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FILM NOTES

for

BOUNDARY-LAYER CONTROL*

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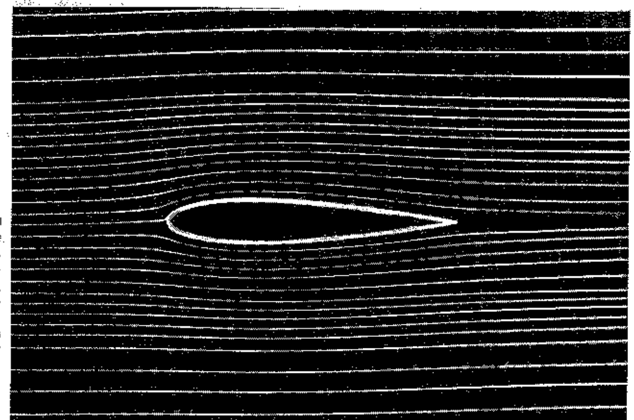
Introduction

Although potential theory can be used to explain many aerodynamic phenomena, there are cases in which the boundary layer — the thin layer of fluid next to a solid surface in which effects of viscosity may be considered concentrated — significantly alters theoretical predictions. A simple example is the flow past an airfoil. The airfoil section in Fig. 1 is in a narrow wind tunnel at zero angle of attack. Kerosene smoke provides the flow visualization. At low angles of attack, the streamline pattern about such a shape is very close to the predictions of inviscid theory. However, a drag force not accounted for by such a theory exists. This drag is largely due to viscous shear forces and is called *skin-friction drag.*



1. Smoke flow past airfoil at zero angle of attack.

In regions over the surface in which the boundary-layer flow is laminar, the fluid mixing and viscous skin friction are low. However, such laminar flows are often unstable and develop into turbulent flows. Turbulent flows involve more rapid mixing, which produces higher skin-friction drag. On occasion, the combined action of viscous forces and an adverse pressure gradient produces a reversal of the flow next to the surface which, in turn, causes separation of the adjacent flow from the surface. This situation is exemplified in Fig. 2, where the flow on the top surface is separated and the airfoil is said to be *stalled.*

The presence of the boundary layer has produced many design problems in all areas of fluid mechanics. However, the most intensive investigations have been directed towards its effect upon the lift and drag of wings. The techniques that have been developed to manipulate the boundary layer, either to increase the

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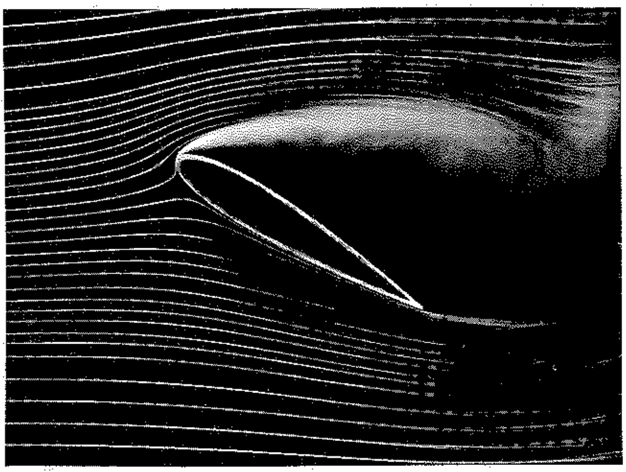


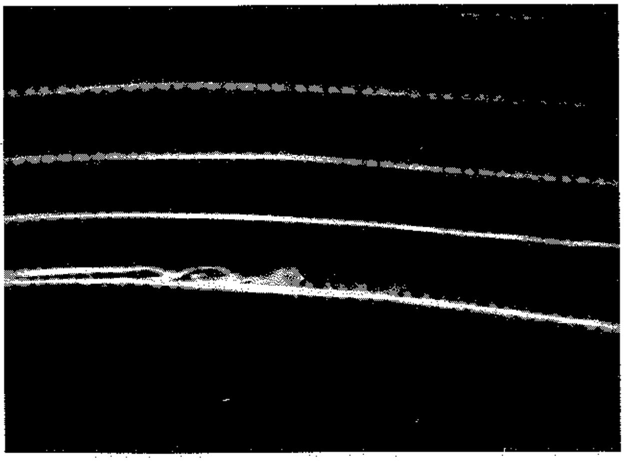
2. **Same airfoil at large angle of attack with flow separation.**

lift or decrease the drag, are classified under the general heading of *boundary-layer control.*

