residual stresses after the leading-edge temperatures return to steady-state conditions.

Concluding Remarks

A finite element thermoviscoplastic analysis method, which employs a unified constitutive model, is used to predict the thermoviscoplastic response of a leading edge subjected to the heating and pressure from an oscillating shock-shock interaction. Both elastic and viscoplastic analyses of a B1900+Hf leading edge were performed. The elastic analysis tends to overestimate stresses. The viscoplastic response during the second cycle is quite different even though the applied loading was the same as the first cycle. The viscoplastic analysis provides more realistic stresses because the inelastic behavior is included. The leading edge experiences plastic strain in the high heat flux region. The predicted plastic region extends from the outer to inner surface and increases with time as the shock oscillates across the leading edge.

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Hypervelocity Stagnation-Point Heating Rate Discrepancies

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Introduction

PROPOSED Earth entry velocities for space exploration vehicles are typically in the range of 12–16 km/s. These high-energy flowfields result in very large radiative and convective surface heat fluxes. An earlier investigation[1] had scoped the magnitude of these fluxes for several velocities as well as for candidate thermal protection systems. The calculations of Ref. 1 were based on a variable Lewis number with a binary diffusion coefficient computed for molecular nitrogen and atomic oxygen. The selection of a dominant species for the binary diffusion assumption has also been employed in Martian entry[2] and in aerobrake[3] analyses. This species combination of molecular nitrogen and atomic oxygen for a binary diffusion calculation would seem to be appropriate for at least the inner flowfield regions since these are the dominant species.

However, for the velocities previously noted, the choice of molecular nitrogen and atomic oxygen as the dominant pair for binary diffusion through the shock layer is not appropriate. At the very high temperatures that characterize the majority of the flowfield for these hypervelocity conditions, molecular nitrogen is either not present or is present only as a trace species. As a result, a computational study was conducted to assess the influence of different methods of implementing the Lewis number in flowfield calculations on the heat transfer. For this study, the calculations were based on several freestream velocities and wall temperature assumptions. Since significant differences were noted in the convective heating predictions, the purpose of this Note is to highlight these results and offer some related observations.

Computational Procedure

The viscous shock-layer (VSL) method of Ref. 1 was used to compute the flowfields for the present study. For brevity, the basic equations and boundary conditions are not presented herein but are the same as those used in Ref. 1. For this study, the calculations are based on an equilibrium-air assumption for the flowfield chemistry and do not include radiation effects. The thermodynamic and transport properties are based on the investigation of Ref. 4

Discussion of Results and Conclusions

Stagnation-point convective heating calculations were performed at 70-km altitude for a nose radius of 3.05 m and the freestream velocities and wall temperatures shown in Table 1. The first temperature value for each velocity is the radiative equilibrium wall temperature for the variable Lewis number case. The heating rates and associated ratios are computed for three calculations of the Lewis number. One of these calculations is for a variable Lewis number computed through the shock layer. The related binary diffusion coefficient calculation is based on the assumption that molecular nitrogen and atomic oxygen are the dominant species. The surface Lewis number, which is computed with the radiative equilibrium

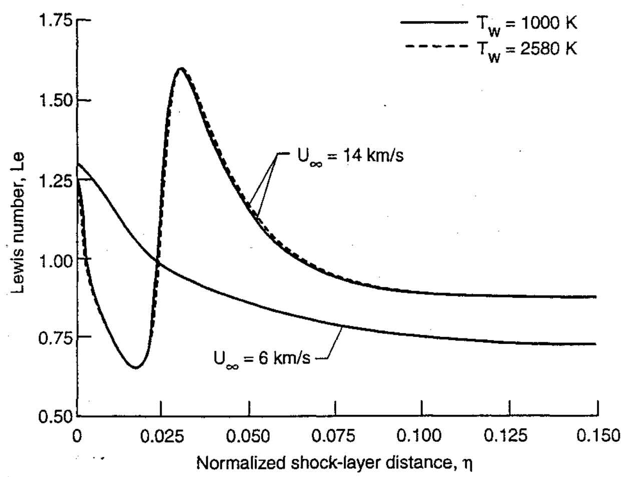

Fig. 1 Shock-layer Lewis number distribution for different freestream velocities and wall temperatures.

