

Study of Very Low-Power DC Plasma-Jet Microthrusters

Hideyuki Horisawa* and Itsuro Kimura**

* Department of Aerospace Engineering, Tokai University
1117 Kitakaname, Hiratsuka-shi, Kanagawa, 259-1292 Japan.
horisawa@keyaki.cc.u-tokai.ac.jp

** Professor Emeritus, University of Tokyo, and Nara Textile Inc.
4-19-4 Nakahara, Isogo, Yokohama, 235-0036 Japan.

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An experimental study was performed to evaluate the feasibility of plasma-jet microthrusters operation at very low power levels ranging 2 ~ 20 W. Two types of very low-power plasma-jet microthrusters ((a) gas-propellant type, and (b) solid-propellant type) were fabricated and tested. Discharge characteristics and propulsive performances were estimated for each thruster. In this study two types of nozzles, an insulated nozzle and a conventional nozzle, were tested for the gas-propellant type. The insulated nozzle consists of an assemble of an insulator and a tungsten anode. In the insulated nozzle, a ceramic material, or an insulator, was used as a part of a constrictor to allow an arc column to penetrate further downstream of the constrictor, or to maintain the high-voltage mode discharges, and to reduce the electrode losses. A solid-propellant plasma-jet microthruster was newly developed and fabricated from Boron-Nitride. PTFE was utilized as the propellant. Tungsten electrodes with the gap of 0.5 ~ 1.0 mm were used. The thrust performance test for each nozzle was conducted in a vacuum vessel. A calibrated thrust stand which consists of a cantilever with a laser-optical lever was used for the thrust measurement. Stable operations at input power levels ranging about 2 ~ 20 watts were confirmed.

1. Introduction

Feasibility studies of microspacecrafts are currently under development for the mass less than 100 kg with an available power level for propulsion of less than 100 watts.¹⁻²⁰ Various potential propulsion systems for microspacecraft applications, such as ion thrusters⁴⁻⁷, field emission thrusters^{8, 9}, PPT^{10, 11}, vaporizing liquid thrusters^{12, 13}, resistojets¹⁴⁻¹⁶, microwave arcjets¹⁷, pulsed arcjets^{18, 19}, etc., have been proposed and are under significant development for primary and attitude control applications.¹ As for low-power DC arcjets operational at power levels down to about 300 watts, several investigations have been conducted on their use for north-south stationkeeping (NSSK) on geosynchronous satellites.²¹⁻³² However, there has been little focus on the study of DC arcjets operational at very low-power levels, i.e., less than 100 watts²⁰, for microspacecraft propulsion devices, relating not only to the thrust performance but to fundamentals of the very low-

power DC discharges³³ as well. The structural simplicity of an arcjet may be favorable for both size and mass reduction of the thruster; also, further reduction of the input electrical power, to less than 100 watts for example, may be effective for reducing the mass of the power supplies. In addition, very low-power operation of arcjets, especially at reduced specific power levels with lower temperature of the propellant which is heated through the discharge, will elongate the life of electrodes and reduce the electrode losses and frozen flow losses, resulting in higher thrust efficiency.³⁴ Although the specific impulse achievable during operation will be reduced at low specific power levels, it will be recovered to some extent through the achievement of loss reduction.

In this study, a feasibility study of two different types of DC plasma-jet type microthrusters, a very low-power gas-propellant plasma-jet and a very low-power solid-propellant plasma-jet are conducted. In the very low-power gas-propellant plasma-jet

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microthruster, a gaseous propellant as conventional arcjets is utilized, while in the very low-power solid-propellant plasma-jet, which is newly developed, a solid-propellant is installed and its vaporized gas is heated by the electric discharge, and accelerated through the nozzle. The objective of this study is to investigate the fundamentals of discharge characteristics and the thrust performance of the very low-power plasma-jet microthrusters with electrical input power levels ranging from approximately 2 to 20 watts in order to ascertain the effective operational condition which possibly results in higher thrust performance. In this study, the conditions for stable operation and thrust performance, such as thrust, specific impulse and thrust efficiency, of the thrusters are evaluated.

