JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 12, No. 1, January–March 1998

Prediction of Ultraviolet Radiation in Nonequilibrium Hypersonic Bow-Shock Waves

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Ultraviolet emissions radiated by nitric oxide and atomic oxygen are computed for hypersonic nonequilibrium flow conditions corresponding to the Bow-Shock Ultra-Violet-2 flight experiment. The flowfield is analyzed using the direct simulation Monte Carlo method. Radiation is then estimated using a nonequilibrium radiation code. New results are presented that incorporate a number of recent physical and numerical models. Good agreement is obtained between flight data and predictions over a range of altitudes for both nitric-oxide and atomic-oxygen emissions. Sensitivity to a number of modeling assumptions of the emissions predicted at altitudes above 70 km is considered. It is found that the emission is very sensitive to the translational energy accommodation coefficient. It is also extremely sensitive to the freestream chemical composition assumed. By contrast, the high-altitude emission is insensitive to dissociation and exchange reaction models.

Introduction

RADIATION is emitted from flowfields associated with high-velocity vehicles and missiles. These optical emissions are generated by 1) the bow shock formed in front of the vehicle, and 2) interaction between the rocket plume of the vehicle and the ambient atmosphere. There are well-defined system needs for accurate prediction of ultraviolet, visible, and infrared radiation. Unfortunately, numerical simulation of typical flows is made difficult by conditions of thermochemical nonequilibrium. This paper is the latest in a sequence of investigations[1–4] that seek to improve the ability to compute ultraviolet emissions generated in the bow shock of a hypersonic vehicle flying at high altitude. The approach adopted continues to involve the development and application of advanced numerical techniques using physical models calibrated against flight data.

The Bow-Shock Ultra-Violet-2 (BSUV-2) hypersonic flight experiment was flown in 1991.[1] The vehicle geometry consisted of a spherically capped cone with a nose radius of about 10 cm. BSUV-2 re-entered the atmosphere at 5.1 km/s and provided data in the altitude range from 110 to 60 km. Experimental measurements of the ultraviolet emission resulting from nitric-oxide and vacuum-ultraviolet emission as a result of atomic-oxygen resonance transitions were obtained. Calculation of the radiative emission has been performed in a decoupled approach.[2] In earlier work, the chemically reacting flowfield was computed using continuum (CFD) and direct simulation Monte Carlo (DSMC) methods. Then, the emission was predicted from the flowfield solutions using the nonequilibrium radiation code NEQAIR. Initial calculations of the NO and O emissions for BSUV-2 were successful for altitudes at 80 km and lower. Above 80 km, the predicted emission was too low by as much as two orders of magnitude at the highest altitude considered. Comparison of the experimental data with the computational results from Candler et al.[2] for variation in nitric-oxide emission as a function of altitude is shown in Fig. 1.

Broadly speaking, there are three main processes to be modeled in the computation of emission in these flows: 1) fluid mechanics, 2) chemistry, and 3) radiation. The rarefied fluid mechanics should be accurately simulated because both continuum and DSMC methods have been applied and cross checked for consistency. For radiation, the NEQAIR code has been improved and calibrated extensively through comparison with the BSUV data (from both flights 1 and 2) and through comparison with laboratory data. Nevertheless, there remains some uncertainty in the model, particularly as the degree of nonequilibrium increases at high altitude. The degree of uncertainty of the radiation model is estimated to be at least a factor of 2.

In this paper, the focus is on the computation of the nonequilibrium BSUV-2 flowfields using the DSMC technique. The primary goals of the study are to update emission predictions using a number of recent modeling improvements, and to assess the sensitivity of the numerical data to the modeling of gas–surface interaction. The role of this physical mechanism has not previously been studied for the BSUV-2 flight conditions. A further goal is to identify those aspects of the high-altitude simulations that are most significant in determining the emissions radiated. Three particular assumptions employed in the simulations are considered: 1) modeling of dissociation reactions, 2) modeling of exchange reactions (nitric-oxide formation through the Zeldovich reaction), and 3) chemical composition of the atmosphere.

This paper describes the gas–surface interaction models, and the dissociation and exchange reaction models employed in the present study. Determination of the atmospheric chemical composition at high altitude is discussed. Numerical results are presented for variation of general flowfield properties as a function of altitude. These data are used to compute emissions from nitric oxide and atomic oxygen. Comparison is made with the measurements from BSUV-2 and are found to be very favorable. Sensitivity of the computed emissions to the assumptions made in the DSMC calculations are then considered.

Received May 27, 1997; revision received Sept. 18, 1997; accepted for publication Sept. 19, 1997.

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Modeling Assumptions

The DSMC code employed in the present study is based on the vectorized algorithm described in Ref. 5. The code includes finite rates of rotational and vibrational relaxation, and dissociation, exchange, and recombination chemical reactions. A key development of the new code is the implementation of a numerical weighting scheme that allows accurate and efficient simulation of species that are present in trace amounts. For the altitude range of interest here, both nitric oxide and atomic oxygen (the species for which flight measurements were made) are present in the atmosphere at mass fractions that range between 10^{-6} and 10^{-3}, and are therefore considered trace. The new weighting scheme conserves momentum and energy in each collision and is described in detail in Ref. 6. In the following, a more detailed description is made of the aspects of the DSMC simulations that are varied in the present study. A brief description of the procedure used for computation of nonequilibrium radiation is also included.

