A Preliminary Study of Mars Air-breathing Electric Propulsion

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Abstract: In order to investigate the applicability of electric propulsion in Martian atmosphere, a rectangular microwave electron source and a cylindrical plasma source were designed and fabricated. The design of this plasma source was based on a cylindrical hall thruster. Through some experiments, it was confirmed that the plasma source was able to be operated with the electron produced by the microwave electron source in the simulated Martian atmosphere, and that carbon dioxide was dissociated by both microwave discharge and dc discharge. More detailed investigation and improvements are necessary to discuss the applicability.

I. Introduction

MARS is covered with carbon dioxide enriched atmosphere. Because there is little oxygen gas in Mars, almost fuels for chemical propulsion do not burn in the Martian atmosphere. Electric propulsion, typical non-chemical propulsion, may be appropriate for the Martian atmosphere propulsion. However, dissociation of carbon dioxide occurs in discharge plasma. Therefore, hollow cathodes, typical electron source of electric propulsion, may not be applied to the plasma production because the cathode is damaged by the dissociated gas: carbon dioxide and oxygen. Because microwave discharge is a kind of electrodeless plasma production, this discharge type may be appropriate for the Martian atmosphere plasma production.

The purposes of this preliminary study are (1) design of microwave electron source and cylindrical plasma source, (2) operation of both the sources in simulated Martian atmosphere, and (3) investigation the applicability of Mars atmosphere electric propulsion.

II. Mars Atmosphere

The main component of Mars atmosphere is carbon dioxide. The concentration of carbon dioxide is approximately 95% [1)]. The temperature and pressure of Mars atmosphere have seasonal fluctuation of approximately 30%. The typical temperature of the atmosphere is 240 K, and the typical pressure is 0.7 kPa. The relationship between the typical pressure (p [kPa]) and the altitude (h [m]) is expressed in the following equation:

$$P = 0.669 \exp(-0.00009 h)$$

The ionization cross section of carbon dioxide is shown in figure 1 [2)]. This figure shows that this cross section is comparable to that of argon or krypton, and that the first ionization potential is almost equal to that of xenon. However,

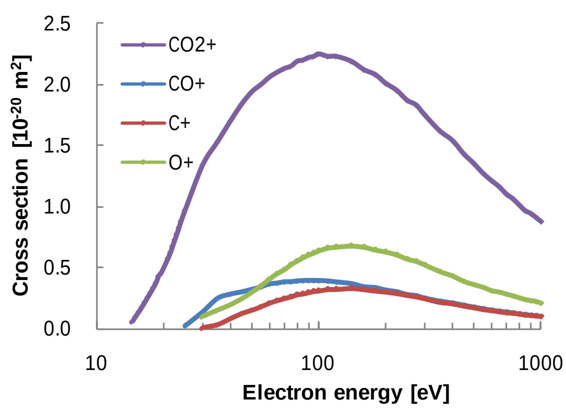


Fig. 1 Cross section

this figure also shows that carbon dioxide is dissociated against over 19 eV electron. The produced components of this dissociation are carbon oxide, oxygen and carbon. These dissociated gases affect the operations of electron source such as hollow cathode, filament cathode, and so on.

III. Thruster and Apparatus

A. Rectangular Microwave Electron Source (“mw”)

The shape of “mw” is two-dimensional rectangular parallelepiped as shown in figure 2. The plasma is generated by microwave discharge. The frequency is 2.45 GHz. This “mw” are composed of three rectangle iron plates, SmCo permanent magnets, a stainless steel mesh plate, and a stainless steel straight antenna. The iron plates and magnets form the magnetic field for ECR discharge, the mesh is set around the four sides of the “mw” for the prevention of microwave dissipation. There is no downstream plate. The dimensions of “mw” are 30 x 50 x 30 mm. This “mw” breathes the surrounding air as a working gas through the metal mesh. The microwave power is supplied through the stainless steel straight antenna. The electron is produced within the “mw” discharge chamber with the microwave power, and emitted from the “mw.”

B. Cylindrical Hall-effect Plasma Source (“mh”)

The shape of “mh” is two-dimensional cylinder as shown in figure 3. This “mh” was designed by reference to the TCHT-3 [3)]. The TCHT series thrusters were designed and developed by Tahara et al. The “mh” is composed of circular iron plates, an aluminum plate, an insulator plate, a copper anode ring and SmCo permanent magnets. The iron plates and magnets form the diffusion magnetic field within the discharge space. The insulator plate is made of synthetic mica, and is put between the upstream parts and the downstream parts of the “mh.” The copper anode ring is set on this insulator plate. The diameter of “mh” is 50 mm, and the length is 30 mm. The diameter of the discharge space is 30 mm, and the length is 12 mm. This “mh” breathes the surrounding air as a working gas through the aperture between the magnets as shown in figure 4. The electron emitted from the downstream electron source, such as the “mw,” flows into the copper ring with positive potential through the cylindrical discharge space of “mw”. The plasma is generated by the electron with circular motion.

