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UPPER-SURFACE-BLOWING FLOW-TURNING PERFORMANCE

William C. Sleeman, Jr.
NASA Langley Research Center

Arthur E. Phelps III
Langley Directorate, U.S. Army Air Mobility R&D Laboratory

SUMMARY

Jet-exhaust flow-turning characteristics were determined for systematic variations in USB (upper-surface blowing) exhaust nozzles and trailing-edge flap configuration variables from experimental wind-off (static) flow studies. For conditions with parallel flow exhausting from the nozzle, jet height (as indicated by nozzle exit height) and flap radius were found to be the most important parameters relating to flow turning. Nonparallel flow from the nozzle, as obtained from an internal roof angle and/or side spread angle, had a large favorable effect on flow turning.

Comparisons made between static turning results and wind-tunnel aerodynamic studies of identical configurations indicated that static flow-turning results can be indicative of wind-on powered-lift performance for both good and poor nozzle-flap combinations but, for marginal designs, can lead to overly optimistic assessment of powered-lift potential.

INTRODUCTION

The need for systematic study of upper-surface-blowing (USB) nozzle and flap variables has been recognized for identifying favorable combinations of primary variables that would provide good static flow turning and accompanying good wind-on powered-lift performance. The present parametric studies of USB nozzle and flap design variables were undertaken to fulfill this need for basic USB design information, as well as to improve understanding of the flow phenomena associated with generation of powered lift.

Static flow-turning studies offer a relatively simple and inexpensive means of evaluating the high-lift performance potential of a range of USB configuration variables. It is recognized that other factors, such as thrust recovery efficiency, are important to powered-lift performance; however, without good flow turning, a configuration has little chance of developing acceptable powered-lift characteristics. Static flow-turning data for a broad range of configurations can identify promising nozzle-flap configurations for subsequent powered-lift evaluation with forward speed effects in wind-tunnel tests. Past experience generally has shown that configurations with good static flow turning also provide appreciable lift increments due to power, whereas configurations that showed poor flow turning at static conditions also had very little gain in lift due to power. One of the objectives of the work presented herein was to determine effects of a broad range of nozzle-flap configurations on static flow-turning angles. The second objective was to determine how well the wind-on lift characteristics of USB configurations could be inferred from static flow-turning characteristics.

Static tests were conducted on a USB nozzle-flap model that provided for systematic variations of basic design parameters over a nozzle-pressure-ratio range from about 1 to 3. Eight values of nozzle height, seven values of flap radius, and five values of run length ahead of the flap were investigated for parallel flow from the exhaust nozzle. The basic nozzle was modified internally to provide four internal roof angles and two side spread angles in addition to the basic parallel flow (0°) angles. Both static data and wind-on tests in the Langley V/STOL wind tunnel of a few complete models with rectangular exhaust nozzles and with full-span leading-edge blowing provided comparative information for assessing the applicability of static flow-turning results.

SYMBOLS

C_L — lift coefficient, $\frac{\text{Lift}}{qS}$

C_μ — thrust coefficient, $\frac{\text{Thrust}}{qS}$

H — nozzle height, height of nozzle roof above nozzle floor at exit

q — test dynamic pressure

R — flap radius, effective turning radius of USB flap at tangent point to upper surface of wing airfoil

S — reference wing area

α — angle of attack of wing chord line

δ_f — flap deflection, angle of flap chord line at trailing edge with respect to wing chord line

USB — upper-surface blowing

Notation:

Run length — length of straight flow run downstream of nozzle exit to beginning of flap curvature

Flow-turning angle	effective static turning angle of jet flow after passing over flap, as determined from wind-off force measurements, $\tan^{-1}\sqrt{\frac{\text{Normal force}}{\text{Axial force}}}$
Nozzle pressure ratio	ratio of total pressure in exhaust nozzle to ambient total pressure
Nozzle roof angle	internal angle of nozzle roof with respect to nozzle floor
Nozzle spread angle	internal spread angle of nozzle sides measured from nozzle center line (slanted to spread exhaust flow laterally over wing and flap)

STATIC TESTS OF NOZZLE-FLAP VARIABLES

Model Description

A photograph of the static test model is shown in figure 1 with half of the nozzle block removed to show some of the inside details. High-pressure air was supplied from a pipe and brought to the model through a special plenum. The whole model assembly was mounted on a strain-gage balance, and the static flow-turning characteristics were determined from the measured forces. All measured data were corrected for tares associated with the air-supply hookup.

A schematic drawing of the model is given in figure 2 to indicate configuration variables investigated. Eight values of nozzle height ranging from 0.635 cm to 5.080 cm were investigated by the use of interchangeable nozzle blocks. Five values of run length ahead of the flap were investigated over a range from 0 cm to 10.16 cm; seven values of flap radius from 2.54 cm to 20.32 cm were investigated with circular arc flaps. The arc length of the flap having the largest radius was 32 cm from the beginning of curvature to the trailing edge (fig. 2). This length was held constant for all smaller values of flap radius by the addition of straight segments that formed the flap trailing edge. (See figs. 1 and 2.)

The width of the exhaust nozzle remained constant while other nozzle parameters such as spread angle and nozzle height were varied. The span of the flap was sufficiently large to contain the flow for all conditions of the exhaust nozzle investigated (fig. 2). All tests of the model were conducted over a range of nozzle pressure ratios which varied from about 1.1 to 3.1 for nozzle heights equal to or less than 2.54 cm (nozzle aspect ratio of 7); for the largest nozzle height of 5.08 cm (nozzle aspect ratio of 3.5), the maximum pressure ratio that could be obtained was limited to about 1.6 because of mass-flow and total-pressure limitations of the air-supply system.

Effect of Pressure Ratio on Flow Turning

The flap and nozzle variables investigated in the present study provided over 300 different configurations which were tested over a range of nozzle pressure ratios. This paper presents only selected portions of the vast amount of data obtained, to illustrate the principal findings and to summarize the results.

