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Cavity Enhanced Absorption Spectroscopy of High Enthalpy Plasma Flow under Mechanical Vibration

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Cavity enhanced absorption spectroscopy (CEAS) and cavity ring-down spectroscopy (CRDS) are applied to measure the excited state atomic oxygen (3s ^{5}S) in an arc heated air flow. By introducing a microwave discharge plasma generator as an OI reference cell, it is possible to sweep the laser frequency in the range of the absorption line and identify the absorption signal even under a mechanical vibration. As a result the absorption signal is detected in both measurements and the minimum detectable absorbance of this system is estimated at 3.0×10^{-4}. However the disagreement is found between two measurement results. As a reason for this disagreement the saturation effect in the CRDS measurement is considered.

Nomenclature

c = speed of light
d = length of absorber
I = transmitted laser intensity
k = absorption coefficient
L = cavity length
R = reflectivity of the mirror
t_{RD} = ring-down time
ν = frequency of laser

I. Introduction

For the development of the thermal protection system (TPS) of a reentry vehicle, arc heated wind tunnels are often used. Detailed characterization of the flow is necessary because their flow is in thermochemical nonequilibrium. Spectroscopic measurements are favorable to understand thermally nonequilibrium flow. Mainly three spectroscopic methods have been applied to the arc heated wind tunnel flow characterization. Emission spectroscopy is used to estimate the rotation and vibration temperatures by molecular spectra fitting method using a radiation code such as SPRADIAN2[1]. Laser induced fluorescence is used to measure estimate the translational temperature by measuring the Doppler broadening of the atomic oxygen and nitrogen.[2-4] Particle number density is also available though, the calibration using a reference cell is necessary. Laser absorption spectroscopy (LAS) has been applied to measure the translational temperature, flow velocity and number density of absorbing particles.[5,6] However, when the electron excitation temperature is so low that the number density of the excited state atoms is very small, the absorption is not available. That is, sensitivity in LAS is lower than those in former two methods. Thus enhancement of sensitivity in LAS is necessary. In this work the highly sensitive laser absorption spectroscopy is applied to the arc heater wind tunnel characterization.

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Enhancement of sensitivity in LAS has been achieved by building up an optical cavity using highly reflective mirrors. Cavity enhanced absorption spectroscopy (CEAS) [7,8] and cavity ring down spectroscopy (CRDS) [7,9] are well known as the highly sensitive laser absorption spectroscopy. In the application of CEAS and CRDS to the plasma wind tunnel measurements mechanical vibration caused by a vacuum pump, high pressure cooling water or other experimental facilities can be a disturbance to the optical cavity.[10] In this work a microwave discharge plasma generator is introduced as an OI reference cell and it is possible to sweep the laser frequency around the absorption line. As a result the absorption line can be identified even under the low signal-to-noise ratio condition. Then the results of CEAS and CRDS are evaluated and the saturation effect is discussed.

II. Optical Cavity and Spectroscopy Theories

A. Fabry-Perot Cavity

The optical cavity built by two highly reflective mirrors is known as a Fabry-Perot cavity and the transmitted profile from the cavity is known as an Airy function. In the theory of the Fabry-Perot cavity the incident laser light at a frequency ν transmits the cavity instantaneously. And the transmitted intensity I_t can be equated as a function of ν as shown in Eq. (1).

$$\frac{I_\mathrm{t}}{I_0} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(\frac{\nu}{c}L\pi)}. \tag{1}$$

Here I_0, R, c and L are the incident laser intensity, mirror reflectivity, wavelength, speed of light, and cavity length respectively.

