21PB-094

Observation of bright and dark emission structures formed in an expanding arcjet plasma
アークジェット膨張部に形成されるプラズマ発光の明暗構造の観測

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We developed an arcjet plasma device having a supersonic conical nozzle. Depending on the gas pressure in the expansion section, the bright and dark emission structures were formed. In order to understand the mechanism for formation of the phenomenon, we measured plasma parameters (electron density and temperature) by visible emission spectroscopy. The analysis showed that no temperature variation was observed around the bright emission region (T_e ~ 0.3 eV), whereas the plasma density significantly increased by a factor of two. On the other hand, the cell width of the shock wave calculated from compressible fluid dynamics was in good agreement with the experimental value, indicating that this emission structure was caused by the shock cell described by a conventional flow dynamics.

1. Introduction

Arc discharge is one of the most important plasmas in the scientific and engineering fields. We developed an arcjet plasma device [1,2]. Recently, bright and dark emission structures were found to be formed in the arc expansion section. According to compressible fluid dynamics, this structure is probably a shock wave that occurs for an under-expansion in the supersonic free jet.

In order to understand the mechanism for the generation of this emission structure, the spatial distribution of plasma parameters (temperature and density) along the jet axis was measured by emission spectroscopy. As a result, no temperature variation on the jet axis was observed, whereas the density increased at the bright emission region.

The width of the periodic emission structure was measured by He I monochromatic image. The shock width calculated from compressible fluid dynamics agreed with the experimental value, indicating that the structure could be described by the conventional gas dynamic theory.

2. Experimental Setup

Figure 1 shows a schematic diagram of the arcjet plasma device. Helium arc plasmas are generated between a cathode (2.4 mmϕ Ce/W rod) and copper anode. The plasma expands through a conical anode nozzle into a low-pressure region. The throat diameter and diverging angle of the supersonic nozzle are 1 mm and 40°, respectively. The discharge current and voltage are I = 30–50 A and V_d ~ 30 V, respectively. The electrode gap is less than 3 mm, and the arc discharge is operated at ~1200 Torr. The pressure in the expansion section is kept to be less than 10 Torr by using rotary and mechanical booster pumps.

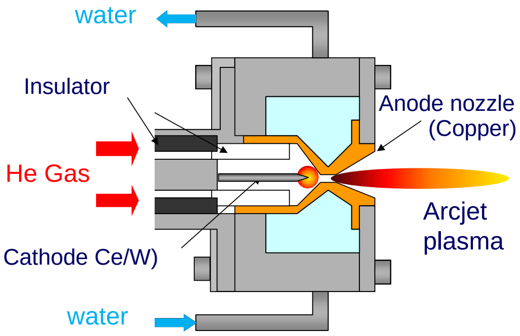

Fig. 1 Schematic of the arc discharge source.

A visible spectrometer with 1.0-m focal length and a 2400-grooves/mm grating is used to measure high-resolution spectrum. The detector is a charged coupled device (CCD) camera. A two-dimensional (2D) spatial image of the emission is observed by fully opening the entrance slit.

3. Results and discussion

Figure 2 shows a 2D emission image of He I 2^1P-5^1D (438.8 nm) transition at a discharge current of 30 A. The bright emission appeared around 17 and 38 mm from the anode exit. The electron temperature was evaluated by the Boltzmann plot [3, 4], indicating no variation around the bright emission region. The reason for this is considered that the temperature might not be determined

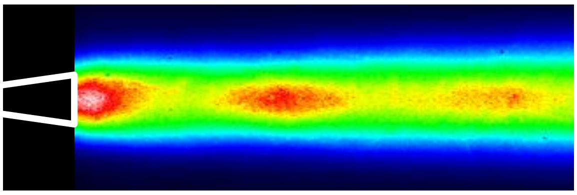

Fig. 2 2D emission image of He I 438.8 nm.

accurately, because the absolute variation was too low to evaluate from this method.

Furthermore, we determined the electron density by the Stark broadening width [3-6]. To this end, the line emission of He I 392.6 nm was measured. Figure 3 plots the spatial distributions of the density evaluated from the Stark width on the jet axis. Around the bright emission regions, the densities increase due to compression waves from the jet boundary, as described below.

According to the compressible fluid dynamics, the shock occurs in an under-expansion regime, where the Prandtl-Mayer type expansion wave intersects and the compression and expansion wave are generated repeatedly due to the reflection at the jet boundary, resulting in the density and temperature rise in the shock cell [7, 8]. Here, the width (wavelength) of shock cell is given by the following Prandtl formula [8],

$$\frac{\lambda}{D} = \frac{1}{2.405}\pi\left(M^2 - 1\right)^{\frac{1}{2}}, \qquad (1)$$

where λ is the wavelength of the shock cell, D is the average diameter of the shock and M is the average Mach number. If we assume that the gas with a stagnation pressure of p_0 is freely-expanded into the ambient pressure p_A, we obtain the following equation,

$$\frac{p_0}{p_A} = \left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}, \qquad (2)$$

where γ is the ratio of the specific heats. The cell width λ~ 17 mm and average diameter D ~ 4 mm measured by 2D image are substituted into Eqs. (1) and (2), yielding $M = 3.7$ and $p_0/p_A = 76$. The value of the pressure ratio obtained is in excellent agreement with experimental one for $p_0 = 760$ Torr and $p_A = 10$ Torr. Hence, the bright and dark emission structure was caused by the shock wave.

4. Summary

In order to understand the mechanism for formation of the periodic emission structure in the arcjet He plasma, we determined the plasma parameters by means of spectroscopic observation.

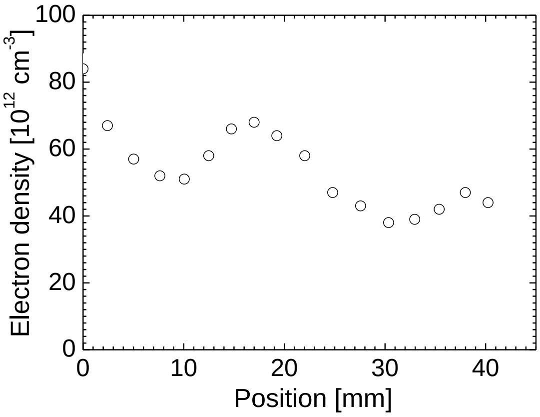

Fig.3 Spatial distribution of the electron density.

As for the electron temperature, no distinct variation along the jet axis was observed, while the density significantly increased at the bright emission region. Finally, the wavelength of shock cell calculated from the Prandtl formula was in good agreement with the experimental value. Hence, the formation mechanism of the bright and dark emission structure could be explained from the conventional compressible fluid dynamics.

Acknowledgments

This work is performed with the support and under the auspices of the NIFS Collaboration Research program.

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