Modeling of Gas–Surface Interaction

In all of the previous BSUV-2 numerical analyses using both CFD and DSMC techniques, it has been assumed that the fluid is fully accommodated thermally to the surface of the vehicle at a temperature of 500 K. In the DSMC method, this means that the thermal accommodation coefficients associated with each internal energy mode (translational, rotational, and vibrational) are set to one. There are two undesirable aspects of this approach. First, the surface temperature is unknown and the value of 500 K is employed only as a reasonable value. Second, it is generally accepted that under hypersonic flow conditions, the assumption of full accommodation is inaccurate.

While full accommodation at 500 K is retained as the default approach in this study, the use of accommodation coefficients less than unity is also considered. When an accommodation coefficient of α is employed, this means that a fraction $1 - \alpha$ particle collisions from the surface are treated as specular. For the translational mode, values ranging from 0.7 to 1.0 are employed to correspond with data derived from a hypersonic flight experiment.[7] Hypersonic freejet experiments[8] conducted on the interaction of nitric oxide with a silicon carbide surface indicated that the accommodation coefficient for the rotational mode should be 0.5, and that value is used here. For the vibrational energy mode, no data could be found in the literature. Using the premise that the vibrational mode is less likely to be accommodated thermally than the rotational mode, a value of 0.1 is employed. Finally, because the vehicle surface temperature is not known, the effect of changing the wall temperature is also considered.

Modeling of Dissociation Reactions

For the flow conditions of BSUV-2, where the velocity is 5.1 km/s, the dissociation of molecular oxygen plays a major role in determining emission from atomic oxygen. In addition, this dissociation reaction is an important precursor to the formation of nitric oxide. There is almost no dissociation of molecular nitrogen under these conditions. Two different models are employed to simulate all dissociation reactions. The default model is the threshold line dissociation model developed in Ref. 9 that is based on the model proposed by Macheret et al.[10] In this model, account is taken of the vibrational favoring using arguments from collision dynamics. An important property of the threshold line models[9,10] is that they predict significantly higher rates of dissociation compared to other dissociation models under conditions where the vibrational temperature is significantly lower than the translational temperature. This is the environment found in the BSUV-2 flows at high altitude.

To assess the impact of this new dissociation model in the present application, use of the vibrationally favored dissociation model (VFD) of Ref. 11 is also made. The VFD model is phenomenological in nature and uses a disposable parameter ϕ to control the amount of vibration–dissociation coupling.

Modeling of Nitric Oxide Formation

The first Zeldovich reaction

$$N_2 + O \rightarrow NO + N$$

is the only significant source of nitric-oxide production for the BSUV-2 flight conditions. This reaction also plays an important role in determining the concentration of atomic oxygen. The default model for this reaction employed in the present study uses a database of reaction cross sections obtained from a quasiclassical trajectory (QCT) analysis, as discussed in Ref. 4. In Ref. 4, a new DSMC chemistry model was developed that gave generally good correspondence with the QCT data. In the present study, direct interpolation and extrapolation of the QCT cross sections is used in the DSMC computation to provide greater accuracy with little overall loss in numerical efficiency.

For comparison, the total collision energy (TCE) DSMC chemistry model[12] is also employed to simulate the Zeldovich reaction. This model is identical to the VFD model when the vibration–dissociation coupling parameter ϕ is set to zero. The rate of reaction used in the TCE model is the value recommended by Park et al.[13]

Chemical Composition of the Atmosphere

In the early simulations of the BSUV-2 flows,[2] the chemical composition was estimated from the Air Force Geophysical Handbook.[14] It was not expected that the mass fraction of atomic oxygen would be an important parameter, and a value of 4×10^{-6} was assumed for all altitudes. In practice, up to an altitude of about 80 km, the relative chemical composition of the atmosphere is nearly constant with the mass fractions of molecular nitrogen and oxygen being equal to those at sea level and all other species existing at mass fractions less than 10^{-5}. Above 80 km, photodissociation of molecular oxygen leads to a significant increase in the relative concentration of atomic oxygen.

A more accurate approach to defining the composition of the atmosphere is offered by the Mass Spectrometer Incoherent Scatter (MSIS) model.[15] This takes as input the longitude and latitude of the flight, and the date (to estimate effects of the solar cycle). The MSIS model gives a mass fraction of O at 90 km of about 7×10^{-4}. This is significantly larger than the value used in the previous high-altitude studies. The chemical composition of the atmosphere given by the MSIS model is used as the default condition in this study. To assess sensitivity of the DSMC solutions to this aspect of the simulation, the lower value used in Ref. 2 for freestream atomic-oxygen mass fraction is also considered.

Unfortunately, computation of NO concentration is not included in the MSIS model. From measured data,[16] the NO concentration at 90 km gives a mass fraction of about 1×10^{-7}. For all of the flow conditions considered in the present study, the amount of NO produced through chemistry far exceeds the amount of NO in the freestream. Hence, precise specification of the atmospheric concentration of NO is not important in these studies.

