Investigation of Heat Transfer and of Suction for Tripping Boundary Layers

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An experimental investigation was made to determine the feasibility of tripping the laminar boundary layer on an airfoil by means of heat transfer. Model surface temperatures up to 500°F were used in heating the first 8% of the airfoil. The effect of heat transfer on both favorable and adverse pressure gradients was studied. In a second experiment, the effect of suction through an isolated hole on tripping was investigated. Three configurations of $\frac{1}{32}$-in.-diam suction holes were tested, one hole at the 1% chord point, another at 5%, and a $1\frac{1}{2}$-in. spanwise row of holes, $\frac{3}{64}$ in. apart at 2%. It was found that transition was not precipitated by either heat transfer or suction, within the limits of these experiments, for a chord Reynolds number between 1.6×10^6 and 2.46×10^6. The experimental findings for the heated leading edge were checked by the boundary-layer stability analysis, and excellent qualitative agreement was obtained.

Nomenclature

c	= $c_r + ic_i$, complex velocity, Eq. (3)
c_i	= amplification rate parameter, Eq. (3)
c_r	= velocity of propagation of Tollmien-Schlichting wave, Eq. (3)
i	= $(-1)^{1/2}$, imaginary operator for complex variable
k	= size of tripping device
p	= pressure
$R, R_k, R_\delta, R_{\delta^*}, R_x$	= Reynolds number, based on free-stream conditions; friction velocity u^*k/ν; boundary-layer thickness $u_e\delta/\nu_e$; displacement thickness $u_e\delta^*/\nu_e$; and x distance $u_\infty x/\nu_\infty$; respectively
T	= temperature
$u, \bar{u}, u^*, u_e$	= velocity: x component, normalized u/u_e, friction $(\tau_w/\rho_w)^{1/2}$, and x component at edge of boundary layer, respectively
v	= y component of velocity
x, y	= distance, along body surface and measured perpendicular to surface, respectively
α	= wave number, Eq. (3)
δ, δ^*	= thickness of boundary layer and displacement, respectively
μ	= dynamic viscosity
$\bar{\mu}$	= normalized dynamic viscosity, μ/μ_e
ν	= kinematic viscosity
$\rho, \bar{\sigma}$	= density and normalized density ρ/ρ_e, respectively
Φ	= amplitude function of the Tollmien-Schlichting wave, Eq. (3)

Subscripts

c	= chord
e	= edge of boundary layer
x, y	= derivative with respect to x and y, respectively
w	= wall
∞	= free stream
$(\ )'$	= differentiation with respect to y

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1. Introduction

THE subject matter of this paper brings to mind the old saying, "the operation was successful but the patient died." It is the story of two attempts at tripping the boundary layer by means other than roughness. Both failed, but the work is being published in the hope that it will stimulate thought on the problem and perhaps lead to a better solution for a long-standing need. The paper has scientific, if not practical, interest because of the detailed boundary-layer stability analysis contained herein, which qualitatively explains the failure of heating as a tripping device. It is this scientific success that suggested the opening quotation.

In order to simulate full-scale Reynolds numbers in wind tunnels it is often necessary to fix transition at some desired position on the model, as for instance the full-scale location. This can be accomplished in several ways. The most common method uses tripping devices of the protruding type. Either a wire or a roughness element, attached to the surface of the model in a spanwise direction, artificially precipitates transition at the desired position. Generally, the criterion for this occurrence of transition close behind the tripping device is given by a Reynolds number R_k based on friction velocity u^* and the size of the tripping device k, where k is usually the height of the roughness element or the diameter of the wire.

An alternative method of fixing transition is to inject air into the boundary layer through a row of holes on the model. According to the tests carried out in Ref. 1, the rate of air injection for transition can be very small. The minimum amount of air injection necessary to trip the boundary layer is about 0.015 times the mass flow in the boundary layer.

