Application of NO Laser-Induced Fluorescence in JF-10 Detonation-Driven Shock Tunnel

H. Yan, S. Zhang, and X. Yu

Abstract We have presented our recent progress in the application of $\gamma(0,0)$ band NO LIF in the hypersonic flow with total enthalpy of 16.2 MJ/kg generated by JF-10, a H_2/O_2-detonation-driven shock tunnel. The strong luminosity behind the shock wave is competing against the fluorescence signal, and the photon collecting efficiency of such facilities is limited by its large dimension. To cope with the problems, the laser sheet of a conventional planar LIF is rotated 90° along its propagation direction, so that the fluorescence signal collected by the camera concentrates on a sharp line. This setup makes LIF signal stand out even after the shock wave. With this setup, the S/N ratio is also increased; thus single-shot measurement is achievable. In this paper, the rotational temperature of the flow is estimated based on two-line thermometry.

1 Introduction

1.1 Backgrounds

Laser diagnostics are helpful tools for the investigations of gas flows. Laser depletion detection methods can provide precise and accurate results, such as temperature and species concentration, in the uniform flow. Other techniques such as laser-induced fluorescence (LIF) that involves photon emission phenomena provide spatial resolved quantities.

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Ground testing facilities are capable of providing hypersonic high-enthalpy flows with Mach number exceeding 10 [1]. Nevertheless, measurements in high-enthalpy flows generated by detonation-driven shock tunnels are always challenging since the long-repeat cycle and intensive background luminosity. Behind the shock wave, the heated gas has very strong visible and UV emissions, which overwhelmed the fluorescence signal.

By the aid of optical tagging methods, which sharply increase the abundance of specific fluorescence species in the region of interest, LIF can be used to measure the velocity of the flow field with satisfying spatial resolution and precision [2] and is promising for temperature measurement; however, by adding a tagging second laser, the complexity and the expanse of the system are greatly increased. In this paper, we demonstrated our latest progress in the applications of LIF in JF-10 shock tunnel. The spatial resolved temperature is both in the free stream and after the shock wave.

1.2 Theory

LIF thermometry is based on assumption that the fluorescence molecules reach its thermal equilibrium in its rotational degree of freedom. It obeys Boltzmann distribution over its rotational states. In this paper, the rotational temperature of the flow is inferred by comparing the fluorescence signal of two distinct excitation transitions within the γ(0,0) band of NO. When excited by a specific transition, the fluorescence strength is proportional to the population at the initial rotation level and is also affected by several factors including the quenching rate which is dependent on the local temperature and pressure. It has been discussed that using weak laser excitation which avoids saturation and by assuming that the laser overlaps on each excitation line in the same manner, the expression for the temperature depended fluorescence strength ratio reduced to the following format [3]:

$$\frac{S_1}{S_2} = C_{12}\left(\frac{S_{J''J'1}}{S_{J''J'2}}\right)\left(\frac{2J_1''+1}{2J_2''+2}\right).\exp\left(-\frac{F\left(J_1''\right)-F\left(J_2''\right)}{kT}\right) \tag{1}$$

where is $S_{J''J'}$ the Honl-London factor of the transition, J'' is the total angular momentum quantum number of the lower state, and $F(J'')$ denotes the rotational term energy.

2 Experimental Setup

The main LIF apparatus includes a narrowband frequency-doubled dye laser, which is pumped by Nd:YAG laser, an intensified charge-coupled device (ICCD), and timing circuit, which triggers the Nd:YAG laser, and ICCD and the detonation of the shock tunnel. The laser is tuned to the $\gamma(0,0)$ band of NO at 226 nm with a linewidth of 0.3 cm^{-1}. The timing circuit lets the laser to warm up in 200 cycles at 10 Hz, and for a specified time before it triggers the last laser shot and the ICCDs, it triggers the detonator of the shock tunnel.