Computation of Nonequilibrium Radiation

The nonequilibrium radiation code NEQAIR (Ref. 17) is employed for the prediction of ultraviolet emission from the DSMC flowfield solutions. The modeling of ultraviolet emission with this code is discussed for nitric oxide in Ref. 18 and for atomic oxygen in Ref. 19. A common assumption made in using the NEQAIR code is that a quasi-steady-state (QSS) exists for the number densities of the electronically excited species. The assumption requires that the time scale of chemical processes is much smaller than the time scales for diffusion and for changes in overall properties. Under these conditions,

the local values of temperatures and ground-state species number densities obtained from the DSMC computation may be used to compute the populations of the electronically excited states.

Results

The presentation of results is divided into three sections: 1) flow properties and subsequent emission for nitric oxide, 2) flow properties and subsequent emission for atomic oxygen, and 3) sensitivity of high-altitude NO emission to reaction models and atmospheric composition. Consideration of the sensitivity of emission predictions to gas–surface interaction modeling is included in the first two subsections.

Nitric Oxide Emission

Emission for nitric oxide was measured on BSUV-2 along the stagnation streamline using both photometers and spectrometers. Details may be found in Ref. 1. The flight data have already been shown in Fig. 1. Prediction of the magnitude of NO emission depends primarily on the bulk translational temperature of the gas and the nitric-oxide concentration along the stagnation streamline. The variation computed using the DSMC technique along the stagnation streamline of translational and vibrational temperatures, and of nitric-oxide concentration, are compared for three different altitudes in Figs. 2a–2c, respectively. The Knudsen numbers for the BSUV-2 vehicle are 0.008, 0.033, and 0.215 for the altitudes of 71, 80, and 90 km, respectively. The results illustrate how the shock wave becomes significantly thicker at higher altitudes. It is also clear that a large degree of thermal nonequilibrium exists under all three conditions.

The results shown in Fig. 2 are generated using accommodation coefficients of one for all energy modes. In Figs. 3a and 3b, stagnation streamline profiles of translational temperature and nitric-oxide concentration are shown for the 90-km condition where the effect of varying the gas-surface modeling is considered. It is clear that the reduction of the accommodation coefficient for translational energy α_t leads to an increase in translational temperature and a small increase in NO concentration. Variation of the other accommodation coefficients had much less impact on the flowfield properties. In addition, use of a wall temperature of 1000 K instead of 500 K had almost no effect on the flow, except at very small distances from the surface.

Because the NO emission depends on the translational temperature and nitric-oxide concentration, it is clearly of interest to consider how the different values of α_t affect the predicted radiation. In Fig. 4, new emission predictions based on the flowfield solutions generated in the present study are shown. The most important conclusion to be made about the data shown in Fig. 4 is that good agreement between measurement

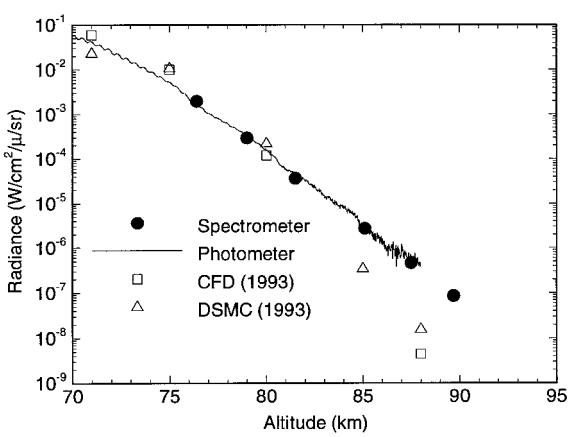

Fig. 1 Comparison of data measured by BSUV-2 and previous numerical predictions for NO emission as a function of altitude.

