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Flowfield Calculations Past an Entry Probe with Ablated Nose Shape

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Nomenclature

$\bar{n}$ = coordinate normal to body surface, m
$\bar{p}$ = pressure, N/m^2
$\bar{q}_w^C$ = convective heating rate, W/m^2
$\bar{q}_w^R$ = radiative heating rate, W/m^2
r = local body radius, $\bar{r}/\bar{R}_n$
$\bar{R}_n$ = nose radius, m
$\bar{R}_b$ = base radius, m
$\bar{s}$ = coordinate tangential to body surface, m
$\bar{T}$ = temperature, K
$\bar{T}_w$ = surface temperature, K
$\bar{T}_\infty$ = freestream temperature, K
$\bar{V}_\infty$ = freestream velocity, m/s
z = axial distance from the stagnation point, $\bar{z}/\bar{R}_n$
z_l = axial distance between the stagnation point and juncture point, $z_l/\bar{R}_n$
$\bar{\rho}_\infty$ = freestream density, kg/m^3
$\bar{\delta}$ = shock standoff distance, m
κ = local curvature, $\bar{\kappa}\bar{R}_n$

Introduction

OUTER planet entry probes encounter severe aerothermal environments which are characterized by high energy flow, large heat transfer rates to the probe's surface, and high rates of mass injection from the probe's ablative heat shield into the shock-layer flow. Because of the recession of the probe's ablative heat shield, the shape of the probe continuously changes as it moves into the atmosphere of the planet. Most flowfield analyses for predicting the heating rates to the probe's surface[1-3] assume that the heat shield maintains a constant shape and neglect the effects of the probe shape change on the flowfield. It is essential to study the effects of the shape change on the flowfield in order to reduce the uncertainties involved in designing the heat shield.

The purpose of the present investigation is to study the effects of ablated nose shapes on the flowfield solutions. A time-dependent finite-difference method developed in Ref. 4 is found capable of handling the probe with ablated nose shapes. Solutions are obtained for the laminar flow of a radiating mixture of hydrogen-helium in chemical equilibrium. The freestream conditions correspond to a point on a typical Jovian entry trajectory. The initial probe shape is a 45-deg half-angle spherically blunted cone.

Detailed flowfield solutions are presented with increasing amount of nose blunting. The effects of shape change on surface pressure, shock standoff distances, and radiative and convective heating rates are discussed.

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Governing Equations and Methods of Solution

In the present analysis, solutions are determined for the laminar flow of a radiating mixture of hydrogen-helium in chemical equilibrium past a blunt axisymmetric body at zero angle of attack. Six chemical species are used to describe the gas mixture. These species are H_2, H, H^+, He, He^+, and e^-. The governing equations and the method of solution are given in Ref. 4. The methods of calculating the thermodynamic and transport properties of the gas mixture and radiative heat flux are also given in Ref. 4.

Body Geometry and Input Conditions

Figure 1 shows a 45-deg half-angle spherically blunted cone along with three more probes with ablated nose shape. These are numbered 1, 2, 3 and 4, respectively. The geometry of the nose of the three ablated probes is given in Table 1. In all cases the cone portion remains the same. For the spherically blunted cone, the nondimensional curvature κ is equal to one for the spherical portion and then goes to zero on the cone. In the case of ablated probes, the nondimensional curvature increases from one at the axis of symmetry to a larger value at the juncture point and then goes to zero on the cone. The curvature jump at the juncture point increases with increasing bluntness as is seen from the last column of Table 1. Because of these large changes in the curvature of the body, most blunt body computer codes do not work for such bodies. However, the explicit method of Ref. 4 is found adequate in treating these bodies.

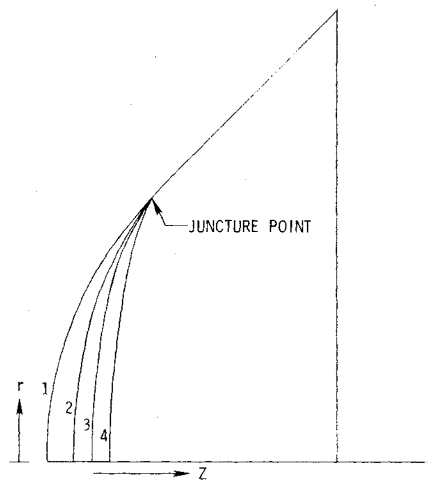

Fig. 1 Probe shapes.

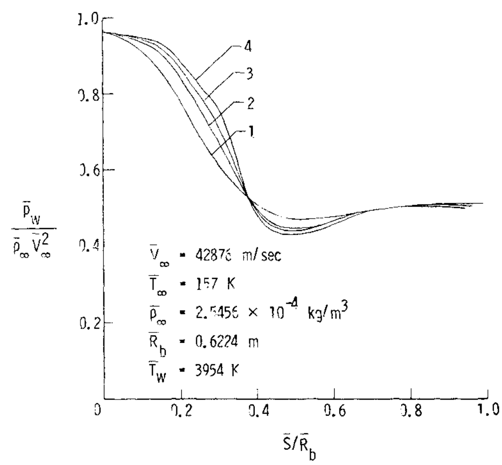

Fig. 2 Surface pressure distributions for original and ablated probes.