C. Cylindrical Microwave Plasma Source (“mhw”)

The “mhw” is almost the same as the “mh.” The insulator plate of the “mhw” has a hole, and a stainless steel straight antenna is set at the center axis of the upstream parts through the hole. The microwave power supplied through this antenna produce the Martian atmosphere plasma. If the downstream parts were applied with positive potential against the upstream parts, the electron produced within this microwave plasma flows into the downstream aluminum plate, and produced the other plasma (dc plasma). The “mhw” works as an electron source if the potential of both the parts is the same.

D. Experiment Procedure and Apparatus

The “mw,” “mh” and “mhw” is set and operated within a cylindrical vacuum chamber. The diameter of vacuum chamber is approximately 50 cm, and the length is approximately 1 m. After sufficient evacuation by a rotary pump, carbon dioxide gas is filled in the vacuum chamber. The pressure is manual regulated in order to simulate Mars atmosphere. The carbon dioxide gas is not cooled. The pump is not operated while carbon dioxide gas is filled for

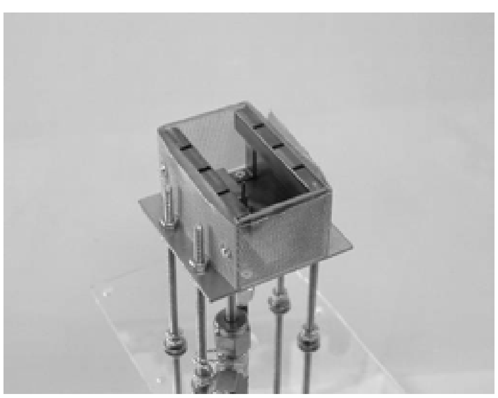


Fig. 2 “mw”

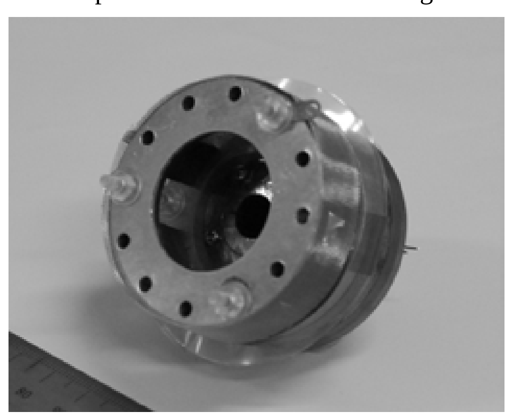


Fig. 3 “mh”

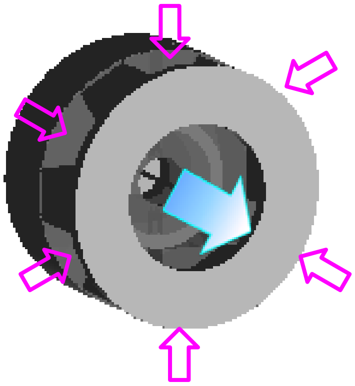


Fig. 4 Flow pattern of "mh"

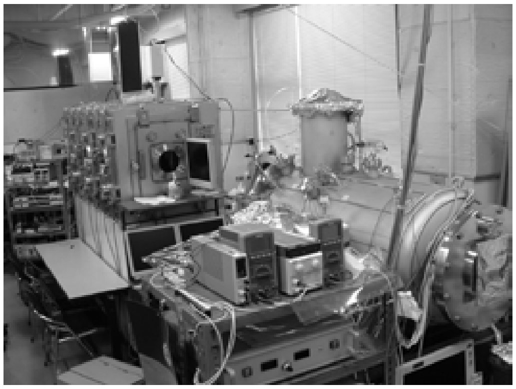


Fig. 5 Schematic of experiment apparatus

the prevention of the toxicity gas inhalation. The "mw," "mh" and "mhw" are operated within the simulated Mars atmosphere. The gas within the vacuum chamber is detected by QMS (quadrupole mass spectrometer) set at another vacuum chamber. Figure 5 shows the schematic of these experiment apparatus. The currents and voltages are measured in these experiments. However, the electron emission current can not be separately measured because this DC block can only isolate the direct current of center conductor.

