Experimental Study of Nonequilibrium Phenomena behind Strong Shock Waves Generated in Super-orbital Reentry Flight

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(1 February 2003)

Abstract: The flow behavior in a thin air behind the shock wave with a shock velocity around 12 km/sec was investigated experimentally. For the experiment, a free-piston-driven shock tube was used and a radiation from behind the shock front was investigated spectroscopically. Being based on the radiation spectrum emitted from the region behind the shock wave, the distributions for rotational and vibrational temperatures of N_2 and N_2^+ , and electron density were determined. These results were compared with those for a pure nitrogen gas which was investigated previously. It was found that there is remarkable resemblance between the distributions in an air and in a pure nitrogen gas. This suggests that the existence of molecular oxygen in an air has only a little influence on the behavior of temperatures of N_2 or N_2^+ , and the behavior of electron density behind the shock wave, compared with those observed in a pure nitrogen gas.

1. INTRODUCTION

The prediction of the flow field is an important issue for designing the reentry body which conduct an atmospheric flight with a hyper speed. The prediction, however, is not simple because, in the shock layer, various real gas phenomena occurs depending on the flight speed. Generally speaking, the faster the speed is, the more complex the real gas phenomenon is. The existing method is based on the experience gathered for the flight speed range smaller than that of the MUSES-C reentry capsule. Therefore, for the prediction of the flow field for the MUSES-C capsule, the top priority task is to gather the experience or the experimental data about the flow field. Unfortunately, such data is scarce currently. This is the reason for us to start to gather such data. For this purpose, we examine the flow behavior behind the shock wave with a shock velocity similar to the flight speed of the MUSES-C capsule; around 12 km/sec. First of all, a nitrogen gas was investigated as a test gas through which the shock wave propagates. This is because, in the nitrogen gas, the real gas effect such as chemical reaction is limited in compare to the air which comprises both nitrogen and oxygen. In this

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investigation, we measured the distribution of (1) the vibrational rotational temperatures, (2) electron number density, by means of the spectroscopic technique^{1, 2}. From this investigation, the phenomena which can not be predicted by the existing flow model. One is the abnormally lower rotational temperature, and another is the abnormally large electron number density just behind the shock wave. The theoretical understanding of these phenomena is underway. In parallel to the theoretical understanding, and based on the investigation of the phenomena observed in a nitrogen gas, we attempt to investigate the behaviour of the flow generated in an air. To this aim, the investigation by the shock tube was carried out by using an air as a test gas. In this report, we focus on this topic. To investigate the behavior of rotational and vibrational temperatures of N_2 or N_2^+ , electron excitation temperature, and electron density behind the shock wave in an air, and to clarify the difference in the nonequilibrium behavior behind the shock wave between for an air and for a pure nitrogen gas.

2. EXPERIMENTAL SETUP

In the experiment, was employed the double diaphragm free-piston-driven shock tube equipped at the Institute of Space and Astronautical Science in Japan. In this shock tube, the fastest shock propagation velocity of approximately 15 km/sec in an ambient pressure of 0.1 torr could be attained. To avoid any impurity in a test gas, the simulated air composed of oxygen 22% and nitrogen 78% was employed as for the test gas. In the present experiment, the test conditions for the initial ambient pressure 2.1 and 0.3 torr were selected, which produces a shock wave propagating at the velocity of 8 and 12 km/sec, respectively. Needless to say, the shock wave propagation velocity of 8 and 12 km/sec corresponds to the reentry velocity from the lower earth orbit and of the direct reentry from an interplanetary orbit, respectively.

In order to investigate the nonequilibrium phenomena behind the shock wave, radiation

Fig. 1: Experimental setup of optical system.

emitted from the highly-heated region behind the shock wave was investigated.

Figure 1 shows the optical setup at the measurement section of the shock tube. In this shock tube, the flow property behind the shock wave is considered to be one-dimensional. As a matter of the fact, since the shock front is almost perpendicular to the wall of the tube and the investigated region behind the shock front is comparatively near the shock front, we can

assume that the non-uniformity for the flow behind the shock wave, which might be caused by the thick boundary layer, is small and the radiative characteristic is almost uniform in the direction parallel to the shock front. As shown in the Fig.1, a radiation emitted from a location apart from the shock front by a selected distance is focused on the entrance slit of the spectrometer (ORIEL MS127i) by means of an ellipsoidal mirror and is decomposed into a spectrum by the spectrometer. The spatial resolution of the measurement in this system is less than 1.2 mm.