Data showing effects of nozzle pressure ratio on flow turning for various nozzle aspect ratios are presented in figure 3. Flap radius, flap turning angle (90°), and run length were held constant. The jet flow turning as illustrated in figure 3 is the angle of the jet flow after it passes over the wing and flap. The test results show turning angles that extended to about 50°, which indicates that the jet flow did not adhere to the 90° flap all along the flap but separated at some point ahead of the trailing edge.

The nozzle aspect ratio was changed by varying the jet exit height, and a decrease in the nozzle aspect ratio was accompanied by an increase in the height and attendant flow thickness. The results of figure 3 show an expected reduction in flow turning as the jet thickened (decreased nozzle aspect ratio). Also, as the jet height increased, conditions were reached where the flow could no longer negotiate the turn over the flap at higher pressure ratios and the abrupt loss in flow turning shown for some curves indicates sudden detachment of the flow. Past experience has shown that such sudden detachment can occur if the corner is too sharp (small turning radius), the jet is too thick, or the pressure ratio is too high.

Effects of pressure ratio on flow turning for a range of flap radius are shown in figure 4, where flap radius is expressed nondimensionally as a function of nozzle height. For these tests, the nozzle aspect ratio (and nozzle height) was held constant, as was the flap angle of 90°. Past experience would lead one to expect increases in flow turning with increasing turning radius (ref. 1); however, the data of figure 4 show progressive decreases in turning with increasing radius at pressure ratios up to 2.2. As mentioned previously, the smallest radius was too sharp for flow turning at high pressure ratios, and abrupt detachment was shown for pressure ratios above 2.2. Additional details on effects of flap radius, particularly in the lower range, will be discussed later.

The test results over a range of pressure ratio presented in figures 3 and 4 are fairly typical of the nature of the characteristics obtained for a wide range of nozzles and flap geometry, and most of the data showed only minor variations in turning angle with pressure ratio at low and moderate pressure ratios. The test results at low values (<1.5) of nozzle pressure ratio were found to be indicative of the maximum flow turning to be expected from a given configuration. A nozzle pressure ratio of 1.4 has been selected as representative of a quiet, high-bypass-ratio propulsion system and will be utilized for the remaining discussion of the static tests of nozzle-flap variables.

Effect of Flap Radius on Flow Turning

Data which show effects of flap radius on flow turning for small increments over a broad range of nozzle aspect ratios are presented in figure 5. These results are for a nozzle pressure ratio of 1.4 and a constant run length. The flap radius is nondimensionalized by the nozzle height.

While radius-height ratios up to 32 were included in the results of figure 4, the results of figure 5 are concerned only with the lower end of the radius range (to values of about 8).

The results of figure 5 show the expected increase in flow turning with increasing radius at very low values of radius-height ratio, but a breakaway point is evident beyond which little or no increase in turning occurs as the radius increases (for each nozzle aspect ratio). Each nozzle aspect ratio had its own breakaway point except possibly for the aspect-ratio-28 nozzle, for which data were lacking. These test results also show that there is some upper limit to the flow-turning angle that can be obtained with a particular parallel-flow nozzle/flap combination.

The data of figure 5 were generally representative of data obtained at other pressure ratios and run lengths. Increasing the nozzle pressure ratio from the 1.4 value used for figure 5 to a value of 2.0 caused only a slight reduction in flow turning, while variations in flow turning with run lengths greater than zero were relatively small. Most of the data available from this investigation were used to develop the following figure (fig. 6) which accounts for second-order effects by shaded areas which replaced the discrete lines of figure 5. Breakaway points for several nozzle aspect ratios are indicated by the numbers shown on the rising shaded band in figure 6. This rising shaded band separates the region where flow turning is available from the region where flow turning is not available with parallel flow nozzles and 90° flaps. The rising band extends to about 60° flow turning for a flap radius ratio of around 4, but this good turning is obtained only with a very large nozzle aspect ratio.

Experience with USB nozzle-flap configurations in other studies has demonstrated that flow-turning angles equal to or better than the 60° shown in figure 6 have been obtained on models with relatively low-aspect-ratio nozzles. The question naturally arises as to why these low-aspect-ratio nozzles were able to provide such high turning. Since the high-aspect-ratio nozzle of the present study provides a very thin jet, the effective jet height at the start of turning is perhaps of more fundamental importance than nozzle height. Low-aspect-ratio nozzles can turn flow if there is some means of thinning and spreading the flow. Several means for causing the exit flow to thin after leaving the nozzle have been used successfully and include the use of external deflectors, a large internal roof angle, and appreciable nozzle side flare.

Effects of Nozzle Internal Angles

The present nozzle-flap study included systematic variations in internal roof angle and side spread angle as shown schematically in the sketches in figure 7. Flap radius and run length were varied but the nozzle aspect ratio of 7.0 was held constant. Typical turning-angle results are also presented in figure 7 as a function of internal roof angle for three values of spread angle. These test results are for a nozzle aspect ratio of 7 and a radius-height ratio of 4. For parallel exit flow (see fig. 6), the flow turning at these values of aspect ratio and radius would be 25° to 30°, which is consistent with the flow turning shown in figure 7 at 0° roof angle and 0° spread angles. Attainment of 60° turning can be obtained either by increasing only the roof angle to 30° or by using 20° of spread angle and 0° roof angle (fig. 7). Combinations of roof angle and spr[illegible] angle can provide up to 80° of flow turning. The trade-offs in roof and spread angle, as illustrated in figure [illegible], provide the designer with some freedom of selection to minimize problems such as high cruise drag associated with high boattail/roof angles.

WIND-TUNNEL TESTS OF COMPLETE USB MODELS

The preceding discussion has been concerned with wind-off static turning and design variables that influence flow turning for rectangular nozzles. The second part of this paper deals with forward speed effects for complete USB model configurations in wind-tunnel tests. Emphasis is given to the determination of how well the wind-on lift characteristics can be inferred from the static flow-turning characteristics.

