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Hypersonic Boundary-Layer Transition on Ablating and Nonablating Cones

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Introduction

IN the design of re-entry vehicles, effects of the ablating protective heat shield on the vehicle flowfield are especially important with high-performance, slender configurations. Mass transpiration, nose shape changes, and surface roughness are a few of the parameters that can alter the location of natural boundary-layer transition, thus affecting the local surface heat transfer and vehicle aerodynamic characteristics. Recent results of investigations dealing with boundary-layer transition on ablating cones are given in Ref. 1–4, but limited data exist concerning actual magnitudes of reductions in the transition Reynolds number due to ablation. Here, we present preliminary results from an experimental investigation conducted to determine the effect of ablation on transition on slender cones at a nominal Mach number of 7.

Discussion

The ablating models used in this investigation were 10° half-angle cones with an axial length of 12 in., composed of paradichlorobenzene ($C_6H_4Cl_2$), which is a low-temperature subliming material with uniform ablation rates. A sharp stainless-steel nose tip prevented blunting and maintained "sharp cone" conditions at the boundary-layer edge. The ablating models were identical in initial external geometry to the nonablating model that was instrumented with thermocouples for heat-transfer measurements.

The investigation was conducted in the Langley 11-in. hypersonic tunnel. Tunnel stagnation pressure varied from 185 psia to 609 psia for a range of freestream unit Reynolds numbers of 1.68×10^6–6.21×10^6/ft. For the ablating models, tunnel stagnation temperature was about 1280°R, whereas for the metal model, tests were conducted at stagnation temperatures of about 1055° and 1280°R, giving a slight variation in the ratio T_w/T_t in order to assess the effect of these small changes in tunnel conditions on boundary-layer transition. The freestream Mach number was between 6.82 and 6.88 depending on unit Reynolds number.

Results

Transition was determined from Stanton number distributions for the metal nonablating model, and by surface recession measurements for the ablating models. The beginning of transition for the metal model was the surface location where the Stanton numbers began to deviate from laminar theory, and the end of transition was taken as the peak Stanton number. For the ablating model, surface recession was measured at three peripheral locations about each ablated model, $\phi = 0°$, 90°, and 180°, with the start of transition taken as the location where surface recession began to increase from the measured laminar value. There was no significant unsymmetrical transition observed so the average of the three readings was taken as the transition location.

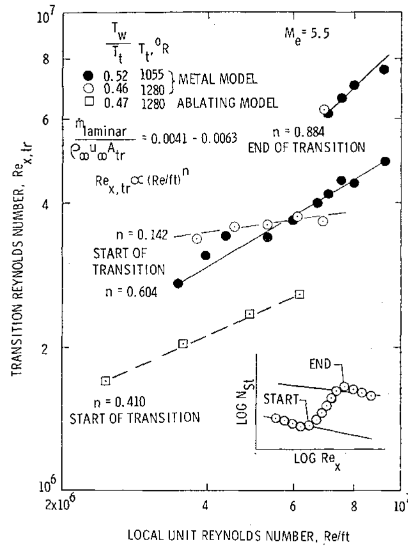

Fig. 1 Effect of mass addition on transition Reynolds number on a slender cone.

Transition Reynolds numbers for both the metal cone and the ablating cones are presented in Fig. 1. Transition Reynolds numbers for the ablating cones were about 30–40% lower than those for the metal cone for nondimensional mass ablation rates of $\dot{m}_{\text{laminar}}/\rho_\infty u_\infty A_{\text{tr}} = 0.0041$ to 0.0063. In this expression $\dot{m}_{\text{laminar}}$ represents the amount of mass injected into the laminar boundary layer and A_{tr} is the cross-sectional area of the cone at the start of transition. As a comparison, results from Ref. 4 on an 8° half-angle ablating cone ($C_6H_4Cl_2$) at $M_\infty = 10$ and with $\dot{m}_{\text{laminar}}/\rho_\infty u_\infty A_{\text{tr}} = 0.0070$ to 0.0076 indicate a 6–12% reduction in transition Reynolds number.

In the present ablation tests, a rearward facing step was formed at the interface of the ablation material and the nonablating steel tip. The maximum value of this step (end of test run) was about 0.040 in. However, this step was not believed to influence transition significantly based on studies in Ref. 3 with oversized tips on a metal cone model at nearly the same local Mach number as in the present experiment. For Larson's tests the rearward facing step was 0.05–0.10 in. and the transition Reynolds number was reduced a maximum of 10%. In addition, unpublished data obtained by Stainback at Langley on a 5° half-angle slightly blunted cone at $M_\infty = 8$ with a rearward facing step of 0.040 in. indicate no noticeable effect of the step on transition over a local Mach number range of 3.7–6.3. The effect of these steps on transition is more pronounced in the lower supersonic Mach number range, as noted in Ref. 5.

The unit Reynolds number effect on transition varied from weak to strong for the ablating and nonablating transition Reynolds numbers. From the faired lines through the data, power-law relations of the form $Re_{x,\text{tr}} = C(Re/\text{ft})^n$ were calculated. The resulting values of the power-law exponent were $n = 0.410$ for the ablating cones at $T_w/T_t = 0.47$ (start of transition), $n = 0.142$ for the metal cone at $T_w/T_t = 0.46$ (start of transition), $n = 0.604$ for the metal cone at $T_w/T_t = 0.52$ (start of transition), and $n = 0.884$ for the metal cone at $T_w/T_t = 0.52$ (end of transition).

