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Controlling the Leading-Edge Vortex on the Vortex Flap Using Mass Injection

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Abstract

An attempt has been made to raise the drag reduction effectiveness of the leading edge vortex flap (LEVF) by using mass injection. The investigation was conducted in the 1.4m by 1.4m low speed wind tunnel and the 0.4m by 0.4m water tunnel of CARDC (China Aerodynamic Research and Development Center) on a half-span model of 74-degree delta wing incorporated a full span and constant chord leading edge vortex flap with the deflection of 30°, with the emphasis on exploring the optimal blowing configuration of "trapping" the leading edge vortex on the LEVF over an angle of attack range of -4° to +44° and at a Reynolds number of 2.27×10^6 and 8.8×10^3, respectively. The test included the force measurement and pressure distribution measurement in the wind tunnel and flow visualization in the water tunnel. The results indicate that the normal spanwise blowing (SWB), i.e. a single nozzle in the vicinity of wing leading edge, substantially enhances leading edge vortex and expands the vortex flow dominated region over the LEVF at high angles of attack. Multi-nozzle blowing at the wing root is a potential means of "trapping" the vortex over the LEVF and raising the benefits of LEVF, and to exploit its benefits in drag-reduction fully the further investigation is needed.

Nomenclature

C_p	pressure coefficient
C_r	wing root chord
C_x	drag coefficient
C_y	lift coefficient
C_μ	jet momentum coefficient
l	wing semi-span
x	chordwise distance to wing apex
α	angle of attack

Introduction

Vortex flap is a leading edge device of reducing the lift-induced-drag of the thin slender wing with high sweptback by controlling flow separation, in which it is desirable to allow the vortex be formed above a specially designed deflected flap surface to induce a forward component of force and hence compensate the drag increase due to the loss of leading edge suction, as a result the drag reduction is achieved (see Fig. 1)[1,2,3]

Unfortunatelly, it was found that the drag reduction is seriously restricted by the angle-of-attack, since the vortex moves inboard and upward and, therefore far from the surface of vortex flap with incresing of angle-of-attack[4]. So, to trap the vortex over the LEVF is one of the approaches of improving the benefits of LEVF at moderate and high angles of attack.

It is well known that the SWB is a effective aerodynamic measure of "trapping" the leading edge vortex over the wing surface[5,6]. This is accomplished by directing a concentrated jet from the wing-fuselage junction in a direction essentially parallel to the wing leading edge. Spanwise blowing can enhance the leading edge vortex generated naturally on the thin slender wings with high sweptback and delay its breakdown up to higher angles of attack, and consequently improve the high angle of attack characteristics (see Fig. 2). But it not easy to control the position of vortex due to the complex nature of the interference between the jet and vortex, and the effects of some blowing parameters, such as the nozzle location, the jet sweptback angle and etc., on the vortex flow are quite dependant on the wing geometry. So, it is even more difficult to trap the vortex over the vortex flap with such a small area and chord[7,8,9].

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The purpose of present investigation is to explore optimal blowing configuration with highest drag reduction effectiveness for a 74° delta wing through determining the effects of some relative blowing parameters and nozzle configurations on benefits of vortex flap in drag reduction by means of force characteristics and pressure distribution measurement in wind tunnel and flow visualization in water tunnel. The tests were conducted in 1. 4m by 1. 4m wind tunnel and 0. 4m by 0. 4m water tunnel of CARDC.

Experimental Details

Force testing was conducted in 1. 4m by 1. 4m wind tunnel with a half-span model of 74° delta wing-fuselage combination incorporated a full-span and constant chord vortex flap with the deflection of 30° at a Reynolds number of 2.27×10^6. For the pressure measurement a total of 73 pressure holes are distributed at six spanwise section which are at x/Cr = 0. 10, 0. 27, 0. 44, 0. 61, 0. 78 and 0. 95, with 3 holes for the section I, 10 holes for the section II and 15 holes each for the rest sections, and the sixth pressure hole for each section is located on the hinge line of LEVF. The fuselage is a simple cylinder with a faired nose, in which a air chamber is included to supply the compressed air for SWB. Fig. 3 illustrates the geometry of the model.

The model was suspended on a four component balance which was mounted on the turntable in the ceiling of the wind tunnel for setting the angles of attack (see Fig. 4). The air chamber is isolated from model, so that the jet thrust is not included in the force data measured by the balance. The aerodynamic forces were measured by a four component strain gage balance installed on the ceiling of testing section outside the tunnel.

