CHAPTER V

THE COMPUTATION OF AEROTHERMAL LOADS ON AN AXISYMMETRIC AEROASSISTED ORBITAL TRANSFER VEHICLE

V.1 Introduction

In the previous chapter we applied the computational method to experimental configurations with the hope of validating the numerics and to some extent, the physical models. The comparisons to experiment were very good for all of the test cases computed and thus we have some confidence in the numerical method and its ability to compute flowfields for similar flight conditions. In this chapter we will discuss the application of the numerical technique to a problem of current research and design interest.

Several conceptual designs for vehicles that would maneuver in the earth's atmosphere have been proposed recently (Howe (1985)). In particular, the Aeroassisted Orbital Transfer Vehicle (AOTV) would be used to transfer payloads between low and high earth orbits. During return from high earth orbit, it would fly into the atmosphere and, using aerodynamic drag, slow down to low earth orbit speed. This aerobraking has the advantage of reducing the amount of fuel required for an orbital transfer and therefore, increasing the payload. The vehicle would fly in the upper reaches of the atmosphere, with nominal perigee at 78 km. At these altitudes and speeds, the flowfield enveloping the body is significantly removed from thermo-chemical equilibrium. The degree of nonequilibrium affects the aerodynamic forces and convective heating acting on the vehicle. And in the AOTV flight regime, the chemical and thermal state of the flowfield has a particularly large influence on the radiative heating.

In an effort to understand and measure the aerothermal loads acting on such an AOTV, a flight experiment has been proposed. The Aeroassist Flight Experiment (AFE) vehicle, which would be a ellipsoidally-blunted and raked cone forebody, would be flown into the atmosphere to mimic the trajectory of an AOTV. The test cases that are considered in this chapter are for the nominal AFE flight conditions for the part of the trajectory where the vehicle is in the continuum regime. An axisymmetric approximation to the

AFE forebody has been presented which is made up of an ellipsoid with a 2.3 m nose radius joined to a 60° half-angle cone (Dogra *et al.* (1987)). This is the configuration that has been used in the following computations. Results are presented for the perigee conditions at 78 km and 8.91 km/s and at the approximate limit of the continuum regime at 90 km and 9.89 km/s. The converged solution of the flowfields is used to compute the radiative power emitted at each point in the flow so that the radiative heating to the body may be determined. The computations are compared to previously published direct simulation Monte Carlo results (Moss *et al.* (1988)).

V.2 Radiation Calculations

The computation of the radiative emission from the flowfield was performed by first obtaining a converged solution for the case of interest using the seven-species reacting flow algorithm. However this procedure does not account for the presence of the diatomic nitrogen ion, N_2^+, which can be important in the regime of the AFE vehicle. This ion also produces a great deal of radiation. A quasi-steady-state (QSS) analysis, similar to the one discussed in Section IV.5.1, may be used to approximately determine how much of this ion is present in the flowfield.

The QSS approach is based on the assumption that the N_2^+ producing reaction is in equilibrium at the local thermo-chemical conditions. This reaction is

$$N + N \rightleftharpoons N_2^+ + e^-, \tag{5.2.1}$$

and in equilibrium we have

$$K_{eq} = \frac{k_f(T)}{k_b(\bar{T})} = \frac{N_{N_2^+} N_{e^-}}{N_N^2}, \tag{5.2.2}$$

where the forward rate constant has been assumed to be a function of T alone, while the backward rate constant has been assumed to be characterized by the average temperature, $\bar{T} = \sqrt{T_{vN_2} T_e}$. The number density of electrons is the sum of those already computed to be in the flowfield (denoted by $N^*_{e^-}$) and those produced by reaction (5.2.1), which will be equal to $N_{N_2^+}$. Therefore, we can write

$$
\begin{aligned}
N_{\mathrm{N}_2^+}\left(N_{\mathrm{N}_2^+} + N^*_{\mathrm{e}^-}\right) &= N_{\mathrm{N}}^2 k_f(T)\frac{K_{\mathrm{eq}}(\bar{T})}{k_f(\bar{T})} \\
&= N_{\mathrm{N}}^2\left(\frac{T}{\bar{T}}\right)^{\eta_m}\exp\left(\frac{\theta_m}{\bar{T}} - \frac{\theta_m}{T}\right)K_{\mathrm{eq}}(\bar{T}),
\end{aligned}
\tag{5.2.3}
$$

where the Arrhenius form of the forward rate (with constants η_m and θ_m) and a curve-fit expression for the equilibrium expression are used[1].

