High Enthalpy Flow Diagnostics by Cavity Enhanced Absorption Spectroscopy

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[Abstract] For the temperature measurement of nitrogen/oxygen flows generated by arc wind tunnels, the cavity enhanced absorption spectroscopy method was adopted. Installing Brewster windows on a vacuum chamber, a resonator was successfully formed between a pair of high-reflectance mirrors placed out of the chamber. As a result, sensitivity was enhanced by two orders of magnitude compared with the conventional single-pass laser absorption spectroscopy. Using this system, the absorption profiles of atomic oxygen were measured in an argon/oxygen flow.

Nomenclature

A = Einstein coefficient
c = velocity of light
d_0 = absorption length
d_{CEAS} = effective absorption length in cavity enhanced absorption spectroscopy
g = statistical weight
i = absorbing state
I = transmitted laser intensity
I_0 = probe laser intensity
j = excited state
k = absorption coefficient
K = integrated absorption coefficient
k_{B} = Boltzmann constant
M_A = atomic mass
n_i = number density of absorbing state
R_{eff} = effective reflectance of the mirrors
T_{tr} = translational temperature
λ_0 = center absorption wavelength
ν = laser frequency
ν_0 = center absorption frequency
$\Delta\nu_{\mathrm{D}}$ = full width at half maximum of the profile

I. Introduction

When the spacecraft entry of the earth or other planets, their entry velocity will be several km/s and then they are exposed to severe heat loads by aerodynamic heating.[1,2] Then, Thermal Protection System is essential to protect spacecraft from such severe conditions.[3] Therefore, high enthalpy flow generators have been developed to simulate their environments. However, their exact flow conditions are mostly unknown because they are usually in strong thermo-chemical non-equilibrium. Therefore, it is useful to measure the chemical composition and enthalpy in these flows for the evaluation of TPS, as well as for the validation of CFD models of non-equilibrium flows.

In our previous study, laser absorption spectroscopy (LAS) has been applied to the flows of the arc wind tunnels and the inductively coupled plasma wind tunnels, and the number density of meta-stable atomic oxygen and

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translational temperature were measured.[4,5] In these measurements, strong absorption signals of the OI at 777.19 nm line were observed in oxygen or argon/oxygen flows. Then the number density OI at absorbing state $3s^5S$ was estimated as 3 x 10^{15} – 3 x 10^{17}m^{-3}. However, in nitrogen/oxygen flows, the OI ($3s^5S$) number density was lower than the detectable limit of 3 x 10^{15} (fractional absorption of 1%).[6] This would be because large part of input energy was consumed in nitrogen dissociation, resulting in lower temperature. In fact, although LAS was tried to be applied to the nitrogen/oxygen flows generated by constricted arc wind tunnels in Japan Ultra-high Temperature Materials Institute and segmented arc wind tunnels in ISTA/JAXA, the absorption signals could not be detected. Although in the nitrogen/ oxygen flows generated by IPG3 or PWK3 in Stuttgart University, the absorption signals could be detected, the signals were so small and it could be detected only near the center of the flows. Then, it was found that the sensitivity of LAS was required for the diagnostics in whole nitrogen/oxygen flows.

Recently, cavity ring down spectroscopy (CRDS) has been employed as one of the high sensitive laser absorption spectroscopy.[7,8] In this method, the decay rate of light intensity inside a stable optical resonator, often called the ring-down cavity (RDC), is measured. Laser is first injected into the RDC, and is then interrupted in below μs by an acousto-optic modulator[9] or a mechanical chopper.[10] The transmitted laser intensity decays exponentially in time. The decay rate is proportional to the total optical losses inside the RDC as a function of the laser frequency. The lower detection limits of the number density for many species have been demonstrated to be from 10^{13} to 10^{16}m^{-3}.[11]

However, for the data acquisition schemes of CRDS, the complexity and cost of digitization is high, especially in high-performance systems where a large number of bits (e.g., 12 to 14) and high speed (e.g., 100MHz) is required simultaneously.[12] To simplify CRDS and eliminate the requirement for digitization of a time-domain signal, cavity-enhanced spectroscopy (CES) was developed. CES has many different implementations.[13,14] In this study, Cavity Enhanced Absorption Spectroscopy (CEAS),[15,16] which is the simplest method in the CES methods, was applied for sensitivity enhancement. In this method, a diode laser can be used without pulsation. Moreover, it enables us to have enough amplified power, while providing detection sensitivity comparable to CRDS.