These methods, employed to fix transition, in order to simulate full-scale Reynolds numbers in wind tunnels, have one important drawback in common. When a boundary layer is tripped by either one of these methods, the behavior of the model is not the same as if the transition had occurred naturally at the same position. Thus, artificial tripping must be done with a minimum disturbance of the flow. Consequently, when protruding tripping devices are used, it is desirable to select optimum dimensions for them. This can easily be accomplished for one test speed by choosing the appropriate value of R_k. However, the optimum dimensions of a wire, or of a roughness element adequate to cause transition, vary with test speed and angle of attack. According to Ref. 1, the ratio of the size of the tripping device k, to the distance from the leading edge of the model x, namely, k/x, varies approximately as $(u_e k/\nu)^{-3/4}$, where u_e is the velocity just outside the boundary layer. Therefore, the size of the tripping device must be progressively decreased, with an increase in speed, in order to maintain the least disturbance necessary for transition.

Another shortcoming arises if a wire is used to fix transition on a small model at a high test speed, for even if the diameter is optimum, the increase of velocity associated with boundary-layer separation at the wire may cause a shock wave near the wire. The critical Mach number is then lower, and the rise in drag coefficient with Mach number beyond the critical occurs earlier than for the model without a wire.

Another drawback to tripping devices of the protruding type is the drag of the tripping device itself. If the drag of the model is of interest, it is necessary to determine the incremental drag of the transition device. As a first approximation, the trip drag can be assumed to be proportional to the square of the height of the device. The proportionality factor varies with section lift coefficient and has to be determined experimentally. For this reason, an accurate determination of the transition-trip drag may be quite tedious and can waste a large amount of valuable test time.

The method of fixing transition by injecting air into the boundary layer has similar drawbacks. A very small leakage of air into the laminar boundary layer causes a large increase in the profile drag of the model.[1] However, this method has the merit that the rate of air injection can be adjusted to give, at each test speed, the minimum disturbance necessary to fix transition at the desired position and will not cause a local shock wave at high test speeds.

Because of these shortcomings, the methods used at this time are not entirely satisfactory. The present study is an investigation of two attempts to find other methods for fixing transition in wind tunnels. Heat transfer was the original idea of the proposal, and it was conceived by the second author. The idea was discussed with Dr. John Williams of the Royal Aeronautical Establishment, who suggested the additional scheme of suction through holes as an alternative that might have promise. Because this second scheme was easy to incorporate in the test program, it was added. Consequently, the present study covers both techniques.

According to analysis of the laminar boundary layer, the stability is greatly influenced by the transfer of heat from the wall to the boundary layer.[2] The effect of heat transfer is analogous to the effect of an adverse pressure gradient in that it develops an inflection point in the heated velocity profiles. This destabilizing effect of heating is chiefly due to the variation of the viscosity coefficient μ with temperature, and can be explained by using the momentum equation

$$\rho u u_x + \rho v u_y = -p_x + (\mu u_y)_y \tag{1}$$

Since at the surface u and v are 0, this equation reduces to

$$p_x = [(\mu u_y)_y]_w \tag{2a}$$

where the subscript w refers to the values at the wall.

Equation (2a) can also be written as

$$(u_{yy})_w = (1/\mu)[p_x - (u_y \mu_y)_w] \tag{2b}$$

If the viscosity coefficient is taken to be proportional to the square root of the absolute temperature, then, in the presence of a temperature gradient in the y direction, μ will vary with y. For a flat plate, the pressure gradient p_x is 0, so that for a heated flat plate the temperature and consequently the viscosity coefficient will decrease with y. Since $(u_y)_w > 0$, the curvature of the velocity profile at the wall, namely, $(u_{yy})_w$, is also greater than 0. But near the outer edge of the boundary layer, u_{yy} is negative. Therefore, at some point

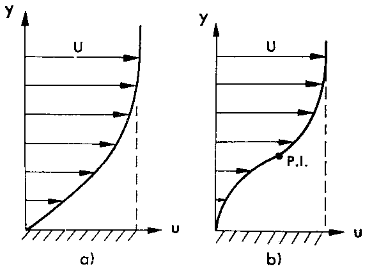


Fig. 1 Velocity distribution in a boundary layer; a) with no heat transfer, b) with heat transfer.

within the boundary layer $u_{yy} = 0$; that is, the velocity profile has an inflection point (see Fig. 1).