The QSS assumption will tend to give good results in the regions where the gas is near thermo-chemical equilibrium, but will over-predict the number of N_2^+ ions where the gas is undergoing compression and is significantly nonequilibrium. Thus this method gives an upper bound on the ion concentration in the forebody flowfield.

The results of the seven-species computation and those from the QSS analysis for the concentration of N_2^+ were fed into the NEQAIR (nonequilibrium air radiation) algorithm of Park (1985b) which calculates the total radiative power emitted from the gas between wavelengths of $0.2\,\mu$m and $1.5\,\mu$m. This code uses the thermodynamic quantities and species concentrations from the flowfield solution as inputs. It then calculates the number densities of various electronic states by invoking the so-called quasi-steady-state condition for the conservation of electronic energy states. The quasi-steady-state analysis is based on the assumption that the rates for populating and depopulating an electronic state are much larger than the difference between them, which is the rate of change of the state population. The rates for population and depopulation are known functions of the thermodynamic state of the gas.

The gas is assumed to be optically thin above $0.2\,\mu$m, namely that it absorbs none of the emitted radiation, and optically opaque for wavelengths below $0.2\,\mu$m. Also it is assumed that the amount of radiative emission is small relative to the total energy content of the gas. Thus, we do not have to couple the radiative heat loss to the flowfield calculation. The so-called tangent-slab approximation is also made. With this simplification, we assume that the radiative flux at a point on the body is the product of the integral of the radiative power in the gas normal to the wall and the total solid angle, 2π. This may be written as

[1] See Appendix A, Reaction 7 for these constants.

$$
\begin{aligned}
q_{\mathrm{rad}} &= 2\pi \int_0^\infty Q_{\mathrm{rad}}(\eta)\,\mathrm{d}\eta, \\
q_{\mathrm{rad}\,i} &\simeq 2\pi \sum_j Q_{\mathrm{rad}\,i,j}\left(\eta_{i,j+\frac{1}{2}} - \eta_{i,j-\frac{1}{2}}\right).
\end{aligned}
\tag{5.2.4}
$$

Using these assumptions, it is an easy matter to determine the radiative emission and the radiative heating of the surface.

V.3 Results for AFE Vehicle

The flowfield around the axisymmetric version of the AFE vehicle was computed for two conditions in the proposed trajectory. The first is for perigee at 78 km and a free-stream velocity of 8.91 km/sec. The second is the case at 90 km and 9.89 km/sec which is the approximate limit of the continuum regime. Both cases were run with an assumed fixed wall temperature of 1000 K and a fully non-catalytic wall. The following table gives the flight conditions and the reactivity for each case. The composition of the air at 78 km is assumed to be 79% N_2 and 21% O_2 and at 90 km to be 76.6% N_2, 23.233% O_2 and 0.167% O (by mass).

Table 5.1. Conditions for AFE Test Cases 1 and 2.

	Case 1.	Case 2.
H (km)	78	90
T_∞ (K)	197	188
ρ_∞ (kg/m^3)	2.779×10^{-5}	3.142×10^{-6}
u_∞ (m/s)	8910	9890
$\mathcal{M}_\infty$	31.6	36.4
Ψ_{O_2}	293	35.9

A plot of the grid that was used for the low altitude case is presented in Figure 5.1. It shows the elliptically blunted nose, with radius 2.3 m, followed by the 60° half-angle cone. The shoulder of the body was rounded to ensure that there would be supersonic conditions at the exit.

V.3.1 Results for AFE Vehicle at Perigee (78 km)

The perigee conditions of the AFE flight trajectory will expose the vehicle to the highest radiative and convective heating. The greatest deceleration will occur at this point

also, so that the accurate prediction of these aerothermal loads is critical to the design of the AFE. A discussion of the nature of the flowfield and the surface heating follows. The results are compared to the direct simulation Monte Carlo calculations of Moss, Bird, and Dogra (1988). The results will indicate some questionable features of both the continuum and particulate approaches.

