Prevention of Transition over a Backward Step by Suction

Mansop Hahn* and W. Pfenninger†
The Boeing Commercial Airplane Company, Seattle, Wash.

A study was made on prevention of transition of the flow downstream of a backward facing step by means of suction. Distributed suction was approached through closely spaced slots in the region downstream of the step. The optimum location and rate of suction to maintain laminar flow downstream of the step were determined. The effects of step height Reynolds number on transition of the boundary layer with and without suction were investigated. Suction in the region slightly upstream of reattachment shortened the reattachment length by about 20% and was very effective in preventing transition. The minimum suction rate required for laminarization of the flow downstream of the step was equivalent to 15-20% removal of the boundary-layer displacement thickness upstream of the step. The transition Reynolds number based on step height was increased from 1100 without suction to 2200 with suction.

Nomenclature

b = spanwise length of slot
h = step height
L = distance between leading edge and step
Q = suction mass flow rate
Re = Reynolds number
u = velocity component in streamwise direction
u_e = velocity at boundary-layer outer edge
$\bar{u}'$ = rms value of u component fluctuation
u_{ps} = velocity at preseparation condition
x = distance from step, (+) downstream, (−) upstream
x_r = reattachment length
y = distance from surface in lateral direction
δ = boundary-layer thickness
$\delta_0{}^*$ = displacement thickness upstream of step
γ = turbulence intermittency
ν = kinematic viscosity
ρ = air density

Introduction

ONE of the problems uninvestigated in the field of laminar boundary-layer control is that of prevention of transition of separated boundary-layer flow over discontinuous surfaces, such as steps and gaps. One such problem is the control and prevention of transition of laminar flow over a backward facing step. Forward or backward facing steps often exist at the joints between the wing and control surfaces on flaps of airplanes. These may induce premature boundary layer transition and increase drag on laminar flow control wings. To date few experimental as well as analytical results of this problem are available.

The purpose of the present work was to investigate the feasibility of preventing such laminar-to-turbulent transition downstream of a backward facing step by stabilizing the boundary layer in the neighborhood of the reattachment region by means of distributed suction.

The experiments were conducted in a low subsonic flow. The influence of step height and distance between leading edge and step on transition of the boundary layer downstream of the step were investigated. Distributed suction was approached through closely spaced slots located in the region downstream of the step. Emphasis was given to determining the optimum location and rate of suction for laminar flow downstream of the suction region. For this purpose the velocity and turbulent intensity profiles of the boundary layer were investigated with and without suction. The relation between reattachment length and suction rate was observed.

Received March 5, 1973; revision received June 22, 1973. This work was conducted in 1969 with Boeing Independent Research and Development Funds.

Index category: Boundary Layers and Convective Heat Transfer—Laminar.

*Specialist Engineer. Member AIAA.

†Propulsion Aerodynamist. Member AIAA.

Experimental Apparatus and Procedure

Wind Tunnel and Test Conditions

The experiments were conducted in the 46 × 36 cm test section of closed circuit type subsonic wind tunnel at Boeing. The static pressure and temperature of the test section were near atmospheric condition. The freestream velocity varied from 6 to 19 m/sec. The turbulent intensity of the freestream was about 0.04%. The Reynolds number per meter ranged from 0.4×10^6 to 1.1×10^6/m.

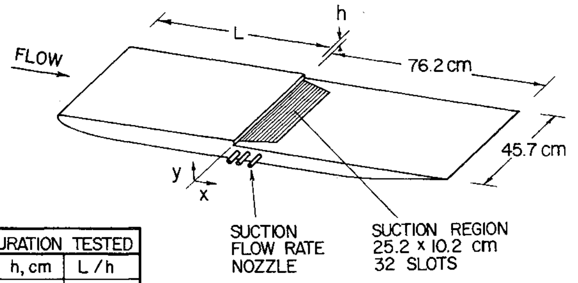
Test Model

The basic model configuration and dimensions are shown in Fig. 1. The upper surface of the model has a backward facing step. The step height and the distance between leading edge and step were variable as shown in the table of Fig 1. The model spanned the 46 cm wide test section and was installed at an angle of attack of about 1.0°, thus avoiding a negative pressure peak at the leading edge of the test surface. The potential flow velocity on the flat surface slightly increased in the flow direction, thus preventing premature transition on the test surface upstream of the step.

