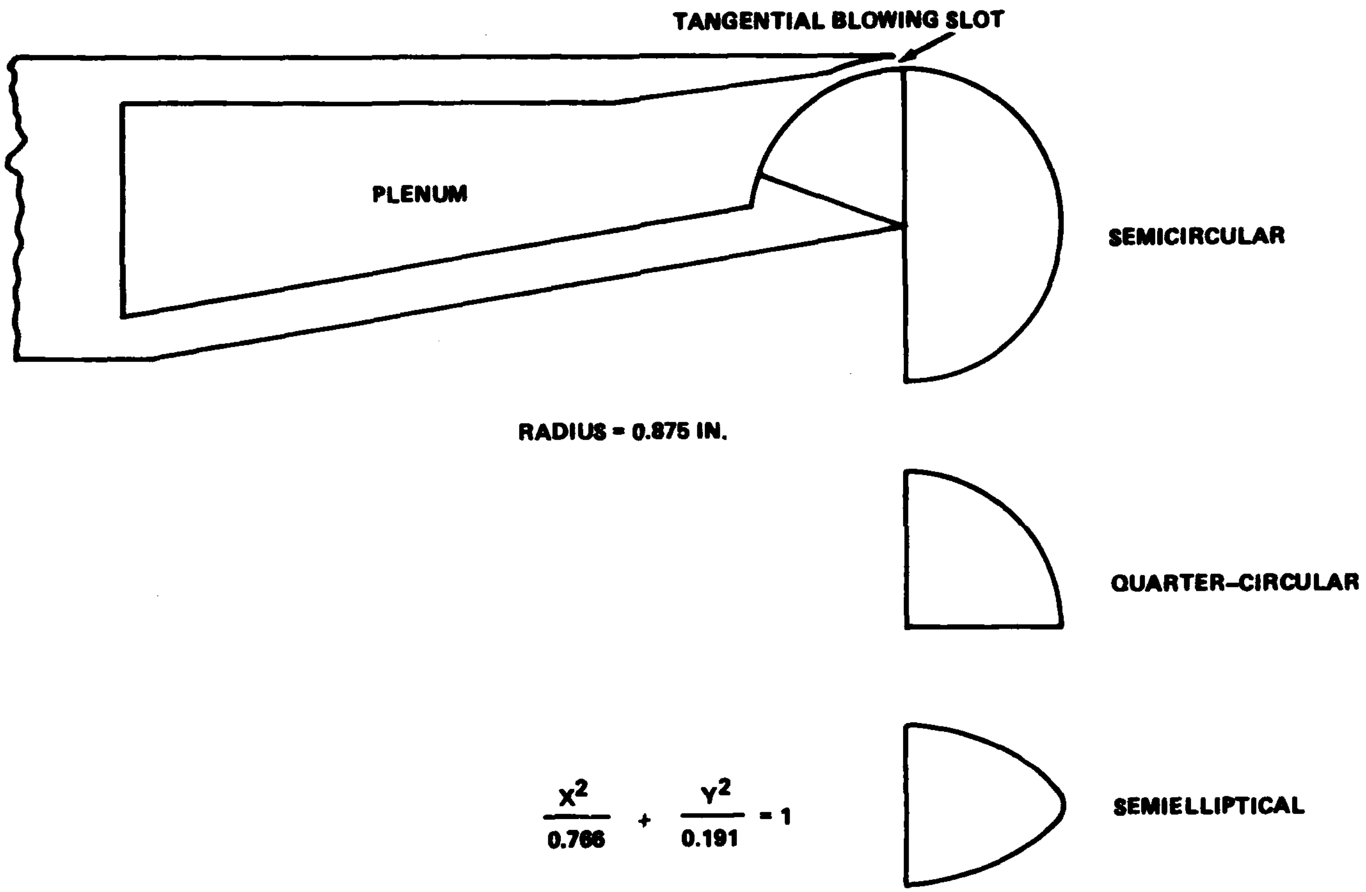

Figure 3 - Thrust Deflecting Surface Geometry

require far less than 90 deg of thrust deflection. With a reduced base thickness, the quarter-circular and semielliptical deflecting surfaces could more easily be incorporated into the design of a high performance aircraft while still providing an acceptable range of thrust deflection.

The radius of both circular deflecting surfaces was 0.875 in. (22.225 mm). Therefore, the base thickness of the quarter-circular surface was half that of the semicircular deflecting surface. The base thickness of the semielliptical surface was also half the base thickness of the semicircular surface. Near the blowing slot, the radius of the semielliptical surface was greater than the radius of the circular surfaces, which would be benefical to jet attachment at higher thrust levels.

Alternately, these deflecting surfaces were mounted with a plenum assembly on a six-component balance. This balance measured the force recovered on the deflecting surface. A turbojet simulator, shown in Figure 4a, was mounted on a second balance. The second balance was used to determine the thrust produced by a turbojet simulator. The net deflected thrust and angle of thrust deflection was determined from the sum of the forces measured by these balances.

The turbojet simulator was an ejector-type simulator. An aspect-ratio-seven, two-dimensional nozzle was added to the simulator for this investigation. This nozzle had an exit area of 6.281 in^2 (40.512 cm^2) and produced a maximum thust of approximately 80 lb (356 N).

Flow fences were placed on the plenum assembly at the width of the two-dimensional nozzle; see Figure 4b. Tangential blowing was limited to the span of the slot between flow fences (6.6 in., 16.8 cm). The distance between the nozzle exit and the tangential blowing slot could be set at three discrete lengths. The slot could be placed directly adjacent to the nozzle exit, at one equivalent nozzle diameter (2.83 in., 7.18 cm), or two equivalent nozzle diameters (5.66 in., 14.38 cm) aft of the nozzle exit.

The tangential blowing slot was formed by a gap between the deflecting surface and one surface of the plenum assembly which terminated in a knife edge, as shown in Figure 3. The unpressurized height of this slot was set at 0.018 in. (0.457 mm) which expanded to 0.052 in. (1.321 mm) when the plenum was pressurized at a pressure ratio of 3.31. The momentum of the tangential

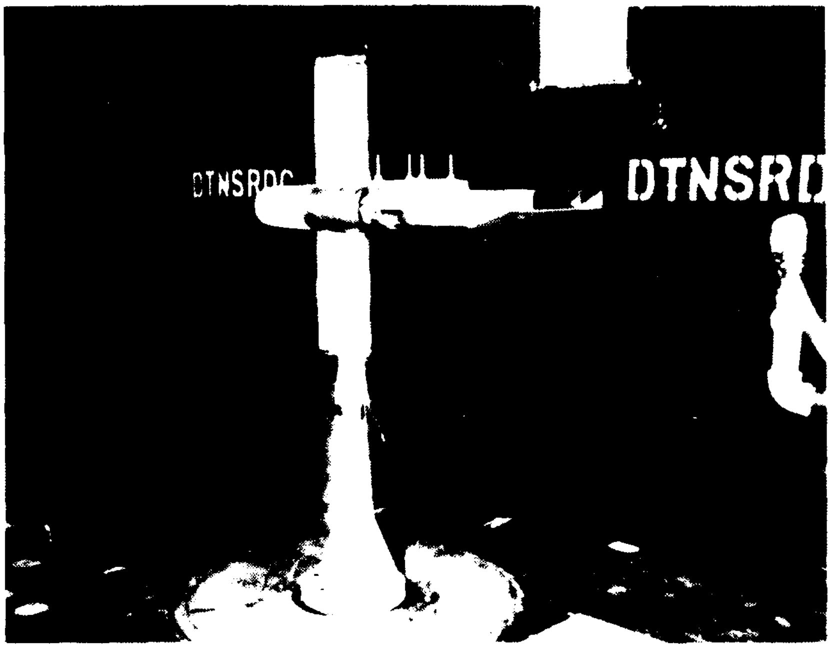

Figure 4a - Turbojet Simulator with Two-dimensional Nozzle

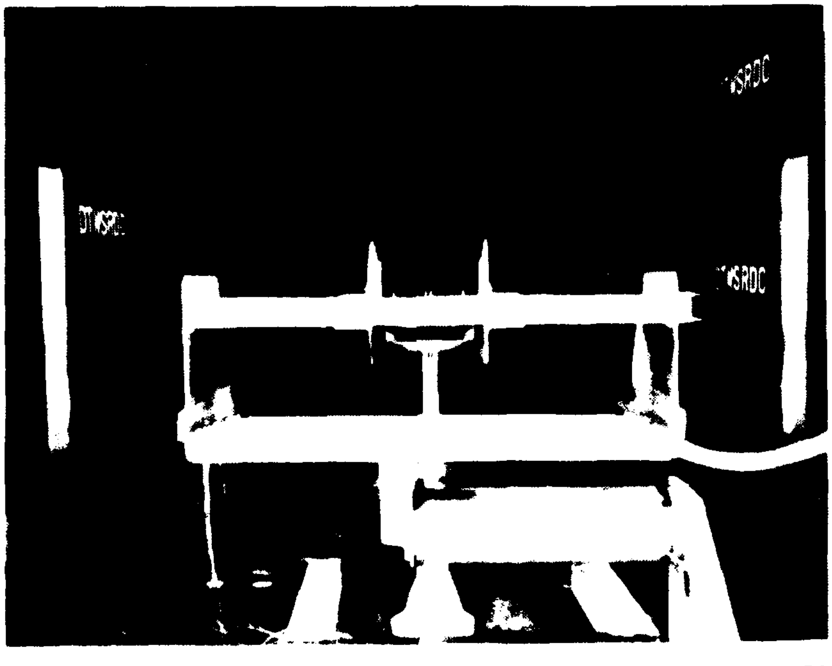

Figure 4b - Pneumatic Thrust Deflector Mounted above Turbojet Simulator

Figure 4 - Pneumatic Thrust Deflector for Cold Gas Investigation

blowing was controlled by setting the air pressure in the plenum. The momentum of the tangential blowing, in turn, controlled the thrust deflection angle (θ). Plenum total pressure and temperature were measured to determine the jet velocity at the blowing slot (V_{slot}). Mass flow ($\dot{m}$) of the air entering the plenum was measured using a venturi meter.

