EVALUATION OF ELECTRODYNAMIC TETHER PROPULSION TO OTV

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Abstract

An electrodynamic tether is one of the applications of tether system, and it can work as a thruster and a power generator by altering the direction of the current. The performance of electrodynamic tether as a thruster is described in this paper by Orbital Transfer Vehicle (OTV) mission analysis and plasma contactor experiments. In the mission analysis, the optimum altitude range for the electrodynamic tether propulsion was estimated. Also obtained from the calculation was that the performance of a plasma contactor has considerable effects on the overall tether system performance. Therefore it is necessary to understand the physical phenomena in plasma contactor operation. As a first step of the experimental approaches, the plasma contactor operation in a simulation plasma was conducted using a hollow cathode and some meaningful result were obtained.

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 tether, artificial gravity generation by rotating two bodies connected with tether and measurements of upper atmosphere by multi probes on the long tether. The Electrodynamic tether is a kind of tether application that possesses 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 (It is called J x B effect). So, it can use for orbit raising thrust force or orbit lowering drag force depending on the direction of the current. Electrodynamic tether also has the potential to provide a near-propellantless propulsion system, using the energy from sunlight converted to electrical energy. Therefore, electrodynamic tether system can be applicable for various missions such as station-keeping, power generator, orbit raising, and the deorbit of large-sized debris when some practical problems such as the tether cutting would be solved.

ProSEDS space experiment[1], which is proposed by NASA Marshall Space Flight Center will demonstrate the use of electrodynamic tether propulsion system. This mission demonstrates that the drag thrust will deorbit the Delta II upper stage to reduce the debris on orbit. The other hand, similar mission[2] is proposed in Japan. It is considered that H-II upper stage deorbit system using electrodynamic tether.

If electrodynamic tether is applied to OTV, it is important to make a comparison of the performance between electrodynamic tether and other propulsion systems such as ion propulsion. On the other hand, the performance of electrodynamic tether propulsion system depends on the plasma contactor electron emission and collection processes. It is important to validate the contactor emit or collect current phenomena by experiments.

There are several types of plasma contactors such as sphere used TSS-1R[3], electron gun, hollow cathode, bare wire[4] that was adopted in ProSEDS and the field emitter array that is being considered by the Terminator Tether™[5].

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It has been reported that the hollow cathode plasma contactors are able to emit and collect ampere-level electron currents with low impedance[6]. And the largest advantage of the hollow cathode plasma contactor is that the same device can both emit and collect electrons. The electrodynamic tether that uses the hollow cathode plasma contactor can generate orbit-rasing or orbit-lowering thrust force, depending on the direction of current through the tether. Thus, a hollow cathode plasma contactor is the ideal device to provide electrical connection with the space plasma for electrodynamic tethers.

Some analytical investigations[7-9] and experimental studies[10-12] of electrodynamic tether have been conducted. In this study, to evaluate the performanc of electrodynamic tether propulsion, OTV mission numerical analysis and the plasma contactor experiments using hollow cathode have been performed as a first attempt.

OTV Mission Analysis

Simulation Model

The numerical simulation of the orbit-rasing mission using the electrodynamic tether at lower earth orbit is conducted and the calculation results are compared with the result of ion thruster applicated case[13]. The performance parameters to be compared are thrust, specific impulse, transfer time and payload ratio.

The models of this analysis are based on two-dimensional motion on the equatorial plane, two bodies problem between the space vehicle and the consideration of the earth shadow. The assumptions of this analysis are summarized in Table1.

Table 1 Assumptions

Tether Length	L	[km]	10
Tether Current	I	[A]	10
Initial Mass	M_0	[kg]	8000
Initial Orbit Altitude	H_0	[km]	500
Propellant			Xe
Propellant Flow Rate	$\dot{m}$	[SCCM]	9

When the conductive tether with current flow I across the geomagnetic field, the Lorenz force is induced by the interaction between the current and the geomagnetic field.

$$T = IB_H L \tag{1}$$

Where B_H is the geomagnetic field strength and L is the tether length.

$$B_H = B_0 \cos\varphi \left(\frac{R_e}{R_e + H} \right)^3 \tag{2}$$

This Lorenz force becomes thrust for the electrodynamic tether.