B. Cavity Enhanced Absorption Spectroscopy

If the absorber exists in the optical cavity the ratio of intensities measured with and without absorption losses, $I_\mathrm{t}/I^0_\mathrm{t}$ can be equated as following.

$$\frac{I_\mathrm{t}}{I_\mathrm{t}^0} = \frac{(1-R)^2\exp(-kd)}{1-R\exp(-kd)^2}. \tag{2}$$

Here k is the absorption coefficient and d is the length of the absorber. In CEAS R has to be measured accurately. The measurement of R is achieved either by measurement of the absorber which absorbance is known, or by measurement of the ring-down time of the cavity. And sensitivity of CEAS, i.e., the minimum detectable absorbance kd_min is described as Eq. (3) using the minimum detectable change in the transmitted intensity ΔI_min.[7]

$$kd_\mathrm{min} = (1-R)\frac{\Delta I_\mathrm{min}}{I}. \tag{3}$$

C. Cavity Ring-down Spectroscopy

At the CRDS measurement the laser is switched off immediately after the transmitted intensity reaches the threshold level. Then the transmitted intensity shows the decay signal (ring-down signal). The temporal intensity is equated as

$$I_\mathrm{t}(t) = I_\mathrm{t}(0)\exp\left(-\frac{t}{t_\mathrm{RD}}\right). \tag{4}$$

Here t_RD is the ring-down time, which is expressed as

$$t_\mathrm{RD} = \frac{L}{c(1-R+kd)}. \tag{5}$$

From this value k can be estimated.

III. Experimental Setup and Data Processing

A. Cavity Enhanced Absorption Spectroscopy and Cavity Ring down Spectroscopy

The experimental setup is shown in Fig. 1. As a light source an external cavity diode laser (New Focus Inc. Model 6300) was used. In this work the turning range was fixed as 36 GHz and the frequency of laser frequency modulation is 1 Hz so the sweeping speed is 72 GHz/s. And the laser was operated around 777.19 nm which corresponds to the absorption line of atomic oxygen (3s ^{5}S). The etalon is used as a wave meter, which free spectral range (FSR) is 0.75 GHz. The microwave discharge plasma is generated on the optical table as the OI reference cell of atomic oxygen. By using this reference, it is possible to sweep the laser frequency around the absorption line and identify the absorption signal. At the CRDS measurement an acousto-optic modulator (AOM, ISOMET, 1205C-2) is used for the switching of the laser. The laser light is introduced to the wind tunnel through an optical fiber. The output laser energy is about 0.8 mW/mm^2. The optical cavity was built up by using the highly reflective mirrors (Layertec.) with a diameter of 1 inch. and a radius of curvature of 1500 mm. The cavity length is 1980 mm, which corresponds to the free spectral range of 75.7 MHz. This value is small enough to detect the broadening of the absorption profile which is about 5 GHz. To avoid the contamination of the mirror caused by the wind tunnel flow, the mirror is mounted outside the chamber. And the chamber windows between the mirrors are mounted at the Brewster angle. So the polarization of the light is controlled by the polarization controller so as to be matched with the Brewster angle. The reflectivity of the cavity is 0.99356. The signals of etalon and photo detector at the microwave discharge tube are recorded by a logger (KEYENCE, NR2000) and the signal from the photo multiplier tube (PMT, Hamamatsu Photonics, H8249) is recorded by a digitizer (Agilent Technologies, DP306) on the PC-board.

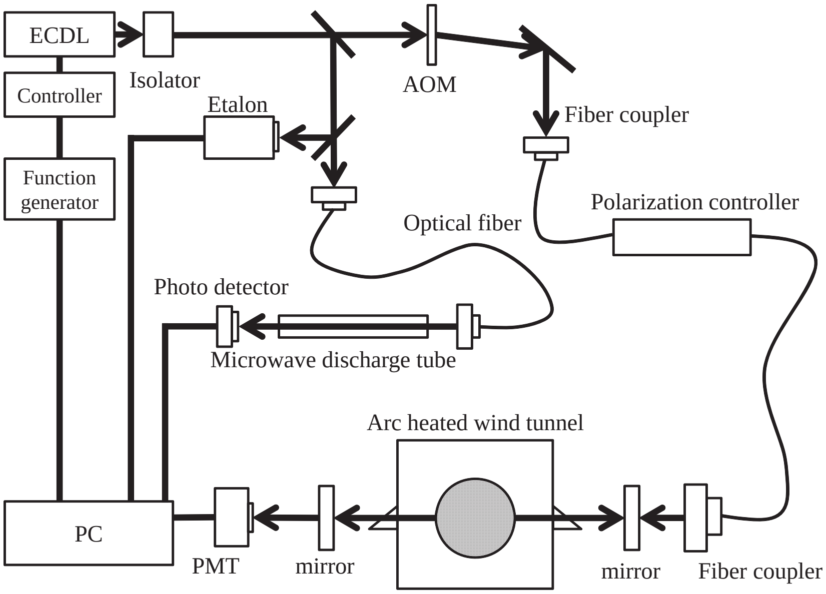

Figure 1 Experimental setup of CEAS and CRDS. The cavity length is 1980 mm and the wavelength of laser is 777.19 nm.