Thirty-two suction slots were located in the region downstream of the step as shown in Fig. 2. Each slot was 0.076 mm wide and 0.508 mm deep. The slots were uniformly spaced at 3.175 mm intervals. The slots were grouped in three regions and each group was connected to individual suction chambers to allow different chordwise suction distributions during the optimization process of the suction distribution. Some of the slots were sealed with cellophane tape. Three flow rate measuring nozzles were installed at the side walls of each suction chamber (Fig. 1).

Flow Measurements

A constant temperature hot-wire anemometer was used to determine the mean velocity and turbulent velocity fluctuations in the boundary layer. A Pitot probe was also used for velocity measurements. The reattachment location of the separated flow was detected by means of smoke ejected from a flattened tube at an angle normal to



CONFIGURATION TESTED		
L, cm	h, cm	L / h
38.1	.191	200
76.2	.191	400
76.2	.399	191

Fig. 1 Model configuration.

free stream. At the reattachment location the spreading of the smoke in both upstream and downstream direction was observed.

Results and Discussion

Flow without Suction

Typical results of boundary-layer velocity and turbulent intensity profiles for laminar separated flow over the step and transitional and turbulent flows after reattachment are shown in Fig. 3. Velocity profiles reduced from both Pitot tube and hot-wire measurements are in excellent agreement in the laminar flow region upstream of the step ($x/h = -10$) and in the turbulent flow regions downstream of transition ($x/h = 133$). In the transitional region ($x/h = 60$) slight disagreement appears near the surface. The discrepancy was believed to be caused by inaccuracy involved in mean velocity measurements with the hot-wire probe. The laminar boundary-layer profile at $x/h = -10$ closely agreed with the theoretical profile calculated by an exact solution. The profile of the boundary-layer velocity fluctuations at $x/h = -10$ is typical for laminar boundary layers; its maximum rms value of 0.73% occurred at about $y/\delta = 0.4$. The highest velocity with laminar flow at $x/h = -10$ was found to be 34 m/sec, corresponding to a length Reynolds number $Re_L = 1.7 \times 10^6$.

In Fig. 4 oscilloscope traces of the chordwise flow velocity fluctuation, u', are shown for the flow corresponding to Fig. 3. A laminar flow oscillation appears in the separated flow region downstream of the step, ($x/h = 0$ to 25). The amplitude of the oscillation gradually grows toward the reattachment region ($x/h = 25$). The oscillation is, however, not of a regular sinusoidal type. The fluctuation of the flow downstream of the reattachment ($x/h = 27.5$) still appears to be a laminar type oscillation. Fluctuation intensities corresponding to the oscillation are shown in Fig. 3. In the transitional region ($x/h = 60$), turbulent fluctuations of high frequency appear in the flow, but laminar low frequency oscillations persist between turbulent fluctuations. The turbulent intensity in this region is much higher than that of the laminar type oscillation region of the separated flow. In the turbulent region ($x/h =$

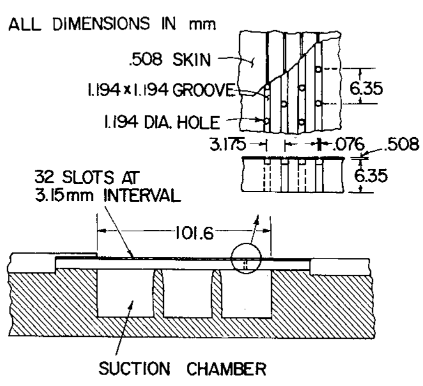


Fig. 2 Details of suction chamber and slot.