Testing was conducted by setting the distance between the nozzle and blowing slot, holding thrust (F_N) constant, and varying the tangential blowing momentum ($\dot{m}V_{slot}$) to determine the range of thrust deflection achievable. Three calibrated or undeflected thrust levels were investigated: 80 lb (356 N), 68 lb (303 N), and 56 lb (249 N).

The range of thrust deflection achieved by blowing tangentially over the semicircular deflecting surface (Figure 5) provides a reference for comparison with the thrust deflection achieved with the quarter-circular (Figure 6) and semielliptical (Figure 7) deflecting surfaces. Angles of thrust deflection (θ) are presented for lines of constant nozzle thrust (F_N) versus the tangential blowing momentum ($\dot{m}V_{slot}$) required to produce this thrust deflection in Figures 5, 6, and 7. Recovered thrust is also presented in these figures as a fraction of the sum of the nozzle thrust and blowing momentum of the jet sheet.

The normal (N) and axial (A) forces on which the thrust recovery and thrust deflection are based represent the net system normal and axial forces. These forces combine the measured nozzle thrust and measured force recovered around the deflecting surface. The angle of thrust deflection (θ) was determined from the relationship:

$$\theta = \tan^{-1}\left(\frac{N}{A}\right)$$

Several characteristics of pneumatic thrust deflection are illustrated in Figure 5. As previously indicated, the angle of thrust deflection is controlled by varying the momentum of the tangentially blown jet sheet. Following any line of constant thrust in Figure 5 illustrates how the angle of thrust deflection (θ) increases with increasing tangential blowing momentum

($\dot{m}V_{slot}$). In Figure 5a, with the tangential blowing slot directly adjac the nozzle exit, the range of thrust deflection for a thrust of 81 lb (3 varies from 0 deg without blowing to a maximum deflection of 31 deg achi with a blowing momentum of 13 lb (58 N). Increasing the blowing momentu above this level results in a decrease in the thrust deflection angle. decrease in thrust deflection results from separation of the jet sheet a slipstream from the deflecting surface. The momentum at which separatio occurs is a function of the velocity of the slipstream and the geometry slot and deflecting surface. Previous investigations have shown separat can be delayed to a higher blowing momentum by increasing the radius of deflecting surface.

Comparing the three lines of constant thrust in Figure 5a illustrate at constant blowing momentum the angle of thrust deflection increases as nozzle thrust decreases. Reducing the thrust from 81 lb (361 N) to 58 1 (258 N) while maintaining a blowing momentum of 13 lb (58 N) results in percent increase in thrust deflection, from 31 deg to 43 deg. Higher th requires a higher force recovery along the deflecting surface for the sa thrust deflection.

Prior to the slipstream separating from the deflecting surface, the force generated by the nozzle and recovered from deflecting the slipstre represented over 80-percent of the sum of the measured thrust and blowin momentum. With the tangential blowing slot directly adjacent to the noz exit, the nozzle thrust and force recovery along the semicircular deflec surface (Figure 5a) varied from 93 percent with no thrust deflection ($\theta = 0$ deg) to 88-percent thrust recovery at a thrust deflection of 30 d

Comparing the range of thrust deflection achieved with the quarter-circular (Figure 6) and semicircular (Figure 5) deflecting surfa shows an equivalent pneumatic thrust deflecting capability since the su are identical up to 90 deg. For a thrust of 79 lb (352 N), a thrust deflection of 29 deg is achieved at a blowing momentum of 15 lb (67 N) the blowing slot of the quarter-circular deflecting surface directly ad to the nozzle exit (Figure 6a). This deflection is similar to the defl of 31 deg achieved with the semicircular deflecting surface under simul conditions.

Below a thrust deflection of 50 deg, the slipstream separates from the deflecting surface after flowing around this surface less than 90 deg. The lower half of the semicircular deflecting surface provides little toward thrust recovery for a static thrust deflection below 50 deg.

A more limited range of thrust deflection was achieved with the semielliptical deflecting surface. For a thrust of 80 lb (356 N), a thrust deflection of 20 deg was achieved at a blowing momentum of 16 lb (71 N) with the tangential blowing slot directly adjacent to the nozzle exit (Figure 7a). This is 67 percent of the thrust deflection achieved with the circular deflecting surfaces under similar conditions. However, there was no sudden dropoff in jet turning noticed on the semielliptical data at high thrust, an operating condition which could prove quite valuable.

Reducing the thrust while maintaining a constant blowing momentum, unlike the circular deflecting surfaces, does not result in a significant increase in thrust deflection. The thrust deflection at a blowing momentum of 16 lb (71N) increased to 25 deg when the thrust was reduced to 58 lb (258 N) with the blowing slot at the nozle exit (Figure 7a). The circular deflecting surfaces under similar conditions produced a thrust deflection over 40 deg. The radius of the semielliptical deflecting surface decreases too rapidly for the slipstream to remain attached through 90 deg of the arc.

Both quarter-circular and semielliptical deflecting surfaces provided effective thrust deflection over the range of 0 to 20 deg of deflection. This compares favorably with the range projected for some deflectable two-dimensional nozzles. Either of the deflecting surfaces could be incorporated into a high performance aircraft more easily than the semicircular deflecting surface. However, a semicircular deflecting surface is required for thrust deflections of 90 deg or more.

Figure 5 - Thrust Deflection and Recovery with Semicircular Deflecting Surface

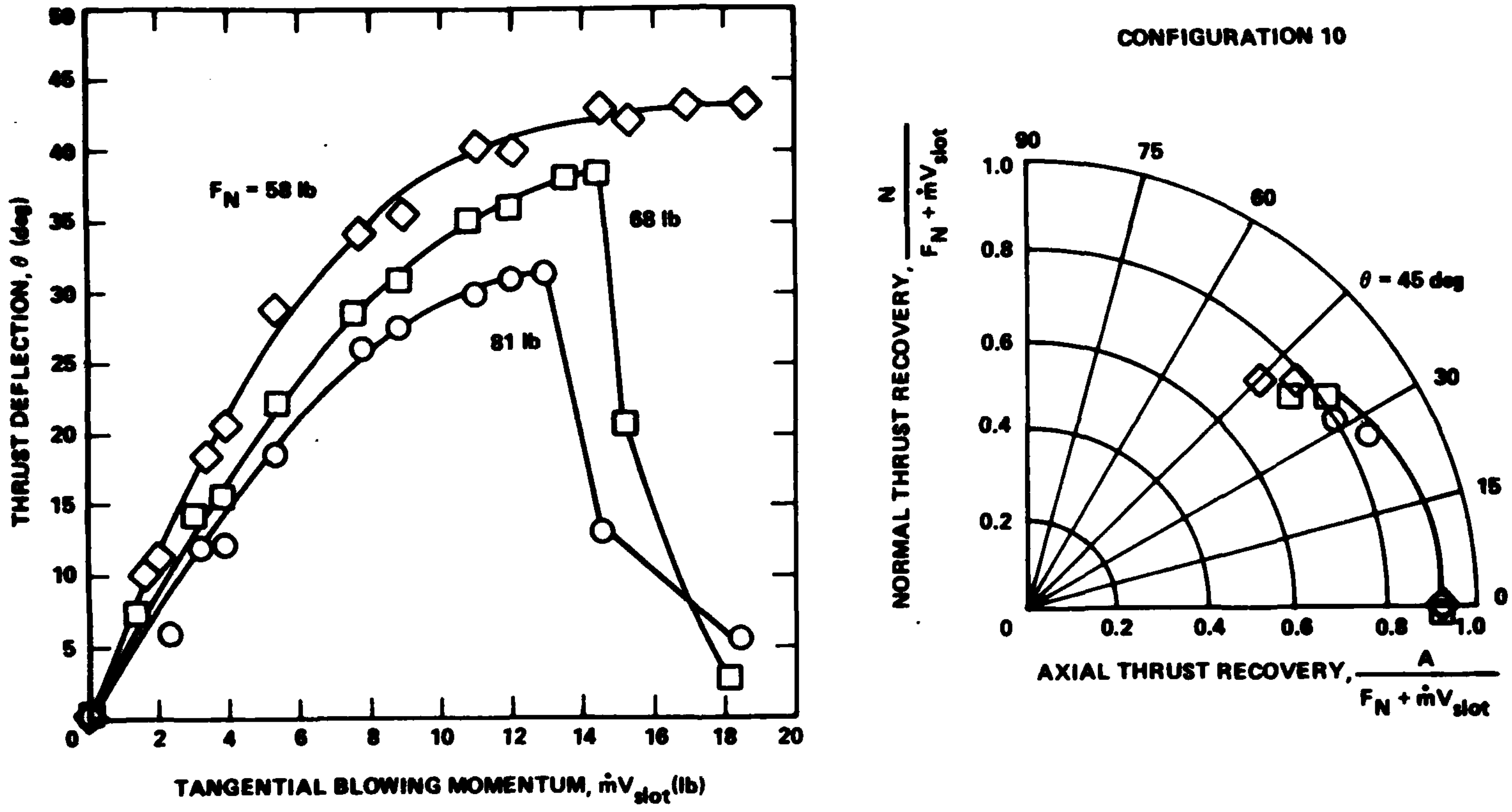
CONFIGURATION 10

Figure 5a - Tangential Blowing Slot at Nozzle

Figure 5 (Continued)

