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Slot Heating Associated with Roll Control Fins

T. Taz Bramlette*
Sandia Laboratories, Livermore, Calif.

Nomenclature

b = skin thickness
c = heat capacity
d = slot depth
L = model length
M = Mach number
$\dot{q}$ = heat-transfer rate
$Re_{\infty,L}$ = freestream Reynolds number based on model length
Re_τ = friction Reynolds number, $(\tau_w/\rho_e)^{1/2}(\rho_e w/\mu_e)$
T = temperature
t = time
w = slot width
y = slot depth coordinate
μ = viscosity
ξ = angular coordinate
ρ = density

Subscripts
o = stagnation
w = wall
∞ = freestream

Introduction

ONE means of controlling the roll rate of small re-entry vehicles consists of fins located near the base of the vehicle. Installation of these fins, however, results in a circular slot of varying depth in the heat shield, which presents a potential aerothermal design problem. The desirability of a wide slot to minimize the probability of binding conflicts with the need for a narrow, deep slot to minimize the heat input to the fin actuation mechanism. Moreover, the effect of the complex flowfield that exists in the region near the fin on slot heating is not known. The present results were obtained as part of an experimental study of the aerothermodynamics associated with small fins in laminar, hypersonic flow.[1]

Facility, Model, and Experimental Technique

The tests were conducted in the Air Force Flight Dynamics Lab. (AFFDL) High Temperature Facility,[2,3] which is a hypersonic blowdown wind tunnel. Nominal test conditions were $M_\infty = 10$, $Re_{\infty,L} = 1 \times 10^6$ ($Re_\tau \approx 90$), and $T_w/T_o = 0.27$. The model was a 7° half-angle sharp cone which had small fins mounted near its base. For the slot heating tests the fin was swept 60° from the normal, had a cylindrical leading edge, and a length, height and width of 1.83, 0.5, and 0.3 in., respectively. The fin was surrounded by a circular slot which had a width of 0.05 in. and a depth which varied from 0.51 in. to 0.75 in. The walls of the slot were constructed of stainless steel ($b = 0.030$ in.) and instrumented with Chromel-Alumel thermocouples. A sketch of the model and the thermocouple locations are presented in Fig. 1.

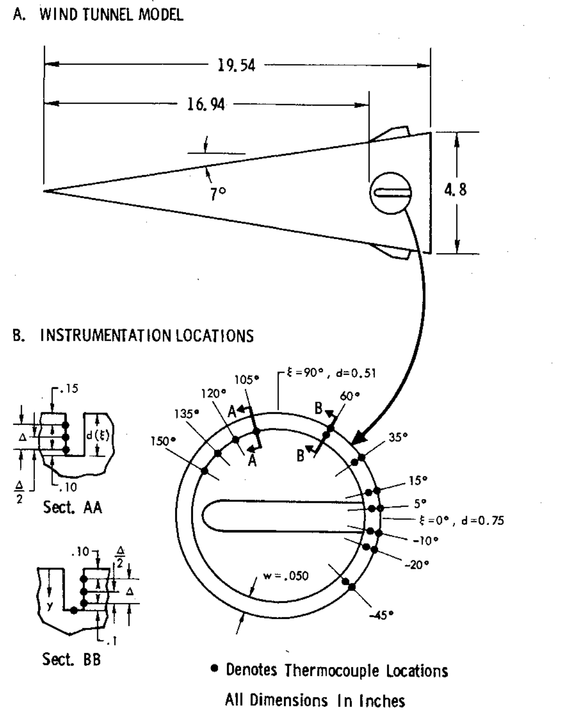

Fig. 1 Sketch of wind-tunnel model.

Thermocouple data were taken at a sampling rate of 57 times/sec when the model reached the flowfield core. The heat transfer rate was obtained from the relation

$$\dot{q} = \rho c b (dT/dt)$$

In general, the temperature rise was less than 40°R. Consequently, no correction for surface conduction or radiation was made.

Results

Figure 2 presents results which are influenced by the flowfield in the fin/cone corner region. The heat transfer rate has been

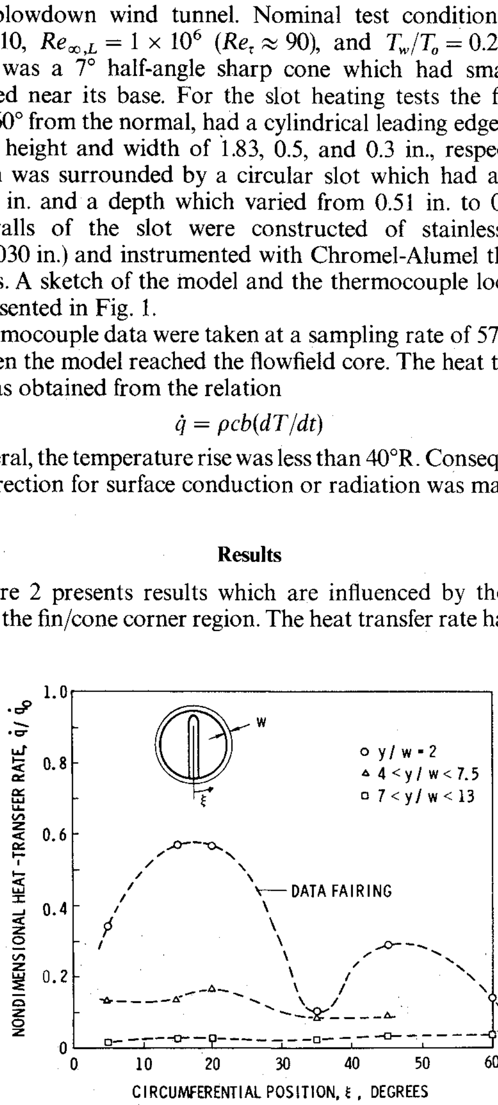

Fig. 2 Slot heating for different circumferential positions.