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Table 1 Stagnation convective-heating calculations

Freestream velocity, km/s U_∞	Wall temperature, K T_w	Convective heating, W/cm² q_{VLE}	q_{CLE}	q_{LE4}	Diffusion heating ratio $(q_d/q_c)_{VLE}$	$(q_d/q_c)_{CLE}$	$(q_d/q_c)_{LE4}$	Conduction heating ratio $(q_k/q_c)_{VLE}$	$(q_k/q_c)_{CLE}$	$(q_k/q_c)_{LE4}$
6	1400	21.2	23.6	24.4	0.01	0.02	0.01	0.99	0.98	0.99
	1000	21.7	24.2	24.9	~0	~0	~0	1.0	1.0	1.0
12	2280	154	212	222	0.32	0.28	0.30	0.68	0.72	0.70
	1000	158	216	226	~0	~0	~0	1.0	1.0	1.0
14	2580	226	321	342	0.53	0.48	0.50	0.47	0.52	0.50
	1000	232	329	347	~0	~0	~0	1.0	1.0	1.0

Subscripts:
c = convective (diffusion and conduction)
d = diffusion
k = conduction
VLE = variable Lewis number
CLE = constant Lewis number
LE4 = Lewis number = 1.4

Table 2 Wall Lewis numbers

Freestream velocity, km/s U_∞	Wall temperature, K T_w	Lewis number Le
6	1400	1.294
	1000	1.304
12	2280	1.271
	1000	1.311
14	2580	1.252
	1000	1.309

wall temperature condition for the variable Lewis number case, is held constant through the layer for the second case. The third case is for flowfield calculations using a constant value of 1.4 for the Lewis number. Shock-layer Lewis number (Le) distributions are shown in Fig. 1 for different freestream velocities and wall temperatures. At a freestream velocity of 14 km/s, different wall temperature values are shown to have an insignificant influence on the Le distribution through the shock layer as might be expected. However, the very large variations in the Le distribution at 14 km/s were not expected. A more likely anticipated Le distribution is shown by the results for the 6-km/s case. The minimum and maximum Le values for the 14-km/s case are computed at shock locations which also represent conditions of full oxygen and nitrogen dissociation. The Le values shown for the two velocity cases at a normalized shock-layer distance η of 0.15 are essentially constant to the shock location ($\eta = 1.0$). The wall Le for the conditions considered in this Note are presented in Table 2.

Several observations can be noted from these tabulated data. At higher velocities, the discrepancy in the predicted heating rate for different assumptions of the Lewis number through the shock layer is as large as 50%. The differences illustrate the need for a more detailed evaluation, i.e., a multicomponent calculation of the diffusion contribution to the heating. For the high and low wall temperature values for each velocity condition and each assumption for implementing the Lewis number, there is only a 2–3% difference in the corresponding heating rates. This result is very interesting since for the higher wall temperature values, diffusion comprises about 30 and 50% of the convective flux for the 12- and 14-km/s cases, respectively. The heating values that are presented for the lower velocity condition indicate that the present methods for implementing the Lewis number in the flowfield calculations have little impact on the heating rates. A VSL analysis of Moss[5] showed that the influence of Lewis number, even for multicomponent diffusion calculations, was also small for calculations at similar low values (~6 km/s) of velocities. Another study[6] using the boundary-layer equations also included multicomponent diffusion effects in calculations at about 6 km/s. The analysis of Ref. 5 was based on a 5-species air mixture whereas the study of Ref. 6 employed a 7-species model. The conclusions of both investigations were the same including the influences of multicomponent diffusion on the surface heating. However, at hypervelocity conditions, the insensitivity of the Lewis number calculation on the heat-transfer calculation is obviously not a correct conclusion even for low wall temperatures for which the surface diffusion contribution to the convective flux is very small in comparison to the conduction term. Thus, the need for multicomponent diffusion calculations is clearly demonstrated at hypervelocity conditions even for nonablating surfaces.

Note that an effective binary diffusion coefficient[7] was used in the flowfield study of Ref. 8. This coefficient is based on a weighted-average calculation of the individual binary coefficients and provides a significantly faster computational method than the corresponding multicomponent calculation. However, the accuracy with which this effective coefficient approximates the multicomponent diffusion characteristics in a flowfield is not presently known.

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Leeside Shock-Layer Transition and the Space Shuttle Orbiter

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Nomenclature

R_{NS} = Reynolds number evaluated behind a normal shock, based on Orbiter length (32.77 m)

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