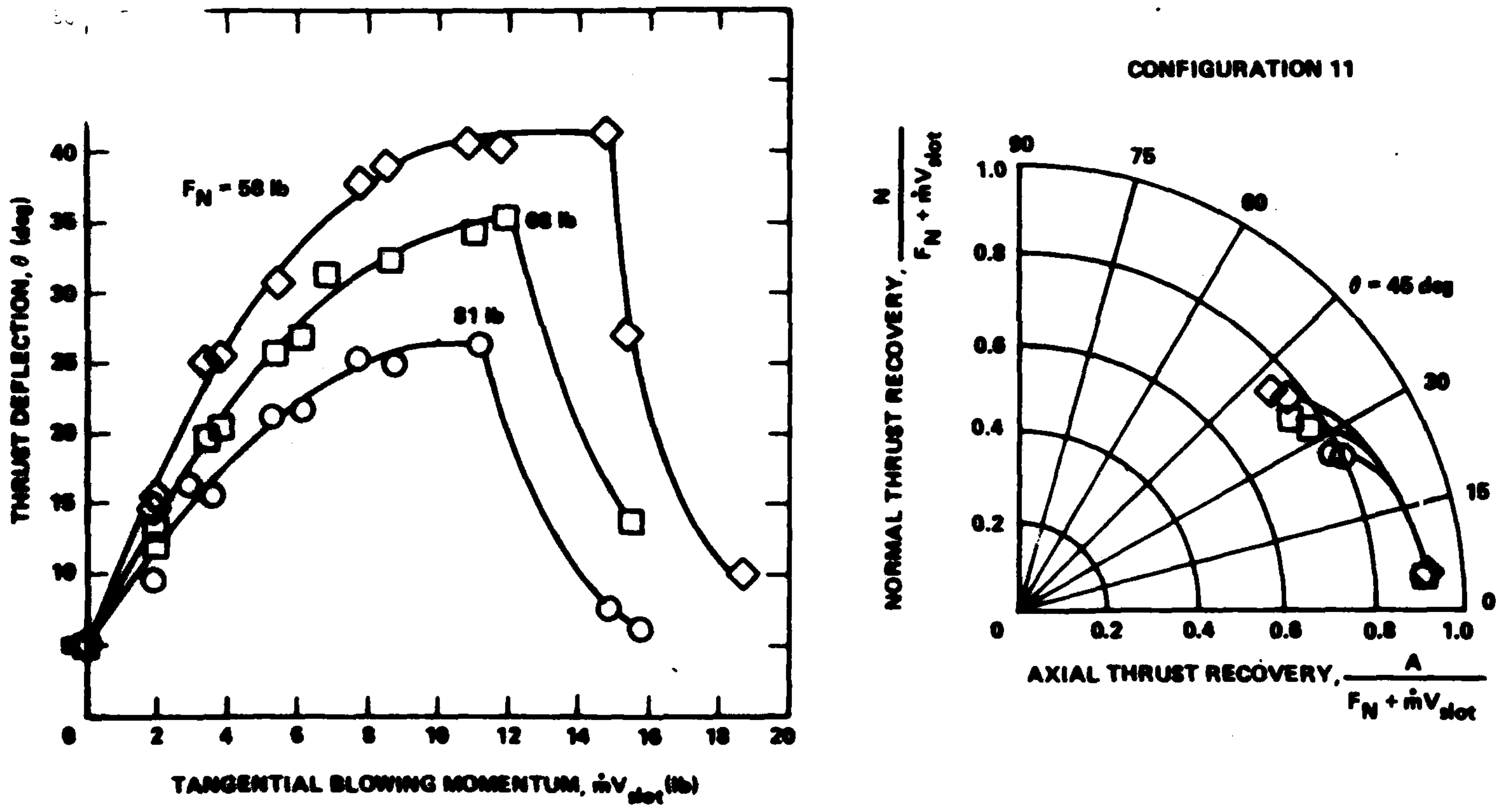

Figure 5b - Tangential Blowing Slot One-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 5 (Continued)

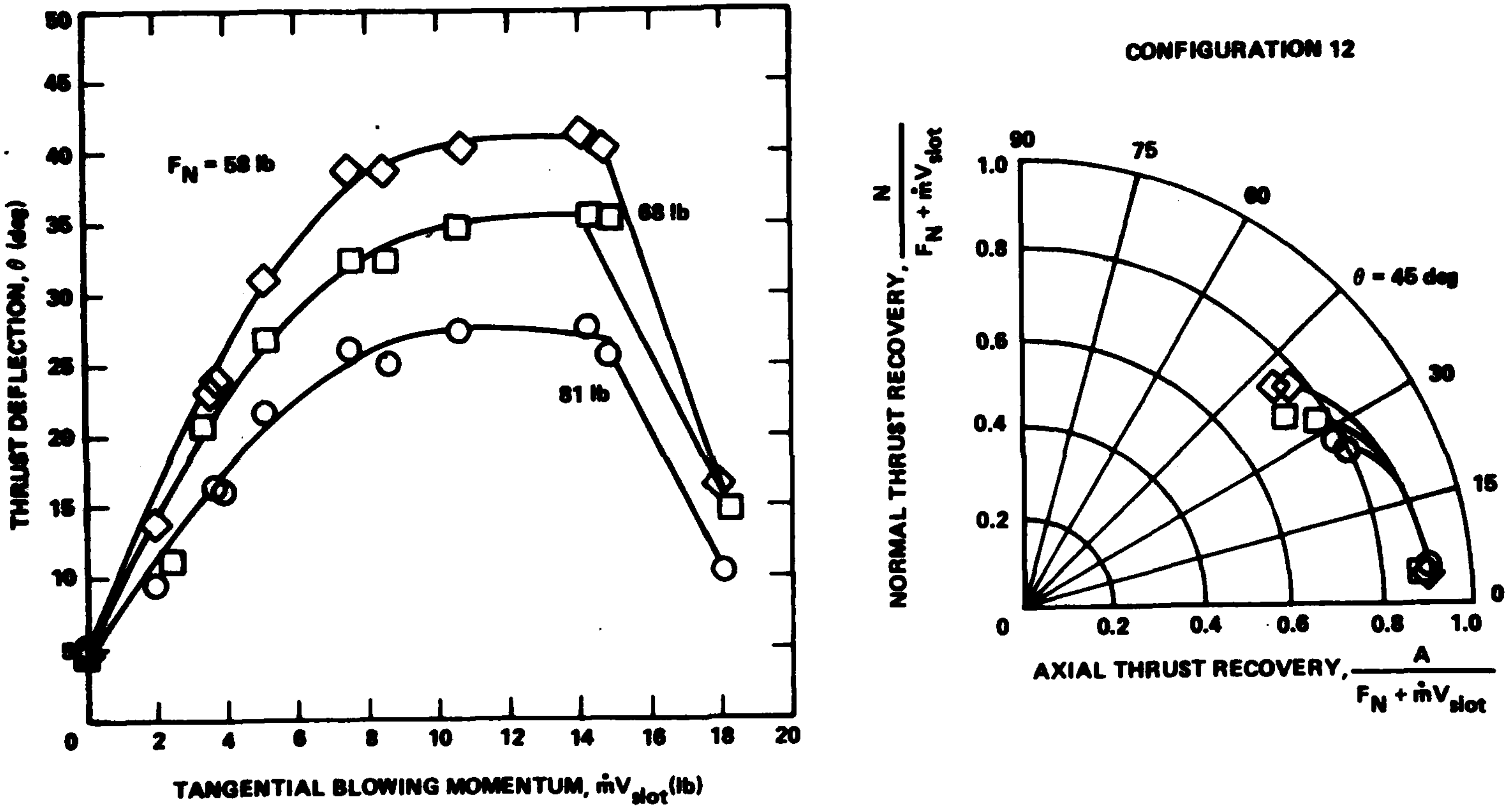

Figure 5c - Tangential Blowing Slot Two-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 6 - Thrust Deflection and Recovery with Quarter-Circular Deflecting Surface

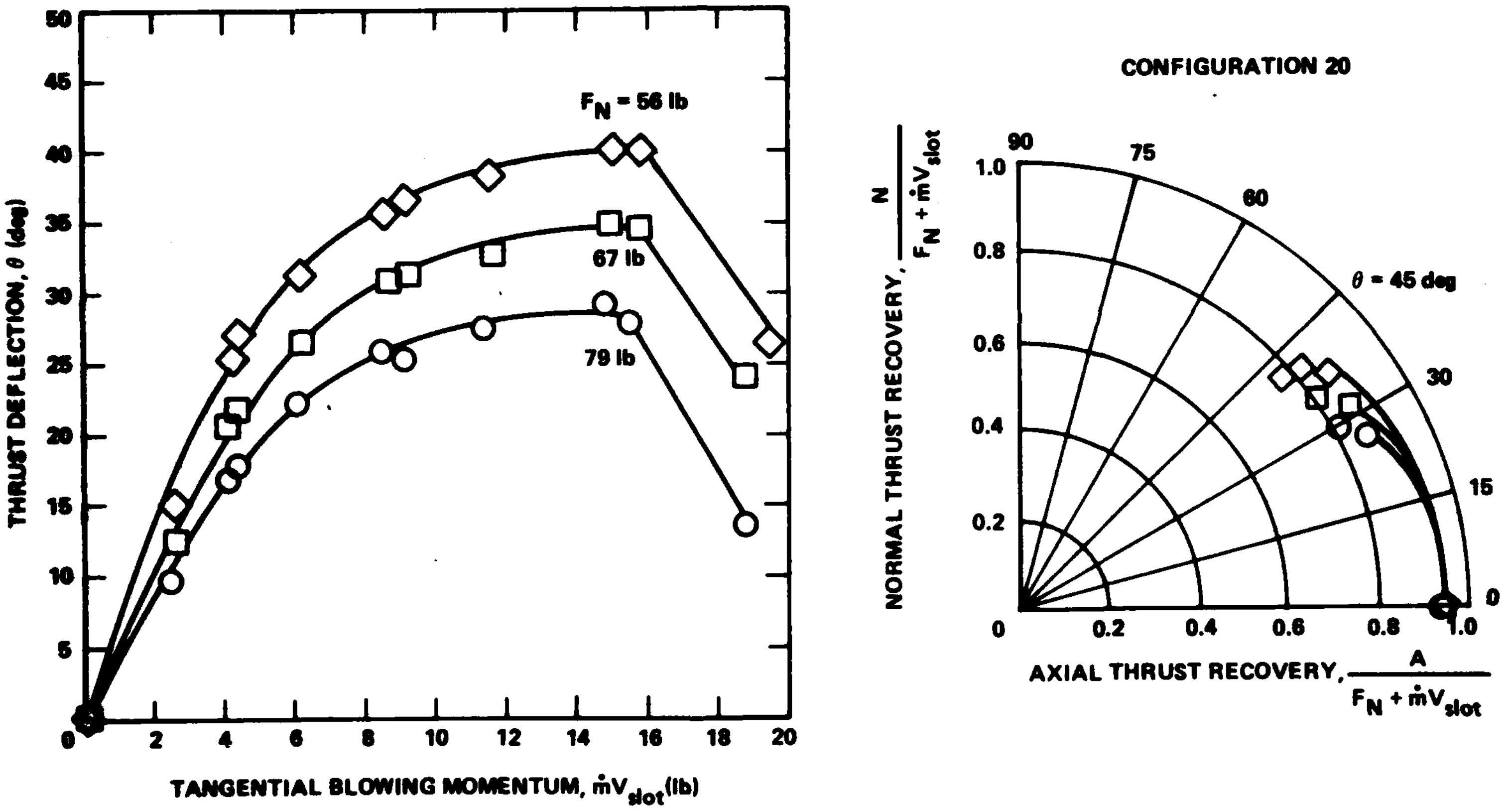

Figure 6a - Tangential Blowing Slot at Nozzle

Figure 6 (Continued)

