Experimental and numerical study on radiating shock tube flows for spacecraft reentry flights

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Received: 27 March 2019; Revised: 12 July 2019; Accepted: 11 September 2019

Abstract
The objective of this study is to investigate thermochemical processes in the shock layer by shock-tube experiments. In this study, the temporal profile of radiation intensity is observed by time-resolved emission spectroscopy. The measured radiation profiles are compared with the calculated radiation profiles to validate the chemical reaction processes considered in the calculation. The measured radiation profiles are different from the calculated ones, especially in the region ahead of the shock front. The measured radiation intensities for N₂, N₂⁺, and N start to increase ahead of the shock front. On the other hand, the calculated radiation intensities start to increase at the shock front. This difference could be caused by precursor phenomena which are not considered in the present calculation. The details of precursor phenomena has not been clarified. However, the present study has indicated some of the interesting results. From the radiation profiles observed in the region ahead of shock front, electronic excitation of N₃, photoionization and photodissociation of N₂ are found to occur. It is also found that the radiation profiles between experiment and calculation differ in the shock layer, showing that precursor phenomena have a great influence on thermochemical processes in the shock layer. In future, thermochemical processes should be modeled by incorporating precursor phenomena.

Keywords: Reentry, Shock layer radiation, Shock tube, Time-resolved spectroscopy, Precursor phenomenon

1. Introduction

Thermochemical processes in the shock layer around spacecraft reentering the earth atmosphere should be clarified for the development of the body because they play a key role in determining aerodynamic forces and heating rates. The assessment of reentry flight environments has been carried out by a computational fluid dynamics (CFD) simulation with a thermochemical model. The calculated result highly depends on the accuracy of the model applied in the simulation. A reliable thermochemical model with high accuracy needs to be developed for the better assessment of reentry flights.

In past studies, some thermochemical models were developed and applied for the assessments of flight environments (Gnoffo, et al., 1989; Gupta, et al., 1989; Park, 1990; Park, 1993). Yamada et al. (2012a; 2012b) conducted spectroscopic measurements using a shock tube in order to validate the two-temperature model which had been widely used for numerical analysis in reentry flight conditions (Park, 1988; 1989). In these studies, the spatial distribution of emission spectra was observed by time-frozen spectroscopy. The temperatures of chemical species in the shock layer were deduced from the measured spectra and compared with the calculated temperatures. The measured temperatures disagreed with the calculated ones immediately behind shock waves, showing a discrepancy of the internal relaxation process calculated by the two-temperature model. In these studies, the two-temperature model was validated in terms of the temperatures, clarifying the relaxation process among internal energy modes. On the other hand, the chemical reaction processes in the shock layer are also important for assessing the entry flight environments accurately. The accuracy of the reaction rate coefficients used in the two-temperature model is questionable because they were deduced from the comparison with limited experimental data obtained in conditions which differ from actual reentry flight conditions. Therefore, the two-
temperature model should be validated in terms of temporal profiles of shock layer radiation which depend on the chemical reaction processes in the shock layer.

The objective of this study is to investigate the chemical reaction processes in the shock layer. The temporal radiation profiles are observed in a reentry flight condition and compared with the calculated temporal radiation profiles to validate the reaction rate coefficients used in the calculation. The measured radiation profiles disagree with the calculated radiation profiles, showing the discrepancy of the physical modeling considered in the calculation. The present result has implied that the disagreement is caused by precursor phenomena occurring ahead of the shock wave. In the following, experimental methods are described in Chapter 2. Then, numerical methods are described in Chapter 3. The results and discussion are shown in Chapter 4. Finally, the conclusion of this study is shown in Chapter 5.

