AIAA 97 - 3358

Diode-Laser Absorption Methods for Diagnosis of Arcjet Plasma

F. Y. Zhang, T. Iida, K. Komurasaki and
T. Fujiwara

School of Engineering
Nagoya University
Nagoya 464-01, JAPAN

33rd AIAA/ASME/SAE/ASEEJoint Propulsion Conference & Exhibit
July 6 - 9, 1997 / Seattle, WA

DIODE-LASER ABSORPTION METHODS FOR DIAGNOSIS OF ARCJET PLASMA

F. Y. Zhang[1], T. Iida[2], K. Komurasaki[3] and T. Fujiwara[4]

Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-01, JAPAN

Abstract

Diode-laser absorption technique is introduced to measure plasma plume parameters in a 4 kw argon arcjet thruster. Intensities of an incident laser beam and three transmissions through an argon discharge tube, a Fabry-Perot etalon and the arcjet exhaust plasma flow are simultaneously recorded with a digital oscilloscope. The flow velocity is derived from Doppler shift and the temperature was determined based on the full width at half maximum(FWHM) of plume absorption profile. The measured velocities and temperatures of plumes are ranged from 640m/s to 2310m/s and from 1188 K to 6144 K.

Introduction

Laser spectroscopy techniques have recently been developed to provide fast, sensitive, and nonintrusive means of measuring flow parameters in supersonic combustion and hypersonic flows.[1-9] The recent progress of semiconductor diode lasers, which are operable at the wavelengths in the range of 650-1550 nm at room temperature, and in particular, their power, reliability, and large spectral coverage, have been of great importance for a continuously increasing use in both pure and applied spectroscopy among these methods because diode-lasers are compact, rugged, cost effective, simple to operate and compatible with the laser optical fiber transmission. This nonintrusive spectroscopic technique, which is realized by a careful line-shape analysis, provide a powerful tool for the general control of amplitude and frequency stability in the frame of highly sensitive spectroscopy. The wavelengths of diode-laser beam can be easily tuned by controlling the laser working temperature and injection current, and the fast changing rate of injection current makes it possible to measure the unsteady flow with high temporal resolution up to the order of hundred KHz.[9] Meanwhile, the ability to focus the probe laser into the specific location allows the measurements with high spatial resolution. It is likely to provide basic and important information on molecular spectral features of interest and has been shown that the temperature and species concentration may be determined simultaneously by a spectral scanning of a single, isolated spectral line without verifying equilibrium between electronic, vibrational and rotational temperatures.[7]

The purpose of this paper is to investigate the applicability of this technique to the diagnosis of a plasma plume exhausted by a 4 kw-class arcjet thruster with argon propellent. Diagnostics of the plume by determining the conditions of the flow field can lead to a better understanding of the plasma dynamics. Since the flow velocity and temperature correlate with the arcjet thrust and plume enthalpy, the present study is focused on the measurement of the plume velocity and temperature. The probe laser is focused to a small diameter in the arcjet plume. The subsequent transimision is collected and imaged onto a photo diode detector. The flow properties are derived from the behavior of the absorption signals as a function of the laser frequency.

The velocity is determined from the Doppler shift between the absorption profiles of the argon discharge tube and the plume flow. The temperature is determined from the transition full width at half height maximum of the absorption profile through the plume.

Diagnostic theory

The laser absorption formula is well established and is characterized by the Beer-Lambert law as,[1]

$$\Delta I/I_0 = 1 - exp(-1013.25\kappa_\nu P_{abs} L) \quad (1)$$

where ΔI is the absorbed laser intensity, I_0 is the incident laser intensity, P_{abs} is the partial pressure of the absorbing species, L is the path length, κ_ν is the absorption coefficient which is effectively described as:

$$\kappa_\nu = 1.10 \times 10^{-21}\left(\frac{\pi e^2}{mc^2}\right)\left(\frac{2.73 \times 10^{-4} N_L}{T}\right) f_B f \Phi(\nu) \quad (2)$$

where e and m are the charge and mass of the electron, respectively. N_L is the Loschmidt number (m^{-3}) and T is the temperature. f_B is the Boltzmann fraction of the absorbing level. f is the transition