The first plot, Figure 5.2, is a plot of the density along the stagnation streamline and shows that the shock layer and the boundary layer are distinct in this case. Let us define the standoff distance to be the point where the density rise is six times the free-stream density. With this definition, the shock standoff is 0.137 m, or 5.96% of the nose radius. The density at the stagnation point is 144 times the free-stream density. The large density rise across the shock is caused by the high degree of chemical reaction that occurs on the stagnation streamline as seen in Figure 5.3, which is a plot of the mass concentrations on the stagnation streamline. All of the oxygen and much of the nitrogen is dissociated in this case and most of the gas remains dissociated at the vehicle surface even with the influence of the cooled wall. The large degree of reaction is also evident in the next figure which is a semi-log plot of the molar concentrations of the chemical species, including the computed QSS concentration of N_2^+. The peak molar concentration of nitric oxide ions is about 1.83×10^{-3} or 0.333% mass concentration. Thus, even for this highly reactive flowfield, there is a very small proportion of ions. The peak molar concentration of nitrogen ions is slightly larger than that of the nitric oxide ions. This corresponds to the results of Park (1987) for a similar case. Thus it appears that the QSS approximation is reasonable for the stagnation streamline. There is also evidence that the minor constituents of the gas diffuse ahead of the primary reaction zone just behind the shock. Small concentrations of the reaction products are present at greater than $\eta = 0.16$ m which is ahead of the density rise, and as we will see, beyond the temperature increase. The number density of electrons on the stagnation streamline is plotted Figure 5.5. It shows the strong rise in electrons across the shock wave with a peak of 2.22×10^{19} /m^3. The drop in electron number density near the wall is due to the rapid recombination of electrons and ions in the cool wall region.

The temperature distribution on the stagnation streamline is plotted in Figure 5.6 and shows a behavior similar to the previous test cases. There is a strong degree of thermal nonequilibrium behind the shock, but for this highly reactive case, the electron and vibra-

tional temperatures equilibrate with the translational-rotational temperature within about 50% of the distance to the wall. This plot also shows that the vibrational temperature slightly over-shoots the translational-rotational temperature. This is most likely caused by the gas reacting rapidly and losing thermal energy to chemical energy. This drives the translational-rotational temperature down because the energy required for reaction is assumed to come from the translational-rotational energy pool. However, the vibrational temperature is unaffected because only the average vibrational energy is removed from the the vibrational energy pool due to reaction. Thus the vibrational temperature can temporarily over-shoot the translational-rotational temperature on the stagnation streamline. In practice, we would not expect this to occur, which indicates a possible fault with the way the energy of dissociation is apportioned between the translational-rotational and vibrational modes. A more accurate treatment would employ preferential removal of vibrational energy due to dissociation as discussed in Section II.3 (see also Marrone and Treanor (1963) and Treanor and Marrone (1962)). The electron temperature shows a similar behavior as that in the RAM-C II results, namely that it rises near the shock due to translation-electron exchanges, and rises further downstream as the vibrational temperature becomes excited and the electron-vibration exchanges become more efficient. There is again evidence of the electrons diffusing ahead of the shock wave shown in this plot which causes the electron temperature to lead slightly the translational temperature.

Figure 5.7, is a plot of the radiative emission power along the stagnation streamline. The peak value of $2.63\,\mathrm{W/cm^3}$ at $\eta = 0.0816\,\mathrm{m}$ corresponds to the point where the temperatures are most nearly in equilibrium and where the vibrational and electron temperatures are largest. There is little radiation from the parts of the flowfield where the electron temperature is less than 5000 K. This plot indicates the strong dependence of the radiation intensity on the vibrational and electron temperatures. An accurate modeling of their excitation mechanisms is mandatory in obtaining the correct radiative emission and consequently, heating.