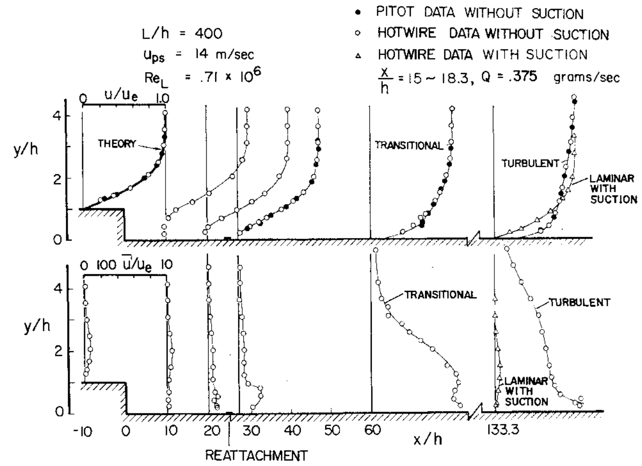


Fig. 3 Velocity and turbulent intensity profiles of flow over a step.

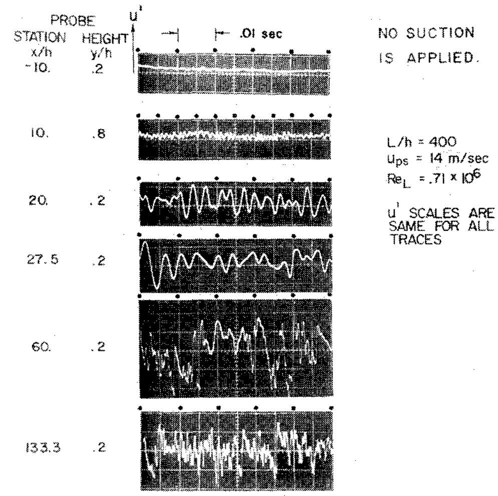


Fig. 4 Oscilloscope traces of velocity fluctuation of flow over a step.

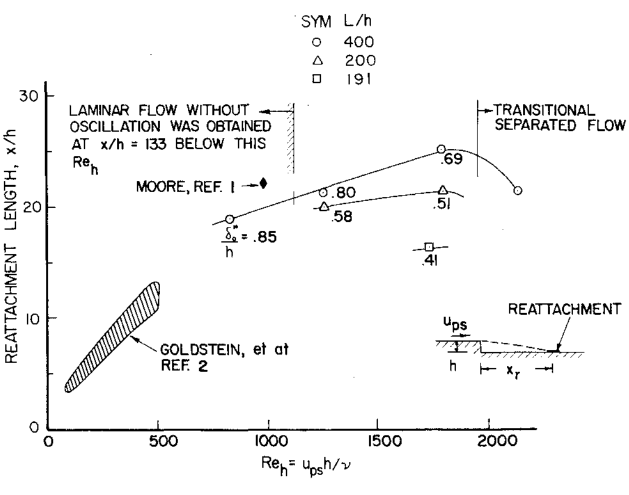


Fig. 5 Reattachment lengths of separated flow over a step without suction.

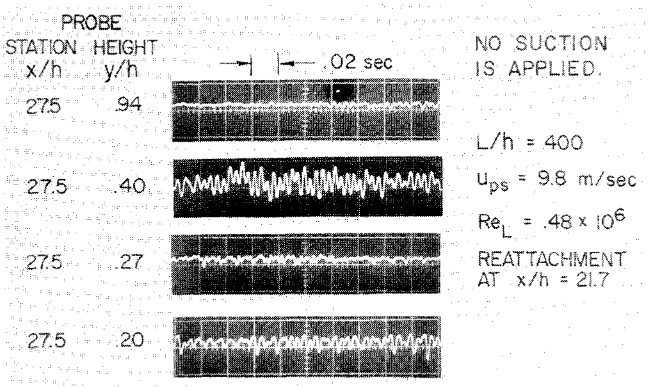


Fig. 6 Velocity fluctuation variations in the direction normal to the surface at reattachment region.

