JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 20, No. 3, July–September 2006

# Technical Notes

*TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).*

## Multiband Radiation Model for Simulation of Galileo Probe Entry Flowfield

Shingo Matsuyama*
*Japan Aerospace Exploration Agency, Chofu 182-8522, Japan*
and
Yuji Shimogonya,† Naofumi Ohnishi,‡ Akihiro Sasoh,§
and Keisuke Sawada¶
*Tohoku University, Sendai 980-8579, Japan*

### Nomenclature

| | | |
|---|---|---|
| $A_1$–$A_5$ | = | fitting parameters in Eq. (2) |
| $c_1$–$c_4$ | = | coefficients in Eq. (3) |
| $n$ | = | molar concentration, mol/m$^3$ |
| $T$ | = | temperature, K |
| $\kappa_\lambda$ | = | absorption coefficient at given wavelength, m$^{-1}$ |
| $\lambda$ | = | wavelength, Å |
| $\sigma_\lambda$ | = | absorption cross section at given wavelength, m$^2$/mol |

*Subscripts*

| | | |
|---|---|---|
| $e$ | = | electron |
| $i$ | = | species $i$ |
| itb | = | index of table data point for temperature |
| jtb | = | index of table data point for electron number density |

*Superscripts*

| | | |
|---|---|---|
| $i$ | = | species $i$ |

### Introduction

WHEN the Galileo probe vehicle entered the Jovian atmosphere, the peak heating rate and the heat load on the forebody heat shield amounted to 300 MW/m$^2$ and 3000 MJ/m$^2$, respectively.[1,2] As a result, massive ablation occurred that resulted in a substantial reduction of the heat shield mass.[1] The flight data revealed that there was a significant discrepancy of the final recession profile from that given by the preflight prediction. Indeed, the amount of recession occurred at the stagnation region deduced from the flight data was almost three-fourths and that at the frustum region was almost double when compared with those given by the preflight prediction.[2] This discrepancy has yet to be explained.

Recently, in our previous study,[3] we succeeded in reproducing the large recession occurring at the frustum region and gave one consistent explanation for why the radiative heat flux along the frustum region of the Galileo probe was larger than the preflight predictions. It was found that the number densities of radiation-absorbing carbonaceous species in the ablation layer were substantially decreased by excessive diffusion and dissociation reactions caused by the enhanced turbulence effects. To obtain this result, an accurate calculation of a strongly radiating flowfield over the Galileo probe that accounted for detailed spectral radiative properties was used.

The line-by-line method[4] is known to yield the most accurate spectral radiative properties of high-temperature gases. However, it is not suitable for coupling with a flowfield calculation because of its enormous computational load. The modern multiband radiation models can reduce the computing time of the line-by-line calculation at least by a factor of 100 and reproduce the line-by-line result within a small error.[5,6] In these models, it is customary to assume that the absorption coefficients depend only on temperature, assuming in advance typical electron number densities within the shock layer. This treatment, however, is not suitable for the Galileo probe entry case because the line shape of atomic hydrogen has significant dependence on electron number density. In this study, therefore, we give a new implementation of the radiation multiband model that depends on both the local temperature and electron number density.

### Formulation

In the present multiband model for the computation of the Galileo probe entry flowfield, the participating chemical species are assumed to be H, $H^+$, C, $C_2$, $C_3$, O, $O_2$, and CO. Radiation mechanisms considered in the multiband model are given in Ref. 3. The line-by-line absorption cross sections are obtained using our in-house code, which was developed based on the NEQAIR85. In this code, the spectroscopic data needed for computing spectral radiative properties, such as the Einstein A coefficient, the sum of the squares of the electronic transition moments, and the Franck–Condon factor, are updated to the latest available values. The absorption coefficients of the gas mixture are calculated at 4781 wavelength points for the wavelength range from 750 to 15,000 Å. These wavelength points are carefully selected to include all the important atomic lines that participate in the energy transfer in the shock layer.[5] Continuum radiation, as well as absorption due to molecules, is also accounted for.

Let us first describe the conventional multiband model.[5,6] The absorption coefficient of a gas at a given wavelength point is expressed as a sum of those for individual species, which can be written as

$$k_\lambda = \sum_i n_i \sigma_\lambda^i \tag{1}$$

The cross-section values are evaluated by a curve fit in the form

$$\sigma_\lambda^i = \exp\left\{A_{1\lambda}^i \big/ z + A_{2\lambda}^i + A_{3\lambda}^i \ln(z) + A_{4\lambda}^i z + A_{5\lambda}^i z^2\right\} \tag{2}$$

Received 4 March 2005; revision received 1 October 2005; accepted for publication 3 October 2005. 