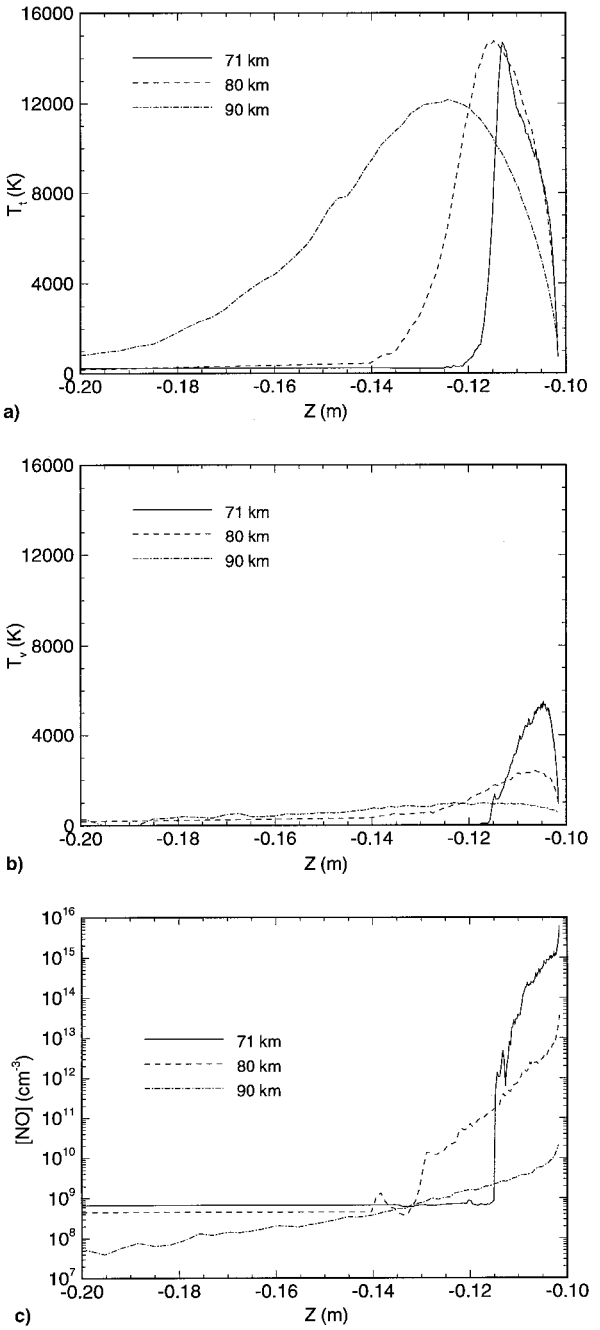

Fig. 2 Variation in a) translational temperature, b) vibrational temperatures, and c) nitric-oxide concentration profiles along the stagnation streamline as functions of altitude.

and prediction is obtained over the entire altitude range. It is significant to note that the good agreement obtained previously at low altitudes[2] is retained here with all of the new physical models. The source of the improvement in the high-altitude predictions is discussed later in the paper. Another important conclusion from Fig. 4 is that the emission predicted at high altitude is very sensitive to the translational energy accommodation coefficient. At 90 km, there is a factor of 5 difference in NO emission obtained with values of $\alpha_t = 0.7$ and 1.0.

Before considering in detail the dependence of the predicted spectra on gas–surface interaction, it is appropriate to consider the BSUV-2 flight data. In Fig. 5a, two self-normalized spectra measured at 79 and 90.8 km are compared. The spectral scan at 90.8 km is at an altitude where the surface modeling sensitivity can be best tested. Comparison of this scan with that at 79 km shows the high-altitude data to be signal limited. As

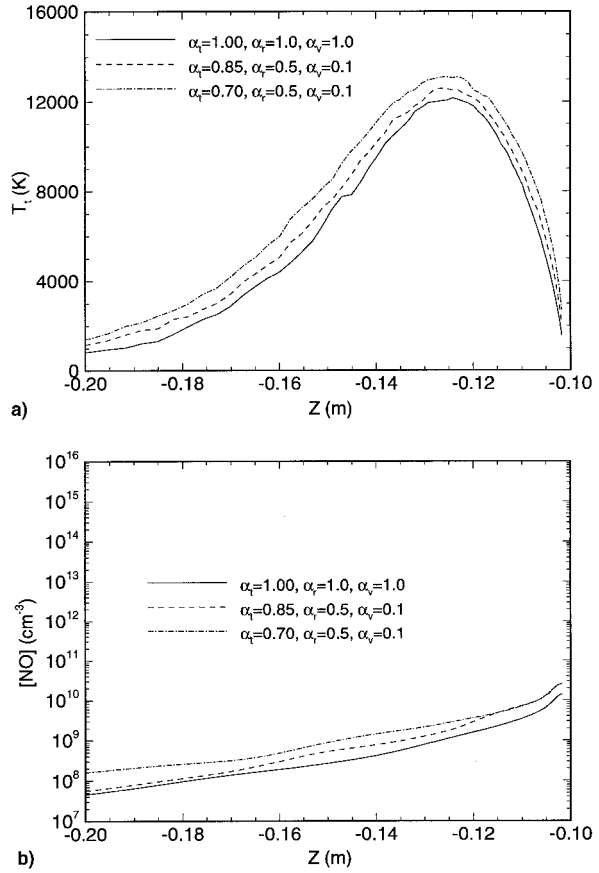

Fig. 3 a) Translational temperature and b) nitric-oxide profiles along the stagnation streamline as functions of a gas–surface interaction model at 90 km altitude.

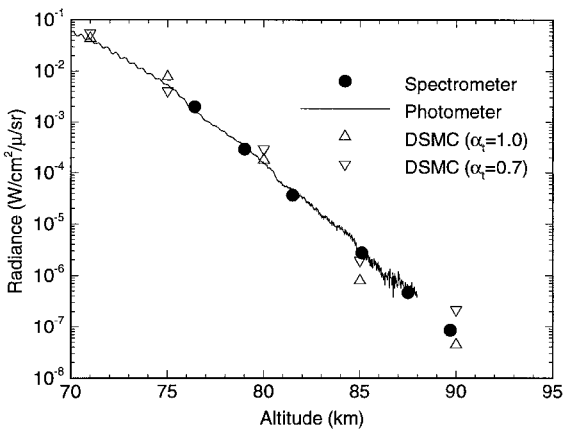

Fig. 4 Comparison of data measured by BSUV-2 and new numerical predictions for NO emission as a function of altitude.

the rocket descended, the increasing signal strength provides a scan at 79 km with much better signal-to-noise. However, by self-normalizing each spectra, one can see that the vibrational spectral features remain the same between 90.8 and 79 km. The evolution of the spectra from the higher to the lower altitude provides confidence in the use of the higher altitude, noisier spectrum.