Nomenclature

\[ C \] : reaction rate constant, \( \text{m}^3\text{mol}^{-1}\text{s}^{-1} \)
\[ D_e \] : electron free diffusion coefficient, \( \text{m}^2\text{s}^{-1} \)
\[ k_B \] : Boltzmann constant, JK\(^{-1} \)
\[ k_f \] : forward reaction rate coefficient, \( \text{cm}^{-3}\text{mole}^{-1}\text{s}^{-1} \)
\[ M \] : unspecified third body
\[ n \] : temperature exponent on reaction rate coefficient
\[ n_e \] : electron density, \( \text{m}^3 \)
\[ P_0 \] : ambient pressure ahead of the shock wave, Pa
\[ T_a \] : geometric average temperature, K
\[ T_d \] : characteristic temperature, K
\[ T_e \] : electron temperature, K
\[ T_t \] : translational-rotational temperature, K
\[ T_v \] : vibrational – electron – electronic excitation temperature, K
\[ T_x \] : unspecified temperature, K
\[ T_0 \] : mean temperature of electrons produced by photoionization, K
\[ t \] : relative time to the shock front, \( \mu \text{s} \)
\[ V \] : shock velocity, km/s
\[ X \] : relative distance to the shock front, mm
\[ \dot{\omega} \] : production rate of electrons by photoionization, \( \text{m}^3\text{s}^{-1} \)
\[ \eta_e \] : thermal conductivity of electrons, Wm\(^{-1}\)K\(^{-1} \)

2. Experimental Method
2.1 Shock tube facility
In this study, a shock tube facility is used to simulate shock waves generated around space vehicles in a reentry flight condition. A schematic drawing of the shock tube facility is shown in Fig.1. The shock tube is composed of a high-pressure reservoir, a compression tube, a low-pressure tube, vacuum tank, and a free piston moving in the compression tube. The shock tube facility is located on movable mounts and connected to the vacuum tank. A shock absorbing mechanism is placed between the compression tube and low-pressure tube to protect the facility from the impact produced by the diaphragm rupture. This facility works according to the Stalker principle (Stalker, 1966). The free piston, driven by high-pressure air, adiabatically compresses helium which is used as a driver gas. When the pressure of helium reaches a critical value, a steel diaphragm bursts and a shock wave is formed in the low-pressure tube where the test gas is filled. The low-pressure tube with 44 mm square cross-section is made of aluminum alloy to reduce emissions from impurities. The test section with four quartz windows are located 2300 mm downstream from the diaphragm. The compression tube and low-pressure tube are evacuated to a pressure of 0.6 Pa using a root pump (EDWARDS, EH250) backed up by an oil rotary pump (TOKUDA, DRP-1400) before it is filled with a test gas. The facility can generate shock velocities ranging from 4.0 to 8.0 km/s with test gases of air, Ar, N\(_2\), CO\(_2\), and CO\(_2\) - N\(_2\) mixture, covering the typical planetary entry flight conditions (Yamada, et al., 2013b).
2.2 Time-resolved spectroscopy

A schematic drawing of the optical instrumentation at the test section is shown in Fig. 2. The shock velocity at the test section is measured by the double-laser schlieren measurement system (Yamada, et al., 2012a). Two laser beams are placed along the flow direction aligned to pass through the test section perpendicularly to the axis of the shock-tube flow. The optical path is adjusted by flat mirrors to reach separate avalanche photodiodes (APD). The deflection of the beams due to a steep density gradient at the shock front causes a change in the output signals of the APDs. The shock velocity at the test section can be obtained from the beam distance and the time interval of the change in the output signals. Since the laser beams used for the shock velocity measurement have a beam diameter of 0.5 mm, the uncertainty in the measured shock velocity is estimated to be 1.6%.

Time-resolved emission spectroscopy is applied to measure the temporal profile of radiation emitted from the shock layer. This technique provides information on the evolution of the radiation as a function of time. A monochromator (JASCO, CT-25C) is used with a 1200 lines/mm grating and the entrance slit is fixed at 50 μm in this study. A quartz convex lens is used to focus the radiation on the entrance slit of the monochromator. To record the radiation, a photomultiplier tube (PMT) (Hamamatsu, R12829) is placed behind the exit slit of the monochromator. The spectral response of the PMT ranges from 185 to 900 nm and its peak sensitivity is at 400 nm. The rise time of the PMT is 2.2 ns. The exit slit is adjustable depending on the measured wavelength range. The signal produced by the PMT is recorded by a digital oscilloscope (Agilent Technologies, DSOX2024A) and used to trigger the oscilloscope at the instant of the shock arrival. The temporal resolution of this measurement is estimated to be within 100 ns, considering the rise time of the PMT itself and the load resistor of 50Ω. The line of sight for the monochromator is aligned to intersect the upstream laser beam at the center line of the shock tube axis. During the measurement, the laser schlieren signals and PMT signals are monitored by the digital oscilloscope simultaneously, enabling us to obtain the time profile of radiation intensity correlated to the shock front which is located at the origin of the time scale.
2.3 Test conditions