Flow visualization were made in the CARDC 0. 4m by 0. 4m water tunnel using a one-third scaled force model which is made of the plexiglass. Some small holes are distributed on the leading edge and upper surface of the wing for injecting dye to visualize the flow field about the wing. The vortex flap made of the glass fibre rainforced plastics is hollow to allow the water go through for tip blowing.

Results and Discussion

The mechanism of using the SWB to raise drag reduction benefits of LEVF is considered as two aspects. The first, the SWB could enhance the leading edge vortex generated naturally and increase the vortex induced lift. The second, the SWB could control the position of leading edge vortex and trap it over the vortex flap as far as possible up to higher angle of attack.

Accordingly, it would be possible to raise the benefits of vortex flap in drag reduction and expand its effective range of angle of attack.

The discussion about the results obtained from this investigation is presented as following:

1. The effect of nozzle locations

The nozzle location, as indicated by previous investigations, is a sensitive factor affecting the aerodynamic benefits of SWB. Being lack of satisfactory theoretical analysis to the interaction between the jet and vortex, the optimal nozzle locations for various configurations have, therefore, been characterized by extensive "cut and try" approaches with emphasis on wind-tunnel. Moreover, the emphases of previous research were placed on enhancing the vortex flow and improving the wing lift characteristics, whereas the purpose of this investigation is to trap the vortex over the LEVF. It is concerned not only the vortex enhancement, but also the change of the vortex position induced by mass injection.

Fig. 5 shows the pressure distribution with SWB at different chordwise location at $\alpha = 15°$. It is seen that the leading edge vortex is held over the vortex flap as far as the fifth section, and SWB at the various chordwise locations has no significant effect on the pressure distribution at all the sections. At $\alpha = 25°$, the effect of SWB on the pressure distribution becomes obvious. It can be seen that with blowing-off, the peak suction has already moved inboard to the hinge line of vortex flap at the section Ⅲ, whereas the peak suction vanished over the section Ⅳ, showing the vortex breakdown has taken place. With blowing-on at 24%Cr, the peak suction goes up and moves outboard to the vortex flap at the section Ⅲ. The jet also has induced a small peak suction at the section Ⅳ near the flap hinge line. When the nozzle is moved backward to 34%Cr, the effects of mass injection on the section Ⅱ and Ⅲ is alleviated, but enhanced at the section Ⅳ. With the nozzle moving backward further, the effects of the jet on the vortex becomes less obvious. At $\alpha = 35°$, it is seen from the Cp-plot that most part of the wing is dominated by the unregular separated flow with blowing-off, while blowing at 24%Cr induced a large peak suction at the section Ⅱ and Ⅲ near the flap hinge line. The effects, however, on the pressure distributions at more aft sections of the wing rapidly decrease due to the jet decay. When the nozzle is located at 34%Cr, the peak suction over the section Ⅱ and Ⅲ is slightly lower than the nozzle at 24%Cr and has already crossed the hinge line of the vortex flap. It is interested that at the section IV, the peak suction with high level returned to vortex flap, showing the core of vortex turned outboard under the induction and obstacle effects of the jet. It suggests that the rearer the nozzle is located the weaker the effects of jet on the forward sections are, but the stronger on the rearer sections. Nevertheless, the benefits of the blowing at rearer location in total aerodynamic characteristics are not so high as that of the blowing at forward position due to the much less contribution to aerodynamics produced by rear part of the wing.

Fig. 8 presents the lift characteristics with blowing at various chordwise locations. It indicates that SWB has no significant effects on the lift characteristics at angles of attack below 24°, while at angles of attack greater than 24° SWB results in considerable increase of lift coefficient. The nozzle chordwise location has substantial effects on the increment of the lift coefficient caused by blowing. As the nozzle is located at 24%Cr (i. e. at the hinge line of vortex flap) the increment of maximum lift coefficient is about 0.17, larger than the result obtained by blowing at 67%Cr by approximately 0.10. The characteristics of lift induced-drag with blowing at diffirent chordwise locations are shown in Fig. 9. The SWB and it's chordwise location has significant effects on reducing the lift-induced-drag, especially at high angles of attack. For example, at Cy = 1.0, the reduction of lift-induced-drag is 0.23 and 0.08 for blowing at 24%Cr and 67%Cr, respectively. It could be concluded from the discussed above that the blowing is not only able to enhance the vortex over the wings, but also to control the position of the vortex. So the great potential capability for raising benefits of vortex flap in drag reduction would be exploited if the nozzle location is carefully selected.