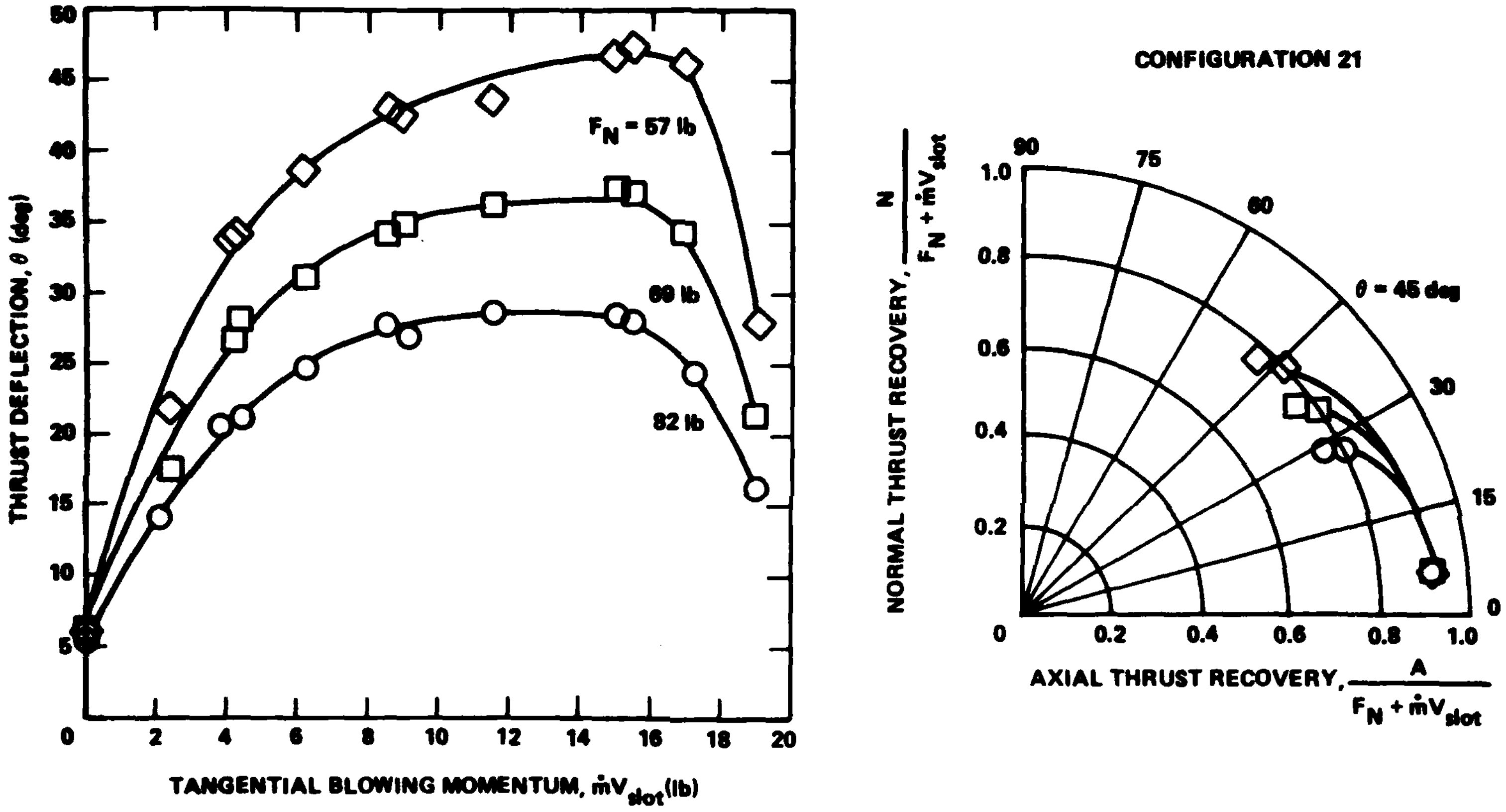

Figure 6b - Tangential Blowing Slot One-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 6 (Continued)

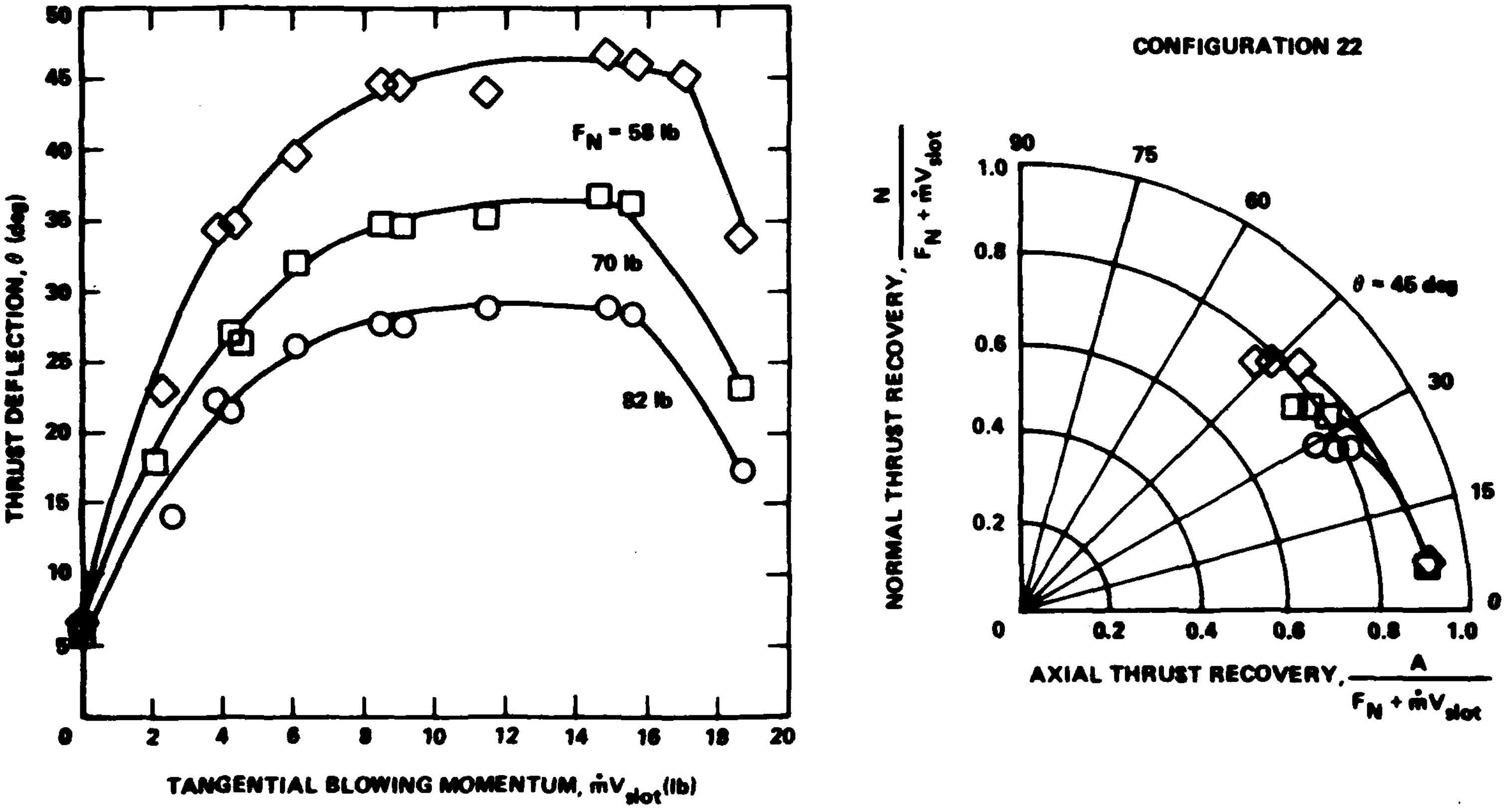

Figure 6c - Tangential Blowing Slot Two-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 7 - Thrust Deflection and Recovery with Semielliptical Deflecting Surface

