CARS Measurement of Vibrational /Rotational Temperatures with Total Radiation Visualization behind Strong Shock Waves of 5-7 km/s

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Abstract. In the development of aerospace technology the design of space vehicles is important in phase of reentry flight. The space vehicles reenter into the atmosphere with range of 6-8km/s. The non-equilibrium flow with radiative heating from strongly shocked air ahead of the vehicles plays an important role on the heat flux to the wall surface structure as well as convective heating. The experimental data for re-entry analyses, however, have remained in classical level. Recent development of optical instruments enables us to have novel approach of diagnostics to the re-entry problems. We employ the CARS (Coherent Anti-Stokes Raman Spectroscopy) method for measurement of real gas temperatures of N_2 with radiation of the strong shock wave. The CARS signal can be acquired even in the strong radiation area behind the strong shock waves. In addition, we try to use the CCD camera to obtain 2D images of total radiation simultaneously. The strong shock wave in front of the reentering space vehicles is experimentally realigned by free-piston, double-diaphragm shock tube with low density test gas.

Keywords: CARS measurement, Hypervelocity shock wave, Vibrational temperature, Rotational temperature, Total radiation

INTRODUCTION

In the development of aerospace technology the design of space vehicles is important in phase of reentry flight. The space vehicles reenter into the atmosphere with hypervelocity of 6-8km/s. The non-equilibrium flow with radiative heating from strongly shocked air ahead of the vehicles plays an important role on the heat flux to the wall surface structure as well as convective heating. It is necessary to clarify these radiative heating phenomena for the improvement on reliability of heatshield design [1]. So far, some reports have been published [2], but these papers have not given the satisfactory data on radiating non-equilibrium flow. Until now in performing CFD, we are suffering from the lack of satisfactory data on radiative non-equilibrium flow.

In this research we try to apply the CARS (Coherent Anti-Stokes Raman Spectroscopy) method [3] to the measurement of real gas temperatures with radiation behind the strong shock wave. [4] The two lasers are used in this method, which are Nd:YAG laser and dye laser, respectively. When the lasers excite nitrogen molecules in experimental real gas, the CARS signal is generated and taken by spectrograph. The vibrational and rotational temperatures are estimated by spectral matching method with least square method between experimental data and theoretical calculation data. The CARS signal seems to be acquired even in the strong radiation area behind the hypervelocity shock waves of 5-7km/s. In addition we try to use the CCD camera to obtain 2D images of total radiation simultaneously. The strong shock wave flow in front of the reentering space vehicles is simulated by free-piston, double-diaphragm shock tube with low density test gas.

In this paper the shock wave velocity of 5-7 km/s has been treated, and we have successfully obtained the vibrational and rotational temperatures from CARS data with spectral matching method. We have also observed total radiation behind the strong shock wave simultaneously with the phenomena.

THEORY OF THE CARS MEASUREMENT

Incident YAG laser beams at frequencies ω_1 (pumping beam) and ω_2 (Stokes beam) interact through the third order nonlinear electric susceptibility $\chi^{(3)}_{CARS}$ of the gas molecule to produce coherent Anti-Stokes radiation ω_3 at $\omega_3 = 2\omega_1 - \omega_2$ as follows:

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

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

where n_1 , n_2 and n_3 are the refractive indices at ω_1, ω_2, ω_3 , respectively and c is the velocity of light, l is interaction length, k_1, k_2 and k_3 are the wave vectors of the pumping, Stokes, and CARS beams, respectively, where ε_0 is the permittivity of free space. The CARS signal is enhanced on the condition of phase matching, $\Delta k = 0$. The incident velocity of laser beams, i.e. two pump beams (k_1) and a Stokes beam (k_2), are aligned in order to satisfy this vector relation. In this state the CARS signal can be obtained at highly coherent light beam. Moreover, emission intensity is proportional to the cube of incident beams (the square of pump beam and the first power of Stokes beam). The susceptibility $\chi^{(3)}_{\mathrm{CARS}}$ is written by

$$\chi^{(3)}_{CARS} = \sum_j K_j \frac{\Gamma_j}{2(\omega_j - (\omega_1 - \omega_2)) - i\Gamma_j} + \chi_{nr} \quad (3),$$

where the j summation is over vibration-rotation transitions in the vicinity of $\omega_1 - \omega_2$, ω_j is the Raman resonance frequency, Γ_j is the Raman line width (Full Width at Half Maximum), χ_{nr} is a background and non-resonant contribution due to electrons and remote resonances, and K_j is written by

$$K_j = \frac{2n_1 c^4}{n_2 \hbar \omega_2^4} N \Delta_j \left.\frac{d\sigma}{d\Omega}\right|_j \Gamma_j^{-1} \quad (4),$$

where N is the number density of the Raman active molecule, Δ_j is the population difference between the upper and lower vibration-rotation states, and $(d\sigma/d\Omega)|_j$ is the cross-section for spontaneous Raman scattering.

