Effect on Electron Emission of Inductively Coupled Plasma Cathode's Length

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Abstract: Hollow cathode is a common electron source for an ion engine and a hall effect thruster, because it achieves high electron emission current with relatively low consumption of gas and electric power. However, an oxide insert of hollow cathode limited a lifetime and operation of these thrusters because of its degradation and depletion. In order to liberate thrusters from these limits of hollow cathode, inductively coupled plasma cathode was studied in our previous study. In this paper, to increase electron emission current, length of inductively coupled plasma cathode was changed. As a result, 10 A of electron emission current was obtained at 40 mm ICP/C, 0.5 mg/s of mass flow rate and 40 W of RF power.

I. Introduction

For station keeping and orbit transfer of satellites, electric propulsion systems such as ion engine and hall effect thruster have been increased in demand.[1] Ion engine and hall effect thruster needs electron sources for ionization of propellant gas and neutralization of ion beam. However, lifetime of these electrical propulsion systems is critical issues limited by acceleration electrodes and these electron sources. In general, a hollow cathode (H/C) has been selected as an electron source because it can provide large electron current with low power and propellant consumption; however, H/C's lifetime is limited by depletion and degradation of thermionic emitter[2]. In addition, it needs to preheat before its ignition. The emitter must be kept away from contacting with active gas, such as oxygen; thus, H/C must be strictly controlled.

In order to replace as electron source, different types of cathodes for electric propulsion systems have been investigated and developed. For electron production, these new types of cathode employ either microwave or radiofrequency (RF) discharge[3]. In microwave type, electron cyclotron resonance plasma (ECRP) has been employed, and this type cathode had been used in space such as Hayabusa asteroid explorer[4]. However, in this type of electron source, electron number density is limited by cutoff frequency, and this type's power efficiency is less than50%[5]. Table 1 shows comparison between H/C and ICP/C.

RF type of electron source, which employ inductively coupled plasma (ICP), has been proposed for ion engine and hall effect thruster. Basic characteristics of ICP/C had been investigated.

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In our previous study, in order to improve performance of ICP/C, its ignition and electron emission characteristics had been investigated as function of orifice dimension, ion collector shape and total number of coils[6]. In this improvement, 0.52 A of electron emission had been achieved at 24 W of RF power, 0.15 mg/s of propellant mass flow rate and 40 V of anode voltage.

In this study, to improve overall performance of ICP/C, electron emission characteristics are investigated as function of discharge vessel's inner diameter and length.

Table 1. Comparison between H/C and ICP/C.

	ICP/C	H/C
Beam Diamter	12 cm	
Screen Grid Voltage	1,000 V	
Acceleration Grid Voltage	500 V	
Dischrge Current	3.0 A	
Main Propellant Feed Mass Flow Rate	0.72 mg/s(xenon)	
Discharge Cathode Mass Flow Rate	0.08 mg/s(xenon)	
Power Consumption of Discharge Cathode	120 W	4 W
Dischrge Voltage	33.7 V	34.7 V
Thrust	17.4 mN	17.3 mN
Specific Impulse	2,280 s	2,260 s
Propellant Utilization Efficiency	58.20%	58.20%
Ion Production Cost	661 W/A	324 W/A
Total Power Consumption	560 W	450 W
Thrust-to-Power Ratio	31 mN/kW	38 mN/kW

II. Experimental Apparatus and Procedure

A. Inductively Coupled Plasma Cathode

Fig. 1 shows schematic diagram of ICP/C are discharge vessel, induction coil, ion collector and orifice plate. The discharge vessel is made of glass, and seven vessels, which length and diameter were varied, were employed to investigate effect of vessel dimensions on electron emission characteristics, summarized in Table 2. The copper wire is wrapped around the discharge several times, and induction coil always keeps 1.1 μH. To maintain ICP/C at quasineutrality, the cylindrical ion collector, made of stainless steel, was inserted into the discharge vessel, shown in Fig. 2. It has an axial slit for effectively applying *dB/dt* field into plasma. In addition, the azimuthal *dB/dt* field is suppressed for serving as a Faraday shield the plasma within ICP/C. For electron emission, there is orifice at the

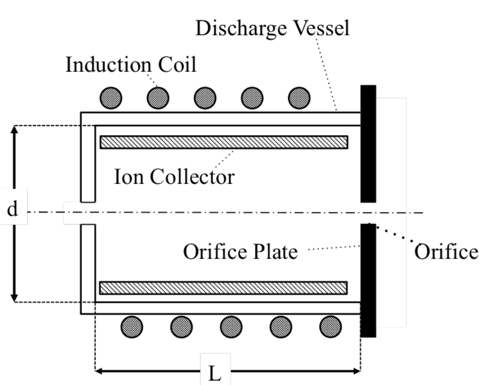


Figure 1. Schematic Diagram of ICP/C.