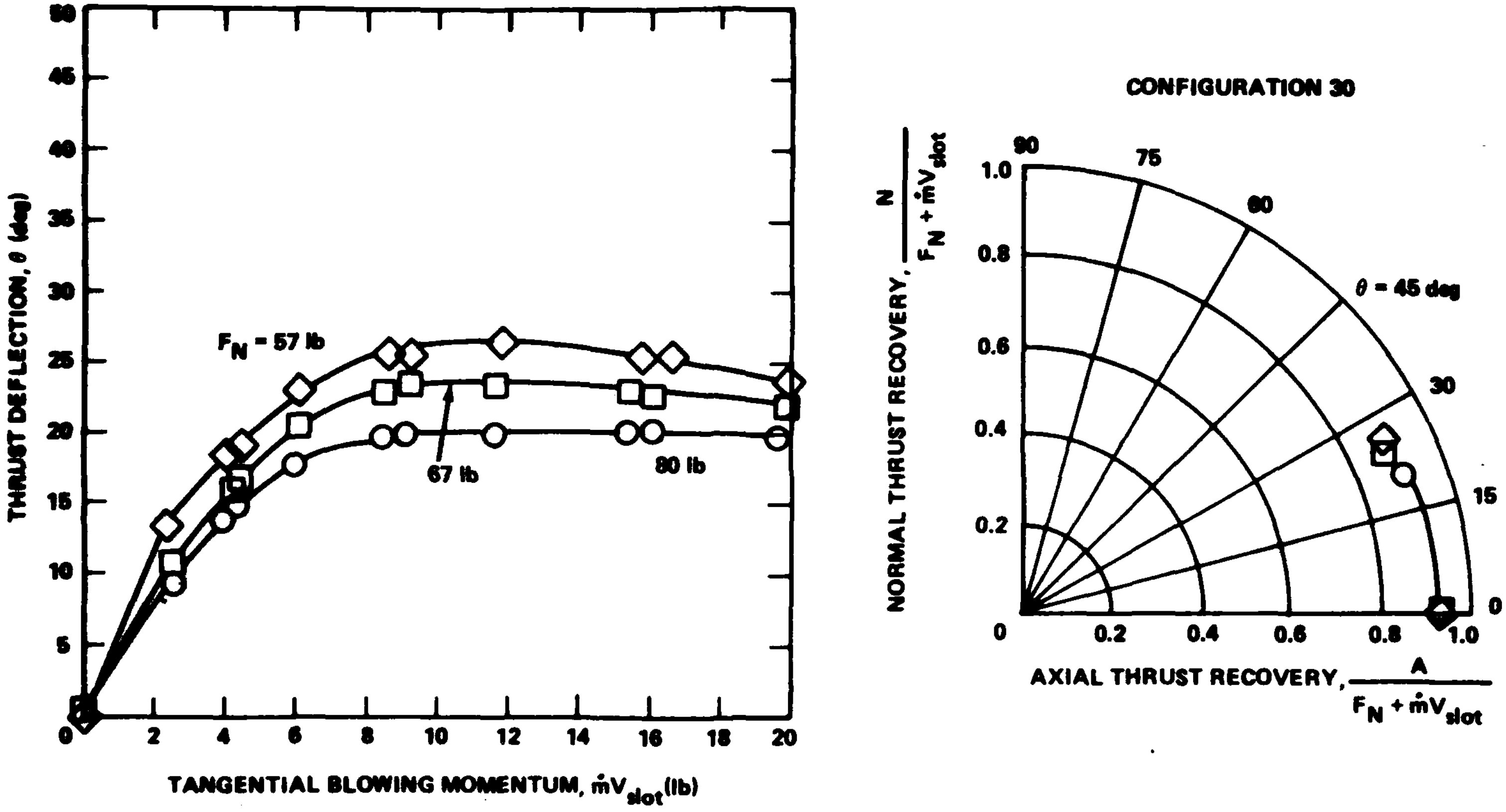

Figure 7a - Tangential Blowing Slot at Nozzle

Figure 7 (Continued)

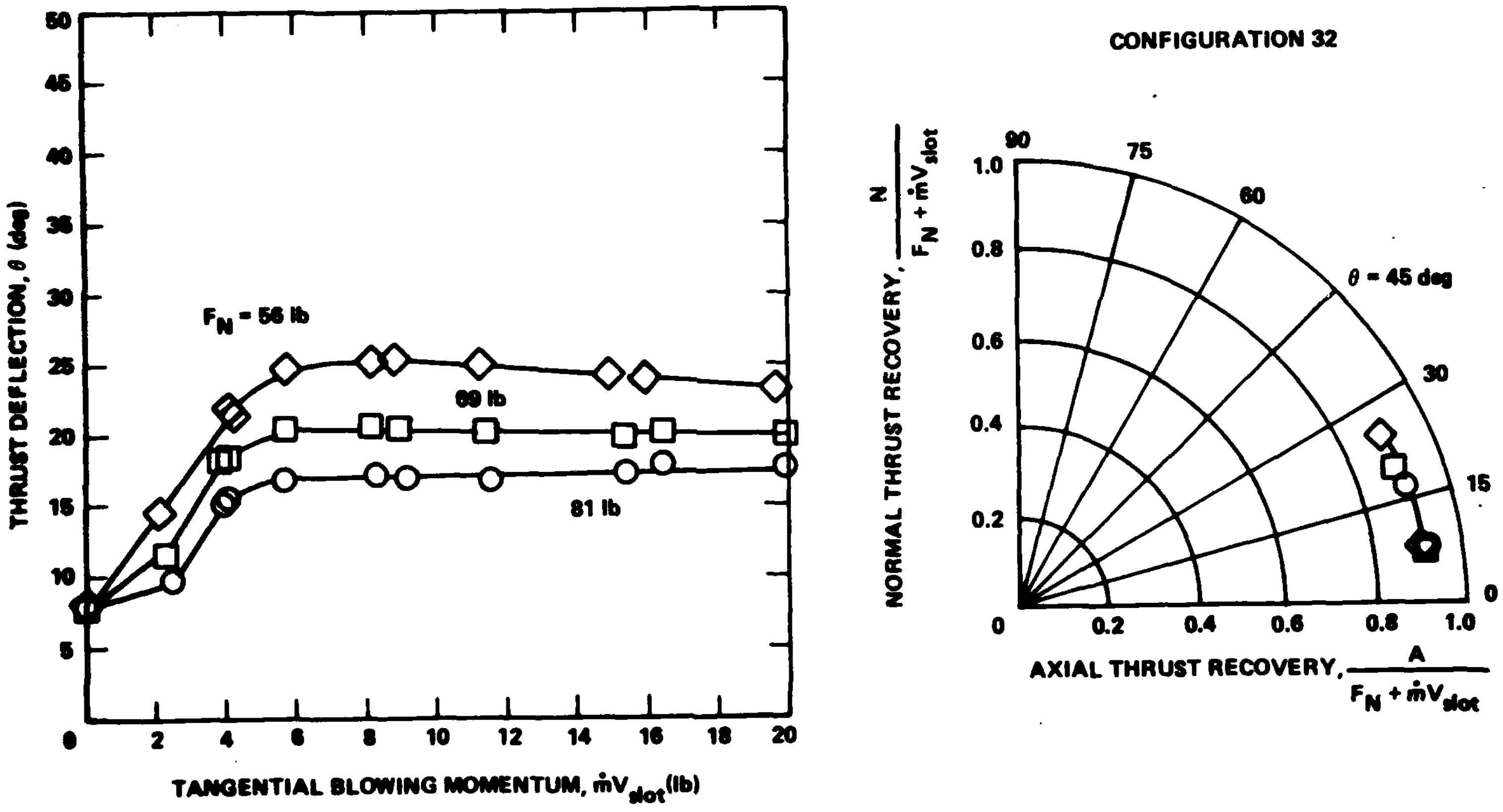

Figure 7b - Tangential Blowing Slot Two-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 7 (Continued)

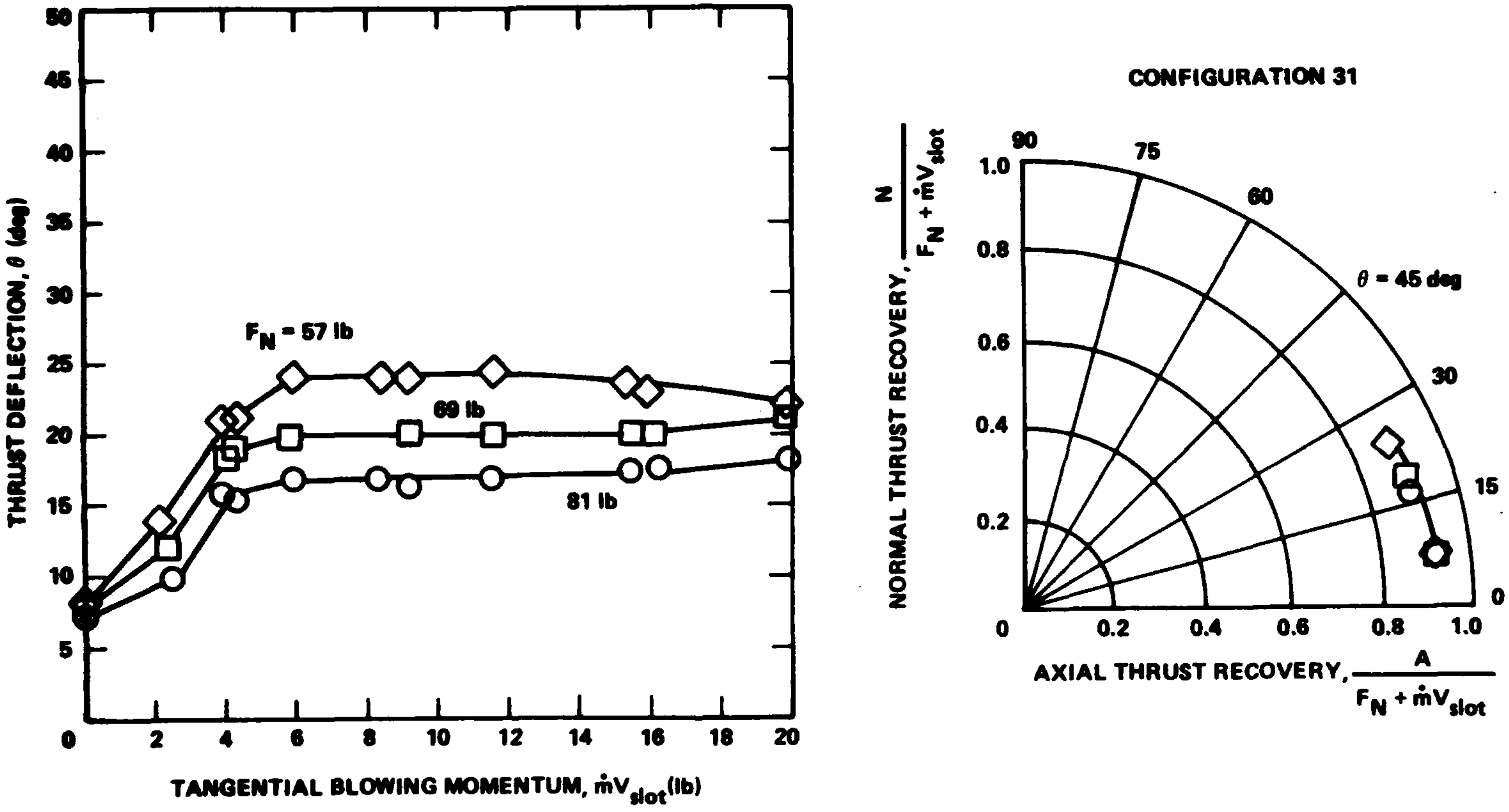

Figure 7c - Tangential Blowing Slot One-Equivalent-Nozzle-Diameter Aft of Nozzle

HOT GAS INVESTIGATION

The thrust deflecting capability of the pneumatic thrust deflector was also demonstrated in a hot gas investigation. A small turbojet, the J402-CA-400, was used as a hot gas generator for this investigation. Uninstalled characteristics of this turbojet are presented in Table 1.