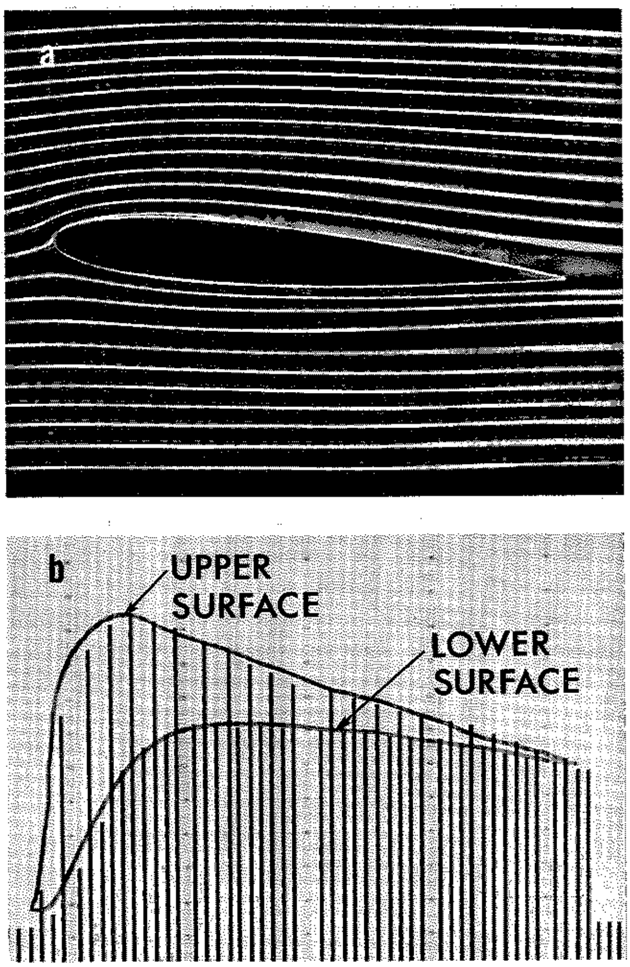
Two boundary-layer phenomena for which controls have been sought are the *transition* of a laminar layer to a turbulent flow and the *separation* of the entire flow from the surface. By maintaining as much of the boundary layer in the laminar state as possible, one can reduce the skin friction. By preventing separation, it is possible to increase the lifting effectiveness and reduce the pressure drag. Sometimes the same control can serve both functions.

Controlling Transition by Shaping the Airfoil

Transition to turbulence is associated with instability of the laminar boundary layer. When studied with the aid of high-speed photography (Fig. 3), disturbances in the laminar flow are seen to amplify to the point of forming large eddies. These in turn produce the highly disorderly motion of turbulent flow. The location on the surface at which transition occurs depends both upon the stability of the laminar boundary layer and upon the nature of the disturbances. Factors producing disturbances, such as surface roughness, noise, vibration, heat, or airstream turbulence, can sometimes be avoided or isolated. The stability of the laminar boundary layer may also be influenced by manipulating the pressure gradient produced by the flow over the surface.



3. **High-speed photograph of boundary layer on airfoil undergoing transition. Large eddies are formed prior to breakdown into turbulence.**



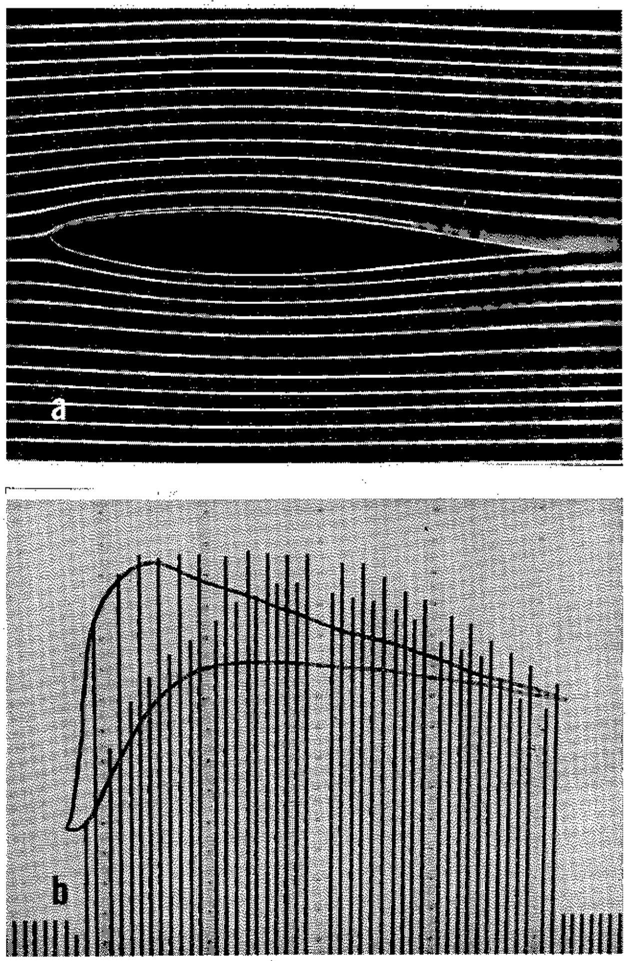
4. **Conventional airfoil profile at moderate angle of attack. (a) Smoke visualization shows laminar flow extending to about 25% of the chord length. (b) Manometer bank shows pressure distribution on upper and lower surfaces.**

Combinations of favorable and unfavorable pressure gradients occur over the surfaces of aerodynamic shapes. An airfoil with its point of maximum thickness located about 25% of its chord length aft of the leading edge, placed at a moderate angle of attack (such as might correspond to cruising flight of an airplane), has a minimum-pressure point near the leading edge (Fig. 4).* Thus, the upper surface aft of this

*The pressure taps on the airfoil surface are connected to the manometer tubes to show pressure distribution. As with a soda straw, a pressure *decrease* causes a *rise* in the fluid level in the tube. Thus a high level indicates a low pressure.

point is subjected to an *adverse* gradient. Increasing the angle of attack increases the adverse gradient. Such gradients are destabilizing, so that the amount of laminar flow over a structure decreases with increasing adverse pressure gradient.