For application of CEAS to plasma wind tunnels, not only high measurement accuracy but also high spatial resolution and short measurement time are necessary. In conventional high sensitive method, multi-pass absorption spectroscopy,[17] the spatial resolution gets worse. Then the temperature distribution in the plasma wind tunnels is hard to be obtained by Abel inversion. Therefore, the laser beam should be focused at the measurement region. Furthermore, in general, from 100 to 1000 results were averaged in CEAS.[15,18] Then, it takes long time for measurement. However, the run time of huge plasma wind tunnels is limited to no more than 20 minutes.

Therefore, the spatial resolution, detection limit, measurement accuracy, data amount and measurement time of CEAS were examined using plasma torch under the atmospheric pressure. As a result, it was found that in CEAS, the spatial resolution could be less than 1mm, the sensitivity was successfully increased more than two orders of magnitude compared with conventional single-pass LAS, in the line with 6 x 10^{-4} absorbance at the center frequency, averaging for 10 sweeps reduced the random error to less than 5% and 100MSampe data amount was needed for acquisition of the distribution at one plane with 25GHz frequency range.

In CEAS, the sensitivity gets worse because of the loss in the cavity. For the avoidance of this influence, the high reflectance mirrors are placed in the vacuum chamber as the chamber window. However, the temperature in the chamber of the plasma wind tunnels is so high and the number of reactive gas such as atomic oxygen is so large. Then it is worried that the high reflectance mirrors are contaminated.

Therefore, in this experiment, the Brewster windows are used for chamber windows. Using them, the cavity could be constructed without placement of their mirrors in the vacuum chamber. Then CEAS could be applied to the arc wind tunnel.

II. Theory

A. Laser Absorption Spectroscopy

The relationship between laser intensity I and absorption coefficient $k(\nu)$ is expressed by the Beer-Lambert law as

$$\int k(\nu)dx = -\ln\left(\frac{I}{I_0}\right). \tag{1}$$

In this experiment, Doppler-broadening $\Delta\nu_D$ is several gigahertz, which is two orders of magnitude greater than all other broadenings, including natural pressure and Stark broadenings. The absorption profile at laser frequency is approximated as a Gaussian profile, expressed as[19,20]

$$k(\nu) = \frac{2K}{\Delta\nu_{\mathrm{D}}}\sqrt{\frac{\ln 2}{\pi}}\exp\left\{-\ln 2\left[\frac{2(\nu-\nu_0)}{\Delta\nu_{\mathrm{D}}}\right]^2\right\} \tag{2}$$

The full width at half-maximum of the profile is related to the translational temperature, expressed as

$$\Delta\nu_{\mathrm{D}} = 2\nu_0\sqrt{\frac{2\ln 2 k_{\mathrm{B}}T_{\mathrm{tr}}}{M_{\mathrm{A}}c^2}}\,. \tag{3}$$

The number density of absorption state is related to the integrated absorption coefficient K as

$$K \equiv \int_{-\infty}^{\infty} k_\nu d\nu \approx \frac{\lambda_0^{\;2}}{8\pi}\frac{g_j}{g_i}A_{ji}n_i\,. \tag{4}$$

B. Cavity Enhanced Absorption Spectroscopy

In CEAS, only a laser beam whose frequency meets the resonance condition can transmit the cavity. Then, the absorption signal is obtained through integration of the total signal transmitted through the cavity. Absorbance kd_{CEAS} in CEAS is expressed as a function of single-pass absorbance kd_0,,[10]

$$1-\exp(-kd_{\mathrm{CEAS}}) = \frac{I_0 - I}{I_0} = \frac{R_{\mathrm{eff}}\{1-\exp(-kd_0)\}}{1-R_{\mathrm{eff}}\cdot\exp(-kd_0)}\,. \tag{5}$$

Here, R_{eff} is the effective reflectance of a pair of high reflectance mirrors.