The spectrum image of the radiation decomposed by the spectrometer was recorded by means of an image-intensified CCD camera (ANDOR IN-STA SPECV IS510 ICCD). The ICCD camera was driven by the delayed signal generated by the pressure sensor mounted upstream of the measurement section. In each run of the shock tube, was recorded one ICCD image for the radiation spectrum emitted from a location with a selected distance apart from the shock front. Accumulating the radiation spectrum data for various locations, which was obtained by driving the ICCD camera with a various delayed time in repeated runs of the shock tube operations, an entire distribution of the radiation spectrum was obtained for the regions behind the shock front.

For this method to make sense, the reproducibility of each run of the shock tube is inevitable. To monitor the reproducibility, not only the pressure signals and the shock propagation velocity measured from them but also the distribution of the total radiation intensity distribution was monitored. For this monitoring, the pin photodiode sensor was installed on the opposite side of the spectrometer. Throughout this experiment, the reproducibility was found to be fairly good.

The He-Ne laser in this figure was used as a light source for the laser schlieren technique to detect the density rise of the shock front, which gives an origin of the distance of the location starting from the shock front.

3. SPECTRUM RESULTS

3.1 Spectrum for the case of 12 km/sec

Typical radiation spectrum at the distance 1.4 mm apart from the shock front is shown in Fig. 2 where the shock propagation velocity is 12.4 km/sec.

As shown in this figure, in the wave length range from 250nm to 500nm, the contribution of N_2 and N_2^+ molecules is dominant. Therefore, the behavior of the spectrum in this wave length range is dominated by rotational and vibrational temperatures of N_2 and N_2^+ . This means that those temperatures can be determined from the measured spectrum. The emission observed at 485nm is the Balmer line of atomic hydrogen which originates from the water vapor evaporated from the shock tube wall. The broadening of Balmer line is primarily dominated by the Stark broadening effect. Since this effect is mainly related to the existence of the electron, the electron number density can be determined from the measured spectrum. Additionally, in the case of the shock propagation velocity of 12 km/sec, the emission from an atomic nitrogen is dominant in the region far from the shock front more than 4 mm. Those emissions enable us to determine an electron excitation temperature of atomic nitrogen by using the relative spectrum intensity method.

When we compare, in the case of shock propagation velocity of approximately 12 km/sec, a radiation spectrum behind the shock wave in an air with the one in a pure nitrogen gas, the radiation spectrum in the case of an air is found to be very similar to that in the case of a pure

Fig. 2: Radiation spectrum behind the shock wave of a propagation velocity 12.4 km/sec and at distance from a shock front of 1.4 mm.

nitrogen gas as shown in Figs. 3a) and b).

3.2 Spectrum for the case of 8 km/sec

In the case of the shock propagation velocity of 8 km/sec, we focus on the wave length region ranging from 280 to 340 nm. In this shock propagation velocity case, however, the radiation spectrum in an air shows a slight discrepancy with that in a pure nitrogen gas, as shown in Figs. 4 a) and b). This discrepancy between in the case of an air and in a pure nitrogen gas is considered to be due to the contribution from NO molecule whose band spectrum peak exists in an ultra violet region. The reason why the radiation from NO is remarkable in the case of the shock propagation velocity of 8.3 km/sec is that NO does not dissociate completely even in the equilibrium state, in contrast to the higher shock propagation velocity of 12 km/sec. This suggests that, in this shock propagation velocity, contribution of not only N_2 and N_2^+ but also NO should be taken into account, unlike in the higher shock propagation velocity, to determine the temperatures being based on the radiation spectrum behind the shock wave in an air.

4. ROTATIONAL AND VIBRATIONAL TEMPERATURES DISTRIBUTION

4.1 Temperature determination method

In order to determine rotational and vibrational temperatures of N_2 or N_2^+ from the measured spectrum, the spectrum fitting method was applied. This is because the spectrum resolution obtained in this experiment is not high enough to determine rotational temperature, from the ratio of each rotational spectrum, independently from the vibrational temperature determination. To calculate the spectrum database theoretically, was employed the radiation calculation code *SPRADIAN 3*, which enables us to predict a radiation spectrum for a number density and temperature of each species. The detail of this method is described in Ref. 1 and Ref. 4. The typical spectrum fitting result is shown in Fig. 5. In this figure, both numerical and ex-

Fig. 3: Radiation spectrum, a) shock propagation velocity of 12.4 km/sec in the case of air, and b) shock propagation velocity of 11.9 km/sec in the case of pure nitrogen.

perimental spectrum in the wave length region shorter than 400nm agree well with each other. The discrepancy observed in the wave length region longer than 400nm is considered to be due to the existence of N and H β lines appearing in the spectrum obtained experimentally. As a conclusion, from this result, rotational and vibrational temperatures of N₂ are determined to be 3500 K and 5000 K, respectively, and those temperatures of N₂⁺ are determined to be 17500 K and 9000 K, respectively. The distribution of temperatures can be obtained by applying this method to each spectrum measured behind the shock wave.

