Evaluation of Plasma Contactor Ground Experiments for Electrodynamic Tether[*†]

Masaya Kozakai[‡] and Haruki Takegahara[§]
Tokyo Metropolitan Institute of Technology
6-6, Asahigaoka, Hino, Tokyo 191-0065, JAPAN
+81-42-585-8600 ex. 2307
koza@astak3.tmit.ac.jp

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Plasma contactors are proposed as good electrical contact devices between spacecraft and ambient ionospheric plasma. Especially, it has been studied as the one of key components of electrodynamic tether. To understand the contacting process with plasma enables various applications of electrodynamic tether system such as orbit raising, deorbit, station keeping and power generation. In this study, a hollow cathode was used as a plasma contactor for both electron emitter and collector. The results show the simultaneous operation of the plasma contactors in the simulated plasma environment. We confirmed the closed current loop formation via ambient plasma between the emitter and the collector. The current level of the order of 5 A was achieved. The results of the ground experiments and the dominant factors affecting the law of scaling are described in this paper.

Introduction

Space tether system has wide variety of applications for technological and scientific missions such as momentum exchange orbit transfer by releasing payload connected with the tether, artificial gravity generation by rotating two bodies connected with the tether and scientific inspections of the upper atmosphere by multi probes on the long tether. The electrodynamic tether is a kind of space tether application that possesses the conducting tether and plasma contactors. It produces thrust on the earth orbit by the interaction between the current through the tether and the geomagnetic field. So, it can be used for orbit raising thrust force or orbit lowering drag force depending on the direction of the current. It also generates electrical power (electromotive force) by the conducting tether across the geomagnetic field. The electrodynamic tether also has the potential to provide a near-propellantless propulsion system, using the energy from sunlight converted to electrical energy. Therefore, the electrodynamic tether system can be applicable for various missions such as station-keeping, power generation, orbit raising, and the deorbit of large-sized debris when some practical problems such as the tether cutting would be solved.

Space debris problems have become of major interest lately from a safety standpoint of space environment. For the future safety guaranty of the space environment, debris reduction must be accelerated before their collisions or break up phenomena. One method to eliminate large debris like upper stage rockets or satellites, tether technology is an effective measure. By applying momentum transfer or electrodynamic tether system, large debris can be deorbited effectively with fuel saving of the remover compared with other propulsion system.

The first tether demonstration in the space was conducted in 1967 with Gemini II[1]. The demonstration illustrated gravity gradient stabilization using nonconducting tether on the low earth orbit. Since this demonstration, many tether missions including the electrodynamic tether have been flown in space. The Plasma Motor Generator[1] (PMG, 1993) demonstrated the principles of electrodynamic tether reboost and

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[‡] Graduate Student.

[§] Professor, Senior Member AIAA.

hollow cathode current collection. The Tethered Satellite System[1] (TSS, 1996) deployed conducting tether from Space Shuttle and generated approximately 2 kW of electrical power. In addition, The Propulsive Small Expendable Deployer System[2][3] (ProSEDS) space experiment, which will demonstrate the use of electrodynamic tether propulsion system, is planed by NASA Marshall Space Flight Center. This mission demonstrates that the drag thrust will deorbit the Delta II upper stage from 400 km circular orbit to reduce the debris on orbit. In Japan, on the other hand, the Institute of Space and Astronautical Science carried out the conductive tether experiments[4] (Charge series) in space. Although, any space experiments have not been conducted since then, similar mission is proposed. It is proposed that H-IIA 2nd stage deorbit system from GTO[5] (250 km perigee and 36,000 km apogee) using the electrodynamic tether.

Plasma contactors are proposed as making good electrical contact between the ends of tether and ionospheric plasma. Several kind of devices which emit or collect electrons are studied for electrodynamic tether such as biased surfaces, an electron gun, a hollow cathode[6], bare wire[7][8][9] and a field emitter array cathode[10]. The performance of electrodynamic tether depends on these devices because of the current through the tether form a closed loop via space plasma. It has reported that the hollow cathode is able to emit and collect ampere-level electron currents with low impedance. The largest advantage of using hollow cathode is that the same device can both emit and collect electrons. Thus, the electrodynamic tether, which mounts hollow cathode plasma contactors both ends of tether, is possible to change the direction of current and it can generate thrust force and drag force. There is a possibility of tether spin on the GTO, so the advantage of hollow cathode will be suitable for our mission. In this study, we will estimate the performance of hollow cathode plasma contactors for electrodynamic tether.

