§10. Transition from Atmospheric Thermal Plasma to Recombining Plasma in Helium Arcjet Generator

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Atmospheric thermal plasmas have attracted a great deal of interest for applications in various engineering and scientific fields such as welding, chemical vapor deposition (CVD), and waste treatment. One of these thermal plasmas, an arcjet expanding through a converging-diverging nozzle with Laval or conical shape has been expected to be a candidate for plasma (electric) thrusters.

Recently, we have developed a compact stationary arcjet plasma source for the purpose of fundamental research on arcjet thrusters and atomic and molecular physics in plasmas [1]. In order to characterize the arcjet helium plasma generated, spectroscopic observations were carried out using a high resolution visible spectrometer.

The stationary He arcjet plasma was generated between an anode and a cathode (Ce/W). The electrode gap length was 1 mm. Both electrodes were cooled by water to prevent them from being damaged due to high-heat flux arc. For the anode, we used a converging-diverging anode nozzle having a throat diameter of 0.5 mmϕ, diverging angle of 5° and exit diameter of 3 mmϕ to promote the adiabatic free expansion into vacuum. The arc discharge current and voltage were up to 200 A and ~20 V, respectively and the pressure at the discharge section was 1~1.4 atm

On the other hand, spectroscopic observation was carried out using a high resolution visible spectrometer (f=1 m, grating: 2400 grooves/mm) with a charge coupled device (CCD) camera. The resolution of the optical system was around 6 pm (the *half* width at half maximum: HWHM of the Gaussian profile) under an entrance slit width of 30 μm. Relative spectral sensitivity of the whole optical system was calibrated by a standard tungsten lamp.

Figure 1 shows the He atomic spectrum (667.8 nm) measured at the position of 45 mm from the nozzle exit, indicating that the line spectrum was slightly broadened due to the Stark effect. Note that the line width was as narrow as 12 pm (FWHM). Fitting procedure of the experimental result with the Voigt function yielded the Stark broadening width, which is a function of the electron density [2]. Comparing this width with the semi-classical equation derived by Griem, we can obtain the electron density. Consequently, the electron density was determined to be $\sim 2\times10^{15}$ cm^{-3} at 45 mm downstream from the nozzle exit.

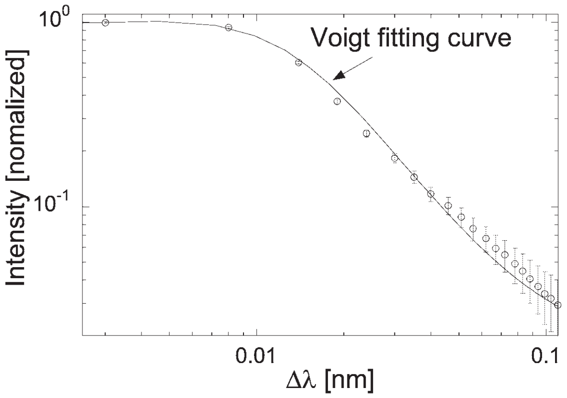

Fig. 1. Line spectrum of neutral He 667.8 nm at the nozzle downstream. A Voigt fitting curve is also shown in a solid line.

On the other hand, the radiative recombination continuum terminated to $2p\ ^3P$ transition, that is, $\mathrm{He}^+ + e \rightarrow \mathrm{He}^*(2p\ ^3P) + h\nu$, was observed. This emission indicates that the thermal arc plasma turned into the strong recombination plasma, where the high density and low temperature recombination plasma was generated. Here, the emission coefficient ε(λ) of the recombination continuum is given by [3],

$$\varepsilon(\lambda) = C\frac{\sigma}{\lambda^5}\exp\left(-\frac{h\nu}{kT_e}\right) , \tag{1}$$

where C is a constant and σ is the photoionization cross section. Figure 2 shows the plot of $\varepsilon(\lambda)\lambda^5/\sigma$ on the photon energy. The best fitted curve which corresponds to T_e=0.33 eV is also represented in the figure.

Finally, the flow velocity of the arcjet plasma was determined by measuring the Doppler shift of He 667.8 nm in the perpendicular and parallel to the expansion axis. The blue shift observed in the parallel direction was 63.4 pm, corresponding to the flow speed of 2.7×10^4 m/s. Assuming that the thermal plasma ejected from the nozzle reaches the terminal velocity, we obtain the temperature of ~6.1 eV at the arc discharge section.

1) S. Namba, K. Nakamura, N. Yashio, S. Furukawa, K. Takiyama and K. Sato, J. Plasma and Fusion Res. SERIES (in press).

2) H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic, New York, 1974).

3) M. Otsuka, R. Ikee, and K. Ishii, J. Quant. Spectrosc. Radiat. Transf. **15**, 995 (1975).

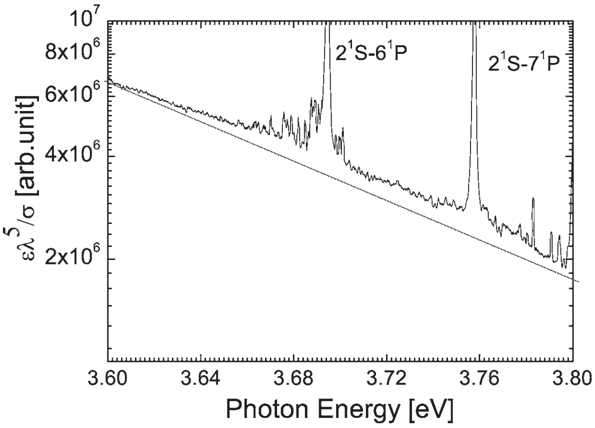

Fig. 2. Recombination continuum spectra terminated to $2p^3P$. The best fitted straight line represents the electron temperature of T_e=0.33 eV