The sensitivity of the emission prediction to the gas–surface interaction model is clearly illustrated in Fig. 5b, which shows a comparison of computed spectra with the BSUV-2 data. Figure 5b shows two computed spectra obtained at 90 km with translational energy accommodation coefficients of 1 and 0.7. An important measure of merit for the computed spectra is how well they reproduce the relative peak shape and heights

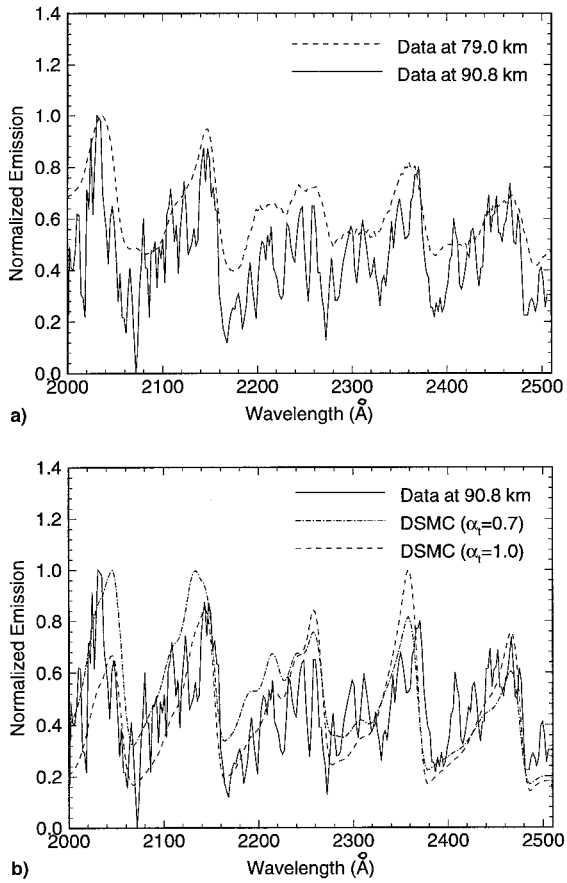

Fig. 5 Comparison of normalized NO spectra a) measured by BSUV-2 at 79 and 90.8 km altitude and b) computed at 90 km altitude.

of the spectral data. There are multiple components to the spectra between 2000 and 2500 Å from different electronic state transitions for the NO and O_2 molecular systems. The branching ratios for all of these transitions are not well known; however, the spectral region between 2000 and 2300 Å is strongly dominated by radiation from the NO(A $\rightarrow$ X) transition. Hence, if emphasis is given to this wavelength portion of the spectra, it can be seen that the calculation with the lower accommodation coefficient gives better agreement with the data. Examination of the DSMC NO vibrational temperatures along the stagnation streamline shows that the lower accommodation coefficient raises the NO vibrational temperature by about 1000 K. This increase in vibrational temperature increases the number of transitions from the higher vibrational levels of the NO(A) state, thereby increasing the calculated peak height at 2050 Å.

Thus, the comparison between calculated spectra and data is a sensitive measure of the computed NO vibrational temperature. When the same comparison is made at 80 (79) km altitude, the agreement in the peak height ratios is much poorer because the NO vibrational temperature is computed to be unreasonably high (about 10,000 K). The flow computations are not sensitive to the surface accommodation model at 80 km, but rather the translational–vibrational energy exchange. The QCT calculations provide a detailed state-to-state treatment of the formation of NO, which is then used in the DSMC calculations. There have not been similar calculations to provide information about the explicitly state-to-state disposal of vibrational energy or quenching of NO. At 80 km, there are sufficient collisions that these reverse vibrational cooling processes must be considered. That level of effort is beyond the scope of this paper.

The second measure of the calculations is the ability to predict the absolute magnitude of the spectral data and computed

Table 1 Comparison of maximum spectral peak heights

Description	Wavelength, Å	Radiance, W/cm^2/sr/μ
BSUV-2 data at 90.8 km	2031	0.94×10^{-7}
DSMC, $\alpha_t = 1.00$	2359	1.1×10^{-7}
DSMC, $\alpha_t = 0.85$	2044	2.0×10^{-7}
DSMC, $\alpha_t = 0.70$	2046	4.7×10^{-7}

spectra. Table 1 shows a comparison of the absolute magnitude of the highest peak, for the three DSMC calculations and the data. Consistent with our first comparison of the spectral shape and peak ratios, the spectral peak does not occur at the same wavelength for each spectra. Hence, the wavelength at which each maximum peak occurs is also indicated. The data and the DSMC calculations with an accommodation coefficient less than 1 produce a maximum peak location at approximately the same wavelength. The DSMC calculation with a maximum peak at approximately 2400 Å has a maximum spectral peak occuring at a wavelength that is consistent with a lower NO vibrational temperature. Again, a higher vibrational temperature appears to be more consistent with the spectral data. Table 1 shows that all of the calculations and the data are in good agreement, with the worst case being a factor of 5. The uncertainty in the absolute magnitude of the spectral radiance data is ±25%. The uncertainty in the wavelength calibration of the instrument of about 10 Å is sufficient to explain the discrepancy in the peak wavelength positions for the DSMC calculations with an accommodation coefficient less than 1. An accommodation coefficient of 0.85 seems to provide the best overall agreement.