B. Arc Heated Wind Tunnel

The operational conditions and photograph of the arc heated wind tunnel flow in IAT-JAXA (Institute of Aerospace Technology, Japan Aerospace Exploration Agency) are shown in Table 1 and Fig. 2. The specific enthalpy is deduced by an energy balance method. This wind tunnel consists of a constricted-arc heater, a conical nozzle with the throat diameter of 25 mm and nozzle exit diameter of 115 mm. Its nominal Mach number at nozzle exit is 4.8. The shock layer is generated by an ultra-high temperature ceramic (UHTC) of which diameter is 40 mm. The measured point is 4 mm away from the surface.

Table 1 Operational conditions of the arc heated wind tunnel.

Current, A	700
Mass flow rate, g/s	10
Specific enthalpy, MJ/kg	21.8
Nozzle exit diameter, mm	115
Diameter of UHTC, mm	40

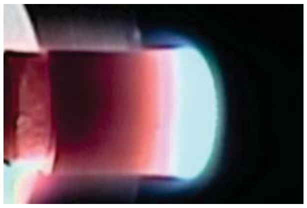

Figure 2 Photograph of the arc heated wind tunnel flow with the UHTC.

C. Data Processing

1. CEAS

To record all resonant signals in one sweep of the laser frequency, the transmitted intensity is recorded for one sweep with a sampling rate of 2 MHz. The mechanical vibration induces a resonant signal of a transverse mode as shown in Fig. 3. In the data processing only the resonant signal of a longitude mode is utilized. About 230 resonant are recorded for one sweep. To get a smooth line of the absorption profile a hundred sweeps are recorded and the peak value is averaged over the range of 37.5 MHz which corresponds to the 5 % of the FRS of the etalon.

2. CRDS

In the CRDS measurement the ring-down events are recorded one by one with a sampling rate of 20 MHz. For one sweep 30 ring-down signals are recorded. To get the smooth line 200 sweeps are recorded and after the acquisition the decay signal is fitted by a least-squire method to an exponential decay using Eq. (4). In the measurement at a vibratory environment the ring-down signal is sometimes caused not by AOM but by the mechanical vibration. At this signal the ring-down time tends to be less estimated. So those data are neglected in the data processing.

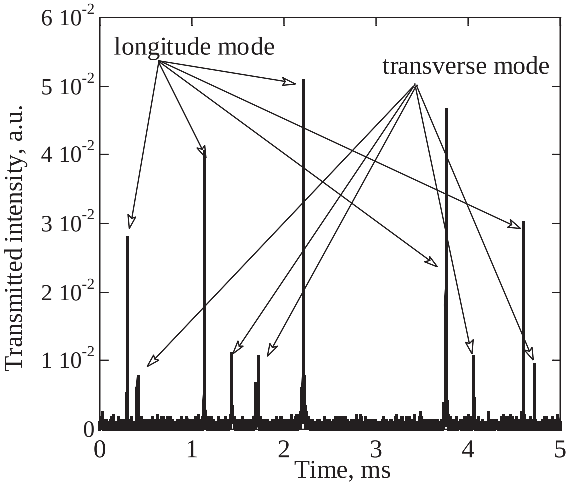

Figure 3 Transmitted intensity under mechanical vibration.

IV. Results and Discussions

The transmitted intensity profile of the CEAS measurement for one sweep is shown in Fig. 4. It is difficult to identify the absorption signal in one sweep, however after averaging over 100 sweeps the signal is detected as shown in Fig. 5. The data are fitted by a least-squire method. The standard deviation of the residual is 3.0×10^{-4}. Thus it can be noted that the minimum detectable absorbance of this CEAS measurement is 3.0×10^{-4} using Eq. (3).