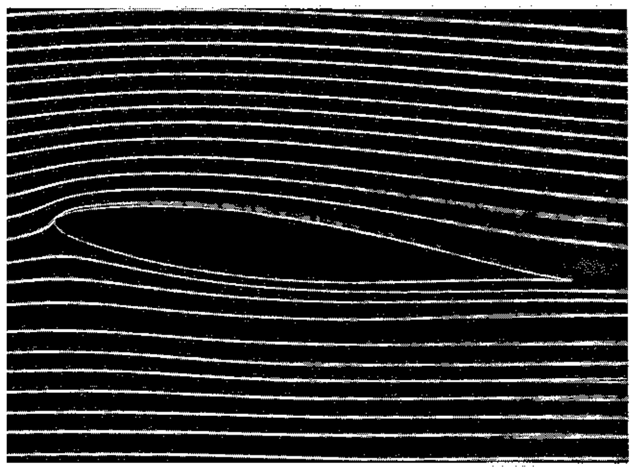
A different airfoil with its maximum thickness at 50% chord (Fig. 5), when placed at an angle of attack



5. High-speed profile at angle of attack producing same lift as airfoil in Fig. 4. (a) Note greater extent of laminar flow on upper surface. (b) Comparison of pressure distribution with that of conventional airfoil (marked outline).

producing the same amount of lift as the airfoil of Fig. 4, has a minimum pressure point farther aft, and the extent of adverse gradient is therefore less. Flow studies show that the extent of the laminar boundary layer is correspondingly increased.

As the angle of attack of the airfoil of Fig. 5 is increased, the situation changes radically. The leading-edge radius of such "laminar-flow" profiles is necessarily small. Therefore, as the forward stagnation point moves downward, the flow passing over the leading edge must accelerate rapidly, producing there a sharp pressure minimum followed by a strong adverse pressure gradient. Under these circumstances the transi-

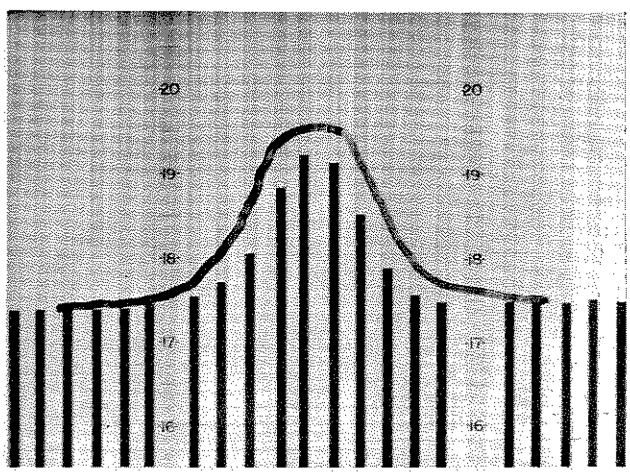


6. High-speed profile at larger angle of attack than in Fig. 5. Transition to turbulence occurs near leading edge.

tion point abruptly moves to the leading edge, covering the entire surface with turbulent flow (Fig. 6).

Turbulent boundary layers thicken more rapidly and produce greater skin friction than laminar layers. Thus, reducing the extent of turbulent flow reduces the drag of the profile. This can be verified experimentally by measuring the flux of momentum deficiency in the wake of the airfoil (by means of an array of total-head tubes located far enough behind the profile that the static pressure in the wake is nearly the same as that in the main flow). The loss in total head reflects a change in streamwise momentum flux, which is a measure of the *profile drag*. Seen on a bank of manometer tubes (Fig. 7), the momentum defect produced by the profile with the greater extent of laminar flow is markedly less than that created by the profile with its maximum thickness at 25% chord, at the same lift coefficient.

Changes in the geometry of an aerodynamic shape provide a method of adjusting pressure gradients so as



7. Manometers connected to total-head tubes illustrate difference in wake momentum loss between conventional profile (marked outline) and high-speed profile at same lift coefficient.

