Arc Heated Wind Tunnel Flow Diagnostics using Laser-Induced Fluorescence of Atomic Species

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Two-photon Laser induced fluorescence diagnostics system for atomic oxygen has been installed at the 750kW arc heated wind tunnel in JAXA in order to obtain velocity, translational temperature, and number density of atomic oxygen simultaneously. It was observed that the center of excitation wavelength is shifted in the shock layer. The Doppler shift due to the free stream velocity has a same order effect on the excitation wavelength. The translational temperature distribution was deduced from spectral broadening and the absolute atomic number density was obtained with a calibration technique by a reference xenon gas cell.

Nomenclature

\( a \) = effective branching ratio of the observed fluorescence transition
\( A_p \) = cross sectional area of laser beam
\( c \) = velocity of light, m/s
\( E_p \) = laser pulse energy, J
\( F(t) \) = normalized temporal profile of laser pulse
\( h \) = Planck’s constant, J·s
\( I \) = electric current, A
\( K_L \) = laser calibration constant
\( K_J \) = spectroscopic calibration constant
\( K_G \) = geometric calibration constant
\( m \) = mass flow rate, kg/s
\( M_A \) = atomic mass, kg
\( N_A \) = Avogadro’s constant
\( N_1 \) = number density of atomic oxygen, m\(^{-3}\)
\( p \) = pressure, Pa
\( R \) = gas constant, J/K·mol
\( S \) = spectrally integrated fluorescence signal
\( T \) = transmittance of optics
\( T_T \) = translational temperature, K
\( v \) = velocity of flow, m/s
\( V \) = volume of imaged region, m\(^3\)
\( \Phi \) = quantum yield
\( \eta_d \) = detector spectral efficiency and gain
\( \lambda_0 \) = center excitation wavelength, nm
\( \Delta \lambda_D \) = Doppler width, nm
\( \Delta \lambda_e \) = full width at half maximum in the excitation profile, nm
\( \Delta \lambda_{\text{laser}} \) = laser line width, nm
\( \rho \) = two photon absorption cross section

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When the spacecraft enters the atmosphere 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. In these facilities, arc heated wind tunnel has served as a source of long-duration, high enthalpy flow. 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. For that reason, various kinds of measurements have been proposed [4].

In our facility, emission spectroscopy has been applied by Fujita, K., et al [5]. Radial distributions of the temperature and the species concentration were obtained in the free stream of a 110-kW inductively coupled plasma heater by the numerical spectrum fitting procedure. However, the temperature and the species concentration in the free stream generated by arc heated wind tunnel could not be estimated because of the strong non-thermo-chemical equilibrium. In addition, axial symmetry was assumed in order to calculate the distribution of the temperature and number density.

Laser-induced fluorescence is an optical diagnostics method that yields space and time resolved populations, in particular of atomic ground states in plasma [6]. LIF has been demonstrated in high enthalpy arcjet facilities at NASA Ames Research Center [7] and inductively heated plasma at Stuttgart University [8].

This paper presents a set of flow property measurements obtained from the application of a laser-spectroscopic instrument to the free-stream flow and the shock-layer flow around the specimen in the 750kW arc heated wind tunnel in JAXA. The measurements were made in three conditions in an air flow. Translational temperature distribution is deduced from the spectral broadening. With noble gas reference cells, the relative fluorescence signal intensity is calibrated and absolute number density of atomic oxygen is obtained.

II. Theory

A. Two-photon Laser Induced Fluorescence of atomic oxygen and nitrogen

The relevant energy level for atomic oxygen is shown in Fig.1. Oxygen atoms are excited via the $2p^4 \quad ^3P_{2,1,0} \rightarrow 3p \quad ^3P_{1,2,0}$ two-photon transition at 225.6nm and detected using the $3p^4 \quad ^3P_{1,2,0} \rightarrow 3s \quad ^3S$ fluorescence transition at 844.6nm. Ground-state atoms are excited resonantly into a higher electric state. The problem of reabsorption is usually absent in two-photon LIF because the fluorescence occurs o an intermediate state due to the selection rules.