2. The effect of the multi-nozzle blowing

According to the above discussion it is reasonably supposed that the blowing from the multi-nozzle arranged at the different chordwise location along the root chord is a available methodology overcoming the jet decay and controlling both the strength and position of the vortex to a greater extent at high angles of attack. The photo (a) and (b) in Fig. 14 illustrate the typical vortex flow patterns obtained in the water tunnel for the same configuration. It is obvious that at $\alpha = 25^\circ$ with blowing-off the leading edge vortex moves onto the wing surface behind the point of 35% of leading edge vortex length, and with the multi-nozzle blowing-on the vortex is pushed toward outboard by the jets, and consequently, the vortex length residing at the vortex flap is increased by approximately 5%. Fig. 6 shows the effects of multi-nozzle blowing on the spanwise pressure distribution at six sections at angles of attack of 15°, 25° and 35°, respectively. At $\alpha = 15^\circ$, the multi-nozzle blowing had no significant effects on the pressure distributions, which is essentially same as the situation with single nozzle blowing. At $\alpha = 25^\circ$, the multi-nozzle blowing greatly changes the wing pressure distributions, the blowing not only increases the peak suction level at most sections of the wing, and most of the peak suctions are kept over the vortex flap. Even on these sections near the rear part of wing the multi-nozzle blowing results in a favorable influence on the pressure distribution. At $\alpha = 35^\circ$, with blowing-off the flow is dominated by separated flow over the most part of wing, while with blowing-on the pressure distribution over each one of the first four sections shows a peak suction located over the vortex flap. Comparing Fig. 5 with Fig. 6, it can be seen that the effecfs of multi-nozzle blowing on the pressure distributions over section II and III are slightly less than that resulted from single nozzle blowing at 24%Cr, because in the case of multi-nozzle blowing, the momentum coefficient of each jet is only one-fifth of total momentum coefficient, much less than that used in the case of single nozzle blowing, when same momentum coefficient is applied for both nozzle configurations. So, multi-nozzle blowing, although it has favourable effects on the flow over rear part of the wing, produces aerodynamics benefits similar to that with single nozzle blowing at near leading part of the wing, which is verified by Fig. 10 and Fig. 11, in which the similar lift—drag characterestics are shown for both nozzle configurations. Finally, it should be pointed out that further investigation is necessary for the momentum distribution in multi-nozzle blowing to get optimal aerodynamics benefits.

3. The effect of tip blowing and tip-multi-nozzle combined blowing

In photo(c) and (d) of Fig. 14, the flow patterns of the wing with tip blowing and tip-multi-nozzle combined blowing are illustrated. Photo(c) shows that tip blowing could improve the separation flow existing over outer part of the wing and makes the core of the vortex turn to outboard at mid-span of the wing. Photo(d) illustrates the effects of tip-multi-nozzle combined blowing on the leading edge vortex. It is obvious that with blowing-on the vortex core moves toward to outboard of the wing and the extent of vortex over the vortex flap expands. The results for both blowing configurations obtained in the wind tunnel are presented in Fig. 7, 12 and 13, respectively. The tip blowing has no effects on the pressure distribution at lower angles of attack. At moderate and high angle of attack range the peak-like pressure distribution existing under blowing-off is flattened due to blowing and no improvement to the flow over the outer part of wing is shown from the pressure distribution (see Fig. 7). However, from Fig. 12 and 13 no obvious adverse effects of tip blowing on the lift-drag characteristics can be seen. So further investigations are needed to understand the mechanism of tip blowing. In Fig. 7 the effects of tip-multi-nozzle combined blowing with larger momentum coefficient are also presented. Even though the momentum coefficient was increased the pressure distribution had not obviously changed at $\alpha = 15^\circ$, showing the natural leading edge vortex is fully developed. The substantial effects of blowing occurs at angle of attack of 25°, in which the great changes in pressure distributions have taken place even at the last section, and a obvious peak suction in pressure distribution at all sections can be seen near the outboard part of wing. As angle of attack increases up to 35°, the combined blowing induces singificant peak suction over the sections before section Ⅳ. The effects, however, alleviated on the sections V and Ⅳ due to the serious separation of flow at such a high angle of attack. Fig. 12 indicates that with combined blowing on the maximum lift coefficient increases by about 0.25. Comparing with blowing-off the stall characteristics is improved to a some degree. Fig. 13 shows that with blowing-on the lift-induced-drag factor reduces by 9% at lower angles of attack, and at high-α, when the vortex breakdown and the drag increases significantly, blowing results in considerable drag reduction, for example, at $\alpha = 28^\circ$ the drag coefficient decreases by 0.11 due to the blowing, which is more than 20% of the lift-induced-drag with blowing-off. These results indicate again that the SWB is a valuable aerodynamic measure improving drag reduction effectiveness of vortex flap at moderate and higher angles of attack.