On the assumption that molecules have Boltzmann distributions based on the rotational (T_r) and vibrational (T_v) temperatures, Δ_j can be expressed as

$$\Delta_j = \frac{(2J+1)g_I}{Q_r Q_v} \left[\exp\left(\frac{-F_{v,J}hc}{kT_r}\right)\exp\left(\frac{-G_v hc}{kT_v}\right) - \exp\left(\frac{-F_{v+1,J}hc}{kT_r}\right)\exp\left(\frac{-G_{v+1}hc}{kT_v}\right) \right] \quad (5),$$

where $F_{v,j}$ and G_j are the rotational and vibrational energy terms, respectively and g_I is the spin degeneracy, 6 for even-J rotational levels and 3 for odd-J levels in N_2, and Q_r and Q_v are the rotational and vibrational partition functions, respectively.

From Eqs. (1), (3), and (4), CARS signal is approximately proportional to the square of number density of molecule. Therefore, it is not easy to detect the CARS signal from low-pressure and strongly radiating gas of hypervelocity conditions. In this sense the strongly radiating hypervelocity flows behind the shock wave of high Mach number above 10 may be the most difficult objectives of this spectroscopic diagnostics.

As written in the following section, the measured CARS spectra are coupled and fitted with calculated CARS signals by parametrically changing Tv, Tr as free parameters to decide the temperatures in our study .

SPECTRAL FITTING METHOD

The CARS spectroscopic data obtained by our experiment relate to the energy levels which correspond to the kinetic conditions of the molecule. Vibrational/rotational temperatures are determined by fitting the computer-generated and theoretical spectra to the observed CARS spectra. This spectral fitting method is explained as follows.

First, theoretical spectra are developed by the computer program, which include the vibrational/rotational temperatures, the Raman line widths and non-resonant parameters, and these parameters are varied in the assigned bounds. Secondly, square mean errors of normalized emission intensity between the computer-generated theoretical spectrum and observed CARS spectrum are calculated, and finally vibrational/rotational temperatures of nitrogen molecule are determined, where the error become minimum by least square method for designated wavelength range.

Raman line width corresponds to the half width at half maximum of Raman line, and is a function of pressure, temperature and rotational quantum number of the molecule. Non-resonant parameter is a constant. It unconcerned element about ro/vibrational Raman resonance.

EXPERIMENTAL APPARATUS

Apparatus for shock wave generation

We have used a free-piston, double-diaphragm shock tube to generate the strong shock waves in low-density gas as shown in Fig. 1. This shock tube has been used to generate radiating hypervelocity and 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 off by a quick action piston valve, the first diaphragm (steel of 3.3mm thickness), and the second diaphragm (aluminum of 1mm thickness). The test section of the low-pressure tube is 40mm × 40mm square and there are the three windows at the observing section. The CARS laser beams are crossed in this section. The two observation windows of the test section are mounted near a focal lens with some distance from the sidewall of the shock tube. The sidewall of shock tube has holes along the optical path of laser beam. The other window is top of wall in test section and we obtain the total radiation from this window by CCD camera.

The shock velocity is measured by the ion probes mounted on the sidewall of the test-section. Initially the solenoid-controlled piston valve moves quickly and launches the free-piston. Then the adiabatic compression of helium ruptures the steel diaphragm and generates shock wave in buffer tube. Finally, the hypervelocity shock wave is generated in test section by the reflection of shock wave and rupture of aluminum diaphragm. The shock wave velocity depends on the pressure of low-pressure tube with the test gas, and we describe this pressure as initial pressure.