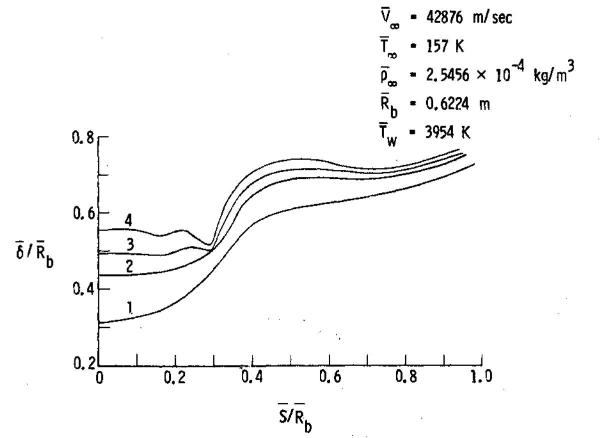

Fig. 3 Shock standoff distances for original and ablated probes.

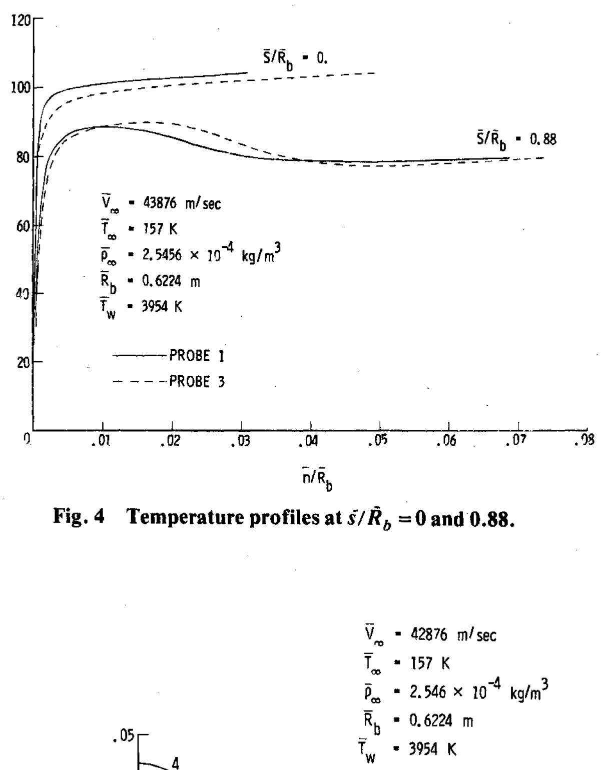

Fig. 4 Temperature profiles at $\bar{s}/\bar{R}_b = 0$ and 0.88.

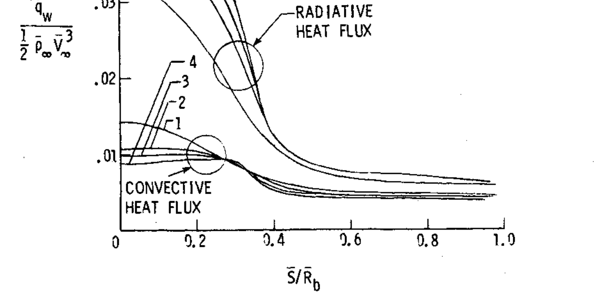

Fig. 5 Surface heating rate distributions for original and ablated probes.

Results and Discussion

Numerical solutions are presented for an atmospheric model consisting of 89% H_2 and 11% He by volume. The freestream conditions correspond to a point on a typical Jovian entry trajectory. These conditions are taken as $\bar{V}_\infty = 42,876$ m/s, $\bar{\rho}_\infty = 2.5456 \times 10^{-4}$ kg/m³, and $\bar{T}_\infty = 157$ K. The nose radius for the spherically blunted cone is taken as 0.3112 m and the nose radius for the ablated probes are given in Table 1. The base radius in all the cases is taken as 0.6224 m. The surface temperature is assumed to be 3954 K.

Table 1 Nose geometry for ablated shapes, $r = (2z + bz^2)^{1/2}$ for $0 \le z \le z_l$

Probe number	$\bar{R}_n$, m	b	z_l	κ at z_l
2	0.461807	−3.59115	0.14850	3.4781
3	0.546473	−5.42893	0.11155	5.7632
4	0.655320	−8.24500	0.081395	9.9380

Figure 2 shows the surface pressure distributions for various probe shapes considered. It is seen that as the nose bluntness increases, the surface pressure level in the nose region also increases. The figure also shows that the increasing curvature discontinuity at the juncture point results in more and more overexpansion and recompression of the flow around the juncture point. All the probes are seen to approach the same pressure level on the conical portion irrespective of the nose bluntness.

Figure 3 shows the corresponding shock standoff distances which are seen to increase significantly in the nose region with increasing nose bluntness. The shock standoff distances for the third and fourth probes also show clearly the effect of large curvature discontinuity at the juncture point.

The temperature profiles are plotted in Fig. 4 at two body locations of probes 1 and 3. The figure shows that at the stagnation point, the extent of the high temperature gases is significantly increased for probe 3 as compared to probe 1. There is little difference in the temperature distributions on the conical portion of the probe, as is seen from the profiles at $\bar{s}/\bar{R}_b = 0.88$.

The surface radiative and convective heating rates are plotted in Fig. 5 for all four probes. The radiative heating rates in the nose region are seen to increase substantially with increasing nose bluntness. This is because for the ablated probe, the extent of the high temperature gases in the nose region is increased, which results in higher radiative heat transfer to the probe's surface. Figure 5 also shows that the convective heating rates decrease with increasing nose bluntness. This is primarily due to the increased shock standoff distances for the ablated probes, which lower the gradients near the surface. The heating rate distributions also show that the nose bluntness effects are mostly restricted to the nose region and have little impact on the downstream flowfield.

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