Further Development of Pneumatic Thrust-Deflecting Powered-Lift Systems

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Wind-tunnel evaluations of two pneumatic thrust-deflecting powered-lift systems have been conducted to develop the capabilities of interchangeable thrust recovery and reversal as well as longitudinal pitch trim. A circulation control wing/vectored thrust configuration employed underwing Pegasus-type nozzles to redirect the horizontal thrust component as needed for STOL operation and to provide nose-up pitching moment for trim. Although they provided a vertical thrust component to lift, the vectoring nozzles were relatively ineffective in augmenting aerodynamic lift. A circulation control wing/over the wing blowing configuration pneumatically deflected engine thrust for additional high lift beyond that provided by CCW alone. It also allowed pneumatic conversion of the resultant force along the flight path from thrust recovery to thrust reversal as required for takeoff or approach. Both configurations thus offer possible solutions to STOL operational problems, one by pneumatic/mechanical means and the other primarily pneumatically.

Introduction

A NUMBER of recent model- and full-scale investigations have verified the pneumatic thrust-deflecting and lift-augmenting capabilities of the blown circulation control wing (CCW) high-lift system synergistically combined with such powered-lift propulsion systems as upper-surface blowing (USB) or over the wing (OTW) blowing.[1-3] The resulting CCW/USB and CCW/OTW configurations have experimentally yielded very high circulation lift values, the capability to pneumatically deflect engine exhaust for additional lift augmentation, and the potential for significant STOL performance. However, accompanying these benefits, certain problem areas have arisen that must be addressed prior to this application to effective STOL aircraft. These problems are related directly to the use of deflected thrust as a portion of the lift component and to the longitudinal location of that thrust component on the aircraft.

Associated with nearly every type of powered-lift system augmenting wing lift by engine thrust deflection or pneumatic blowing is the problem of trimming the aircraft longitudinally in pitch. This arises because of the extreme aft loading of the wing due either to high suction over the flap surfaces or the far-aft vertical component of the deflected thrust. Further difficulties occur due to the very low freestream dynamic pressure at which these aircraft are able to fly and the resulting lack of aerodynamic control forces. Frequently, the solution has been enlarged multielement tail surfaces employing both leading- and trailing-edge devices. The resulting weight, complexity, and oversizing relative to cruise requirements may cause the powered-lift STOL capability to be seriously compromised.

A second problem inherent with thrust-deflecting powered-lift systems is the higher engine thrust levels necessary to yield the desired high-lift levels; these frequently result in large thrust recovery along the flight path. While such is quite desirable for takeoff, climbout, or wave-off, it is not acceptable on approach. Here, short landing ground rolls are achieved by very low approach speeds down steep glide slopes and require the equilibrium of aircraft thrust, drag, and weight components along the flight path. Failure to achieve this equilibrium results in reduced thrust and powered lift, shallower glide slopes, and overall reductions in STOL performance. Thus, what is needed to resolve both of these problems is a thrust-deflecting system that can interchange thrust recovery with high-drag generation, while at the same time maintain large lift values and pitch trim without unacceptable tail complexity. Development of such systems has been the objective of recent investigations at Lockheed-Georgia Company. These will be presented in the following discussion.

Powered-Lift System Characteristics

A typical thrust-deflecting CCW/USB powered-lift system[2,3] is shown in Fig. 1. The CCW/OTW system developed at Lockheed-Georgia[1] is quite similar, except that the engine is mounted above the wing on a pylon to avoid cruise drag due to viscous scrubbing of engine exhaust over the wing upper surface. For both configurations, excellent flow entrainment over the round or near-round CCW trailing edge yields effective thrust deflection and increased circulation lift produced by the blowing momentum. At relatively low thrust and blowing levels, both CCW-based concepts yield roughly the same lift (see Fig. 2, where $C_T = T/qS$ and $C\mu =$ blowing momentum$/qS$), but that lift is considerably higher than when the system employs a large single-slotted mechanical flap to deflect the thrust, as shown. Figures 3 and 4 depict the increased lift that can be produced by increasing the engine thrust and blowing momentum. At zero incidence, a lift coefficient greater than 7 can be obtained. This is usable lift if there is sufficient CCW blowing to turn the thrust and offset its horizontal component so that the net drag is zero in the approach mode and if it can be trimmed longitudinally. However, these figures emphasize the above-mentioned problems. In Fig. 3, higher C_T yields large thrust recovery (negative C_D) at reduced blowing levels, making this condition unacceptable for approach flight. Figure 4 shows the large nose-down quarter-chord pitching moments resulting from the aft wing loadings due to higher thrust or blowing. If not reduced, these moments will require huge downloads generated by complex horizontal stabilizers and will result in lift loss to trim. These figures demonstrate that there is a substantial need to develop a powered-lift configuration which can still maintain the high lift levels, but can also trim out the associated pitching moments and offset the large horizontal thrust recovery values.

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CCW/Vectored Thrust Concept

One means of accomplishing the above was postulated to be the combination of CCW with an underwing-mounted engine with Pegasus-type vectoring nozzles, as shown in the model schematic of Fig. 5. The concept involves locating the nozzles so that they will entrain and augment the wing flowfield and produce (with rapid nozzle rotation) variation in the flight path horizontal force from thrust recovery on takeoff to thrust offset ("drag" generation) on steep approaches. (An actual aircraft would, of course, support the engine on a much smaller pylon than on the generic model test configuration shown.) An additional benefit could be generation of a nose-up pitching moment for longitudinal trim if the nozzles were located far enough forward under the wing to add a thrust-induced moment about the center of gravity. To develop this concept, a small-scale wind-tunnel investigation was undertaken; the details and findings of that effort are the subject of the present paper.

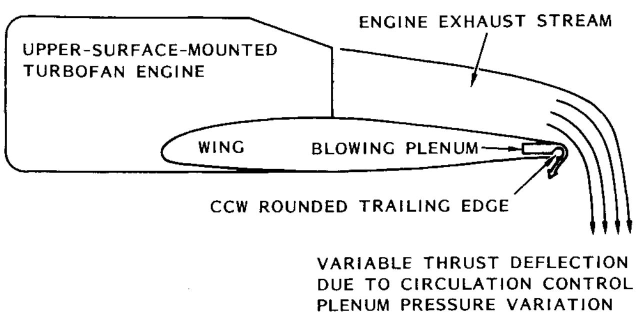

Fig. 1 CCW/USB pneumatic thrust-deflecting powered-lift system.