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* Member of Technical Staff, Systems Development Division. Member AIAA.

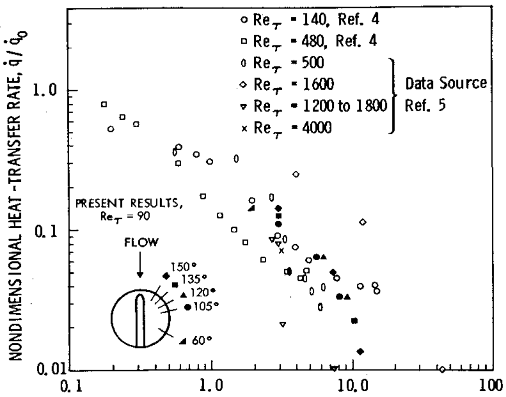

Fig. 3 Slot heating as a function of depth.

normalized by the undisturbed value on the cone and is plotted against the circumferential angle measured from the back of the fin. For the uppermost location ($y/w = 2$) two peaks in heating in the circumferential direction are observed. These peaks correspond closely in location to the high shear and high heat transfer noted in the fin corner region,[1] which was attributed to the existence of vortices. At depths between 4 and 7 slot widths, a single peak is discernable. At depths greater than this, no peaks are present, and the heating level has dropped to values characteristic of deep transverse slots.[4,5]

Data from the forward portion of the slot, which is out of the region of fin influence, are compared with data from earlier investigations of transverse slots[4,5] in Fig. 3. The data from Ref. 4 are for laminar flow, while those from Ref. 5 are for turbulent flow. The data are presented as normalized heat-transfer vs normalized depth. Although it has been noted by Winkler et al.[5] that this is not a unique correlating parameter (and in fact, that such a parameter has yet to be found) it is useful for the purpose of comparison. The present results indicate the same general trend of decreasing heat transfer with increasing depth that is exhibited by both the laminar and turbulent data. For depths of approximately ten slot widths, the heating level has decreased to approximately 2% of the surface value. Furthermore, the angular position does not appear to significantly influence the heat transfer rates.

In summary, the heat transfer in circular slots associated with fins has been found to be similar to that observed in transverse slots in regions which are not influenced by the fin-induced flowfield. In regions influenced by the fin, the in-depth heating is initially similar to that on the cone surface. However, at depths greater than approximately ten slot diameters, the heating level is characteristic of that observed in transverse slots.

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Radial Base Heat-Transfer Gradients in Turbulent Flow

BRUCE M. BULMER*
Sandia Laboratories, Albuquerque, N.Mex.

Nomenclature

A_B = base area
h = heat-transfer coefficient
k = thermal conductivity
M = Mach number
Nu = Nusselt number
Pr = Prandtl number
$\dot{q}, \bar{\dot{q}}$ = heat flux and average heat flux, respectively
r = base coordinate measured from base outer edge
R = base coordinate measured from base centerline
R_B, R_N = base and nose radius, respectively
R_N/R_B = bluntness ratio
Re = Reynolds number
α = angle of attack
θ_c = cone half angle

Subscripts

b = base or outer base condition
c = local cone (boundary-layer edge) condition
r = characteristic length measured from base outer edge
s_L = based on wetted length of cone
∞ = freestream condition

I. Introduction

ADEQUATE descriptions of the thermal environment associated with viscous separated flows are of practical interest to the design of hypersonic space vehicles. However, the separated near wake (or base flow) region of various entry and re-entry configurations is not well understood, and, for this reason, the "state-of-the-art" approach continues to rely substantially on empirical relations derived from experimental ground or flight test data. In particular, heat-transfer data correlations are frequently utilized to establish thermal protection requirements in the base flow region of a hypersonic vehicle.

Although low heating environments are characteristic of the base region (as compared to other regions of a vehicle), the base may comprise a significant fraction of the vehicle surface and, hence, weight of the thermal protection system. This is particularly true for very blunt, high-drag planetary entry probe configurations[1] whose afterbodies constitute a comparatively large surface area (50% or more of the total vehicle surface) and corresponding heatshield weight. Slender high-performance re-entry vehicles currently of interest generally experience severe heating environments and, as a result, require thermal protection materials (e.g., ablators) in the base cover design. Although the base of these slender configurations represents a considerably smaller fraction ($\sim$10–20% for $5° < \theta_c < 15°$) of the total vehicle surface area, optimization of the base heatshield design is still desired to reduce the base cover weight and insure an acceptable vehicle static margin. Therefore, in establishing thermal protection requirements for a hypersonic space vehicle, an accurate description of the heat-transfer distribution across the base may be necessary to realize significant advantages in over-all heatshield design.

Early experiments[2,3] revealed radial base heat-transfer variations (or gradients) in laminar and turbulent axisymmetric flows. Laminar theory[4] does not predict the base heat-transfer gradient;

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* Member of the Technical Staff, Re-Entry Vehicle Aerothermodynamics Division. Member AIAA.