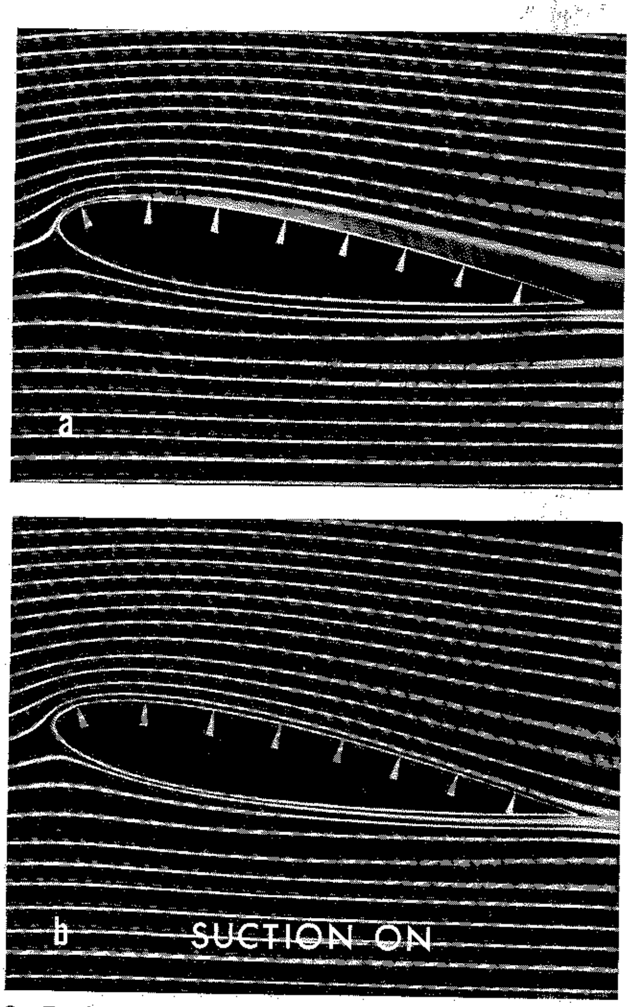
to favor the existence of laminar boundary layers. However, regions of adverse gradient can never be completely avoided. On occasion, changes in the geometry, while helpful at some angles of attack, worsen the situation at other angles.

Controlling Transition by Suction

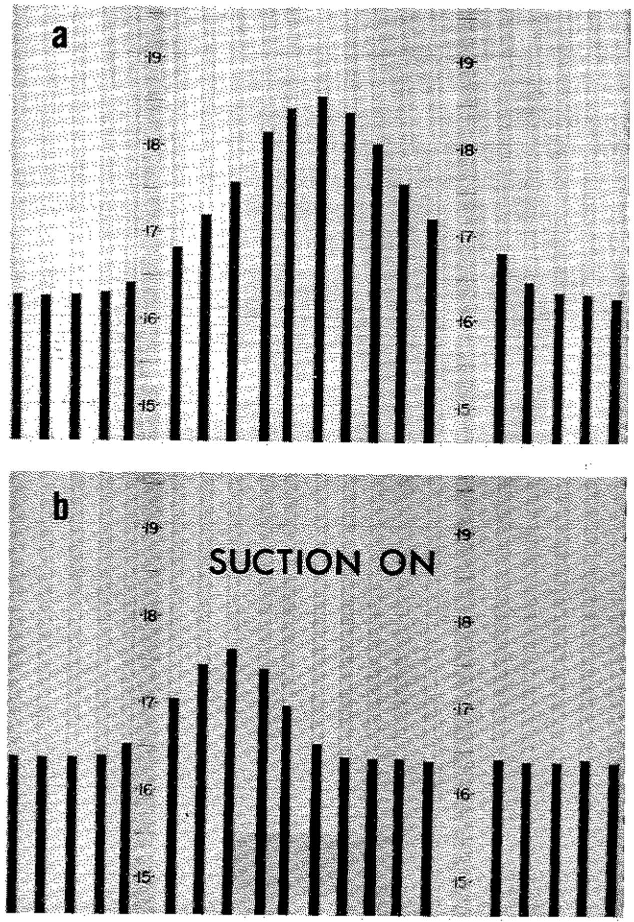
A rather different means of stabilizing the boundary layer is the use of *suction*. Suction may be applied either through porous surfaces or through a series of finite slots, as in Fig. 8. When applied in this manner, suction reduces the thickness of the boundary layer by removing the low-momentum fluid next to the surface. A more stable layer results, and transition to turbulence is delayed.

To achieve stabilization of the boundary layer at various angles of attack, compromises must be made as to the number of slots, their location, and the amount of suction flow through each slot.

A wake survey (Fig. 9) shows that, even with such compromises, suction can be effective. Without suction the wake is broad, indicating high drag. The application of suction greatly reduces the streamwise momentum loss in the wake. If the suction is applied only on one surface, as in the case demonstrated, the wake reduction will not be symmetrical (cf. Fig. 7).



8. Profile with suction slots on upper surface (indicated by arrowheads). (a) Suction off. Boundary layer is turbulent over most of upper surface. (b) Suction on. Laminar flow restored to upper surface.



