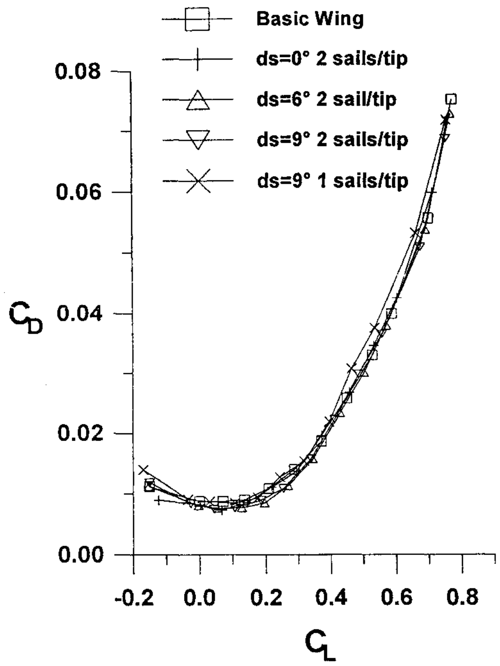

Fig. 3 Effect of delta planform tip sail incidence angle on drag polar.

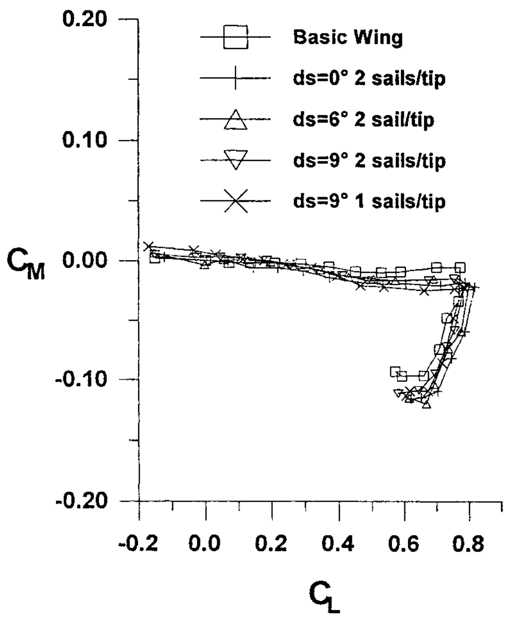

Fig. 4 Effect of delta planform tip sail incidence angle on pitching moment coefficient.

probably due to this tip configuration experiencing a lift increment resulting from suction induced by the wingtip vortices.[10]

Concluding Remarks

This study details an investigation of the effect of delta planform tip sail incidence on wing performance. The results suggest that based on an equal AR comparison, sails have a negligible effect on lifting performance, except for a moderate increase in the maximum lift coefficient. The wing's zero lift angle of attack becomes increasingly positive as the sails' incidence angle is increased. Reductions in drag compared to the basic wing were observed for sail angles of 6 and 9 deg for C_L ranging from 0 to 0.37. Using only one sail/tip resulted in a reduction in performance compared to the basic wing.

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Wall Temperature Effects on the Stability of Laminar Boundary Layers

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Nomenclature

h = nozzle throat height
L = distance from nozzle entrance
M = freestream Mach number
N = N factor in e^N for Tollmien–Schlichting wave
p = pressure
T_{aw} = adiabatic wall temperature, °R
T_w = wall temperature, °R
u = boundary-layer velocity in the x direction
u'' = second velocity derivative in y
x, y = coordinates in streamwise and normal directions
μ_w = viscosity coefficient

Introduction

A UNIQUE, low-disturbance supersonic wind tunnel is being developed at NASA to advance supersonic laminar flow studies at cruise Mach numbers for the High Speed Civil

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Transport. The distinctive aerodynamic features of this new quiet tunnel will be a low-disturbance settling camber, laminar boundary layers on the nozzle walls, and steady supersonic diffuser flow.

It is anticipated that design requirements of the nozzle for the full-scale laminar flow supersonic wind tunnel must include the active control to laminar boundary layer on the nozzle wall to maintain the boundary-layer laminar. In other words, the active control of supersonic transition on nozzle walls is necessary to preserve the laminar boundary layer. Because of the novel drive system, there is no easy way to implement a suction-type boundary-layer device. The alternative is to use heating or cooling applied along the nozzle wall. Therefore, the effects of supersonic laminar flow with distributed wall surface heating and cooling for active control are studied and reported in this Note. To validate the prediction and analysis tools, a flat plate case is chosen in the study before the effects of wall temperature on a supersonic wind tunnel are evaluated.

Methods of Approach

The methods used to characterize the state of the stability are 1) stability modifier criterion based on the curvature of the boundary-layer velocity and 2) a spatial linear stability method to computer N factors for Tollmien–Schlichting waves. The latter method may be used to predict the transition onset location as N factor = 9 to 11. The calculation is carried out by two basic computational fluid dynamics (CFD) codes: a compressible boundary-layer code by Harris,[1] and a linear stability code by Malik.[2] The detailed boundary-layer velocity profiles calculated by the boundary-layer code are utilized to qualitatively analyze the state of boundary-layer stability based on the stability modifier criterion.[3] The outputs of the boundary-layer code also provide the inputs into the Malik's stability code to determine the value of the N factor. The results of these two criteria have indicated the consistent prediction for the state of the boundary-layer stability.

