TRANSONIC SHOCK-BOUNDARY LAYER INTERACTION CONTROL

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Abstract

At off-design flow conditions conventional as well as modern supercritical transonic airfoils suffer from the occurrence of compression shocks and shock-induced separations, causing a strong drag rise due to additional wave and pressure drag. Ultimately, strong interactions between the shock and the downstream separated flow field, the onset of "buffeting", limit the range of applicability of a transonic airfoil. In an experimental investigation, performed in the DFVLR 1m x 1m Transonic Wind Tunnel, the effects of local boundary layer suction through a single slot, a double slot, and through a perforated strip were evaluated. It will be shown that by active suction the overall aerodynamic performance can be considerably improved. Moreover, the double slot and the perforated strip, each with a cavity underneath the surface, exhibited even <u>without</u> suction a most favourable "passive" effect on the overall flow development, thus, offering a very promising means for extending the limiting boundaries of transonic airfoils.

Nomenclature

b	span
b_s	span of suction region
c	chord length
c_D	drag coefficient
c_L	lift coefficient
c_p	pressure coefficient
$c_p{}^*$	c_p at sonic condition
$c_Q = \dot{m}/(\rho_\infty U_\infty b_s c)$	suction coefficient
D	drag
L	lift
$\dot{m}$	suction mass flow rate
M	Mach number
Re	Reynolds number (based on chord)
t	airfoil thickness
U	flow velocity
x	chordwise distance from leading edge
α	angle of incidence
δ^*	displacement thickness
ρ	density

Subscripts

b.o.	buffet-onset
d.r.	drag-rise
s	shock
T.E.	trailing edge
1	conditions ahead of shock
∞	free stream conditions

1. Introduction

The interaction between the boundary layer and a compression shock, which may appear on the wing of a modern jet transport aircraft at transonic speed, is one of the dominating factors limiting the range of applicability of a transonic airfoil. Advanced transonic airfoils have, at the design condition, an extended region of supersonic flow on the upper surface, terminated by a shockless recompression. In comparison to a conventional airfoil at the same flight velocity, the drag is, mainly due to lower wave drag, substantially reduced. The shockless recompression, however, is limited to a small range of Mach number/angle of incidence combinations, and deviations from the design condition will result in the occurrence of a shock and correspondingly increasing wave drag. In addition, due to the strong pressure gradient in the shock region the boundary layer is drastically thickened, Fig. 1., thus increasing the pressure drag. At highly "off-design" Mach numbers or incidences, a rapidly growing shock-induced separation bubble and/or a trailing edge separation interact strongly with the shock, affecting the entire flow field over the rear part of the airfoil. Descriptions of this complex interaction between shock and downstream flow development on transonic airfoils have been given by Pearcey[1] and by Stanewsky[2]. Ultimately, the onset of shock oscillations, associated with a loss of lift and a very strong increase in drag, mark the "buffet-boundary".

Experiments of Finke[3] on a circular arc profile and a conventional airfoil at transonic speed showed, that shock oscillations could be suppressed either by tangential blowing or suction, the blowing and suction rates, however, beeing fairly high. At much lower suction rates (approximately an order of magnitude) the onset of buffeting on a supercritical airfoil was successfully delayed by the present authors [4,5] applying single slot suction at the shock location. Encouraged by these results the investigation was continued with suction through a perforated strip and a double slot in the shock region, in order to extend the effectiveness of local boundary layer suction to a greater range of flow conditions (shock locations). In the non-suction case also the "passive" effect of these suction arrangements in the shock region was evaluated. Similar experiments of passive shock wave-boundary layer control for transonic airfoil drag reduction by placing a perforated strip with a cavity underneath in the shock region were reported by Bahi et.al[6]. The large pressure difference over the shock leads to a combined suction and bleed effect through the perforation and cavity, affecting the shock strength and downstream flow development. Savu et al.[7] extended the perforated region and cavity to close to the leading edge in order to suppress shocks on a transonic airfoil totally. So far, only theoretical considerations and some schlieren photographs, but no measurements, have been shown.

In the present paper the effects of the three different suction methods as well as the passive effect of the perforated strip and the double slot on the aerodynamic performance of the airfoil will be demonstrated for a wide range of flow conditions. Characteristic flow features and the effect of different boundary layer thicknesses will be discussed.

2. Experimental Details

2.1 Test Set-Up

The experimental investigation was performed in the 1m x 1m Transonic Wind Tunnel Göttingen of the DFVLR, which is a closed-circuit continuous tunnel with 6% open perforated walls. The model tested was the two-dimensional supercritical airfoil VFW-VA-2. Its general arrangement in the wind tunnel is sketched in Fig. 2. The model with a chord length of c = 200 mm and a relative thickness t/c = 0.13 spanned the tunnel width and was attached at both ends to rotatable end-plates in the tunnel side walls, employed to change the angle of attack, Fig. 3. The upper half of the rotatable end-plates is of glass, providing schlieren or other optical observations on the upper side of the airfoil. The surface pressure distribution was measured in the symmetry plane at 32 positions on the upper surface, including the trailing edge, and at 22 on the lower surface. The lift was obtained by integrating the measured pressure distribution. Two-dimensionality of the flow on the upper side could be checked by two additional rows of pressure taps, each 200 mm off the center section. The drag was evaluated from wake rake traverse two chord lengths downstream of the model. In addition, boundary layer measurements with a combined pitot-static-directional probe were made in a plane 50 mm off the center section[8,9]. The onset of buffeting was determined by schlieren observations on a video monitor and by observing the RMS-value of the wing root bending moment.

The basic model was equipped with interchangeable inserts allowing measurements with the surface closed, with a single slot, a double slot, and with an 8 % open electron beam drilled perforated strip. Position and details of the different suction arrangements are shown in Fig. 4. The single slot was directly connected to the suction duct, whereas the double slot and perforated strip had a cavity underneath the surface which was connected to the suction duct by throttling holes. The suction duct was connected outside the model at both ends to a common pipe leading to a vacuum reservoir. In cases with suction, the mass flow rate was measured in the suction line and set for a constant suction coefficient of $c_Q = 6 \times 10^{-4}$ by a computer controled valve.