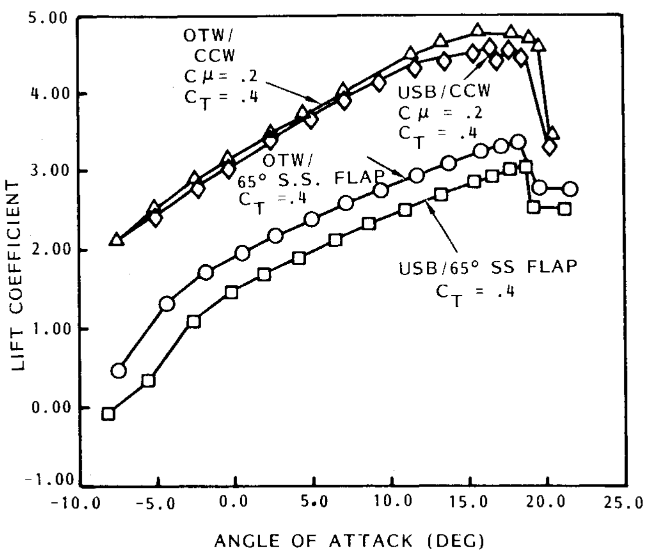

Fig. 2 Comparison of OTW and USB configurations combined with mechanical or round-trailing-edge CCW flaps.[1]

Small-Scale Tunnel Investigations

Model

With major emphasis being a confirmation of the above benefits of the CCW/vectored thrust (VT) configuration, an existing small-scale powered-lift model was modified and tested in the Lockheed-Georgia 30×43 in. Model Test Facility (MTF). The model used was the same generic powered-lift model empoyed in Ref. 1 and thus allows direct comparison of results. Propulsion and high-lift systems were removable to allow alternate configurations to be installed. The 24 in. semispan CCW/VT model is shown installed in the MTF in Fig. 6, with more detail of the wing and flap shown in Fig. 7. Note from Fig. 5 that a system of interchangeable plenums representing the engine nacelle allowed large variations in the nozzle horizontal location ($-0.10c \leq x_{noz} \leq 1.16c$) and vertical displacement below the wing ($-0.54c \leq z_{noz} \leq -0.29c$). (These are the locations of the nozzle center of rotation; the nozzle exit planes rotate about this center on a 2.56 in. radius.)

The CCW airfoil profile employed here is a variation on the pure round trailing-edge configuration commonly being used in high-lift and rotary wing applications.[4,5] The CCW flaplet seen in Fig. 7 is a small-chord, flat-surface flap with 14 deg half-angle that deflects about the center of the round CCW trailing edge. Thus, when the flaplet is deflected to the 86.7 deg position employed in this test, the CCW jet can turn a maximum of 100.7 deg from the aft horizontal. The flaplet's purpose is to keep the blowing jet deflection at a constant angle in the vicinity of the strongest engine nozzle influence,

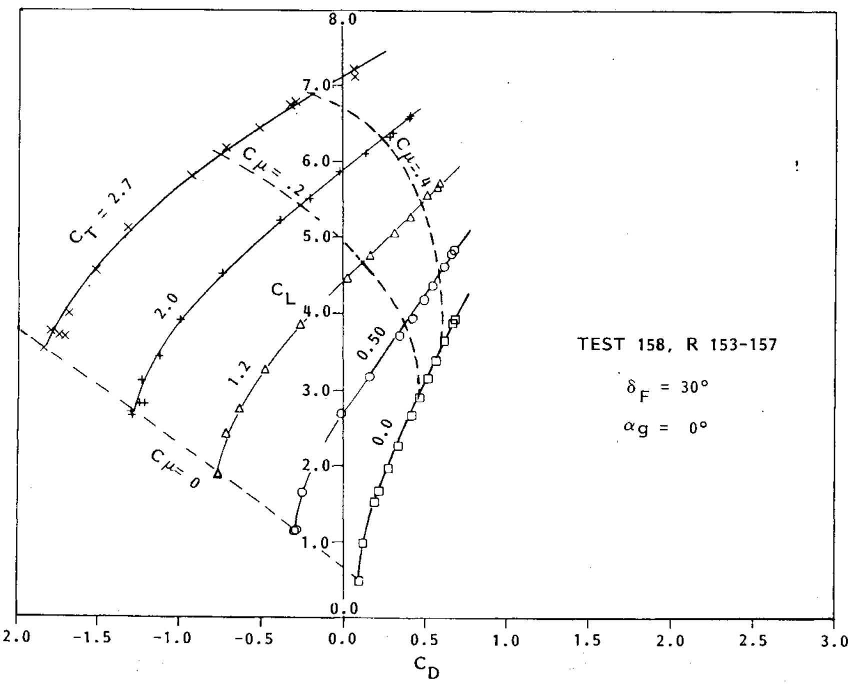

Fig. 3 Drag polars for CCW/OTW configuration with CCW flap.

rather than allow the jet separation angle to vary with momentum coefficient C_μ as it normally would for a round-trailing-edge CCW. This means, of course, that it yields the high-lift augmentation with low C_μ only until the jet turning angle reaches the flaplet upper surface; at higher C_μ, it then behaves as a conventional blown flap.

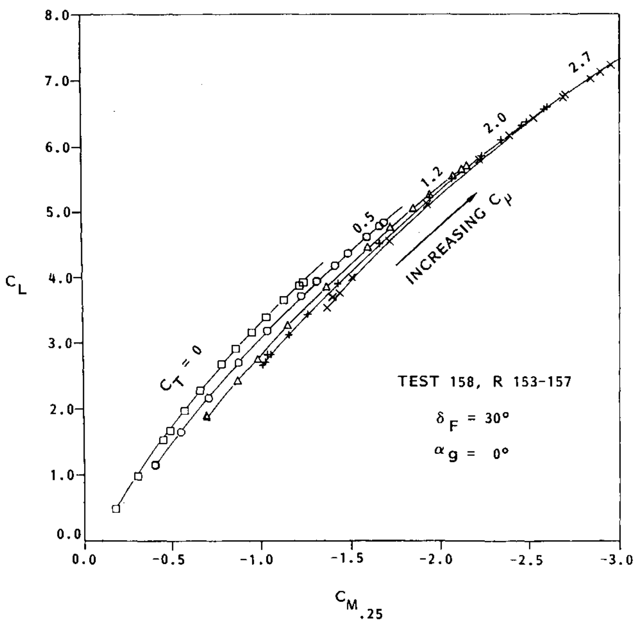

Fig. 4 Pitching moment generated by CCW/OTW configuration with CCW flap (tail-off).

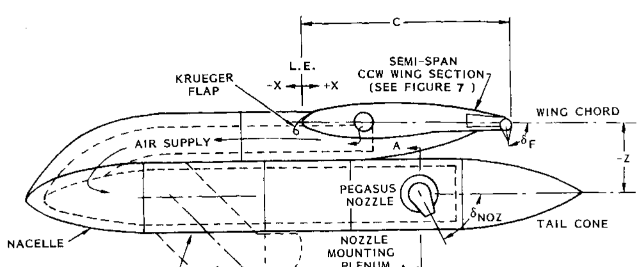

Fig. 5 Schematic of CCW/VT model.