In this study, two cases of test conditions are used as shown in Table 1. Nominal shock velocity is 6.0±0.3 km/s in both cases. In case 1, shock velocity is 6.0±0.3 km/s and test gas pressure is 50 Pa. In case 2, shock velocity is 6.0±0.3 km/s and test gas pressure is 100 Pa. Pure N\textsubscript{2} is used as the test gas simulating the Earth atmosphere. Air is not used in this study because the physical processes are more complicated than those of N\textsubscript{2}. The reproducibility of the test condition could be a problem in impulse facilities such as a shock tube. In the shock tube facility, the deviation from the targeted shock velocity is less than 5\% in most cases, which brings about the uncertainty on the radiation intensity of about 10\%.

Radiations of the N\textsubscript{2} (2\textsuperscript{+}) (1, 0) band head, N\textsubscript{2}\textsuperscript{+} (1-) (0, 0) band head, and N \text{3p }4S\textsubscript{0} - 3s 4P triplet are targeted in this study. The monochromator settings for spectroscopic measurements are shown in Table 2. Each wavelength region is selected to cover the targeted band heads.

<table>
<thead>
<tr>
<th>Case</th>
<th>Test gas pressure, Pa</th>
<th>Shock velocity, km/s</th>
<th>Test gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>6.0±0.3</td>
<td>N\textsubscript{2}</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>6.0±0.3</td>
<td>N\textsubscript{2}</td>
</tr>
</tbody>
</table>

Table 2 Monochromator settings for targeted band heads

<table>
<thead>
<tr>
<th>Setting</th>
<th>Grating, lines/mm</th>
<th>Slit width, (\mu m)</th>
<th>Wavelength region, nm</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Input slit Output slit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1200</td>
<td>50</td>
<td>690</td>
<td>315-317</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>50</td>
<td>1380</td>
<td>389-393</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>50</td>
<td>2070</td>
<td>741-747</td>
</tr>
</tbody>
</table>

3. Numerical analysis

3.1 Flow calculation

The following assumptions are introduced for the numerical analysis of a shock tube flow:

1. The flow is one-dimensional.
2. The species considered here are N\textsubscript{2}, N, N\textsubscript{2}\textsuperscript{+}, N\textsuperscript{+}, and e\textsuperscript{-}.
3. A thermal nonequilibrium is considered by introducing the two-temperature model proposed by Park: The translational and rotational temperatures are regarded as a common temperature \(T\), while the vibrational temperature of each molecule, electronic excitation temperature of each species, and translational temperature of free electrons are regarded as another common temperature \(T\textsubscript{v}\).
4. The ionized gas is electrically quasi-neutral.

Based on the assumptions mentioned above, the flow field in the shock tube is computed using a computational fluid dynamics (CFD) code which solves the one-dimensional Navier-Stokes equations given by

\[
\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial F\nu}{\partial x} = W
\]  

where \(Q\), \(F\), and \(W\) are the vector of conserved quantities, the flux vector, and the source term vector, respectively. These vectors are given by

\[
Q = \begin{pmatrix} \rho_s \\ \rho u \\ E_v \\ E \end{pmatrix}, \quad F = \begin{pmatrix} \rho u \\ pu^2 + p \\ E_v u \\ (E + p)u - u\tau_{xx} + q_x \end{pmatrix}, \quad F\nu = \begin{pmatrix} 0 \\ p_s h_s u_s \\ q_v + p_s e_{v_s} u_s \\ (E + p)u - u\tau_{xx} + q_x \end{pmatrix}, \quad W = \begin{pmatrix} W_s \\ 0 \\ 0 \end{pmatrix}
\]
The vibrational energy source term $W_v$ is described as

$$W_v = Q_{TV} + Q_{TE} + Q_{IE} + Q_{DV} \quad (3)$$

The first term of Eq. (3) is the rate of the energy exchange between the translational and vibrational modes. This is described by the Landau-Teller formula modified by Park (Park, 1988) as shown

$$Q_{TV} = \sum_{s=molecule} \rho_s \frac{e_{es}^* e_{es}}{T_s^{MW} + T_s^{P}} \left( \frac{T_{shock} - T_s}{T_{shock} - T_{vshock}} \right)^{\gamma - 1} \quad (4)$$

