Sensitivity of Boundary-Layer Transition to Surface Irregularities for Space Shuttle Applications

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Introduction

THE purpose of this note is to illustrate the sensitivity of boundary-layer transition on hypersonic lifting geometries at high angles of attack (α) to relatively small amounts of surface roughness (irregularities). Tests were conducted in the AEDC-VKF Hypervelocity Wind Tunnel F (Hotshot), on a 0.011-scale model of the McDonnell Douglas (MDAC) Phase B, STS Orbiter configuration[1] at simulated hypersonic re-entry conditions. Measurements of laminar, transitional, and turbulent flow heating rate distributions and the location of boundary-layer transition were obtained. Selected data are presented for a freestream Mach number (M_∞) of 10.8 and $\alpha = 40°$.

Results and Discussion

The model profile with a few pertinent dimensions is presented in Fig. 1. Theoretical model centerline distributions of surface pressures (p_s) normalized by the freestream pitot pressure (p_o'), surface Mach number (M_e) and local surface Reynolds number (Re_e) for two freestream Reynolds number (Re_∞) values are shown in Fig. 1. The theoretical calculations were based on inviscid, conical flow (tangent cone) calculations.[2]

Experimental centerline heating rate ($\dot{q}$) distributions for laminar, transitional and fully turbulent flow conditions are shown in Fig. 2 and compared with theoretical calculations. The theoretical distributions were calculated by a cross-flow method in conjunction with conical flow edge conditions.[2] Good agreement between the experimental and theoretical laminar and turbulent results is shown.

The data in Fig. 2 represent both "smooth body" transition data and "tripped" transition data affected by model surface roughness (irregularities). To obtain the "smooth body" transition data, it was necessary to remove the first three heat-transfer gages on the model windward centerline and fill the 0.25-in. diam holes with a contoured metal plug. This was required even though the measured discontinuities over the first three gages were less than 0.001 in. The surface finish with the metal plugs installed was $\lesssim$ 20 rms μin.

The use of the definition "smooth body" transition data is preferable to "natural" transition because of the effect of freestream aerodynamic noise disturbances on transition.[3,4] The interaction between aerodynamic noise disturbances and surface roughness at supersonic speeds was reported in Ref. 5.

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Index categories: Boundary-Layer Stability and Transition; Supersonic and Hypersonic Flow.

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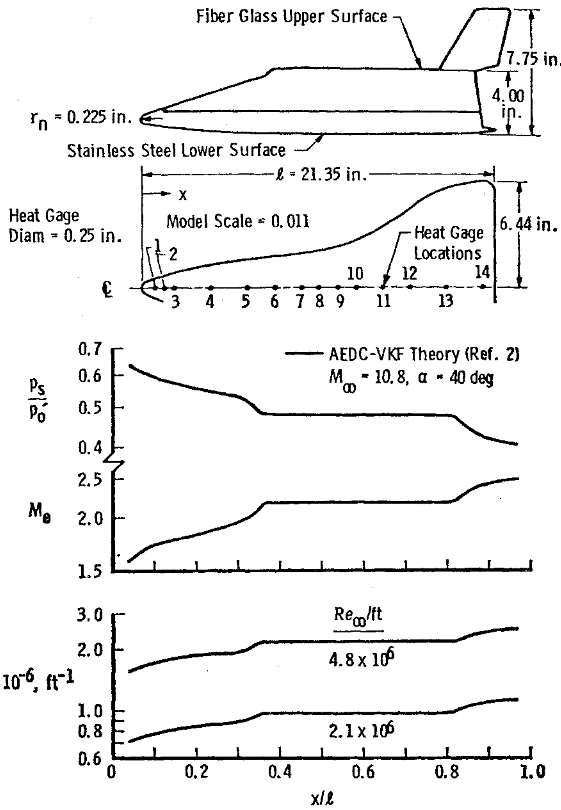

Fig. 1 Inviscid lower surface centerline parameters.