Conclusions

Based upon the investigation conducted for a 74° delta wing incorporated a full span and constant chord vortex flap with the deflection of 30° to determine the benefits in drag reduction of vortex flap by using spanwise blowing, following conclusions can be made:

1. The SWB, as a effective measure for controlling leading-edge vortex, could augment the effect of vortex on the vortex flap, and therefore raise the drag reduction effectiveness of vortex flap at higher angle of attack range.

2. The chordwise location of jet is a sensitive factor in achieving the optimal benefits in drag reduction. For the present configuration the single nozzle blowing near the hinge line of vortex flap is more effective than blowing at rearer location in enhancing the vortex, controlling the position of the vortex over the vortex flap and raising the drag reduction effectiveness of vortex flap.

3. The concept of multi-nozzle blowing is a potential measure to compensate the effect brought by the jet decay and enhance the vortex over the aft part of the wing. Further investigation is needed to get optimal jet momentum coefficient combination of each nozzle, so as to get maximum drag reduction effectiveness of vortex flap.

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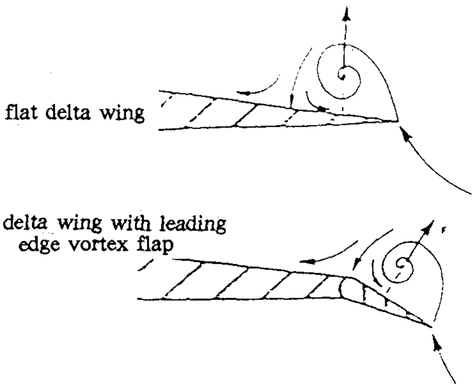


Fig. 1 Concept of leading edge vortex flap (ref. ICAS-88-4. 5. 2)

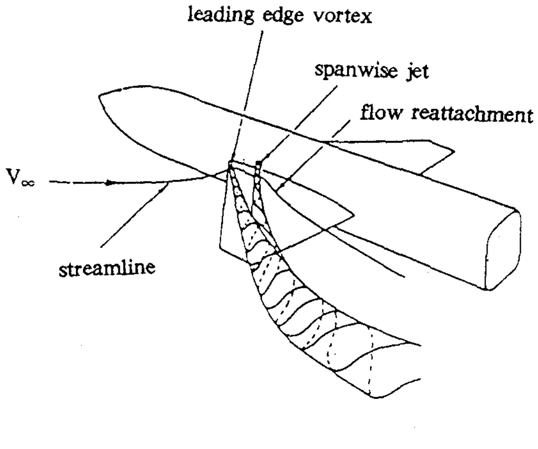


Fig. 2 Concept of spanwise blowing (ref. NASA TM X-73998)