2.2 Test Conditions

Most of the measurements were made at an off-design Mach number of $M_\infty = 0.78$ (design condition: $C_L = 0.55$ at $M_\infty = 0.75$). At this Mach number the shock was expected to be located at the position of the suction devices. The Mach numbers covered during the course of the measurements, however, ranged in some cases from $M_\infty = 0.60$ to 0.86. The Reynolds number, based on chord length, was held approximately constand at $Re_\infty = 2.5 \times 10^6$ for all Mach numbers tested. In order to simulate more realistic turbulent flow conditions, the boundary layer was artificially tripped by carborundum strips placed at 30 % chord on the upper and at 25 % on the lower surface. For the single slot and the double slot model at $M_\infty = 0.78$ the effect of different initial boundary layer conditions was investigated by placing the tripping device on the upper surface at 8 % chord and at 15 %, respectively.

3. Experimental Results

3.1 Active Shock-Boundary Layer Interaction Control

3.1.1 Effects on Force Coefficients

The experimental investigation of affecting the shock-boundary layer interaction on a transonic airfoil by local boundary layer suction in the shock region started with measurements on the single slot model [4,5] at $M_\infty = 0.78$. At suction rates as low as $c_Q = 6 \times 10^{-4}$, the aerodynamic performance of the airfoil at maximum lift conditions could be considerably improved. This suction rate is reasonably low to be feasible for practical application, and higher suction rates showed only small further improvements. Therefore, the investigation of the effects of double slot suction and suction through a perforated strip was continued with the same suction coefficient.

Although a greater range of Mach numbers has been investigated, the effect of suction on the lift of the different model configurations is shown in Fig. 5 only for three Mach numbers close to the design Mach number. The largest improvement at $M_\infty = 0.78$ compared to the closed-surface model, is gained by single slot suction, while suction through double slot and perforated strip give still substantial, but somewhat smaller improvements. Suction through the perforated strip becomes less effective at lower Mach numbers, and at $M_\infty = 0.74$ the maximum lift is even lower than on the closed surface model. Double slot suction, on the contrary, is seen to be very effective at all Mach numbers shown. The lift is appreciably increased and exhibits for the lower Mach numbers even at high incidences no distinct maximum. For Mach numbers higher than the ones shown here, the same trend in the lift curves was observed. Also by suction through the perforated strip at higher Mach numbers the maximum lift generally was increased [8,9].

The drag as well is most favourably affected by suction. In comparison with the results of the basic closed-surface model, pronounced drag reductions are observed for all suction variants, but marked differences also occur between the various suction arrangements, Fig. 6. At $M_\infty = 0.78$ and low incidence the drag is unaffected by single slot suction, but is considerably reduced for $\alpha > 3.5°$. Double slot suction reduces the drag even at low incidence for all Mach numbers shown. With increasing angle of attack, however, the differences become less or even zero at a certain incidence, but then at higher α the drag is drastically reduced. Suction through a perforated strip at $M_\infty = 0.78$ results in drag reductions of the same order as double slot suction.

These dramatic changes in lift and in drag are the consequence of influencing the boundary layer development over the rear part of the upper surface of the airfoil by suction. Boundary layer measurements are too time consuming as to be made at all flow conditions, and they are especially in the shock region or in a separation bubble very problematic. Therefore, in the following the changes in lift and drag will be explained by the variations of characteristic flow features due to variations in the boundary layer development.

3.1.2 Shock Location

On a transonic airfoil most of the lift on the upper surface is created by the supersonic region with correspondingly low surface pressures. Measurements on the present airfoil have shown that at constant Mach number the lower surface pressure distribution is relatively unaffected by variations of the upper surface flow. Therefore, changes of lift are mainly due to variations of the extent of the supersonic region or of the shock location.

For a range of Mach numbers the shock locations of the basic closed-surface model are shown in Fig. 7. The shock exhibits the generally observed behavior of moving downstream with increasing incidence (and shock strength) to a certain most downstream position (c_{Lmax}). Then a rapid upstream movement, which normally is accompanied by shock oscillations (buffeting) occurs. The latter could be observed during the measurements in schlieren visualizations and observing the RMS-value of the wing root bending moment. By comparing the shock behavior with a corresponding lift curve in Figure 5, the close relation between shock location and lift becomes evident.

By suction the shock behavior is drastically changed, Fig. 8. On the single slot model the shock is held in a rearward position ahead of the suction slot over a range of angles of attack, until it abruptly moves upstream and starts oscillating. Compared with the results of the closed-surface model the shock is held by single and double slot suction in a constant rearward position over a much larger range of incidence, causing the corresponding increase in lift. It is remarkable, that for double slot suction the final upstream movement is not as abrupt as in the single slot suction case, and that here no severe shock oscillations were observed.

The range of constant shock locations on the model with suction through a perforated strip is compared to slot suction reduced, Fig. 9. The shock moves upstream at even lower angles of attack than on the closed-surface model for the lower Mach numbers, and the shock location at $M_\infty = 0.74$. being further upstream, reflects the lower c_{Lmax} in Figure 5. At shock positions so far upstream of the suction device shock location cannot be expected to be affected very much by suction. With increasing Mach number and shock locations closer to the perforation, the efficiency of suction is increased.

3.1.3 Trailing Edge Pressure

Another characteristic flow feature on transonic airfoils is the behavior of the trailing edge pressure. Its rapid decrease to negative values indicates the presence of a growing separated region, be it a shock-induced separation bubble extending to the trailing edge, or a separation starting at the trailing edge itself [1,2]. Here, the trailing edge pressure behavior will be used to explain, at least partly, the differences in drag occurring in Figure 6.

The trailing edge pressures for the basic closed-surface model are shown in Fig. 10 for a range of Mach numbers and angles of attack. They clearly demonstrate by their decrease at a certain incidence the occurrence of separation at the trailing edge (see also the changes in the corresponding lift curves of Figure 5), with a corresponding increase in drag. With double slot suction, Fig. 11, the divergence of trailing edge pressure is delayed to higher incidences. At $M_\infty = 0.76$, for example, the trailing edge pressure starts to deviate at $\alpha = 4°$ on the closed-surface model and at $\alpha = 5°$ on the double slot model. This difference in the occurrence of trailing edge separation causes the large drag reduction observed at the corresponding angle of attack in Figure 6. Due to the strong interaction between shock and downstream boundary layer development on the closed-surface model, the shock moves upstream as soon as separation occurs at the trailing edge. With double slot suction, however, the gradual decrease of trailing edge pressures reflects a less strong shock-boundary layer interaction, and the upstream movement of the shock is delayed even in the presence of trailing edge separation. Suction through a perforated strip as well delays the occurrence of trailing edge separation to higher incidences, Fig. 12, but the rapid decrease of trailing edge pressure indicates that thereafter a very strong shock-boundary layer interaction, causing severe buffeting, occurs.