This destabilizing effect of heating has been fully confirmed by the experiments of Liepmann and Fila,[3] who have shown that the laminar boundary-layer velocity profiles on a heated flat plate indeed have an inflection point, and that, because of the heating, the transition point moves forward. Similar results confirming the theoretical predictions have also been obtained by Brown,[4] who has made heat-transfer measurements in a laminar boundary layer generated on the outer surface of a cylinder aligned axially with a Mach 2.5 flow. On the unheated model, transition from a laminar to a turbulent boundary layer has occurred at about $R = 1.5 \times 10^6$. With heating, transition has moved forward and has occurred at $R = 0.8 \times 10^6$.

The effect of heat transfer on the stability of flows in the presence of a pressure gradient, either favorable or adverse, cannot in general be predicted as readily as it is predicted for a flat plate. A favorable pressure gradient ($p_x < 0$) stabilizes the boundary layer, and an adverse pressure gradient ($p_x > 0$) makes it highly unstable. Since heat transfer has a destabilizing effect on the flow, heating the surface would tend to overcome the stabilizing effect of a favorable pressure gradient and thus tend to move transition forward. On the other hand, the effect of heat transfer in the presence of an adverse pressure gradient would be additive; in other words, both effects contribute to the instability of the flow. Consequently, the position of transition would tend to move forward. To find out how big this effect is with moderate heating in the presence of a pressure gradient and how much it contributes to the instability of flow with regard to moving the position of transition forward is one purpose of this investigation.

According to extensive experiments on suction, it has been shown[2] that application of a distributed suction to the surface of a body decreases the boundary-layer thickness, which stabilizes the boundary layer, and hence retards transition. On the other hand, it has also been shown that suction applied through an isolated hole is an effective means of precipitating transition.[5] The latter case can be explained as follows. Consider a two-dimensional flow over an isolated hole with suction. Since the boundary layer is rotational in nature, the transverse vorticity lines (vortex lines perpendicular to the plane of the motion) are convected with the boundary layer. A portion of each transverse vortex line may be imagined to be sucked into the perforation as it crosses it, and the part of the line just outside the perforation is stretched, as the remainder of the line drifts downstream, producing a pair of trailing vortices. Increase of suction into the perforation strengthens the trailing-vortex pair, and eventually a limit is reached when instead of diffusing and decaying without affecting transition, the trailing-vortex pair reaches a region where disturbances in the vortex amplify, and it breaks down to turbulence. With a little further increase in suction, the point of breakdown moves up to the perforation.

The experiments on suction through an isolated hole are not as extensive as those on distributed suction. More experiments are necessary to investigate the effect of various hole patterns and suction-velocity ratios on the flow and on the transition.

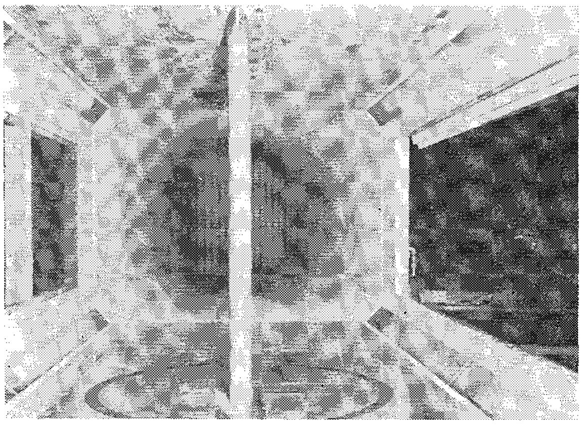


Fig. 2 Model and test section looking downstream.