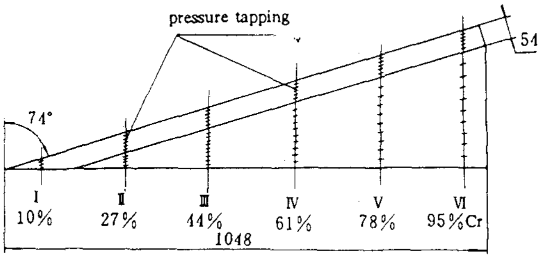


Fig. 3 Model geometry

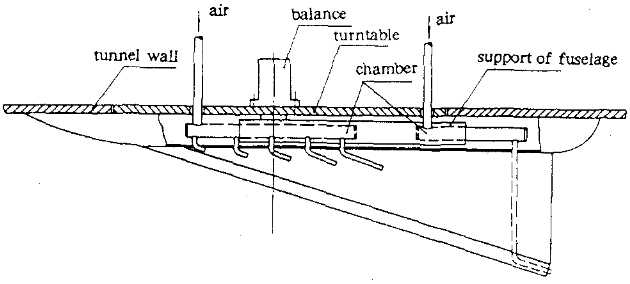
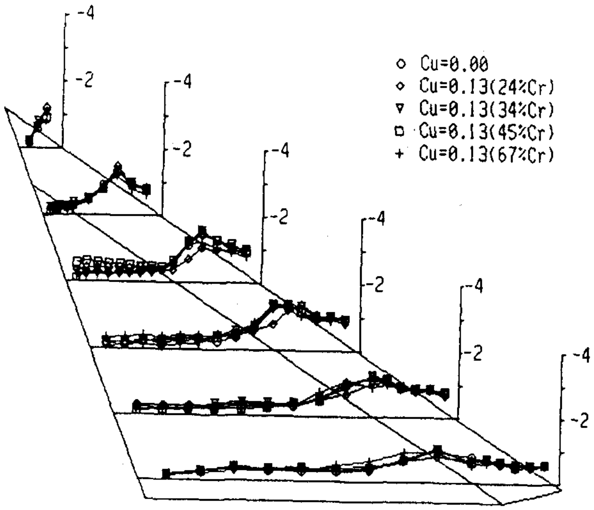
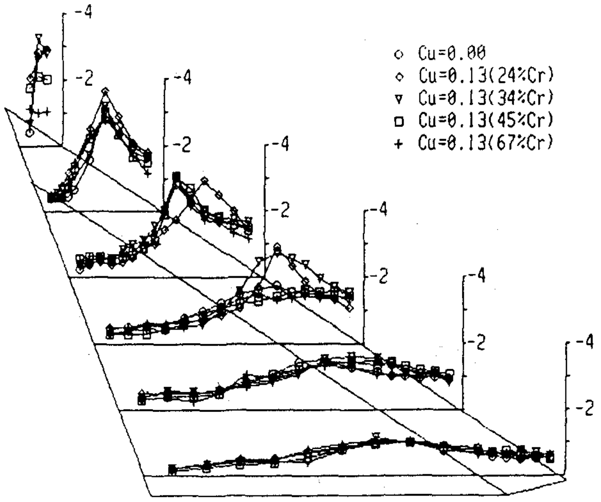


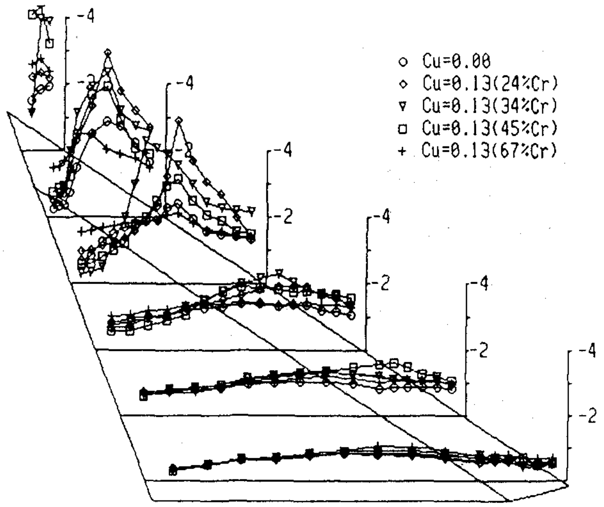
Fig. 4 Sketch of model installation in wind tunnel



(a) α=15°.

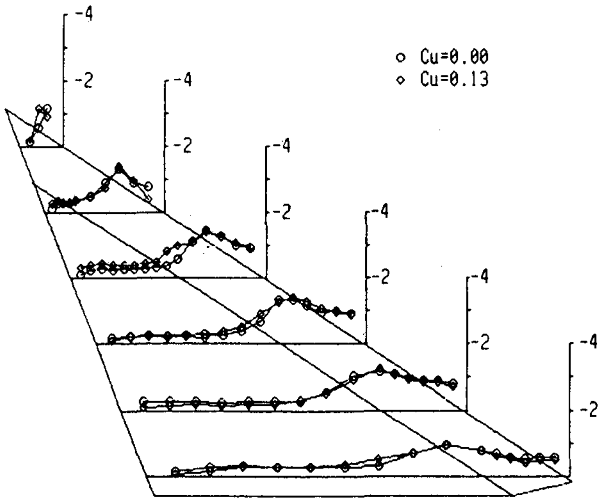


(b) α=25°.