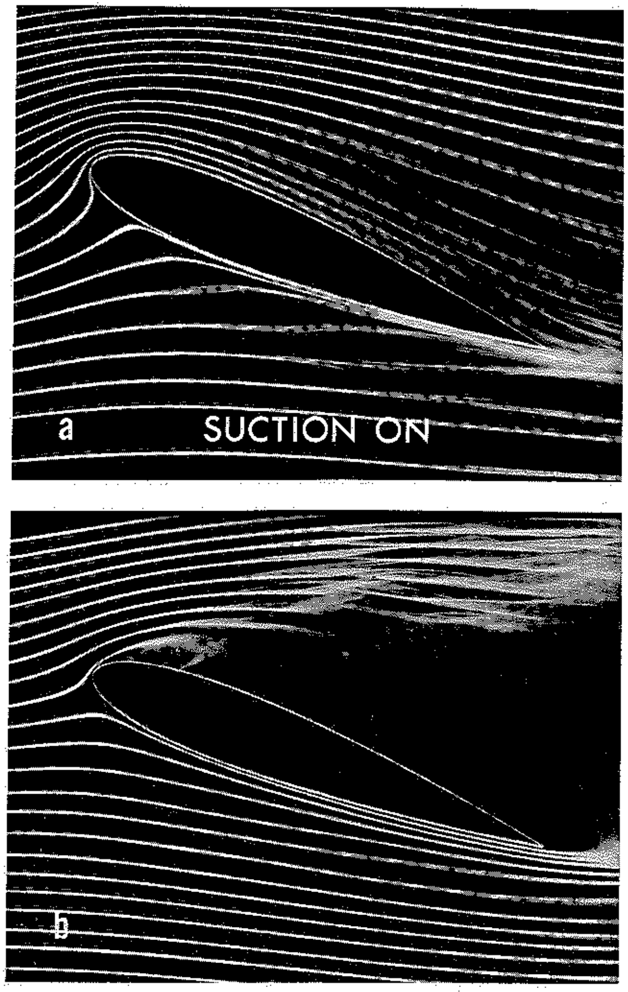
9. Manometers connected to total-head tubes illustrate wake momentum loss of multi-slotted profile. (a) No suction. (b) Suction on.

Power is needed to achieve this drag reduction. The optimum condition occurs when the total drag — the aerodynamic drag plus the suction power converted to an equivalent drag — is a minimum.

Controlling Separation by Suction

There are many cases in which control of boundary-layer separation is important. Suction can be used for this purpose, too. If a profile equipped with suction slots is placed at a high enough angle of attack (Fig. 10a), suction will not be able to maintain the entire boundary layer in the laminar state. It can, however, exert a profound effect upon the turbulent layer, frequently keeping the flow attached well beyond the angle at which stalling occurs without suction (Fig. 10b). In general, more suction power is required to attach a flow that is already stalled than to maintain attached flow at the same angle of attack.

Separation control by suction is accomplished by



10. Multi-slotted profile of Fig. 8 at high angle of attack. (a) Suction on. Separation is prevented. (b) No suction. Flow totally separates from upper surfaces.*

drawing the low-momentum layers from the bottom of the boundary layer into the suction slots. This draws the higher-energy air from the outer layers closer to the surface.

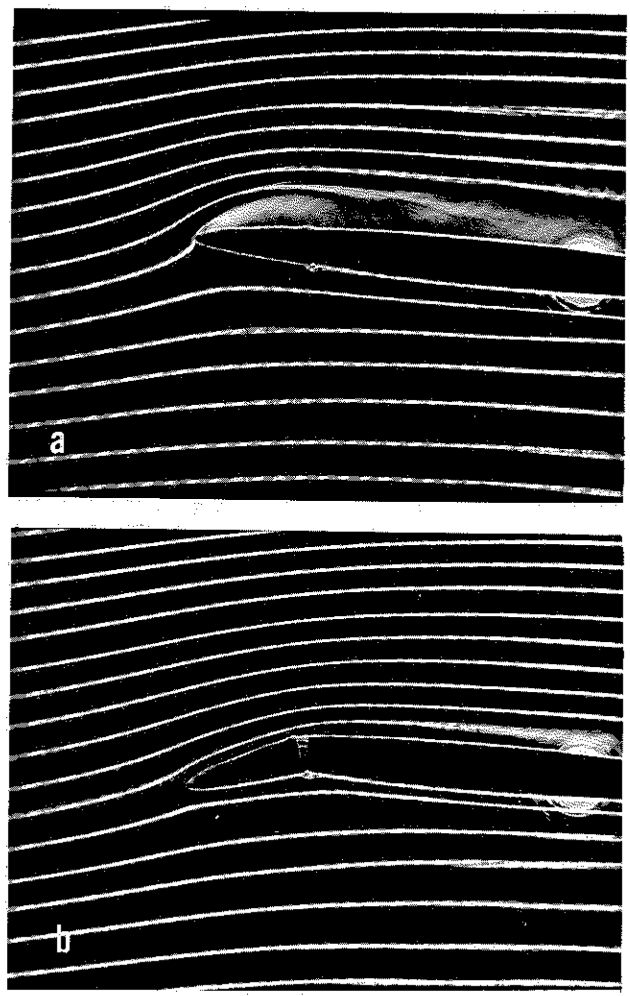
Controlling Separation by Variable Geometry and by Blowing

Separation control can also be accomplished by other techniques. Laminar separations such as those that occur at the sharp leading edge of a thin profile can frequently be avoided by a change in geometry that alters the pressure field, such as the deflection of a *nose flap* (Fig. 11).

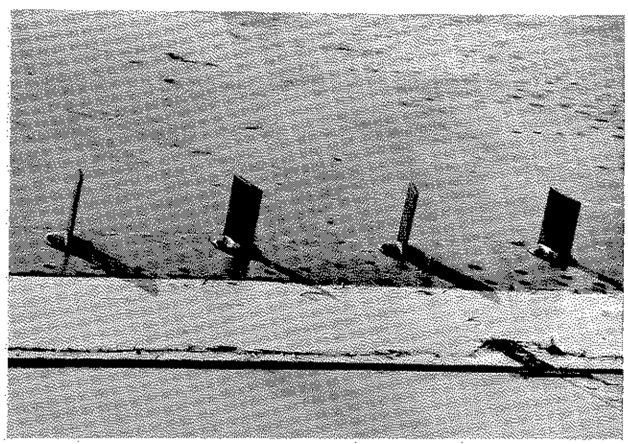
Vortex generators (Fig. 12) can help to delay separation by mixing high-momentum fluid from the outer flow with low-momentum fluid next to the airfoil surface.