---

[1] Corresponding author, Graduate student, Dept of microsystem eng, Email: zhang@micro.nuae.nagoya-u.ac.jp
[2] Research assistant, Dept of Aerospace Eng, member AIAA [3] Assistant professor, Dept of Aerospace Eng, member AIAA
[4] Professor, Dept of Aerospace Eng, Dept of Microsystem Eng, member AIAA

where *e* and *m* are the charge and mass of the electron, respectively. N_L is the Loschmidt number (m^{-3}) and *T* is the temperature. f_B is the Boltzmann fraction of the absorbing level. *f* is the transition oscillator strength, and $\Phi(\nu)$ is the line shape function.

The velocity and temperature measurement of the plasma flow are based on exploiting the Doppler shift, $\Delta\nu$ and Doppler half-width, $\Delta\nu_D$, respectively. The strategy to measure Doppler shift usually consists of a simultaneous recording of the absorption profiles at different angles with the flow. The accuracy of the Doppler-based velocity measurements depends on a Doppler-shift-to-linewidth ratio, and a signal-to-noise ratio of the absorption. Although a perpendicular and a oblique laser beam to the flow are generally chosen in the velocity measurement, the transmission beam through an argon discharge-tube was used here to set the relative zero point of Doppler shift to simplify the test. The Doppler shift, $\Delta\nu$ is determined from the relative frequency shift between the absorption profiles of the argon discharge tube and the plume flow. The angle of the oblique laser beam direction with respect to the gas flow, ϕ is defined as shown in Fig. 1. The flow velocity, *V* can be derived from the following equation:

$$V = \frac{\Delta\nu\, c}{\nu_0 \cos\phi} \qquad (3)$$

where *c* is the speed of the light, ν_0 is the absorption center frequency.[1]

The temperature is determined from the broadening feature of the plume absorption profile. Generally the shape of the absorption profile is assumed to be the Vogit profile which contains Lorenz broadening and Doppler broadening. In the case with high enthalpy flow at low background pressure, predominant broadening mechanism is the Doppler broadening. [3][7] Therefore the absorption profile can be simplified at the thermodynamic equilibrium as the following function:

$$g_D(\nu) = \frac{2}{\Delta\nu_D}\sqrt{\frac{\ln 2}{\pi}}\exp\left(-4\ln 2\frac{(\nu-\nu_0)^2}{\Delta\nu_D^2}\right) \qquad (4)$$

where $g_D(\nu)$ is referred to as the Doppler line shape function, $\Delta\nu_D$ is the transitional full width at half maximum(FWHM), or Doppler half width given by:

$$\Delta\nu_D = \frac{2\nu_0}{c}\sqrt{\frac{2\ln 2\,\kappa T}{m}} \qquad (5)$$

where κ is Boltzmann's constant, m is the atom mass, T is the translational temperature.

Diode-laser Absorption Spectroscopy System

The experimental setup for the measurements is presented in Fig. 1. A diode(LT017MDO, SHARP Corp.) is used as a laser source. It is attached to a small Cu block to keep in thermal contact with a temperature controller in which a film heater, a Berthier cooler and a sensing thermistor are bonded, the collimating lens is set on a adjustable block. An active electronic feedback control by a ALP-7033CA LD Driver(ASAHI Datasystems Corp.) is used to set the laser beam power and stabilize the temperature of the diode laser within 0.01 K. The tunable wavelength is from 790 nm to 830 nm. At a driving current of 65 mA at 25°C, the diode laser nominally provide an output power of 40 mW/cm^2 at a wavelength of 810 nm. The diode-laser is driven by a low noise current source (Model 7316, KIKUSUI Electronics Corp.) and laser current is modulated with a Sub-Audio Generator AG-212 (SANWA Radio Measurement Corp.).