For the tether system by using hollow cathode as a plasma contactor, the plasma cloud that is formed adjacent to the plasma contactor enables the tether system to interact with ionospheric plasma. As a result, electrical circuit is formed between the tether wire and ionosphere. Besides, hollow cathode needs working fluid for its operation. The working fluid is important role in electrodynamic tether to flow the current. Therefore, we defined the equivalent specific impulse to electrodynamic tether by considering the working fluid as a propellant. The equivalent specific impulse is represented by next equation.

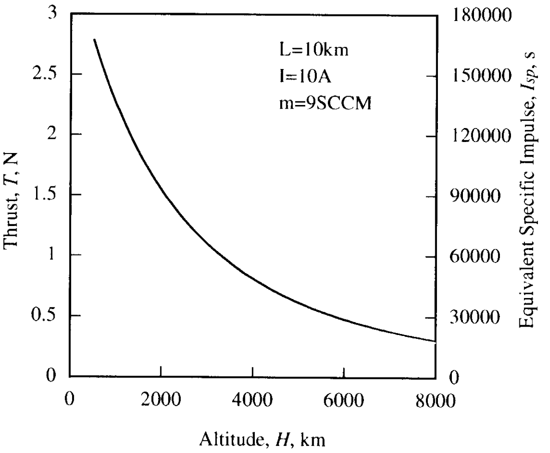

Fig. 1 Variation of thrust and equivalent specific impulse

$$I_{SP\text{-}eq} = \frac{T}{2\dot{m}_{eq} g} \tag{3}$$

Since the hollow cathode is mounted both ends of tether, as an emitter and a collector, the propellant consumption is twice the amount.

Required power of the electrodynamic tether system is represented by the next equations.

$$P = \frac{IV_D}{\eta_P} \tag{4}$$

$$V_D = V_{ind} + IR_T + \Delta V_{pc} + IR_P \tag{5}$$

Where η_P is the power utilization efficiency. In this equation, the induced electromotive force V_{ind}, voltage drop in the tether wire IR_T, voltage drop at plasma contactor ΔV_{pc} and the voltage drop in the ionosphere IR_P were included. The voltage drop at the plasma contactor is derived from the theoretical model[14] between the plasma cloud formed by plasma contactor and the ambient ionospheric plasma.

System mass details is designated by the formula,

$$M_0 = M_{pl} + M_p + M_W + M_s + M_T \tag{6}$$

Where M_{pl} is the payload mass, M_p is the propellant mass, M_W is the power source mass, M_s is the structure mass, and M_T is the tether mass.

Results of Analysis

Figure 1 shows the variation of thrust and equivalent specific impulse with altitude for tether length