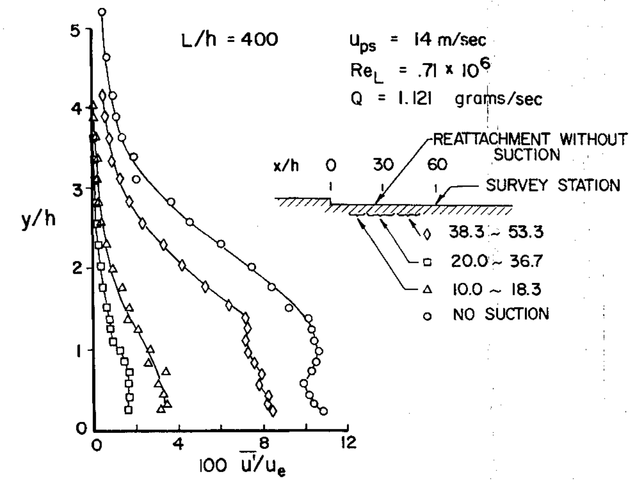


Fig. 7 Turbulent intensity variation with suction at different locations.

133) the oscilloscope trace indicates a completely turbulent fluctuation, and the turbulent intensity profile shown in Fig. 3 indicates also a typical turbulent boundary-layer flow.

Reattachment Length without Suction

In Fig. 5 the reattachment lengths, as evaluated from smoke observations, are shown and compared with available data by other investigators.[1,2] The reattachment length gradually increases with step height Reynolds number in the regime of "pure" laminar separation. The

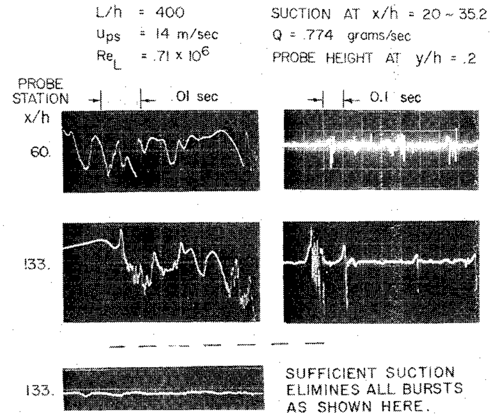


Fig. 8 Velocity fluctuation variations at regions downstream of suction locations.

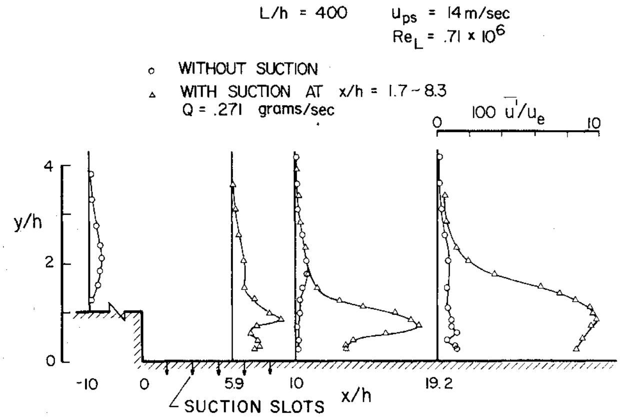


Fig. 9 Turbulent intensity variation with suction at the region immediately downstream of step.

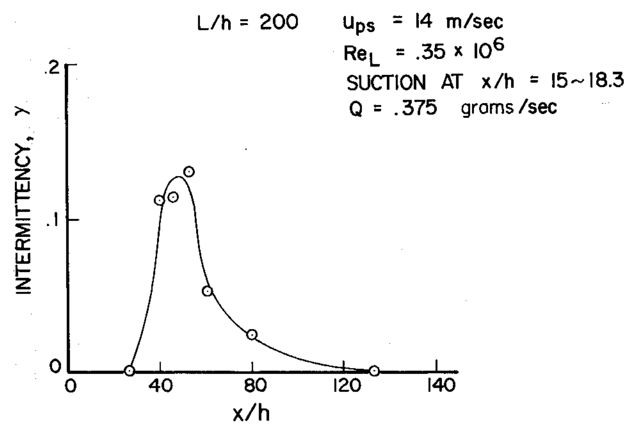


Fig. 10 Turbulent intermittency of unstable zone downstream of suction location.

