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Technical Note

Radiative Heating of Ablating Carbon Phenolic Heat Shields

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Nomenclature

m	=	nondimensional mass injection rate
$q_{T,\mathrm{cold}}$	=	total cold wall heating rate, including both convection and radiation, $\mathrm{W/m^2}$
U_∞	=	freestream velocity, m/s
ρ_∞	=	freestream density, $\mathrm{kg/m^3}$
Ψ_R	=	ratio of radiative heating rate corrected for blowing effect to cold wall, radiative heating rate

I. Introduction

Carbon phenolic has been used as an ablative heat shield material on numerous atmospheric entry vehicles, including the Galileo Jupiter probe, the four Pioneer Venus probes, and various military reentry vehicles [1]. High heating rate entries for which a carbon phenolic thermal protection system is appropriate remain a topic of considerable interest [2], especially since Jupiter is the only gas giant yet to have been explored by an atmospheric entry vehicle. Moreover, the substantial discrepancy between preflight heating predictions for the Galileo probe and heating rates inferred from in-flight measurements has lead to considerable effort to develop a better understanding of aerothermal environments under such extreme conditions [2,3].

It is well known that the injection of ablation products from the surface of a carbon phenolic heat shield into the boundary layer can produce significant reductions in both the convective and radiative heating reaching the stagnation point as compared with the rates experienced by nonablating or "cold" walls. Detailed calculations of this "blowing" effect have been carried out for Earth, Mars, Venus, and Jupiter entry vehicles [4–11]. These studies have involved determinations of radiative transport for the numerous chemical species present in the shock layer, including the products of ablation.

An approach taken in some of the previous studies has shown that for a given freestream condition, the change in the radiative heat transfer at a point on the surface (as compared with the no blowing case) depends upon a nondimensional parameter, m, defined as the ratio of the ablation product mass injection rate at the specified surface location to the freestream mass flow rate ($\rho_\infty U_\infty$) [4]. This functional dependence is illustrated in Fig. 1, that is adapted from [4]. Of course, the actual flow condition corresponds to a single point on this curve, since a specified flow field will produce a distinct mass injection rate at each point on the surface. In [7], a slightly different approach was taken, and it was shown that for the entry of a probe into the Jovian atmosphere, the percent reduction in stagnation-point radiative heating could be correlated with the radiative heating rate for the nonablating surface. The work in [7] was done using a quasi-steady-state ablation analysis and assuming a blownoff boundary layer with only ablation species near the wall.

II. Methodology and Results

It would be desirable to have a simple technique that could be used throughout the trajectory of an entry vehicle to estimate the reduction in radiative heating caused by ablation products. Such a technique could be incorporated into engineering level simulation codes to produce more accurate preliminary designs and trade studies. In an effort to answer this need, we have adapted the approach taken in [7] and plotted Ψ_R (the ratio of the corrected radiative heat transfer divided by the cold wall radiative heating) against the total cold wall heating rate, $q_{T,\mathrm{cold}}$ (including both radiation and convection). The results, shown in Fig. 2, were developed using calculations for Jovian entries originally presented in [7], along with a single result for Earth entry from [4].

The smooth shape of the plotted data suggests that the cold wall heating rate could be used in conjunction with a curve fit of Fig. 2 to provide reasonably accurate estimates of the reduction in radiative heating caused by ablation products for a wide variety of entry conditions. The following correlation equations were developed to fit the data and are represented by the solid line in Fig. 2:

$$\begin{aligned}
&\text{For} \quad q_{T,\mathrm{cold}} < 0.7439(10^7)\ \mathrm{W/m^2}, \qquad \Psi_R = 1\\
&0.7439(10^7)\ \mathrm{W/m^2} < q_{T,\mathrm{cold}} < 1.125(10^8)\ \mathrm{W/m^2}\\
&\quad \Psi_R = 6.677(q_{T,\mathrm{cold}})^{-0.12}\\
&q_{T,\mathrm{cold}} > 1.125(10^8)\ \mathrm{W/m^2} \qquad \Psi_R = 333.7(q_{T,\mathrm{cold}})^{-0.331}
\end{aligned} \tag{1}$$