Experimental Apparatus and Test Conditions

The 24-in. semispan CCW/VT model was mounted on the MTF floor balance located on the 43 in. lower wall of the tunnel. The geometric full-span aspect ratio was 5.47 based on an undeflected cruise chord length of 8.78 in. The jet blowing slot height was 0.015 in. Corrected freestream dynamic pressure of approximately 8 psf (corresponding to flight speeds of around 50 kn, typical of these powered-lift aircraft) yielded a test Reynolds number of 0.35×10^6 and allowed a larger range of momentum and thrust coefficients to be evaluated. Thrust coefficients T/qS were determined from static thrust calibrations conducted at each nozzle angle. The nozzle exit area was scaled so that the sum of both nozzle areas was equivalent to the total engine exit area of the semispan powered-lift model of Ref. 1. Momentum coefficients ($C_\mu = \dot{m} V_j / qS$) were determined from measured jet mass flow $\dot{m}$ and isentropic jet velocity V_j calculated from measured pressure ratio and temperature. Freestream dynamic pressure was corrected for

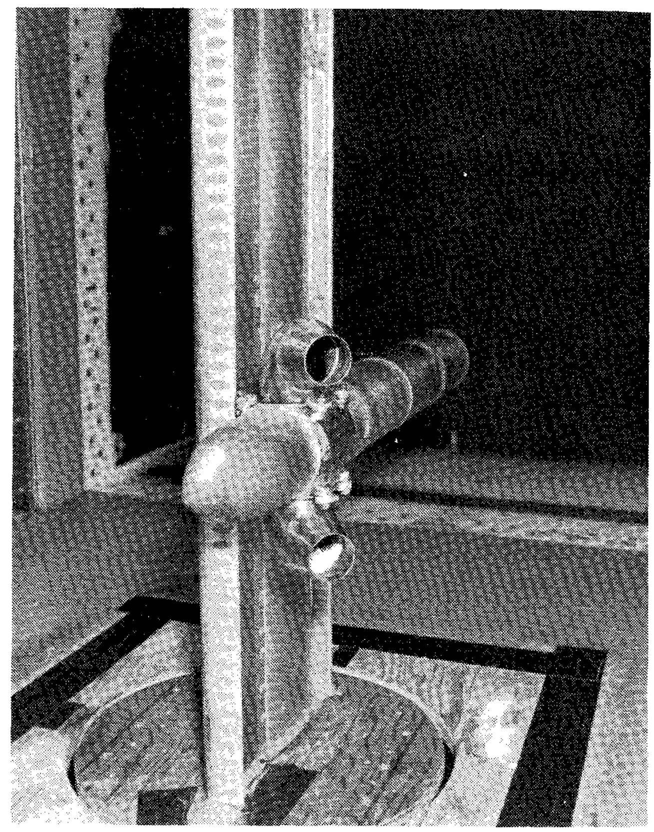

Fig. 6 Aft-lower-surface view of CCW/VT model ($\delta_F = 86.7$ deg, $\delta_{LE} = 60$ deg, $\delta_{noz} = 45$ deg, $x_{noz} = 0.84c$).

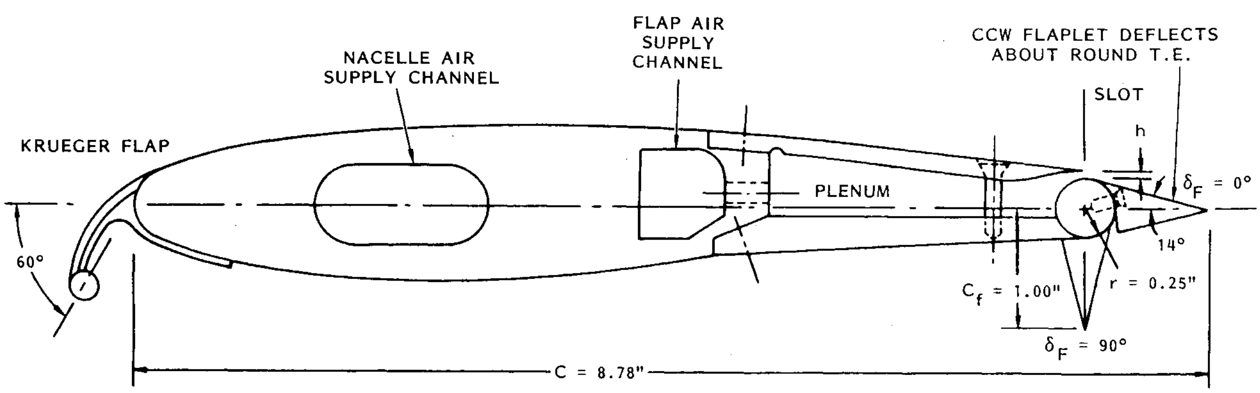

Fig. 7 CCW airfoil profile with deflecting flaplet ($h = 0.015$ in).

tunnel blockage, while incidence as well as force and moment coefficients were corrected for tunnel wall interference.[6]

Results and Discussion

Based on previous experience with the powered-lift characteristics of this semispan CCW wing section, the majority of the data to be discussed were recorded at a typical blowing coefficient $C_\mu = 0.22$, geometric angle of attack (uncorrected) $\alpha_g = 0$ deg, and flaplet deflection angle $\delta_F = 86.7$ deg. Typically, at each nozzle location, a range of thrust coefficients was run for each of a series of nozzle deflection angles δ_{noz}. The following performance comparisons resulted.

Nozzle Deflection Variation

Variations in lift, drag, and pitching moment with thrust coefficient and nozzle deflection are shown in Figs. 8–10 for an aft and lower nozzle location. The linear variation of lift with thrust in Fig. 8 emphasizes the vertical thrust component $C_T \sin\delta_{noz}$. The power-on drag polars of Fig. 9 further emphasize these effects of nozzle deflection, as the thrust component rotates from thrust recovery to lift to thrust reversal (note that the thrust coefficient increases radially outward along each constant-nozzle-angle curve). This figure confirms the possibility of this type of system providing strong in-flight horizontal force control. Figure 10 shows that for this aft nozzle location, increased thrust increases nose-down pitch for all nozzle angles except those nearly horizontal and aft facing. In this location, vectored thrust does not appear to be a solution to the pitch problem being investigated.