The second term of Eq. (3) is the rate of the energy exchange due to the elastic collisions between the electrons and heavy particles given by

$$Q_{TE} = 3 \rho_e R (T - T_v) \sum_{s=electron} \frac{v_{es}}{M_s} \quad (5)$$

The third term of Eq. (3) is the energy loss of electrons due to the electron impact ionization given by

$$Q_{IE} = - \sum_{s=ion} n_e \lambda_s \quad (6)$$

The fourth term of Eq. (3) is the vibrational energy change at dissociation and recombination and given by

$$Q_{DV} = \sum_{s=molecule} 0.3D_0 W_s \quad (7)$$

Following Park (1988), six chemical reactions listed in Table 3 are considered in the CFD code. In these reactions, the forward reaction rate coefficient $k_f$ is expressed as

$$k_f = CT_s^n \exp(-T_d / T_s) \quad (8)$$

The backward reaction rate coefficient $k_b$ is obtained from the forward reaction rate coefficient divided by the equilibrium constant $K_{eq}$ and given by

$$k_b = k_f / K_{eq} \quad (9)$$

The chemical reaction source term for species $s$, $W_s$ is obtained using $k_f$ and $k_b$ and given by

$$W_s = M_s \sum_r \left( \beta_{s,r} - \alpha_{s,r} \right) \left[ k_{f,r} \prod_j X_j^{c_{f,j,r}} - k_{b,r} \prod_j X_j^{b_{f,j,r}} \right] \quad (10)$$

In the present calculation, a shock wave is generated by impinging a hypersonic flow on a wall instead of solving the shock tube problem. This method is suitable for investigating the thermochemical nonequilibrium processes behind the shock wave because the effect of expansion waves can be reduced. Figure 3 shows the coordinate system and computational region used for the calculation. The total length of the computational region is 50 mm. The grid spacing is set to 167 $\mu$m in the entire computational region, generating 300 grid points. In a previous study, it is shown that the numerical solution of the CFD code with 300 grid points sufficiently converges (Yamada, et al., 2013a). An example of
the free stream condition corresponding to case 2 is shown in Fig.3. Pressure $P_\infty$ and temperature $T_\infty$ are 100 Pa and 300 K, respectively, corresponding to the test gas in the shock tube. After a hypersonic flow of $u_\infty = 5.55$ km/s impinges on the wall, the shock wave is derived and propagates leftward at a shock velocity of $U_s (= U_s - u_\infty)$ until travelling a distance of 45 mm from the wall. The boundary condition at the wall is as follows: the flow velocity at the grid point 300 is set to zero ($u_w = 0$). Other physical properties at the grid point 300 are set to the ones at the grid point 299. The calculated shock wave can be regarded as the shock wave propagating at a shock velocity of $U_s = 6.0$ km/s in a stationary gas on the shock fixed coordinate system ($u_\infty = 0$) corresponding to the shock wave observed in a shock tube. In the calculated results, the shock front is located at the origin so that the spatial position is represented as the relative distance to the shock front $X$.

The governing equations are integrated by a cell-centered finite volume scheme. The inviscid fluxes are evaluated by the Advection Upstream Splitting Method (AUSM-DV) Scheme (Wada and Liu, 1994) whose spatial accuracy is extended to second-order using the Monotonic Upstream-centered Scheme for Conservation Laws (MUSCL) approach (Leer, 1979) with the minmod limiter. The viscous fluxes are evaluated by central differencing. Time integration is performed with a Courant number of 0.1, which is combined with diagonal point implicit method (Everhardt and Imlay, 1992) for maintaining the stability of the source term.