To check the validity of these equations, a comparison was made with two test cases. In the first of these, the preceding equations were applied to the entry of the large Pioneer Venus probe. A reduction in the peak stagnation-point radiative heating of just over 20% ($\Psi_R = 0.796$) was predicted. This compares quite favorably with the 20% blockage reported in [10]. In the second test case, our equations were incorporated into the NASA Ames Research Center Jupiter entry code, JAE [12]. This program used the atmospheric structure and composition deduced from the Galileo flight data [13] to calculate the vehicle's trajectory, the aerothermal heating during entry into the Jovian atmosphere, and the surface recession of the forebody's carbon phenolic heat shield. The radiative heating on the blunt nose was computed assuming one-dimensional transport as a function of the freestream velocity component normal to the shock wave. This assumption was considered to be valid in part because of the thin shock layer. Using the normal velocity and freestream density, the shock layer temperature and pressure were found, which determined the radiative intensity. The intensity was combined with the local shock layer thickness to compute the unblocked radiative heating from the shock layer. The heating rates thus calculated were corrected for the nonadiabatic effect due to radiative emission. For portions of the probe where the boundary layer was laminar, radiative blockage by ablation vapors from the surface was calculated using the relations described in this Note. Based on calculations in [14], radiative blockage by ablation products was assumed to be zero in

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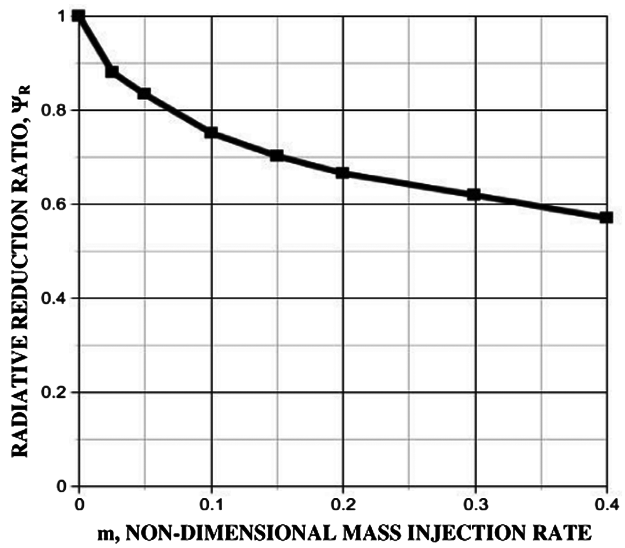

Fig. 1 Radiative ratio as a function of nondimensional mass injection rate. Adapted from [4]. Earth entry, altitude 60.96 km/s, nose radius 3.05 m, freestream velocity 15.24 km/s.

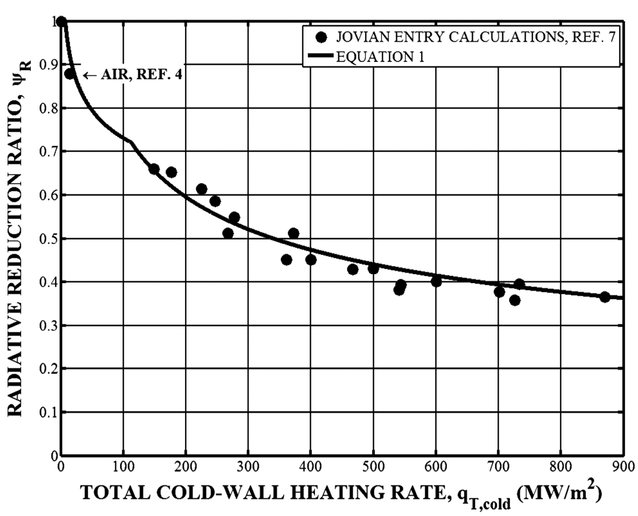

Fig. 2 Radiative ratio as a function of the total cold wall heating rate.

areas where the boundary layer was fully turbulent. Blockage in areas with a transitional boundary layer was varied linearly from the laminar to the turbulent value. The code predicted a total mass loss due to surface ablation of 82.5 kg, with a stagnation-point surface recession of 4.9 cm. The flight heat shield was instrumented with a set of recession gages that provided data suitable for comparison with our calculated results. These gages, symmetrically located 21.8 deg off the stagnation point, determined the actual surface recession to be 4.13 $\pm$0.25 cm [15], while the JAE code predicted a recession of 4 cm, which was within the band of experimental uncertainty for the flight data. In addition, the forebody total mass loss determined from flight telemetry was 79 $\pm$4 kg [15], once again comparing closely with the 82.5 kg loss predicted using our methodology.

III. Conclusions

The success of this simple approach at predicting radiative blockage for our two test cases suggests that similar correlation equations could perhaps be developed for other ablative materials. While approximate methods of this type are not intended to replace detailed calculation such as those in [2–11] (and indeed are based upon those detailed calculations), these equations could be incorporated into engineering level simulation codes, enabling higher fidelity preliminary designs and more accurate and rapid trade space studies for future planetary missions.

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