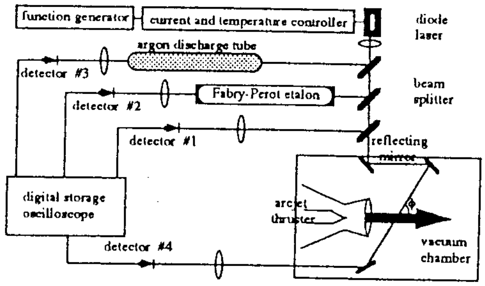

Fig. 1 Experimental schematic for arcget plasma measurement with a diode-laser absorption techique

The output of the diode-laser is splitted into four components. The first component is directly recorded with a photo-diode detector #1 as a function of time. The second passes through an argon discharge-tube, in which steady discharge is maintained in a low pressure argon cell mounted in a microwave cavity. The transmission signal is detected by #2 to give the reference peak of absorption. The third component passes through a Fabry-Perot(FP) etalon, and the signal is detected by #3 to provide a reference measurement of the change in relative wavelength during the scanning of laser-oscillation frequency. Rest of the laser beam passes through the argon plume generated by the arcjet. The transmission signal is recorded by detector #4.

During the measurement, the laser was modulated with a triangular function at a rate of 50 Hz superimposed on a current 70 mA. The diode temperature was maintained at 26.30 °C. The laser-wavelength was swept from 810.50 nm to 812.06 nm around Ar I absorption line of 811.531 nm. The TPS-708 photo diodes (TOSHIBA Electronics Cor.), which have high sensitivity at the wavelength of about 810 nm, are used as detectors, and these signals are simultaneously recorded with a DL1540 Yokogawa 4-channel digital oscilloscope.

Arcjet Thruster

The plasma flow is generated by heating a propellant gas up to several eV with the electric energy in a arcjet thruster. In the arcjet thruster, the arc extends from a cathode tip through a throat and attaches diffusely to a nozzle-anode in a low pressure diverging section. Ionization reaction, followed by large expansion, contributes to nonequillibrium conditions at the exit plane, and makes it difficult to analyze the gasflow dynamics of arcjet plume.

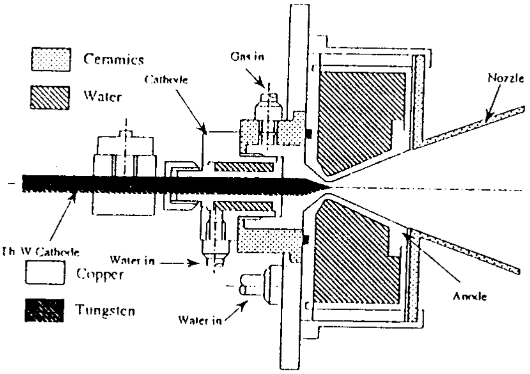

Fig. 2. A cross-section view of the arcjet thruster.

Figure 2 shows the cross-section of the arcjet thruster used in this study. It consists of a tungsten cathode, a water-cooled copper anode and a expansion nozzle. The cathode, made of the thoriated tungsten, has a diameter of 5 mm, a length of 120 mm, and a half tip angle of 30 degree. It is located in a stagnation plenum in the converging section of the anode. The anode has a 3 mm long constrictor channel with a diameter of 2 mm. An extended nozzle is made of ceramics. Its diverging angle is 25 degree, and its exit plane diameter is 52 mm.

The arcjet thruster is installed in a 1.2 m in diameter and 1.5 m long cylindrical stainless-steel vacuum chamber, which is evacuated at 10,000 l/s by a pumping system consisting of two diffusion pumps, a roots blower and a rotary pump. 0.3 Torr background pressure is maintained during the operation. Argon gas flow is regulated by a thermal massflow controller.

Results and Discussion

A total of 60 cases of measurements are performed at the flow rate ranging from 0.06 g/s to 0.30 g/s and the discharge current ranging from 100 A to 180 A. They are conducted at the different distance from the exit plane ranging from 7 cm to 45 cm . The laser beam was probed into the flow with the angle $\phi=60°$. In this case, with knowledge of laser beam wavelength, $\lambda_0=811.531$ nm, the Doppler shift, $\Delta\nu$ is directly related to the velocity, V by the following relation:

$$V(m/s) = 1623.0\ \Delta\nu(GHz) \qquad (5)$$

The translational temperature,T can be determined from the full width at half maximum (FWHM), $\Delta\nu_D$ by the following relation:

$$T(K) = 570.91\ \left[\Delta\nu_D(GHz)\right]^2 \qquad (6)$$

Figure 3 shows the typical experimental

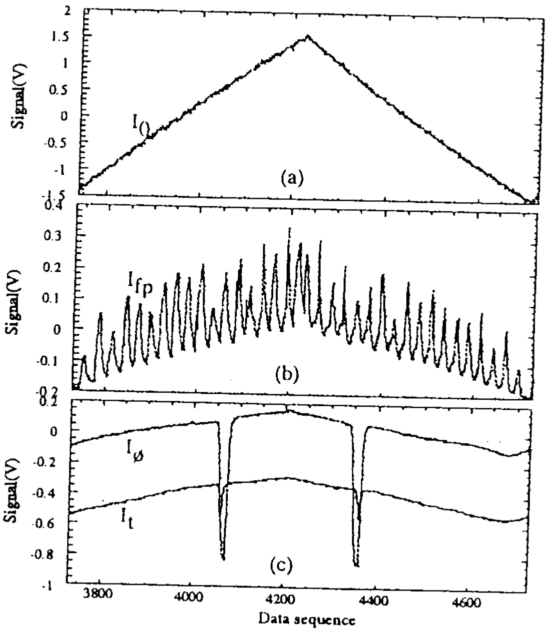

Fig. 3. Typical experimental record in the digital oscilloscope at a distance,7 cm with a massflow rate, 0.12 g/s and a input power, 3.6 kw. (a) temporal variation incident laser intensity, I0. (b) Fabry-Perot(FP) etalon signal, Ifp. (c) transmission signals through the arcjet plume, Iø and the argon discharge-tube, It.

records. Each recorded trace consists of 10,030 data points at an interval about 0.02μs. Fig. 3(a) is the temporal variation of incident laser intensity, I_0 and 3(b) shows a record of the FP etalon transmission signal, I_{fp}, which contains forty fringes. The temporal spacing of the fringes is not constant due to the unsymmetric characteristic of the reference intensity of the diode-laser in both ascending and descending ramps. In Fig. 3(c), the upper trace displays the transmission profile of the oblique probe laser beam, I_ϕ, and the lower trace records the transmission signal through the argon discharge tube, I_t.

The first step in the analysis of recorded absorption signals is to convert its time base into an optical frequency scale by the comparison of frequency spacing with FP etalon fringes. As described above because of the unsymmetric and nonlinear characteristic of the reference intensity of the diode-laser, the peak of FP etalon fringes is not equidistant in time. A direct fit was made to determine their peak positions as shown in Fig 4. The residual between the measured and fitted data is very small.

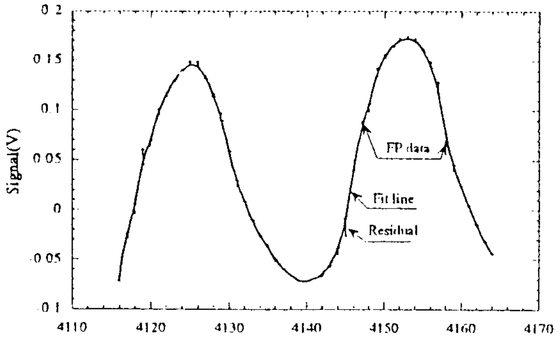

Fig. 4. FP data and residuals with direct fit

Figure 5 shows the absorption profiles. The absorption profiles are obtained from the differences between the incident laser signal and the transmission signals, I_0-I_t and I_0-I_σ respectively. As previously stated, the predominant broadening mechanism of absorption is Doppler broadening. Therefore, a three-parameter gaussian line shape fit was made on the laser absorption profiles to determine the peak positions, maximum intensities and to derive the transition full widths at half maximum(FWHM) of the Doppler broadening and the Doppler shift. The fittings were based on the software of KaleidaGraph. The reduced profiles were also shown in Fig. 5.