Four-Engine Model With Radius Flaps

A photograph of the four-engine USB configuration in the Langley V/STOL tunnel is shown in figure 8. The wing had supercritical airfoil sections with a maximum thickness of 9.3 percent chord, a nominal quarter-chord sweep angle of 30°, an aspect ratio of 7.48, and a taper ratio of 0.247. Test results and a detailed description of this model are given in reference 2. This model provides a very good tie-in with the nozzle-flap study just discussed inasmuch as it used aspect-ratio-6 rectangular exhaust nozzles and a 90° radius flap. It should be noted that both the chord and area of the flap decreased as the deflection decreased from 90°; the arc length was proportional to flap deflection angle (i.e., the arc length of the 45° flap was half of that for the 90° flap).

Both static flow-turning and companion forward speed test results at 0° angle of attack are given in figure 9 for a range of flap deflections from 45° to 90°. Static test results presented in figure 9 show consistent increases in flow turning with increasing flap deflection, and the turning angles were essentially invariant with thrust. The level of flow turning was fairly good; that is, the nozzle-flap configuration turned the flow about two-thirds of the flap deflection (60° turning for 90° flap). Characteristics of the wind-on lift that could be inferred from these fairly good static flow-turning data are that lift should increase in a smooth and steady manner with increased thrust, and that lift should increase for a given thrust, proportionate to changes in flap deflection. These characteristics are certainly evident in the wind-on data of figure 9, and the static turning data can be considered indicative of the wind-on lift characteristics to be expected.

Four-Engine Model With Modified Slotted Flap

Representative test results on the same basic model just discussed but with different high-lift flaps are given in figure 10. The modified flap system is shown at three different deflections in the sketches at the top of figure 10. The flap was originally a double-slotted flap for an externally blown flap model; the flap was modified for upper-surface blowing by filling in the gaps between flap elements. The resulting flap-radius—nozzle-height ratios shown in figure 10 are judged to be the approximate effective values.

The static flow turning at low and moderate thrust appears to be fairly good, in that the flow angle was about equal to the flap deflection and was relatively invariant with thrust except for the first few data points at the lower flap angles. In the middle-to-high thrust range, however, abrupt detachment of the flow occurred for the highest flap deflection, as evidenced by the large decrease in flow turning. It could be inferred from these static results that the wind-on lift at low thrust would vary in proportion to the flap deflection but at high thrust would suffer a loss in lift in going to the highest flap deflection. The actual wind-on lift data, however, show that lift coefficients for the highest flap deflection were always lower than those for the lower flap deflections. The static data therefore are overly optimistic and not directly indicative of the wind-on characteristics obtained.

Previous experience with upper-surface-blown configurations has indicated that poor wind-on powered-lift characteristics almost always accompany poor static flow-turning characteristics. Likewise, good invariant static flow turning generally can be taken to indicate correspondingly good wind-on lift characteristics. Considerable uncertainty can exist between these extremes of very good and poor static turning; however, where appreciable variations in flow turning with static thrust occur, anomalies in the wind-on lift can generally be expected. The sudden detachment of the flow shown for the 65° flap deflection in figure 10 suggests that the flow at low thrust was only marginally attached, and the addition of more thrust and/or addition of the free-stream velocity caused the jet flow to detach. In this last example, static flow-turning results gave some indication that the jet flow was only marginally attached for some configurations and, with forward speed, would be expected to detach. The question then arises as to the likelihood of a situation where the static flow-turning data gave no indication of marginal attachment, while in fact, forward speed effects would cause the flow to detach. The discussion in the next section deals with such a situation.

USB Model With Full-Span Leading-Edge Blowing

A photograph of the leading-edge-blowing model is shown in figure 11. The model had blowing over the upper surface of the wing from a small full-span slot located near the wing leading edge. The model had a double-hinge plain flap with a very small radius on the forward element. A sketch of the model airfoil, showing the blowing slot at 19 percent chord and the deflected flap, is given at the top of figure 12. The use of a double-hinged flap allowed a matrix of flap combinations to be investigated by setting the rear flap and varying the deflection of the forward element over a range of angles. In order to cover more model configurations than could be easily handled by the data presentation used with the previous figures, the data of figure 12 are presented as a function of total flap deflection.

Flow-turning angles and wind-on lift coefficients are presented in figure 12 as functions of total flap deflection for $C_\mu = 2.0$ with the wind on and for static thrust corresponding to $C_\mu = 2.0$ with the wind off. None of the basic wind-off flow-turning data showed unusual variations with static thrust. Static test results of figure 12 show that flow turning increased as the total flap deflection increased, and turning angles up to 85° were obtained at the highest flap deflection. The wind-on lift data of figure 12 show increases in lift with flap deflection up to a point and then a decrease in lift. It is interesting to observe that the lift peak always occurred at 45° deflection of the front flap (45° front + 0° rear = 45°, 45° front + 15° rear = 60°, and 45° front + 30° rear = 75°). These results indicate that good static flow turning may not always be indicative of correspondingly good power-on lift characteristics. An assessment of the lift potential based on the static turning data for this leading-edge-blowing model would be optimistic for flow-turning angles in excess of about 60°.

CONCLUDING REMARKS

Static test results obtained in an investigation of parallel-exit-flow USB nozzle and flap geometric variations over a range of nozzle pressure ratio from about 1 to 3 showed very little effect of pressure ratio on static flow turning for configurations with well-established flow. Test results obtained at low pressure ratios were indicative of the maximum flow-turning performance to be expected. Some gains in flow turning were even realized by the use of a small (2.54 cm) run length ahead of the flap, but further increases in run length produced relatively small changes in turning. Flow-turning angles increased when the jet height decreased and increased with flap radius up to a point, beyond which little or no increase was evident. The jet height, as indicated by the nozzle exit height, and the flap radius were the most important parameters relating to flow turning for parallel flow from the nozzle. Non-parallel flow from the nozzle, as obtained from an internal roof angle and/or side spread angles, had a large favorable effect on flow-turning angles.

