Development of $J \times B$ Arc Discharge Thruster Using Metal and Gas Propellants for Future Space Transporters

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Abstract: In order to transport a large amount of materials from the lower orbits to the geostationary orbit in low cost, a new type electric thruster using solar energy has been considered to be developed. For this target, a parallel electrode $J \times B$ arc discharge thruster using metal wire and gas propellants has been developed. The discharge is ignited by contact of a metal wire to a carbon cathode. In this experiment, thrust of around 0.12 N and the specific impulse of around 1000 s are obtained under the condition of 500 A of discharge current, 25-45 mT of magnetic field and 10 kPa of argon gas. By automatic feeding of the metal wire, the automatic repetitive-pulse-discharge is successfully carried out. We are now trying to improve the thruster by increasing the input power and by modifying the electrode shape.

Nomenclature

B_0	=	applied magnetic field density
d_G	=	gap distance
F_t	=	force to the target
I_d	=	discharge current
p	=	gas pressure
T	=	thrust
t	=	time
t_d	=	discharge time

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I. Introduction

Near future, people will go into our solar system and construct many space bases.[1] Near the earth, space solar power systems (SSPSs)[2] and debris removal systems will be developed. For these projects, however, there are many problems to be solved. One of the major problems is the sending cost of construction materials to the space, for which more than 10,000 US$/kg is needed. To construct a SSPS station, 10 thousand tons of construction materials should be transported to the geostationary orbit (36000 km high). In order to reduce the transportation cost dramatically, development of new propulsion systems for space-transporters is necessary. Here, we are considering about a model of combinational-transportation system as shown in Fig. 1. To transport cargos to the lower orbit (about 400 km high), the chemical propellers are used. From this orbit to the geostationary orbit and further altitude, electric propellers[3, 4] will be used, which are driven by the solar energy and the transporters stay in the orbits.

To realize this electric propellers, we are studying about a ***J*x*B*** arc discharge propeller.[5-8] In order to suppress the operation price, the solar energy should be used. And the propellants should be cheap and have high efficiency. Long operation time, robustness and simple structure are also needed.

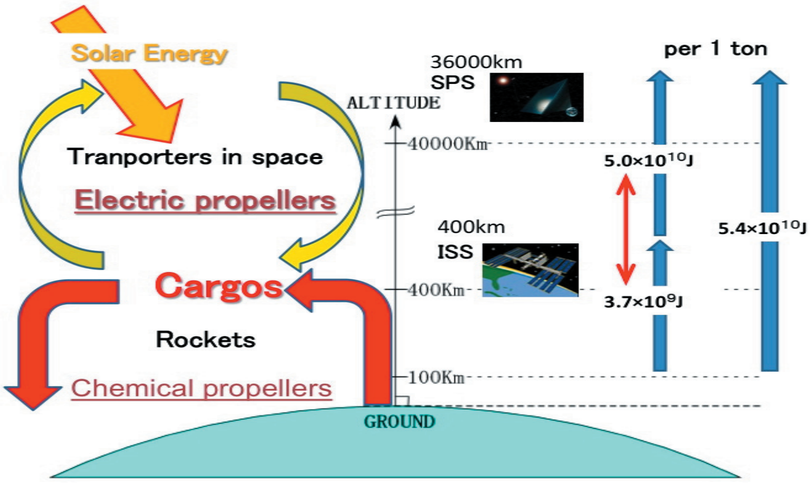


Figure 1. The model of combination system for the transportation of cargos to the geostationary orbit.

Model schematic of the ***J*x*B*** arc discharge thruster[9] is shown in Fig. 2. By using a DC power source, an arc discharge is ignited at one end of the parallel plate electrodes, where a steady magnetic field is applied by a set of magnetic coils. By the ***J*x*B*** force, the plasma is accelerated to the ***J*x*B*** direction and jetted out from the other end (exhaust nozzle). Previously, gas material is used as propellant.[9] Here, both solid (a metal wire) and argon gas are used as propellants.

By increasing the discharge current and the magnetic field, we can increase the thrust force. To the efficient use of the propellants, efficient ionization of gas and solid materials is required. One of our major targets of this study is to develop the high-efficiency thruster using this style. Here, we write about the developed machine, and basic properties of the discharge as a function of discharge parameters (discharge current, magnetic field, gap distance, gas pressure *etc*.) .