### Table 3 Chemical reactions and the reaction rate coefficient

<table>
<thead>
<tr>
<th>Reaction, $k_r = CT_r^a \exp(-T_d / T_x)$</th>
<th>$M$</th>
<th>$C$</th>
<th>$n$</th>
<th>$T_d$</th>
<th>$T_x$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissociation reaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_2 + M \rightarrow 2N + M$</td>
<td>$N_2, N_2^+$</td>
<td>7.0$^{15}$</td>
<td>-1.60</td>
<td>113200</td>
<td>$T_a$</td>
<td>Park, 1992</td>
</tr>
<tr>
<td>$N_2 + M \rightarrow 2N + M$</td>
<td>$N, N^+$</td>
<td>3.0$^{16}$</td>
<td>-1.60</td>
<td>113200</td>
<td>$T_a$</td>
<td>Park, 1992</td>
</tr>
<tr>
<td>$N_2 + e^- \rightarrow 2N + e^-$</td>
<td>$3.0^{18}$</td>
<td>-1.60</td>
<td>113200</td>
<td>$T_v$</td>
<td>Park et al., 2001</td>
<td></td>
</tr>
<tr>
<td>Associative ionization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N + N \rightarrow N_2^+ + e^-$</td>
<td>$4.4^1$</td>
<td>1.50</td>
<td>67500</td>
<td>$T_i$</td>
<td>Park, 1992</td>
<td></td>
</tr>
<tr>
<td>Electron impact ionization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N + e^- \rightarrow N^+ + e^-$</td>
<td>$2.5^{28}$</td>
<td>-3.82</td>
<td>168600</td>
<td>$T_v$</td>
<td>Park, 1992</td>
<td></td>
</tr>
<tr>
<td>Charge exchange reaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_2 + N^+ \rightarrow N_2^+ + N$</td>
<td>$1.0^6$</td>
<td>0.50</td>
<td>12200</td>
<td>$T_i$</td>
<td>Park, 1992</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 3 Computational region](image)

### 3.2 Radiation calculation

In the present study, shock layer radiation along a given line of sight is calculated using the radiation analysis code SPRADIAN 2 (Fujita, et al., 2008) which computes the emission, absorption coefficients, and radiation transport at the given thermochemical conditions using a line-by-line technique. The internal states of molecules and atoms are assumed to be populated according to the Boltzmann distribution. To simulate the intensity obtained by the monochromator, the radiative transfer equation is integrated across the shock tube diameter (44 mm) at each axial position. The properties...
along the line of sight are assumed uniform because the boundary layer effects are not considered. The resulting intensity values are integrated over the wavelength intervals corresponding to the observation.

In the present study, numerical analysis is carried out in a non-coupled manner. The procedure of this analysis is shown in Fig.4. First, the flowfield in a shock tube is calculated using the CFD code. Then, the flow properties (temperatures and species densities) obtained from the CFD calculation are used as input parameters for SPRADIAN2 and the radiation intensity at each axial position is calculated, generating the spatial profile of radiation intensity. To compare the calculated radiation profile with the measured one, the spatial profile of radiation intensity is converted into the time profile by dividing the relative distance to the shock front \( X \) by the measured shock velocity \( V \).

4. Results and Discussion

4.1 Calculated results

Figures 5 (a) and (b) show the calculated temperatures and species densities in case 2. The vibrational-electron-electronic temperature, \( T_v \), is significantly lower than the translational-rotational temperature, \( T_t \), immediately behind the shock front. In this region, \( T_v \) is raised through collisional processes. \( T_t \) and \( T_v \) tend to equilibrate as the time from the shock front increases. Dissociation of \( \text{N}_2 \) is more significant than ionization because the species density of \( \text{N} \) increases rapidly behind the shock front, which is three orders of magnitude higher than those of other species. In our past study (Yamada et al., 2018), the calculated temperatures were compared with the measured temperatures which were deduced from the molecular spectra of \( \text{N}_2 \). It is confirmed that our simulation can reproduce the experimental result within the margin of the error bars. Figure 6 shows the calculated radiation spectrum at 1.8\( \mu \)s after the passage of the shock front, which is computed using the flow properties in Figs. 5 (a) and (b). The spectrum is dominated by strong line spectra of \( \text{N} \) below 200 nm, and band spectra of \( \text{N}_2 \) and \( \text{N}_2^+ \) in the vacuum ultraviolet (VUV) and ultraviolet (UV) regions. The radiation intensity in the VUV and UV regions is higher than that in the visible (VIS) and near infrared light (NIR) regions. The spectrum in the VUV region is characterized by strong line spectra of \( \text{N} \) below 200 nm, band spectra of \( \text{N}_2 \) (BH2), and \( \text{N}_2 \) (LBH). The spectrum in the UV region is dominated by \( \text{N}_2 \) (2+) and \( \text{N}_2^+ \) (1-) band systems. The spectra in the VIS and NIR regions are dominated by \( \text{N}_2 \) (1+) band system and atomic lines of \( \text{N} \). Figures 7 (a) and (b) show the detail spectra in the UV and VIS regions, respectively. In the UV region, many band heads of \( \text{N}_2 \) (2+) and \( \text{N}_2^+ \) (1-) can be identified. The band heads of \( \text{N}_2 \) (2+) (1,0) at 315.9 nm and \( \text{N}_2^+ \) (1-) (0,0) at 391 nm are measured in this study because they are unobstructed and free from other band systems. In the VIS region, there are many band heads of \( \text{N}_2 \) (1+). However, their band heads are not clear. Atomic lines of \( \text{N} \) 3p 4S0 - 3s 4P triplet are seen at around 745 nm which are measured in this study.
Fig. 5 Calculated flow properties in the shock tube