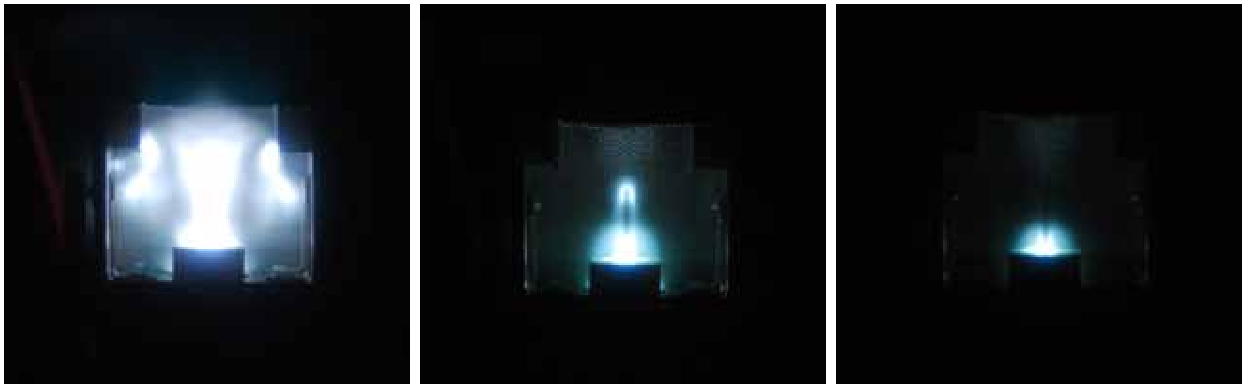
IV. Results and Discussion

A. Plasma Production of "mw"

Figure 6 shows the photograph of the produced plasma within the "mw" discharge chamber against the carbon dioxide pressure. The typical forward and return microwave power was 20 W and 1 W, respectively. This figure indicates that the microwave plasma produced within the "mw" is smaller as the gas pressure is higher. Through the "mw" operation, it was cleared that the "mw" can ignite its plasma in the gas pressure of between approximately 30 Pa and approximately 200 Pa, and that the "mw" can keep its produced plasma in the gas pressure of 6000 Pa. In addition, it was confirmed that the electron current detected by the target was approximately 5.5 mA when with the target potential was +500 V and the gas pressure is the same as the Mars surface pressure (700 Pa).

B. Plasma Production of "mhw"

[no dc plasma] Figure 7 shows a typical photograph of the produced plasma within the "mhw" discharge chamber. The forward and return microwave power was 20 W and 1 W, respectively. Through the "mhw" operation, it was cleared that the "mhw" can ignite its plasma in the gas pressure of between approximately 30 Pa and approximately 8000 Pa, and that the "mhw" can keep its produced plasma in the gas pressure of 8000 Pa with very low power. The ignition pressure range and its sustainable microwave power are shown in figure 8. In addition, it was confirmed that the electron current detected by the target was approximately 37 mA when the target potential was +300 V and the gas pressure was approximately 50 Pa.



(a) 110 [Pa(CO_2)] **(b) 700 [Pa(CO_2)]** **(c) 850 [Pa(CO_2)]**

Fig. 6 CO_2 microwave plasma of "mw"

Fig. 7 CO_2 microwave plasma of "mh"

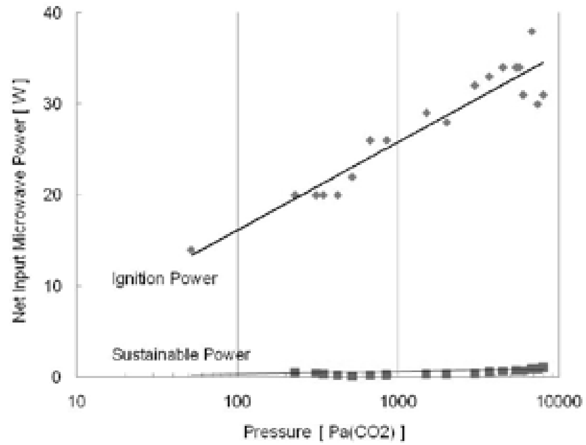


Fig. 8 Ignition/sustainable range of "mh"

[with dc plasma production] Through the experiments, it was confirmed that the discharge current was approximately 18 mA when the potential between upstream part and downstream part was 300 V and the gas pressure was approximately 50 Pa.

C. Coupling Operation with "mw" and "mh"

Figure 9 shows the photograph while both the "mw" and "mh" were operated when the gas pressure was 50 Pa. The anode ring potential is 400 V, and the discharge current is approximately 35 mA. The consumption power for the mh discharge is approximately 14 W. Although the discharge power is low, it seems that the "mh" was operated as a miniature hall thruster because the convex plasma at the downstream of "mh" is similar to that produced by typical cylindrical hall thruster.