The next plot, Figure 5.8, shows the calculated convective heating to the surface of the AFE at perigee as a function of distance from the nose. The stagnation point convective heating value is $19.1\,\mathrm{W/cm^2}$, and this stays fairly constant on the ellipsoidal part of the body, then at the ellipsoid-cone juncture, at $\xi = 0.7\,\mathrm{m}$, the convective heating drops to a

nearly constant $12\,\mathrm{W/cm^2}$ for the length of the cone. There is a slightly larger convective heating at the shoulder of the body, but this drops off rapidly as the flow expands and cools. The stagnation point convective heating is considerably lower than the $24.8\,\mathrm{W/cm^2}$ that Moss *et al.* (1988) calculated. This discrepancy may in part be due to the inclusion of a catalytic wall boundary condition in their study. The influence of a catalytic wall on the convective heat transfer can be profound for cases where the flowfield is highly reactive such as this one. This is caused by the wall promoting recombination of monatomic species at the wall, thus raising the translational-rotational temperature near the wall. Scott *et al.* (1984) report that the ratio of the convective heat transfer for a non-catalytic wall to that for a fully catalytic wall in the AOTV peak heating regime is approximately 0.3 to 0.4. The Monte Carlo results of Moss used a partially catalytic surface and consequently the effect would not be as large. Clearly a useful extension of the current model would be to include the effect of wall catalycity.

The radiative heat transfer to the surface as calculated by (5.2.4) is plotted in Figure 5.9. The peak radiative heating for this case occurs at the stagnation point and is computed to be $5.94\,\mathrm{W/cm^2}$. This decreases rapidly and reaches a fairly constant value of about $0.5\,\mathrm{W/cm^2}$ on the conical surface. The stagnation point radiative heat transfer was computed by Park using the stagnation-point radiation program (SPRAP)[2] for this case. The result was $6.61\,\mathrm{W/cm^2}$, which is 11% higher than the current value. Thus there is very good agreement with the SPRAP code.

The next figures give a more qualitative description of the AFE flowfield in the form of contour plots. Figure 5.10 is a contour plot of the pressure, and shows clearly the strong bow shock wave and that for much of the AFE body the surface pressure is nearly constant. The rapid expansion of the flow around the shoulder is also evident. The next two figures are plots of the percent N_2 and O_2 mass concentration. The first shows that the gas is most highly reacted at the stagnation point and the peak degree of reaction decreases with axial distance. The second shows that essentially the entire shock layer is devoid of O_2. Figure 5.13 shows that the number density of electrons is about $10^{19}\,/\mathrm{m^3}$ for the bulk of the flowfield. Figure 5.14 plots the contours of translational-rotational temperature and shows that much of the flowfield is at a temperature of about $10,000\,\mathrm{K}$. A comparison

[2] See Park (1987) for details.

with the next figure, which presents N_2 vibrational temperature contours, shows that these two temperatures are nearly in equilibrium for a large part of the flowfield. However, Figure 5.16 shows that the electron temperature remains at about 8000 K for this region. Thus even with this highly reactive flow, there is still a degree of thermal non-equilibrium present.

The final plot for this case is Figure 5.17, a contour plot of the radiative emission power from the flowfield. The largest emission occurs at the stagnation point where the temperatures and the density are highest. The radiative power falls off rapidly from this point to a fairly constant level on the conical section of the body.

In summary, the results from this case indicate that the flowfield is highly reactive and radiative. The stagnation point heat transfer results are consistent with previously published experimental work. A major portion (31%) of the heat transfer to the stagnation point is from radiation for this non-catalytic wall case; this proportion would be less for a catalytic wall. The inclusion of thermal nonequilibrium for this case is mandatory for the accurate calculation of radiation because approximately a 5% error in the vibrational and electron temperatures results in a factor of two error in the radiative emission. This sensitivity supports the physical model used in this study.

V.3.2 Results for AFE Vehicle at 90 km

The next and final case that we will consider is the axisymmetric AFE vehicle at 90 km on entry when it is travelling at nearly 10 km/s. Although the vehicle does not experience its peak heat transfer at this point, the aerothermal characteristics are still important because they help determine the total heat load and flight trajectory. The conditions at this point are similar to the previous case except that the density is considerably (9 times) lower and the speed is slightly greater. The result is that the flowfield is much less reactive than the perigee conditions and this has a large affect on the aerothermodynamics of the AFE.