Static tests and wind-on tests of complete USB models in a wind tunnel indicated that the static flow-turning results can be indicative of wind-on powered-lift performance for both good and poor conditions. For marginal conditions, the static results can lead to an overly optimistic assessment of wind-on powered-lift potential.

REFERENCES

1. Phelps, Arthur E., III: Aerodynamics of the Upper Surface Blown Flap. STOL Technology, NASA SP-320, 1972, pp. 97-110.

2. Sleeman, William C., Jr.; and Hohlweg, William C.: Low-Speed Wind-Tunnel Investigation of a Four-Engine Upper Surface Blown Model Having a Swept Wing and Rectangular and D-Shaped Exhaust Nozzles. NASA TN D-8061, 1975.

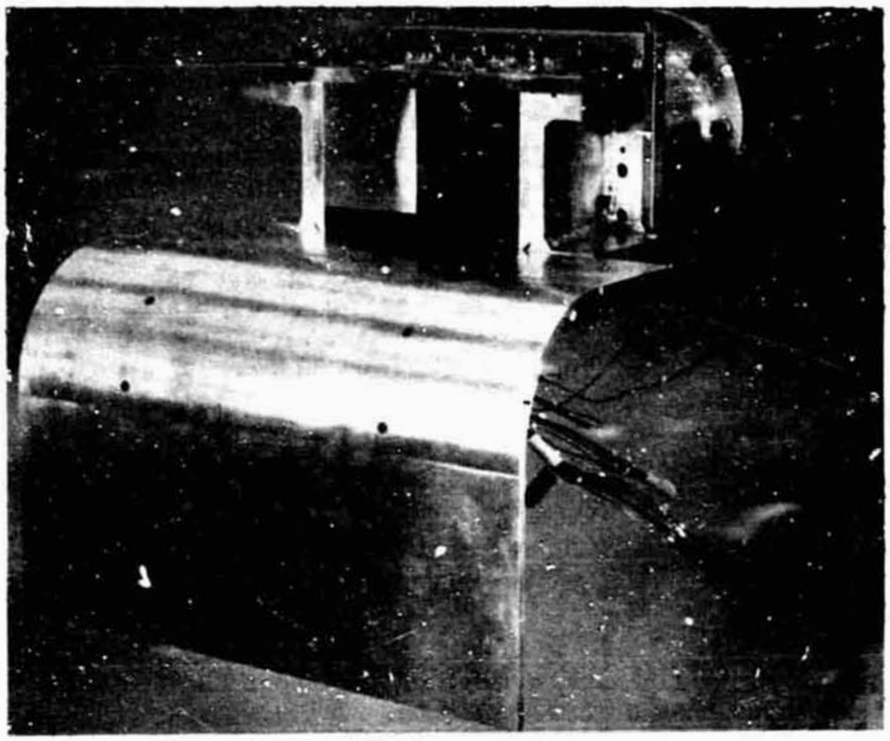

Figure 1.- Model used in static tests of USB nozzle and flap variables.

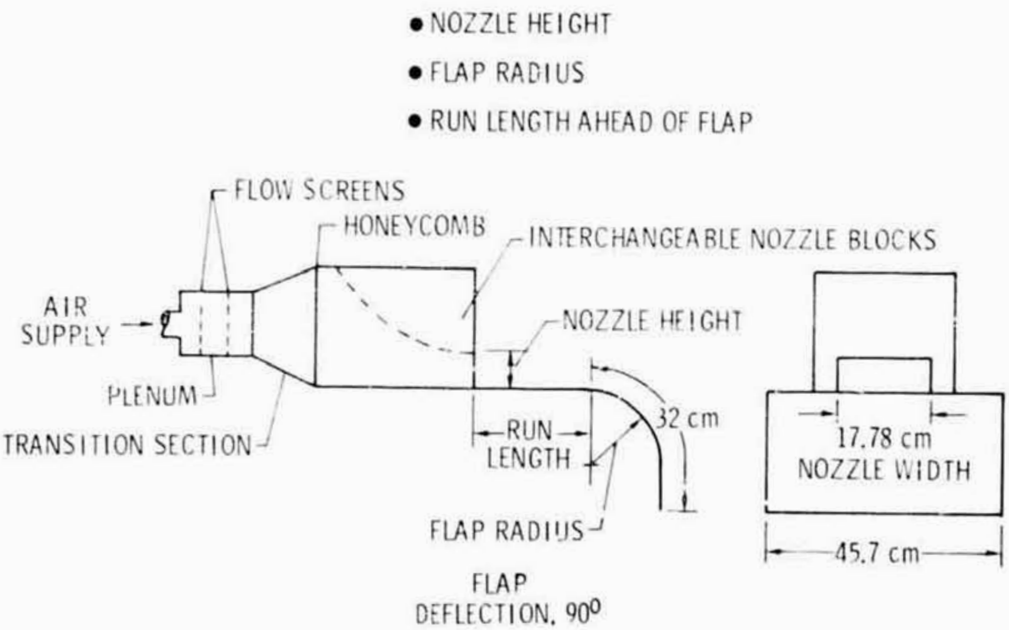

Figure 2.- Model configuration variables for parallel exit flow.

