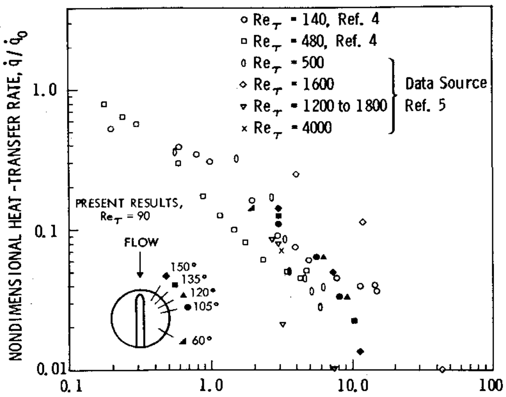

Fig. 3 Slot heating as a function of depth.

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

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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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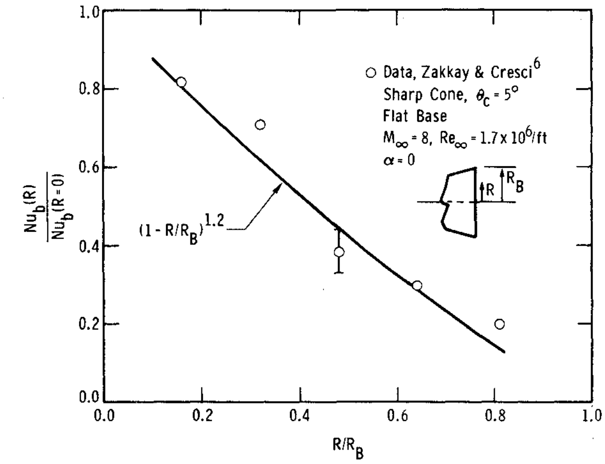

Fig. 1 Turbulent base Nusselt number distribution on a slender cone.

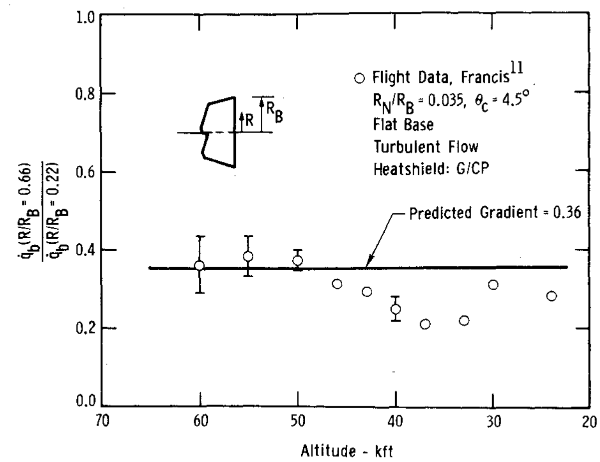

Fig. 2 Base heat-transfer gradient on a slender ablating re-entry vehicle.

however, a number of ground tests utilizing free-flight or wire-supported models confirm that significant gradients occur in laminar flow for both blunt entry probe[5] and slender cone[6-9] configurations. Additional ground test data indicate a similar behavior for slender cones in turbulent flow.[6,10] More recently, instrumented full-scale re-entry vehicles have provided telemetered base heat-transfer data in hypersonic entry conditions. Though somewhat limited in scope, these flight data[11-13] also reveal substantial variations across the vehicle base in turbulent flow.

Base heat-transfer gradients appear to be influenced by a number of flow and geometrical characteristics, for example, forebody boundary-layer condition (laminar or turbulent), angle of attack, afterbody configuration, mass addition due to heatshield ablation, and so forth. In particular, turbulent data for flat-based cones at zero angle of attack indicate that the heat transfer generally decreases from a maximum at the centerline to a minimum at the edge of the base.[6,11,13] In this Note, radial base heat-transfer gradients are examined in more detail. A simple geometric relation is derived from results reported previously to determine the turbulent base heat-transfer distribution for slender flat-based cones at zero angle of attack. Several comparisons with available ground and flight test data are included to demonstrate the applicability of this distribution to various configurations and flow conditions.

II. Analysis

To examine heat-transfer gradients in turbulent flow, consider the base heat-transfer correlation previously developed from re-entry vehicle flight data[13]

$$\frac{Nu_{b,r}/Pr_b}{Nu_{c,s_L}/Pr_c} = 35.5\left(\frac{Re_{b,r}}{Re_{c,s_L}}\right)^{2.2} \tag{1}$$

where the characteristic length r is defined by

$$r = R_B - R \tag{2}$$

Equation (1) yields an interesting result if the base pressure is considered uniform across the base. Constant pressure on a flat base is a valid assumption in turbulent flow[6,14,15] unless mass addition due to heatshield ablation is sufficient to cause radial base pressure gradients.[16] For uniform base pressure, the outer base properties (defined by a Prandtl-Meyer expansion) are constant across the base flow region, and for this case Eq. (1) implies that the radial base heat-transfer distribution is a function of R/R_B only

$$\frac{Nu_b(R)}{Nu_b(R=0)} = \frac{h_b(R)}{h_b(R=0)} = (1 - R/R_B)^{1.2} \tag{3}$$

Note that the unit Nusselt number and heat-transfer coefficient ratios are equivalent because the thermal conductivity k_b is uniform with R.

If the wall temperature is relatively constant across the base, Eq. (3) may be expressed directly in terms of the base heat flux,

$$\dot{q}_b(R)/\dot{q}_b(R=0) = (1 - R/R_B)^{1.2} \tag{4}$$

Equation (4) may be utilized to obtain, for example, the average heat flux to a circular flat base

$$\bar{\dot{q}}_b = \frac{1}{A_B}\iint_{A_B} \dot{q}_b \, dA = 0.28\dot{q}_b(R=0) \tag{5}$$

where the integration is performed with the change of variables given by Eq. (2).