TABLE 1 - TURBOJET CHARACTERISTICS

Designation	J402-CA-400
Type	Single shaft turbojet
Compressor	Single transonic axial compressor with a single centrifugal compressor; max airflow 9.6 lb/sec (4.35 kg/s); pressure ratio 5.8
Turbine	Single stage axial
Performance	Max sea level static thrust 660 lb (2.94 kN) at 41,200 rpm

A two-dimensional nozzle was added to the turbojet for this investigation. This nozzle-duct had an aspect-ratio-seven rectangular exit of 29 in^2 (186 cm^2). The small turbojet with the two-dimensional nozzle and bellmouth inlet produced a maximum static thrust of 550 lb (2.4 kN) at 40,800 rpm. The test arrangement is shown in Figure 8a.

The cylindrical thrust deflecting surface used in this investigation was semicircular in cross section. This surface had a diameter of 3.5 in. (8.9 cm) and could be mounted in one of three discrete positions aft of the nozzle exit. These positions were 0, 5, and 10 in. (0, 12.7 and 25.4 cm) aft of the nozzle which correspond to 0, 0.82, and 1.64 equivalent nozzle diameters. Flow fences were mounted on the deflecting surface at the width of the nozzle; see Figure 8b. Tangential blowing was limited to the 17.5 in. (44.5 cm) span between the flow fences.

Suspended from one common six-component balance were the thrust deflecting surface and the turbojet with a bellmouth inlet and two-dimensional nozzle. To determine the achievable range of thrust deflection and thrust recovery, the net system forces were measured while maintaining a constant engine rpm and varying the tangential blowing momentum. The nozzle thrust (F_N) was assumed constant for a constant engine rpm. The value assumed for the nozzle thrust was the net system force at the rpm maintained, but without tangential

Figure 8a - Bellmouth Inlet, J402-CA-400 Turbojet and Two-Dimensional Nozzle Suspended From Six-Component Balance

Figure 8b - Cylindrical Thrust Deflecting Surface and Two-Dimensional Nozzle

Figure 8 - Pneumatic Thrust Deflector for Hot Gas Investigation

blowing ($\dot{m}V_{slot} = 0$). This procedure was repeated with the deflecting surface at each of the three downstream positions. The resulting thrust deflection and thrust recovery, discussed in detail in Reference 1, are presented in Figure 9.

COMPARISON OF HOT AND COLD GAS INVESTIGATION RESULTS

Trends typical of pneumatic thrust deflection previously illustrated using the cold gas results are also found in the results from the hot gas investigation. Thrust deflection increases for a constant thrust with increasing tangential blowing momentum. The maximum thrust deflection angle increases with decreasing nozzle thrust.

A closer comparison is obtained by comparing the results presented in Figures 5 and 9. The pneumatic thrust deflector with the semicircular deflecting surface used in the cold gas investigation is geometrically similar to the pneumatic thrust deflector used in the large-scale hot-gas investigation. Based on a ratio of nozzle-thrust/nozzle-exit-area, the results from these investigations can be directly compared, as shown in Figure 10. A thrust of 280 lb (1.2 kN) produced by the turbojet is comparable to a thrust of 60 lb (267 N) produced by the turbojet simulator.

The range of thrust deflection achieved in both investigations is similar. Nominally higher deflections were achieved when the cold gas of the turbojet simulator was deflected. A maximum thrust deflection of 35 deg was achieved during the hot gas test at a thrust of 279 lb (1.2 kN) with the deflecting surface 1.64 equivalent nozzle diameters aft of the nozzle exit (Figure 9c). At a comparable thrust of 58 lb (258 N) and the deflecting surface 2.0 equivalent nozzle diameters aft of the nozzle exit (Figure 5c), the cold slipstream of the turbojet simulator was deflected a maximum of 41 deg. (These results are compared directly in Figure 10b.) The cold gas test produced slightly better results, due inpart to the deformation of the hot gas nozzle and slot. In general, cold gas adequately predicts hot engine results.

Figure 9 - Hot Gas Thrust Deflection and Recovery with Semicircular Deflecting Surface

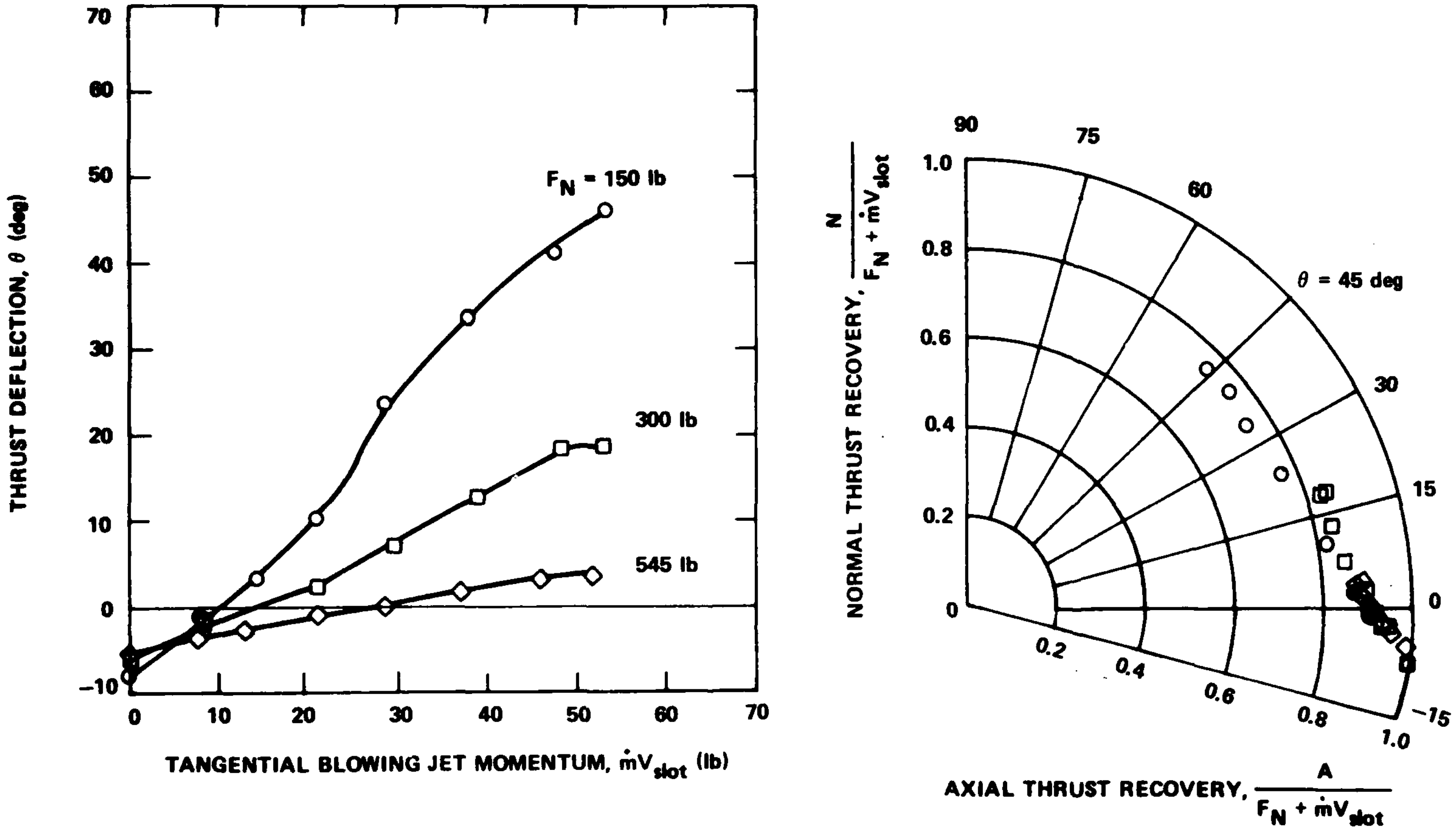

Figure 9 (Continued)