Objectives

A plasma contactor has an important role for gathering enough current flow through the tether. For the understanding of the physical phenomena in plasma contactor operation, the plasma contactor experiment in the vacuum chamber using a hollow cathode was conducted. Our previous work[11] performed the plasma contactor single operation in the plasma simulated environment. The purpose in this study is to evaluate the near-field plasma contacting process that associated with electron emission and collection through the simultaneous operation of emitter and collector in order to find the law of scaling in the ground experiment.

Experimental Apparatus

To study the interaction between the plasma that is

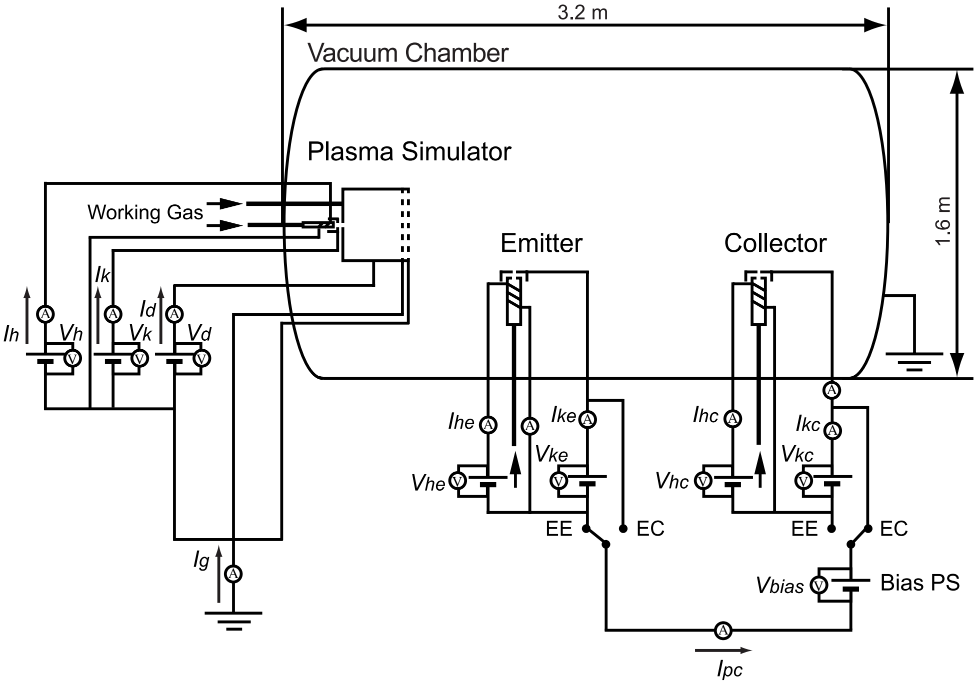


Fig. 1 Experimental setup.

generated by the plasma contactor and the plasma generated by the simulator, the apparatus shown schematically in Fig. 1 was constructed. This apparatus consists of three devices. Two of them are the hollow cathode plasma contactors. And the other device is the space plasma simulator. Argon, krypton and xenon were used for the plasma contactors and the plasma simulator as a working gas.

Plasma Contactors

The mode of the plasma contactor operation was changed by the switch connected to Electron Emission (EE) or Electron Collection (EC) mode in Fig. 1. The collector was operated with 12 cm diameter anode on the keeper electrode. When the emitter and the collector are operated simultaneously, the plasma contactors were separated from the earth potential. Thus, those were operated in floating condition against the ground potential. The operating parameters of hollow cathode were that the keeper current of 0.3 ampere and working gas flow rate of 3.0 SCCM.

Plasma Simulator

The cusped ion thruster with the beam-exhausting diameter of 30 cm and 14 cm were used as the space plasma simulator. This device simulates the ionospheric plasma around a spacecraft. It consists of a hollow cathode, a discharge chamber, and screen and accelerator grids. In the experiments, the operating parameters were fixed as the discharge current of 3 ampere, the working gas flow rate of 30 SCCM for 30 cm and 8 SCCM for 14 cm simulator. No voltage was applied to the grids. The simulator formed 2×10^{7} cm^{-3} of electron number density environment in the vacuum chamber.