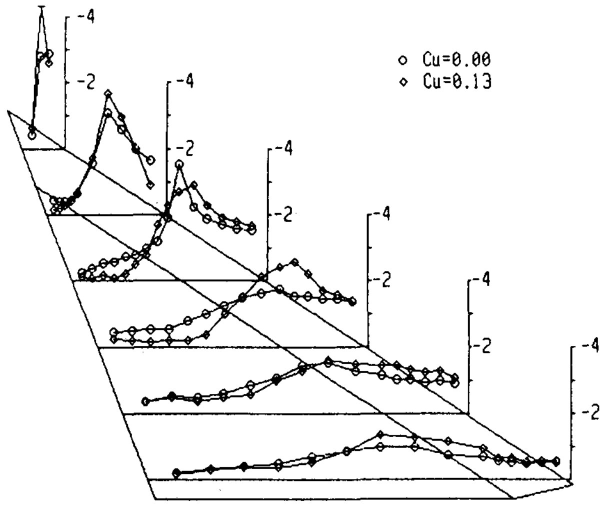


(c) α=35°.

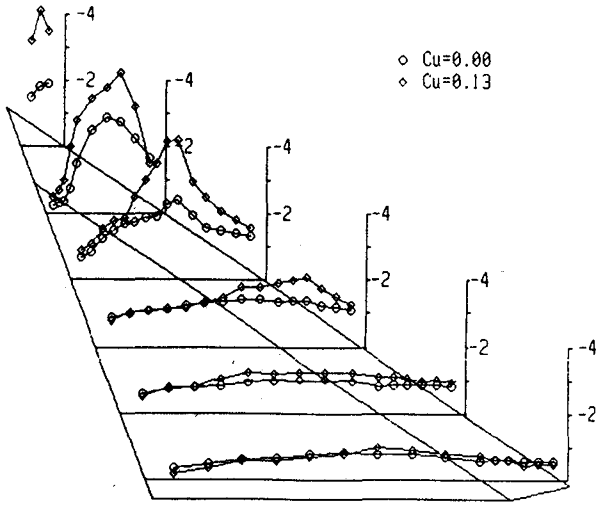
Fig. 5 Effects of nozzle location on pressure distribution (single nozzle)



(a) α=15°.

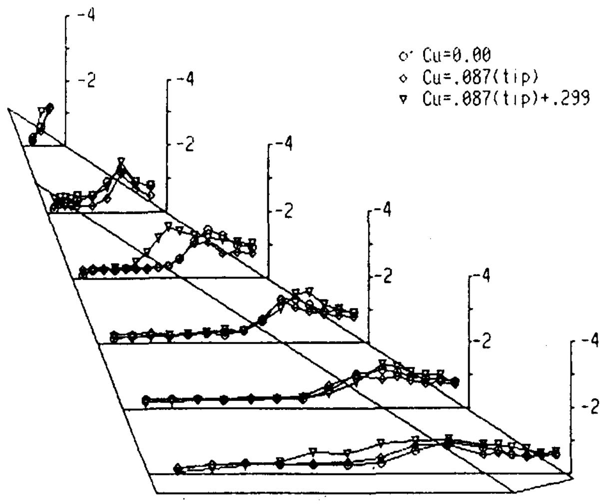


(b) α=25°.

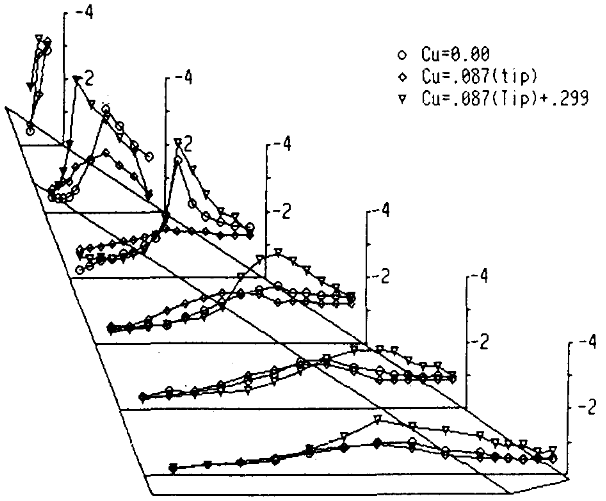


(c) α=35°.