Considering the metal cone data separately, the transition Reynolds numbers were less sensitive to local unit Reynolds number for $T_w/T_t = 0.46$ ($T_t = 1280°$R) as indicated by the $n = 0.142$ power-law exponent. The normal method of varying the wall temperature ratio is to cool the model internally,

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thus varying T_w. However, in the present tests the stagnation temperature was varied to produce a slight change in T_w/T_t. This change in the stagnation temperature level may have influenced the behavior of transition by altering the effect of other interrelated parameters, such as radiated aerodynamic noise from the tunnel sidewalls. The metal cone transition data illustrates the sometimes inconsistent behavior of transition in conventional wind tunnels.

Conclusions

Transition Reynolds numbers were lower for the ablating cones as compared to the nonablating cone, indicating an influence of mass injection on transition. There was a strong unit Reynolds number effect on the ablating cone transition Reynolds numbers. Transition Reynolds numbers obtained on the metal cone displayed both a weak and strong effect of unit Reynolds number, depending on the tunnel stagnation temperature, and thus indicated an influence of small changes in tunnel conditions on boundary-layer transition.

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Shock-Wave Shapes on Hypersonic Axisymmetric Power-Law Bodies

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In this Note experimental observations are reported on the shock-wave shapes over axisymmetric power-law bodies, of the form $y \sim x^{m_b}$, situated in a hypersonic flow. These measurements were made in an attempt to verify certain aspects of asymptotic hypersonic flow theory, where the term asymptotic refers to the flowfield at large distances downstream of the nose of the body. Although the calculation of the asymptotic flowfield for power-law bodies has received considerable attention in the past few years, relatively few experimental observations appear to have been reported in the literature. Freeman, Cash, and Bedder[1] made observations on the shock shapes over seven axisymmetric power-law bodies for values of the exponent m_b in the range $0 \leq m_b \leq 1$, and concluded that the comparison between theory and experiment was far from satisfactory. Kubota[2] reported more complete data on the asymptotic flowfields, including shock shapes, surface pressure distributions and shock layer pressure traverses, for three axisymmetric power-law bodies with $m_b = \frac{1}{2}, \frac{2}{3}$, and $\frac{3}{4}$. Other data on axisymmetric shock shapes have been obtained by Peckham[3] and appear to be similar to those of Ref. 1. Information on the flowfields and shock shapes over plane power-law bodies has been reported by Hornung[4] for $m_b = \frac{1}{2}$ and $\frac{5}{8}$.

It is well known that when the freestream Mach number M is sufficiently large, the hypersonic small-disturbance equations possess similar solutions for the asymptotic shock-wave shapes over power-law bodies. These solutions state that the shock-wave shapes for axisymmetric power-law bodies are given by $y \sim x^{m_s}$, where

$$m_b = m_s \quad \text{for} \quad \tfrac{1}{2} < m_b \leq 1 \tag{1a}$$

and

$$m_b = \tfrac{1}{2} \quad \text{for} \quad 0 \leq m_b < \tfrac{1}{2} \tag{1b}$$

The solutions (1a) were obtained by Lees and Kubota,[5] and correspond to the situation in which the asymptotic flowfield is dominated by the shape of the body. The solutions (1b) are the blast-wave analogy solutions of Lees[6] and Cheng and Pallone,[7] and are appropriate to those body shapes in which the asymptotic flowfield is dominated by the nose bluntness of the body. The solutions (1) may be used as first approximations in asymptotic solutions for the shock-wave shapes. This is discussed by Freeman,[8] who shows in particular that for the range $\frac{1}{2}\gamma < m_b < \frac{1}{2}$ the first correction term to the blast wave solution is due to the perturbation introduced by the body shape. The correction to the shock shape and to the asymptotic flowfield in general for this range of m_b has been computed by Hornung.[9]

In this work a comprehensive study has been made of shock-wave shapes on axisymmetric power-law bodies in the range $0 \leq m_b \leq 1$ in an attempt to verify the first-order solutions (1). Comparisons are made with the results of Freeman and co-workers, and the effects of Hornung's correction term to the first-order solution for $m_b = 0.4$ are indicated.

The experiments were run in the Rosemount Aeronautical Laboratory 12-in. × 12-in. hypersonic wind tunnel at a freestream Mach number of 7.0. Most of the runs were made at a stagnation pressure of 115 psia and a Reynolds number of 6×10^6/in. Several tests were repeated at a stagnation pressure of 135 psia and a corresponding Reynolds number of about 10^7/in. No evident trends in the final data with Reynolds number could be detected. Two families of power-law bodies were used, each family consisting of eight models with values of m_b of 0, 0.1, 0.25, 0.4, 0.5, 0.7, 0.85, and 1.0. The lengths of the two sets were 7 in. and 4 in., and all bodies had a maximum diameter of 2 in. Shock shapes were mea-

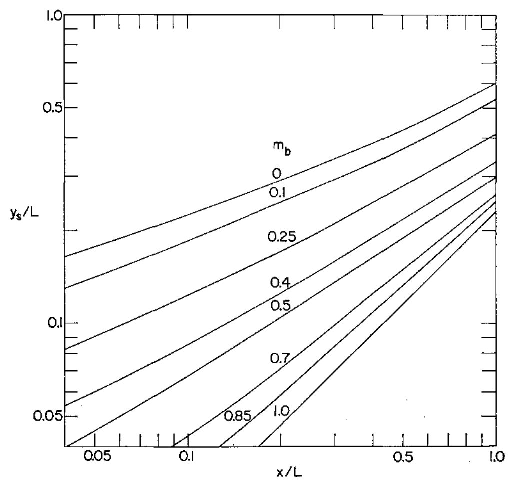

Fig. 1 Typical shock-wave shapes for 7-in. bodies (M = 7.0).

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