2. Equipment and Procedure

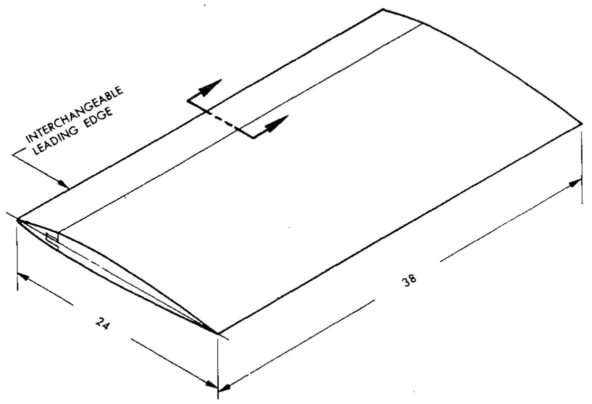
2.1 Wind Tunnel

The tests were conducted in the Douglas wind tunnel at Long Beach. This tunnel is a low-speed, atmospheric tunnel with a 6.7-to-1 contraction ratio, a 38- by 54-in. working section, and has seven low-turbulence screens. It is powered by a 100-hp electric motor driving a 4-bladed fan, giving a maximum capability for continuous running of $R/\text{ft} = 1.3 \times 10^6$ and $M = 0.20$.

2.2 Model

An existing model was used, a wing designated LB-221, which had a 3-ft span, 2-ft chord, and an NACA 64A010 airfoil section. The leading edge was detachable. Figure 2 shows the model, mounted vertically in the test section.

Two different leading edges, one for heating and one for suction, were used with the model. The leading edge used for heating was made of laminated fiberglass with a thickness of 0.060 in. Figure 3 shows the model with this leading edge. A heating element that extended to the 8%-chord point, on both top and bottom surfaces, was embedded approximately 0.006-in. below the surface. The heating elements, made by Electrofilm Inc., consisted of many small wires woven into a "ribbon" or "tape." To prevent heat loss in the streamwise direction inside the airfoil, the back of the heating elements was packed with shredded fiberglass. The heating elements were installed in the model in such a way that heat could be applied independently to the first 2%, 5%, and 8% chord, thus providing chordwise variation of the heating surface. The five 12-in.-long heating elements were symmetrically disposed about the centerline of the model and were capable of heating the surface up to 500°F with the wind blowing. Ten thermocouples made of iron and constantan were placed in the leading edge of the wing, two thermocouples for each element. Figure 4 shows a sketch of the heated leading edge.



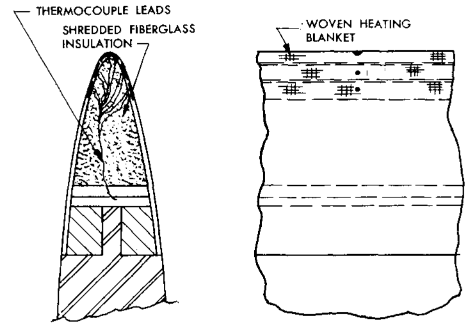


Fig. 4 Heated leading edge, schematic diagram. Heating occurred in only middle 1 ft of leading edge.

The suction leading edge was made of metal, and suction holes with a diameter of $\frac{1}{32}$ in. were drilled at midspan, as follows. One hole was located at 1% chord, eight holes in the spanwise direction were located at 2% chord with their center $\frac{3}{16}$ in. apart, and one hole was located at 5% chord. These suction holes were connected directly into a plenum chamber located as shown in Fig. 5.

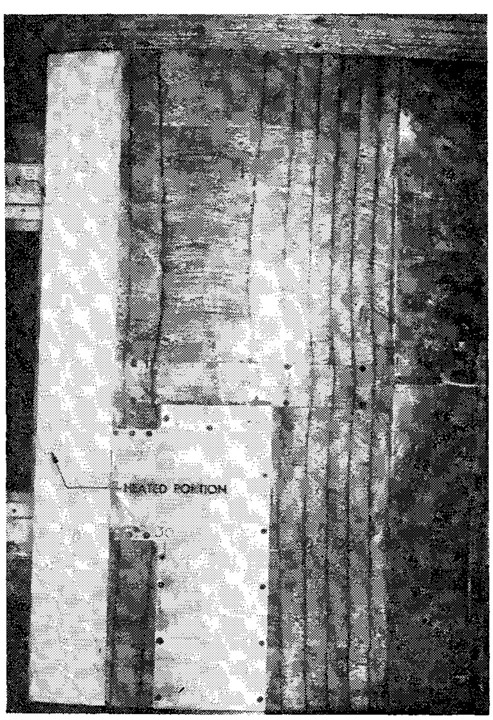


Fig. 3 Model with the leading edge used for heating.