2. Experimental

2.1 Very Low-Power Gas-Propellant Plasma-Jet Microthruster

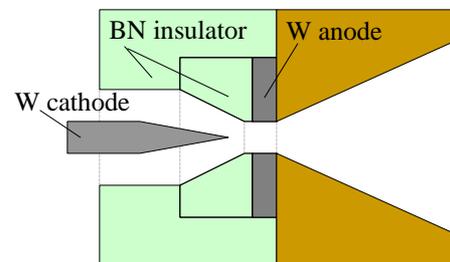
A cross-sectional schematic of electrodes and a nozzle insert of the very low-power gas-propellant plasma-jet used in this study are shown in Fig.1. In general, an plasma-jet nozzle consists of a metallic material, and serves a dual function as an anode and an arc column constrictor, except for a divergent section. In this study, a ceramic material with low heat conductivity for a convergent section and the following part of the constrictor in a nozzle was used. For the ceramic material, high-purity boron-nitride (BN) was used for the part of a constrictor to allow the arc column to penetrate further downstream of the constrictor, or to maintain the high-voltage mode discharges, and possibly reduce the electrode losses. Using the BN-nozzle (BN-insert) and a conventional tungsten nozzle, W-nozzle (W-insert), effects of the constrictor material on characteristics of very low-power DC discharge and the propulsive performance of the plasma-jet were evaluated. The cathode used in the tests was made from a tungsten rod 1 mm in diameter with a conical tip angle of 15 degrees. Nitrogen gas was used as a propellant, and the feed pressure was measured upstream of the plenum.

2.2 Very Low-Power Solid-Propellant Plasma-Jet Microthruster

Figure 2 shows a schematic drawing and a photo of the very low-power solid-propellant plasma-jet microthruster. The thruster (22 mm long, 6 mm wide,

and 4.5 mm thick), consisting of a solid-propellant casing, a discharge chamber and a convergent-divergent nozzle, is made from Boron-Nitride (BN). Two rod electrodes (0.5 mm diameter) were set normal to the thruster (solid-propellant) axis emanating the electric discharge on and along an edge of the solid-propellant. The gap of the electrodes was set 0.5 ~ 1.0 mm. A solid Polytetrafluoroethylene (PTFE, or Teflon®)(13.6 mm long, 2 mm wide, and 0.5 mm thick) was used as the solid-propellant. By heating through the discharge near the edge surface, the solid-propellant was vaporized and thermal energy of the plasma (or the vaporized gas) was converted into the directed kinetic energy through the nozzle. A photo of the thruster, weighing ~ 1.0 gram, is given in Fig.2(b).

In order to investigate the stable operational conditions for both types of thrusters, evaluations of the discharge characteristics under the various conditions by changing the current were conducted in a vacuum chamber. Photos of the exhaust plasma plume at the nozzle exit of both types of thrusters are shown in Fig.3. A calibrated cantilever type thrust stand was used for the thrust measurement under the various conditions.

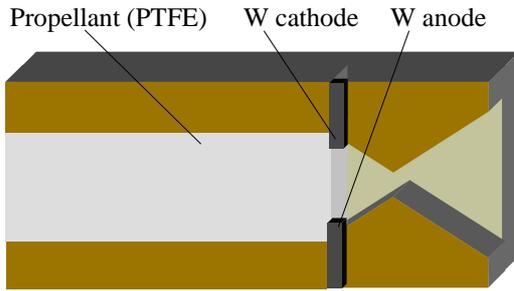


(a) A schematic of discharge electrodes.



(b) A photo of very low-power gas-propellant plasma-jet microthruster.

Fig.1 Very low-power gas-propellant plasma-jet microthruster.

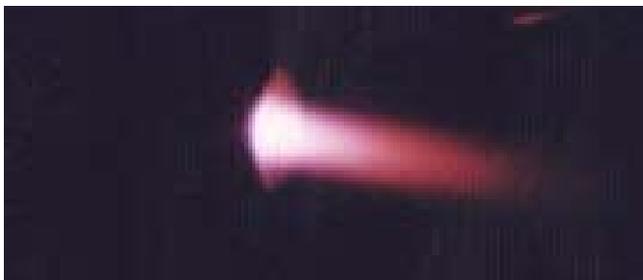


(a) A schematic of discharge electrodes and a solid-propellant.



(b) A photo of very low-power solid plasma-jet microthruster.

