Internal energy relaxation processes of nitrogen plasmas at different electronic states in an entry flight condition

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1. Introduction

Entry flight is a technical issue for the development of space vehicles. Particularly, characteristics of plasma flows around the space vehicles should be clarified to accurately predict aerodynamic forces and heating rates on the body. The authors conducted spectroscopic measurements of shock-heated plasma flows generated in entry flight conditions and the internal relaxation process of molecular nitrogen was evaluated from the measured spectra [1, 2]. It is found that the rotational energy mode shows a significant disagreement with the numerical prediction obtained using the widely used physical model. In this study, the rotational and vibrational temperatures of nitrogen molecules were evaluated from emission spectra of N_2 second positive (2+) bands which were the electronic transition from N_2 $C^3\Pi_u$ to N_2 $B^3\Pi_g$, providing the rotational and vibrational energy modes of the C state. On the contrary, almost all of molecules are expected to be in lower electronic states or ground state in entry flight conditions. Since C state is known to be strongly affected by the neighbouring molecular potential it is questionable whether the rotational and vibrational energy modes of the C state coincide with that of lower electronic states. The purpose of the present study is to investigate the influence of electronic states on the internal relaxation process of nitrogen plasma. In this study, a shock tube facility is used to generate shock-heated nitrogen plasma flows in an entry flight condition. Radiation from the shock-heated plasma flows is observed by spectroscopic measurements and the measured spectra are correlated with the shock front. In addition to the N_2 (2+) bands, we measure the N_2 first positive (1+) bands which are the electronic transition from N_2 $B^3\Pi_g$ to N_2 A $^3\Sigma_u^+$ state, providing the rotational and vibrational energy modes of the B state. From these measured spectra, the rotational and vibrational temperatures are evaluated by a spectrum fitting method. Finally, the rotational and vibrational temperature distributions of the N_2B and C states are obtained as a function of the distance from shock front and the difference of the internal relaxation process will be discussed in this study.

2. Experimental setup and test conditions

In this study, experimental investigation is carried out using a shock tube facility. The facility is a free piston-driven shock tube and has a capable of generating shock velocities ranging from 4.0 to 7.0 km/s with test gases of air, N_2, CO_2-N_2 mixture, covering typical planetary entry flights [3]. The low-pressure tube with 44 mm square cross-section is made of aluminium alloy to reduce emissions from impurities. The test section with four quartz windows are located 2300 mm downstream from the diaphragm. A schematic drawing of the optical measurement system at the test section is shown in Fig.2. The shock velocity at the test section is measured using two laser beams which make deflection at the instance of the arrival of shock waves. In this study, spatially-resolved emission spectroscopy using a fiber alley is conducted to obtain multipoint spectra of shock-heated plasma at a time. This technique provides information on the evolution of the emission spectra as a function of distance from the shock front. In this study, experiments are conducted using N_2 as a test gas. The nominal shock velocity is 5.5±0.3 km/s and the test gas pressure is 50 Pa.

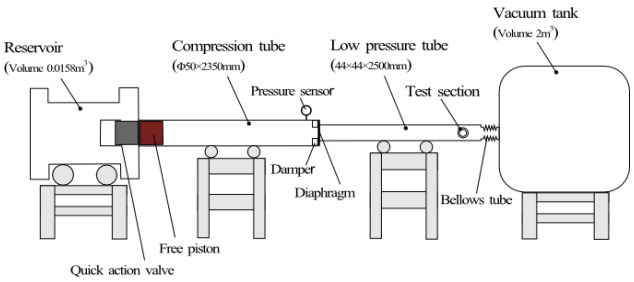


Fig. 1 Shock tube facility

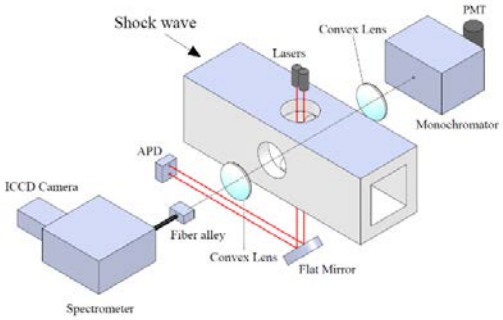
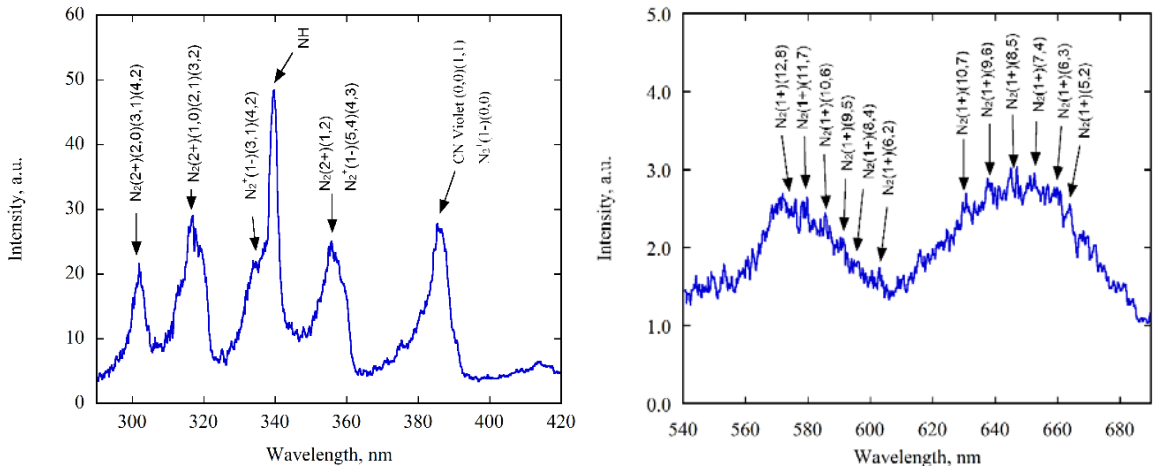


