CARS application to the vibrational/rotational temperature measurement of nitrogen behind shock waves over Mach number 13

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1 Introduction

For the development of aerospace science and technology in Japan, it is necessary to develop the new and original space vehicles. Especially in returning phase of the space vehicle from Japanese section of international space station, there are the produced strong shock waves and non-equilibrium heat problems in front of the leading surface of the reentering space vehicles. To deal with these problems, the reasonable design of heat shield materials and structures are required. Today, however, the data of these problems for the design are not in satisfactory conditions. So it is of great importance to decide the high-enthalpy parameters for heat shield investigation. In this background we have been investigating the hypersonic measurement techniques for these phenomena and gathering the gas-dynamics and radiating data near the front surface of reentering space vehicles.

The main purpose of this study is to measure the vibrational/rotational temperatures behind the hypervelocity strong shock wave by spectroscopic method with high power laser system and high-performance photo-electronics. The hypervelocity strong and radiating shock waves in front of the reentering space vehicles are simulated in our laboratory with a free-piston double-diaphragm shock tube. The vibrational/rotational temperatures are measured and estimated from the CARS (Coherent Anti-stokes Raman Spectroscopy) signal spectral data of nitrogen molecule behind the hypervelocity shock waves.

2 CARS measurement for hypervelocity flow

The CARS is the one of Raman spectroscopy and generally applied to combustion or flame phenomena. We applied this system to shock waves. The CARS system consists of the second harmonics YAG laser, dye laser, optical elements, spectroscope, and CCD camera. We have to obtain the clear CARS signal from our strongly radiating and hypervelocity flow. Therefore, the intensity of CARS signal should be high enough to be analyzed. The following equation shows CARS signal intensity [1]. Incident YAG laser beams at frequencies ω_1 (pump beams) and ω_2 dye laser (Stokes beam) interact together through the third order nonlinear electric susceptibility $\chi^{(3)}{}_{CARS}$ to produce the coherent radiation (ω_3) at $\omega_3=2\omega_1 - \omega_2$, as follows

$$I_3(\omega_3) = \frac{\omega_3^2}{n_1^2 n_2 n_3 c^4 \varepsilon_0^2}\left|\chi_{CARS}^{(3)}\right|^2 I_1^2(\omega_1) I_2(\omega_2) l^2 \left(\frac{\sin \frac{\Delta kl}{2}}{\frac{\Delta kl}{2}} \right)^2, \quad (1)$$

$$\Delta k = 2k_1 - k_2 - k_3, \quad (2)$$

where n_1, n_2 and n_3 are the refractive indices at ω_1, ω_2, ω_3, respectively; c is the velocity of light; l is interaction length; k_1, k_2 and k_3 are the wave vectors of the pump, Stokes and CARS beams, respectively; and ε_0 is the permittivity of free space. The CARS signal is enhanced on the condition of phase matching, $\Delta k=0$. The incident laser beams, i.e. two pump beams (ω_1) and a Stokes beam (ω_2) are aligned in order to satisfy this phase matiching vector relation (BOX CARS).

3 Experimental setup

The optical layout of the CARS measurement system is shown in Figure 1. The CARS system consists of a second harmonics Nd: YAG laser (ω_1), a dye laser (ω_2), optical system, a spectrograph, and an ICCD camera. The laser beam (ω_1) is divided into two beams by a beam splitter (BS). These beams are directed to the dye laser beam (ω_2) by a beam combiner (BC2). Then three laser beams are crossed and focused with the desirable angles in the shock tube observation section. The CARS spectral data are detected by the ICCD camera in spectroscopic image. The entrance slit width for spectroscope is set to 100 μm throughout our observation. The ICCD is mounted on the focal exit of the spectrograph.