Figure 2. 3D model of cylindrical shape of Ion Collector.

Table 2. Details of ICP/Cs.

Items			20mm ICP/C	40mm ICP/C
Vessel material			Glass	
Vessel Diameter	d	mm	20	40
Vessel Length	L	mm	20, 60, 80, 140, 160	40, 80
Orifice Diameter	$D_{orifice}$	mm	1.7	
Inductace of Coils		μH	1.1	

center of the plate, which is made of mica, and its diameter is 1.7 mm. The plate helps keeping inner pressure of ICP/C by covering downstream of discharge vessel.

B. Experimental Setup

Fig. 3 shows the experimental setup. All experiments are conducted in the vacuum chamber, which diameter and length are 0.9 m and 1.2 m, respectively. The vacuum chamber reaches approximately 1.3×10^{-3} Pa by a turbo-molecular pump, when the Xenon mass flow rate is 2.0 mg/s. RF power system and xenon feed systems were attached from outside of the vacuum chamber. RF power system consists of RF generator and impedance matching circuit. The RF generator provides 500 W at most to the coil of ICP/C at 13.56 MHz of frequency via impedance matching circuit. The impedance matching circuit consists of two variable capacitors to eliminate reflected power. There was no reflected power through all experiments because the impedance of RF generator was matched that of the ICP/C by the impedance matching circuit. Xenon feed system consists of xenon tank, mass flow controller (MFC) and a gas isolator. The gas isolator was attached inside the vacuum chamber, and it helps to protect MFC from RF power.

The anode plate was located at 50 mm downstream of the ICP/C's orifice plate. The anode plate was biased positively by DC power supply, which was attached from outside of the vacuum chamber, to extract electrons from the ICP/C.

In order to evaluate effect of discharge vessel dimensions on electron emission characteristics as function of anode plate voltage, the voltage was varied from 0 to 80 V at fixed xenon mass flow rate, 0.5 mg/s. In addition, RF power was varied from 40 to 80 W with increments of 20 W to evaluate.

C. Electron Emission Characteristics

Electron emission characteristics of ICP/C are evaluated at diode configuration. Fig. 4 shows the electrical configuration in this experiment. The target, as an anode, is located at 50 mm downstream of the orifice plate, and it

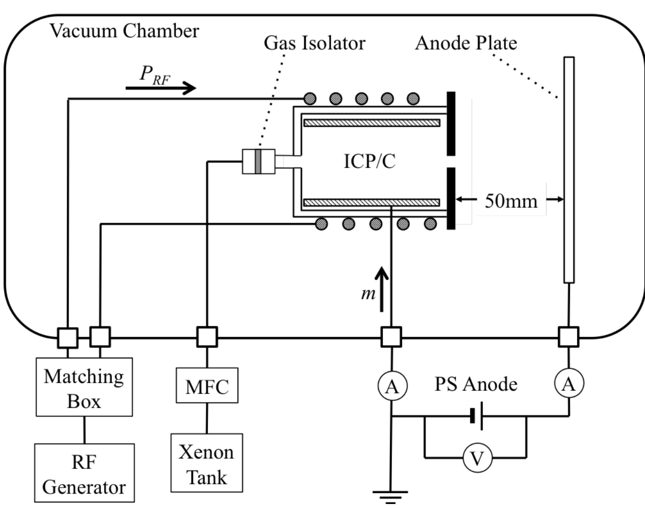


Figure 3.Experimental Setup.