Variation with Blowing

Whereas the above variations are, for the most part, linear with thrust (indicating little aerodynamic entrainment or augmentation), Figs. 11–13 show the variation in forces and moment with CCW blowing coefficient at a constant thrust level. Here, the nonlinear curves indicate strong flow entrainment and augmentation far greater than the horizontal and vertical components of slot thrust. These CCW slot thrust components are actually negligible here, since they are "absorbed" in the viscous jet mixing flow entrainment process at the round trailing edge downstream of the slot. For comparison, data for the CCW alone without the nacelle are also plotted. The CCW/VT curves are of the same shape, but are displaced by nearly constant values, which represent the

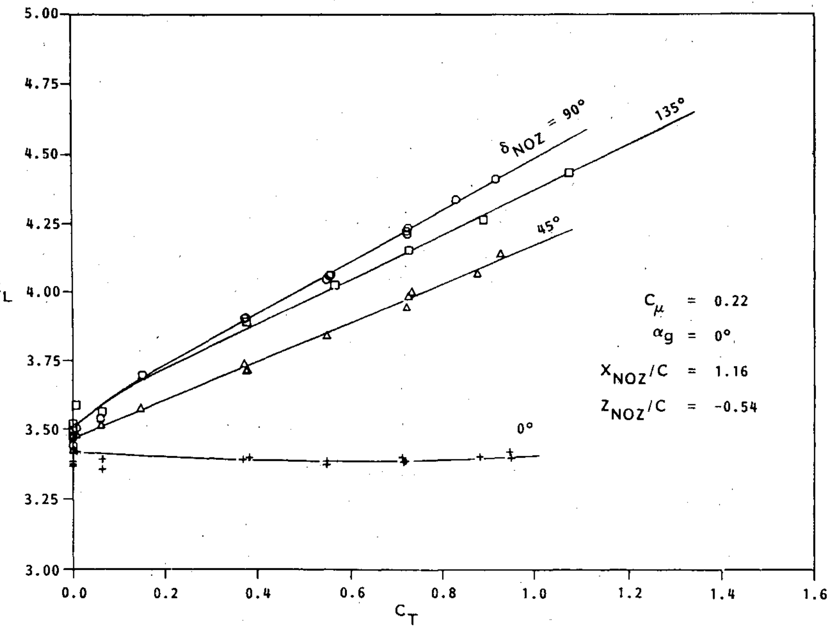

Fig. 8 Lift variation with thrust for aft nozzle location.

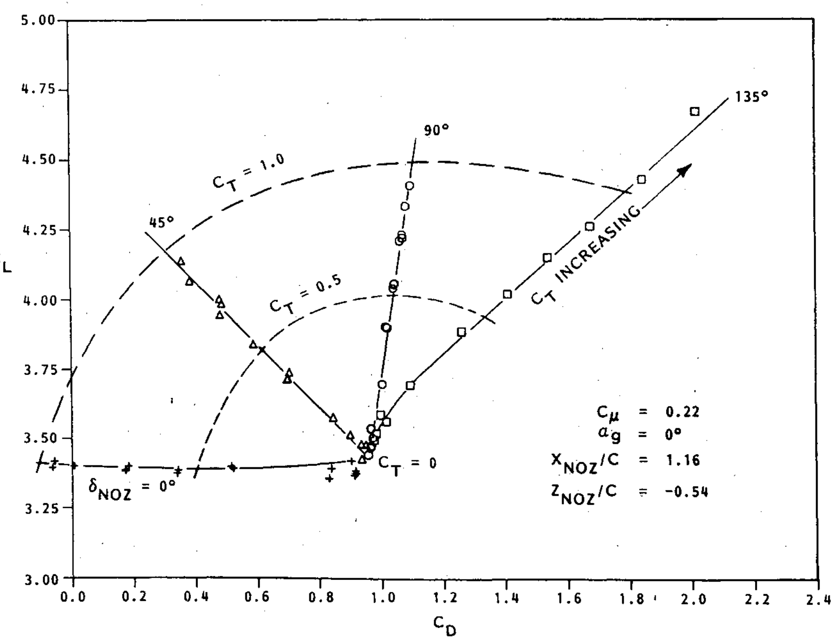

Fig. 9 Drag polars for aft nozzle location.

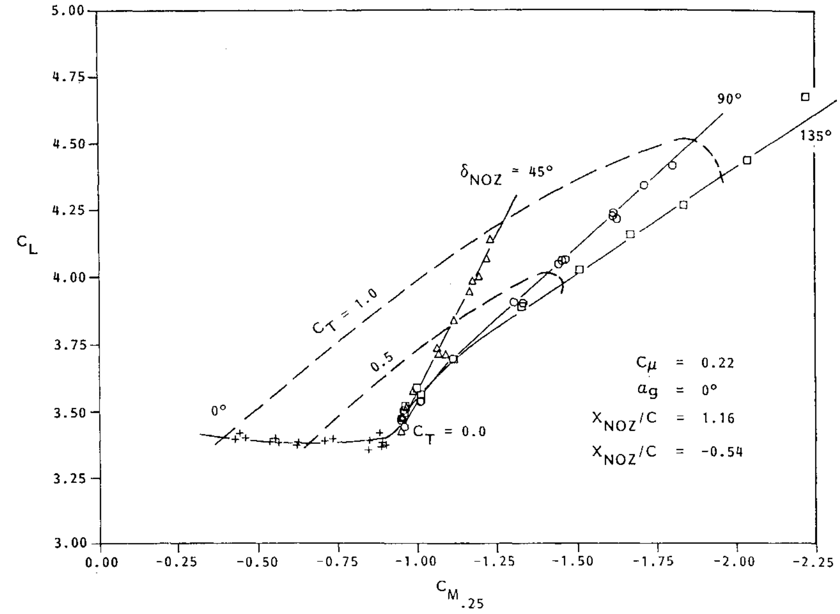

Fig. 10 Pitching moment variation with thrust for aft nozzle location.

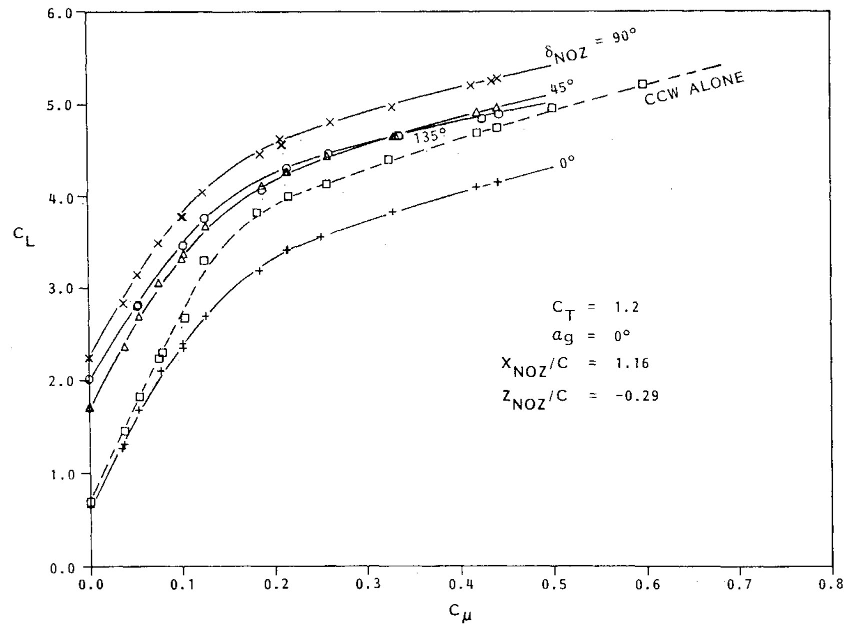

Fig. 11 Lift variation with CCW blowing and nozzle deflection.

respective horizontal and vertical nozzle thrust components. Note that for this moderate-aspect-ratio three-dimensional model, lift augmentation $\Delta C_L/C_\mu$ greater than 20 is produced for C_μ values up to 0.10 and that both drag and nose-down pitch increase with increased blowing.