Test Facility

The plasma contactors and the space plasma simulator were operated in the vacuum chamber, which is the 1.6 m in diameter and the 3.2 m in length. A turbo molecular pump and two cryogenic pumps are used for high vacuum pumping, which perform total pumping speed of 56,200 l/s for nitrogen. The ultimate pressure is 6.7×10^{-5} Pa (5.0×10^{-7} Torr), and the pressure during the typical experiments was lower than 5.7×10^{-3} Pa (4.3×10^{-5} Torr) for xenon. A remote controllable x-y stage was mounted in the vacuum chamber for probe traverse.

Results and Discussions

The simultaneous operation of the emitter and the collector was performed in the space plasma simulated environment. Plasma properties were measured with emissive probe and Langmuir probe. Typical plasma contactor current-bias voltage characteristics were measured in this condition too. Furthermore, the existence of the closed current loop was confirmed.

It must fill the following requirements to indicate the closed current loop formation via ambient plasma because there is limitation of distance between plasma contactors in the vacuum chamber experiments.

1. To keep the current equilibration at the emitter and the collector.
2. It is possible to neglect the current loss at the current loop via ambient plasma (e.g. for vacuum chamber wall).
3. Plasmas that are emitted from both plasma contactors do not interact each other (No discharge happen between the emitter and the collector directly).

Xenon was used for working gas to confirm these requirements.

Correlation of Plasma contactors

Current Equilibrium

Figure 2 shows the emission current of the emitter and the collector against the voltage of bias power supply. The emission current variations are symmetrically with respect to no emission current line with varies the bias voltage. It indicates that the current emitted from the emitter equal the current collected

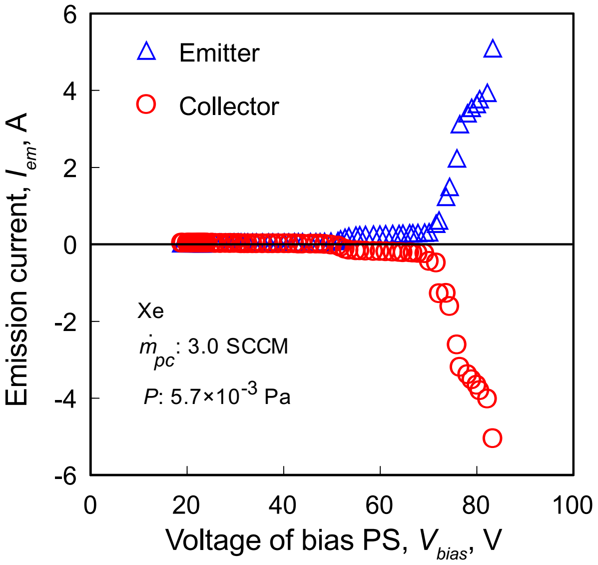


Fig. 2 Emission current variation on simultaneous operation.

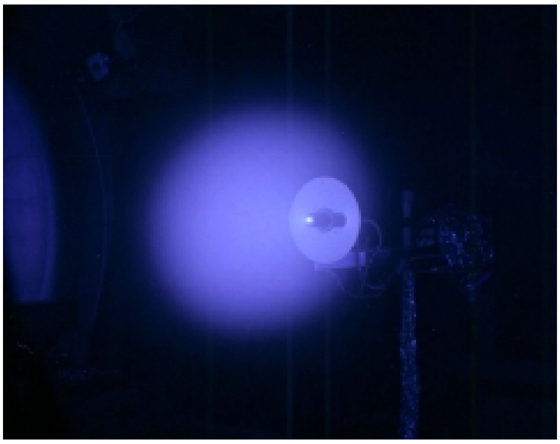


Fig. 3 Photo of plasma cloud on the electron collection mode.

by the collector. That is to say, it can be said that the current correlation between the emitter and the collector was confirmed.