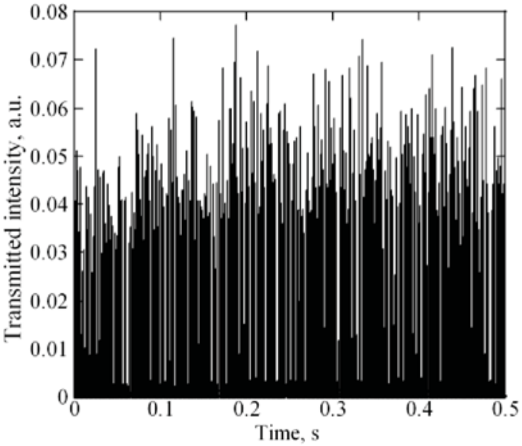

Figure 4 Transmitted intensity of CEAS for one sweep.

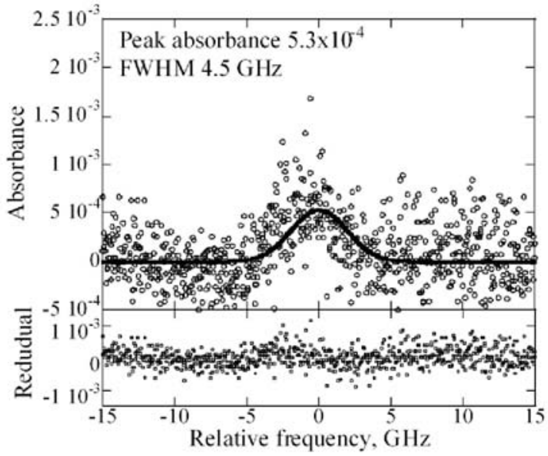

Figure 5 Absorbance profile obtained by CEAS with a fitting line and the residual.

And the ring-down signal with a fitting line is shown in Fig. 6. The ring-down signal is well fitted by Eq. (4). After averaging over 200 sweeps, the absorbance profile is obtained and fitted by a least-squire method as shown in Fig. 7.

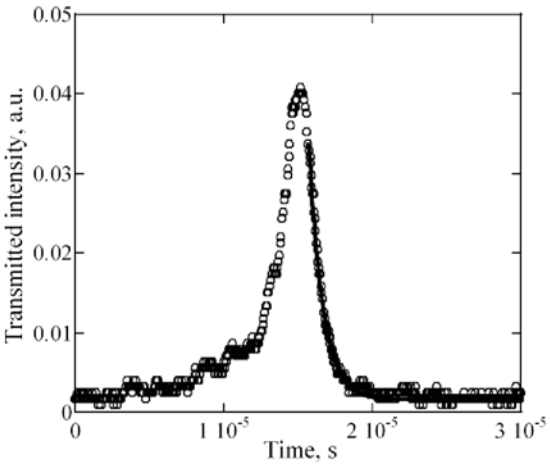

Figure 6 Ring-down signal with a fitting line.

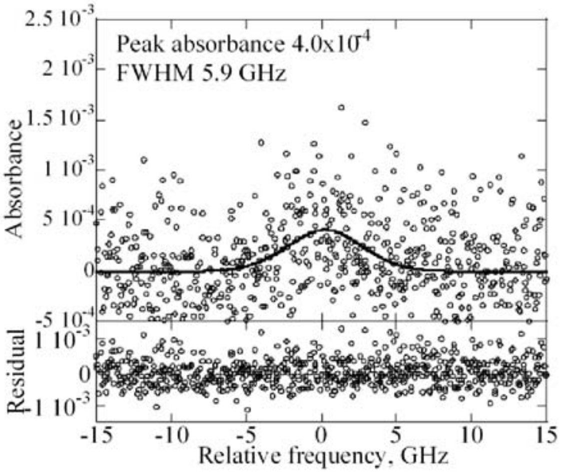

Figure 7 Absorbance profile obtained by CRDS with a fitting line and the residual.