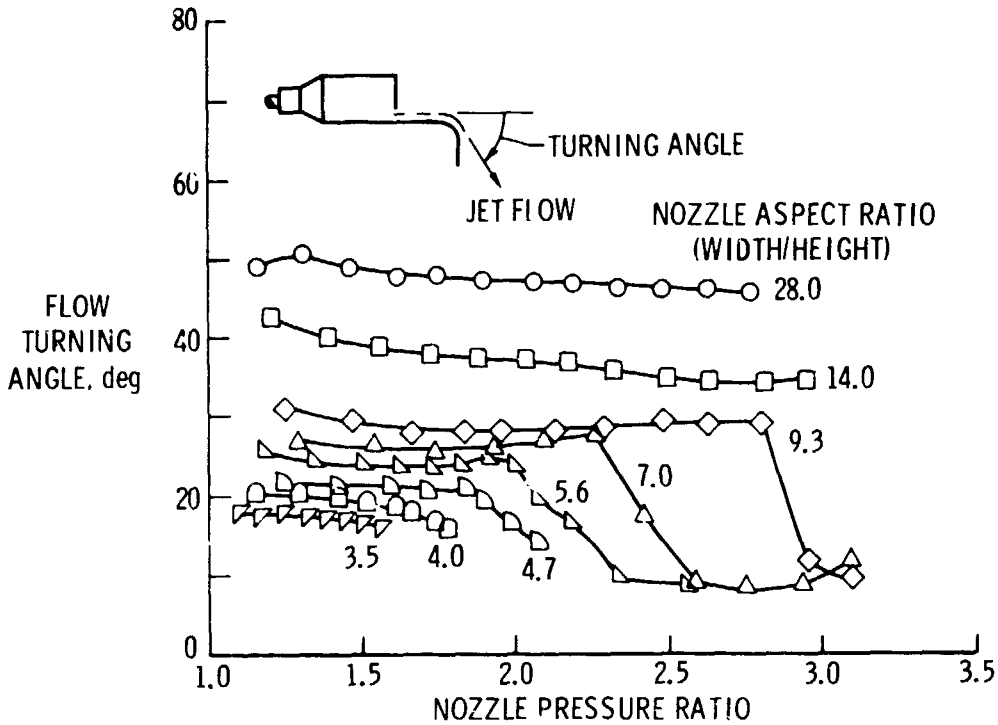

Figure 3.- Effect of pressure ratio on flow turning for various nozzle aspect ratios. Constant flap radius.

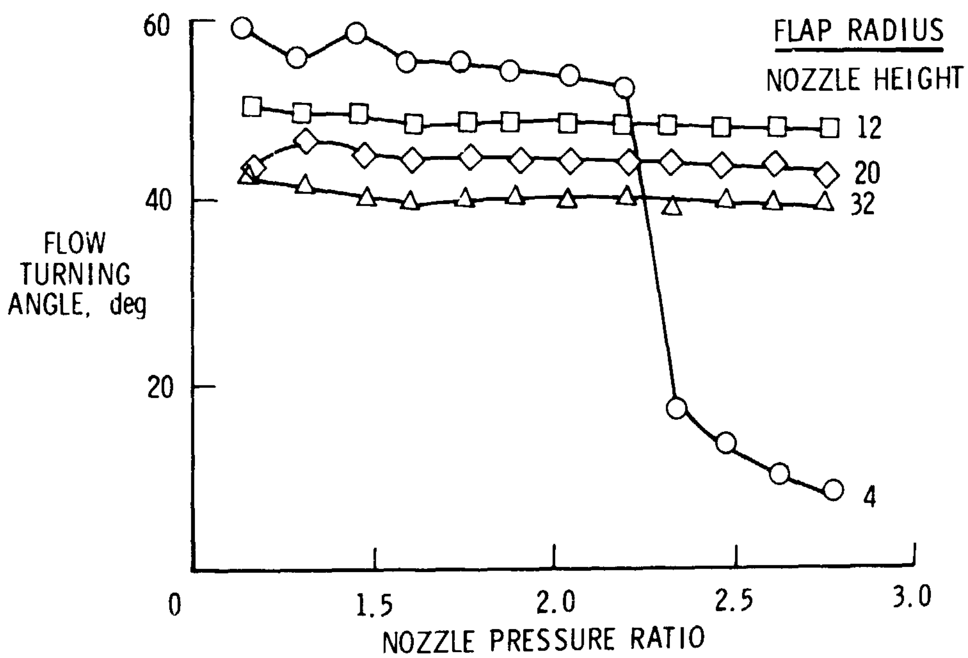

Figure 4.- Effect of pressure ratio on flow turning for a range of flap radius. Nozzle aspect ratio of 28.

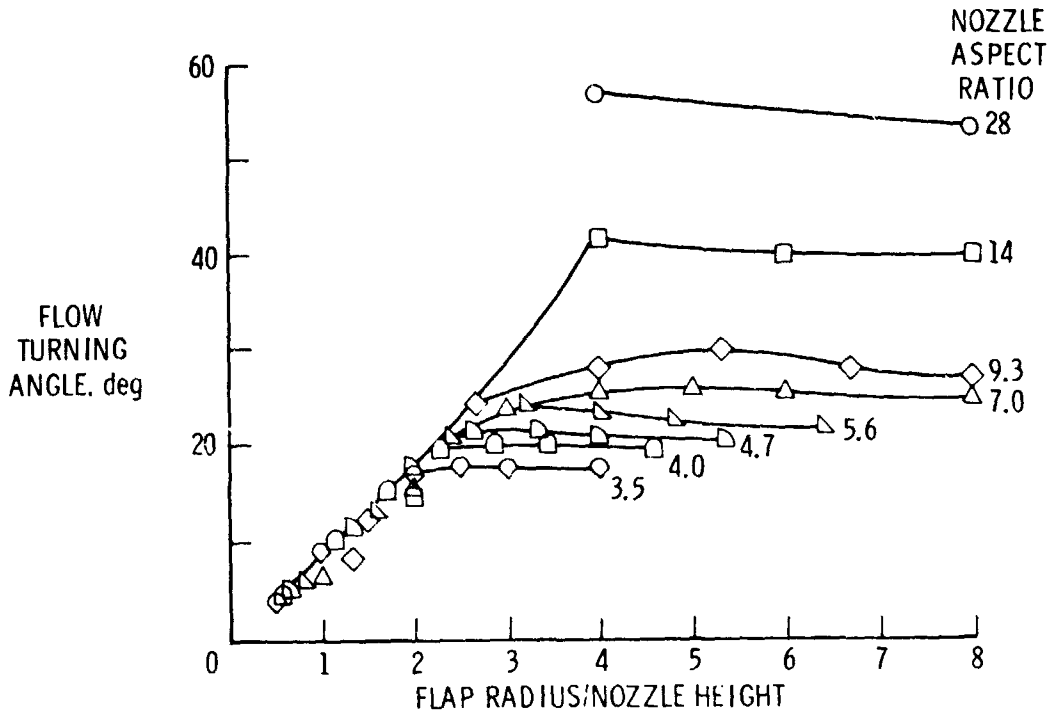

Figure 5.- Effect of flap radius on flow turning for a pressure ratio of 1.4 and a constant run length.

