Electron Temperature Control in a Hot Cathode Arc Discharge Plasma

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1. Introduction

Control of electron temperature $T_e$ has lots of interest in advanced plasma applications as well as basic plasma researches. So far, some methods for the temperature control were applied such as pulse modulation, bias grid, RF heating and so on. In this study, we have attempted that the temperature control by means of varying a quantity of thermal electron emission and a distance of the discharge gap, because the thermal electron emission and the gap distance are essential to sustain arc discharge plasmas.

2. Experimental Setup

2.1 Compact Hot Cathode Arc Plasma Generator

Experiments were performed by using the Compact Hot Cathode Arc Plasma Generator, which had been constructed in our laboratory as shown in Fig. 1. The device has a glass vacuum vessel with 0.8 m in length and 0.14 m in diameter, and is equipped with two solenoidal magnetic coils, which produce a flux density of 10 mT in steady state. Argon gas was poured from discharge region then Argon plasmas were produced in steady state by sophisticated dc discharge system, which is designed to improve the ionization efficiency using a divergent magnetic configuration and a heated LaB$_6$ spiral coil cathode. The electron density $n_e$ can be controlled by changing the discharge current $I_d$. Typical plasma parameters are the electron density $n_e < 5 \times 10^{17}$ m$^{-3}$ and

![Fig. 1. Schematic diagram of the Compact Arc Plasma Generator. The power supply for the cathode heating is floated from the ground.](image)
the electron temperature $T_e < 10$ eV. The plasma diameter is about 0.01 m. A generated plasma flowed into the plasma test region through a orifice at the center of the anode, which diameter is 4 mm. Neutral pressure measured in the plasma test region $P_n$ was less than 0.27 Pa in this study. The anode orifice divides the plasma source and the plasma test regions. The main vacuum pump is a diffusion pump (90 liters/sec).

The electron temperature in the plasma test region was measured by a single Langmuir probe. The location of the probe was 0.4 m away from the anode orifice, where is between two magnetic coils.

2.2 Discharge Region

The details of the discharge part are shown in Fig. 2. This region consists of mainly four parts, a hot cathode, a water-cooling capper anode, a floated electrode and a bellows. A LaB$_6$ cathode (DENKA Beta Plus, Type C-2) was used for a hot cathode. The cathode has double spiral coil structure in order to avoid the influence of magnetic field. The diameter of the cathode is 10 mm and the length is 25 mm. The cathode temperature is increased by ohmic heating followed with direct current $I_h$. A quantity of thermal electron emission depends on the temperature of the cathode. The emission current density $j$ can be described as a function of the cathode temperature $T$ by the Richardson-Dushman equation as following:

![Fig. 2. Details of discharge region of the Compact Arc Plasma Generator. The hot cathode is surrounded by a floating electrode with a glass port and a bellows.](image-url)
\[ j = AT^2 \exp\left(-\frac{e\phi_w}{kT}\right), \quad (1) \]

where \( A \) is Richardson constant, \( \phi_w \) is the work function of the cathode material, \( k \) is the Boltzmann constant. Figure 3 shows the plots of the eq (1) for several cathode materials. The thermal electron emission has strong dependence on the cathode temperature in our experimental conditions. Due to the discharge voltage \( V_d \) was limited to 200 V by the DC power supply, \( I_h > 26 \) was needed to make a breakdown for Argon.

A bellows connected between the Anode and the cathode in order to vary the discharge gap (see in Fig. 2). To avoid thermal damage caused by electron and ion heat flux, the bellows is electrically floated. Both flanges of the bellows are fixed at a linear guide rail in order to allow moving in the axis direction. The variable distance is from 15 mm to 45 mm as the discharge gap.

3. Experimental Results and Discussion

Figure 4 shows the dependence of \( V_d \) and \( T_e \) measured at the center of the plasma column on the cathode heating current \( I_h \). \( V_d \) is increased by decreasing of \( I_h \) in the range of 15 and 28 A. The \( V_d \) is almost constant between \( I_h = 5 \) and 15 A. In the case of \( I_h = 0.3 \)A, the cathode temperature was sustained by plasma itself. With respect to \( T_e \), we observed high-energy tail within all \( I_h \) region of the experiments. The bulk \( T_e \) shows almost constant value (\( \sim 2 \) eV), however, the \( T_e \) of high-energy tail components is gradually increased by rising of \( I_h \). During \( I_h \) variation, the different heating mode of the cathode is observed as shown in Fig. 5. In the case of high \( I_h \) (Fig. 5 (c)), the tip of cathode is dark. This means the temperature of the part is low because of the low resistivity due to the large cross section of the heating current path. However, the cathode has high-capability of thermal electron emission because the area of high temperature (bright) region is enough large, therefore, \( V_d \) becomes small. On the other hand, at \( I_h = 0.3 \) (Fig. 5 (a)), the tip of cathode becomes the brightest part of the cathode. It seems that self-heating caused by the concentration of ion.

Fig. 3. Dependence of thermal electron emission on the cathode temperature for the materials LaB\(_6\), W, W/Th and Mo.
influx is occurred at this position. In this case, the electron emission area is smaller than the other cases. Therefore, $V_d$ is needed to rise in order to keep the discharge current.

![Graph](image)

Fig. 4. Dependence of the discharge voltage $V_d$ and electron temperature $T_e$ on the cathode heating current $I_h$ during Ar discharge ($I_d = 5$ A, Gas flow = 1.5 sccm, $P_n = 1.9$ mTorr). Closed circles, open squares and open circles show $V_d$, $T_e$ of high energy tail component and $T_e$ of bulk component, respectively.

![Images](image)

Fig. 5. Photographs of the hot LaB$_6$ cathode for different cathode heating current during same conditions as Fig. 4. The anode is located on the left side of each photo.

3. Summary

Experiments were performed by using the Compact Hot Cathode Arc Plasma Generator with a LaB$_6$ hot cathode and a variable gap driving system. Decreasing the heating current of the cathode, probe measurements showed decrease of $T_e$ of high-energy tail component for Argon plasmas. Simultaneously, a change of cathode heating mode was observed. These results indicate a possibility of the control of $T_e$ (or energy distribution function) by using these methods.