Effects of Nozzle Location

Data were recorded for a number of nozzle vertical and horizontal locations. Whereas the vertical location produced relatively little variation in test results, this parameter is probably more important in ground clearance and structural considerations. However, horizontal nozzle movement produced significant variations in certain parameters. Figure 14 presents data for the most forward nozzle location evaluated, $-0.10c$. The variations of lift and drag with thrust for this location are not shown because they were linear and very similar to Figs. 8 and 9. However, as can be seen in Fig. 14, the forward nozzle position results in less than full recovery of the vertical thrust component as lift. This is because the engine exhaust counteracts the streamline deflection and prevents circulation around the wing. This is seen most clearly for the zero nozzle deflection case, where lift loss results from increased aft thrust even though the thrust component is in the horizontal direction.

The major effect of forward nozzle location is seen in the pitching moment data of Fig. 14, as compared to that of Fig. 10. For all but the 135 deg nozzle deflection (where the thrust vector apparently passes below the c.g.), increasing the vertical thrust vector at the forward locations reduces nose-down pitch. However, even with this thrust location, the pitching moment due to CCW with $C_\mu = 0.22$ was never totally trimmed ($C_M = 0$) by the thrust vector. (Admittedly, no horizontal tail contribution is included and that would certainly provide some nose-up capability, but the intent here was to trim the configuration using the thrust contribution.)

A summary of all the data taken for a number of horizontal nozzle locations is presented in Figs. 15–17 for the nozzle located $-0.54c$ below the wing chord. Here, incremental forces and moments due to a typical thrust coefficient of 0.5 are shown at a constant CCW blowing value of 0.22. These increments are the coefficients at $C_T = 0.5$ less those at $C_T = 0$ and, thus, represent the change due solely to the thrust compo-

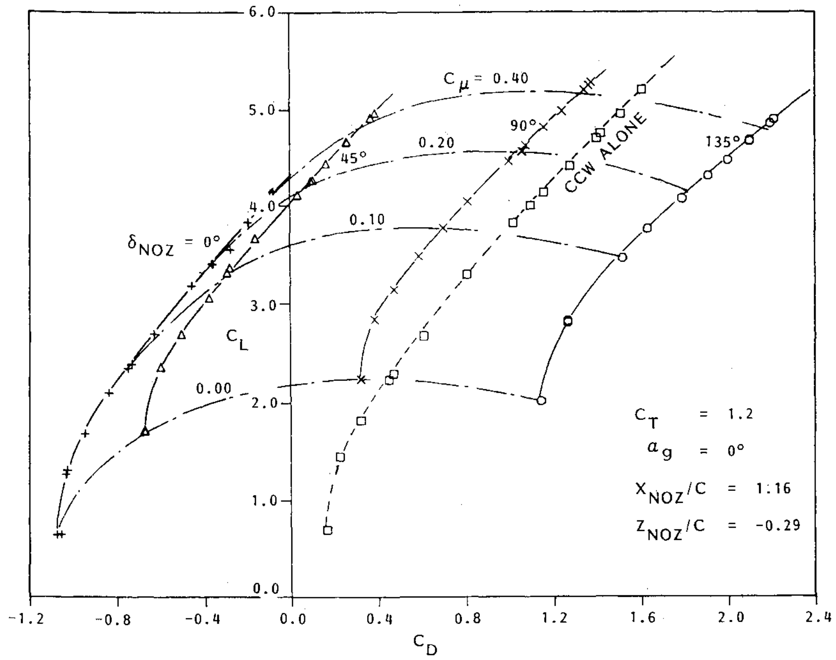

Fig. 12 Effect of blowing and nozzle rotation on CCW/VT drag polars.

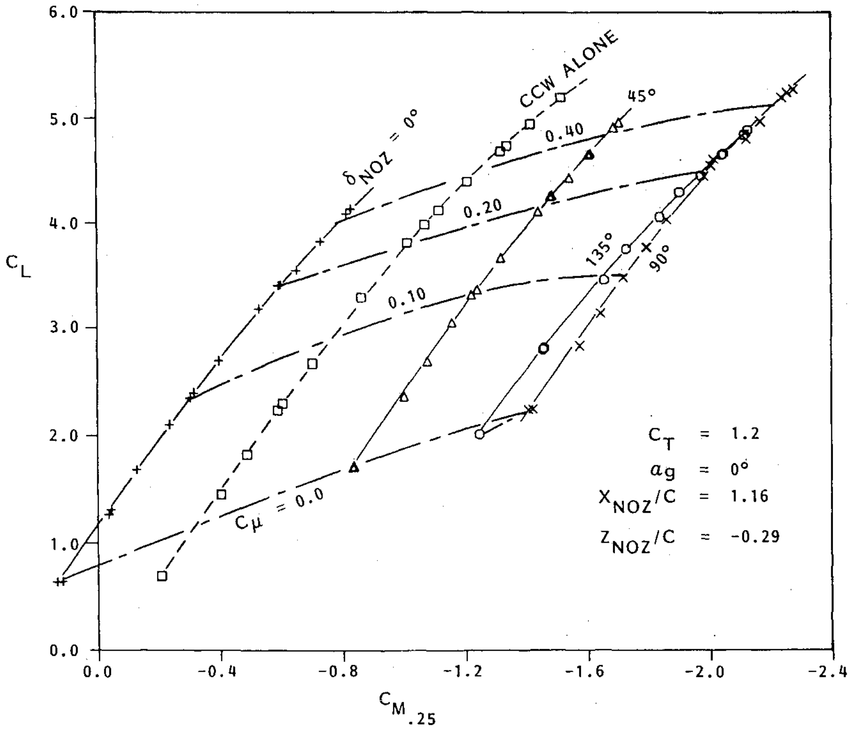

Fig. 13 Pitching moment variation with CCW blowing and nozzle deflection.

nent. Thrust coefficients up to 1.5 were evaluated and the increments due to higher thrust are roughly proportional to those shown here, based on linearity with C_T (see Figs. 8 and 9).

Incremental lift increases slightly as the nozzles are moved aft. As mentioned above, the forward location counteracts wing circulation, while it is seen here that the aft positions tend to augment it slightly by entraining the wing flowfield. If lift augmentation due to thrust is calculated based only on the vertical component of thrust, rather than total C_T, the results shown in Table 1 are seen for the horizontal location extremes when the nozzle is located vertically at $-0.54c$.

While the lift augmentation due to the vertical thrust component should be zero in Table 1 for $\delta_{noz} = 0$ deg, in actuality a negative lift increment is generated at all nozzle locations (as Fig. 15 shows) due to interference with wing upwash and circulation when the nozzles are undeflected. The augmentation exceeds $+1.0$ only at the aft nozzle location, due to slight entrainment of the wing flowfield there. The maximum lift augmentation of only 1.29 is due to the fact that the CCW alone is entraining most of the flowfield over the wing (Fig. 11 shows $\Delta C_L/C_\mu$ values greater than 20) and little remains for the thrust to entrain.