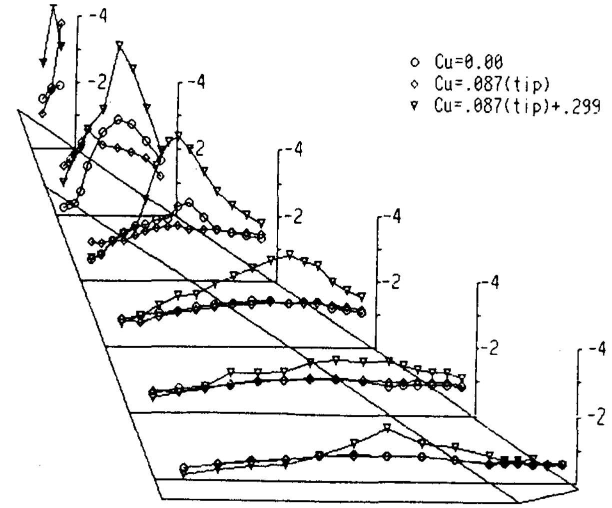
Fig. 6 Effect of multi-nozzle blowing on pressure distribution (five nozzles)



(a) α=15°.



(b) α=25°.



(c) α=35°.

Fig. 7 Effect of combined blowing on pressure distribution (tip & multi-nozzle)

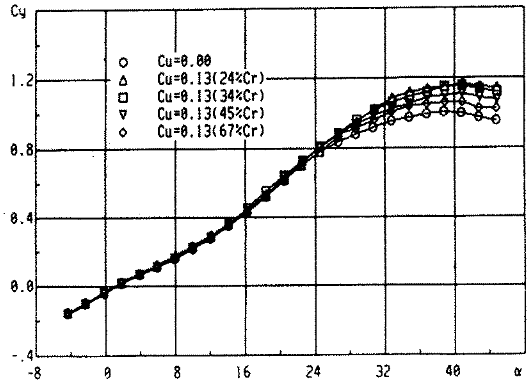


Fig. 8 Effect of nozzle location on lift characteristics (single nozzle)

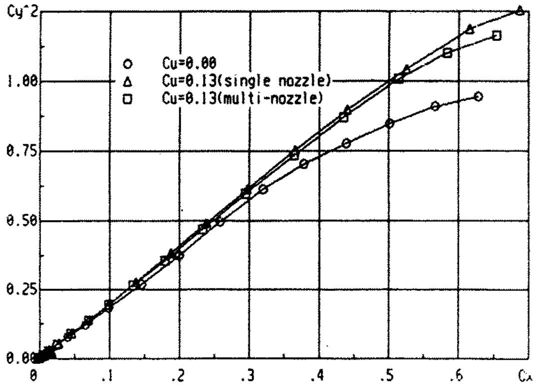


Fig. 11 Effect of multi-nozzle blowing on lift-drag characteristics (five nozzle)

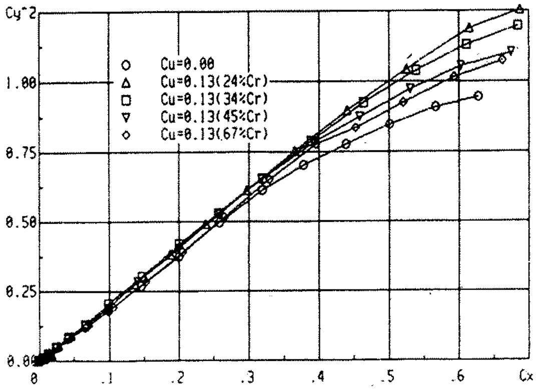


Fig. 9 Effect of nozzle location on lift-drag characteristics (single nozzle)

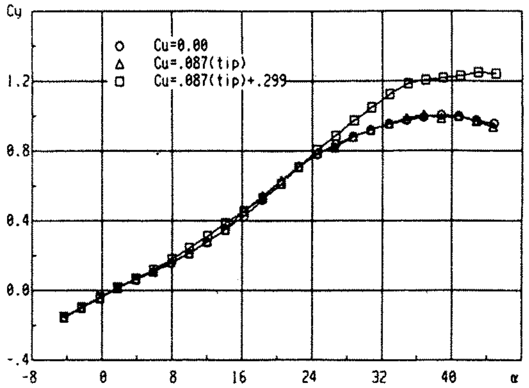


Fig. 12 Effect of combined blowing on lift characteristics (tip & multi-nozzle)