3.2 Passive Shock-Boundary Layer Interaction Control

The suction devices were placed at a position on the model, where at an off-design Mach numbers of about $M_\infty = 0.78$ the shock location was expected. The two slots were 7.5 % c apart and the perforated strip was 7.5 % c wide, each with a cavity underneath the surface which was connected to the suction duct by throttling orifices. Such arrangements (without suction) located in a flow with a large pressure gradient will produce a secondary flow through the cavity. At the higher pressure some of the boundary layer flow will be drawn into the cavity and flow out in the region of low pressure, eventually forming a small separation bubble. The consequences of the double slot/cavity and perforation/cavity arrangements without suction on the flow development and shock-boundary layer interaction will be discussed in the following.

3.2.1 Force Coefficients

The experiments on the different models without suction were carried out in the same Mach number range as in the cases with suction. For clarity, however, only for three relevant Mach numbers close to the design Mach number, the lift coefficients of the models with double slot and with perforation are compared to the results of the closed-surface model, Fig. 13. The double slot/cavity arrangement increases at high incidence the lift considerably in the entire Mach number range, without showing distinct lift maxima. The strong favourable effect of the perforation/cavity arrangement, to be observed at $M_\infty = 0.78$, vanishes at $M_\infty = 0.76$ and reduces at $M_\infty = 0.74$ even the maximum lift. The drag curves, Fig. 14, show drag reductions of the same order as in the case with active suction. Therefore, most of the improvements in lift and drag have to be attributed to the passive effect of the two suction arrangements, which makes active suction through double slot or perforated strip unnecessary.

The most important parameter describing the efficiency of an airfoil is its lift-to-drag ratio. These ratios are depicted in Fig. 15 as function of the lift coefficient. Although the largest improvements in lift and drag were measured at high incidence, this figure reveals, that even at the design-lift $c_L = 0.55$, the lift-to-drag ratio is appreciably increased at all Mach numbers by the passive effect of the double slot/cavity arrangement. For the model with perforated strip at $M_\infty=0.78$ the increase of this ratio is largest, but is unknown for the lower Mach numbers, because only a few drag measurements were made on this model.

3.2.2 Drag-Rise Boundary

Due to shocks and eventually shock-induced separations, appearing in the flow field, wave and pressure drag are increased, leading with increasing Mach number at constant lift at some point to a rapid rise in total drag, whose onset defines the "drag-rise boundary". Different criteria may be used to define this boundary. For the model with closed-surface and with double slot/cavity arrangement, the drag-rise Mach numbers are compared in Fig. 16. The drag-rise Mach number is here defined as the Mach number for wich, for constant lift, the drag has increased by $\Delta c_D = 0.0020$ with respect to the corresponding value at $M_\infty = 0.60$. Due to the passive effect of the "suction" device, the drag rise is shifted most favourably to higher Mach numbers or considerably higher lift.

3.2.3 Buffet Boundary

The ultimate boundary for a transonic airfoil, the "buffet boundary", is as well most favourably affected by passively controlling the shock boundary layer interaction, Fig. 17. Compared with the closed-surface model, the onset of buffeting on the model with perforation is unaffected at lower Mach numbers, but delayed to considerably higher lift coefficients at higher Mach numbers. The double slot/cavity shows to be effective in the entire Mach number range. Furthermore, as mentioned before, this device revealed, contrary to the other configurations, no severe shock oscillations in the schlieren observations during the experiments, and only weak buffeting was indicated by the RMS-value of the airfoil root bending moment. Beyond $M_\infty > 0.82$ buffeting ceased completely, although the flow was fully separated from the shock to the trailing edge.

3.2.4 Shock Location

Details of the secondary flow in and around the passive devices were not obtained in the present investigation. Therefore, the large improvements gained can only be interpreted by the effects of the secondary flow on characteristic flow features. Due to the combined suction and bleed effect of the double slot/cavity arrangement the shock is located far more downstream than on the model with single slot without suction and on the closed-surface model, Fig. 18. Hereby the lift is increased and the more or less constant location up to high incidences may explain the non-existence of a lift maximum. The perforation/cavity arrangement is not as effective for the Mach numbers shown in Fig. 19, but it is obvious that this device becomes more efficient at higher Mach numbers with shock locations in the perforated region (see also buffet boundaries in Figure 17).

3.2.5 Trailing Edge Pressure

Rapidly decreasing trailing edge pressures indicate the presence of a separation at the trailing edge, increasing the total drag. Compared with the closed-surface model, the divergence of the trailing edge pressures is delayed on the double slot model, Fig. 20, which results in a corresponding drag reduction. The same trend is observed in Fig. 21 for the model with the perforation/cavity arrangement.

Due to the strong interaction between shock and trailing edge flow, the shock normally starts rapidly moving upstream and oscillating immediately after trailing edge separation is indicated by the trailing edge pressure. This behavior could be observed on the closed-surface and single slot model. By comparing Fig. 18 and 20, the strong passive effect of the double slot/cavity on the shock boundary layer interaction may be demonstrated. Initially, at $M_\infty = 0.78$, the shock is located ahead of the rear slot, Fig. 18, but the increasing strength of the secondary flow out of the front slot with increasing angle of attack causes the shock to move upstream to a position ahead of the front slot. Although the trailing edge pressure indicates the development of a strong separation, Fig. 20, the shock remains in a most rearward location. From this fact it is concluded that the double slot/cavity secondary flow interrupts the interaction between shock and trailing edge flow. This may explain not only the gain in lift but also the occurrence of only very weak buffeting. The same trend is observed for all Mach numbers tested. A comparison of Fig. 19 and 21 for the perforated strip model at $M_\infty = 0.80$ indicates the same effect of secondary flow on the shock boundary layer interaction in a certain range of incidences as being the reason for the increase of the buffet boundary at higher Mach numbers. It is postulated that due to the less concentrated inflow at the rear of the perforation at a certain angle of attack, however, the interaction between shock and trailing edge flow can no longer be suppressed and severe buffeting occurs.

4. Effect of Boundary Layer Thickness on Shock-Boundary Layer Interaction Control Efficiency

In the preceding chapters it was shown that active suction through a single slot or a double slot improved the aerodynamic characteristics of the present airfoil considerably and that in the case of double slot suction a passive effect was responsible for most of the improvements. All measurements were made at a constant Reynolds number with boundary layer transition fixed at 30 % chord. The Reynolds number capability of the wind tunnel, in which the measurements were made, was too low to change boundary layer properties reasonably by Reynolds number variation. In order to study the effect of different boundary layer thicknesses on the efficiency of active or passive shock boundary layer interaction control, the tripping device was placed further upstream to obtain a thicker boundary layer at the interaction region.