Drag changes in Table 1 and Fig. 16 shows relatively little effect of nozzle longitudinal location, but large effects of nozzle deflection angle, with maximum augmentations of -1.11, -0.91, and 1.39 for 0, 45, and 135 deg, respectively, occurring at intermediate longitudinal locations. Note that absolute values of drag augmentation greater than 1.0 (as well as the nonzero values at 90 deg deflection) are due to changes in lift-induced drag, in addition to the horizontal thrust component. For both the lift and drag data above, increments for the nozzle vertically closer to the wing were slightly less than those shown. The only major effect of vertical distance was in changing the length of the moment arm to the c.g., with a corresponding change in the pitching moment contribution.

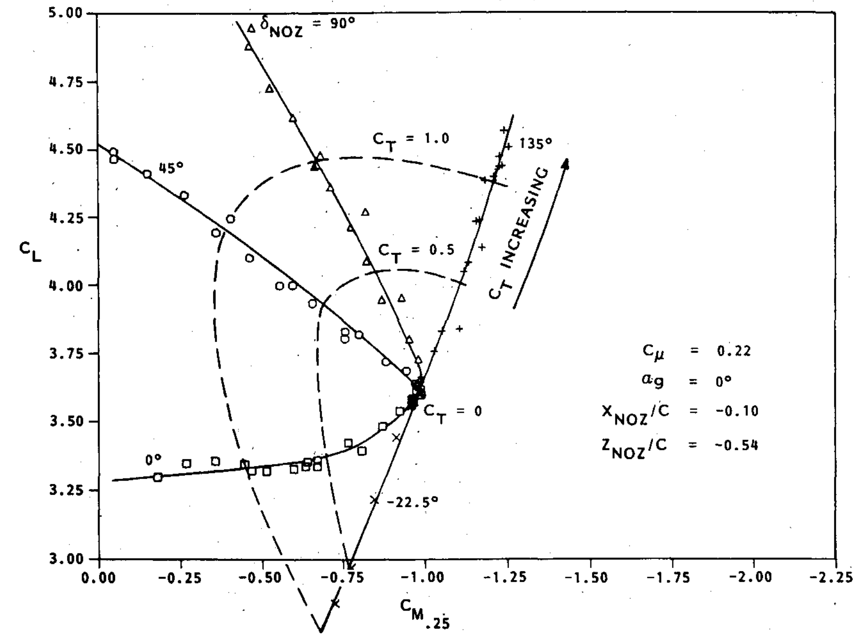

Fig. 14 Pitching moment variation with thrust for forward nozzle location.

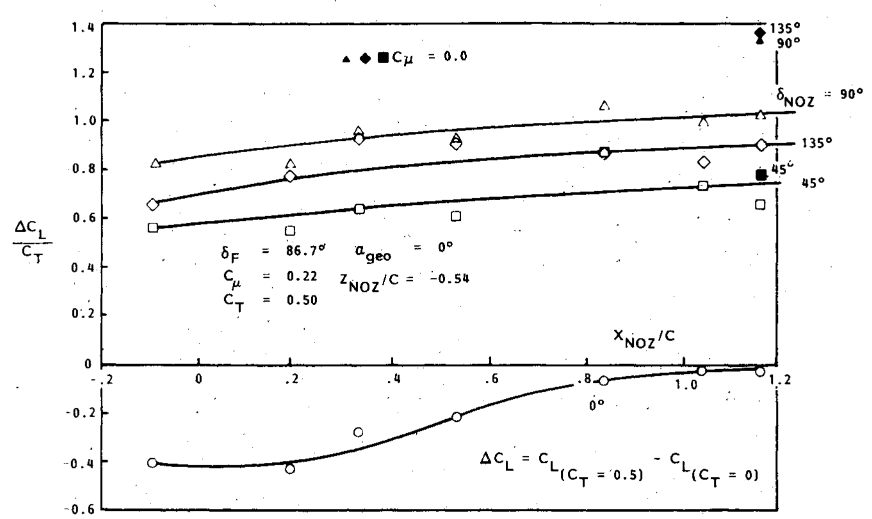

Fig. 15 CCW/VT incremental lift variation with horizontal nozzle location.

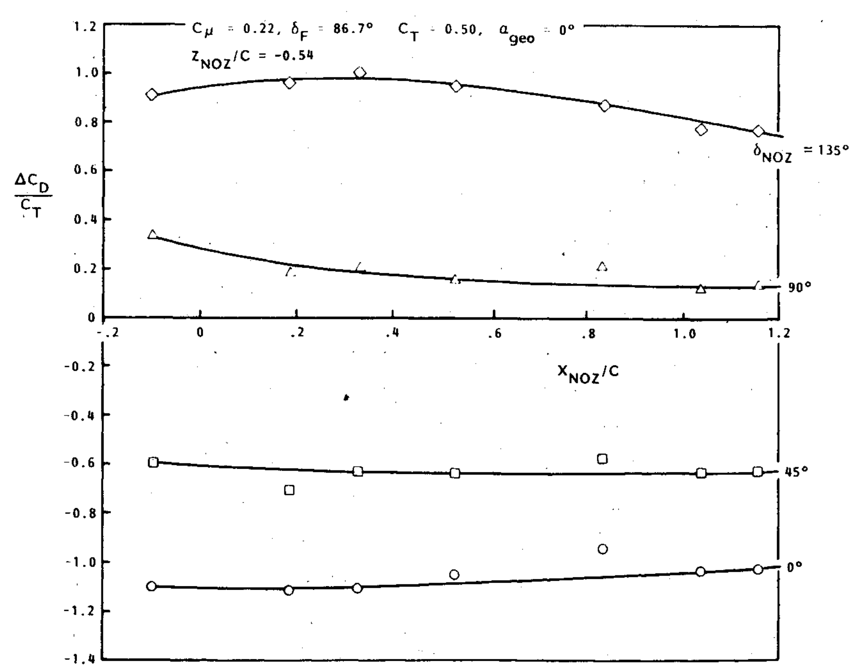

Fig. 16 CCW/VT incremental drag variation with horizontal nozzle location.

Figure 17 confirms that nose-up pitching moment is indeed generated at forward and lower nozzle positions with the smaller nozzle deflections. This is obviously due to maximizing the moment arm when the thrust vector is ahead of and below the c.g. (these results will vary if the c.g. is moved from the wing chordline to a lower position in the aircraft fuselage). However, at this C_μ, the pitching moment due to CCW alone that must be trimmed is about -1.0 (see Fig. 13) and thus a C_T of 1.5–1.7 with a forward nozzle location and a deflection of 0–45 deg are needed to trim (tail contribution not considered). From the above, it appears that, of all the configurations tested, there is no nozzle deflection/position combination that provides large lift, drag, and nose-up pitch simultaneously.