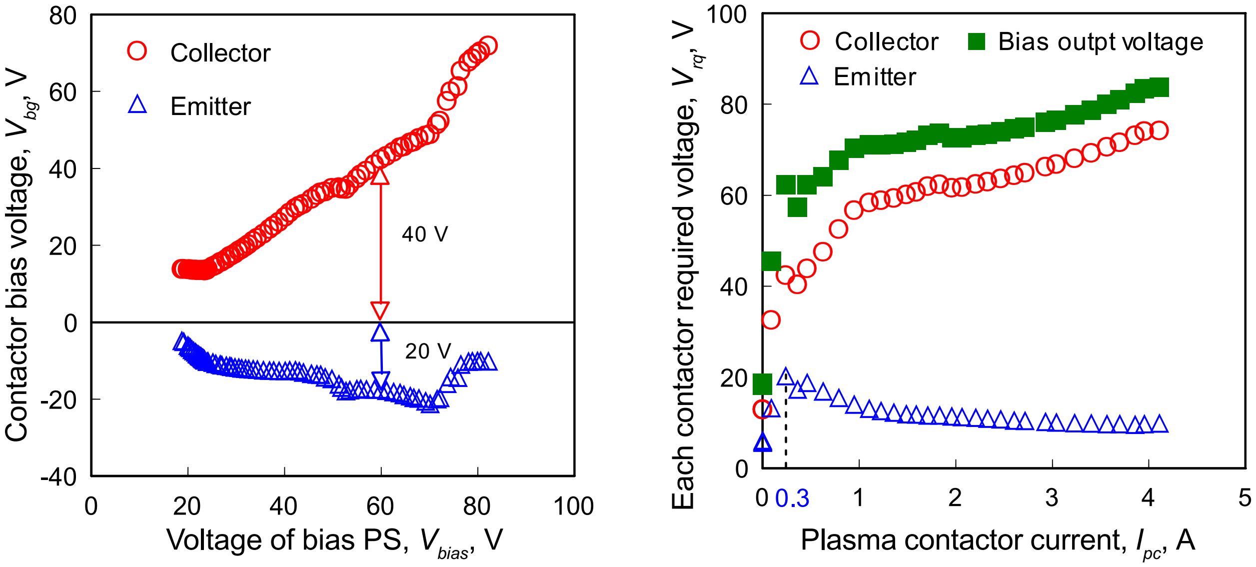
Figure 3 shows the plasma contactor operation at the contactor potential of 70 V. In this potential, the collector is operated in the ignited mode. It was accompanied by the appearance of a bright luminous area called plasma cloud that typically extends several centimeters from the contactor and somewhat spherical in shape. The emission current shows a sharp change at the bias voltage of 70 V. Thus, when the plasma cloud forms, the plasma contactor current increased.

Davis *et al.*[12] have described electron collecting model as following. A hollow cathode plasma contactor is a plasma source that emits neutral atoms, ion, and electrons. A high-density plasma cloud is formed near the potential of the source, which is on the order of 20-100 V above the potential of the surrounding plasma. Background electrons are accelerated to the elevated potential and ionize the neutrals, generating more plasma. The presence of the high-density plasma serves to enlarge the sheath. As the collected current is roughly the thermal current times the sheath area, more current is collected for a given potential difference by the plasma-enlarged sheath. If low ionization energy gas exists near the collector, plasma cloud forms easily with low bias voltage. Thus, it seems that xenon is suitable to the working gas of collector. So it seems that the plasma contactor current depends on the ionization near the collector.

Distribution of bias voltage

The plasma contactors were operated in floating condition as shown in Fig. 1, it is interested that how the bias voltage distribute to the emitter and the collector. Each contactor bias voltage against the voltage of bias power supply is shown in Fig. 4(a). The reference voltage of contactor bias voltage is the earth potential. The bias power supply allots its voltage between the emitter and the collector by itself to equilibrate the emission current as shown in Fig. 2. For example, when the bias power supply outputs 60 volt, 20 volt was allotted to the emitter and 40 volt was allotted to the collector.

Figure 4(b) provides a plot of bias voltage and each contactor required voltage difference as a function of the plasma contactor current. Both of the required voltage difference of the emitter and the collector increase sharply at first. It increases as plasma



(a) Distribution of bias voltage.

(b) Voltage requirement.

Fig. 4 Each contactor voltage.

contactor current up to 0.3 A, above which it decreases gradually at the emitter. It shows that the discharge mode of the emitter translate from plume mode to spot mode. At the collector on the other hand, it shows sharp increase as plasma contactor current up to 1 A, then it increases like proportionally to the plasma contactor current. Similar transitions of collector operation happen too. The required voltage difference of the collector is higher than that of the emitter over the whole current range. As shown in these figs, collector operation requires higher voltage than that of emitter to flow same amount of current to or from the ambient plasma, Anticipated is that the collector performance becomes dominant on the electrodynamic tether system. These figs show that there is a positive correlation between the bias voltage and the collector required voltage.