B. Flow Velocity

Provided that there is no collisional shift in the arcjet flow, the flow velocity in the arcjet free stream is measured from the Doppler shift $\delta\nu$ of the two photon absorption line resonance frequency from static conditions:

$$v = \frac{\Delta \nu_0}{c} \cos \theta.$$  

(1)

C. Translational temperatures

The basic procedure for extracting translational temperatures from observed lineshapes for two-photon transitions was described by Marx and Allen [9]. The width of the resulting spectrum in absolute frequency is given by the following expression:

$$\Delta \nu_c = \sqrt{\Delta \nu_{laser}^2 + \Delta \nu_{1\nu}^2}.$$  

(2)
Here, $\Delta \nu_L$, $\Delta \nu_{\text{line}}$ and $\Delta \nu_D$ are the total linewidth of the observed profile, the laser linewidth and the Doppler width, respectively. The Doppler width is related to the translational temperature, $T_{\text{tr}}$, by the following expression:

$$
\Delta \lambda_D = \frac{2 \ln 2 \lambda_0}{c} \sqrt{\frac{2k_B T_{\text{tr}}}{M_A}}.
$$  \hspace{1cm} (3)

**D. Absolute atomic number density**

The fluorescence signal spectrally integrated over the excitation lineshape is proportional to the atomic number density, which is written as follows [10]:

$$
S = K_o K_j K_L \cdot N_i \phi \left( \frac{E_p}{h \nu L} \right)^2.
$$  \hspace{1cm} (4)

Here $K_o$, $K_j$, and $K_L$ are three calibration or proportionality constants, which are written as follows:

$$
K_o = \frac{\Delta \Omega}{4\pi} V,
$$

$$
K_j = T \eta_1 \sigma_{12}^{(2)} a.
$$

$$
K_L = \frac{1}{A^2_p} \int_0^\nu F^2(t) dt.
$$  \hspace{1cm} (5)

Some researchers made additional measurements in order to convert the integral signal values to absolute atom number density by quantification of the temporal and spatial characteristics of the laser pulse and the signal collection efficiency, and measured values of the absolute two-photon excitation cross section for the transition and of the second order coherence factor for the laser used in these experiments [11]. The uncertainties in these quantities, particularly the two photon absorption cross section and laser temporal and spatial characteristics introduce the largest sources of error in measurements of the absolute number density. Recently, the calibration method using noble gas such as xenon has been applied [12]. The idea is that the experimental setup is calibrated by measuring a known number density using a two-photon excitation of a rare gas with an excitation wavelength nearby the one of atomic oxygen shown in Fig. 1. The two-photon resonances of atomic oxygen have corresponding transitions in xenon as also shown in Fig. 1. A prerequisite for its applicability is that two-photon LIF excitations are performed with identical spatial, spectral, and temporal intensity distribution of the laser radiation. Thus, the temporal, spatial, and spectral properties can be constant for both measurements as long as the excitation is not influenced by saturation. Therefore, the number density of atomic oxygen is expressed as follows:

$$
N_i(O) = \frac{K_j(Xe) S(O)}{K_j(O) S(Xe)} N_i(Xe).
$$  \hspace{1cm} (6)

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![Energy level diagrams for the two-photon LIF process in a) oxygen and b) xenon](image-url)
III. Experimental Setup

A. Measurement system

The flow property measurements described in this paper are derived from measurements of fluorescence signals induced by two-photon excitation of atomic oxygen. A schematic diagram of the measurement system for LIF is illustrated in Fig. 3. A tunable dye laser (ScanMate 2E, Lambda Physics) pumped with a third harmonic (355nm) of a Nd:YAG laser (Spectra-Physics Quanta-Ray LAB 170-10) was used as a laser oscillator. A Coumarin 47 dissolved in methanol was used as the dye. The target wavelength was obtained on the basis of frequency mixing in a nonlinear optical crystal. Two dielectric mirrors were used to direct the beam through a quartz window and down the centerline of the flow field. When the appropriate test conditions were attained during the arcjet experiments, the excitation wavelength from the dye laser was scanned through the atomic oxygen absorption transition near 225nm, and the fluorescence signal was recorded as a function of wavelength by an intensified CCD camera (1280 x 1024 array with 6.7mm pixels, LaVision Nanostar camera), coupled to a NIR Nikon lens (105mm, f/1.8). The precise wavelength from the dye laser was measured by wavemeter. In order to eliminate the emission from the plasma flows, a band pass filters was inserted in front of the ICCD camera. The laser pulse and the camera exposure were synchronized with each other by a Programmable Timing Unit. 50 photos were summed at each wavelength for improving the signal to noise ratio. The captured data was transferred to the computer via fiber optic link. A quartz window in order to detect the fluorescence signals was located as the chamber window. The excitation rate scales with the square of the laser intensity in the case of two-photon absorption from a single beam. The laser intensity is measured by the Energy Monitor.