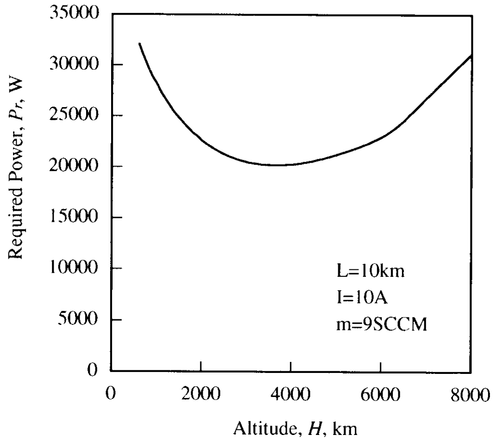

Fig. 3 Variation of required power with altitude

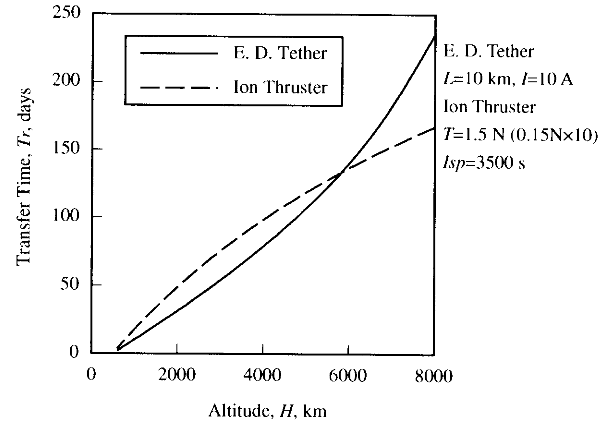

Fig. 4 Comparison of transfer time

Table 2 Mass details

		Electrodynamic tether	Ion thruster
Propelannt	[kg]	28	477
Structure	[kg]	257	255
Power source	[kg]	643	953
Tether	[kg]	93	
Payload	[kg]	6979	6315
Payloac ratio		0.87	0.79

of 10 km, tether current of 10 A and propellant flow rate of 9 SCCM. Both thrust and equivalent specific impulse decrease with increase in the altitude. This is because the geomagnetic field strength is inversely proportional to the cube of the orbit radius. More noteworthy in this figure is that the ten-thousand order equivalent specific impulse is obtained. This is the strong point of electrodynamic tether propulsion.

Required power as a function of altitude is shown in Fig. 2. It varies with altitude change. The power source must supply against the electromotive force in low earth orbit. It needs large amount of power. The voltage drop at plasma contactor is increased in the altitude rising because the plasma electron density decrease with increase in the altitude. Plasma contactor must form large plasma cloud to operate with constant current.

Figure 3 shows comparison of transfer time for electrodynamic tether propulsion, where tether length is 10 km and tether current is 10 A, and ion propulsion with the thrusts of 1.5 N and the specific impulse of 3500 s. In low earth orbit, as electrodynamic tether generate large thrust compared with ion engine, it arrives at the target altitude faster than ion propulsion to the altitude of about 5800 km. Above this altitude, electrodynamic tether would takes a long time because of the thrust degradation.

Table 2 indicates the mass details of each system. Electrodynamic tether shows high specific impulse in Fig. 1. It affects the mass of payload. Thus, the payload ratio of electrodynamic tether is higher than that of ion thruster. The result shows that electrodynamic tether excel in the ability of OTV to ion thruster. But, the target altitude is limited by required power and transfer time.

The results of this study analyzed only orbit raising. The performance will improve by utilizing the induced electromotive force for power source.

Experimental Apparatus and Procedures

To study the interaction between the plasma that generated by plasma contactor and simulated plasma, the apparatus shown schematically in Fig. 5 was constructed. This apparatus consists of two devices. The one is the hollow cathode plasma contactor shown at the left side. The hollow cathode used was Ion Tech. HCN 250. The other device is plasma simulator that simulates ionospheric plasma shown at the right side. The cusped ion thruster with the beam-exhausting diameter of 14 cm is used as the simulator. It consists of hollow cathode, discharge chamber of 14 cm diameter, and screen and accelerator grids.

Xenon was used both plasma contactor and simulator as a working fluid.

The experiments were conducted in 1.6 m diameter by 3.2 m in length cylinder space chamber. The vacuum environment was maintained using a turbo molecular pump and two cryogenical pumps. The ultimate pressure in this chamber is 6.7×10^{-5} Pa (5.0×10^{-7} Torr), and the pressure during the experiments was approximately 1.0×10^{-3} Pa (1.5×10^{-5}Torr).

The measurements began by measuring the plasma distribution in the space chamber that is formed by the plasma simulator. To simulate the ionospheric plasma in the limited space, the plasma electron number density is needed to be more than that of the ionosphere. The simulator was operated with change in the following parameters: discharge current, propellant flow rate, screen grid and accelerator grid bias voltage.