The frequency double output of the dye laser is split by a 9:1 beam splitter. The main portion of the beam passes through a cylindrical and sphere lens pair which shapes the beam to planar laser sheet that enters the test section. The minor potion is directed to a windowed chamber containing diluted NO, for wavelength tuning, energy correction, and temperature calibration.

The shock tunnel generates flow with enthalpy at 16.2 MJ/kg. The driven section is filled with 4:1 mixed N_2 O_2 gas. An optional blunt body is placed in the test section for a few runs. Fused-silica windows are mounted on the wall of the test section, allowing UV laser beam and fluorescence light to transmit. As is shown in Fig. 1, there are two laser sheet configurations for different situations. The conventional horizontal setup gives 2D information about the flow, while the vertical setup has notable advantages in signal to noise ratio and insensitivity to the nonuniformity in the flow.

All the measurements are taken during the short operating time of the shock tunnel, which is about 3 ms. The timing of laser and ICCD is indicated in Fig. 2 along with signal from pressure sensor in P5 section and photo diode which monitors the luminosity in the free stream.

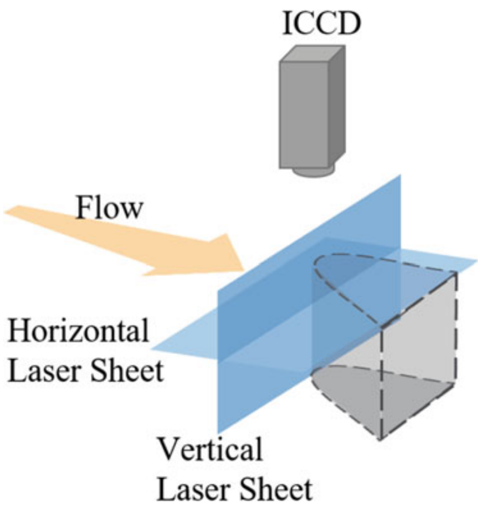

Fig. 1 Configurations in the test section

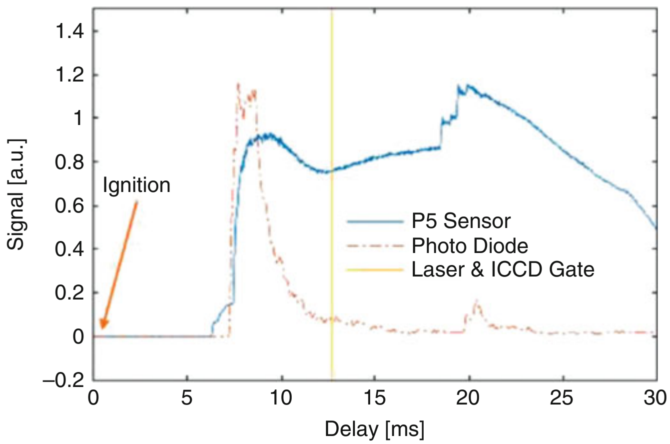

Fig. 2 Timing of the PLIF measurement referred to the shock tunnel conditions

3 Results and Discussions

A vertical laser sheet setup was used for high signal to noise ratio. Figure 3 shows typical LIF images, with small and unmatched structures, taken in the free stream, indicating that the flow is lack of uniformity. The two images were taken with $S(18.5)$ and $Q_1+P_{21}(27.5)$ excitations [4]. The signal strength of each position is a summation of the signal counts over the pixels in the vertical direction on the image with background subtracted. The rotational temperature is estimated based on these two shots. The result has been calibrated by the LIF intensities of the two excitations in an NO reference cell at 300 K. The flat area of the temperature curve gives 370 K, which is lower than 441 K obtained by numerical simulations in such condition [5].