B. 750kW Arc wind tunnel

The experiment has been conducted in the 750kW arc heated wind tunnel located in IAT-JAXA (Institute of Aerospace Technology, Japan Aerospace Exploration Agency). This wind tunnel consists of a constricted-arc heater, a conical nozzle with the throat diameter of 25mm, and a test chamber. Its nominal Mach number at nozzle exit is 4.8. Within the nozzle, the decrease in density during the expansion causes the collision frequency to decrease rapidly and the flow departs from thermochemical equilibrium. The wind tunnel conditions are controlled by the applied electric current and total mass flow rate. Test durations of up to 30 minutes are possible, depending on the
particular conditions. During the tests, the chamber pressure, cabin pressure, and arc conditions are continuously monitored. Stagnation-point heating measurements are typically performed before and after the tests by a water-cooled calorimeter. Three flow conditions, $\dot{m}=10\,\text{g/s}, I=700\,\text{A}$, $\dot{m}=10\,\text{g/s}, I=300\,\text{A}$, $\dot{m}=20\,\text{g/s}, I=300\,\text{A}$, were made in this experiments.

C. Calibration on number density of atomic oxygen

In order to quantify the relative signals, the reference fluorescence signal from xenon noble gas was measured under several pressures. The two-photon LIF-measurements on xenon have been performed without changing the experimental setup at the arc heated wind tunnel. In order to have a well defined amount of xenon at the measurement location, a cold gas cell has been installed into the vacuum chamber.

IV. Result and Discussion

In order to calibrate the relative number density of atomic oxygen, the xenon fluorescence signals were first measured at several pressures. An example fluorescence profile at each pressure is shown in Fig.3. The solid lines are fitting line by Gaussian profile.

When the temperature of the xenon was assumed to be same as room temperature, 300K, and the broadening is affected only by the Doppler Effect, integrated fluorescence signal at each pressure was obtained as shown in Fig. 8. Here, the number density at each pressure was obtained by the ideal gas equation;

$$N_i = \frac{\rho N_x}{RT} \quad \text{(7)}$$

The ideal ratio of the fluorescence signal to the number density is constant to the cell pressure. However, in this experiment, the ratio was large under low pressure and it was low under high pressure. It would be affected by laser intensity, quenching, and so on. We have not yet identified these reasons. Since in this experiment, the ratio was almost same under 200 Pa and 500 Pa, the fluorescence signal under 200 Pa was used for calibration of the relative number density of atomic oxygen.

![Fluorescence signal of xenon at each pressure](image_url)
Second, the fluorescence signals from the atomic oxygen in the arc heated wind tunnel flow were measured. Example photos of LIF signals from atomic oxygen at several wavelengths ($\dot{m} = 10\,\text{g/s}, I = 700\,\text{A})$ are shown in Fig. 5. From these photos, fluorescence profile from two-photon LIF of atomic oxygen in the arc heated wind tunnel flow at each distance from the specimen was obtained as shown in Fig. 6.

Since the laser beam is incident at the angle of 50 degrees to the free stream axis, the center wavelength is shifted at approximately smaller than 7.5mm, where is included in the shock layer. From Eq. (1), the flow velocity difference in the free stream and the shock layer was estimated as follows:

$$\delta v = 3.6 \pm 0.4\,\text{km/s},$$

Sakai, et al. calculated the flow velocity in the free stream by ARCFLO3 code as follows [13]:

$$\delta v = 4.6\,\text{km/s}.$$  \hspace{1cm} (9)

Within the shock layer, the flow velocity would not be static absolutely and its direction would not be vertical to the specimen. As a result, the flow velocity obtained by the Doppler shift would be smaller than that by the simulation. In order to obtain the accurate flow velocity, a static cell of low pressure isotopic nitric oxide, N$^{15}$O, should be used. Nitric oxide is a useful wavelength reference molecule in the ultraviolet, and the isotopic form is used in this application to obtain a closer overlap between the N$^{15}$O and atomic transitions [14].