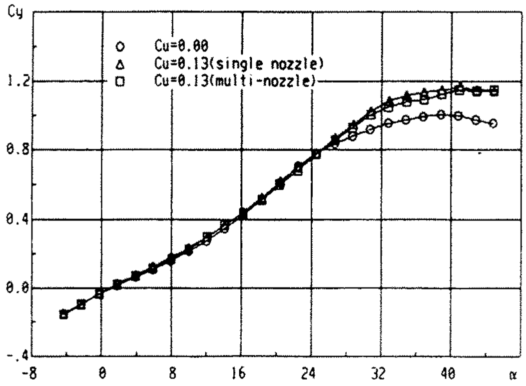


Fig. 10 Effect of multi-nozzle blowing on lift characteristics (five nozzle)

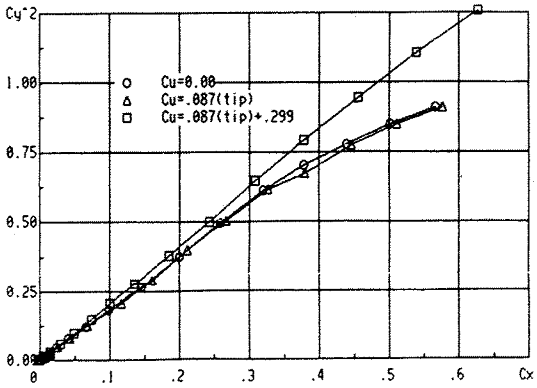
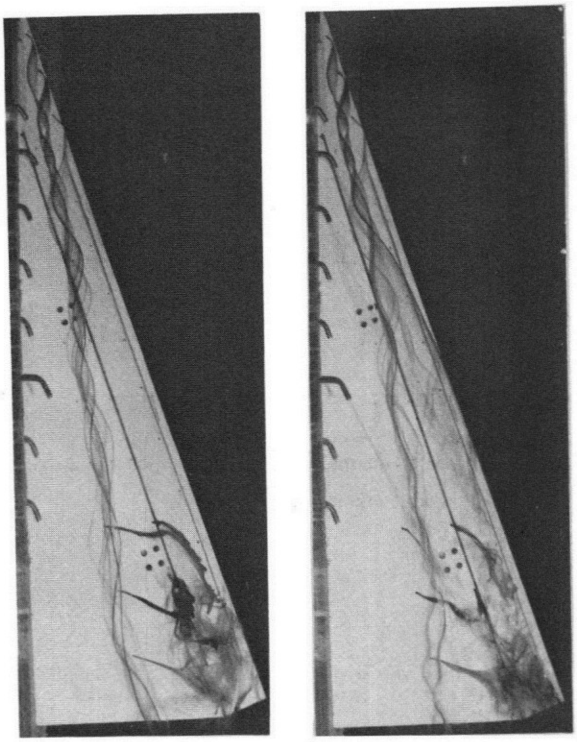
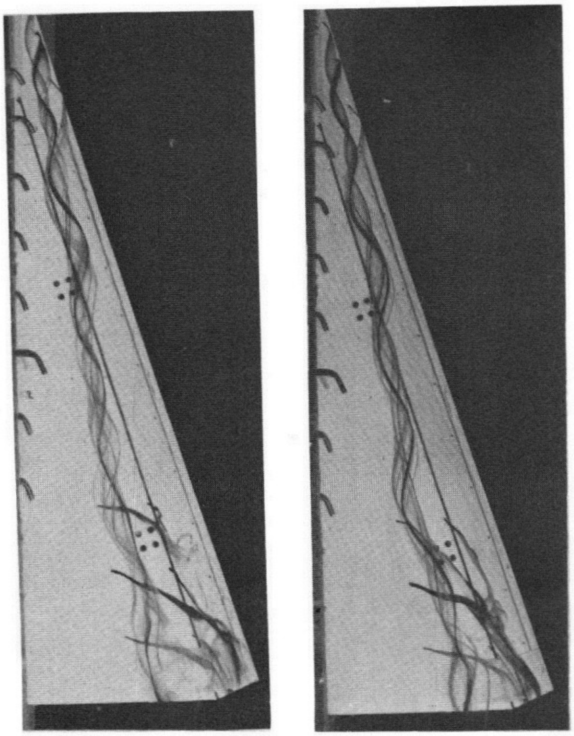


Fig. 13 Effect of combined blowing on lift-drag characteristics (tip & multi-nozzle)



(a) blowing-off (b) multi-nozzle blowing



(c) tip blowing (d) combined blowing

Fig. 14 Effect of mass injection on the flow patterns ($\alpha=25°$)