Current Loss

In this experiment, some current paths seem to be apparent between the collector to the emitter e.g., via ambient plasma, vacuum chamber wall, and plasma simulator. The currents from the earth to the plasma simulator were measured. Figure 5 is a plot of current from the earth to the plasma simulator against the plasma contactor current. The current decreases and has a minimum at -0.15 A, then increases as the plasma contactor current is raised to 3.8 A, above where the plasma simulator current does not show a dependence on plasma contactor current. These tendencies are considered to be from electrons that are collected with a physical anode of 12 cm diameter at low current, as 60 V of bias voltage is applied to the anode shown in Fig. 4(b). The voltage difference forms electric fields towards the plasma simulator, and electrons are accelerated to the anode. The collector operation mode translates to ignited mode at the minimum point. Then, plasma cloud is formed and electrons are collected with the cloud surface as a virtual anode. Electrons are accelerated at the double layer only. After this transition, the plasma simulator is almost unaffected by the contactor voltage difference. But this change is small compared with the plasma contactor current, and the current path through the chamber wall and the plasma simulator can be neglected. The current flow between the plasma contactors is formed from the collector to the emitter via ambient plasma.

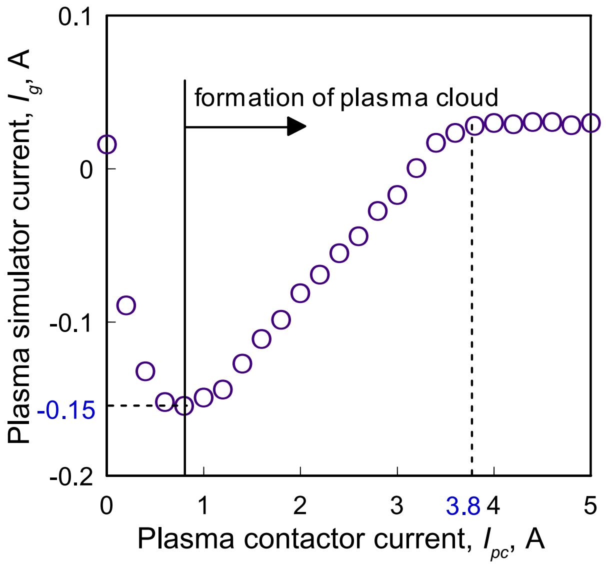


Fig. 5 Current to the simulator from the earth.

Interaction of Plasmas

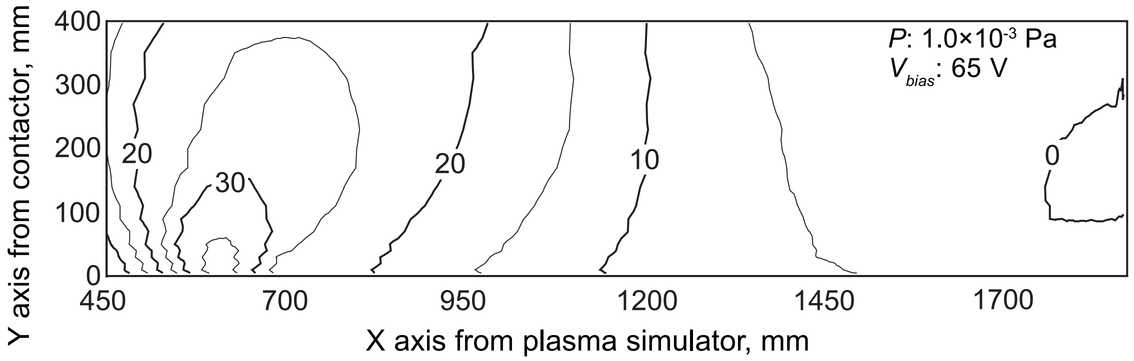
It can be considered a possibility that the current loop is directly formed between the emitter and the collector. This means that the plasmas emitted from each plasma contactors interact with each other and not interact with ambient plasma generated by the plasma simulator, since the distance of plasma contactors is about 1 m. To evaluate this possibility, the plasma potential profiles were measured in the following cases.