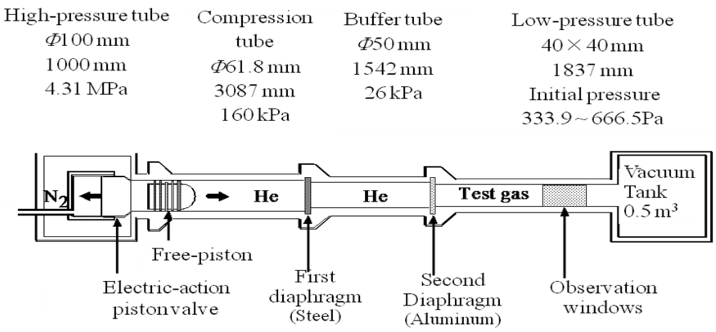

FIGURE 1. Free-piston double-diaphragm shock tube

Optical setup of CARS

The layout of the CARS measurement system is shown in Fig. 2. CARS system consists of a second harmonics of Nd:YAG laser (ω_1), a dye laser (ω_2), optical systems, a spectrograph, and an ICCD camera. The laser beam (ω_1) is divided in two by a beam splitter (BS). These beams are directed to the dye laser beam (ω_2) by a beam combiner (BC2). Three laser beams are crossed and focused with the necessary angles of BOXCARS in the shock tube observation section. Then the angles are shown in Fig. 2(b), the CARS spectra (ω_3) is generated by excited nitrogen molecule behind the hypervelocity shock wave. The CARS spectra are detected by the spectroscopy (SG) and image-intensified CCD camera (II-CCD). The entrance slit width is set to 100μm throughout our observation. The II-CCD is mounted on the focal exit of the spectrograph. Figure 3(a) shows laser trigger system. When shock wave is produced, a charge trigger and electric-action piston valve is applied in this circuit. A fire trigger is applied by

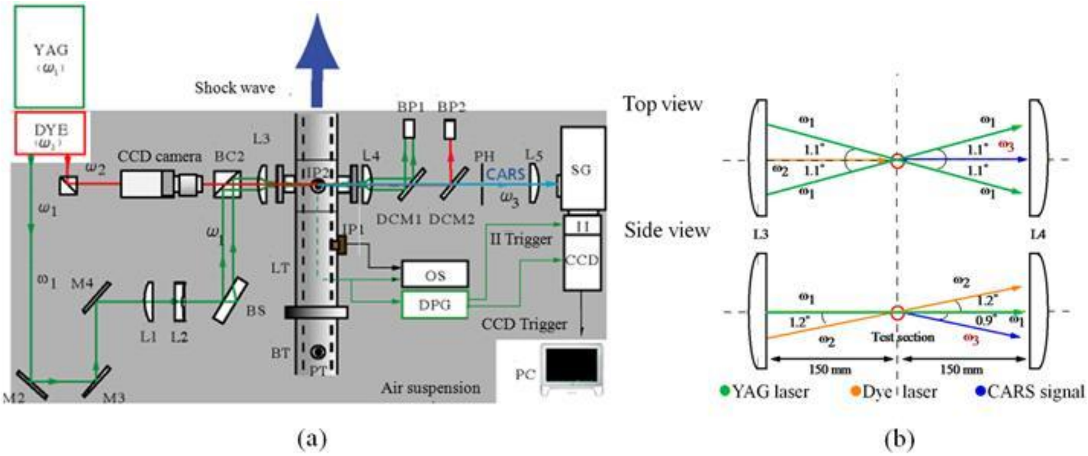

FIGURE 2. Optical set up of CARS system and laser incidence route (top view and side view)

pressure transducer (PT) at buffer tube, and ionprobe (IP2) of the observation window sends a signal to delay/pulse generator (DPG). The DPG receives and sends the signal with delay time to laser system as a fire trigger, image intensifier (I.I.) and CCD camera as trigger. We have succeeded in synchronizing the shock wave with the laser beam, I.I. and CCD camera. The shock wave velocity is calculated by the difference of signal time to oscilloscope from IP1 and IP2. The length between IP1 and IP2 is 277mm.

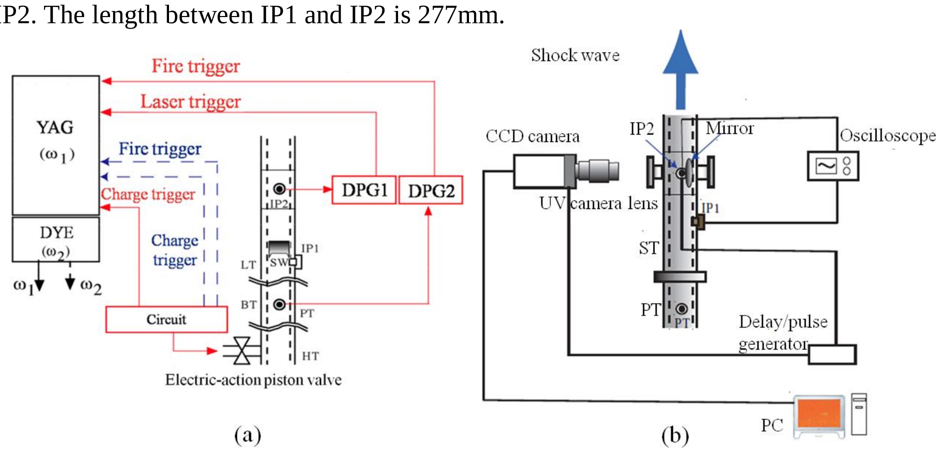

FIGURE 3. Outline of the trigger system synchronizing with hypervelocity shock wave