III. Experimental Setup

The schematic of measurement system for CEAS is shown in Fig.1. A tunable diode laser with an external cavity (Velocity Model 6300, New Focus) was employed which is not accompanied with mode-hops in wide modulation width. The laser frequency was modulated over about 20GHz at a repetition frequency of 0.5Hz using a function generator. High reflection concave mirrors (Layertec) whose curvature radius is 1m were used for constructing a cavity. Lens whose focal length is 0.5m was used for mode-matching. The distance and Free Spectral Range of the RDC were about 1.3m and 115MHz, respectively. Although, the diffraction-limit beam waist of the cavity is 680μm measured waist by a beam profiler (Beamstar-V, Ophir Optronics)was 720μm. (Beam waist とは半径のことですが、これでいい？) A faraday optical isolator was inserted between the tunable laser and the optics to reduce the optical feedback to the laser. An etalon whose FSR is 0.75 GHz was used to measure the frequency modulation. The emission from the plasma was shielded using a band-pass filter whose center wavelength and full width at half maximum are 780 nm and 10 nm, respectively. The transmitted laser intensity was detected by a photo multiplier tube (H8249-102, Hamamatsu). In CEAS, if losses in a cavity due to optical windows are larger than the absorption, the absorption profile cannot be detected. Therefore, in this research, Brewster windows were installed on the flanges of the vacuum chamber. The polarization controller was used for matching the polarization of the laser beam with the Brewster windows. For this control, the laser beam should be coupled into a single-mode fiber. This fiber was functioned as a spatial filter simultaneously.

The schematic of the arc wind tunnel is shown in Fig. 2. In the experiment using pure argon as a working gas, its input power, discharge voltage and mass flow rate were 1,040W, 26V and 4slm, respectively. In the experiment with argon/oxygen premixed gas, mass flow rates of argon and oxygen were set at 5slm and 0.01slm, respectively. Its input power and discharge voltage were 920W and 23V, respectively.

In this research, the absorption lines of ArI at 777.34 nm and OI at 777.19nm were targeted. The plane at 50mm downstream of the nozzle exit of the arc wind tunnel was diagnosed. For ArI diagnostics, an argon glow discharge tube was used to know the center absorption frequency. Its input power, discharge voltage and pressure were 2.0 W, 400 V and 80 Pa, respectively.

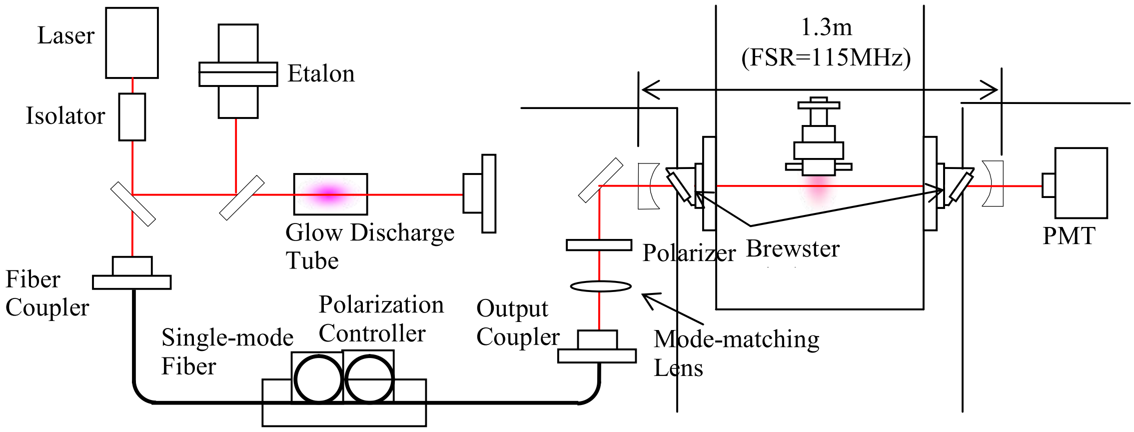

Fig.1 The schematic of measurement system for cavity enhanced absorption spectroscopy