4.2 Temperature distribution for case of 8 km/sec

Figure 6 a) shows temperatures distribution behind the shock wave in an air in the case of shock propagation velocity of 8.3 km/sec. As shown in this figure, in the region just behind the shock front, the measured rotational temperature is highly nonequilibrium with the numerical

Fig. 4: Radiation spectrum, a) shock propagation velocity of 8.3 km/sec in the case of air, and b) shock propagation velocity of 8.3 km/sec in the case of pure nitrogen.

prediction of the translational temperature. Here, the numerical prediction is based on Park's two-temperature-model 7. Since, in the Park model, it is assumed that rotational temperature is fully equilibrium with translational temperature, it can be concluded that the experimental and numerical rotational temperatures significantly disagree at least just behind the shock wave. In the region far from the shock front, both rotational and vibrational temperatures are close to the equilibrium temperature as predicted by Park model. These behaviors are very similar to those observed for a pure nitrogen gas as shown in Fig. 6 b).

4.3 Temperature distribution for the case of 12 km/sec

Figure 7 a) shows temperature distributions behind the shock wave in an air in the case of the shock propagation velocity of 12.4 km/sec. This figure shows that the measured rotational temperature is nonequilibrium with the numerical rotational temperature which is assumed

Fig. 5: Spectrum Fitting ; $V_s=12.4$ km/sec, $L=2.3$ mm, N_2 ($T_r=3500K$, $T_v=5000K$), N_2^+ ($T_r=17500K$, $T_v=9000K$).

to be equal to the translation temperature, and that there is, again, discrepancy between experimental result and numerical prediction based on Park model. As for the vibrational temperature, it is nearly close to the numerical prediction.

In Fig. 7 b), the previous result for a pure nitrogen gas in the case of the shock propagation velocity of 11.9 km/sec is depicted for comparison. It should be noted that the temperature distribution in an air resembles the one in a pure nitrogen gas very well.

In the numerical prediction, however, the difference between an air and a pure nitrogen gas appears in the behavior of vibrational temperature and especially in the difference of the distance by which the temperature distribution reaches the equilibrium state, as shown in Figs. 7 a) and b). The distance to reach the equilibrium state in an air is shorter than that in a pure nitrogen gas. The vibrational temperature behind the shock wave in an air doesn't rise, in a process of the relaxation, as rapidly as that in a pure nitrogen gas.

However, in the experimental result, especially in the case of the shock propagation velocity of 12 km/sec, rotational and vibrational temperatures can't be determined based on the molecular spectrum, because emission from an atomic nitrogen becomes stronger in the region far behind the shock wave more than 4 mm. Therefore, it is difficult to determine experimentally the difference, between in an air and in a pure nitrogen gas, of the distance to reach the equilibrium state. As for the behavior of the vibrational temperature, the difference between in an air and in a pure nitrogen gas is, according to the numerical calculation, at most a several hundred degree which is within an uncertainty unavoidable in the measurement and, therefore, it is difficult to distinguish those differences between in an air and in a pure nitrogen gas in this experiment, even though they appears in the numerical prediction.

5. ELECTRON DENSITY DISTRIBUTION

The local electron density strongly influences the Stark broadening of the Balmer line of hydrogen, besides the weak influence of the electron temperature. Therefore, the electron density can be determined by applying the theoretical spectrum fitting to the measured Balmer

Fig. 6: Temperature distribution, a) shock propagation velocity of 8.3 km/sec in the case of air, and b) shock propagation velocity of 8.3 km/sec in the case of pure nitrogen.

line. The theoretical spectrum of the Balmer line was calculated based on Ref. 5. Figure 8 shows an example of spectrum fitting for the Balmer line. In this figure, the numerical spectrum agrees with the experimental one fairly well. Therefore, it is concluded that the electron density is $4.8 \times 10^{22} \text{ m}^{-3}$, for the electron temperature $3 \times 10^4 \text{ K}$.

Figure 9 a) shows an electron density distribution obtained by applying this method at each location behind the shock wave in an air. As shown in this figure, according to the numerical prediction, the electron density increases gradually just behind the shock wave, and then at the location approximately 7 mm behind the shock wave, it increases rapidly and reaches the equilibrium state. On the other hand, the measured distribution is almost flat and its value agrees with that of the plateau region of the numerical simulation. That is, there is a big discrepancy, just behind the shock wave, between experimental result and numerical prediction. This discrepancy between the experimental result and the numerical prediction was already observed behind the shock wave in a pure nitrogen gas as shown in Fig. 9 b).