As mentioned in Eq. (2), the laser broadening at each measurement should be estimated in order to calculate the translational temperature. It was obtained by the wavemeter, while the value was overestimated and the Doppler broadening was estimated as negative value. Therefore, in this analysis, the laser broadening was estimated so that the maximum translational temperature is 1,500 K and the minimum one is 500 K. In this case, the translational temperature distribution was obtained as shown in Fig.7. The calculated translational temperature by Sakai et al. is also shown in this figure. These results have large difference. Moreover, the shock distance was also different between them.

Fig.4 Ratio of the Fluorescence signal intensity to the number density of xenon at each pressure

![Graph showing the ratio of fluorescence signal intensity to xenon number density at different pressures.](image-url)
Fig. 5 Example photos of the LIF signals from atomic oxygen at several wavelengths ($m = 10\text{g/s}$, $I = 700\text{A}$)

(a) $\lambda = 225.65\text{nm}$

(b) $\lambda = 225.6535\text{nm}$

(c) $\lambda = 225.6555\text{nm}$

(d) $\lambda = 225.6595\text{nm}$
Comparing with the reference signal from the xenon, the number density distributions of atomic oxygen in the arc heated wind tunnel flow at $\dot{m} = 10\,\text{g/s}$, $I = 700\,\text{A}$ were obtained as shown in Fig.6. The simulated distribution by Sakai, T., et al. at same condition is also shown in this figure. Each integrated fluorescence signal was calculated by the estimated laser broadening. The error bar shows the differences due to the laser broadening. From this figure, it was found that the laser broadening has little influence on the number density measurement. The experimental results were of the same order of magnitude as the simulated result.

Fig.6 Example profile from two-photon LIF of atomic oxygen in the arc heated wind tunnel free stream at each distance from the specimen ($\dot{m} = 10\,\text{g/s}$, $I = 700\,\text{A}$)

Fig.7 Translational temperature distribution in the arc heated wind tunnel ($\dot{m} = 10\,\text{g/s}$, $I = 700\,\text{A}$): each point shows the experimental results and solid line shows the calculated one

Comparing with the reference signal from the xenon, the number density distributions of atomic oxygen in the arc heated wind tunnel flow at $\dot{m} = 10\,\text{g/s}$, $I = 700\,\text{A}$ were obtained as shown in Fig.6. The simulated distribution by Sakai, T., et al. at same condition is also shown in this figure. Each integrated fluorescence signal was calculated by the estimated laser broadening. The error bar shows the differences due to the laser broadening. From this figure, it was found that the laser broadening has little influence on the number density measurement. The experimental results were of the same order of magnitude as the simulated result.
In the same way, the number density distributions of atomic oxygen at the other conditions were obtained as shown in Fig. 9. In these enthalpy regions, almost all of oxygen are dissociated. Therefore, the number density of atomic oxygen is constant when the mass flow rate is constant. In a similar manner, the number density becomes two times larger when the mass flow rate is two times larger.

Fig. 8 Number density of atomic oxygen in the arc heated wind tunnel ($\dot{m} = 10\text{g/s}, I = 700\text{A}$): each point shows the experimental results and solid line shows the calculated one.

Fig. 9 Number density distribution of atomic oxygen in the arc heated wind tunnel at several flow conditions.
V. Conclusion

i. Laser induced fluorescence diagnosis system for atomic oxygen has been installed to the 750 kW arc heated wind tunnel in JAXA.

ii. The shift of center wavelength in the free stream compared with that in the shock layer was about 3.6 km/s. This value is smaller than the simulated value. The reason would be because the velocity in the shock layer is not zero perfectly.

iii. The laser broadening has large influence on the translational temperature. In this experiment, the laser broadening was estimated so that the translational temperature was the range from 500 K to 1500 K.

iv. The number density of atomic oxygen in the arc heated wind tunnel was deduced with the xenon gas cell. The estimated value was same order of magnitude as the simulated one.

References