Augmentation without CCW Blowing

Since lift augmentation due to thrust deflection was minimal for the CCW/VT configuration above due to CCW flowfield entrainment, additional data was taken without blowing on the CCW flaplet. Figure 18 shows the lift variation with C_T, where the separated flowfield from the highly deflected flaplet is entrained by the deflected thrust, especially

Table 1 Lift augmentation due to vertical thrust deflection

	$\Delta C_L / C_T \sin\delta_{noz}$		$\Delta C_D / C_T \cos\delta_{noz}$	
δ_{noz}, deg	$x_{noz}/c = -0.10$	$x_{noz}/c = 1.16$	$x_{noz}/c = -0.10$	$x_{noz}/c = 1.16$
0	—	—	−1.10	−1.03
45	0.79	1.05	−0.84	−0.90
90	0.83	1.03	—	—
135	0.93	1.29	1.28	1.09

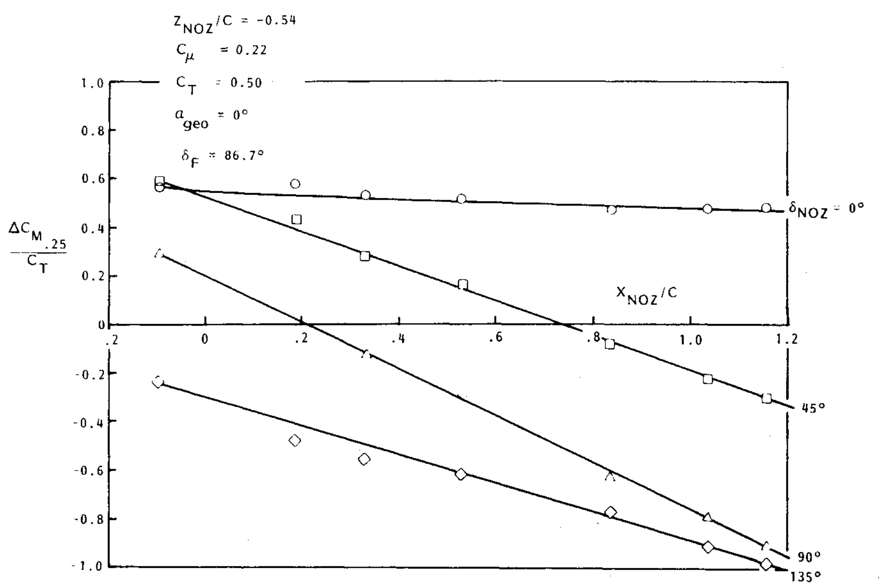

Fig. 17 CCW/VT incremental pitching moment variation with horizontal nozzle location.

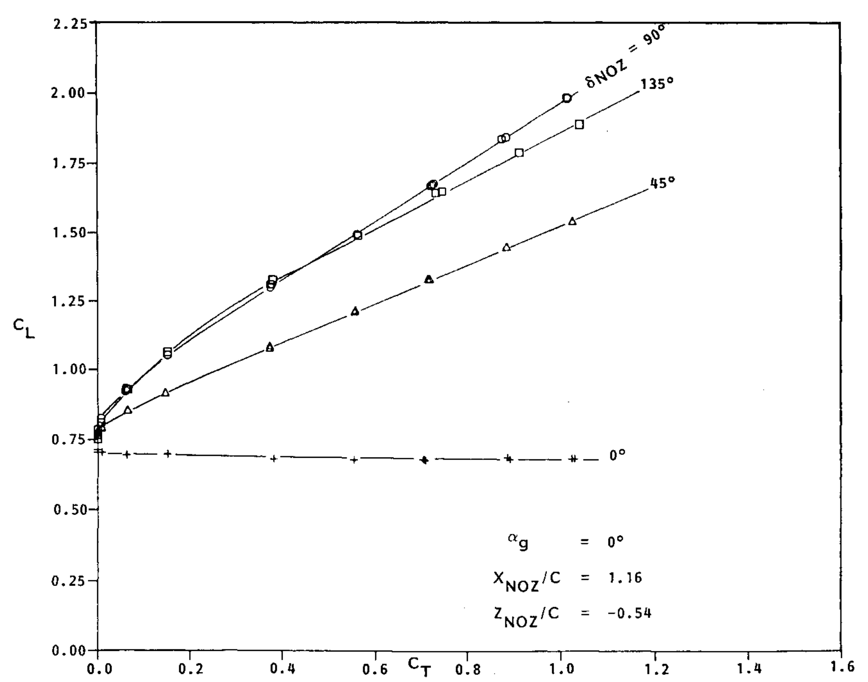

Fig. 18 Lift variation with thrust and nozzle deflection ($C_\mu = 0.0$).

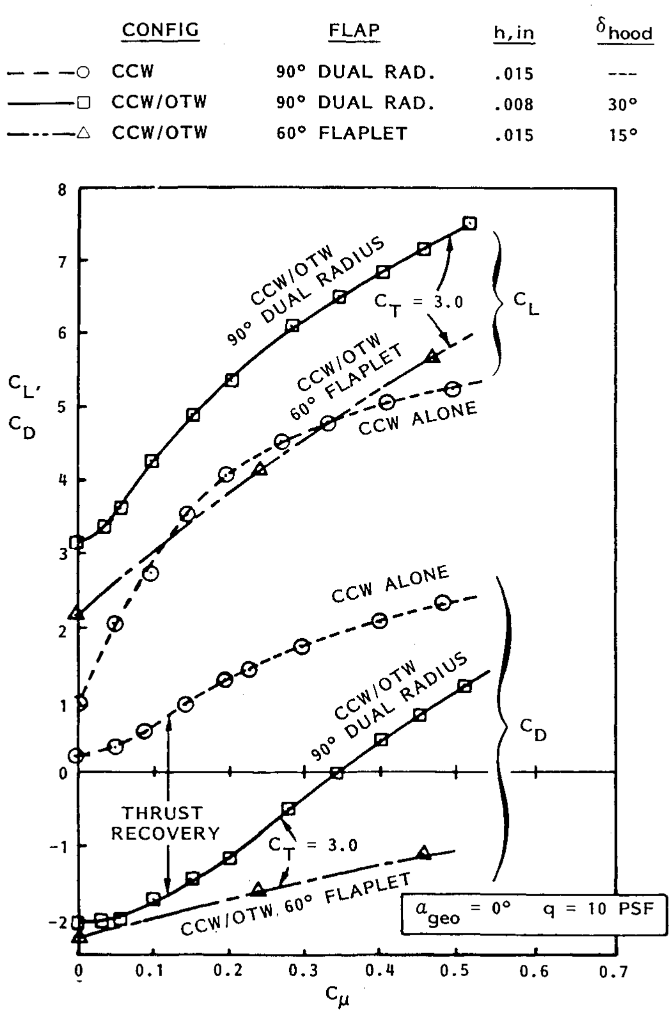

Fig. 19 Effect of CCW/OTW trailing-edge configuration on lift and drag.

with larger nozzle deflection angles. Figure 15 (solid symbols) verifies these increased lift increments, which correspond to lift augmentations of 1.14, 1.29, and 1.93 for 45, 90, and 135 deg nozzle deflection, respectively. These are appreciable increases over the values when $C=0.22$, but it must be remembered that the overall lift levels at $C_\mu=0$ are not large, so these larger augmentations of unblown lift may still not yield large STOL potential.