Fig. 7: Temperature distribution, a) shock propagation velocity of 12.4 km/sec in the case of air, and b) shock propagation velocity of 11.9 km/sec in the case of pure nitrogen.

Electron density behavior experimentally observed behind the shock wave in an air well resembles that previously observed in a pure nitrogen gas. In the numerical result, however, the difference in an electron density between an air and a pure nitrogen gas appears slightly. According to the numerical prediction, the electron density in the equilibrium state in an air is higher than in a pure nitrogen gas. But this difference can't be observed experimentally since the difference is small enough to be within the uncertainty unavoidable in the experiment.

6. ELECTRON EXCITATION TEMPERATURE DISTRIBUTION

In the region far behind the shock front more than 4 mm, the emission from the atomic nitrogen becomes prominent in the case of the shock propagation velocity of 12 km/sec. Therefore, the electron excitation temperature of atomic nitrogen can be determined by making use of the relative line intensity method. For the temperature determination, atomic lines in the

Fig. 8: Spectrum fitting at H β line; $V_s=12.4$ km/sec, $L=4.85$ mm, $N_e=4.8 \times 10^{22} \text{m}^{-3}$, $T_e=30000\text{K}$.

Fig. 9: Electron density distribution, a) shock propagation velocity of 12.4 km/sec in the case of air, and b) shock propagation velocity of 12.6 km/sec in the case of pure nitrogen.

wave length regions of 380-440 nm and of 480-540 nm were selected. Figures 10 a) and b) show the radiation spectrum at the location of 14.87 mm behind the shock wave. The atomic spectrum line which were used for temperature determination is indicated by the wave length and transition array as shown in these figures. By using the transition probability A_{ij} , the statistical weight g_i based on Ref. 6, and the relative radiation intensity of energy transition I_{ij} , the quantity $\ln(I_{ij}/A_{ij}g_i)$ is plotted against upper energy level as shown in Fig. 11. From this figure, the electron population is observed to be close to the Boltzmann distribution, which is assumed for the present temperature determination method. The electron excitation tem-

Fig. 10: Radiation spectrum of N, shock propagation velocity of 12.4 km/sec, 14.87 mm distance behind the shock wave in air, a) wave length region 380nm-440nm, b) wave length region 480nm-540nm.

Fig. 11: Boltzmann plot ; shock propagation velocity 12.4 km/sec, distance from the shock front 7.9 mm.

perature can be determined to be 6600K at the distance of 7.9 mm behind the shock front.

Figure 12a) shows the electron excitation temperature distribution behind the shock wave in an air in the case of the shock propagation velocity of 12.4 km/sec. From this figure, it is observed that an electron excitation temperature obtained from the experiment is distributed around 6000 - 7000 K, and is lower than that predicted by the numerical prediction based on Park's two-temperature-model.

Fig. 12: Electron excitation temperature distribution, a) shock propagation velocity of 12.4 km/sec in the case of air, and b) shock propagation velocity of 11.9 km/sec in the case of pure nitrogen.

It should be noted that the electron excitation temperature in the figure equals to the vibrational temperature shown in Figs. 12a) and b), since the equilibrium between them is assumed in the Park's model. Being compared to the previous results for the pure nitrogen gas shown in Fig. 12b), the behavior of the present electron excitation temperature for an air is found to be very similar to that for a pure nitrogen gas.

7. CONCLUSION

The vibrational and rotational temperatures of N_2 , N_2^+ molecules, the electron excitation temperature of atomic nitrogen, and the electron number density were determined based on the radiation spectrum, for an air behind the shock wave propagation with 8 km/sec and with 12 km/sec. In the shock propagation velocity of 12.4 km/sec, the radiation spectrum in an air, in the wave length region for the spectrum contributed by nitrogen originated molecules (i.e., N_2 , N_2^+), well resembles that in a pure nitrogen gas examined previously. As a result, the rotational and vibrational temperature distribution tendencies of N_2 and N_2^+ are similar to that in a pure nitrogen gas. Therefore, the following conclusion which is similar to that for a pure nitrogen gas is reached; 1) rotational temperatures of N_2 and N_2^+ are nonequilibrium with the translational temperature and show disagreement with the Park's two-temperature-model, 2) vibrational temperatures of N_2 and N_2^+ are also nonequilibrium with the translational temperature, but almost agree with the numerical prediction.

The behavior of the electron density distribution behind the shock wave in an air shows disagreement with the numerical prediction, especially at the region just behind the shock wave. This is, again, similar to the result obtained previously for a pure nitrogen gas.

As for the electron excitation temperature behind the shock wave in an air, its behavior is also almost similar to that in a pure nitrogen gas.

Although the difference between an air and a pure nitrogen gas appears theoretically, such difference is too small to be detected in the present experimental setup.

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