On the single slot model transition was fixed at 8 % chord instead of 30 % as during the main experiments, which resulted at an angle of attack of $\alpha = 4°$ in a change of displacement thickness ahead of the shock from $\delta_1^*/c = 0.0014$ to 0.0022. The gain in lift for both cases with suction is shown in Fig. 22a. Due to the thick boundary layer the maximum lift is shifted to a lower angle of attack and the increase in lift is reduced. The shock locations at $\alpha = 4.5°$ for both transition locations are close to the suction slot, Fig. 22b, but for the thick boundary layer the pre-shock Mach number is smaller than for the thinner boundary layer, which causes the difference in the lift increase due to boundary layer control. Beyond $C_{L_{max}}$ the shock has moved far upstream and suction becomes inefficient.

For the double slot model the transition location was changed only from 30 % chord to 15%. The gain in lift due to active suction as well as due to the passive effect of the double slot/cavity arrangement is depicted in Fig. 23. This figure demonstrates again that most of the improvement in lift is gained by the passive effect. The different boundary layer thicknesses have only minor influence on the efficiency of passive shock-boundary layer control below $\alpha = 5°$. At higher incidences the thick boundary layer reduces the efficiency of the passive effect which for the thinner boundary layer, remains highly effective. Note, that compared to the single slot configuration, the trip was here only moved to the 15% chord station.

5. Concluding Remarks

In the present investigation the interaction between the shock and the downstream flow development on a transonic airfoil was actively influenced by local boundary layer suction in the shock region through different suction arrangements. Single slot suction at $M_\infty = 0.78$ was most effective, due to the concentrated suction at optimum position with respect to the shock location. The maximum lift was considerably increased and drag reductions were obtained by delaying shock-induced and trailing edge separation. How the efficiency varies with Mach number is not yet known, but presumably the efficiency will decrease with shock locations off the suction slot.

Suction through a double slot was effective in the entire Mach number range investigated,largely increasing the lift and reducing the total drag. Suction through a perforated strip had only a favourable effect at Mach numbers of $M_\infty > 0.76$ and even decreased the maximum lift at lower Mach numbers.

Even without suction the double slot/cavity arrangement exhibited in the entire Mach number range tested - the perforation/cavity arrangement only at higher Mach numbers - an unexpectedly strong passive effect on the flow development in the shock boundary layer interaction region and over the rear upper surface. Due to the secondary flow through the passive "suction" arrangements, caused by the strong pressure gradient in the shock region, the lift is increased and the drag is largely reduced. Thus, most of the improvements gained with active suction must be attributed to the passive effect. Although no details of the secondary flow were measured, the large improvements can be explained by the behavior of the characteristic flow parameters mainly affected.

Furthermore, it is postulated that the double slot/cavity arrangement interrupts or suppresses at high incidence largely the interaction between shock and trailing edge flow, thus delaying strong shock oscillations and hence the onset of severe buffeting. The perforation/cavity arrangement gives at higher Mach numbers also evidence of this mechanism.

So far only one slot spacing and perforation width and constant cavity depth have been investigated. Variations of these geometric parameters in further investigations may lead to even greater improvements of the aerodynamic characteristics of the airfoil. Measurements on a larger model utilizing more sophisticated measuring techniques in the shock boundary layer interaction region are planned for the near future and are anticipated to reveal details of the secondary flow and its effect on the overall flow development.

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AGARD-CP-365, 1984, pp. 24-1 ÷ 24-13

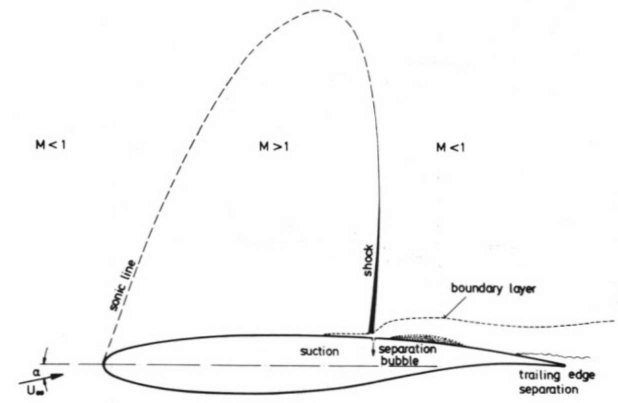


Fig. 1 Model of Transonic Shock-Boundary Layer Interaction

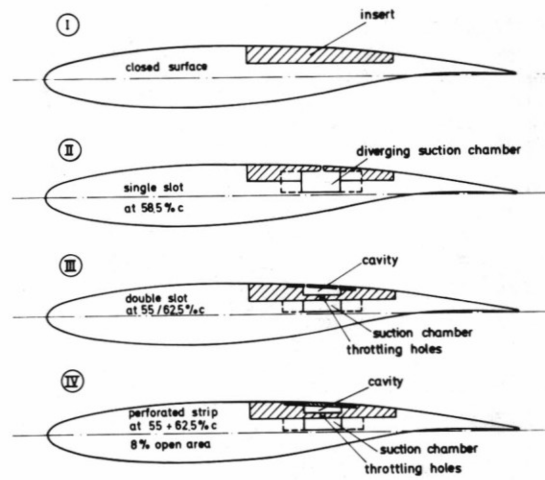


Fig. 4 Model Configurations

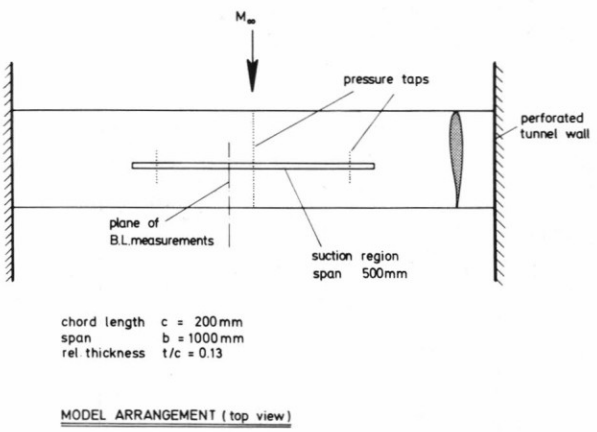


Fig. 2 Model Arrangement (Top View)