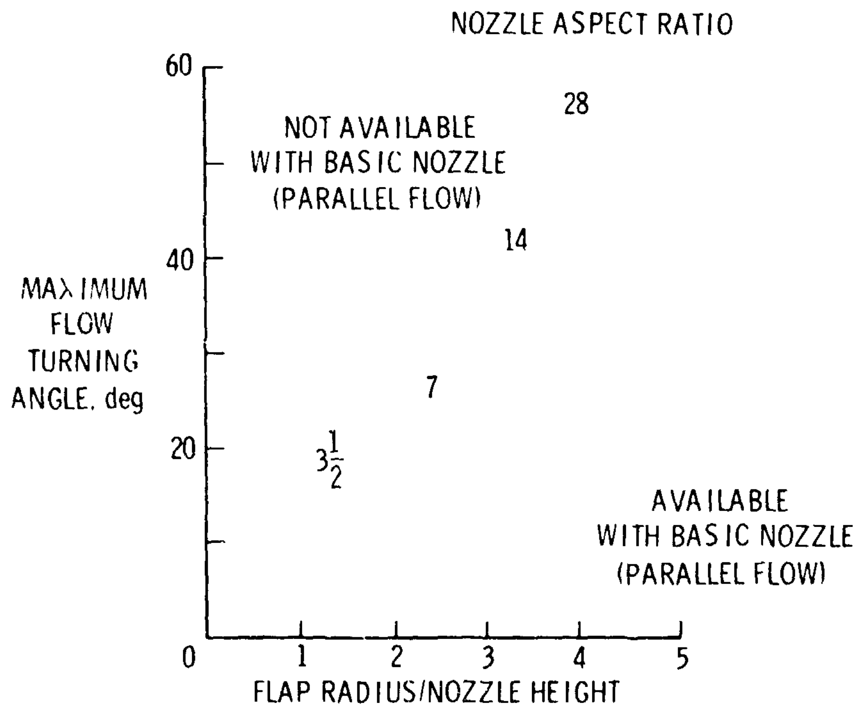

Figure 6.- Effect of flap radius on maximum flow turning for a range of pressure ratio and run length.

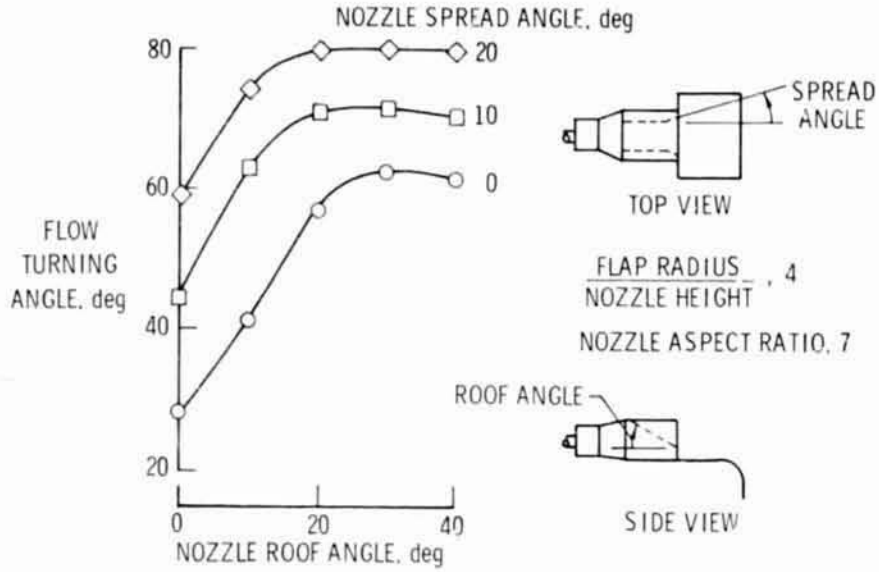

Figure 7.- Effects of nozzle roof angle and spread angle on flow turning.