From the fitted profile the translational temperature and number density are deduced as shown in Table 2. Here the distribution of the properties assumed to be uniform. The difference of the Doppler broadening between CEAS and CRDS leads to a large deviation of the translational temperature, and it is necessary to figure out the reason of this discrepancy.

Table 2   Physical properties deduced by the CEAS and CRDS measurements.

	Translational temperature, K	Number density, m^{-3}
CEAS	4300	5.1×10^{13}
CRDS	7400	5.2×10^{13}

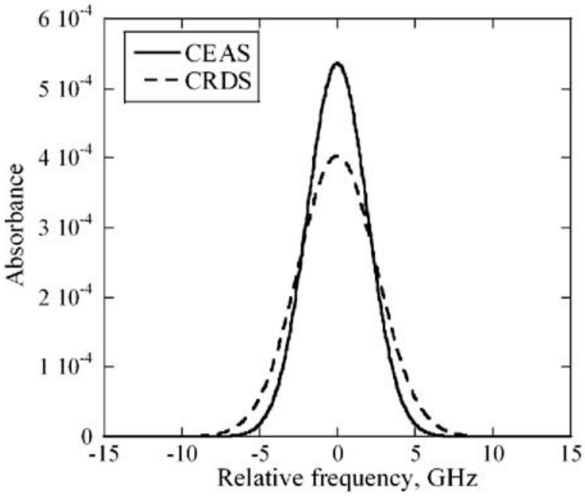

Figure 8 Fitted absorbance profiles of CEAS and CRDS.

Figure 8 shows the Gaussian profiles fitted to the experimental data of CEAS and CRDS by a least-squire method. Near the center of the profile the absorbance obtained by CRDS is lower than that of CEAS. At the center frequency the absorbance of CRDS is 75 % of that of CEAS. And the full width at half maximum (FWHM) of the profile obtained by CRDS is 1.3 times wider than that of CEAS. The reason for this disagreement is the saturation in the CRDS measurement. As discussed in Ref. 11, when the intensity of laser is high the measured absorption profile is wider than the true value as shown in Fig. 9. For the comparison of the laser energy of the CEAS and CRDS measurement the transmitted intensity profiles are calculated as shown in Fig. 10. In this calculation *R* =0.9935 and the laser is switched off at 80 % of the peak value of CEAS signal. In the CEAS measurement the absorbance is deduced from the peak intensity of each resonant signal and the energy which contributes to the absorption corresponds to the peak value which is indicated as a bold line in Fig. 10. In contrast in the CRDS measurement the energy stored in the cavity contributes to the absorption profile which is indicated as a shadow area in Fig. 10. Thus in the CRDS measurement the laser energy is larger than that of CEAS and the absorption profile obtained by CRDS is saturated.

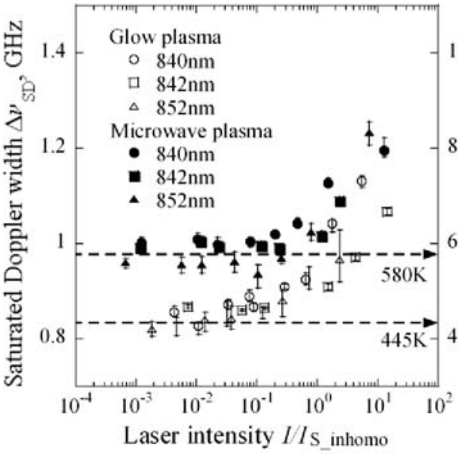

Figure 9 Relationship between absorption coefficient and laser intensity. (Details are described in Ref. 11.)

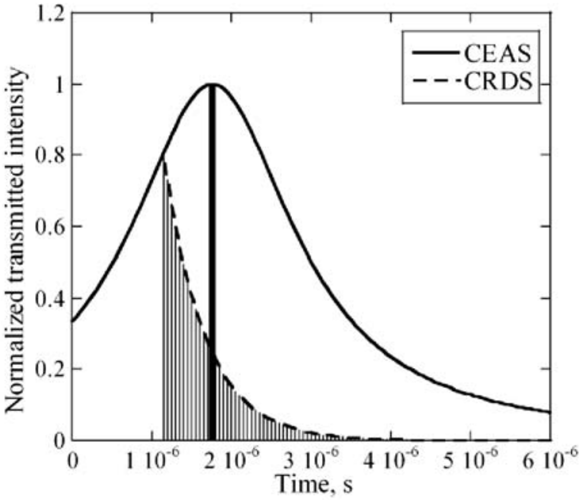

Figure 10 Relationship between absorption coefficient and laser intensity.