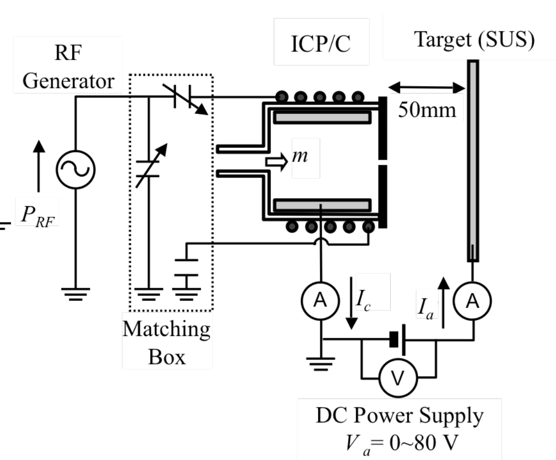


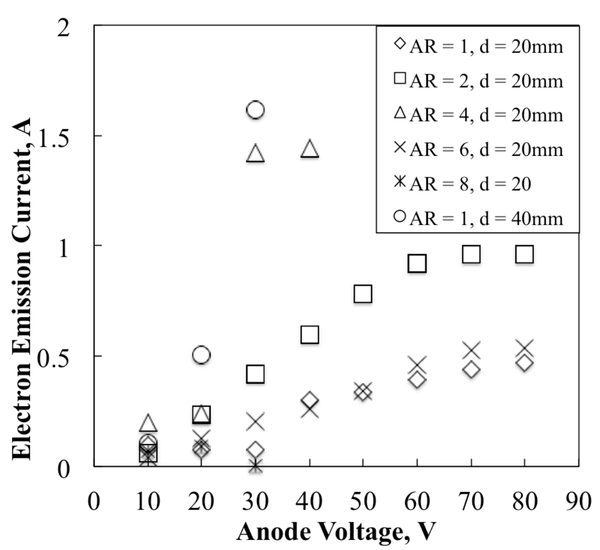
Figure 4. Diode configuration with ICP/C.

is biased positively by DC power supply.

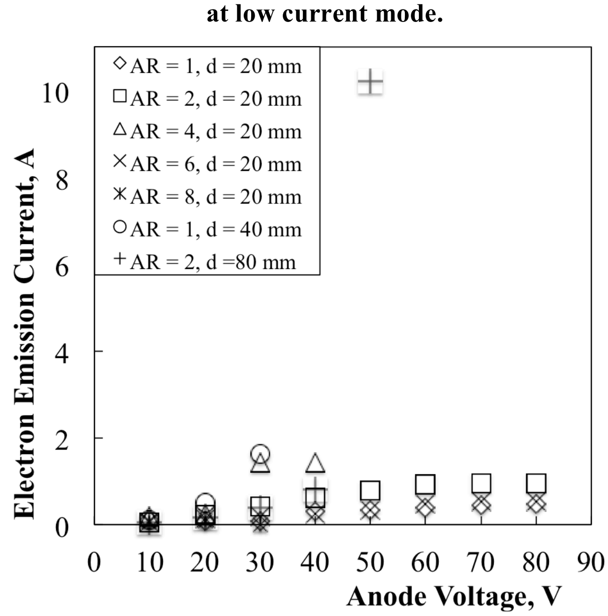
After the ICP is sustained stationary, Xenon mass flow rate and RF power are set as follows: Xenon mass flow rate of 0.5 mg/s and RF power of 40, 60, 80 W. When the target bias voltage is varied from 0 V to 80 V, the electron current extracted from the ICP/C and the ion current collected by the ion collector are measured. The ion collector also has an axial slit, which allows the axial *dB/dt* fields into the plasma, but suppresses the circumferential *dE/dt* field, effectively serving as a Faraday shield for the plasma within ICP[6].

III. Results and Discussions

Fig. 5 shows current-voltage characteristics of ICP/Cs when RF power and Xenon mass flow rate are 40 W and 5sccm, respectively. Electron emission was increased when anode voltage was increased. Fig. 6 shows aspect ratio (L/d)-saturated electron emission characteristics when RF power is 40 W and Xenon mass flow rate is 0.5mg/s. Maximum saturated current of ICP/Cs which diameter of discharge vessel are 20mm and 40mm (20 mm ICP/C and 40 mm ICP/C) are 1.5 A at d=80 mm and 10 A at d=20 mm, respectively. From these results, it was confirmed that optimum length exists around 80 mm. Especially optimum length of 20 mm ICP/C is less than 140 mm and more than 40 mm. In the 40mm ICP/C, optimum length is more than 40mm. When 10 A was obtained at 40 mm ICP/C, this saturated electron emission was limited by over current limiting circuit of DC power supply. Therefore, it's conceivable that saturated electron emission is larger than 10 A. So, Fig. 7 shows current-voltage characteristics of 40mm ICP/C when RF power are 40, 60, 80 W and Xenon mass flow rate is 4sccm. Electron emission was confirmed at 40 W and 60 W. However, when RF power was 80W, electron emission was not observed. When electron emission was elevated, changing behavior of ICP in a discharge vessel was observed and it is confirmed that an ion collector in a discharge vessel was melted. So, it was confirmed that there were two current modes. One is low current mode when emission current is approximately 1A, other is high current mode which electron emission is approximately 10 A. Additionally, when ICP/C mode was changed from low current mode to high current mode, discharge was occurred at an ion collector. This increase of electron emission has been never observed on previous studies, therefore plasma parameter should be measured by a langmuir probe and a spectroscope.