*Researcher, Computational Science Research Group, Institute of Aerospace Technology; smatsu@chofu.jaxa.jp. Member AIAA.
†Graduate Student, Department of Aerospace Engineering.
‡Research Associate, Department of Aerospace Engineering. Member AIAA.
§Professor, Institute of Fluid Science, Sendai 980-8577. Associate Fellow AIAA.
¶Professor, Department of Aerospace Engineering. Associate Fellow AIAA.

where $z = 10{,}000/T$ and $A^i_{k\lambda}(k = 1, 2, 3, 4, 5)$ are fitting parameters. Those fitting parameters are determined according to the following procedure. First, the cross-section values of each species are calculated by the line-by-line method at five typical temperatures in the shock layer (for example, 3000, 6500, 10,000, 13,500, and 17,000 K for the Galileo probe entry case). The electron number density at each temperature is required for the calculation of free–bound and free–free absorption and the Stark broadening of the atomic line. These values can be estimated by means of an equilibrium assumption with the pressure evaluated behind the shock wave and the selected five temperatures. By solving the resulting five simultaneous equations, the fitting parameters can be determined.

The aforementioned treatment gives fair agreement with the results given by the line-by-line method if the dependence of radiation properties on electron number density is relatively weak. Unfortunately, this is not the case for the Galileo probe entry flight because the Stark broadening of atomic lines from hydrogen atoms is significant and strongly depends on the electron number density. Moreover, the atomic hydrogens are the dominant contributor to the radiative heating exerted on the Galileo probe. Therefore, the conventional multiband model can give erroneous results if the electron number density used in obtaining the fitting parameters is poorly chosen.

Now we describe an alternative approach to obtaining the cross-section values, in which bilinear interpolation[7] in terms of both temperature and electron number density is utilized. We first tabulate the absorption cross-section values at the specified temperatures and electron number densities using the line-by-line method.[4] The absorption cross-section is then given by

$$\sigma^i_\lambda(T, n_e) = c_1 + c_2 T + c_3 n_e + c_4 T n_e \tag{3}$$

The coefficients $c_1$–$c_4$ in the above expression are defined as

$$c_1 = \sigma^i_{\lambda(\text{itb}),(\text{jtb})} - \frac{\partial \sigma^i_\lambda}{\partial T} T_{(\text{itb})} - \frac{\partial \sigma^i_\lambda}{\partial n_e} n_{e(\text{jtb})} + \frac{\partial^2 \sigma^i_\lambda}{\partial T \partial n_e} T_{(\text{itb})} n_{e(\text{jtb})}$$

$$c_2 = \frac{\partial \sigma^i_\lambda}{\partial T} - \frac{\partial^2 \sigma^i_\lambda}{\partial T \partial n_e} n_{e(\text{jtb})}, \qquad c_3 = \frac{\partial \sigma^i_\lambda}{\partial n_e} - \frac{\partial^2 \sigma^i_\lambda}{\partial T \partial n_e} T_{(\text{itb})}$$

$$c_4 = \frac{\partial^2 \sigma^i_\lambda}{\partial T \partial n_e} \tag{4}$$

where $\sigma^i_{\lambda(\text{itb,jtb})}$, $T_{(\text{itb})}$, and $n_{e(\text{jtb})}$ are the absorption cross-section value, the temperature, and the electron number density at the data point (itb, jtb), respectively. The derivatives in the above expressions are evaluated by the first-order difference approximation using the tabulated data.[7] Note that the first derivatives so obtained can be discontinuous at the table data points. However, the computed results exhibit no problem leading to inaccuracies. The bilinear interpolation of Eq. (3) is applied to all the participating chemical species.

In the calculation of the Galileo probe entry flowfield, the cross-section data are tabulated for the temperature range from 3000 to 17,000 K and the electron number density ranges from $10^{10}$ to $10^{18}$ cm$^{-3}$. The temperature range is divided into 14 segments at regular intervals, whereas the electron number density range is divided into 10 segments at regular intervals in the logarithmic scale. The obtained tabulated cross-section data is found to be sufficiently smooth for the present purpose.

## Results and Discussion

We attempt to justify the developed multiband radiation model in terms of reproducing the radiative heat flux profiles given by the detailed line-by-line calculation. In what follows, therefore, the computed radiative heat flux profiles and that given by the line-by-line method are compared with respect to typical shock layer properties obtained in our previous study[3] for the peak heating condition of the Galileo probe entry flowfield. In Ref. 3, we solved the Navier–Stokes equations in the axisymmetric form using our in-house code. We assumed thermochemical equilibrium in the calculation. The equilibrium gas properties were obtained by utilizing the free-energy minimization method. The flowfield data used in the present study are identical to those presented in Ref. 3. The radiation model detailed in this study is also identical to that employed in Ref. 3. In this study, one-dimensional radiative transfer calculations assuming the tangent-slab approximation are carried out along the shock layer profile shown in Fig. 1 with different radiation models.