pure laminar regime defined here includes the regime where laminar type oscillation takes place in the laminar separated shear layer and the reattachment zone. The oscillation amplitude in the reattachment zone increased both with step height Reynolds number, Re_h, and length Reynolds number, Re_L. As transition occurred in the shear layer, the reattachment length suddenly decreased. Figure 5 also shows that for a given step height Reynolds number the reattachment length increases as the displacement thickness upstream of the step increases. The present data show substantially higher values of laminar reattachment length and step height Reynolds number

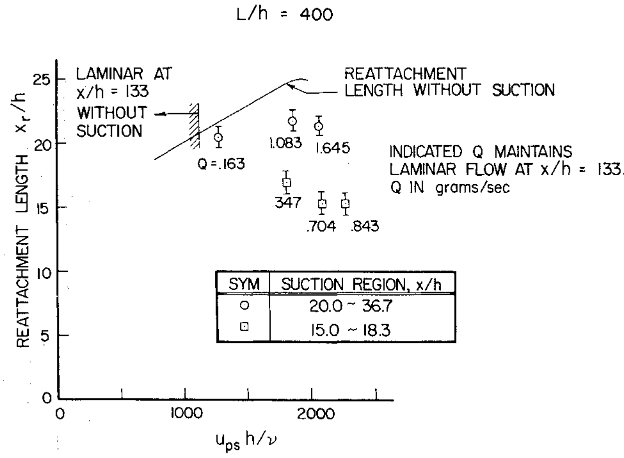


Fig. 11 Reattachment length of separated flow with suction.

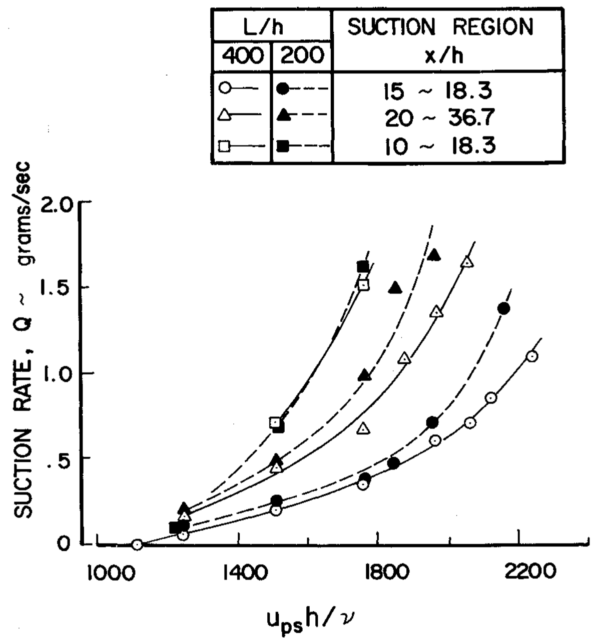


Fig. 12 Minimum suction rate required to maintain laminar flow without turbulent bursts at x/h = 133.3.

compared with data obtained by Goldstein et al.[2] The high values of reattachment length and step height Reynolds numbers obtained in the present experiment may be attributed to the low turbulence level of the wind tunnel. In the reattachment region the variation of the u'-velocity fluctuation in the direction normal to the surface suggested a phase reversal. Phase reversals in the u'-fluctuation were observed in oscillating laminar boundary layers by Schubauer and Skramstad.[3] Present data showed similar observations in the reattachment regions as shown in Fig. 6. The amplitude of the u'-fluctuation near the wall initially decreases as the hot-wire probe moves away from the wall, but the amplitude increases again at a distance further away from the wall. Finally, u' decreases to the freestream level at larger y-distances.