With the blunt body placed in the hypersonic flow, strong shock wave occurs, and the flow is expected to be heated up to several thousand K. Two-line LIF thermometry is performance at two different locations downstream the head of the blunt body with $R_1 + Q_{21}(13.5)$ and $Q_1 + P_{21}(28.5)$ excitation. Although the strength of luminosity after shock is at the same level as the LIF signal, it can be subtracted from the image when using vertical laser sheet setup. The LIF data is shown in Fig. 4a, b. The noise in the signal strength line is up to 20%, producing up to 200 K fluctuation in the temperature line. By applying a 10-point moving average function on the signal strength data, the fluctuation in temperature is reduced. In Fig. 4c, the position of the measurement is indicated on an image with the luminosity background. One can see that the two lines have consistent free stream temperature. The line closer to the head of the blunt body has the higher peak temperature. As it moves downstream, the area with levitated temperature against the free stream gets colder but wider, and it dispatches from the edge of the model. This trend is comparable to the simulation of reentry of space vehicle [6].

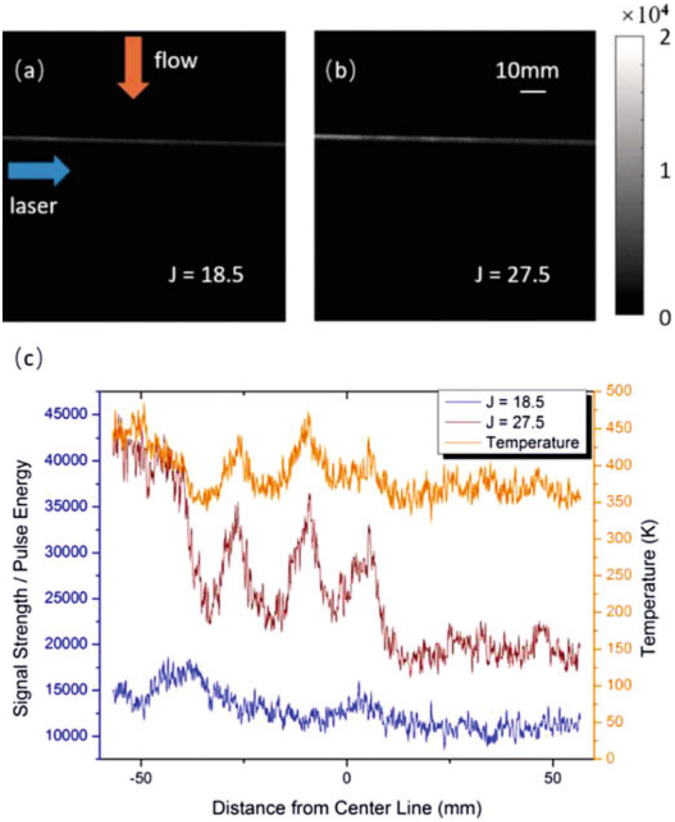

Fig. 3 (**a**, **b**) LIF images (**c**) LIF signal strength and rotational temperature vs. distance from center line

The absolute temperature after the shock is lower than our expect, noting that the stagnation temperature T_0 of the flow is above 7000 K. The depletion due to the on-resonance absorption is estimated according to previous measurement and the latest numerical simulation, which showed that in JF10 the density of NO is about 4.5×10^{14} cm^{-3} with 4:1 mixed N_2 O_2 driven gas. A Lifsim simulation [7] of the two selected excitation lines with $J = 13.5$ and $J = 28.5$ gives 8% and 2% laser depletion accordingly in the free stream over a 20 cm path, which corresponds to the laser-absorbing area outside the imaging area. It brings up to 10% increment in the observed temperature. The sources of random errors are the 10% fluctuation of the laser energy, the nonuniformity of the flow, and the noise level. The accuracy of this technique could to be improved in the following ways: perform additional calibration at temperature above 1000 K, record the final laser pulse energy with energy meter or calibrated photodiode, and investigate the influence on fluorescence processes by chemical reactions and ionization.