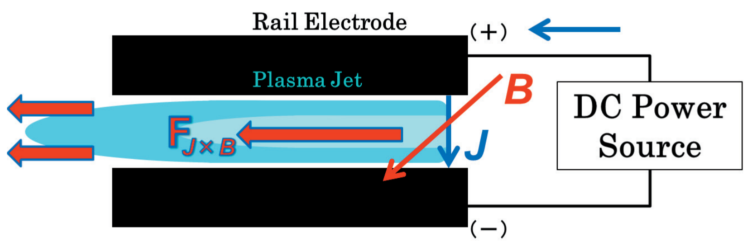
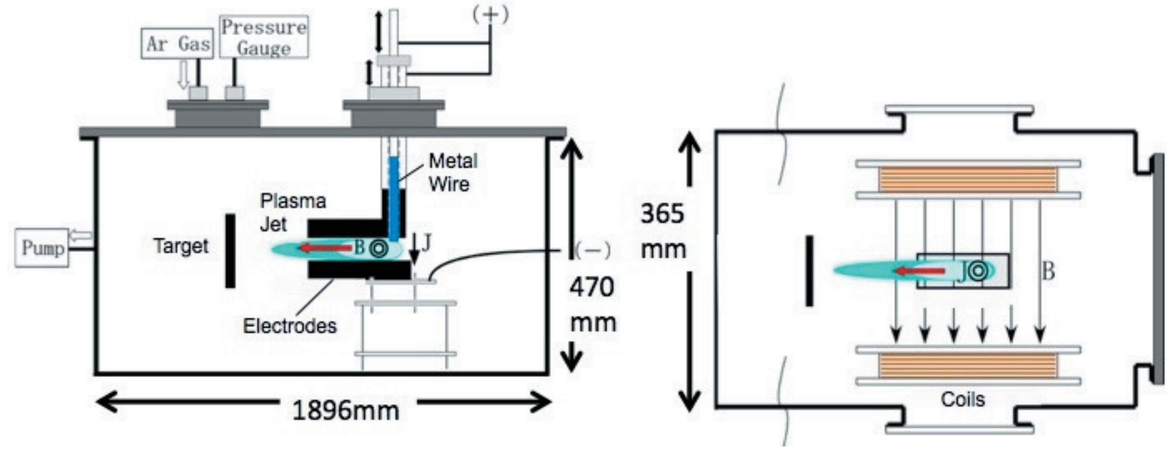


Fig. 2. Schematic of the *J*×*B* arc discharge thruster.

II. Experimental Setup and Method

Figure 3 shows schematic of the experimental setup. In a rectangular vacuum chamber (1896 x 365 x 470 mm), two carbon electrodes, a pair of solenoid coils and a target are set. The chamber is evacuated by a rotary pump. During the experiment, the chamber is closed and a fixed pressure of Ar gas is introduced. By the magnetic coils, 0 – 50 mT of magnetic field can be applied in the discharge region. Schematic of the parallel–plate carbon electrodes is shown in Fig. 4 (the lower electrode (cathode) has 80 mm long, 22 mm wide and 10 mm thick). An L-shaped upper electrode (anode) has a vertical hall, where a metal wire goes through. A metal wire (solid propellant like an iron wire or an aluminum wire) is fed from upper side using a motor drive to the lower carbon electrode. The discharge current is 0 – 500 A (0 – 45 V) supplied by a DC power supply (Daihen Co. MR-500). By moving the wire and contacting the lower electrode, the arc discharge starts, and the lower part of the wire sublimates by the discharge current. After the pulsed discharge, the wire is moved again to the lower electrode, and the pulsed discharge repeats. The produced plasma is accelerated to left direction by the $\boldsymbol{J}$x$\boldsymbol{B}$ force, and it jets out from the end of the electrodes. The plasma jet hits a metal target (Mo disk, 100 mm in diameter) located near the electrodes, and thrust force is measured by this target. The target is connected to an electric force meter (Imada Co., ZTA-i), which records time variation of the force. Time variation of the discharge plasma is recorded by high-speed cameras.



(a) Side view. (b) Top view.

Fig. 3. Schematic of the experimental setup. The chamber is made of stainless steel.