(a) Temperatures  
(b) Species densities

Fig. 6 Calculated spectrum in a wide wavelength range

(a) UV region  
(b) VIS region

Fig. 7 Calculated spectra in a narrow wavelength range
4.2 Comparison of measured and calculated radiation profiles

The measured and calculated temporal profiles of radiation intensity are shown in Figs. 8 to 10 for two cases. In these figures, the measured temporal profiles of radiation intensity are shown as black solid lines and calculated ones are shown as red solid lines. The measured and calculated radiation intensities are normalized by the maximum value for comparison. From these figures, it is found that the measured temporal profiles are different from the calculated ones especially in the region ahead of the shock front. The measured radiation intensity starts to increase in the region ahead of the shock front while the calculated radiation intensity rapidly increases near the shock front. This radiation ahead of the shock front is considered to be caused by precursor phenomena, which are reported in past studies (Fujita, et al., 2001; Holmes and Weymann, 1969; Katsurayama, et al., 2007; Scott and Leland, 1992; Weymann, 1969; Yamada, et al., 2014). Precursor phenomena are the thermochemical and radiative transfer processes in the region ahead of the shock front, which are considered to be triggered by the strong radiation from the shock layer. From the temporal profile of radiation intensity for N2 in Figs 8 (a) and (b), electronic excitation of N2 is considered to occur ahead of the shock front due to the absorption of radiation energy from the shock layer. The place where N2 starts to radiate is farther from the shock front in case 2. This is due to the difference of test gas pressure. At a lower test gas pressure, more excited N2 is dissociated into N by photodissociation shown in Eq. (13) and ionized into N2+ by photoionization shown in Eq. (11), decreasing the number density of the excited N2. Therefore, the radiation intensity for N2 is weaker in case 1 than that in case 2. In the region behind the shock front, the decline of the measured radiation intensity is slightly faster than that of the calculated one, showing that precursor phenomena have an influence on the relaxation process of N2 in the shock layer.

From the temporal profile of radiation intensity for N2+ in Figs. 9 (a) and (b), photoionization shown in Eq. (11) is found to occur ahead of the shock front. The increase of the radiation intensity seems to start farther from the shock front in case 1. This is considered to be due to the difference of test gas pressure ahead of the shock front because less radiation energy is required to produce N2+ at a lower test gas pressure, increasing the number density of N2+. Therefore, photoionization is more significant in case 1. In the region behind the shock front, the decline of the measured radiation intensity is faster than that of the calculated one in both cases. Generally, in the shock layer, it is said that N2+ is mainly produced by associative ionization shown in Eq. (12). However, electrons are already produced by photoionization ahead of the shock front, suppressing associative ionization behind the shock front. Therefore, the faster decline of radiation intensity for N2+ is obtained in the present study.

From the temporal profile of radiation intensity for N in Figs. 10 (a) and (b), predissociation is found to occur ahead of the shock front. As mentioned above, predissociation seems to be more dominant in case 1, increasing the radiation intensity of N. However, the radiation intensity of N does not become stronger in case 1 because photoionization of N shown in Eq. (14) is more significant. In the region behind the shock front, the measured radiation intensity drops faster than the calculated one. More electrons are produced in the experiment than the calculation due to the precursor phenomena. Therefore, the electron impact ionization process of N is more significant, decreasing the number density of N. As a result, the decline of the measured radiation intensity for N is faster than that of the calculated one.