Case a: Without an ambient plasma (Plasma simulator does not operate in this condition)

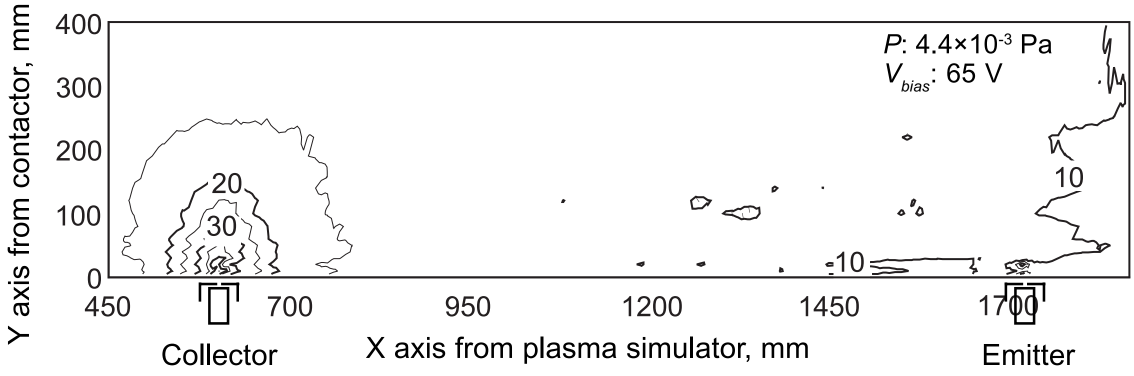
Case b: With an ambient plasma (Plasma simulator operate in this condition)

As a supplementary explanation, the plasma potential profile was uniform all over the vacuum chamber when the plasma simulator operated alone. The plasma contactors are located at X: 600 mm, Y: 0 mm (collector) and X: 1720 mm, Y: 0 mm (emitter). The voltage of bias power supply was fixed at 65 V during the measurements. Figure 6 shows the measurements of opposite role operation of the plasma contactors in Fig. 1. The switches were changed EE to EC at the middle hollow cathode and EC to EE at the right side hollow cathode in Fig. 1.

Figure 6(a) illustrates the plasma potential profile in the vacuum chamber without ambient plasma. Figure 6(b) is that with ambient plasma. It appears that the plasmas affect each other from reason of the potential variation having gradually changed all over the vacuum chamber in Fig. 6(a). This potential variation represent a gentle electric field was formed toward the emitter. And electrons reach to the collector from the emitter. The plasma contactor current was 50 mA in this measurement. In this case, the plasmas interact each other and current loop was formed directly between



(a) without ambient plasma at 50 mA contactor current.



(b) with ambient plasma at 5 A contactor current.

Fig. 6 Plasma potential profiles in vacuum chamber.

the collector to the emitter.

As shown in Fig. 6(b), potential variation has large potential difference near the collector and the emitter. Indicated is that double layer was formed at the boundary between a plasma cloud and ambient plasma. The plasma cloud has a diameter of approximately 15 cm. The plasma contactor current was 5 A in this measurement. There is a constant potential region between the plasma contactors where ambient plasma exists. This measurement shows that the plasmas emitted from the plasma contactors do not directly interact each other. It can be said that the current loop via ambient plasma was confirmed in Fig. 6(b).