A direct comparison of the "tripped" and "smooth body" transition locations as a function of Reynolds number, as shown in Fig. 3, is perhaps the easiest way to determine if the boundary layer was tripped. As clearly shown, the deviation of the "tripped" data from the "smooth body" transition locations is quite dramatic.

Sym	Time from Initial Starting Wave, msec	Re_∞/ft x 10^{-6}	x_t, in.	
○	55	5.60	1.1	Boundary Layer Tripped by Presence of First Three Heat Transfer Gages
□	85	3.85	2.4	
◇	127	2.75	3.7	
◁	148	2.24	11.7	
●	91	5.82	6.9	Smooth Body Transition Data (First Three Heat Gages Removed)
▲	103	4.82	9.5	
■	130	3.86	11.4	
⬥	152	3.29	14.6	

q_0 = Stagnation Heat Transfer Rate on a 0.132-in. Nose Radius (Corresponds to a 2-ft-Diam Hemisphere Scaled down to 0.011) As Determined from a 1.0-in.-Diam Hemisphere Tunnel Monitor Probe

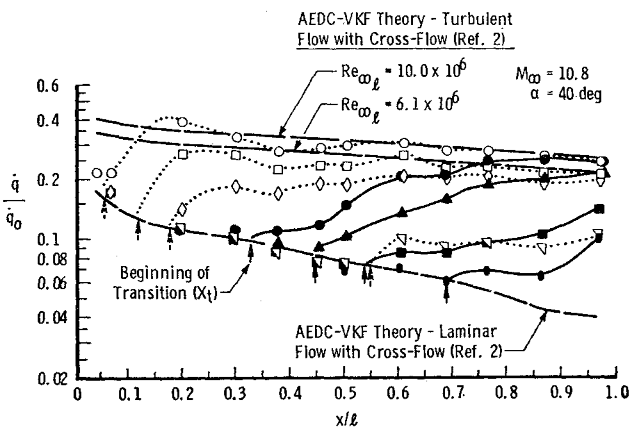

Fig. 2 Heat-transfer-rate distributions and transition locations.

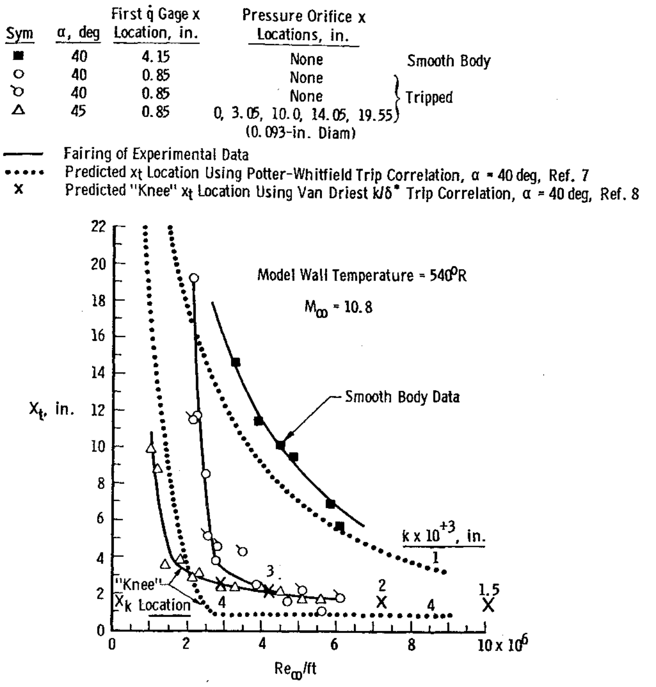

Fig. 3 Predicted effect of surface roughness on transition locations.