V. Conclusion

For the measurement of the arc heated wind tunnel flow the CEAS and CRDS have been applied at the vibratory environment to measure the atomic oxygen in the arc heated air plasma flow. By using the microwave discharge plasma as the OI reference cell the absorption was detected successfully. And the minimum detectable absorbance of this measurement system is estimated at 3.0×10^{-4}. At the peak of the profile the absorbance obtained by CRDS is 75 % of that of CEAS and FWHM of the profile obtained by CRDS is 1.3 times wider than that of CEAS which leads to a large deviation of the translational temperature. As a reason for this disagreement the saturation effect is considered and it is indicated that the saturation occurred in the CRDS measurement because at the CRDS measurement the energy stored in the cavity is higher than that of CEAS.

Acknowledgments

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References

[1]Fujita, K., Mizuno, M., Ishida, K., and Ito, T., “Spectroscopic Flow Evaluation in Inductively Coupled Plasma Wind Tunnel”, *Journal of Thermophysics and Heat Transfer*, Vol. 22, No. 4, 2008, pp. 685-694.

[2]Takayanagi, H., Mizono, M., Fujii, K., Suzuki, T., and Fujita, K., “Arc Heated Wind tunnel Flow Diagnostics using Laser-Induced Fluorescence of Atomic Species”, *47th Aerospace Science Meeting Including The New Horizons Forum and Aerospace Exposition*, AIAA 2009-1449.

[3]Fletcher, D.G., “Arcjet flow properties determined from laser-induced fluorescence of atomic nitrogen”, *Applied Optics*, Vol. 38, 1999, pp. 1850-1858.

[4]Grinstead, J., Driver, D., and Raiche, G., “Radial profiles of arcjet flow properties measured with laser-induced fluorescence of atomic nitrogen”, *41th Aerospace Science Meeting and Exhibit*, AIAA 2003-400, 2003, pp. 1-9.

[5]Matsui, M., Komurasaki, K., and Arakawa Y., “Laser Absorption Spectroscopy in High Enthalpy Flows”, *38th Thermophysics Conference*, AIAA Paper 05-5326, 2005, pp. 2060-2064.

[6]Kim, S., “Development of Tunable Diode Laser Absorption Sensors for A Large-Scale Arc-Heated-Plasma Wind Tunnel,” Doctor thesis, Stanford University, 2004.

[7] Mikhail, M., Andrew J. O., Robert P., and Grant A. D. R., "Cavity ring-down and cavity enhanced spectroscopy using diode lasers", *Annual Report Prog. Chem.*, *Section. C*, Vol. 101, 2005, pp. 100-142.

[8] Engeln, R., Berden, G., Peeters, R., and Meijer, G., "Cavity enhanced absorption and cavity enhanced magnetic rotation spectroscopy", *Review of Scientific Instruments*, Vol.69, No. 11, 1998, pp.3763-3769.

[9] Romanini, D., Kachanov, A., Sadeghi, N., and Stoeckel, F., "CW cavity ring down spectroscopy", *Chemical Physics Letters*, Vol. 264, 1997, pp.316-322.

[10] Takayanagi, H., Fujita, K., Nomura, S., and Komurasaki, K., "Influence of Mechanical Vibration on Cavity Enhanced Absorption Spectroscopy", *27th Aerodynamic Measurement and Ground Testing Conference*, AIAA 2010-4912, 2010, pp. 1-10.

[11] Matsui, M., Komurasaki, K., Ogawa, S., and Arakawa, Y., "Influence of laser intensity on absorption line broadening in laser absorption spectroscopy", *Journal of Applied Physics*, Vol. 100, 2006.