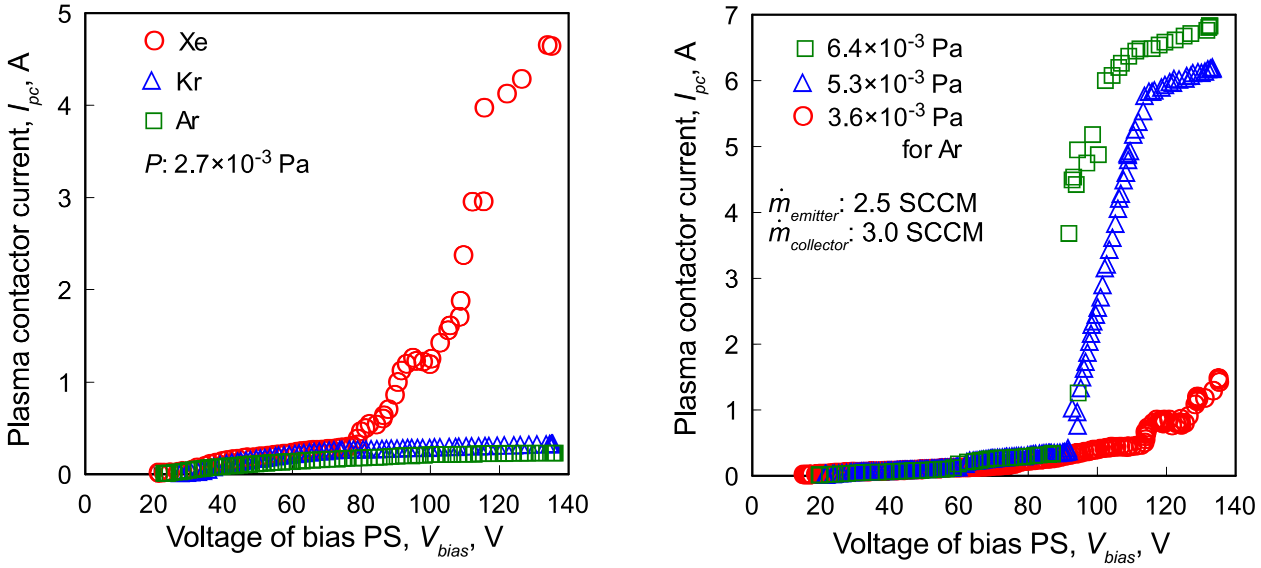
Scaling Law

Since the geomagnetic field intensity decreases with raise a spacecraft altitude, it is considered that the effective altitude of the electrodynamic tether system is 200 km to 6,000 km[13]. It is indicated that to collect ampere level current at collector needs large sized plasma cloud such as several hundred meter or several kilometer in space. To find the law of scaling from space to the ground experiments is indispensable to evaluate the performance of plasma contactor correctly. Williams *et al.*[6] described that several constrains as follow have to be taken account to simulate an ideal space environment in vacuum chamber.

1. similar ambient ionic/atomic species concentrations
2. similar ambient plasma density and temperature levels
3. similar magnetic field intensity and relative contactor /magnetic field velocity conditions
4. an ambient plasma that is not perturbed by vacuum chamber walls or other apparatus.

All of the conditions are not necessary to conduct the ground experiments. Most of study have not been met these conditions. It is necessary to distinguish the dominant factors.

Up until now we have discussed some of the result operated both the plasma contactors and the plasma simulator by xenon. Thus, the background neutrals are principally xenon coming from the contactor and the simulator. Electrons collide these neutrals and ionize. As a result, plasma density and temperature become greater than those expected space condition. The experiments that operated the contactor and the simulator by argon and krypton were conducted to identify the affect of working gas species.



(a) Working gas dependence.

(b) Vacuum level dependence.

Fig. 7 Comparisons of performance curve.

Figure 7(a) represents the current-voltage characteristics at three kinds of gases. Vacuum level for each gas was fixed to 2.7×10^{-3} Pa (2.0×10^{-5} Torr) during the measurements. The plasma contactor current decreases in the order of the increase of ionization energy at the same bias voltage. By applying higher bias voltage for the case of argon and krypton, the current increases like xenon. This tendency indicates that plasma contactor current depends on the ionization at the collector. Thus, plasma contactor current is affected by the characteristics of working gas such as ionization energy and ionization cross-section. Therefore xenon is suitable for working gas. But these gases are not ionospheric species, the gases as background neutrals have influence on the ionization near the collector. That is to say, the ionization of background xenon leads to the increase of plasma contactor current.

Figure 7(b) shows the current-voltage characteristics at different vacuum level. Xenon was fed to the contactor and argon was fed to the simulator to minimize the affect of background xenon gas. The bias voltage at the transition point to ignited mode decreases with decreasing the vacuum level. The mean free path at electron-argon collision is 35 m for 3.6×10^{-3} Pa (2.7×10^{-5} Torr), 24 m for 5.3×10^{-3} Pa (4.0×10^{-5} Torr) and 20 m for 6.4×10^{-3} Pa (4.8×10^{-5} Torr). Because these mean free paths are long compared with vacuum chamber length, it seems that the influence of the collision between electron and background argon is small. But electron collection at the collector with plasma cloud depends on the vacuum level. There are some affect the ionization near the plasma cloud.

Conclusions

Following conclusions were obtained in this study.
1. The closed loop operation of the emitter and collector was successfully performed at the current level of 5 A.
2. The performance curve and potential profile during the simultaneous operation of the emitter and the collector were obtained.
3. They show that collector operation needs of applying higher voltage than emitter operation, because of there are some voltage drop at double layer. Thus, the collector performance becomes dominant on the electrodynamic tether system.
4. The factors affecting the scaling between the ground and space experiments were discussed. The results show that the vacuum level and working gas as background neutral species affect the plasma contactor current. Although there are many factors to confirm the scaling, we will go forward this study to design scaling model.

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