Effects on a Flat Plate and a Supersonic Nozzle

The wall temperature effects on the stability of the laminar boundary layer are investigated on a flat plate at supersonic speed as well as a supersonic tunnel nozzle wall. With specific temperature distributions by heating or cooling on the flat plate or tunnel wall, the stability of the laminar boundary layers is examined to determine the effects of stability characteristics. Subsequently, the supersonic laminar flow can be controlled by cooling or heating the wall at specific locations on a flat plate or tunnel nozzle.

Flat Plate in Supersonic Flow at M = 1.6

The plate with no pressure gradient is heated from T_{aw} = 502°R to T_w = 802°R uniformly. The temperature distribution of the plate is calculated for three cases: T_{aw} = 502°R, T_w = 802°R local strip heated within $0 < x < 10\%$ of the plate, and T_w = 802°R uniformly heated. The temperature profiles at the end of the plate of these three cases are used to examine the velocity curvature of the boundary layer. The velocity curvature, based on the two-dimensional boundary-layer momentum equation in the vicinity of a wall, which is assumed no suction or blowing, is given by Reshotko[3] as follows:

$$\mu_w u'' = -\frac{\partial \mu}{\partial T}\frac{\partial T}{\partial y}\frac{\partial u}{\partial y} + \frac{\partial p}{\partial x}, \quad \text{at} \quad y = 0 \qquad (1)$$

It is seen that the boundary-layer velocity curvature depends on the temperature gradient. The velocity curvature of uniformly heated case, T_w = 802°R, is positive since this case produces a large negative temperature gradient at the wall. The local heating strip case results in a positive temperature gradient at the wall and thus produces a negative velocity curvature. The velocity curvature at the end of the plate for adiabatic and local strip heating cases is plotted in Fig. 1. For the local strip heating case, the second derivative of velocity at the wall has a negative value. Based on the criterion of Eq. (1), the boundary-layer stability of the locally heated case is enhanced. The N factor of the spatial linear stability theory of e^N is computed by e^Malik code (a spatial stability analysis program for transition prediction, see Ref. 2), for several frequencies as shown in Fig. 2. The maximum N factor for the adiabatic case is about 3.7 and may be reduced to about 1.8 for the local strip-heating case. This indicates that the boundary-layer stability is enhanced by heating upstream locally. But for the uniformly heated case also shown in Fig. 2, the N factor increases to 9, which destabilizes the boundary layer.

Supersonic Nozzle at M = 1.6

Local heating and cooling strips are applied at $2.86 \le X \le 3.73$ (in.) downstream of the nozzle entrance at station X = 0 at 600 and 400°R, respectively. The total length of the NASA PoC nozzle and test section from the nozzle entrance to the test-section exit is 9.23 in. (units) as shown in Fig. 3a with heating and cooling strips marked. At the exit of test section X = 9.23 in., the values of the velocity curvatures at the wall for the heating, adiabatic, and cooling cases, i.e., the second derivative of boundary-layer velocity profiles based on Eq. (1), are -5.72×10^{-4}, -7.02×10^{-5}, and $+1.05 \times 10^{-3}$,

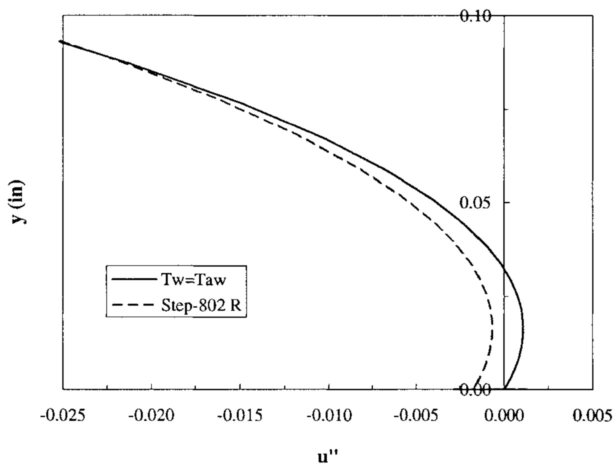


Fig. 1 Second velocity derivative profile for a flat plate laminar boundary layer with strip heating.