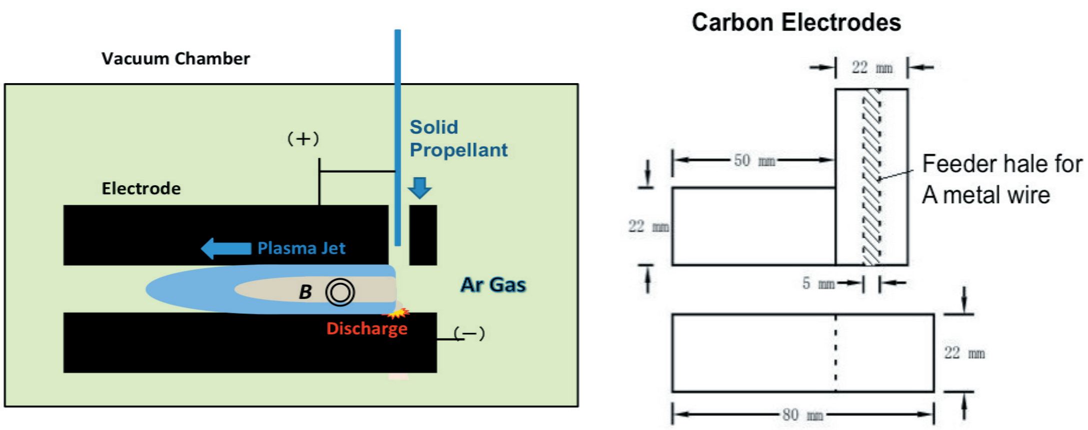


Fig. 4. Schematic of the electrodes (carbon plate type).

III Experimental Results and Discussions

Typical image of the discharge is shown in Fig. 5 (profile), where the plasma jets out to the left direction. Figure 6 shows the force to the target F_t as a function of discharge current I_d. As almost all the plasma jet hits this target and the elastic collision is expected, the thrust T is estimated to be $T\sim 0.50\ F_t$. As the ***J***x***B*** force increases by increasing the discharge current, F_t (thrust) increases by increasing discharge current. F_t as a function of applied magnetic field B_0 is shown in Fig. 7. As the Lorentz force increases by increasing the magnetic field, F_t increases with B_0. Figure 8 shows F_t as a function of gap distance between the electrodes. An optimum distance exists around d_G= 10 – 13 mm.

Figure 9 shows discharge time t_d as a function of applied magnetic field, where I_d = 500 A. As the magnetic field increases, the discharge time decreases. When the magnetic field is less than 25 mT, continuous discharge often takes place. From the calculation of transit time of the plasma sheet, the discharge time should be short. However, the discharge time in our experiment is much longer. So, the generation and propagation of the plasma sheet is not so simple, and it could be wider and it would be re-generated automatically after the one plasma sheet is jetted out. The discharge is not so simple and it should be analyzed carefully.

When we keep the metal wire inserting by the motor drive, automatic repetition of the discharge can be obtained. Figure 10 shows time record of F_t for about 12 s. The insertion rate of the wire is about 2 mm/s. We could obtain repetition of the arc jet. However, the F_t and the discharge time are not so constant, for which we should analyze and improve these properties in future.

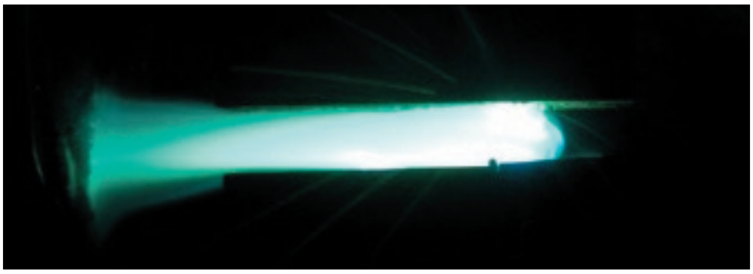


Fig. 5. Typical image of the discharge plasma (profile).

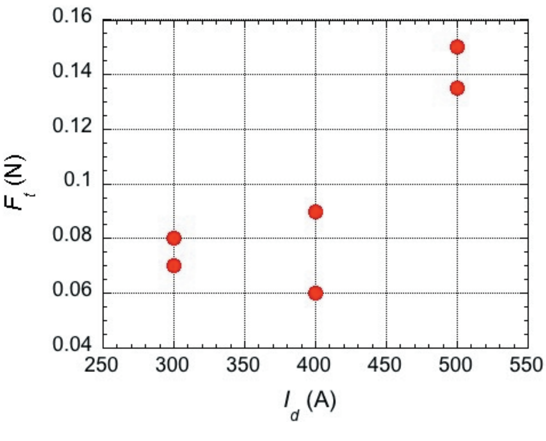


Fig. 6. Force to the target, F_t versus discharge current I_d. B_0= 27.5 mT, p(Ar)= 10 kPa. An iron wire with 1.0 mm in diam is used.