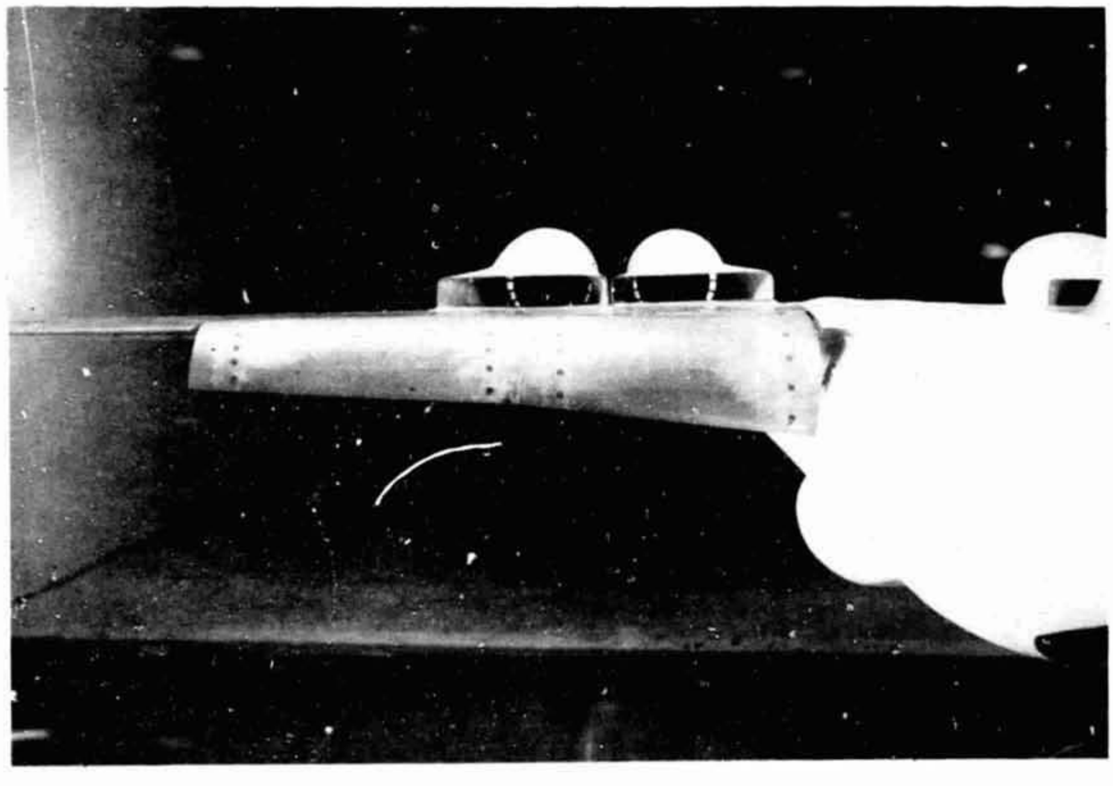

Figure 8.- Four-engine USB model with moderate-radius flaps in the Langley V/STOL tunnel.

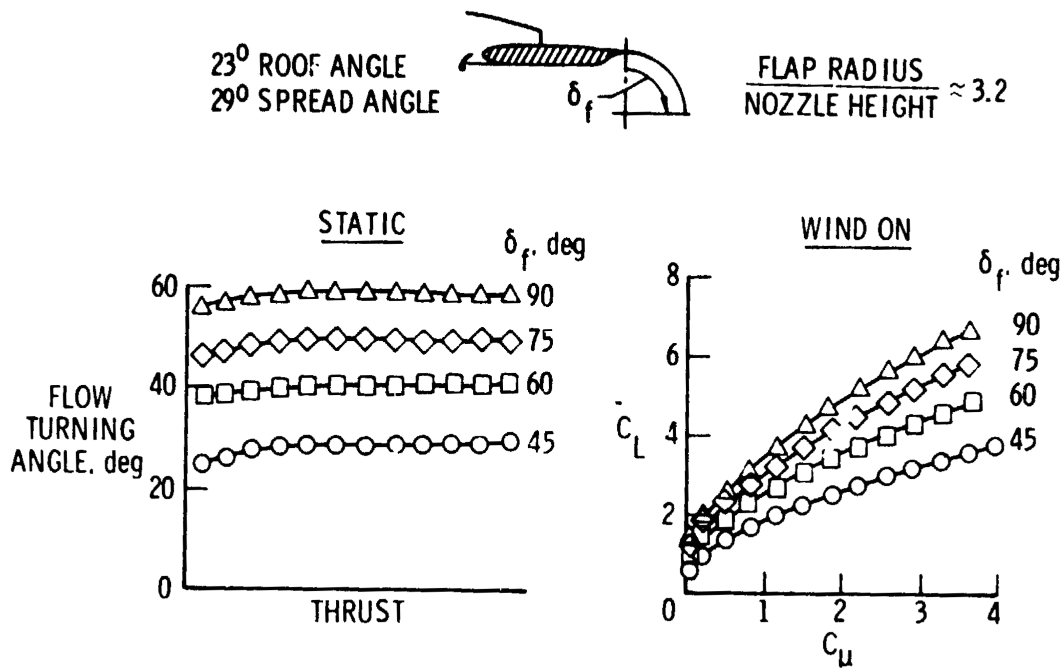

Figure 9.- Static turning and wind-on lift for moderate-radius flap. $\alpha = 0^{\circ}$.

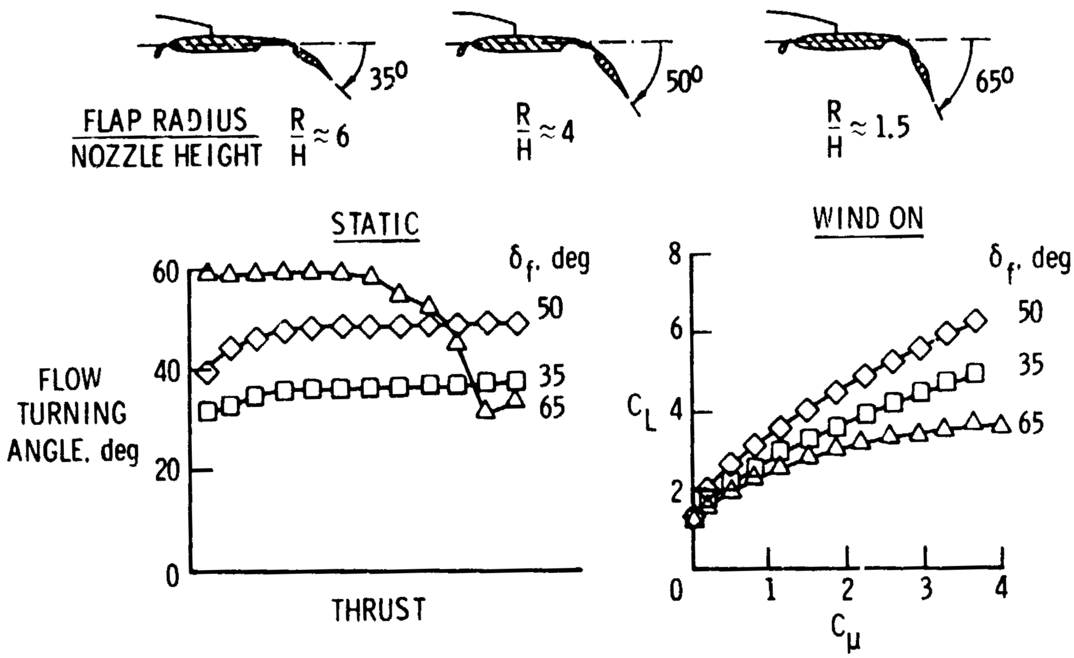

Figure 10.- Effect of flap radius and deflection on static turning and wind-on lift. $\alpha = 0^{\circ}$.