The first series of plots for this case show the characteristics of the flow on the stagnation streamline. Figure 5.18 shows that the density rise across the shock wave is gradual and very large in the boundary layer. The standoff distance based on the six-fold density increase is 0.167 m or 7.24% of the nose radius. The density at the wall is 190 times that

in the free-stream. Although the shock wave is appreciably thick, it has not merged with the boundary layer. The next plot shows the mass concentration of the chemical species on the stagnation streamline. As in the previous case, the flow is highly reactive, but the reactions occur more slowly, and as a result have not reached completion by the time the gas hits the surface. The affect of lowering the density is evident in the distance it takes for O_2 to dissociate; at perigee it took about 0.04 m and in this case, 0.25 m. Figure 5.20 is a semi-log plot of the molar concentrations. It shows that there is a small molar concentration of ions and electrons for this case. A comparison of this plot to the similar one for the perigee case, Figure 5.4, again shows that the reactions are much slower. The number density of electrons, plotted in Figure 5.21, reaches a peak of $2.09 \times 10^{18}\,/\mathrm{m}^3$ at the wall. The reason why there is a slight peak in the number density distribution at the wall may be seen by considering Figures 5.18 and 5.20. There is a rapid density increase in the boundary layer coupled with a somewhat less rapid decrease in the molar concentration of electrons. As the electron number density is proportional to the product of these quantities, it peaks at the wall. This effect would probably not be realized in practice because wall would tend to catalyze ionic recombination and reduce the number density.

Figure 5.22 is a plot of three temperatures on the stagnation streamline. The translational-rotational temperature reaches a peak of $40,000\,\mathrm{K}$, whereas the vibrational temperature of nitrogen gets to nearly $13,000\,\mathrm{K}$ and the electron temperature peaks at 7200 K. Clearly, this case is characterized by a high degree of thermal nonequilibrium with a relatively minor excitation of the vibrational and electron-electronic modes. As such, we would expect the amount of radiation emitted from the flow to be much lower than at perigee, and this is shown in Figure 5.23. The peak radiative power emitted by the flow is $0.0312\,\mathrm{W/cm}^3$, about two orders of magnitude lower than the previous case. The peak emission corresponds to the peak in the vibrational temperature.

The calculated convective heating to the AFE at 90 km is plotted in Figure 5.24. The predicted maximum heating occurs at a location somewhat off the stagnation point, which is not physically correct. This result is most likely caused by an error in the way the axisymmetric shear stress terms are added to the shear stress tensor at the stagnation point. This problem occurs for low density cases only. Other than this problem, the heat transfer distribution is similar, though about 10% lower, than the 78 km case. The

stagnation point heat transfer of 17.6 W/cm^2 is very similar to the 18.4 W/cm^2 reported by Moss *et al.*. The effect of wall catalysis is less important for this case, however the rarified conditions of this case may cause a velocity and temperature slip at the surface, which would influence the heat transfer. This effect is not currently included in the analysis. Figure 5.25 shows the calculated radiative heat transfer as a function of distance along the body. The stagnation point radiative heat transfer is 0.112 W/cm^2, which is much smaller than the convective component (164 times less) and the radiative heat transfer for the previous case (53 times less). The much smaller reactivity and the lower density of this case has essentially caused the radiative heat transfer to lose significance. Figure 5.25 also shows an interesting phenomenon in that the peak radiative heat transfer to the AFE occurs a large distance from the stagnation point, at $\xi = 2.5$ m. The reason for this will become evident when the following contour plots are discussed.

The remaining figures are contour plots of the AFE forebody flowfield at 90 km. The first, Figure 5.26, is a plot of the pressure for this case. The pressure rise through the thick shock wave is evident and the peak pressure occurs at the stagnation point, as expected. The expansion of the flow around the corner is also clearly seen. A comparison to the corresponding plot for the previous case, Figure 5.9, shows that the shock layer is about twice as thick. Figures 5.27 to 5.29 are contour plots of the mass concentration of N_2, O_2, and NO^+ respectively. They show that although the flow reacts to a large extent, with all of the O_2 destroyed in much of the flowfield, the reactions occur over a significant distance. With a close examination of Figure 5.27, it becomes evident that the minimum concentration of nitrogen occurs, not at the nose, but on the shoulder of the body ($x \simeq 0.75$ m and $y \simeq 2.25$ m). Figure 5.29 shows that the peak concentration of NO^+ occurs at the same place. Figure 5.30, a plot of the log of the electron number density, also shows a large number of electrons at this point. A comparison to Figure 5.13, the corresponding plot for the perigee case, shows that the reactions occur much more slowly for the 90 km conditions and that the peak electron number density is about one order of magnitude less. The next three figures are plots of the translational-rotational, N_2 vibrational, and the electron temperatures. The first, Figure 5.31, shows that the maximum translational-rotational temperature occurs behind the shock on the stagnation point, as expected. However, the peak vibrational and electron temperatures exist on the

shoulder of the body, at about the same place that the peak NO^+ concentration occurs. This phenomenon is most evident for the electron temperature, which reaches its maximum of nearly 8500 K at this point, as opposed to 7200 K on the stagnation streamline.