Blowing jets directed into critical areas are also useful. Frequently these can be created by utilizing the pressure differences that exist on the aerodynamic bodies themselves. A *leading-edge slot* is an example (Fig. 13). When open it leads air from the region close to the stagnation point through a converging channel and ejects it at high speed at a point of low

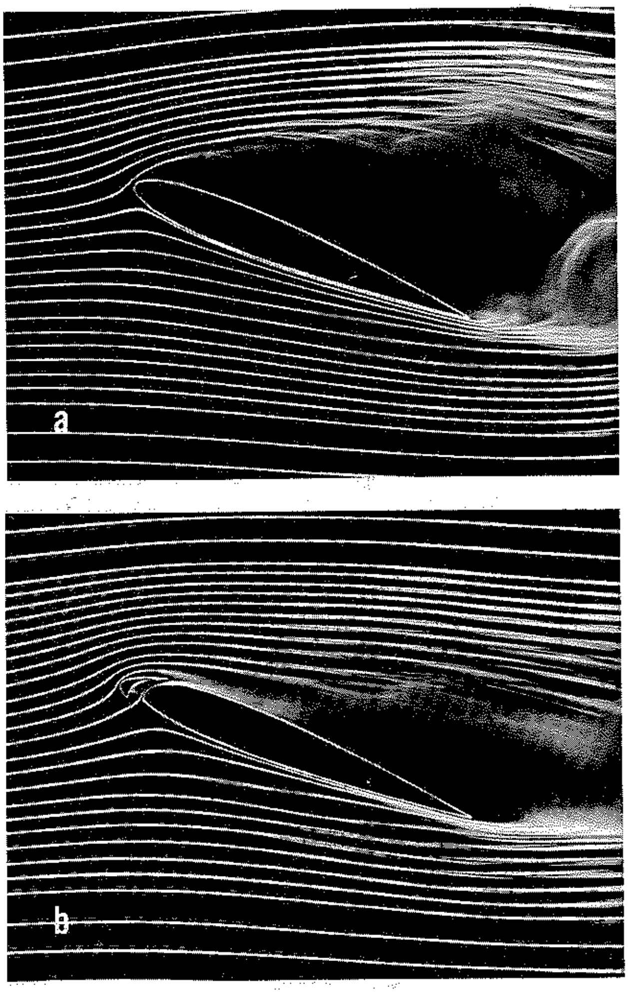
*The blurring of the smoke lines well above the airfoil is a result of disturbances from the side walls of the tunnel (where suction is *not* applied).



11. Thin profile with deflectable nose. (a) No deflection. Separation occurs at leading edge. (b) Nose deflected. Flow remains attached at leading edge.

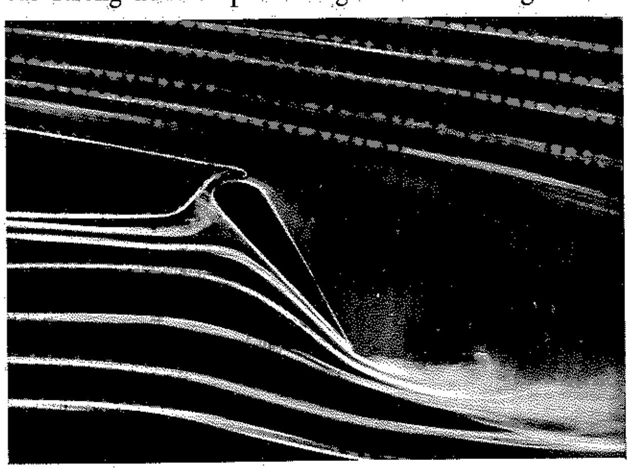


12. Vortex generators on transport-airplane wing.



13. (a) Conventional airfoil at large angle of attack. (b) Leading-edge slot reduces extent of separation.