The second measure of the calculations is the comparison of the absolute magnitude of the spectral data and computed spectra, as shown in Table 1. Table 1 shows that all of the calculations are in good agreement with the absolute magnitude of the data (±25%), given the uncertainties in the modeling. For an accommodation coefficient less than 1, it can be seen that the location of the maximum peak and peak height are in very good agreement with the data. The uncertainty in the wavelength calibration of the instrument of about 10 Å is sufficient to explain the discrepancy in peak wavelength positions. An accommodation coefficient of 0.85 seems to provide the best overall agreement.

Atomic Oxygen Emission

Emission from atomic oxygen at 130.4 nm was measured on BSUV-2 using a photoionization cell along a line of sight (LOS) that subtended an angle of 36 deg with the center of the sphere that represents the nose of the vehicle. Details of the experiment and the radiation model may be found in Ref. 19. Prediction of the atomic-oxygen emission depends primarily on the bulk translational temperature and the atomic-oxygen concentration along the LOS. In Fig. 6, these flow properties predicted by the DSMC technique are shown for three different altitudes. Qualitatively, these are similar to the data shown in Fig. 2 along the stagnation streamline. The bow-shock becomes thicker and more diffuse at higher altitudes. These results are obtained with all accommodation coefficients set to 1. When lower values are employed, similar behavior to that obtained along the stagnation streamline is observed. Specifically, the translational temperature is increased at lower values of α_t.

Comparison is made in Fig. 7 of the prediction and measurement of atomic oxygen emission as a function of altitude. The oscillations in the measured data are caused by precession of the rocket that occurred during flight. The agreement between the BSUV-2 data and prediction is particularly good at high altitude. As with nitric-oxide emission, the radiation at high altitude is found to be sensitive to the gas–surface interaction model. At 90 km, there is a factor of 3 difference between the emissions predicted using values for α_t of 0.7 and 1.0. The comparison between measurement and computation

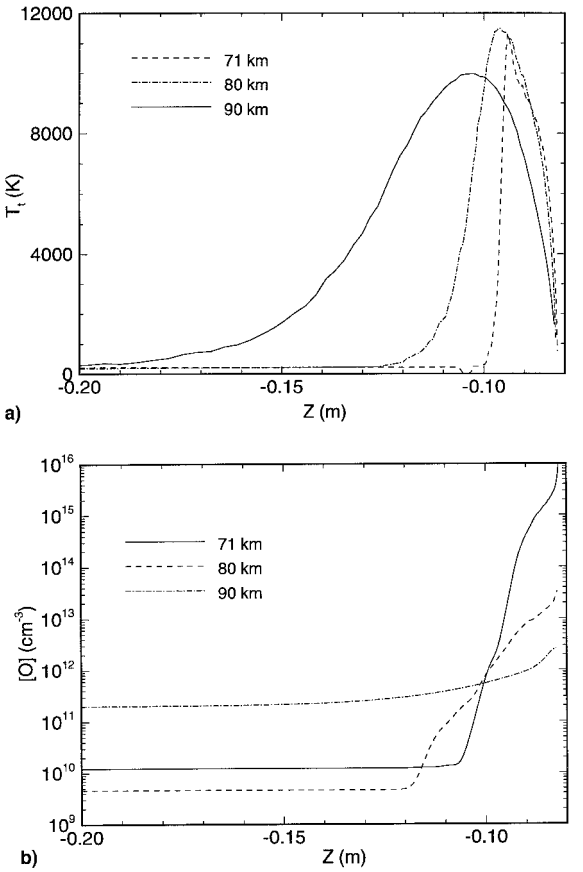

Fig. 6 a) Translational temperature and b) atomic-oxygen concentration profiles along the 36-deg line LOS as functions of altitude.

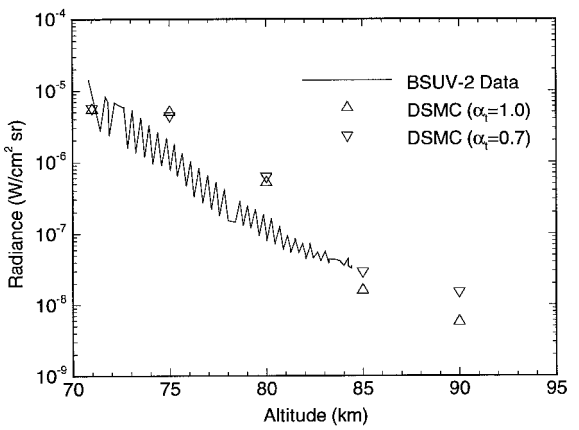

Fig. 7 Comparison of data measured by BSUV-2 and new numerical predictions for O emission as a function of altitude.