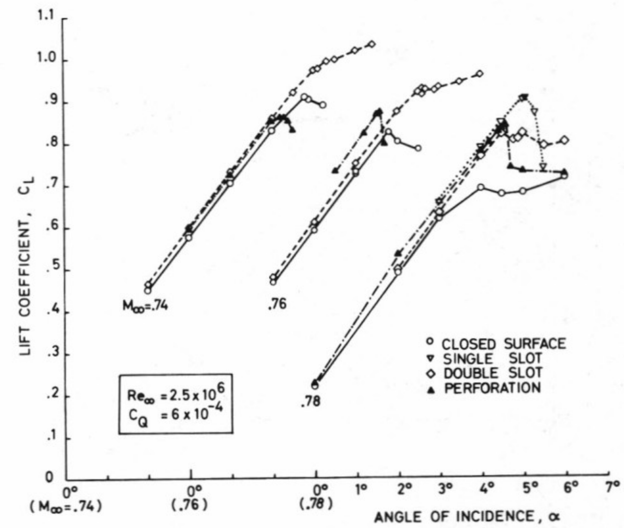


Fig. 5 Effect of Suction on Lift

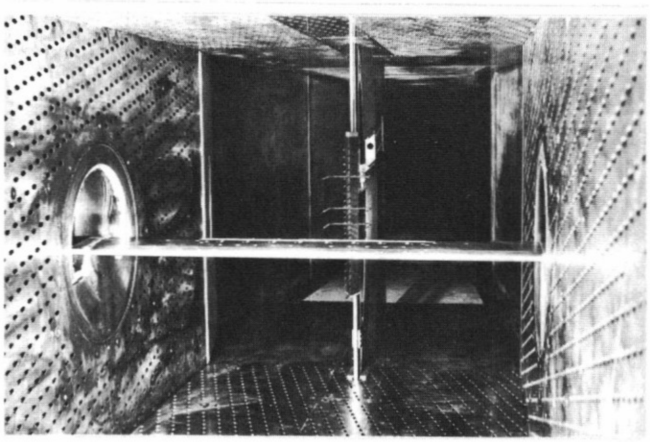


Fig. 3 Photograph of the 2-D Model in the Wind Tunnel

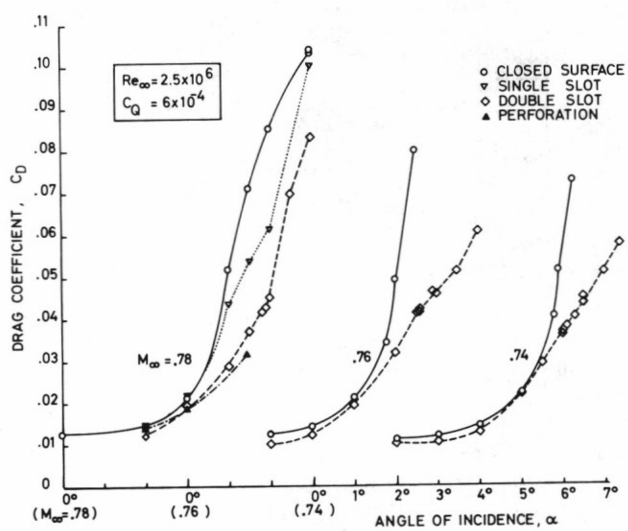


Fig. 6 Effect of Suction on Drag

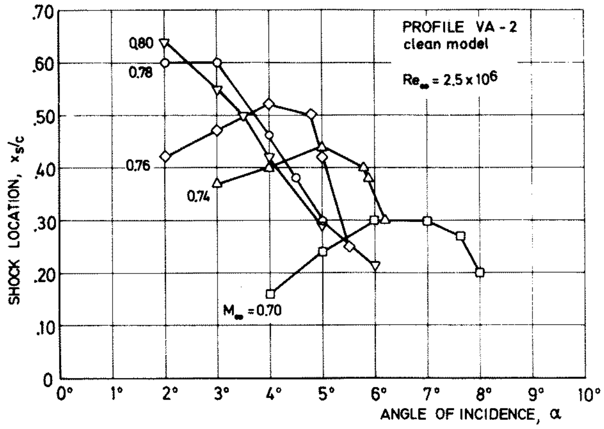


Fig. 7 Shock Locations on Closed Surface Model

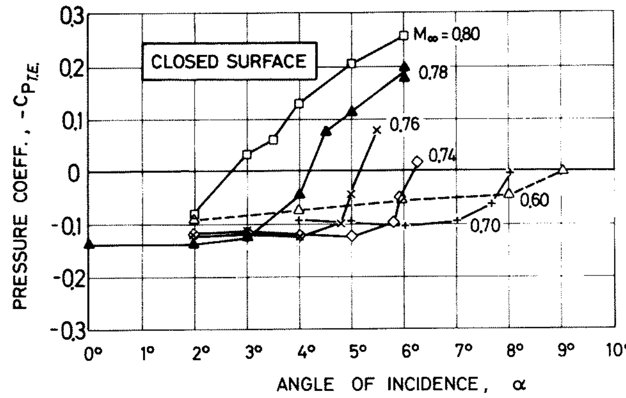


Fig. 10 Trailing Edge Pressures of Closed Surface Model

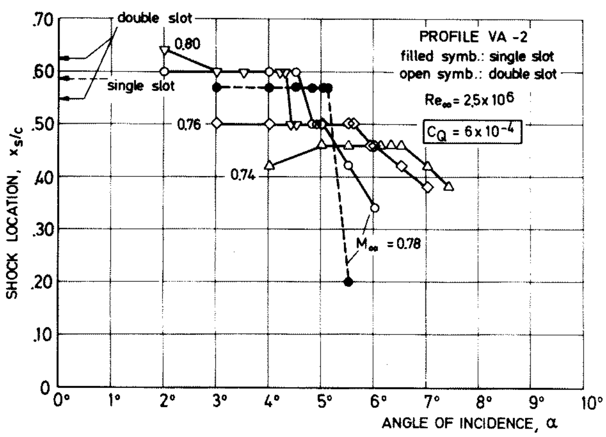