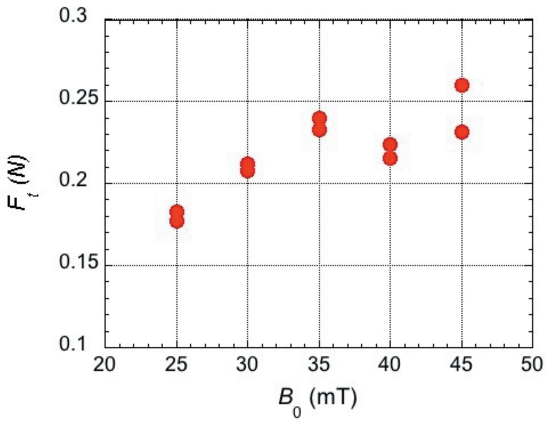


Fig. 7. F_t versus applied magnetic field. I_d= 500 A, p(Ar)= 10 kPa. An iron wire with 3.0 mm in diam is used.

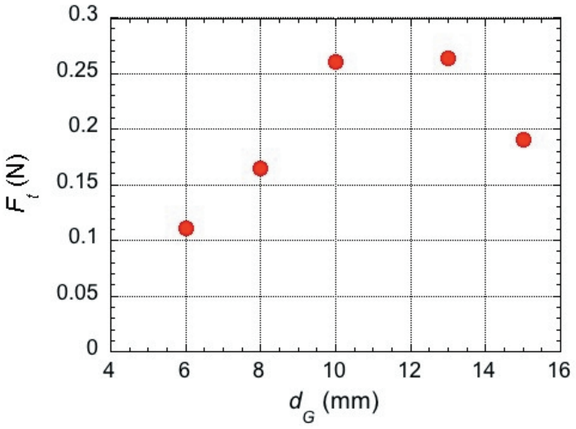


Fig. 8. F_t vs. gap distance between the electrodes d_G. I_d= 500A, B_0= 27.5 mT, p(Ar)= 10 kPa. An iron wire with 3.0 mm in diam is used.

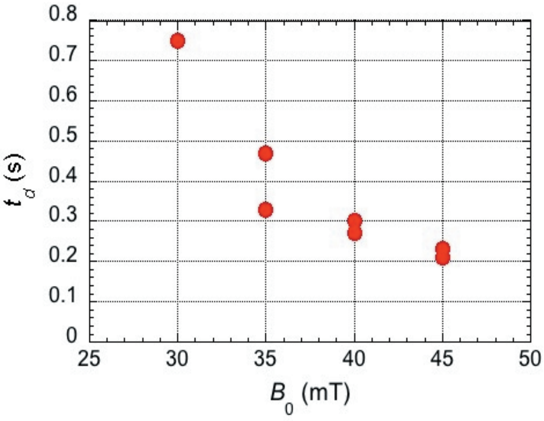


Fig. 9. Discharge time t_d vs. applied magnetic field B_0. I_d= 500 A, p(A)= 10 kPa, d_G= 10 mm. An iron wire with 1.0 mm in diam is used.

When we change Ar gas pressure, the property of the arc jet dramatically changes. When the pressure is less than 5 kPa, F_t (thrust) considerably decreases as shown in Fig. 11. In this condition, the discharge time tends to increase and continuous discharge often takes place. The plasma spreads over between the electrodes. We changed the discharge conditions and repeated the experiment. However, every time, this decrease of F_t is observed. So, at the present time, Ar gas is necessary for the good thrust force. Ar gas would make a well-shaped plasma sheet and accelerates the plasma and gas species, effectively. In case of only the metal vapor, the thrust is weak. We must measure the plasma density and particle density as a function of Ar pressure at the electrode-region, and investigate this mechanism, near future.

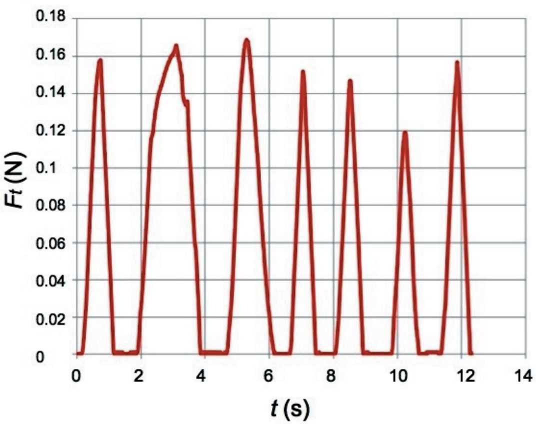


Fig. 10. Time record of the thrust forces in an automatic-repetitive pulse-discharge. I_d= 500 A, B_0= 25 mT, p(Ar)= 10 kPa. An iron wire with 1.0 mm in diam is used.