Plasma contactor was located in 1 m from plasma simulator as illustrated in Fig. 5. It was decided that the electron number density of simulate plasma showed uniform distribution at the place. The experiments were conducted at 2.0 A discharge current, the propellant flow

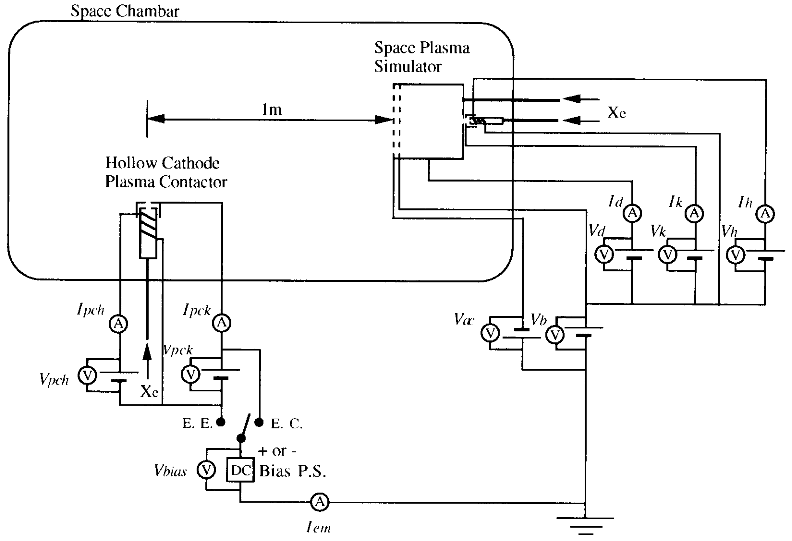

Fig. 5 Schematic of apparatus

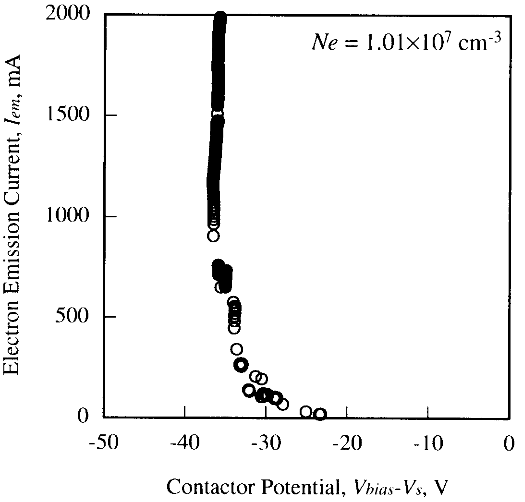

Fig. 6 Variation of electron emission current with contactor potential.

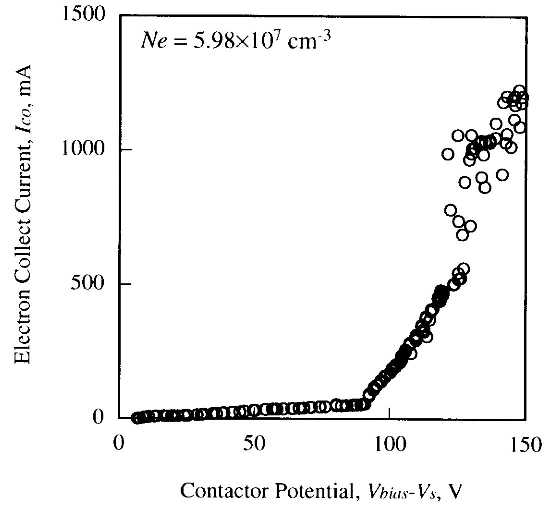

Fig. 7 Variation of electron collection current with contactor potential.

rate of 5.6 SCCM, the cathode flow rate of 2.4 SCCM and no bias voltage both screen and accelerator grid for simulator, and 0.1 A keeper current, 5.0 A heater current and the flow rate of 3.0 SCCM for plasma contactor. The measurements were conducted at 1250 mA emission current and 450 mA collection current with the emissive probe and the Langmuir probe. The mode of the plasma contactor operating was changed by the switch connect to Electron Emission (E. E.) or Electron Collection (E. C.) in Fig. 5.