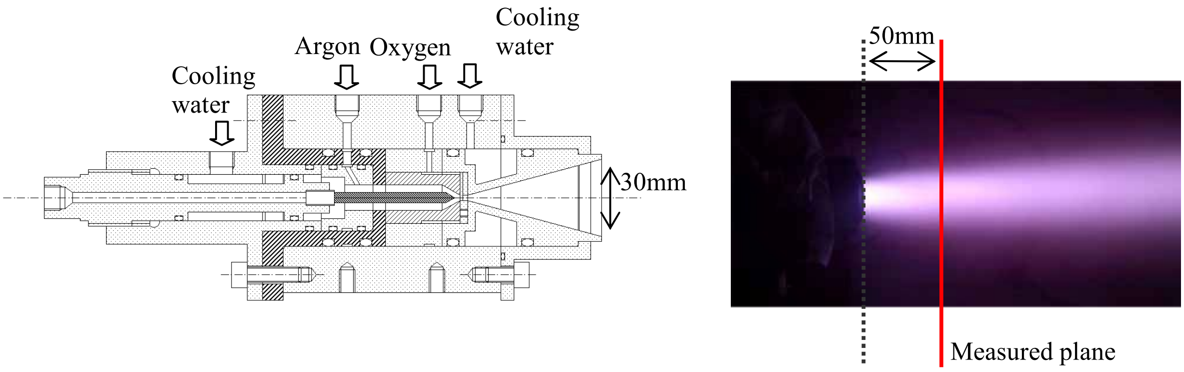

Fig.2 Configuration of arc wind tunnel (left) and its photo in argon operation

IV. Result and Discussion

A. Resonant condition

Figure 3 shows the laser signal transmitted through the cavity was measured without absorption. By taking a mode match, higher order modes had been suppressed.

B. CEAS in Pure Argon Flow

In order to know the effective reflectance of the high reflectance mirrors, CEAS was performed for a pure argon flow at the 40mm from the center axis. Typical CEAS signal of the arc wind tunnel flow, LAS signal of the glow discharge tube plasma along with the etalon signal are shown in Fig.4.

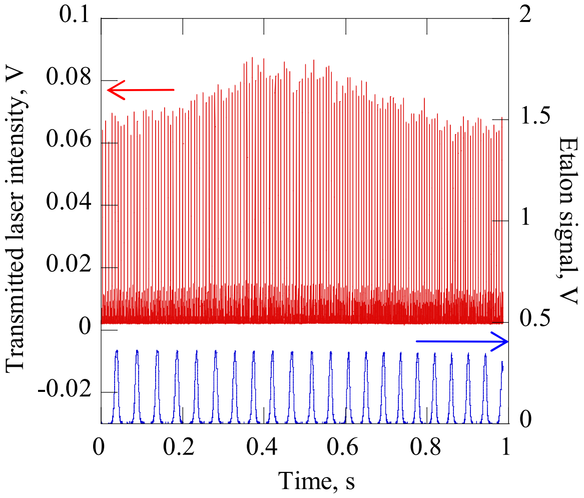

Fig.3 Transmitted laser intensity through the cavity and Etalon signal

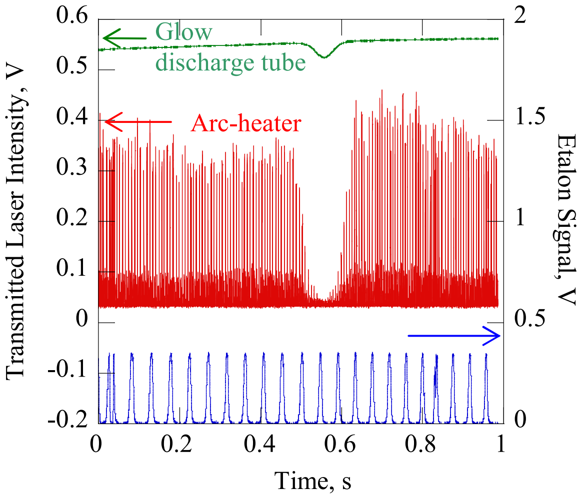

Fig.4 CEAS signal in argon flow generated by arc wind tunnel at 50mm from the nozzle exit and 40mm form the center axis, single-pass LAS signal in the glow discharge tube and etalon signal

In CEAS, the transmitted laser intensity was fluctuated due to the fluctuation of the laser output intensity, the vibration of optical elements, and so on. The effect of these fluctuations can be reduced by averaging multiple sweeps. In this experiment, 50 sweeps were averaged. The averaged absorbance measured by CEAS and single-pass LAS are shown in Fig.5. By fitting Eq. (5), R_{eff} was estimated at about 99.7%. As a result, the sensitivity was successfully enhanced by two orders of magnitude compared with the conventional single-pass LAS.