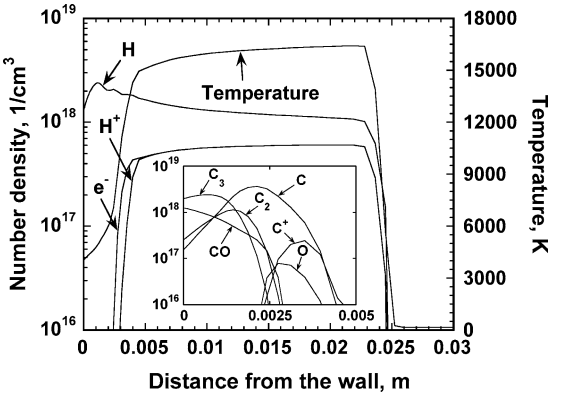


**Fig. 1 Shock layer profile along the stagnation streamline obtained for the peak heating condition of the Galileo probe entry flowfield.[3] The inset shows the near wall distributions of carbonaseous species.**

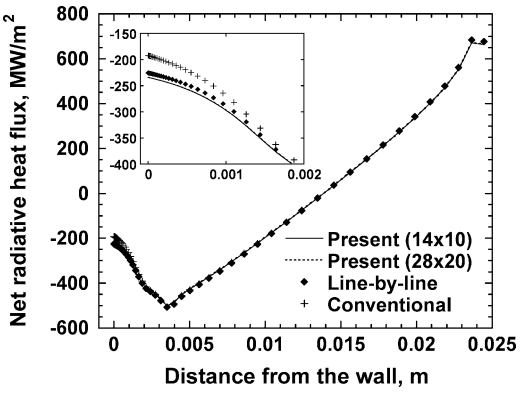


**Fig. 2 Comparison of the net radiative heat flux distributions along the stagnation streamline between the present multiband model, the line-by-line method, and the conventional multiband model. Negative value corresponds to the radiative heat flux toward the wall and vice versa.**

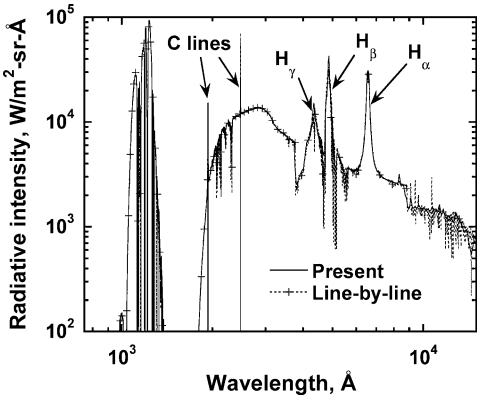


**Fig. 3 Comparison of spectral radiative intensity incident on the wall given by the present multiband model and that given by the line-by-line method.**

In Fig. 2, comparisons of the net radiative heat flux distributions are given. One can find that the present multiband model well reproduces that given by the line-by-line calculation. Note that two radiative heat flux distributions using two different table intervals virtually agree with each other, confirming that the cross-section table with $14 \times 10$ intervals is sufficient for the present purpose. On the other hand, the conventional multiband model obviously fails to

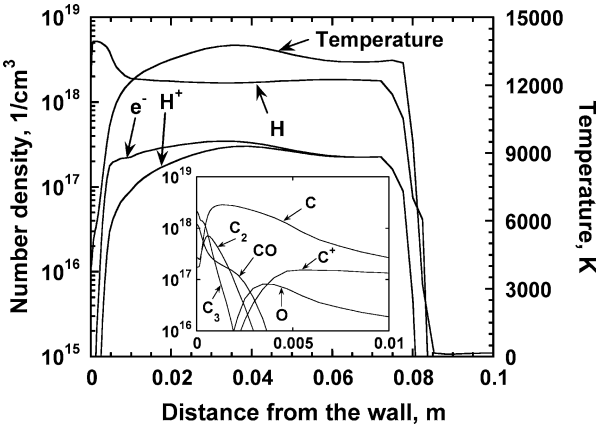


**Fig. 4 Shock layer profile along the line normal to the wall in the downstream frustum region.[3] The inset shows the near wall distributions of carbonaceous species.**

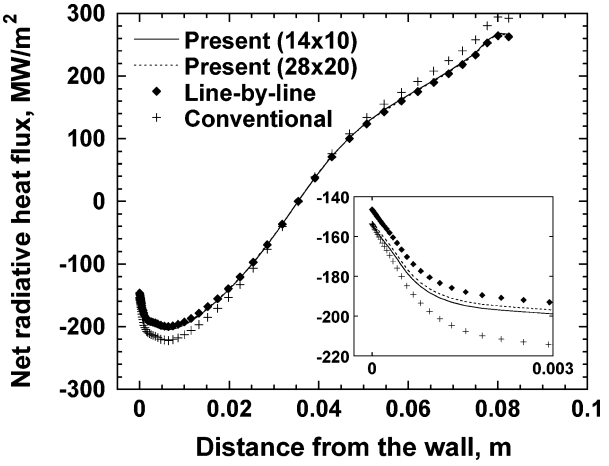


**Fig. 5 Comparison of the net radiative heat flux distributions in the shock layer given by the present multiband model, the line-by-line method, and the conventional multiband model. The inset shows the net radiative heat flux distributions near the wall.**

reproduce the heat flux distribution within the ablation layer near the wall. The radiative heat flux values at the wall are determined to be −226, −234, and −192 MW/m$^2$ by the line-by-line calculation, the present multiband model, and the conventional multiband model, respectively.