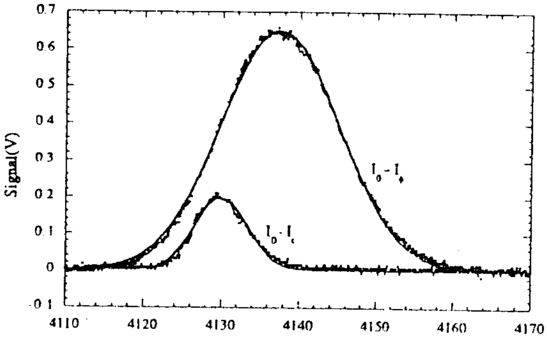

Fig. 5. Absorption profiles and Gaussian fits with a flow rate, 0.12 g/s and a input power,3.6 kw. Top trace shows plasma plume absorption fitted profile,bottom trace shows argon discharge tube absorption fitted profile

With the determination of features both the shifted and unshifted absorption profiles, the time-base reduced profiles can be converted into the frequency-base ones by the comparison of frequency spacing with FP etalon fringes. The Doppler shift, $\Delta\nu$ between the profiles and FWHM, $\Delta\nu_D$ of plume absorption profile can be derived as shown in Fig. 6. The velocity, V and temperature, T are derived respectively from Eq. (5) and from Eq. (6).

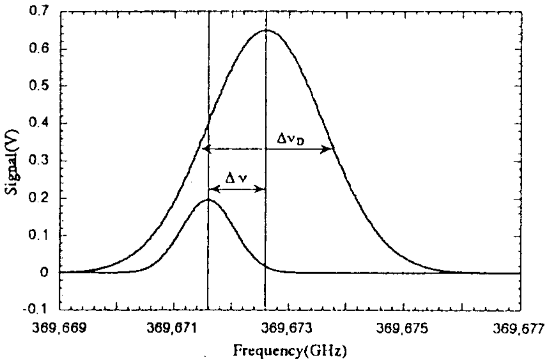

Fig. 6. Doppler shift between absorption profiles and full width(FWHM) of half maxium of plume absorption profile from Fig. 4 and Fig. 5.

Figures 7 and 8 show the plume velocity and

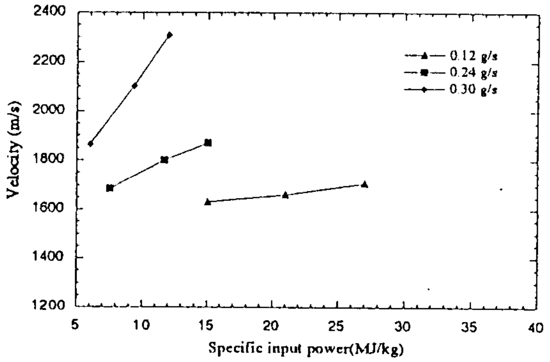

Fig. 7. Plume velocity characteristics for various operation condition at a distance, 7 cm

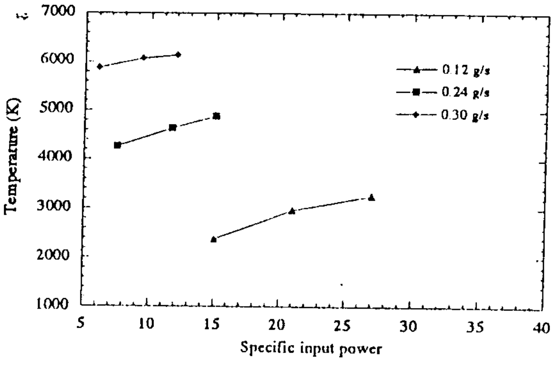

Fig. 8. Plume temperature characteristics for various operation conditions at a distance, 7 cm

temperature characteristics for various operating conditions at the location, 7cm from the nozzle exit. The velocity and temperature increased with the specific input power and the massflow rate. In addition, high velocity and temperature are marked at a large massflow rate. This is interpreted as a phenomenon that the heat flux to the anode from the gas flow is reduced as massflow rate is increased, as it has been shown that the anode temperature increased with the decrease in massflow rate at a fixed specific input power.[11][12] Note that the rate of increase in velocity at a low massflow rate is smaller than that at a high massflow rate. This is because the chamber pressure causes a relatively large velocity decrease at a low massflow rate as described later.[5]