Flow with Suction

The turbulent intensity of the flow downstream of the reattachment region was largely controlled by the suction rate and suction location. In Fig. 7 the turbulence intensity variations with suction location are shown for a constant suction rate. The flow at the survey station (x/h = 60) was transitional without suction. Suction in the reattachment region, i.e., x/h = 20 to 36.7 stabilized the flow downstream of reattachment, so that the flow at the survey station became laminar. Suction in the region upstream of reattachment, i.e., x/h = 10 to 18.3, also stabilized the boundary layer, but less effectively than suction in the reattachment region (x/h = 20 to 36.7). This is due to the higher "residual" turbulence level with suction at x/h = 10 to 18.3, as compared to the level with suction at x/h = 20 to 36.7, as shown in Fig. 7. Although data are not shown in Fig. 7, suction in the region immediately upstream of reattachment (x/h = 15 to 18.3) was found to be most effective in reducing the turbulence level at x/h = 60, but flow instability problems persisted when suction was applied in the region x/h = 15 to 18.3, as will be discussed later. Suction in the region downstream of reattachment, x/h = 38.3 to 55.3, slightly reduced the turbulence level, but the flow still remained transitional at x/h = 60.

In Fig. 8 traces of u'-velocity fluctuations at two streamwise stations (x/h = 60 and 133) are shown for the case of suction in the reattachment region, x/h = 20 to 36.7. Sporadic turbulent bursts still remained in mostly laminarized flow at insufficient low suction rates. (Compare the traces without suction at corresponding stations shown in Fig. 4.) In Fig. 8 traces are shown for slow and fast time scales. The bursts occurring in the right-hand photographs (slow time scale) are shown over a shorter time period (fast time scale) in the left-hand photographs. Laminar type oscillations dominate at x/h = 60, and turbulent bursts occur between laminar type oscillations at x/h = 133. Further increases in suction rate entirely suppressed turbulent bursts as shown in the bottom photograph of Fig. 8. In Fig. 3 the velocity and turbulent intensity profiles of the laminarized boundary layer at x/h = 133 are compared with those without suction.

Suction in the region immediately downstream of the step strongly destabilized the separated shear layer. In Fig. 9 the development of the u'-fluctuations of the separated shear layer in the streamwise direction is shown for low suction rates in the region immediately downstream of the step, i.e., x/h = 1.68 to 8.33. As seen in Fig. 9 the level of the u'-fluctuation rapidly increases to that of a completely turbulent boundary layer at x/h = 20.

When suction was applied in the region immediately upstream of the reattachment region x/h = 15 to 18.3, an unstable zone was detected before the flow was fully laminarized in the region further downstream of this zone. In Fig. 10 a typical result of such an unstable zone is presented in terms of turbulent intermittency. Suction was applied at x/h = 15 to 18.3. Sporadic turbulent bursts appeared in the zone between x/h = 30 and 100. The intermittency was a maximum at x/h = 53 and slowly decreased in the downstream direction, until the flow became completely laminar at x/h = 133.

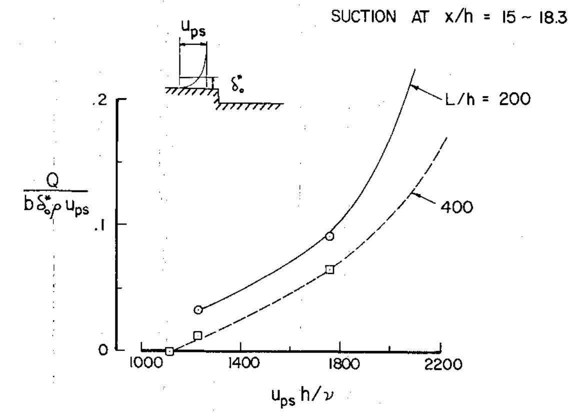


Fig. 13 Minimum suction rate required to maintain laminar flow at x/h = 133.3.