III. Discussion

Equations (3) and (4) are in a convenient form for comparison with ground and flight test data. In Fig. 1, the Nusselt number distribution is compared with $M_\infty = 8$ data of Zakkay and Cresci[6] for turbulent flow on a sharp 5° cone model. The measured centerline Nusselt numbers $Nu_b(R=0)$ were used to normalize the data, and the measured static pressure was uniform across the base. The data are in close agreement with the predicted distribution. These results indicate that turbulent heat transfer varies nearly linearly across a flat base. The behavior of Eqs. (3) and (4) at $R/R_B = 1.0$ results from the particular choice of the characteristic length in Eq. (1). However, the data confirm the expected low heating levels near the edge of the base.

Turbulent flight data were reported by Francis[11] for three identical slender ($\theta_c = 4.5°$) re-entry vehicle configurations with graphite/carbon phenolic (G/CP) heatshields and the same nominal ballistic re-entry trajectory. Data were obtained at two

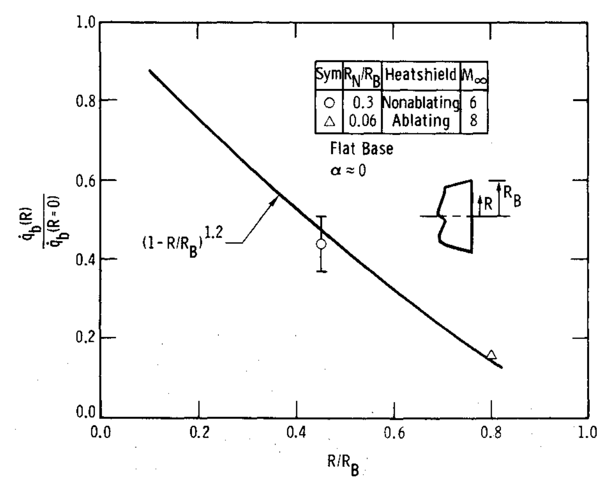

Fig. 3 Flight data showing turbulent gradient on sharp and blunt configurations.

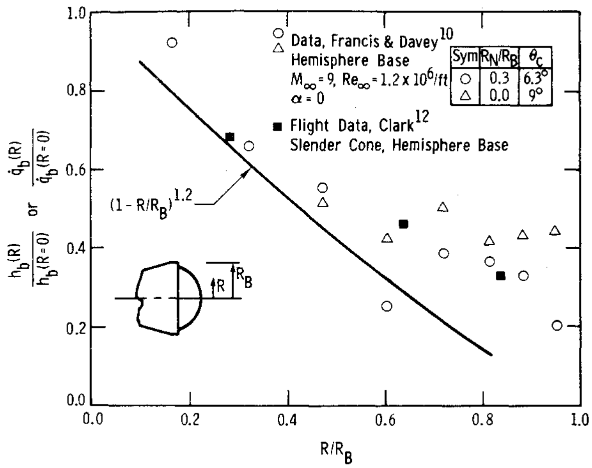

Fig. 4 Turbulent heat-transfer distribution on a hemisphere base.

base radial locations, $R/R_B = 0.22$ and 0.66. Since the centerline heat flux $\dot{q}_b(R = 0)$ was not measured, Eq. (4) may be used to determine the ratio of the cold-wall heat flux at these two radial positions, i.e.

$$\frac{\dot{q}_b(R/R_B = 0.66)}{\dot{q}_b(R/R_B = 0.22)} = \left[\frac{1 - 0.66}{1 - 0.22}\right]^{1.2} = 0.36$$

The flight data are compared to this predicted radial gradient in terms of altitude (Fig. 2). While the data include scatter due to trajectory dispersion, fair agreement with the predicted gradient is seen throughout the turbulent portion of the flights. Mass addition due to heatshield ablation may have influenced the measured heat-transfer gradient, although this effect should be minimal for a low mass-loss ablator.

Additional unpublished Sandia Labs. flight data for two slender re-entry vehicles were obtained on a nonablating blunt cone ($R_N/R_B = 0.3$) and a very low mass-loss ablating sharp cone ($R_N/R_B = 0.06$). The base heat flux ratios corresponding to the maximum measured turbulent heat flux for each flight are compared to the radial distribution in Fig. 3. These data suggest that large differences in forebody configuration do not influence the turbulent base heat-transfer distribution.

A final comparison with experimental data is presented to indicate the effect of afterbody configuration on the turbulent heat-transfer distribution; both ground and flight test data are included in Fig. 4 for a hemisphere base. The $M_\infty = 9$ data of Francis and Davey,[10] obtained on sharp and blunt slender cone models, are plotted in terms of the heat-transfer coefficient ratio. Results[12] for a full-scale re-entry vehicle with similar base geometry are plotted in terms of the heat flux ratio; these data correspond to the peak base heat flux measured during the flight. The heat-transfer distribution and data are in fair agreement for $R/R_B \lesssim 0.6$, but a significant deviation is seen for the larger radii where the afterbody no longer resembles a flat base. Both the ground and flight test data indicate that the base heat-transfer distribution is affected by afterbody configuration (corresponding base pressure distributions are not available to ascertain whether the pressure was uniform across the hemisphere base).

IV. Conclusions

The preceding data comparisons indicate that the turbulent base heat-transfer distribution developed herein is applicable to slender flat-based cones at zero angle of attack. These results support the conclusion that for hypersonic flow, the distribution is not strongly influenced by forebody configuration or flow conditions. However, base geometry apparently has an effect on the heat-transfer distribution; for a flat base, turbulent heat transfer decreases nearly linearly from a maximum at the centerline to a minimum at the edge of the base.

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