Past studies had focused on the ionization process in the precursor region and concluded that photoionization was a main mechanism to cause precursor phenomena. However, there is a possibility that electron free diffusion and electron heat conduction also cause precursor phenomena, especially in the region immediately ahead of the shock front. So, the orders of magnitude among photoionization, electron free diffusion and electron heat conduction are compared using the energy conservation equation of electrons shown in Eq. (15). This equation is formulated on the coordinate system with the shock wave, in which flow properties ahead of the shock wave are regarded as a steady-state flow propagating at a velocity equal to the incident shock velocity. In the right-hand side of Eq. (15), the first term is the energy produced by photoionization, the second term is the energy produced by electron free diffusion, and the third term is the energy produced by electron thermal conduction. In the region immediately ahead of the shock front (about 1 μs before the passage of the shock front), the electron temperature and density are estimated to be about 6800 K and 10^16 m^-3 using the one-dimensional photoionization model (Kawazoe et al., 2019). By using these values, the orders of magnitude for each term in the right-hand side of Eq. (15) are estimated to be 10^6, 10^4, and 10^3 in this order in the present condition. From this result, the electron thermal conduction is found to be most dominant to produce precursor structure in the region immediately ahead of the shock front. This phenomenon can be confirmed from the radiation profiles observed in the present study. In all radiation profiles, the radiation intensity is found to rapidly increase immediately ahead of the shock front. This is considered to be mainly caused by electron heat conduction.

Most of the relevant studies were conducted using monoatomic gases such as argon. These studies are useful to understand the fundamental mechanism of precursor phenomena. However, the knowledge obtained from these studies cannot be directly applied to the Earth’s atmosphere. There are some studies investigating precursor phenomena occurring in N2 and air at shock velocities over 10 km/s where ionization is more dominant than the present condition. The present study has indicated that photochemical reactions and electronic excitation occur ahead of the shock wave at moderate shock velocities of 6.0 km/s and these processes have a significant influence on the shock layer flowfield. Also, the effect of the electron heat conduction is more significant in the region immediately ahead of the shock front. In addition, the temporal radiation profiles from main radiative species in N2 correlated to the shock front are obtained in this study. This data can be useful for validating the modeling of precursor phenomena. In future, influence of precursor phenomena on
the shock layer flowfield should be quantitatively assessed in order to accurately model thermochemical and radiative processes around a space vehicle reentering the Earth’s atmosphere.

\[
\begin{align*}
N_2 + h\nu &\rightarrow N_2^+ + e^- \quad (11) \\
N + N &\rightarrow N_2^+ + e^- \quad (12) \\
N_2 + h\nu &\rightarrow N + N \quad (13) \\
N + h\nu &\rightarrow N^+ + e^- \quad (14)
\end{align*}
\]

\[
\frac{\partial}{\partial x} \left( \frac{3}{2} n_e k_B T_e V \right) = \frac{3}{2} k_B T_0 \dot{\omega} + \frac{\partial}{\partial x} \left( \frac{5}{2} D_e k_B T_e \frac{\partial n_e}{\partial x} \right) + \frac{\partial}{\partial x} \left( \eta_e \frac{\partial T_e}{\partial x} \right) \quad (15)
\]

Fig. 8 Temporal profile of radiation intensity for $N_2$

(a) Case1

(b) Case2

Fig. 9 Temporal profile of radiation intensity for $N_2^+$

(a) Case1

(b) Case2
In this study, temporal profile of radiation intensity is observed by the time-resolved emission spectroscopy. The measured radiation profiles are compared with the calculated radiation profiles to validate the chemical reaction processes considered in the calculation. The measured radiation profiles are different from the calculated ones especially in the region ahead of the shock front. The measured radiation intensities for N$_2$, N$_2^+$, and N start to increase ahead of the shock front. On the other hand, the calculated radiation ones start to increase near the shock front. This difference could be caused by precursor phenomena which are not considered in the present calculation. The details of precursor phenomena have not been clarified. However, the present study has indicated some interesting results. From the radiation profiles observed in the region ahead of the shock front, electronic excitation of N$_2$, photoionization and photodissociation of N$_2$ are found to occur. The orders of magnitude among photoionization, electron free diffusion, and electron thermal conduction show that the electron thermal conduction is significant and cannot be neglected in the region immediately ahead of the shock front. It is also found that the radiation profiles between experiment and calculation differ in the shock layer, showing that precursor phenomena have a great influence on thermochemical processes in the shock layer. In future, thermochemical processes should be modeled by incorporating precursor phenomena observed in the present study.

Acknowledgements

Part of the work was carried out under the Collaborative Research Project of the Institute of Fluid Science, Tohoku University. We acknowledged Mr. Christopher Hart at the University of Queensland for correcting English in this paper.

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