(a) Current-Voltage characteristics at low current mode.



(b) Current-Voltage characteristics at high current mode.

Figure 5. Current-Voltage characteristics of ICP/Cs.

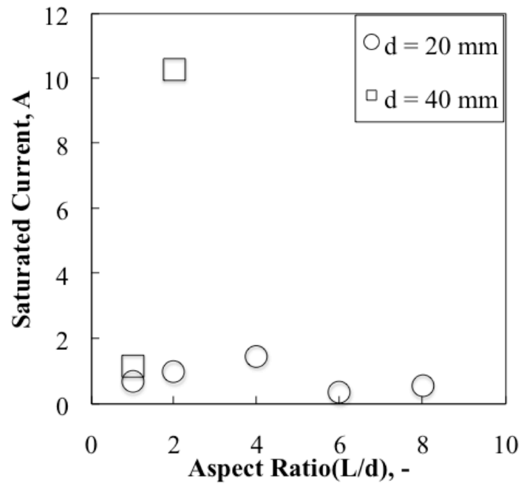
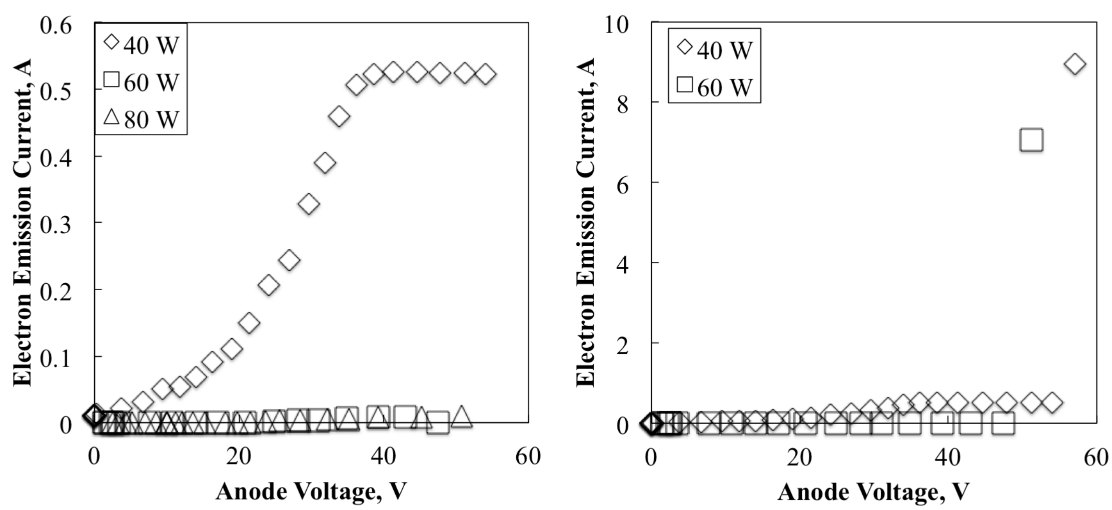


Figure 6. Saturated electron emission of aspect ratio.



(a) Current-Voltage characteristic at low current mode.

(b) Current-Voltage characteristic at high current mode.

Figure 7. Current-Voltage characteristics of 40mm ICP/C.

IV. Conclusion

Through the experiment of inductively coupled plasma cathode, the following results have been obtained.

1) ICP/C has two current modes, which are low current mode and high current mode. The mode transition from low current mode to high current mode occurs when discharge occurred at ion collector.
2) Saturated electron emission of 20 mm ICP/C is 1.5 A at 80 mm of discharge vessel's length, 40 W of RF power with 13.56 MHz and 0.5 mg/s of Xenon mass flow rate. And saturated current of 40 mm ICP/C is 10 A at 80 mm of discharge vessel's length 40 W RF power with 13.56 MHz and 0.5 mg/s of Xenon mass flow rate.

3) It was confirmed that optimum length of 20 mm ICP/C and 40 mm ICP/C is around 80 mm. In the 20 mm ICP/C, 60 mm and 100 mm of length should be experimented. And in the 40 mm ICP/C, 60 mm and 100 mm should be experimented.
4) Plasma parameter of high current mode should be measured by a langmuir probe and a spectroscope.

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