Reattachment Length with Suction

When suction was applied in the region immediately upstream of the reattachment location without suction, the reattachment location moved toward the region of suction. When suction was applied over the region which includes the reattachment location without suction, the reattachment location moved to the start of the suction area. Figure 11 shows the reattachment locations with suction. The suction rate indicated in the figure is the minimum rate required to maintain a laminar flow at x/h = 133.

Minimum Suction Rate Required for Laminar Flow

Figure 12 presents minimum suction rates required for laminarization at x/h = 133 for various step height Reynolds number. Data are shown for two different model configurations and three different suction locations. For both model configurations lower suction rates are required when suction is applied in the region immediately upstream of reattachment, i.e., $x/h = 15$ to 18.3, as compared to other suction locations indicated in the figure. However, as mentioned previously for the cases of suction applied in the region immediately upstream of reattachment, there existed an unstable zone upstream of the fully laminarized region at $x/h = 133$; furthermore, the flow at $x/h = 133$ was found to be very sensitive to the external sound. This instability was especially noticeable for high step height Reynolds numbers, about $Re_h = 2100$. Although suction in the reattachment region, i.e., $x/h = 20$ to 36.7 required higher suction rates than the previous case, the laminarized flow at $x/h = 133$ was found to be very stable and unaffected by external noise.

Figure 12 indicates that the step height Reynolds number for which laminar flow can be maintained at $x/h = 133$ is almost doubled with suction.

In Fig. 13 the minimum suction required to maintain laminar flow at $x/h = 133$ is shown in terms of the dimensionless parameter $Q/b\delta_0{}^*\rho u_{ps}$, expressed in terms of conditions immediately upstream of the step. The extended curves in Fig. 13 are based on calculated displacement thickness $\delta_0{}^*$ for corresponding Reynolds number. Figure 13 shows that the minimum suction parameter required for laminarization represents less suction than the condition of 15 to 20% removal of the boundary-layer displacement thickness upstream of the step. The figure also shows higher minimum suction rates for smaller L/h than for larger L/h. In other words, for a fixed step height Reynolds number, the minimum suction rate required for laminarization is larger for smaller $\delta_0{}^*/h$ than for larger $\delta_0{}^*/h$.

Conclusions

Prevention of premature transition caused by the separated flow over a backward facing step can be achieved by suction in the neighborhood of the reattachment region that occurs without suction. The suction location was selected such as to reduce or eliminate the oscillation in the separated shear layer. Shortening the reattachment length by suction in the region immediately upstream of reattachment was effective in eliminating oscillation in the shear layer. The present experiment showed that 20 to 25 per cent shortening of the reattachment length, depending upon test conditions, was found to be most effective in suppressing boundary layer oscillations and maintaining laminar flow in the region further downstream of the reattachment region. However, suction in this region alone left an unstable zone before fully laminarized flow was achieved in the region downstream of the unstable zone. Additional suction in the region slightly downstream of the shifted reattachment location eliminated this unstable zone. The minimum suction required for prevention of transition was equivalent to 15 to 20% removal of the boundary layer displacement thickness upstream of the step.

A further reduction of the reattachment length below 25% deteriorated the flow stability, thus causing premature transition. Suction in the region immediately downstream of the step introduced a severe disturbance in the separated shear layer, resulting in rapid transition to turbulent flow.

References

[1]Moore, T. W. F., "Some Experiments on the Reattachment of a Laminar Boundary Layer Separating from a Rearward Facing Step on a Flat Plate Aerofoil," *Journal of the Royal Aeronautical Society,* Vol. 64, Nov. 1960, pp. 668–672.

[2]Goldstein, R. J. et al., "Laminar Separation, Reattachment and Transition of the Flow Over a Downstream-Facing Step," ASME Paper 69-WA/FE-5, 1969.

[3]Schubauer, G. B. and Skramstad, H. K., "Laminar-Boundary Layer Oscillations and Transition on a Flat Plate," Rept. 909, 1948, NACA.