at lower altitude is not as satisfactory. At 80 km, the atomic-oxygen vacuum ultraviolet (VUV) model of Ref. 19 predicts that the flow is optically thin. Hence, the total radiation is governed by the gradient of atomic-oxygen concentration along the 36-deg LOS and the translational temperature. It was found that the O concentration was very sensitive to the $O_2 + N_2$ dissociation rate used, and there remains some uncertainty as to its best value. The rate used in this work is different from that used earlier and may account for the poorer agreement between theory and experiment. The lack of agreement with the data is consistent with the inability to predict the NO spectral features at 80 km. The agreement between the predicted and measured O atom radiance at 70 km seen in Fig. 7 probably occurs because of compensating errors. At that altitude (and lower) the flow is optically thicker and the total radiance

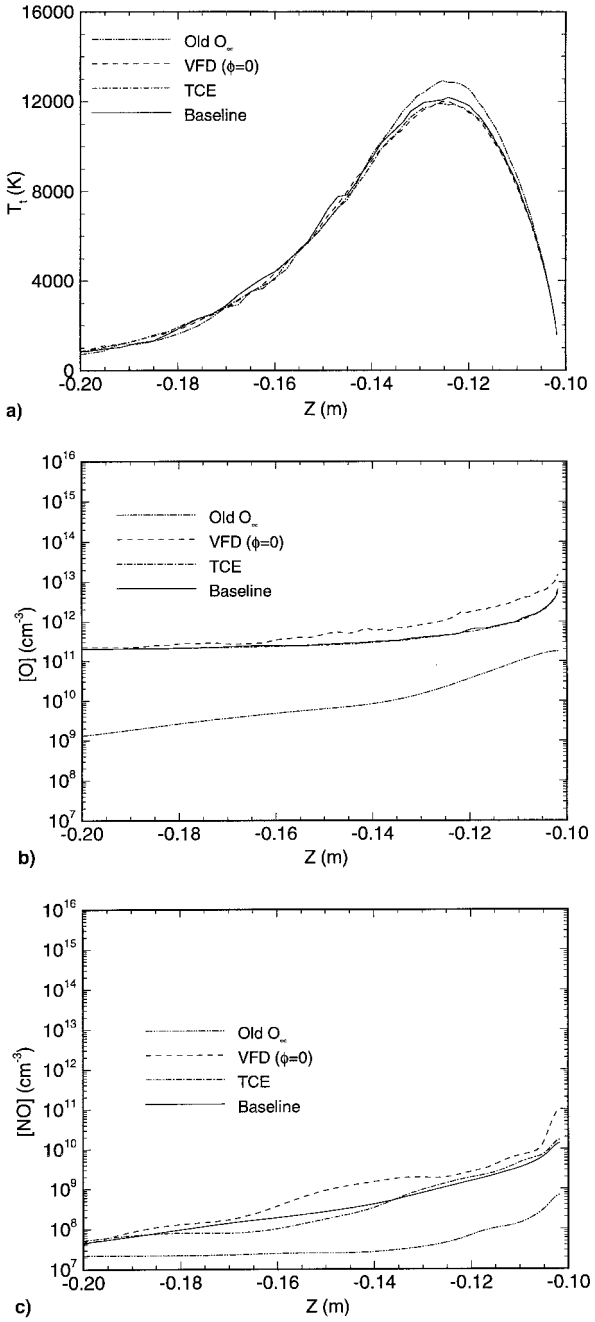

Fig. 8 Profiles of a) translational temperature, b) atomic-oxygen concentration, and c) nitric-oxide concentration along the stagnation streamline at 90 km altitude.

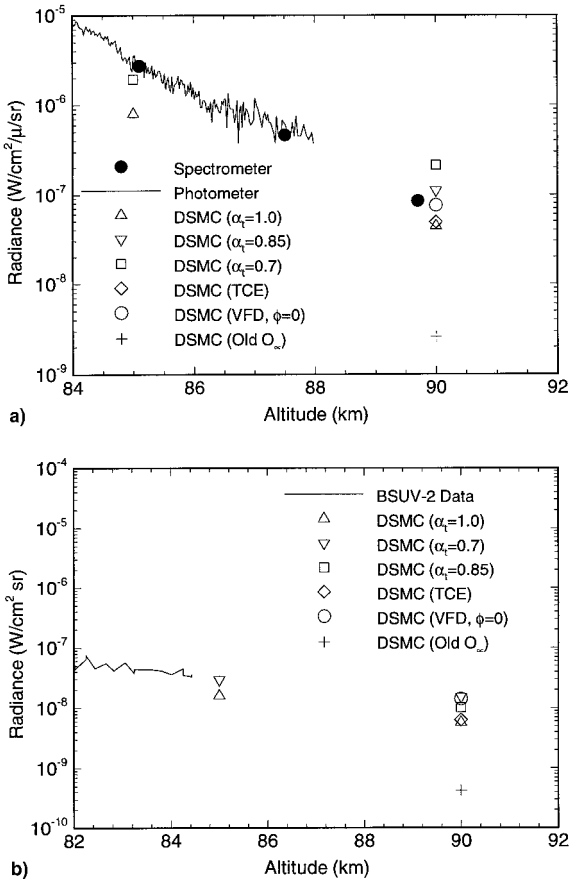

Fig. 9 Comparison of data measured by BSUV-2 and numerical predictions for a) NO and b) O emissions at high altitude.

is influenced by the reabsorption of VUV photons by the cool atomic O in the boundary layer.