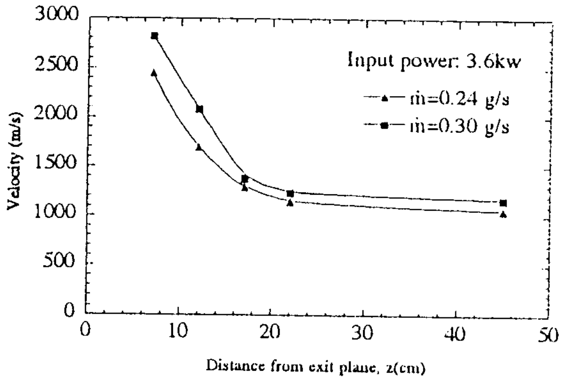

Fig. 9. Flow velocity profiles along the thruster centerline with an input power, 3.6 kw at different massflow rate.

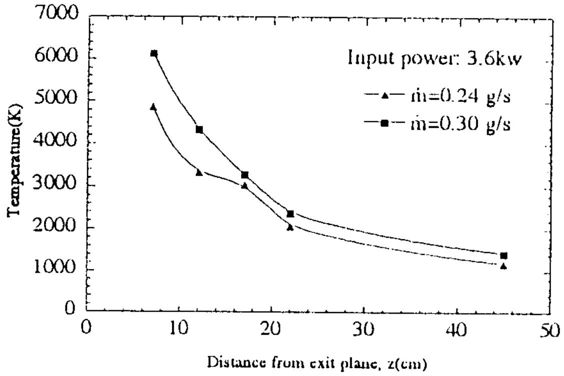

Fig. 10. Flow temperature profiles along the thruster centerline with an input power, 3.6 kw at different massflow rate.

Figures 9 and 10 show the velocity and temperature distribution along the thruster centerline. They decrease quickly near the exit plane. It is considered that the flow near the exit plane experiences a large moment and energy transfer between the arcjet plume and the entrained background gas.[3][10]

Figure 11 shows the photographs of the argon plume from the arcjet thruster. The shape and the brightness of the plasma plume changes with the input power and the propellent flow rate. In the case of low propellent flow rate, the plume length is almost constant for various input power. On the other hand, the plume length greatly increases with the propellent flow rate. It is consistent with the results obtained by the diode-laser absorption velocity measurement (shown in Fig. 7), because the plume length is considered to be proportional to the flow velocity if the fluorescence period is constant.

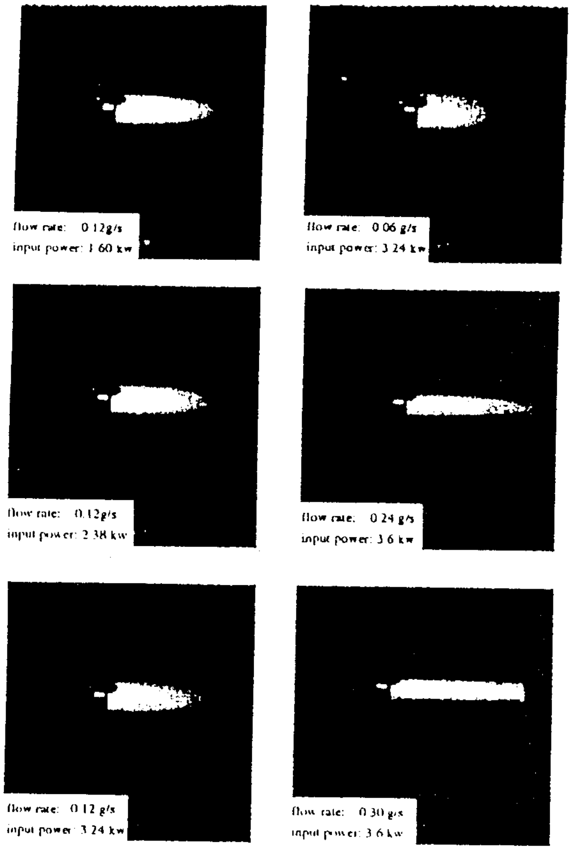

Fig. 11. Photographs of arcjet plume with argon propellent at different operating conditions.

Summary and Conclusion

The diode-laser absorption technique is introduced for the plume parameter measurement of argon plasma flow exhausted from a 4 kw-class arcjet thruster. The diode-laser wavelength was swept from 810.50 nm to 812.06 nm around the Ar I absorption line of 811.531 nm.