In order to use Ar gas, pulse-valve-injection system of Ar gas is now under preparation. The gas will be injected to the electrode-region, and the electrodes are covered with ceramic insulators as shown in Fig. 12. During the pre-examination, there was little damage on the insulators. We will utilize the pulse-injection of Ar gas to the discharge area near future to realize efficient use of Ar gas.

Compared with the simple ***J*x*B*** discharge model as shown in Fig. 2, the experiment included complex phenomena, which should be analyzed. When the Ar pressure is low, the plasma was weakly accelerated to the exhaust direction, and it sometimes stays at the electrode-region. I think that some pinning effect exists on the carbon electrode, which interrupt movement of the plasma sheet. We conjecture that the secondary-electron-emission from the carbon cathode-electrode by ion bombardment strongly depends on the carbon temperature. When the cathode is heated locally only by the discharge current, only the ignition part is heated, and the pinning effect takes place. When the Ar gas pressure is higher, the cathode is widely heated by the plasma and the pinning effect becomes weaker. When the Lorentz force is stronger, the situation would be changed. We need more study about this pinning effect.

When the magnetic field is less than 25 mT, the discharge plasma often does not extinguish and it continues, where the plasma stays at the exhaust part and the plasma jet continues from the exhaust region. From the simple ***J*x*B*** acceleration, the produced plasma sheet is accelerated to the exhaust, jetted out and extinguishes. In our experiment, however, the discharge time is usually much longer than that of one plasma jet, and sometime the

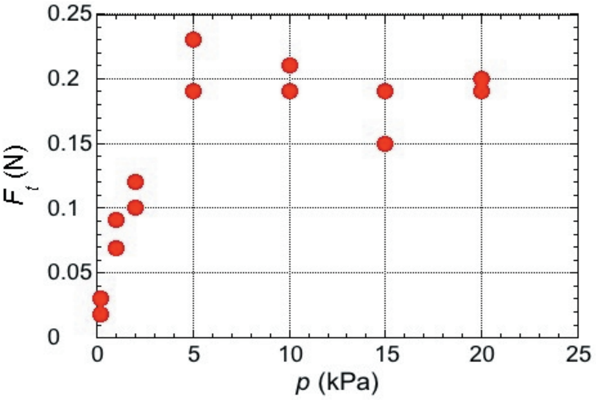


Fig. 11. F_t vs. Ar gas pressure. I_d= 500 A, B_0= 27.5 mT. An iron with 3.0 mm in diam is used.

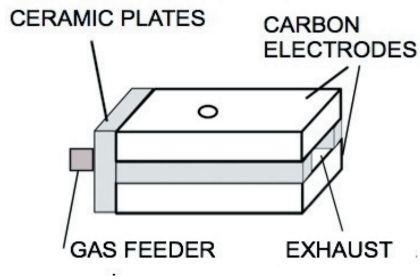


Fig. 12. A new electrodes covered with ceramic plates, by which Ar gas will be efficiently used.

plasma does not extinguish. For this phenomenon, we conjecture that the plasma sheet is automatically re-generated in the electrode region after the plasma sheet is jetted out, and this phenomenon repeats again and again, in which the plasma heats both the electrode's surfaces, and there is high-enough electric field to re-start the discharge. We also should make clear this important phenomenon.

IV Conclusions

We can conclude about the research described here as follows:

1) We could realized the ***J*x*B*** arc discharge thrusterin our newly developed equipment.
2) At the conditions of I_d= 500 A, p(A)= 10 kPa using an iron wire, we could repeatedly make a discharge plasma and it is jetted out to the target. The thrust of about 0.12 N, specific impulse of about 1000 s, and ejection speed of 1- 10 km/s at input power of about 10 kW are obtained.
3) The thrust usually increases by increasing the magnetic field and the discharge current. More than 5 kPa of Ar gas is necessary to obtain good thrust. 10 – 13 mm of the gap distance between the electrodes is good for the good thrust.
4) When the magnetic field is less than 25 mT, the discharge is often continuous. And the discharge time is usually much longer than the one acceleration time of the plasma sheet, which means that automatic re-generation of discharge takes place and the longer discharge time is obtained.
5) When the Ar pressure is less than 5 kPa, the thrust is weak and the plasma is less accelerated. In our experimental conditions, feed of Ar gas is necessary. For the efficient use of Ar gas, pulsed-injection of Ar gas to the electrode region is necessary. The electrode region is covered with ceramic plates to obtain adequate use of Ar gas. This pulse-injection of Ar gas will be examined near future.

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