Sensitivity Studies

Comparison of the DSMC-based NO emissions shown in Figs. 1 and 4 indicates that significant improvement has been made in predicting the high-altitude data. The new results have been generated through the use of new physical models, a new species weighting scheme, and new boundary conditions (specified by the MSIS atmospheric model). To understand exactly how the improved predictions were obtained, several additional simulations are performed at the 90-km altitude condition. First, to examine the role of dissociation modeling, the threshold line model of Ref. 9 is replaced by the vibrationally favored dissociation (VFD) model of Haas and Boyd.[11] The coupling between the vibrational energy and the probability of dissociation in this model is governed by the parameter ϕ. In the present study, $\phi = 0$ is used (no coupling), which is equivalent to using the total collision energy model of Ref. 12. This solution is labeled VFD ($\phi = 0$) and used the QCT model for nitric-oxide production. Second, to examine the role of modeling nitric-oxide formation, the total collision energy model[12] is used in place of the reaction cross sections obtained from QCT analysis. This solution is labeled TCE and here the dissociation reactions are again modeled using the threshold line model. Finally, the role of using the MSIS atmospheric model is assessed by using the mass fraction for O that was employed in the earlier study.[2] This simulation is labeled "Old O_∞" and uses the threshold line and QCT models. In each of these simulations, all accommodation coefficients are set to one.

Several profiles of translational temperature along the stagnation streamline at 90 km altitude are compared in Fig. 8a. There is very good agreement between the different simulations except for the case where the old mass fraction for atomic oxygen is employed. In this case, the peak translational temperature is slightly larger indicating that fewer chemical reactions have occurred in this simulation. In Fig. 8b, the profiles of atomic oxygen are shown. Clearly, the use of the old atomic-oxygen freestream condition has a significant effect. Also, it is found that more dissociation of molecular oxygen occurs when no vibration-dissociation coupling is employed. In Fig. 8c, the profiles of nitric-oxide concentration are compared for the same simulations. The trends are identical to those found for atomic oxygen: a reduced NO concentration with the old atmospheric composition, and an increased NO concentration with no vibration–dissociation coupling. The increase in NO concentration because of the use of a poor dissociation model is relatively small and indicates that production of nitric oxide at these high-altitude conditions is driven not so much by atomic oxygen formed through dissociation of molecular oxygen, but rather through the ambient oxygen atoms.

These conclusions are further illustrated in Figs. 9a and 9b where the emissions computed from these simulations are compared with the other simulations and with the BSUV data. In each case, the main sensitivity of predicted emission arises from specification of the atmospheric composition, and from specification of the gas–surface interaction model. There is a very modest increase in NO emission through use of the dissociation model without vibrational coupling.

Summary and Conclusions

The primary conclusion drawn from the present study is that numerical capabilities have been developed to accurately predict ultraviolet emission from shock-heated air under hypersonic nonequilibrium conditions. Predictions for both ultraviolet emission from nitric oxide and vacuum ultraviolet emission from atomic oxygen were in very good agreement with data measured on the BSUV-2 flight experiment.

Investigations into the sensitivity of the predicted emissions to several modeling assumptions revealed a number of important results. First, the computation of these emissions is sensitive to the modeling of gas–surface interaction especially at high altitude. In particular, the emission results are most sensitive to the value of the translational energy accommodation coefficient. For a modest variation in this parameter from 1.0 to 0.7, at 90 km altitude, the NO emission increased by a factor of 5, and the O emission increased by a factor of 3. These values of the accommodation coefficient lie within the range of uncertainty for this parameter for hypersonic flow conditions. Variation of other energy accommodation coefficients and the surface temperature had essentially no effect on the computed emissions.

At high altitude (90 km), the predicted emissions were found to be very sensitive to the mass fraction of atomic oxygen assumed for the atmosphere. Based on the present study, the concentration of atomic oxygen at all altitudes was found to be adequately represented by the MSIS model.

Rather surprisingly, the emissions computed at the 90-km condition were found to be relatively insensitive to modeling of dissociation and exchange chemical reactions. Only when vibrational coupling was removed was any noticeable difference in the emissions observed. These findings indicate that the mechanism for nitric-oxide formation changes with altitude. At low altitude, the source of atomic oxygen needed for NO production comes from the dissociation of molecular oxygen. For these conditions, the emissions are essentially insensitive to the value assumed for the freestream concentration of atomic oxygen. At high altitude, there is an insufficient number of collisions to produce much atomic oxygen through dissociation. Thus, the rate of formation of nitric oxide at these conditions is determined by the level of freestream atomic oxygen.

Acknowledgments

The work performed at Cornell is funded by the Army Research Office under Grant DAAH04-93-G-0089. Work performed at the Institute for Defense Analyses was carried out under Contract DASW01-94-C-0054 for the Innovative Science and Technology Office of the Ballistic Missile Defense Organization.

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