The spectral radiative intensity distributions incident on the wall given by the present multiband model and that by the line-by-line calculation are compared in Fig. 3. The present multiband model again reproduces spectral intensity given by the line-by-line calculation quite well. Although we do not show the result here, the conventional multiband model overestimates absorption due to carbonaceous species in the ablation layer, which can result in erroneous heat flux distribution near the wall.

Figure 4 shows the shock layer profile along the line normal to the wall at 0.733 m from the stagnation point[3] where the analog resistance ablation detector sensors 7 and 8 are embedded.[1] Because the ionization reaction behind the shock wave is less significant in the downstream frustum region, we can check the accuracy of the radiation models for lower electron number density and for lower temperature using the flowfield properties at this position. We also note that carbonaceous species are significantly diffused in the shock layer at this position. Figure 5 compares the net radiative heat flux distributions in the shock layer. Again, the present multiband model well reproduces that given by the line-by-line calculation. The conventional multiband model, on the other hand, fails to reproduce the heat flux distributions by giving an erroneous radiative source profile, although it gives approximately the same result as the line-by-line method at the wall.

The typical computing time needed to solve the one-dimensional radiative transfer equation on the Itanium 2 workstation using the present multiband model becomes approximately 1/500 of the corresponding time by the line-by-line calculation. We note that the computing time of the present multiband model using the bilinear interpolation is comparable with that needed for the conventional multiband radiation model.

## Conclusions

We have presented a new method for determining the absorption cross-section depending on both the local temperature and electron number density for constructing a multiband radiation model for the calculation of the Galileo probe entry flowfield. It is shown that the present method can favorably reproduce the high-fidelity radiative heat flux values given by the line-by-line method for typical shock layer profiles taken from the computed Galileo probe entry flowfield. It is also shown that the computing cost of the present multiband model is approximately 1/500 of that required for the line-by-line method. The cross-section table with $14 \times 10$ intervals for the temperature range from 3000 to 17,000 K and the electron number density range from $10^{10}$ to $10^{18}$ cm$^{-3}$ is found to be sufficient for providing accurate heat flux values. The present calculation method for obtaining absorption cross section can provide a practical means for computing strongly radiating flowfields that have significant dependence on electron number density.

## References

[1]Milos, F. S., "Galileo Probe Heat Shield Ablation Experiment," *Journal of Spacecraft and Rockets*, Vol. 34, No. 6, 1997, pp. 705–713.

[2]Moss, J. N., and Simmonds, A. L., "Galileo Probe Forebody Flowfield Prediction," *Entry Vehicle Heating and Thermal Protection Systems: Space Shuttle, Solar Starprobe, Jupiter Galileo Probe*, edited by P. E. Bauer and H. E. Collicott, Progress in Astronautics and Aeronautics, AIAA, New York, 1983, pp. 419–445; also AIAA Paper 82-0874, June 1982.

[3]Matsuyama, S., Ohnishi, N., Sasoh, A., and Sawada, K., "Numerical Simulation of Galileo Probe Entry Flowfield with Radiation and Ablation," *Journal of Thermophysics and Heat Transfer*, Vol. 19, No. 1, 2005, pp. 28–35.

[4]Arnold, J. O., Cooper, D. M., Park, C., and Prakash, S. G., "Line-by-Line Transport Calculations for Jupiter Entry Probes," *Entry Heating and Thermal Protection*, edited by W. B. Olstad, Progress in Astronautics and Aeronautics, AIAA, New York, 1980, pp. 52–82; also AIAA Paper 79-1082, 1979.

[5]Park, C., and Milos, F. S., "Computational Equations for Radiating and Ablating Shock Layers," AIAA Paper 90-0356, Jan. 1990.

[6]Gökçen, T., "Computation of Nonequilibrium Radiating Shock Layers," *Journal of Thermophysics and Heat Transfer*, Vol. 9, No. 1, 1995, pp. 34–40.

[7]Liu, Y., and Vinokur, M., "Equilibrium Gas Flow Compositions. I. Accurate and Efficient Calculation of Equilibrium Gas Properties," AIAA Paper 89-1736, June 1989.