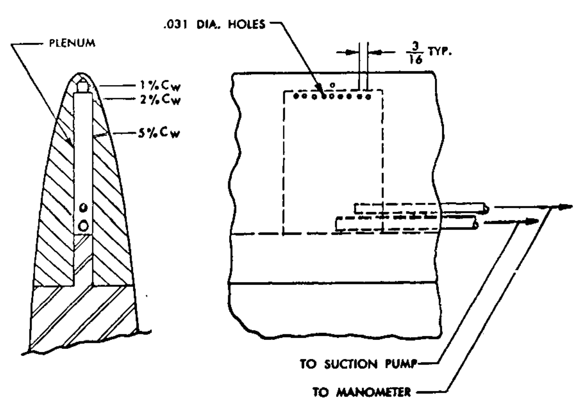


Fig. 5 Suction leading edge, schematic diagram.

2.3 Heating the Model

The leading edge of the airfoil was heated by means of the five heating elements. The temperature of the heating elements was controlled by grouping them into separate circuits. Each element was heated slowly, and the thermocouple temperatures were recorded by a Leeds and Northrup temperature recorder. The power input to each element was recorded by means of a Weston wattmeter.

2.4 Determination of Transition Point

Two methods were used to determine the transition point on the airfoil. During suction runs, the location of transition was determined by means of a china-clay technique and was checked by a stethoscope. When the leading edge was heated, only the stethoscope was used to determine transition.

3. Results and Discussion

3.1 Heat Transfer

At first the tunnel was run at $R/\text{ft} = 0.8 \times 10^6$, with the airfoil at 0 angle of incidence. The transition point on the model was recorded. The stethoscope indicated transition at 65% chord when the model was cold. The model was then heated gradually and temperatures were recorded. When the heated section of the model reached the desired uniform temperature, the transition point was checked. Periodic transition checks at various surface temperatures up to 500°F showed no signs of variation; the transition point remained at 65% chord. The same procedure was repeated for $R/\text{ft} = 1.23 \times 10^6$. Again, no change in the position of transition was observed. That is, the transition point always stayed at 65% chord.

Next, the effect of heat transfer in the presence of a more favorable pressure gradient was investigated. For an angle of incidence of 5° and $R/\text{ft} = 0.8 \times 10^6$, the transition point was recorded at 77% chord on the pressure side of the model. When the leading edge was heated, as before, and the position of transition was checked, no change was observed. The same procedure was repeated for the same angle of incidence mentioned previously, but for $R/\text{ft} = 1.23 \times 10^6$. Again, no change in the position of transition was observed. That is, the transition point was at 77% chord.

3.2 Suction

Three configurations of $\frac{1}{32}$-in.-diam suction holes were used, one hole at the 1% chord point, another at 5%, and a $1\frac{1}{2}$-in. spanwise row of holes $\frac{3}{16}$ in. apart at 2%. Ratios

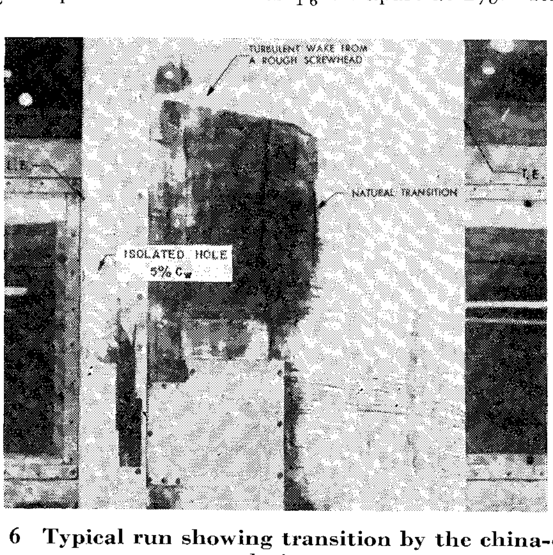


Fig. 6 Typical run showing transition by the china-clay technique.

