§11. Observation of Shock Waves in an Arcjet Plasma Expanding through a Conical Nozzle

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When an arcjet plasma expands through a supersonic nozzle, we have found that a shock cell having a rotational structure can be created. The formation of such a shock strongly depends on the experimental conditions in both the arc discharge and expansion regions. The detailed conditions for their generation are not fully understood. Although a plasma generated in a magnetic field rotates due to the $\boldsymbol{E}\times\boldsymbol{B}$ drift, a magnetic field is not used in the present study. The reason for the helical structure of the shock has not been identified. In order to investigate the dependence of the shock formation on the discharge current, nozzle backing pressure, and residual gas in the plasma expansion region, emission spectroscopy in the VIS/UV spectral region is carried out.

The helium arc plasmas are generated between a copper anode and a cathode consisting of a 2.4-mm-diameter Ce/W rod [1]. The discharge current and voltage are I = 10–30 A and V_d = 30 V, respectively. The electrode gap is around 3 mm, the discharge pressure is up to 1130 Torr, and the helium gas flow rate is 5.0 L/min. The plasma expands through converging and diverging anode nozzles (having a throat diameter of 1 mm and a divergence angle of 40°) into a low-pressure expansion region. A visible spectrometer with a half-meter focal length is used to characterize the expanding arcjet plasmas. The diffraction grating has 150 grooves/mm for broadband emission measurements and 3600 grooves/mm for high-resolution measurements. The detector is a CCD camera. The emission is imaged by a lens onto the end of an optical fiber bundle having 48 cores. The light exiting the fiber is re-imaged by a lens onto the entrance slit of the spectrometer. The measured spectral range is 300 to 750 nm. With a fully open entrance slit (2.5 mm), a two-dimensional (2D) spatial image of the monochromatic emission is obtained. The spectral sensitivity of the system is calibrated using a xenon discharge lamp.

Figure 1 shows a 2D image of the helium neutral emission (at 728 nm for He I 2p ^1P-3s ^1S) at a discharge current of 10 A, voltage of 30 V, various nozzle backing pressures P_0, and pressures in the expansion region P_b. As the residual gas pressure P_b increases, the position of the shock cell gradually moves toward the nozzle. This movement indicates that the shock wave in the arcjet plasma is generated by the collision of plasma and neutral particles in the expansion section, similar to the behavior observed in compressible supersonic gas flow. Consequently, the expansion dynamics can be described in terms of a compressible flow rather than as an electromagnetic fluid [2].

The electron temperature and density can be evaluated from highly-resolved neutral atom spectra [1,3,4]. As for the temperature determination, we analyzed the radiative recombination continuum spectra, yielding a constant value of 0.25 eV along the expansion axis. No distinct rise or drop of the temperature around the shock is observed, because it is evaluated by averaging the intensity over the line of sight. To more accurately determine the temperature, an Abel inversion must be performed, in which the radial emission distribution is obtained. A preliminary analysis shows that this distribution is significantly different from the line of sight results.

To determine the plasma density along the expansion axis, high Rydberg spectra from the He I 2^3P-n^3D series are measured using the grating having 3600 grooves/mm. According to the Inglis-Teller limit, the density is related to the principal quantum number n_s of the last detected line in the series [5],

$$\log(n_e + n_i) = 23.26 - 7.5\log n_s + 4.5\log z, \quad (1)$$

where z is the average charge number. Experimentally n_s = 16 is measured. Equation (3) then yields an electron density of $n_e = 8.5\times10^{13}$ cm^{-3} at x = 5 mm and y = 0, with nearly a constant value between x = 0 and 11 mm. A density jump at the shock front is not observed, because it is also evaluated by the line averaged spectral profile.

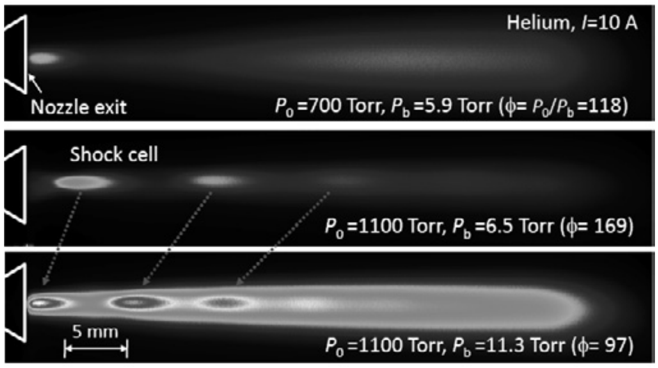

Fig. 1 Dependence of 2D emission image (He I 728 nm) on the gas pressure at a discharge current of 10 A

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