D. Dissociation Rate

Figure 10 shows the dissociation rate derived from the temporal change of QMS detected currents, under the single "mw" operation. This figure indicates that the rate increased as the carbon dioxide pressure and/or microwave power increased, and that the rate is almost proportional to the pressure.

Figure 11 shows the dissociation rate of single "mw" operation and the coupling operation with both the "mw" and the "mh." The difference between the lines implies the rate dissociated by the coupling operation. Because the discharge power of "mh" is slightly lower than the net consumption microwave power of "mw", it seems that the dissociation rate with microwave discharge is higher than that with dc (hall current) discharge.

Because the dissociation rate is large, it seems reasonable to suppose that the microwave discharge source, such as the "mh" or the "mhw," is to be useful as an oxygen generator which changes the carbon dioxide gas to oxygen gas, or as a "Terraforming Mars" measure.

E. Future Works

Judging from these results, the cylindrical hall-effect plasma source with microwave electron source can operate under the Martian atmosphere condition. However, the thrust generation has not yet been confirmed. Moreover, the discharge current against the consumption power is low. Therefore, it is necessary to improve the performance, to investigate the produced plasma and to measure the generated thrust.

Acknowledgments

The author thanks he valuable support by Professor Hirokazu Tahara (Osaka Institute of Technology).

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[3] Tahara, H. and Shirasaki, A.: Effects of Magnetic Field Configuration and Electrically-Floating Metal Plates in Hall Thrusters with Circular Cross-Sectional Discharge Chambers, the 30th International Electric Propulsion Conference, IEPC-2007-338, 2007, pp.1-14.

Fig. 9 Coupling operation of "mw" and "mh"

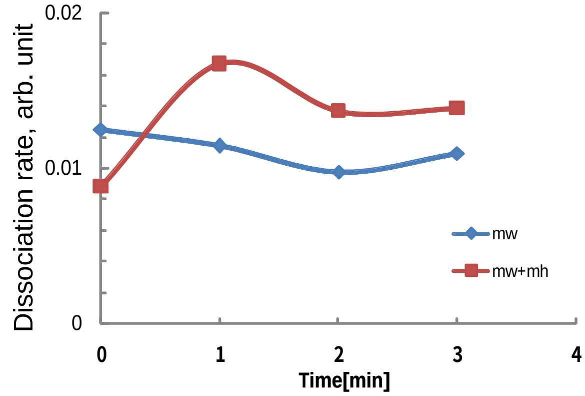
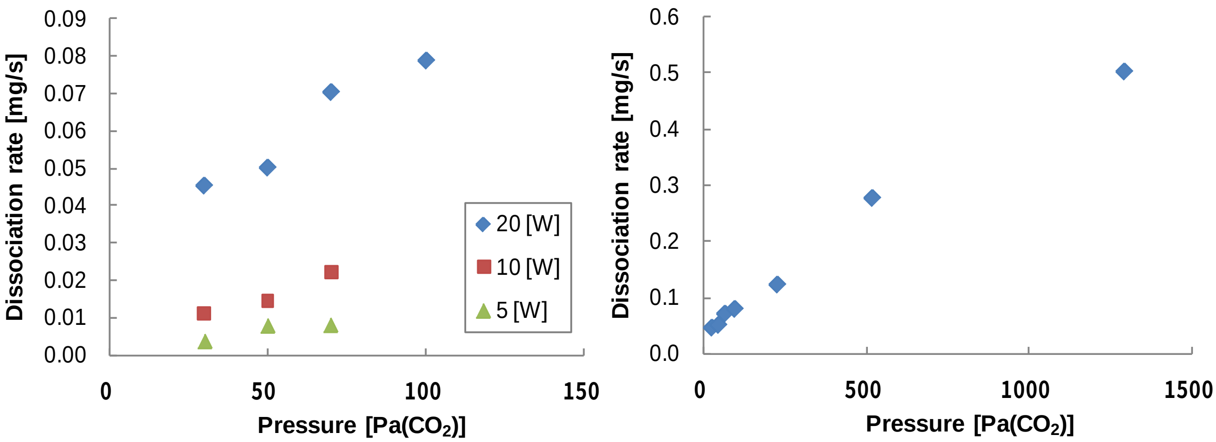


Fig. 11 Dissociation rates



(a) microwave power

(b) CO_2 pressure

Fig. 10 Dissociation rate of "mw"