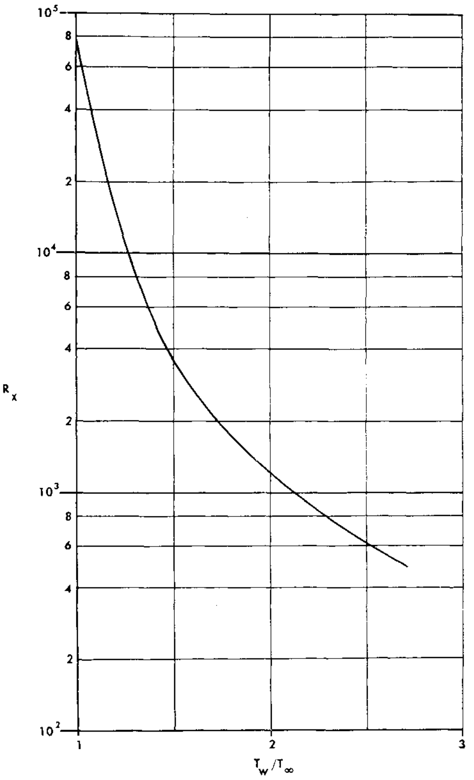


Fig. 7 The minimum critical x-Reynolds number as a function of wall temperature for a flat plate at low speed for Tollmien-Schlichting waves.

of suction velocity to tunnel velocity of up to $v/u_\infty = 1$ were used, with the same Reynolds numbers as those of the heat-transfer tests, 0.8×10^6 and 1.23×10^6 per ft.

At first, only the hole at 1% was used while the others were plugged with carefully smoothed cellophane tape. As in the heat-transfer tests, transition occurred at 65% chord. Then, only the suction holes at 2% were used, with the rest plugged as before. Again, there was no apparent change in transition. The same result was obtained when only the suction hole at 5% was used. When the suction hole at 5% was enlarged to $\frac{1}{16}$-in. diameter and the same procedure was followed, no significant change in the transition point was observed.

The determination of transition position in all the suction tests was investigated by using the china-clay technique, and the results were checked by means of a stethoscope. Figure 6 shows a photograph of the model with china clay, indicating the (invariant) transition when the isolated suction hole at 5% was used.

4. Discussion

The effect of heat transfer on transition, in the absence of a pressure gradient in both subsonic and supersonic flow, is a well-studied and well-known phenomenon.[3,6,7] According to these studies, surface heating has a marked effect upon transition and consequently upon the transition Reynolds number. Figure 7 shows the results of such a study. According to this figure, the Reynolds number at the onset of instability decreases with increased temperature ratio. For a flat plate with an absolute temperature ratio of 2, the Reynolds number decreases by a factor of about 100. Hence, there would be no difficulty in simulating free-flight conditions in a wind tunnel with a heated model, providing the pressure gradient does not tend to cancel the heat-transfer effect.

The effect of heat transfer in the presence of a pressure gradient has not been investigated so far, either experi-