The reason why a peak in the degree of chemical reaction and thermal excitation happens off the stagnation point is made clear by considering Figure 5.34, which is a plot of streamlines for this case. Particles are introduced in the free-stream and traced through the flowfield. The shock wave is evident where the streamlines curve rapidly. Consider the streamline that enters the flowfield at $y \simeq 0.90$ m. It passes through an oblique, though strong shock wave, and flows around the body, far enough away from the surface that it does not enter the boundary layer. This piece of fluid experiences rather severe heating inside the entire shock layer; an examination of Figure 5.31 shows that the particle is heated to between 35,000 K at the shock, to about 20,000 K, for most of the streamline. And because it travels a significant physical distance, it reacts and thermally excites. Thus because of the nonequilibrium nature of the flow, the peak degree of reaction can occur off the stagnation point, at a location where the gas has had sufficient time within the flowfield to react. The final figure is a plot of the radiative emission from the flowfield. The peak radiation power clearly occurs at the point on the shoulder of the body ($x \simeq 0.75$ m and $y \simeq 2.25$ m) where the maximum thermal excitation of the gas has occurred.

This case of the AFE configuration at 90 km demonstrates clearly the influence that thermo-chemical nonequilibrium can have on the state of the gas. The largest degree of reaction and thermal excitation do not occur at the stagnation point, and as a result, neither does the peak radiative heat transfer.

V.3.3 Comparison of Results to Monte Carlo Simulations

Moss, Bird, and Dogra (1988) have reported stagnation point Monte-Carlo simulation results for the cases discussed above. The heat transfer results have been compared, but in this section the features of the flow are discussed and some differences highlighted.

In the Monte Carlo solution, which was a one-dimensional analysis, the shock stand-off distance must be specified. For both cases considered here, it was set to be 0.11 m, or 4.78% of the nose radius, based on the six-fold density rise used above. This was determined by extrapolating axisymmetric solutions at higher altitudes to those of interest.

This immediately indicates a major difference between the two methods because the computed detachments in this study were 0.137 m at 78 km and 0.167 m at 90 km. The reason why the shock standoff distances are different is evident from a comparison of the degree of chemical reaction and thermal excitation for the two methods. For example, Moss reports that the peak mass concentration of N_2 is nearly 0.6 for the 90 km case, whereas the continuum approach yields a maximum of slightly more than 0.4. Similarly, the vibrational and electron temperatures are significantly more excited in the Monte Carlo solution. The result of the larger reaction of the flow is that the shock standoff distance is diminished. Although the results reported in Chapter IV showed very good agreement with experiment for shock detachment, the test cases were in less severe conditions. Therefore it is not possible to say that the continuum approach has been validated for the AFE flight conditions and which, if either, solution approach is correct. A significant difference in the two approaches is that the seven-species model reported here uses the average temperature for the governing temperature of chemical reaction and the diffusive nature of vibrational excitation is approximated. However, these phenomena are not explicitly considered in the Monte Carlo formulation which would tend to make the reactions and thermal excitation more rapid.

From this brief discussion, it is apparent that the phenomenological description of the physical processes that occur in high temperature gases have a large affect on the flowfield. An accurate model of these interactions is necessary for a good model of the flow and at this point some of the existing models are of questionable accuracy.

V.4 Summary of Axisymmetric AFE Results

From the above discussion of the axisymmetric AFE results, it is possible to make several conclusions. Primarily, the numerical method is capable of computing the severe case of the AFE at perigee conditions where it is traveling at a free-stream Mach number of 32. This flowfield is highly reactive and almost entirely composed of monatomic species. The computations at 90 km demonstrate some interesting features that can occur in nonequilibrium flows. The heat transfer results also conform to previously reported computations with the caveat that they do not include the affect of a catalytic wall. Finally, there are some significant differences between the continuum and Monte Carlo results, probably

because of different physical modeling of reaction rates and thermal excitation.

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