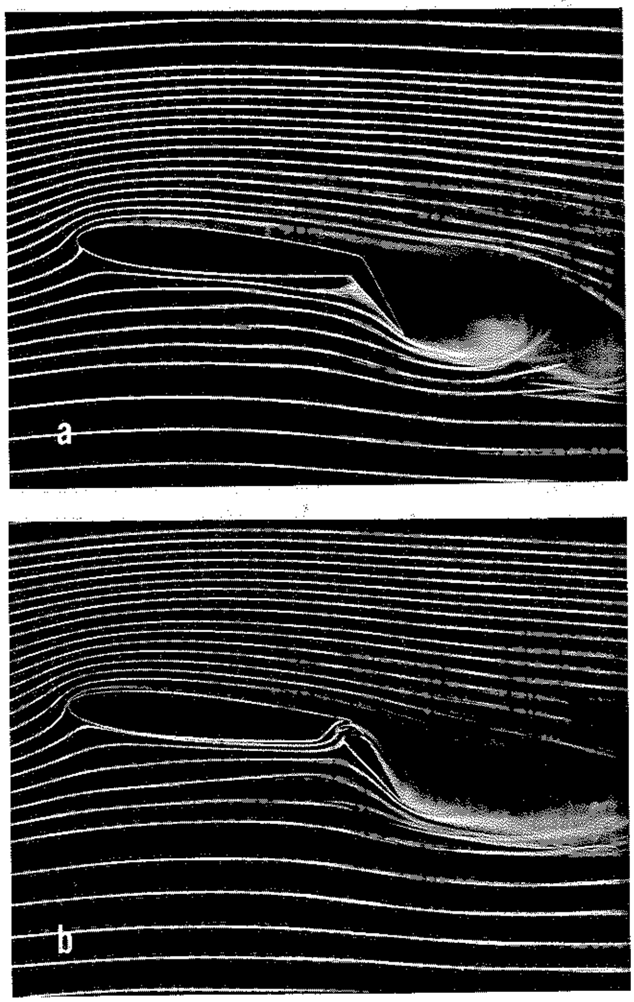
pressure on the upper surface. The same concept is used to decrease the extent of separation on deflected high-lift flaps. Fluid is led from the high-pressure region below the flap through a converging channel and ejected over the upper surface close to the point of minimum pressure (Fig. 14). This helps to overcome the strong adverse pressure gradients existing on the



14. Flow near trailing-edge flap with slot.

upper surface of the flap. Multiple-slot arrangements, though more complicated, have proven to be particularly effective (Fig. 15).*

Still greater effectiveness can be obtained from blow-

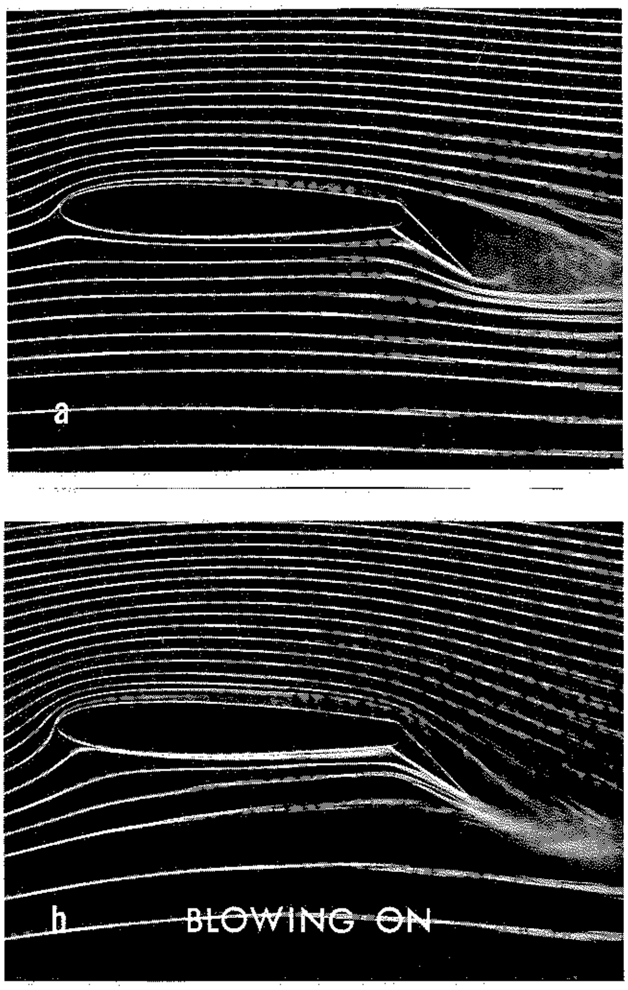


15. (a) Airfoil with deflected trailing-edge flap. (b) Multiple slots reduce degree of separation.

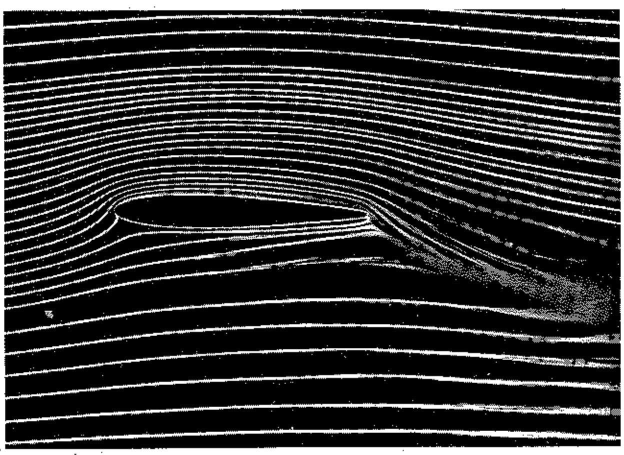
ing jets if they are produced by the direct application of power rather than by the limited pressure differentials obtainable on the body itself (Fig. 16).