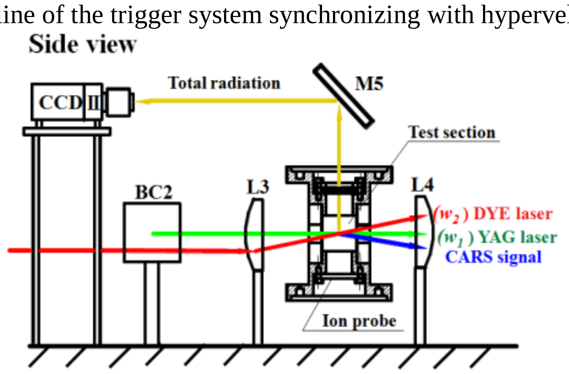

FIGURE 4. Side view of radiation imaging system

Setup for total radiation imaging

The radiation imaging system is shown in Fig. 3(b). The mirror and a circular observation window are mounted on the low-pressure tube. The mirror reflects the total radiation image of shock wave to the CCD camera from the window shown in Fig.4. When the hypervelocity shock wave passes through an ionprobe (IP2) at the observation window, the camera releases the shutter with arbitrary delay time. Three beams using CARS measurement passes under the CCD camera so we can obtain the vibrational and rotational temperature by CARS measurement and simultaneously total radiation imaging by CCD camera in this system.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 5 and Figure 6 show results of initial pressure 666.5 Pa and 333.9 Pa, respectively. In Fig.5 the shock wave velocity is 5.82 km/s, and Mach number of 17.1. In Fig.6 the shock wave velocity is 7.6 km/s, and Mach number of 22.4. Test gas is air. In these figures (a) is result of CARS measurement and (b) is total radiation imaging. The solid line is the spectrum from CARS experiment, and broken arrow is the theoretical calculation spectrum decided in the spectral matching method.