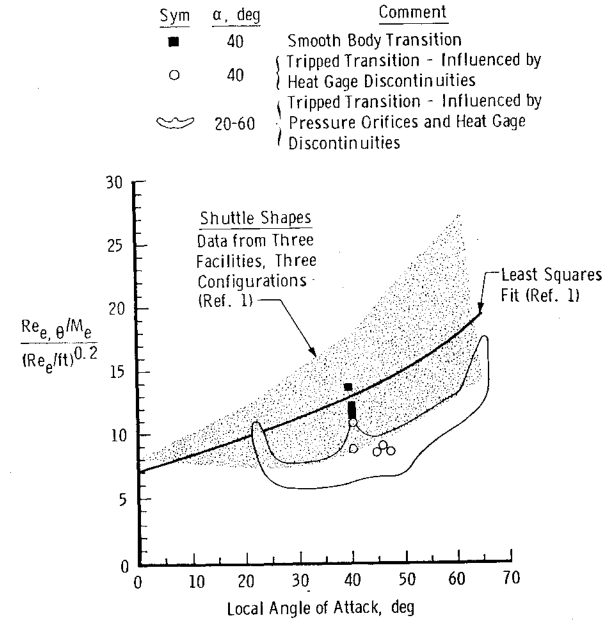

Fig. 4 Comparison of AEDC-VKF tunnel F transition results with MDAC correlation.

Post-test measurements of protuberances associated with the centerline "coaxial"-type heat-transfer gages were of the order 0.0005 to 0.001 in. These are relatively small surface irregularities and it might at first appear that the boundary layer flow on lifting bodies at high angles of attack and high Mach numbers is fundamentally different than has been reported in previous studies; e.g., Ref. 6. However, this is not the case, as shown by the results presented in Fig. 3. The methods of Potter-Whitfield[7] and van Driest-Blumer[8] were used to estimate the surface roughness effects on x_t assuming a single row of spheres were located at $x = 0.92$ in., $x/l = 0.040$. The displacement thickness correlation method of van Driest-Blumer was used.

The x_t vs Re_∞/ft profiles for trip heights of 0.001 and 0.004 in. calculated using the Potter-Whitfield method are presented in Fig. 3 along with calculations of the "knee" or "effective" point location determined using the displacement thickness method of van Driest-Blumer for roughness heights (k) of 0.0015, 0.002, 0.003, and 0.004 in. The agreement between the two methods is considered good. Boundary layer parameters used in the trip correlations were calculated using the method of Adams[2]. At $x = 0.92$ in., the laminar boundary-layer displacement thickness (δ^*) was calculated to be 0.0020 in. for $\alpha = 40$ degrees, $M_\infty = 10.8$ and $Re_\infty/\text{ft} = 4.8 \times 10^6$.

Transition Reynolds number data in terms of the local Reynolds number based on the momentum thickness (θ) are represented in Fig. 4 by the MDAC (Kipp-Masek) correlating parameters.[1] Local flow properties were calculated using ideal gas properties for the wind tunnel test conditions. Assumption of conical flow was used to determine the shock wave angle and flow properties. For surface angles for which a detached shock is predicted, the shock wave angle was assumed parallel to the local deflection angle with isentropic expansion from properties behind the shock to classical Newtonian local pressure.

It is evident in Fig. 4 that the "smooth body" results are appreciably higher than the "tripped" data. This is, of course, as expected; however, it is to be noted that some of the "tripped data" fall within the scatter band of the correlating data. Caution should be exercised if fairly complex correlating parameters such as presented in Fig. 4 are used as the sole criteria for establishing the validity of transition data.

These results show that very small amounts of roughness can be expected to trip the boundary layer on lifting bodies at high angles of attack even at hypersonic speeds. Furthermore, either of the methods of Potter and Whitfield[7] or van Driest-Blumer[8] appear to be adequate for estimating the effects of surface roughness, even for geometries and flow conditions outside the range of original correlating data Of course, further work needs to be done before the validity of the two methods as applied to these geometries and flow conditions is completely established.

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