The velocity and temperature were derived from the Doppler shift between absorption profiles and the full width at half maximum of plume absorption profile. The velocity was ranged from

640m/s to 2310m/s while the temperature was from 1188 K to 6144 K. The results demonstrated the ability of diode-laser absorption technique for velocity measurement of the high velocity and temperature flow.

The plume velocity and temperature were increased with both propellent massflow rate and specific input power. In our test cases, the massflow rate had large effects on the exhausted plume parameters as much as the specific input power. Along the centerline of the plume, the velocity and temperature decrease dramatically near the exit plane due to the background gas entainment.

Acknowledgements

The authors are indebted to Prof. T. Yoshigawa, T. Endo, Dr. Joseph E. Leblanc, T. Kasahara and Mr. S. Cho and D. Kusamoto for valuable discussion and assistance during the research. We are grateful to Inoue Foundation for Science for supporting the presentation.

Reference

1. Arroyo, M.P., Langlogis, S. and Hanson, R.K.: Diode-laser absorption technique for simultaneous measurement of multiple gasdynamic parameters in high-speed flows containing water vapor , *Appl. Opt.* 33(1994), pp.3296-3370.

2. Eckbreth, A. C.: Laser diagnostics for combustion temperature and species(1987), pp. 137-300.

3. Liebeskind, J. G., Hanson, H. K. and Cappelli, M. A.: Laser-induced fluorescence diagnostic for temperature and velocity measurements in a hydrogen arcjet plume , *Appl. Opt.* 32(1993), pp. 6117-6227.

4. Tahara, H., Uda, N., Tsubakishita, Y. and Yoshikawa, T.: Optical measurement and numerical analysis of medium-power arcjet non-equilibrium flowfields, *Proceeding of 23rd AIAA/AIDAA /DGLR/JSASS International Electric Propulsion Conference*, IEPC-93-133, Seatle, WA, September, 1993.

5. Storm, P.V., and Cappelli M. A.: Axial Emission Measurement On a Medium Power Hydrogen Arcjet Thruster , AIAA Paper 94-2743, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June, 1994.

6. Gulczinski, F.S., King, L. B., Foster, J. E., Kim, S. W. And Gallimore, A. D.: Near and Far-field Plume Studies of a 1 KW Arcjet , AIAA Paper 94-3137, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June, 1994.

7. Luck, K.C., Thielen, W.: Measurement of Temperatures and OH-Concentrations in a lean Methane-Air Flame Using High-Resolution Laser-Absorption Spectroscopy. J. Quant. Spectrosc. Radiat. Transfer. Vol. 20. Pp71-79.

8. Miller, J. H., Elreedy, S., Ahvazi, B., Woldu, F., Hassanzadeh, P.: Tunnable Diode-laser Measurement of Carbon Monoxide Concentration and Temperature in a Laminar Methane-Air Diffusion Flame. *Appl. Opt.* 32(1993), pp. 6082-6089.

9. Rea, E. C., and Hanson, R.K.: Rapid extended range tuning of single-mode ring dye lasers, *Appl. Opt.* 22(1983), pp.518-520.

10. Golz, T. M., Auweter-Kurtz, W., Kurtz, W. L. and Schrade, H. O.:High Power Arcjet Thruster Experiments, *Proceeding of 22nd AIAA/AIDAA /DGLR/JSASS International Electric Propulsion Conference*, IEPC-91-012, Viareggio, Italy, October, 1991.

11.Yoshikawa, T., Onoe, K., Tsuri, S., Ishii, M. and Uematsu, K.: Development of a low power Arcjet Thruster, *Proceeding of 22nd AIAA/AIDAA/DGLR /JSASS International Electric Propulsion Conference*, IEPC-91-043, Viareggio, Italy, Ocotober, 1991.

12.Sankovic, J. M., Hamley, J. A., Haag, T. W.: Hydrogen arcjet technology, *Proceeding of 22nd AIAA/AIDAA/DGLR/JSASS International Electric Propulsion Conference*, IEPC-91-043, Viareggio, Italy, Ocotober, 1991.