If more suction or blowing is supplied than that necessary to prevent separation of the flow over a deflected flap, rather more lift is measured than would be expected from the predictions of potential theory. In the case of suction, the low pressure at the slot inlet can act like a concentrated sink, altering the potential flow in a manner that increases the lift. Blowing provides a component of direct momentum, plus a lift attributable to the pressure difference required to curve a blowing-jet sheet. This is the so-called *"jet-flap"* effect (Fig. 17).

*The smoke-emitting tubes upstream are more widely spaced near the top and bottom of the tunnel (cf. Fig. 1). Note that in Fig. 15 and in subsequent pictures some of the lower, widely-spaced smoke lines pass near the airfoils.



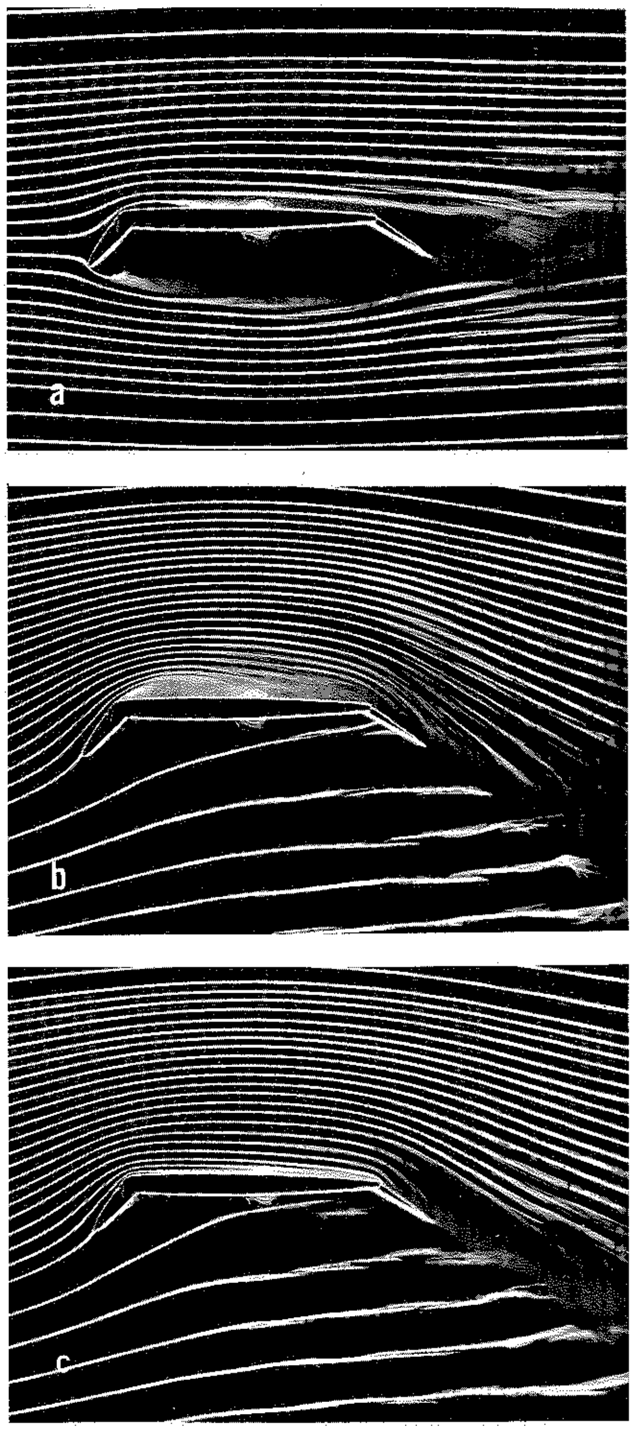
16. Profile with deflected trailing-edge flap. (a) Separation occurs over upper flap surface. (b) Jet issuing from near the hinge blows over upper surface of flap, suppressing separation.



17. Profile equipped with a deflectable jet at trailing edge shows effects of high blowing quantity and large jet-flap deflection.

Separation in More Than One Location

Care must be taken in applying the methods of boundary-layer control. Frequently, prevention of separation at one point may so alter the flow field that new separations are induced at other points. An example is a thin profile with deflected nose and trailing-edge flaps (Fig. 18). Because of severe adverse pressure gradients, major separations occur on the lower surface of the leading edge and over the trailing-edge flap, and a minor separation occurs at the break of the



18. Thin profile with deflected nose flap and trailing edge flap. (a) Separation occurs at three locations. (b) Blowing over trailing-edge flap. Separation is suppressed there, and on underside of leading-edge flap, but separation on upper surface is more severe. (c) Blowing also at break of leading-edge flap. Separation is eliminated.

leading-edge flap, followed by reattachment of the flow (Fig. 18a). When blowing is applied over the trailing-edge flap alone, separation is suppressed at this point and the flow field is so altered that the flow is reattached to the underside of the leading-edge flap (Fig. 18b). Lift has been improved, but the separation at the break of the leading-edge flap is much more severe, and the flow is separated from most of the upper surface. Total reattachment is achieved only when some of the blowing air is diverted from the trailing-edge flap and blown over the knee of the deflected nose flap (Fig. 18c).

Summary

Although only airfoil applications have been considered, the techniques of boundary-layer control can readily be applied to diffusers, to bodies of revolution, and to fluid machinery. They may, in fact, be applied wherever transition or separation of the boundary layer affects performance.

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