Fig. 8 Shock Locations on Double Slot Model with Suction

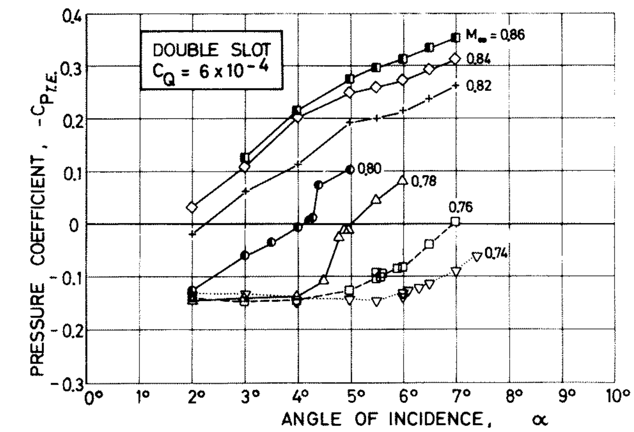


Fig. 11 Trailing Edge Pressures of Double Slot Model with Suction

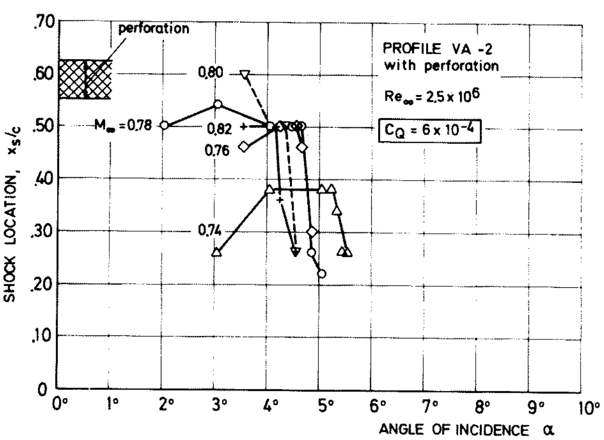


Fig. 9 Shock Locations on Perforated Strip Model with Suction

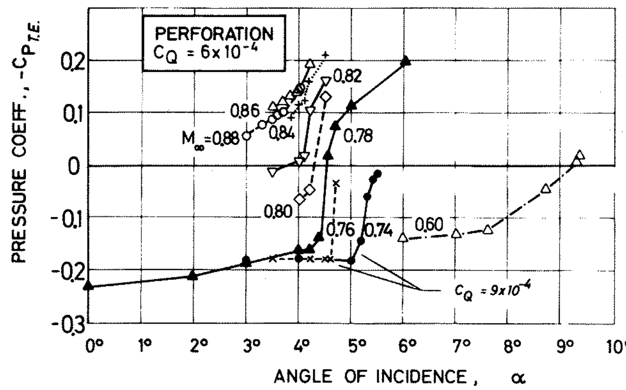


Fig. 12 Trailing Edge Pressures of Perforated Strip Model with Suction

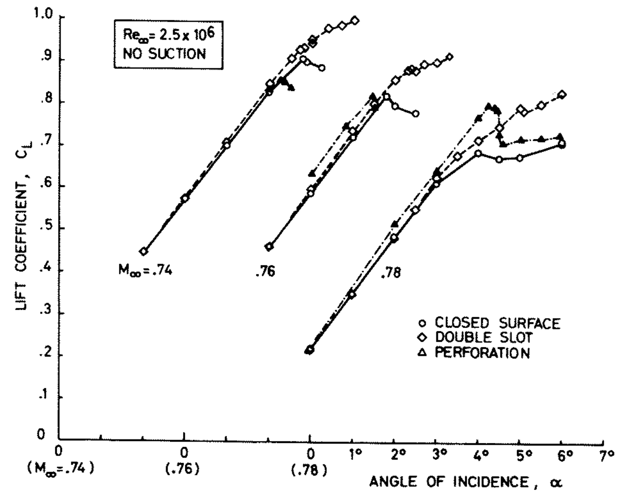


Fig. 13 Passive Effect of Suction Arrangements on Lift

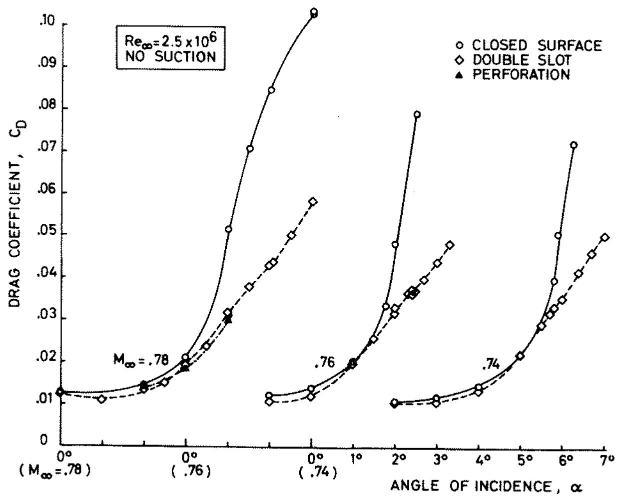