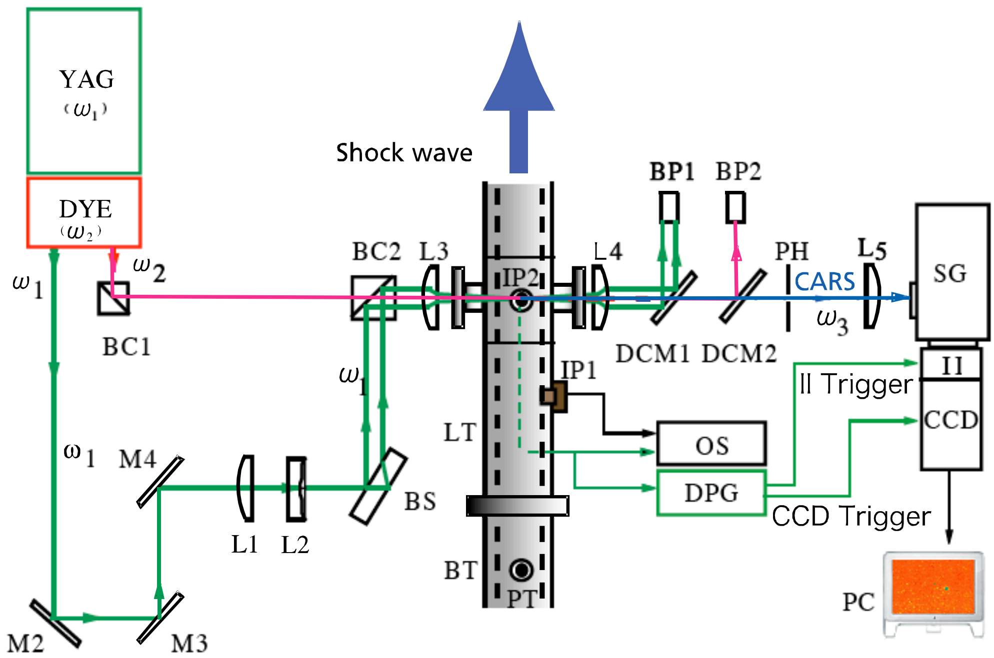

Figure 1. Optical layout of the CARS measurement system

A free-piston, double-diaphragm shock tube is used to generate strong shock waves in low-density gas. This shock tube consists of high-pressure chamber (driver gas is nitrogen), compression tube (helium gas is supplied) and a free piston of 2.4kg mass, buffer tube (supplied gas is also helium), low-pressure tube (test gas is air or nitrogen), and vacuum chamber. These tubes are divided initially by a quick action valve, the first diaphragm (steel of 3.3mm thickness), and the second diaphragm (aluminium of 1mm thickness). The cross section of the low-pressure tube is 40mm×40mm square. The observation windows of the test section are mounted near a focal lens with some distance from the sidewall of the shock tube. This distance prevents high power laser from destroying the window. The shock velocity is measured by the ion probes mounted on the sidewall and underside of the test-section [2],[3].

4 Results and Discussion

With the CARS method described above, we have obtained CARS spectra as shown in Figure 2. These spectra are measured at 9.2mm behind the shock wave front. The measured shock wave velocity in this figure is 4.6km/s of Mach number of 13.6. In this figure, the solid line shows the experimental spectrum and the dotted line shows the theoretical by calculated spectrum. From these results we can determine the vibrational and rotational temperature of nitrogen molecule as 6000K and 7000K, respectively by spectral matching technique.

However, the real hypervelocity shock waves generated in front of the space vehicles sometimes exceed over 6.8km/s of Mach number of 20. We have to try to obtain the spectra data of more higher-speed shock wave data for practical use.

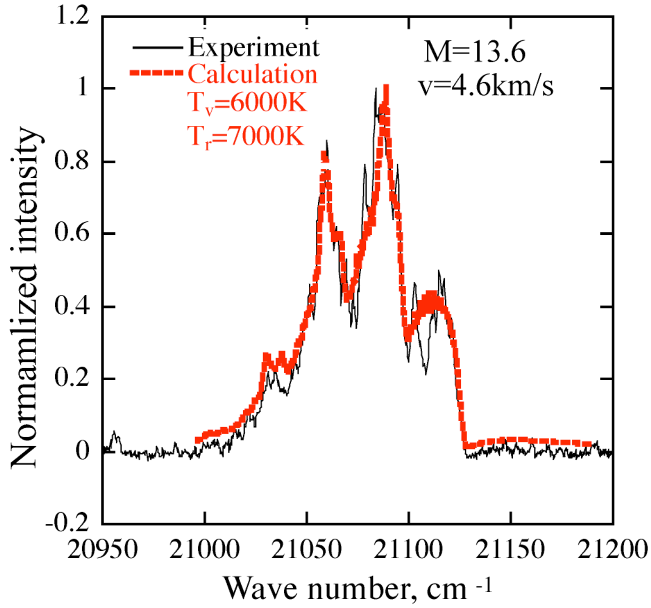

Figure 2. An example of CARS spectrum behind strong shock wave in air.

5 Summary

We have applied the CARS measurement technique to the radiating hypervelocity flows behind the strong shock waves over M=13, and obtained the CARS signals successfully. The CARS application is possible to the hypervelocity radiating phenomena and low-density initial conditions. As the future schedule of this study, enough number of accurate CARS signals under the similar experimental conditions have to be collected to confirm the repeatability of this measurement technique.

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