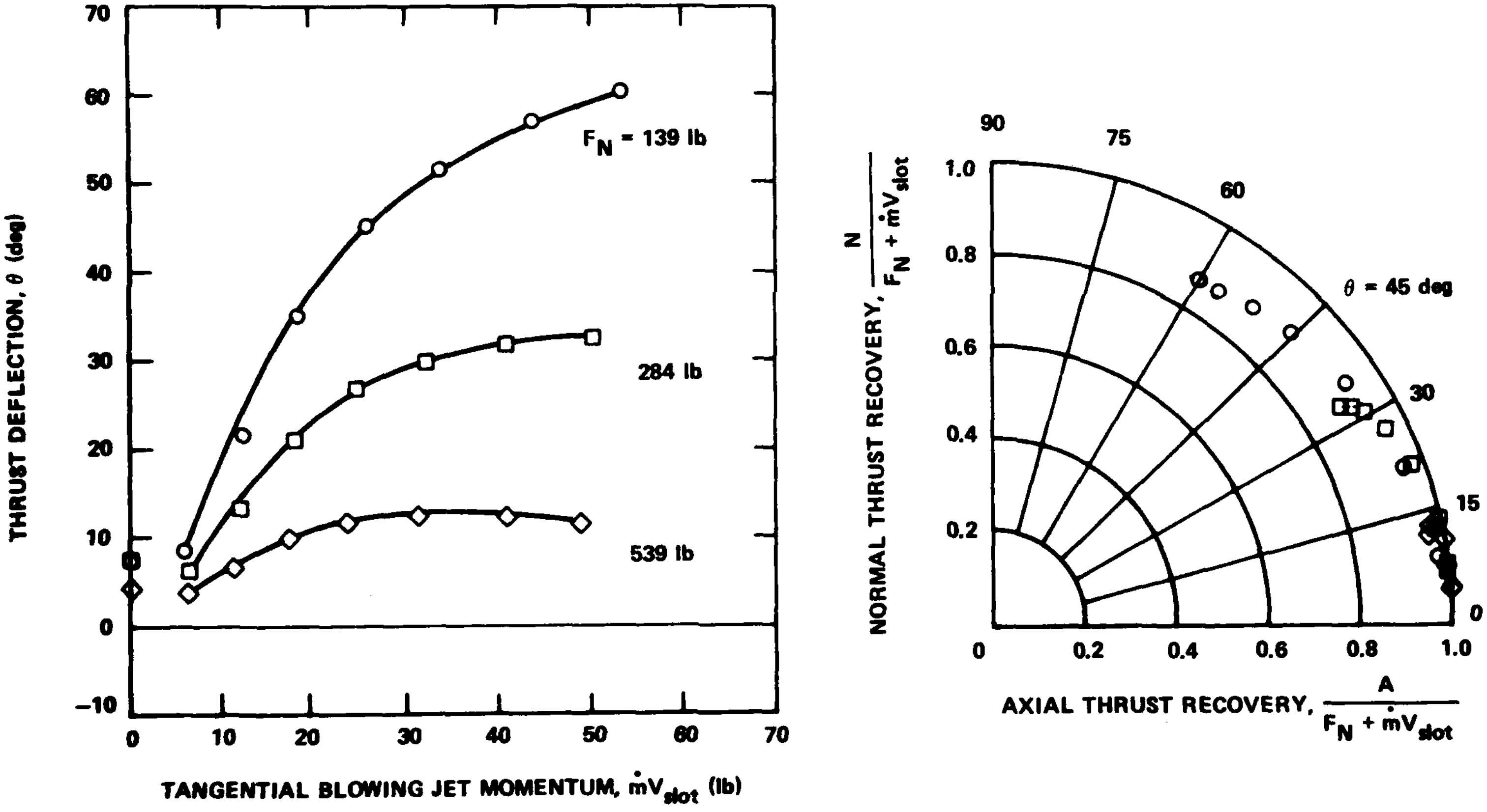

Figure 9b - Tangential Blowing Slot 0.82-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 9 (Continued)

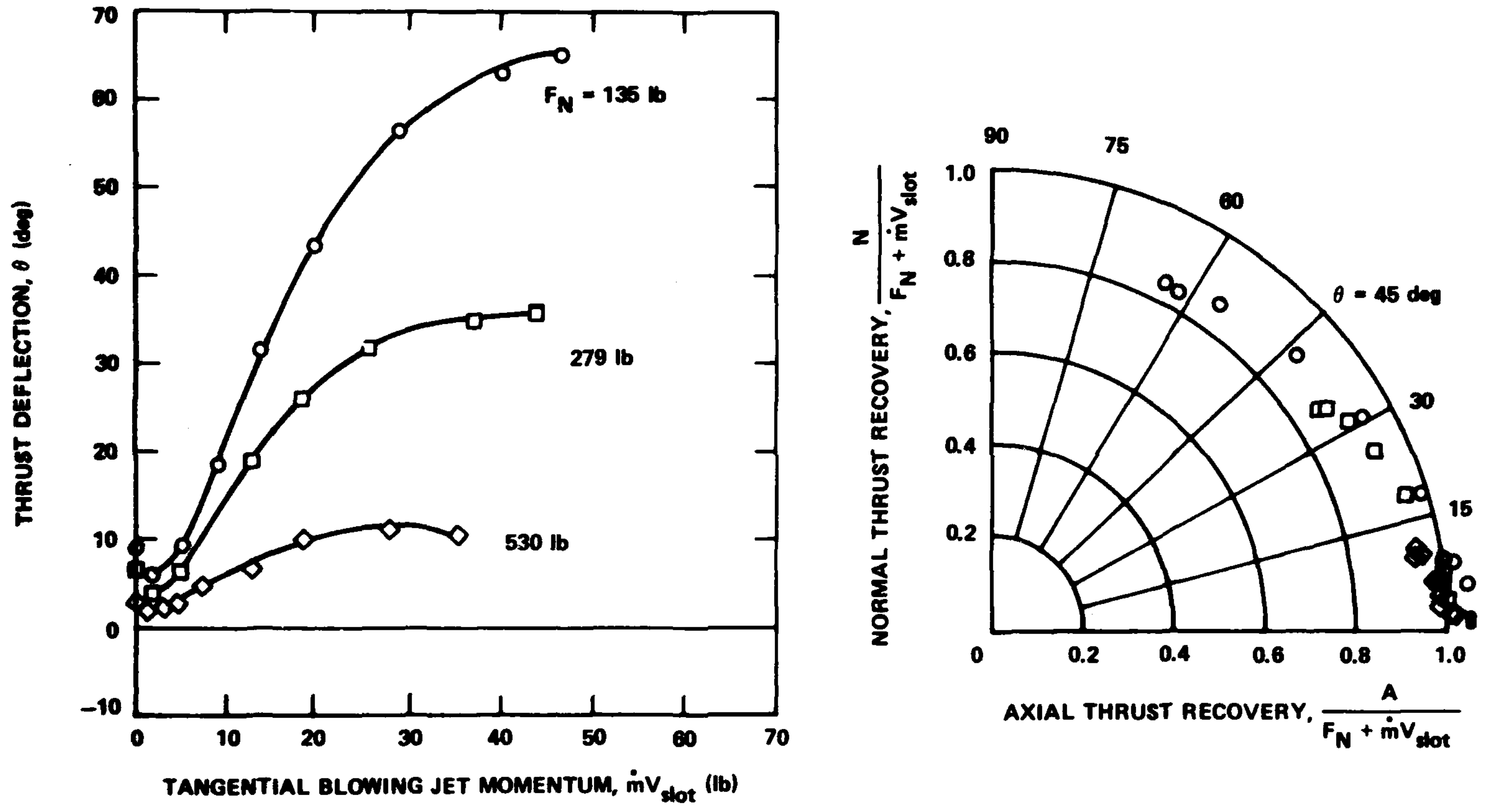

Figure 9c - Tangential Blowing Slot 1.62-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 10 - Comparison of Hot and Cold Gas Results

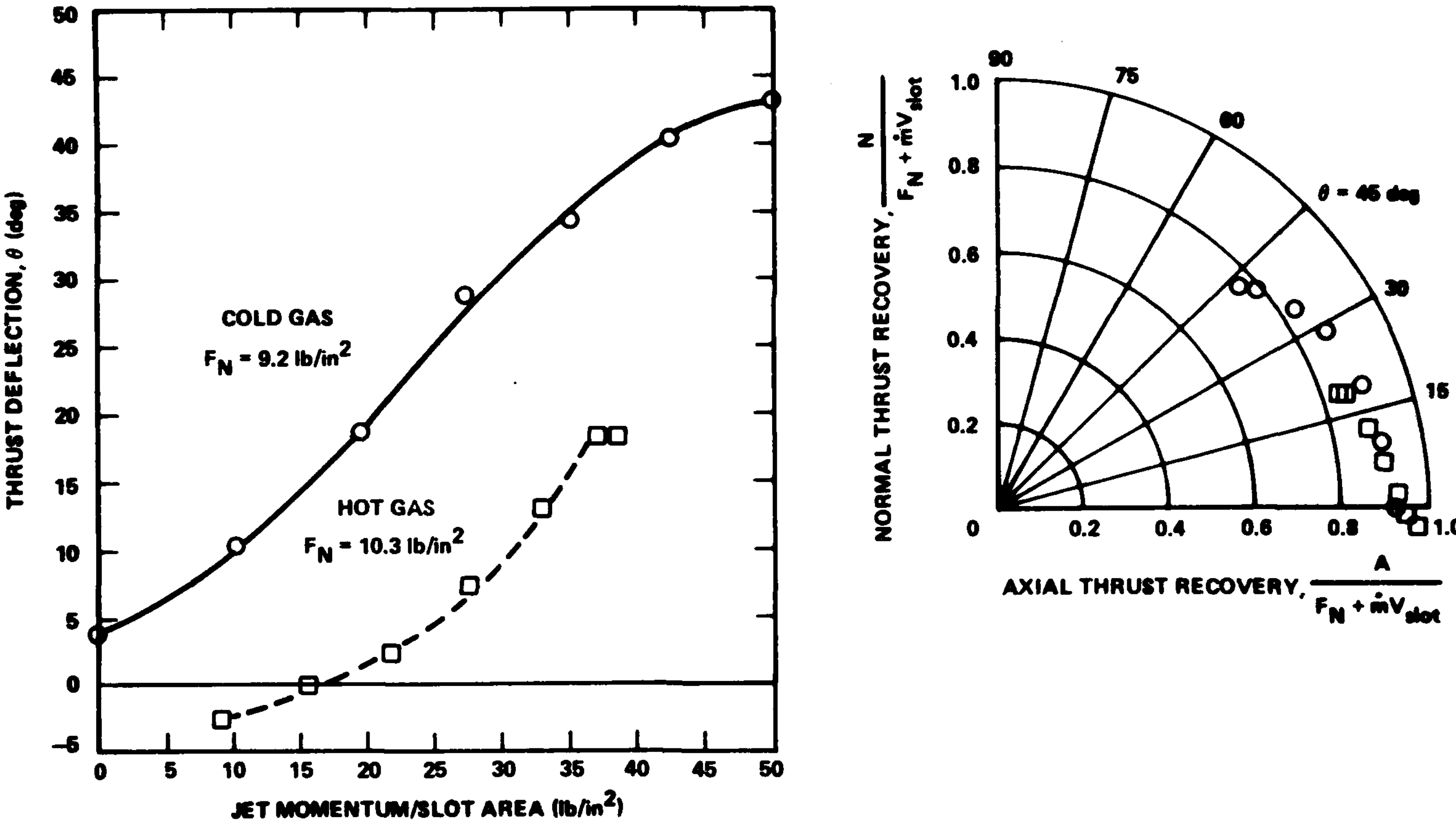

Figure 10a - Tangential Blowing Slot at Nozzle

Figure 10 (Continued)