Fig. 14 Passive Effect of Suction Arrangements on Drag

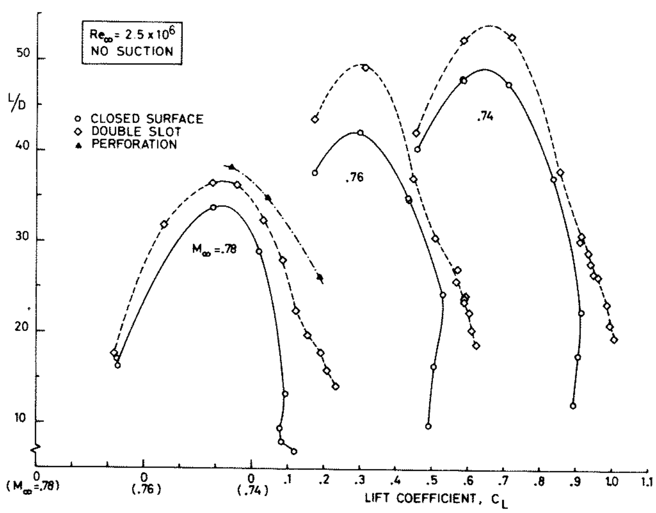


Fig. 15 Passive Effect of Suction Arrangements on Lift to Drag Ratio

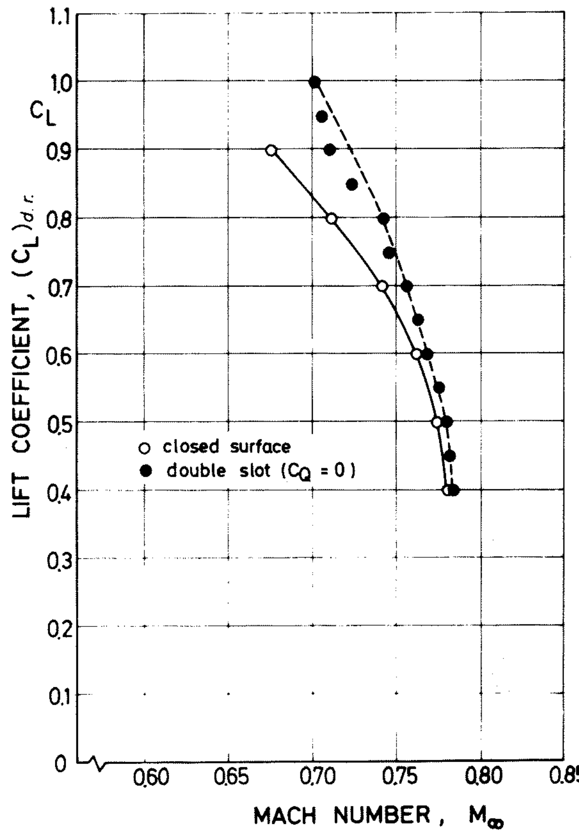


Fig. 16 Passive Effect of Suction Arrangements on Drag Rise Boundary

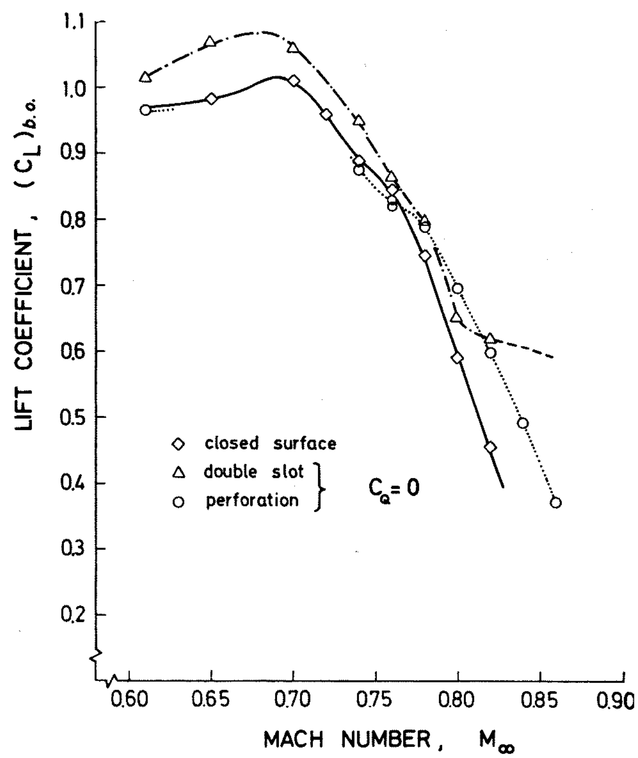
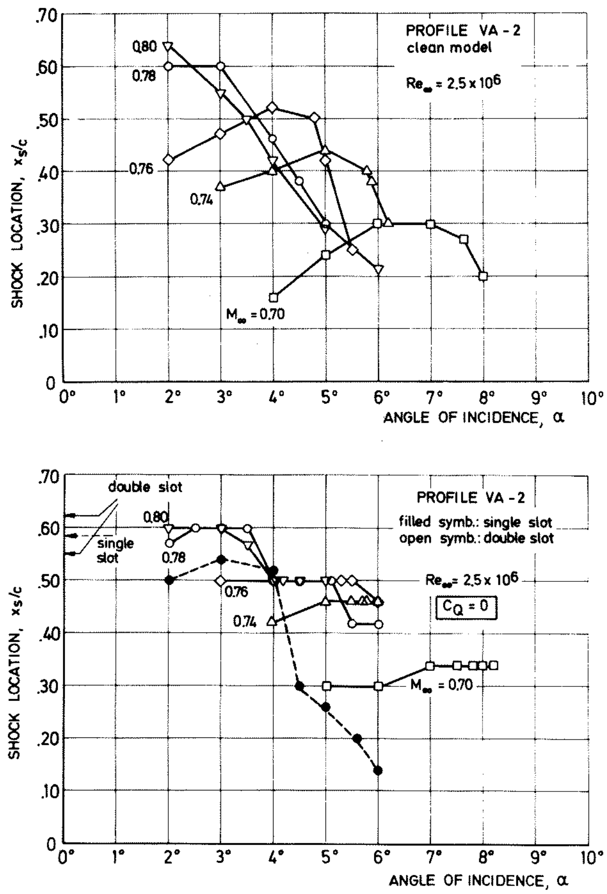


Fig. 17 Passive Effect of Suction Arrangements on Buffet Boundary



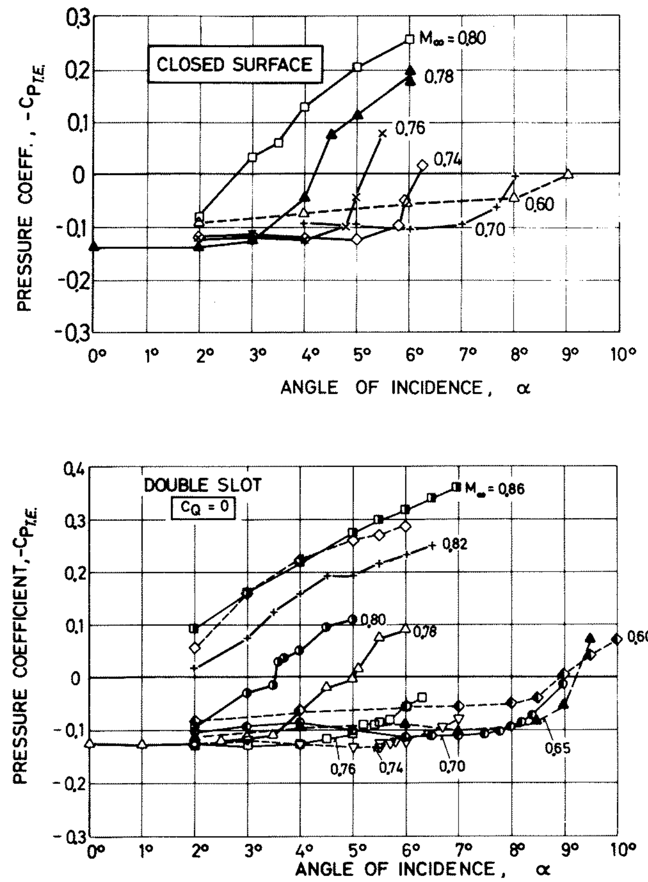
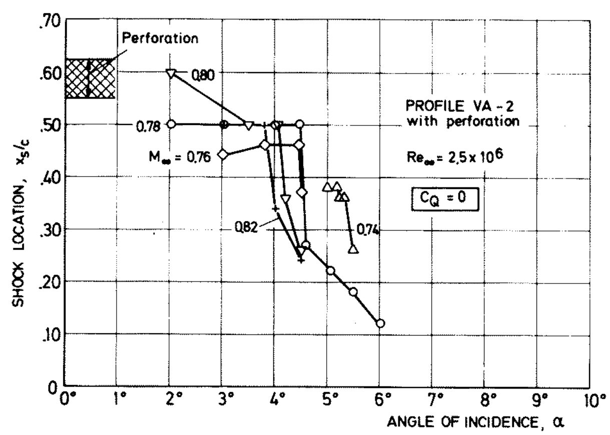