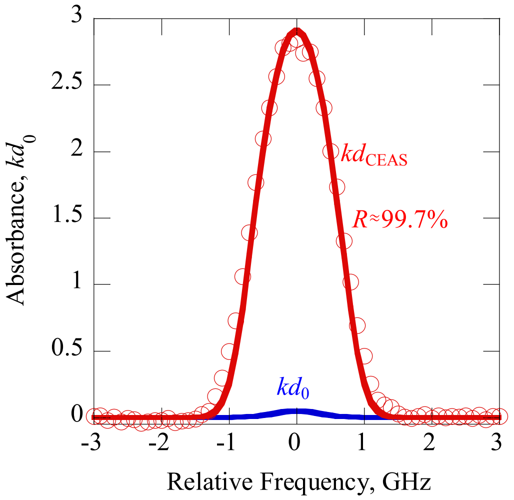

Fig.5 Absorbance in CEAS and single-pass LAS Fitted by the relationship between kd_0 and kd_{CEAS}, the reflectance of the mirrors was deduced as 99.7%.

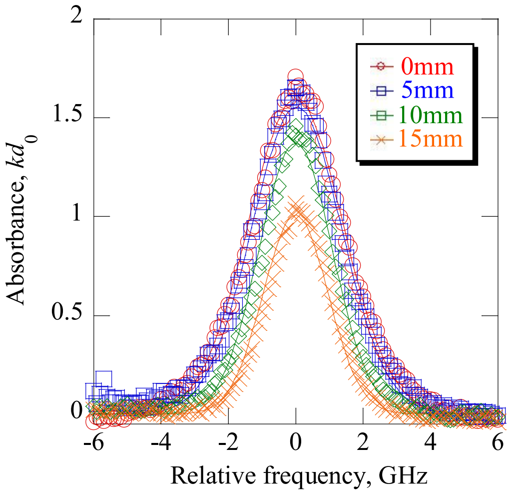

Fig.6 Absorption profiles at each distance from the center axis of the nozzle exit

C. CEAS in argon/oxygen flow

Finally, the argon/oxygen flow was diagnosed by the sensing the absorption profile of meta-stable atomic oxygen. The absorbance kd_0 was calculated using eq. (5), and plotted in Fig. 6. The local absorption profiles were obtained by the Abel inversion. Fitted by a Gaussian profile, the number density and translational temperature distributions were obtained at each radial position as shown in Figs. 7 and 8.

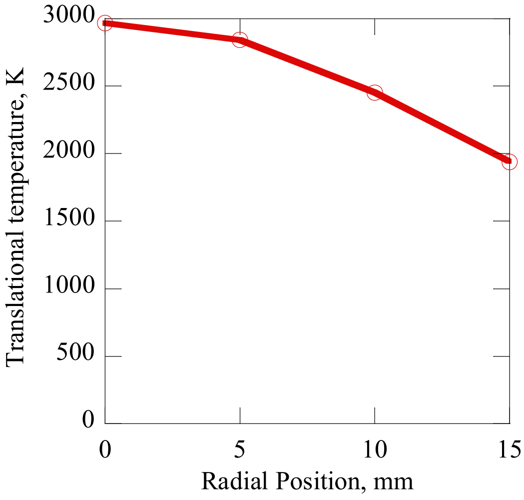

Fig.7 Translational Temperature at each radial position

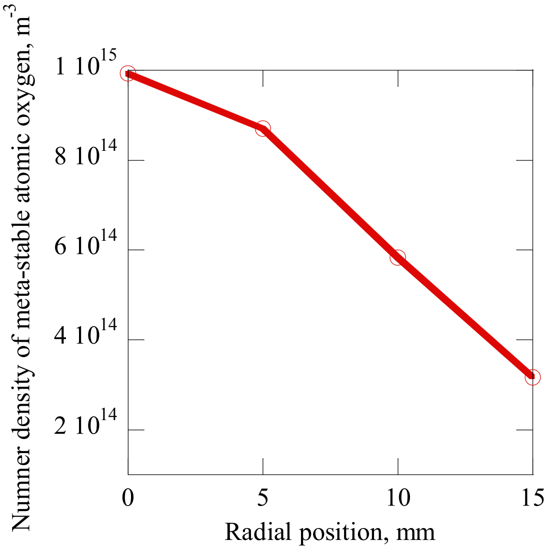

Fig.8 Number density of meta-stable oxygen at each radial position

V. Conclusion(本文を参考のもう一度推敲を)

i. The Cavity Enhanced Absorption Spectroscopy system with Brewster window was developed for diagnostics of an arc wind tunnel with the high reflectance mirrors placed out of the vacuum chamber.
ii. In pure argon flow, the sensitivity was successfully enhanced by the factor of 350 compared with the conventional single-pass LAS.
iii. Using this system, the distribution of the temperature and meta-stable atomic oxygen number density were obtained in the argon/oxygen flow by the absorption signals in the trace of oxygen.

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