Fig. 2 Optical measurement system

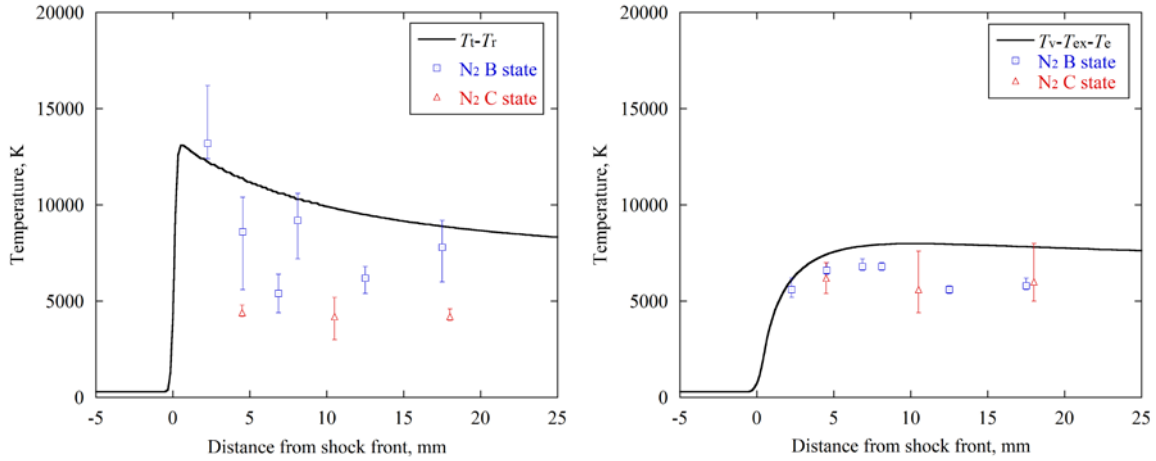
3. Results and Discussion

Figures 3 (a) and (b) show the measured spectra in the near ultraviolet (NUV) and visible (VIS) region, respectively. In the NUV region, the spectrum is mainly composed of the molecular bands of N_2(2+) and N_2^+(1-). The strong intensity of the NH is seen at about 337 nm in the measured spectrum. This is considered to be caused by the contamination of water vapor which is adhere to the test section wall at the replacement of the metal diaphragm. In the VIS region, the molecular bands of N_2 (1+) can be identified free from the other molecular and atomic spectra. In this study, the rotational and vibrational temperatures are derived from the molecular bands of N_2(2+) and N_2(1+) by a spectrum fitting method. First, the numerical spectra are computed using the radiation analysis code SPRADIAN2 [4] for



(a) NUV region (b) VIS region

Fig. 3 Measured spectra of shock-heated nitrogen plasma flow



(a) Rotational temperature (b) Vibrational temperature

Fig. 4 Spatial distribution of temperatures

temperatures ranging from 1000 to 20000 K at 200 K interval to make a spectrum database. For the calculation of $N_2(2+)$, the wavelength range is from 290 to 320 nm because the influence of the $N_2^+(1-)$ and NH is considered to be small. For the calculation of $N_2(1+)$, the wavelength range is from 540 to 690 nm. The least-squares method is applied to find the appropriate spectrum close to the measured one from the database. Finally, the appropriate spectrum gives the rotational and vibrational temperatures for the measured one. Figures 4 (a) and (b) show the spatial distribution of the rotational and vibrational temperatures as a function of the distance from shock front, respectively. In these figures the solid lines are the calculated temperature obtained by the two-temperature model [5]. In Fig. 4 (a), the rotational temperatures of B state is higher than that of C state, showing the deference of rotational relaxation process between B and C states. The rotational temperature of C state is

found to be significantly nonequilibrium with the calculated temperature. In Fig. 4 (b), the vibrational temperatures of B and C states are almost same each other and show a moderate agreement with the calculated vibrational temperature. From the comparison of temperatures between B and C states, a big difference can be seen in the rotational temperature. This is considered to be due to the difference of molecular process for each energy states.

4. Conclusions

To investigate the influence of electronic states on the relaxation process of the nitrogen molecule behind a shock wave, spectroscopic measurements are conducted using a shock tube facility. The emission spectra of $N_2(1+)$ and $N_2(2+)$ bands are obtained in this study and the rotational and vibrational temperatures are derived from these spectra by a spectrum fitting method. Finally, the temperature distributions correlated to the distance from shock front are obtained and compared with the prediction of the two-temperature model. The rotational temperatures of $N_2(2+)$ and $N_2(1+)$ are almost same and much lower than the calculated rotational temperature, showing the significant rotational nonequilibrium. This is considered to be due to the non-Boltzmann rotational population distribution of N_2 (2+) bands with higher vibrational levels ($v' \geq 2$) ranging from 280 to 320 nm. The present result has indicated that the electronic state has a great influence on the internal relaxation process behind a shock wave.

5. Acknowledgement

This work was supported by JKA through its promotion funds from KEIRIN RACE and JSPS KAKENHI Grant Number JP16K06890 and JP17K06946.

6. References

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