Fig. 18 Shock Locations on Closed-Surface and Double Slot Model, Suction off

Fig. 20 Trailing Edge Pressures of Closed Surface and Double Slot Model, Suction off



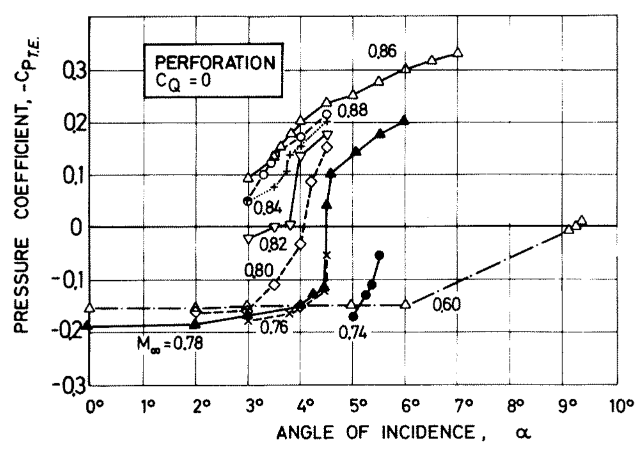
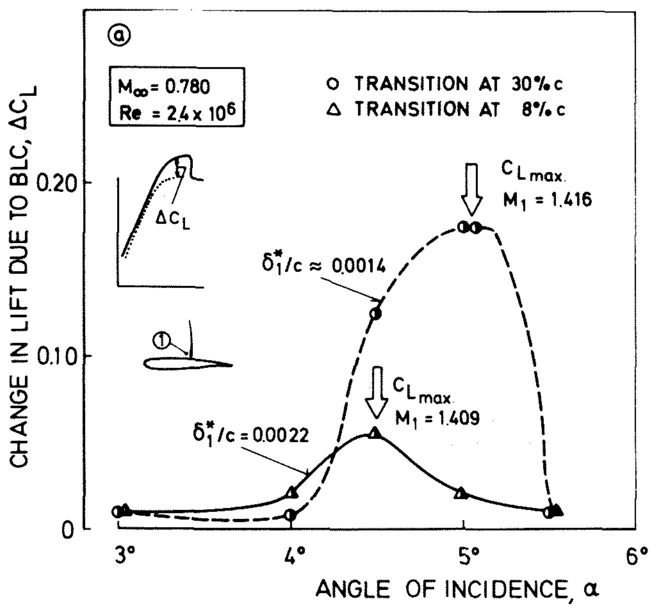
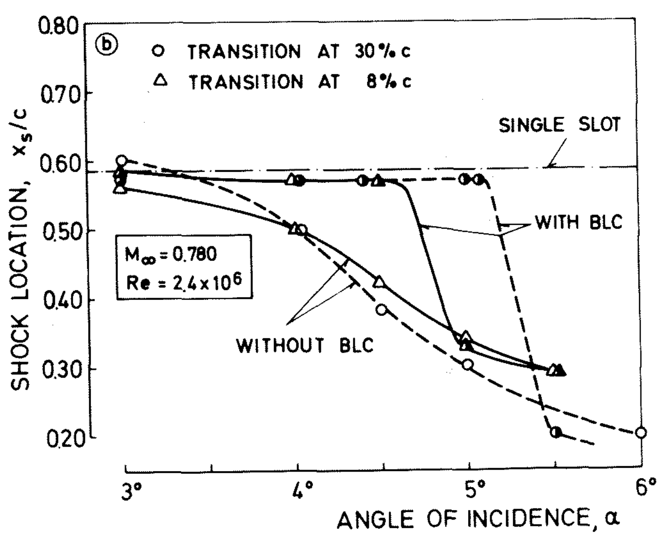


Fig. 19 Shock Locations on Perforated Strip Model, Suction off

Fig. 21 Trailing Edge Pressures of Perforated Strip Model, Suction off



a) Gain in Lift



b) Shock Location

Fig. 22 Effect of Initial Boundary Layer Thickness on BLC-Efficiency for Single Slot Suction

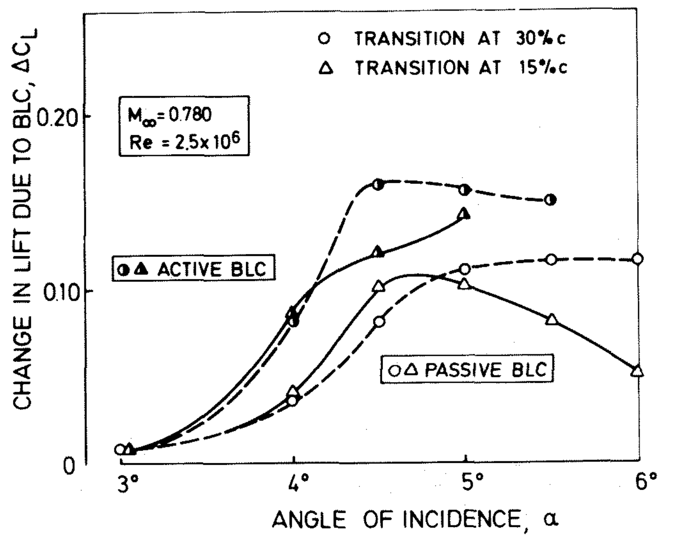


Fig. 23 Effect of Initial Boundary Layer Thickness on BLC-Efficiency for Double Slot Suction