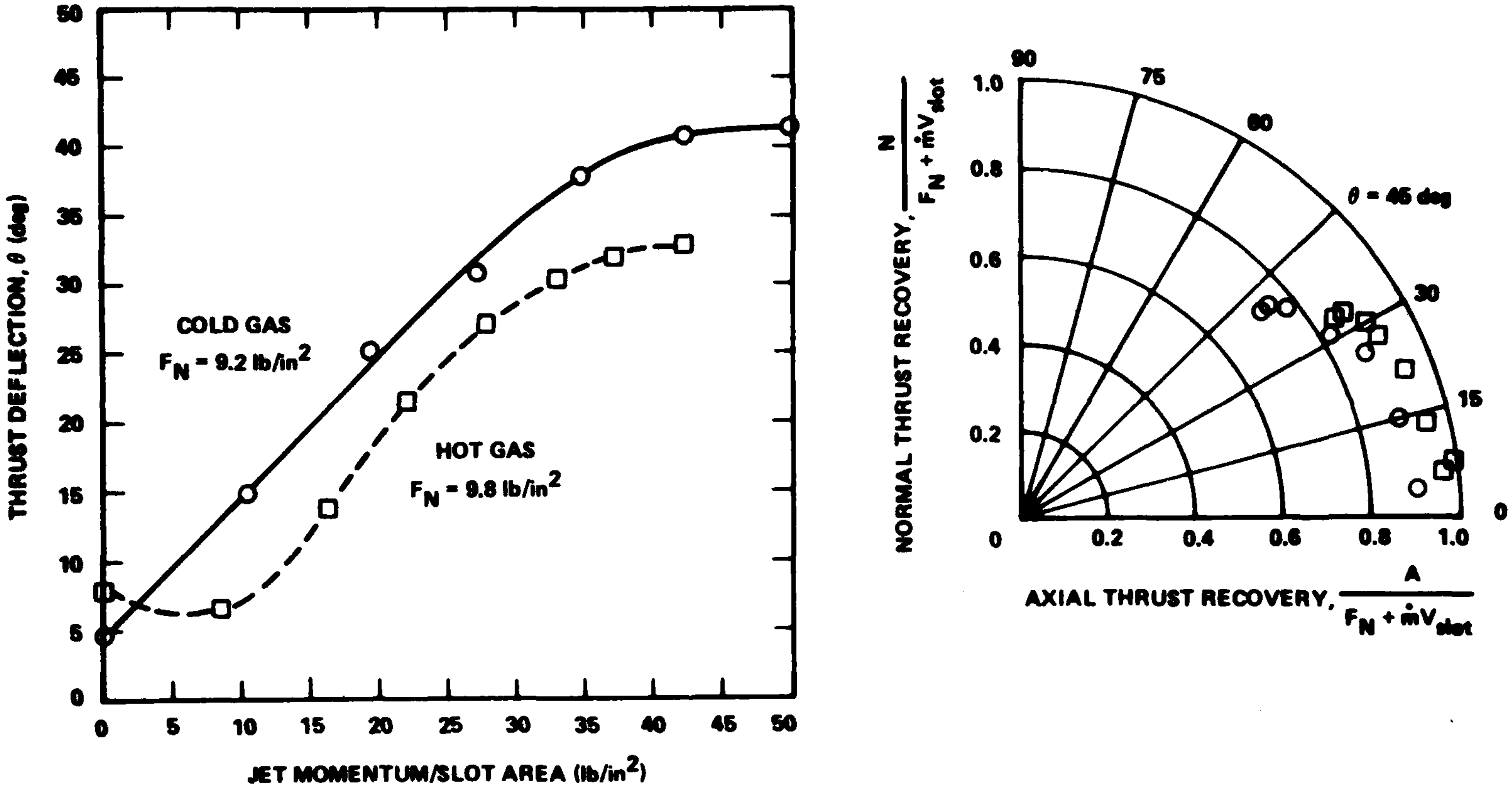

Figure 10b - Tangential Blowing Slot One-Equivalent-Nozzle-Diameter Aft of Nozzle

Figure 10 (Continued)

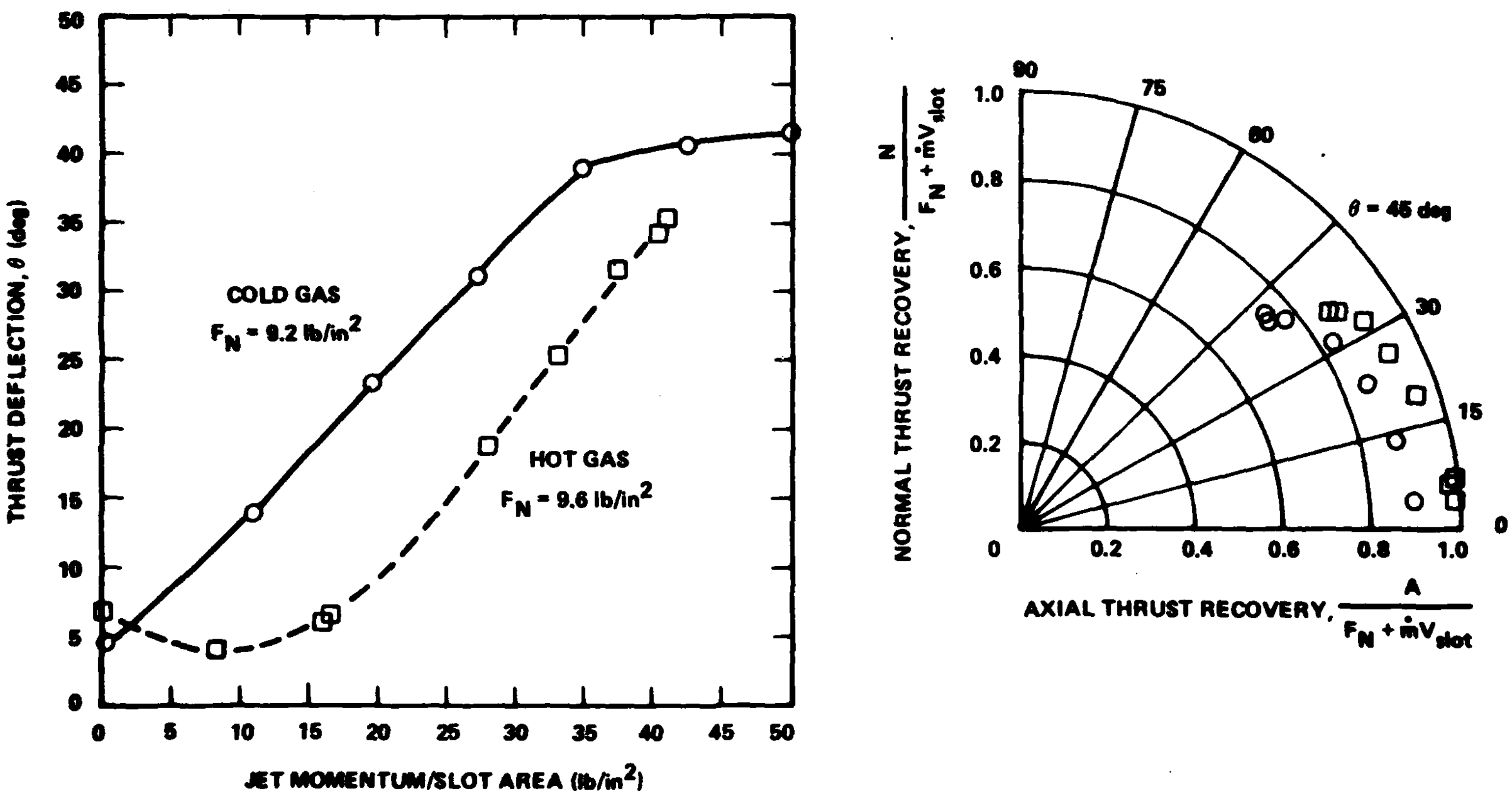

Figure 10c - Tangential Blowing Slot Two-Equivalent-Nozzle-Diameter Aft of Nozzle

SUMMARY

This investigation determined the thrust deflecting capability of a pneumatic thrust deflector with either a semicircular, quarter-circular, or semielliptical deflecting surface. Comparing the range of thrust deflection achieved during this investigation illustrates the following:

1. For the range of thrust deflection between 0 and 50 deg, similar performance was achieved with either the quarter-circular or the semicircular deflecting surface.

2. The maximum thrust deflection achieved with the semielliptical deflecting surface was 67 percent of the maximum thrust deflection achieved with the circular deflecting surface at maximum thrust. However, no dropoff in thrust deflection occurred at higher thrust or blowing.

3. All three deflecting surfaces provided a range of thrust deflection between 0 and 20 deg. This range is sufficient for most applications of the pneumatic thrust deflector.

4. Cold gas results adequately predict hot engine performance for similar pneumatic conditions.

RECOMMENDATIONS

The thrust deflecting capability of the pneumatic thrust deflector has been demonstrated statically in a series of investigations. These investigations included both a hot gas demonstration using a small turbojet and cold gas demonstrations. A wide range of thrust deflection was controlled pneumatically.

Possible geometries for the thrust deflecting surface were determined in this investigation. Generally, the quarter-circular deflecting surface demonstrated the best compromise between performance and size. To be practical, a penumatic thrust deflector must provide a wide range of thrust deflection without adversely affecting the cruise performance of the aircraft. If the deflecting surface cannot be blended into the fuselage geometry, it must be retracted into the fuselage. Retracting the deflecting surface into the fuselage increases the mechanical complexity of the system which might negate the advantage of this system over a deflecting two-dimensional nozzle.

Further development of the penumatic thrust deflector system should address integrating this system into a generic fuselage. The integrated system should be evaluated both statically and in flight. An investigation should be conducted to evaluate how the system can be employed during cruise flight to achieve the best mission performance. Only after the system has matured further will the full potential of the pneumatic thrust deflector be fully understood.

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