Alternative Powered-Lift System

In the CCW/VT configuration, relatively little aerodynamic lift augmentation resulted from thrust deflection since it was unable to produce much entrainment of the wing flowfield. An improved version of the CCW/OTW configuration presented in Ref. 1 has been developed and evaluated as an alternative to enhance lift augmentation and yield large thrust reversals (drag increases) to accompany that high lift at high-thrust settings. The configuration is similar to that shown in Fig. 1, except the engine nacelle has been relocated on a pylon above the wing and the round CCW trailing edge (or the CCW flaplet) has been replaced with a dual-radius CCW trailing edge like that developed in Ref. 4. This CCW trailing edge employs a second larger radius on the flap upper surface that, when deflected 90 deg, provides a maximum possible jet turning of 140 deg from aft horizontal, as compared to 104 deg for the CCW flaplet. This larger radius is better able to entrain the high-energy engine exhaust and deflect it further, thus eliminating significant thrust recovery.

A dual-radius CCW/OTW version of the above semispan model was evaluated in the MTF subsonic tunnel, using the same test techniques as for the CCW/VT model. Figure 19 compares the CCW/OTW employing both dual-radius and flaplet CCW trailing edges with a dual-radius CCW wing alone (same model but without the engine nacelle). Here, the dual-radius CCW alone produces the same or greater lift and much higher drag than the 60 deg flaplet OTW configuration at $C_T=3.0$. The influence of the large induced drag of the dual-radius CCW is apparent. When combined with OTW at $C_T=3.0$, the dual-radius CCW increases the lift coefficient by up to 2.5 over CCW alone, yet allows the horizontal force to

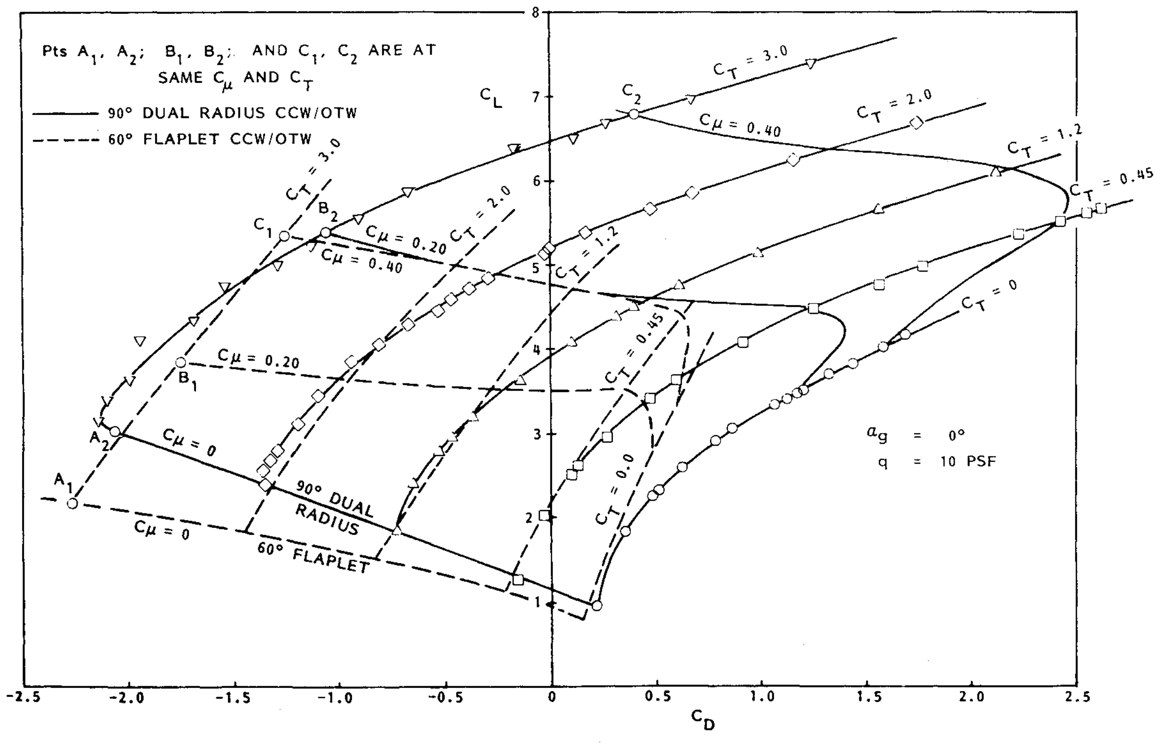

Fig. 20 Comparative drag polars for CCW/OTW configurations.

vary from $C_D = -2.0$ to $+1.2$ merely by varying the blowing coefficient and the resulting thrust deflection. The drag polars of Fig. 20 show this range of capability more completely, again in comparison with the CCW/OTW flaplet configuration. Further increase in thrust recovery (for takeoff or climbout) could be achieved by reduction in flap angle, while increased drag could be generated by increasing flap angle or simply by increasing angle of attack above the 0 deg reported here. The dual-radius CCW/OTW thus appears to be a very powerful means of obtaining high lift as well as strongly varying horizontal force from thrust recovery to high-drag generation. However, since it also yields nose-down pitching moment similar to that shown in Fig. 4, this configuration could perhaps benefit from the trim capability of forward-located vectoring nozzles.

Conclusions

The above investigations have evaluated the capabilities of two powered-lift configurations to address the problem of maintaining high lift in the presence of contradicting horizontal force requirements for STOL takeoff and landing, as well as the need to alleviate the nose-down pitch characteristics of this type of system. Important conclusions are:

1) The combination of CCW with Pegasus-type underwing nozzles allows mechanical thrust vectoring which can add an engine thrust component to the high-lift system and redirect the horizontal force component from thrust recovery to thrust reversal as needed. This arrangement may also be used to generate a nose-up pitching moment to offset the nose-down tendency of powered-lift systems.

2) Pegasus-type nozzles are relatively ineffective in augmenting aerodynamic lift by entraining the upper-surface flowfield, except when the CCW blowing is reduced or terminated and the flap flowfield begins to separate.

3) A dual-radius CCW in conjunction with an OTW engine arrangement allowed considerably greater jet turning angles, with the resulting higher lift augmentation and jet deflection. Increases in CCW blowing converted the engine exhaust from large thrust recovery to thrust reversal without any change in nozzle mechanical deflection.

Both configurations thus offer possible solutions to the STOL problems being addressed, one by the mechanical/pneumatic means of employing vectored thrust with CCW and the other by the pneumatic combination of a dual-radius CCW short-chord flap with an OTW engine arrangement.

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