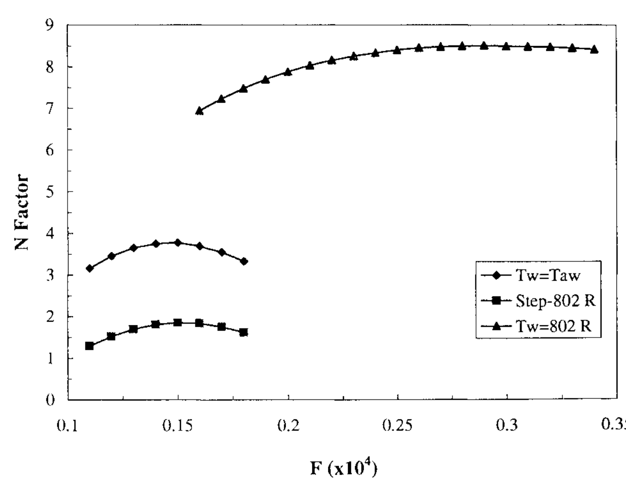
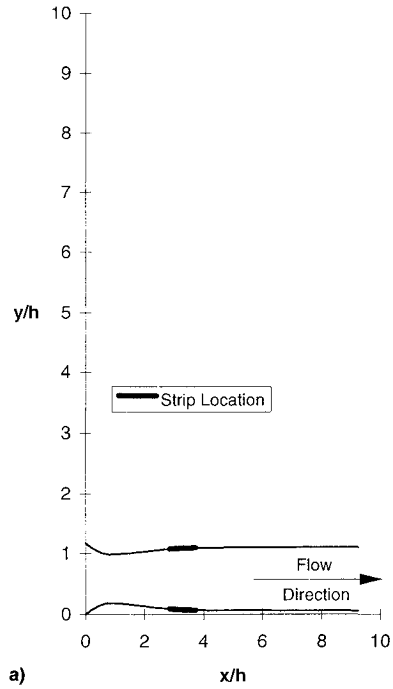


Fig. 2 N factors with strip heating for a flat plate.



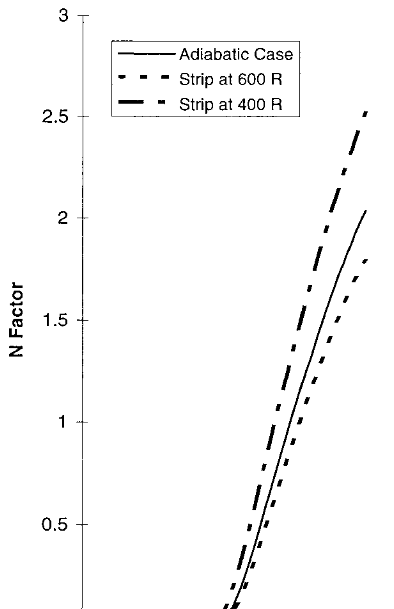


Fig. 3 *N* factor growth with the heating/cooling strip located at 2.86 ≤ *X* ≤ 3.73 for a disturbance frequency of 14 kHz for a NASA supersonic tunnel: a) heating/cooling strip location on the nozzle and test section and b) *N* factor growth along the nozzle and test section.

respectively. Among these three cases, the value of the heating strip case is negative and smaller than those of the cooling and adiabatic cases. This indicates the heating case is more stable than the other two cases. The results of *N* factor from e^Malik code are plotted in Fig. 3b for the *N* factor along the wall of the nozzle and test section where the heating and cooling strip is located at $2.86 \leq X \leq 3.73$ for a disturbance frequency of 14 kHz. The adiabatic case is also plotted in Fig. 3b for reference. The results of the local heating case with 600°R also show that the boundary layer has been stabilized. The results of the local cooling case with 400°R indicates the destabilization of the boundary layer on the nozzle and test-section wall. The *N* factor theory that provides the *N* factor from the initial instability point to the exit of the test section has shown the relative stability among three cases in Fig. 3. It should be noted that results obtained from both the curvature criteria and *N* factor theory have presented the consistent conclusion, the heating strip stabilizes the boundary layer.

Concluding Remarks

The present results show that heating and cooling in a local finite wall region can enhance and destabilize the stability of laminar boundary layers, respectively. Several previous classical theoretical and experimental studies have concluded that the boundary-layer stability will be destabilized with uniform wall heating.[4] On the other hand, the uniformly cooled wall will enhance the boundary layer.[5-7] The present findings indicate that the stability is enhanced as the heating is applied at the upstream of the boundary-layer instability initiated point. Thus, the heating energy flowing downstream creates a positive temperature gradient in the vicinity of the wall ahead of the instability occurring location. This produces cooling effects in the region near upstream of the instability location, and therefore, enhances the boundary-layer stability. The stability is reduced as the cooling is utilized at the same location, since it produces heating effects at the instability point. These results seem to show the same effects as the previous studies except the present mechanism of cooling or heating is localized and limited in certain upstream regions of a flat plate, e.g., the leading edge (10%) of the flat plate or a region downstream of the nozzle throat. The latest theoretical study by Masad and Nayfeh[8] has provided similar results limited to the subsonic flat plate case only. The experimental evidence obtained by Demetriades[9] recently has also indicated a similar trend by heating the throat region's wall to enhance the stability or delay the transition in the boundary layer of a supersonic nozzle. The application of strip heating to the quiet-tunnel's boundary-layer control seems feasible, especially since the heating region is within a limited range of segments.

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