Results and Discussions

The electron current emitted and collected as a function of the voltage difference between the plasma contactor and the simulation plasma are shown in Fig. 6 and Fig. 7. Also, reference result[10] show in Fig. 8. The emission current increase abruptly at the potential of -36 V. The collection current increase gradually up to 90

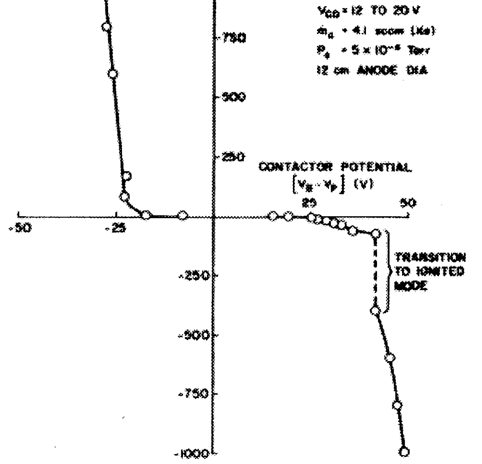

Fig. 8 Measurement of contactor performance by Williams *et al.*[10]

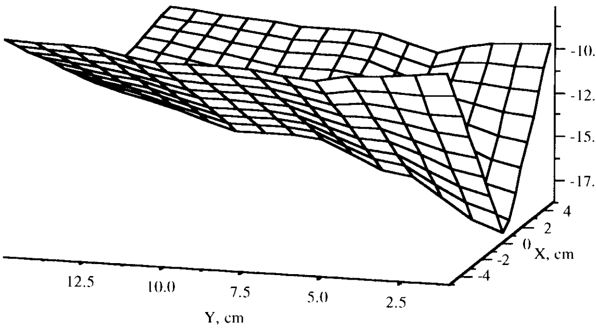

Fig. 9 The potential profile of emit mode at 1250 mA emission current

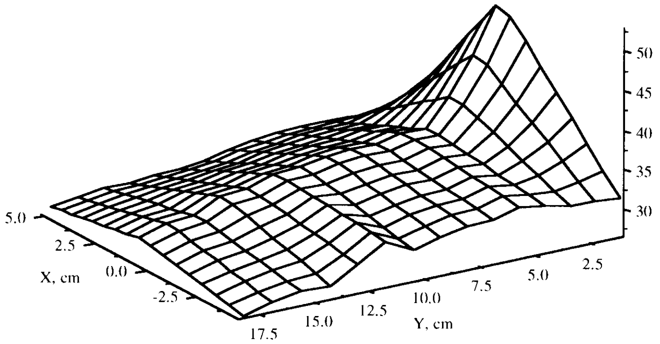

Fig. 10 The potential profile of collect mode at 450 mA collection current

V, above which it increases abruptly. In the collect mode, ignited mode of operation was observed, in spite of the discharge became unstable above 130 V. The potential difference of contactor operated collect mode is twice as large as the result of Williams et al. It is considered by the reason that electron collection area at plasma contactor is small compare with that of Williams et al. They used 12 cm diameter plate as an anode. Although the contactor potential is high, these figures correspond to the result of Williams et al.

Figure 9 and Figure 10 show the potential profile of electron emit and collect mode. The potential profile shows a moderate gradient at electron emission mode. But the potential near the contactor drops rapidly approximately 20 V. The collector potential could not measure at ignited mode in this study. Thus, the double layer was not observed in this result.

Conclusions

Following conclusions were obtained in this study.

1. Mission analysis of electrodynamic tether to OTV was conducted and compared with the result of ion thruster by adopting the equivalent specific impulse.
2. Although the target altitude was limited, the results show that the electrodynamic tether propulsion possesses better performance compared with an ion thruster for OTV use.
3. The hollow cathode plasma contactor was successfully operated in a simulation plasma.

Future Work

To understand the interaction between the plasma contactor and the ambient plasma, it is necessary to test other devices such as bare tether. Also it is important to evaluate the performance of emitter and collector with operate together in the simulation plasma.

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