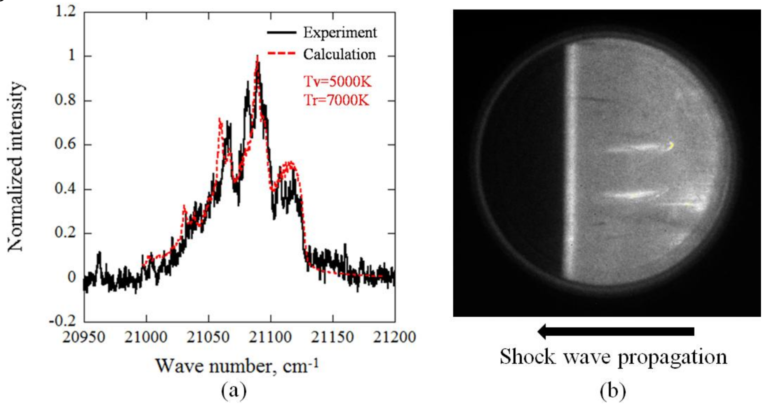

FIGURE 5. Result of Mach number 17.1

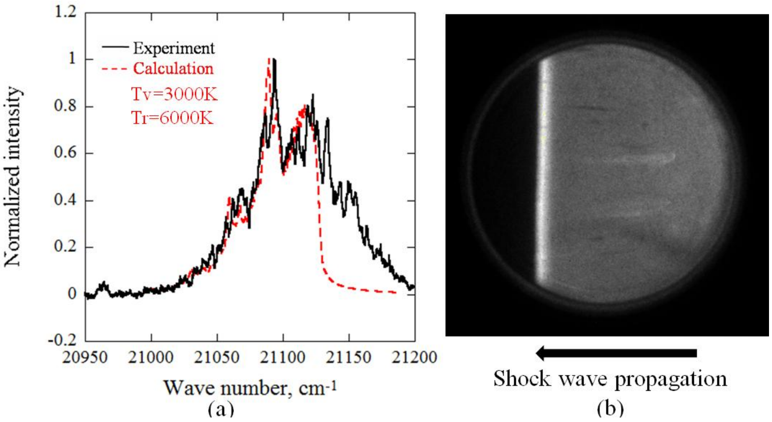

FIGURE 6. Result of Mach number 22.4

Result of CARS measurement

In Fig.5(a) decided vibrational and rotational temperatures are 5000K and 7000K respectively. The measurement position is about 1.25mm from shock wave front. There are three peaks at 21050~21120cm^{-1}. The wave number of left peak is around 21050 cm^{-1}, the center peak is around 21080cm^{-1} and the right peak is around 21100cm^{-1}. From Fig.5(a) the center peak has highest intensity and right peak has lowest at Mach number 17.1. In Fig.6(a), vibrational and rotational temperatures are both lower values of 3000K and 6000K respectively. The measurement position is about 2.19mm from shock wave front. There are area three peaks. However, the experimental spectrum form is different from Mach 17.1. From Fig.6(a) the center peak has highest intensity and left peak has lowest at Mach number 22.4. It is observed that this change depends mainly on vibrational temperature. From Fig.5 and Fig .6 the vibrational temperature at Mach 17.1 is higher than at Mach 22.4. Also our CARS results of Mach 12 or 15 showed that the spectrum forms have higher intensity for the left peak than right. They have high vibrational temperatures about 7000K~11000K.

In Fig.6, there is large discrepancy between the experimental spectrum and the theoretical spectrum around 21130cm^{-1}. In addition, there is some discrepancy between experimental spectrum and theoretical spectrum about other wave number in Fig.5 and Fig.6. It is observed that some of the discrepancy is caused by the noise of other scattering light and the lack of accuracy in spectral matching method. Though non-resonant part shown as χ_{nr} in Eqs.(3) corresponds around 21150cm^{-1} in theoretical spectrum. In this study the calculation program was improved introducing non-resonant part χ_{nr}. There is, however, not much difference about temperatures between the corrected result with non-resonant part and the previous result without non-resonant part. We need to improve the calculation program to reduce the errors between a CARS experimental spectrum and theoretical calculation spectrum.

Result of total radiation

Figure 5(b) and Figure 6(b) show total radiation imaging which was obtained simultaneously with CARS measurement. The shock wave propagates from right to left in these images. We have succeeded to get motion images of strong shock wave front with CARS measurement. These images indicate that the perpendicular shock wave is finely generated in these experiments. From these images high radiation intensity is observed just behind the shock wave front. The 3-dimensional(3D) images show in Fig.7(a) and (b) are enhanced from total radiation imaging of Mach 17.1 and 22.4, respectively. There is peak of intensity just behind the shock wave front. The total radiation intensity in Mach 22.4 is higher than in Mach 17.1. The faster shock wave, the higher intensity is observed behind shock wave.

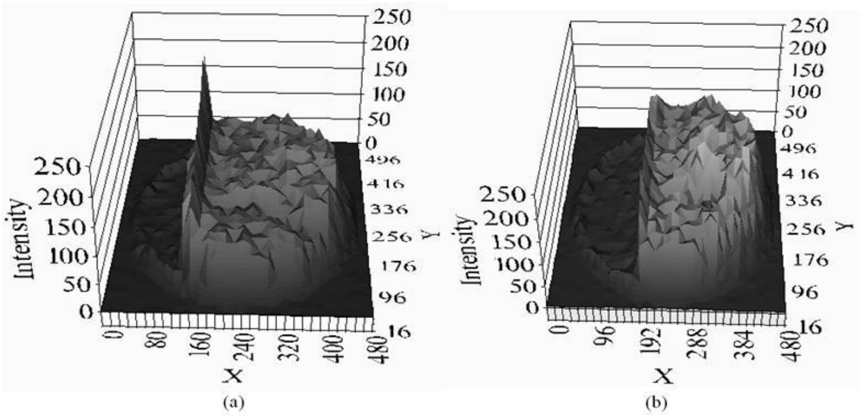

FIGURE 7. 3D images of total radiation

SUMMARY

The CARS signal has been successfully acquired at high Mach numbers range of 17-23. The vibrational and rotational temperatures are estimated 5000K and 7000K, respectively at abour 1.25mm behind shock waves of hypervelocity Mach number of 17.1. Also the vibrational and rotational temperatures are estimated 3000K and 6000K, respectively at 2.19mm behind shock waves of hypervelocity Mach 22.4. We have also performed the high-speed imaging experiment by CCD camera simultaneously with CARS measurement. From the imaging results of total radiation, the stronger radiation has been observed with Mach number 22.4 than Mach number 17.1, especially at just behind shock front.

In the future we will try to obtain the CARS signals behind hypervelocity shock waves over Mach number 25, which corresponds to real shock waves around the space vehicles reentering the atmosphere of the earth. In addition, we will try to improve calculation program of the CARS and analysis of radiation imaging.

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