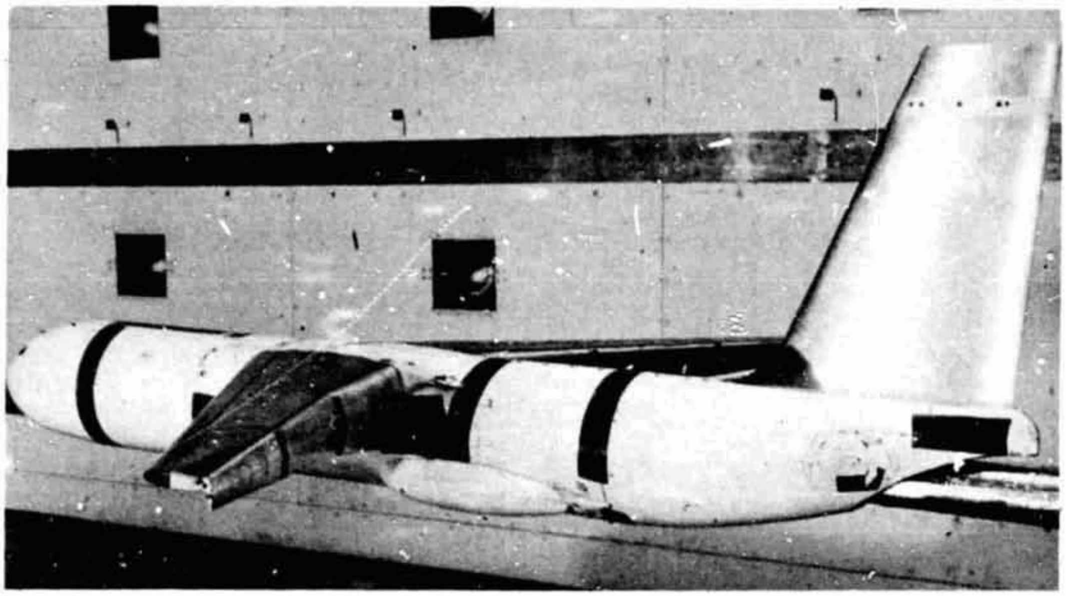

Figure 11.- Full-span leading-edge-blowing model with small-radius flaps in the Langley V/STOL tunnel.

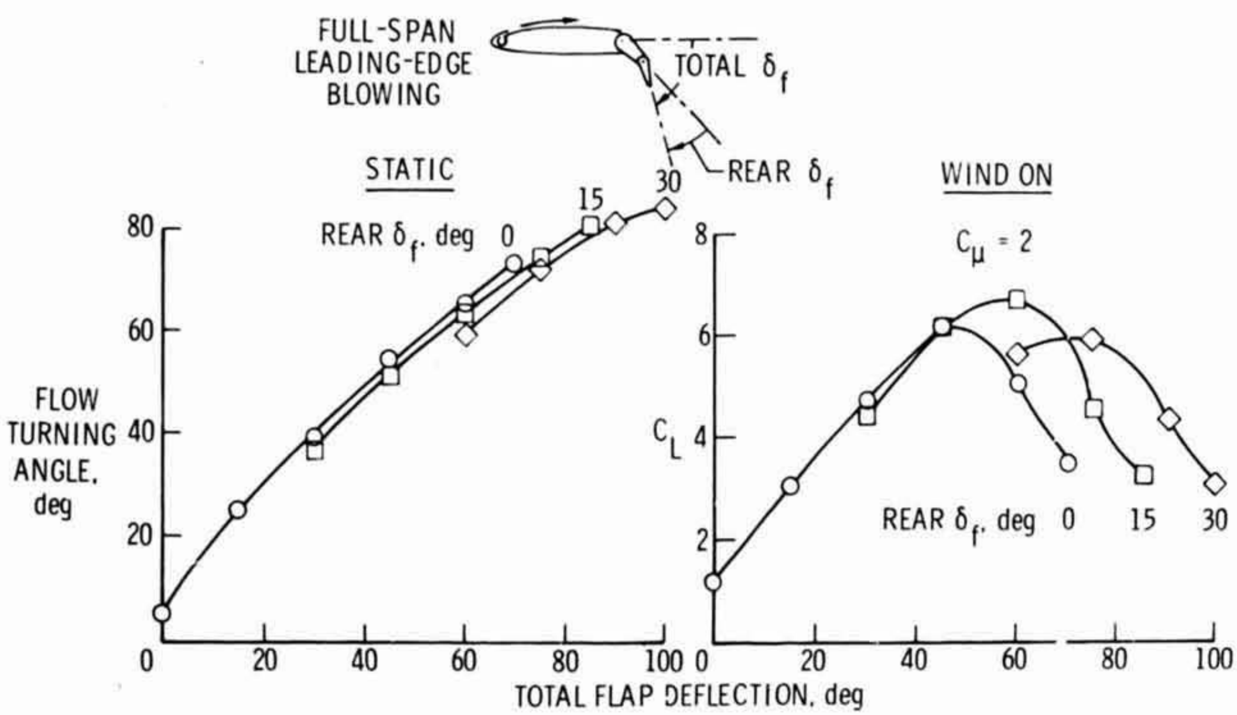

Figure 12.- Static turning and wind-on lift for small-radius flap. $\alpha = 0^{o}$.