Temperature Measurement of HEK-X Expansion Tube Flow by Laser Absorption Spectroscopy

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An expansion tube is a promising facility to simulate atmospheric entry conditions, although its flow conditions have not been completely characterized mainly owing to its short operation time. In this study, laser absorption spectroscopy was applied to diagnose HEK-X expansion tube flow in the Kakuda Space Center. The target is an absorption line of an oxygen molecule at 763 nm. To increase the sensitivity, optical path length was extended by five times using mirrors. Consequently, an absorption profile with a fractional absorption of 2.4 ± 0.3% was detected at a shock velocity of 7.65 ± 0.05 km/s. The estimated translational temperature from the Voigt fitting was 2750 ± 450 K.

Key Words: Expansion Tube, Laser Absorption Spectroscopy, Translational Temperature

Nomenclature

| Symbol | Description |
|--------|-------------|
| c      | velocity of light |
| k      | absorption coefficient |
| $k_B$  | Boltzmann constant |
| M      | molecule weight |
| n      | constant |
| p      | static pressure |
| S      | performance function |
| T      | translational temperature |
| $\nu$  | frequency |
| $\Delta \nu$ | half-width at half maximum |

Subscripts

| Symbol | Description |
|--------|-------------|
| 0      | center of absorption |
| D      | Doppler |
| L      | Lorentz |
| ref    | reference condition |

1. Introduction

An expansion tube is a promising facility to simulate atmospheric entry conditions. As the flow is generated without high-pressure and high-temperature stagnation conditions, the flow conditions might be close to the actual conditions. In other high enthalpy wind tunnels, flow conditions usually have higher degrees of dissociation and higher excitation and vibration temperatures than the actual conditions.1) However, expansion tube flow conditions have not been completely characterized mainly owing to their short operation time of typically a few tens of microseconds.2) Although Pitot tube measurements have been applied, the measured pressure shows discrepancies with the calculated results.3) Therefore, flow conditions, especially in temperature, are important. Laser absorption spectroscopy (LAS) is a unique method to measure the translational temperature within large time resolutions. Another advantage of LAS is portability owing to its compact system.4) In this study, LAS was applied to expansion tube flows in the Kakuda Space Center to measure the translational temperature.

2. Measurement Methods

2.1. Tunable diode laser absorption spectroscopy

The target absorption line is one of the A-bands of the oxygen molecule at 763 nm, whose wavelength can be covered by a diode laser. The absorption profile is the Voigt profile expressed as

$$k(\nu) = \frac{k(\nu_0)}{\pi \Delta \nu_L} \int_{-\infty}^{\infty} \frac{\exp \left\{ -\frac{2(\nu-\nu_0)^2}{\Delta \nu_D} \right\}}{1 + \frac{2(\nu-\nu_0 - \delta)}{\Delta \nu_L}} d\delta.$$  \hspace{1cm} (1)

Here, $\Delta \nu_D$ is the Doppler width expressed as

$$\Delta \nu_D = \frac{\nu_0 \sqrt{\ln 2}}{c} \sqrt{\frac{2kB T}{M}}.$$  \hspace{1cm} (2)

In these test conditions, pressure broadening was dominant compared to other broadenings. Thus, the Lorentz width is expressed as

$$\Delta \nu_L(p, T) = p \left( \frac{T_{ref}}{T} \right)^n \Delta \nu_L(p_{ref}, T_{ref}).$$  \hspace{1cm} (3)

Therefore, $\Delta \nu_L$ is also a function of temperature with static pressure measurement. However, in practice, the curve fitting of Eq. (1) to the measured profiles after substituting Eqs. (2) and (3) is extremely difficult owing to the complexity of the function. Therefore, in this study, the absorption profiles
were analyzed using the following process. First, the Lorentz width is calculated using a given Lorentz temperature. Next, the Voigt function is fitted to the profiles with the calculated Lorentz width and variable Doppler width. Then the temperature from the obtained Doppler width is compared with the Lorentz width and variable Doppler width. Then the temperature was estimated from Doppler width was compared with the Lorentz temperature by the performance function:

$$S = \left( \frac{T_L - T_D}{T_L} \right)^2.$$  \hspace{1cm} (4)

When the performance function is at a minimum, the Lorentz temperature is the true temperature.

2.2. Experimental apparatus

A schematic of the LAS system is shown in Fig. 1. A DFB laser diode was used. The laser wavelength was modulated at a frequency of 50 kHz. Thus, the time resolution was 20 μs. An optical isolator was used to prevent the reflected laser beam from returning into the diode. The laser beam was split into two beams. One beam was directed to an etalon with a free spectral range of 1.5 GHz to calibrate the relative frequency. The other laser beam was passed through the flow five times with four mirrors to increase the sensitivity. The measured position was near the tube exit. The signal detected by an avalanche photodiode with a bandpass filter was recorded on an oscilloscope. The details of the expansion tube HEK-X are shown in Ref. 2).

3. Results and Discussions

The first and second rupture pressure were 52 MPa and 5.57 MPa, respectively. The compression, second and expansion tubes were filled with 94.2 kPa of helium, 7 kPa of air and 50 Pa of air, respectively. The estimated shock velocity from the pressure sensors in the tube was 7.65 ± 0.05 km/s. The static pressure was 45.0 kPa. The fractional absorption of the flow, fitted Voigt function, and performance function are shown in Fig. 2. The absorption signal was detected during the test time because it was a few tens of microseconds and comparable to the time resolution. Here, the fractional absorption was obtained by subtracting the absorption outside the chamber from the measured absorption. The absorption outside the chamber was obtained immediately before the operation, neglecting the absorption of the chamber air of 50 Pa. In this figure, the fractional absorption of the flow was observed to be as low as 2.4 ± 0.3%. The performance function was observed to be at the minimum. The estimated temperature was 2750 ± 450 K. Here the errors were estimated from the fitting errors. Assuming the thermo-chemical equilibrium, the degree of dissociation of oxygen is 6.3%. As the flow is in a non-equilibrium state, the actual degree of dissociation would be lower than the above value.

4. Conclusion

Laser absorption spectroscopy was applied to an expansion tube HEK-X in the JAXA Kakuda Space Center. Accordingly, a fractional absorption of 2.4 ± 0.3% was observed for a shock velocity of 7.65 ± 0.05 km/s, which was deduced by the pressure sensors. The flow temperature estimated from Doppler width was 2750 ± 450 K.

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