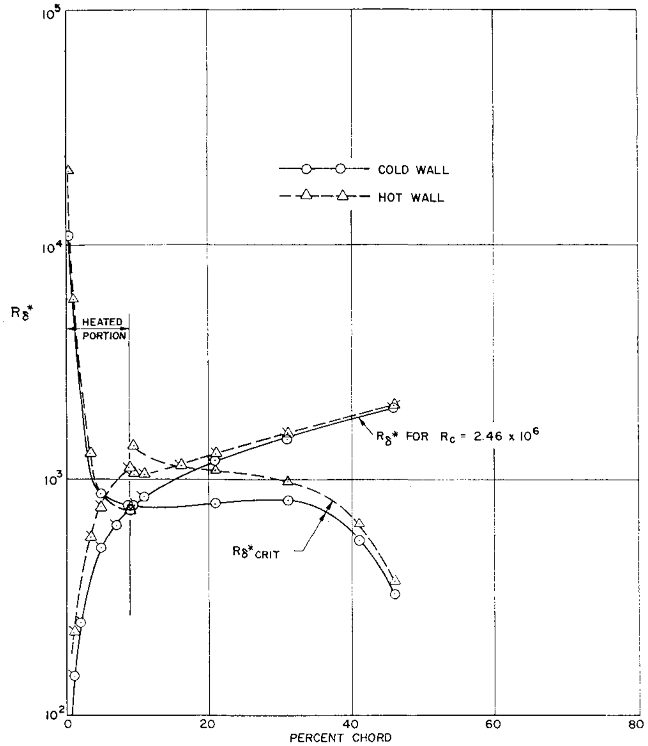


Fig. 8 Effect of heat transfer on the position of instability for the test model (T_W = 400°F, zero angle of incidence).

mentally or theoretically. For some time before this contract was received, work on methods of calculating boundary layers and boundary-layer stability had been going on in the Aerodynamics Research Group at Douglas Aircraft Company, Aircraft Division. For this reason, when the contract was received, an attempt was made to correlate the experimental results with theory, by determining the critical Reynolds number at various stations along the test model. The stability equation, namely, the Orr-Sommerfeld equation, was modified to account for the fluid properties in the boundary layer. The final form of the equation used is

$$\Phi'''' - 2\alpha^2\Phi'' + \alpha^4\Phi = (i\bar{\rho}\alpha R_\delta/\bar{\mu}) \times \{(\bar{u} - c)\Phi'' - [\alpha^2(\bar{u} - c) + \bar{u}'']\Phi\} \quad (3)$$

where the bars denote the quantities normalized with respect to the edge values. To solve this equation, one needs to know the velocity profile, together with fluid properties at each desired station of the test model. For this reason, an existing program[8] was at first used to obtain these quantities. The pressure distribution for zero angle of incidence (theoretical) was taken from Ref. 9. The first 8% of the model was assumed to be at a uniform temperature of 400°F with R/ft = 1.23 × 10⁶. The remainder of the model was considered to be at the temperature of the main stream, namely, at 100°F. The velocity profiles and fluid properties obtained under these conditions were then used in solving Eq. (3) numerically to obtain the critical Reynolds number based on displacement thickness ($R_{\delta^*\text{crit}}$). In all, eight stations were considered for both the heated and the cold airfoil. The results are shown in Fig. 8. The curves labeled R_{δ^*}, for $R_c = 2.46 \times 10^6$, are plots of the actual R_{δ^*} for this airfoil at this Reynolds number. The curves $R_{\delta^*\text{crit}}$ show values of R_{δ^*} at which the boundary layer becomes unstable. Hence, if R_{δ^*} existing on the model is less than $R_{\delta^*\text{crit}}$ at a particular x station, the boundary layer is stable. If R_{δ^*} existing on the model is greater than $R_{\delta^*\text{crit}}$, the boundary layer is unstable. Figure 8 shows that the cold model becomes unstable at about 9% chord, and heating has a relatively weak effect, moving the instability point only about 4% forward. Since transition is usually far downstream of the instability point, this small forward movement is insufficient to move transition on to the heated surface.

Another interesting fact is shown in Fig. 8. In flowing over the heated nose, the boundary layer is warmed; then it encounters the unheated surface, which affects it like a cool wall, and has a stabilizing effect. In fact, for a few percent chord the heated boundary layer becomes stable again, finally attaining permanent instability at about 13% chord. Thus the plot shows that the aft portions tend to neutralize any of the destabilizing effects of the nose, and, consequently, lack of the effect on transition is not surprising. Unfortunately, this kind of stability analysis was beyond the state of the art when the work began. Otherwise the negative results might have been anticipated.

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