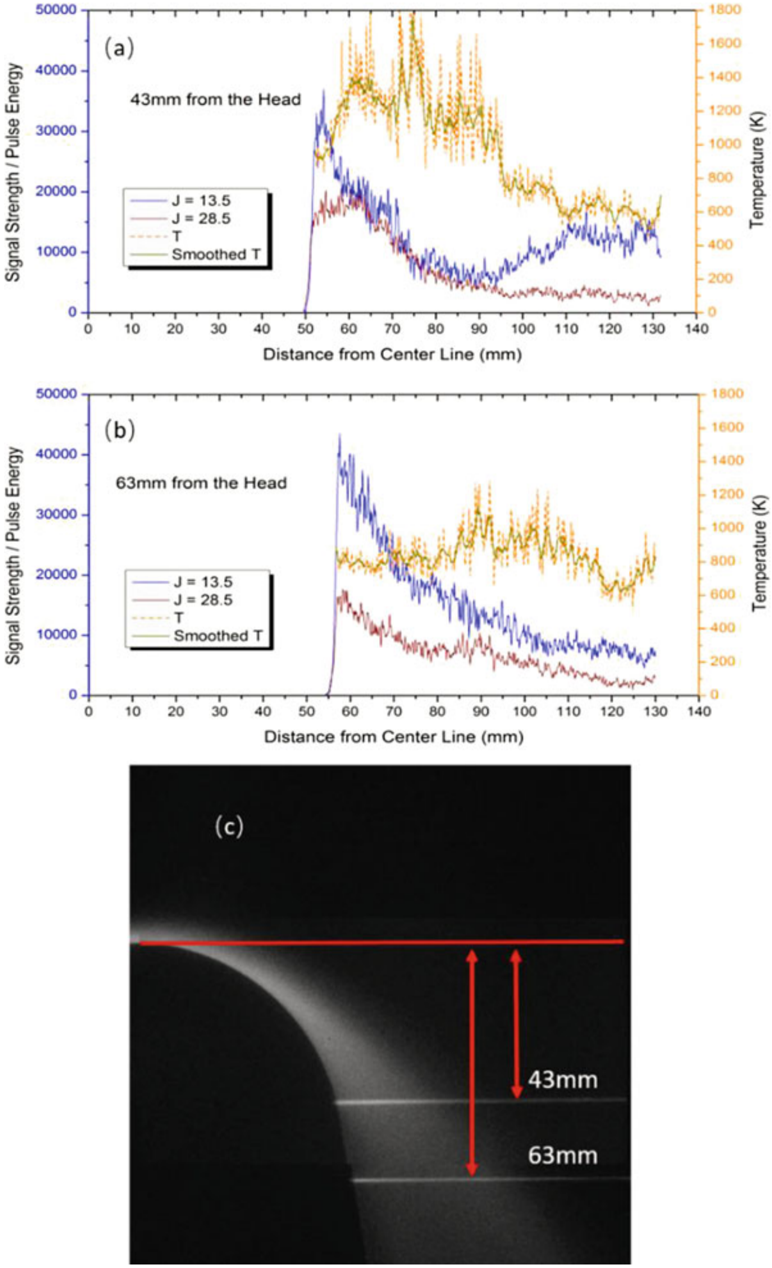

Fig. 4 (**a**, **b**) LIF signal strength and rotational temperature vs. distance from centerline (**c**) position of the measurements on the background luminosity image

4 Conclusion

The γ(0,0) band NO LIF results showed the possibility of obtaining fluorescence signal with satisfying S/N ratio with vertical laser sheet setup. Based on the two-line thermometry, the temperature is indicated in the free stream as well as after the shock wave. The trend of the temperature changing alone the excitation path and moving from the middle of the blunt body to the tail has good agreement with simulations; however, the absolute temperature indicated from two-line thermometry is not validated by numerical simulation of other measurement yet. Further investigation will be focused on the accuracy of the measurement and calibration technique at high temperature.

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