Fig.2 Very low-power solid-propellant plasma-jet microthruster.



(a) Gas-propellant plasma-jet microthruster



(b) Solid-propellant plasma-jet microthruster

Fig.3 Photos of very low-power microthrusters in operation.

3. Results and Discussion

3.1 Characteristics of Very Low Power Gas-Propellant Plasma-Jet Thruster

(1) Current-Voltage Characteristics

The discharge current-voltage characteristics observed for the nozzle with a BN-insert with constrictor diameter $d_{con} = 0.3$ mm are shown in Fig.4. For clarity, only the data taken at flow rates of 0.83 mg/sec and 2.53 mg/sec are shown. It can be seen that the discharge voltage for larger flow rate decreases as the current rises over the range of the current $I = 10 \sim 50$ mA, or 4 ~ 25 watts, and is high, 350 ~ 500 V, compared to that of conventional low-power arcjets. This tendency is a typical electrical characteristic of an arc discharge³⁵, and it was confirmed that the arc discharge was established even at this very low current level. While in the lower flow rate case, or plenum pressure below about 9 kPa, the discharge voltage gradually decreases with decreasing the current. This current-voltage trend is a typical characteristic of a glow discharge³⁵, although this arc-glow transition might be inevitable at this very low current level under the low plenum pressure.

Although not plotted, it was observed that the plenum pressure increases with increasing discharge current. The pressure increases with the current due to the flow blockage induced by a bigger positive column with higher current.²³ The plenum pressure of the nozzle with the BN-insert was also higher than that of the W-insert. It is hypothesized that in the BN case, the discharge anode attachment is further from the cathode tip on the throat or the divergent section of the anode nozzle due to the insulator inserted between the anode and cathode. This results in a decrease in the effective diameter of the throat due to the flow blockage by a positive column and the increase of the plenum pressure as the positive column penetrates further into the throat.

(2) Propulsive Performance

Figure 5 shows the plots of thrust versus plasma-jet input power for various cases. Plots of specific impulse versus input power are shown in Fig.6. It must be noted that the specific impulse at each mass flow rate shows a linear increase even with very low power levels of ~ 25 watts. In all cases, BN-nozzles give significantly higher specific impulse, or higher propulsive performance, compared to W-nozzles over a wide range of input power. Although in the previous

study a significant decrease in the specific impulse for W-nozzles with low mass flow rate, in which the discharge type changes into a glow discharge, such the tendency was not observed in the glow mode case of the present thruster.

Fig.7 shows the replots of Fig.6 where specific power is plotted along the abscissa. The specific impulse shows a linear increase with specific power. In all cases in Figs.6 and 7, it must be emphasized that the specific impulse is significantly higher with the utilization of BN-nozzles compared to W-nozzles. This fact indicates that BN-nozzles may efficiently contribute to the reduction of heat transfer to the constrictor wall or electrode losses.

3.2 Characteristics of Very Low Power Solid-Propellant Plasma-Jet Thruster

The discharge current-voltage characteristics of the very low-power solid-propellant plasma-jet with the electrode gaps of 0.5 mm and 1.0 mm are shown in Fig.8. The discharge voltage is high, 450 ~ 650 V, and increases with the increase of the current, showing a trend of a glow discharge. Moreover, the voltage also increases with the electrode gap. Although the

width of a solid-propellant was 2 mm, the stable operation can be achieved under the smaller electrode gap conditions, in which the projection of a cathode along a propellant edge was better than that of an anode. In each case, stable discharge was observed even under very low-power range of 2 ~ 20 watts.

A SEM micrograph of an used edge surface of the propellant near the cathode is shown in Fig.9. As shown in this photo, the consumption rate around the cathode was much higher than that of the anode. The automatic feeding (sliding) of the solid-propellant was observed without any special feed systems in the thruster. This mechanism is considered to be due to the action of the surface tension between the molten layer of PTFE surface and the cathode surface and/or electrostatic force between them.

Variations of consumption rate of the solid-propellant per unit time with input power are shown in Fig.10. As shown in this figure, the consumption rate increases with the increase of the input power. Small difference of the propellant consumption rate between two gap cases was observed under 10 watts, however, larger amount of propellant was consumed with a smaller electrode gap case especially over 10 watts.

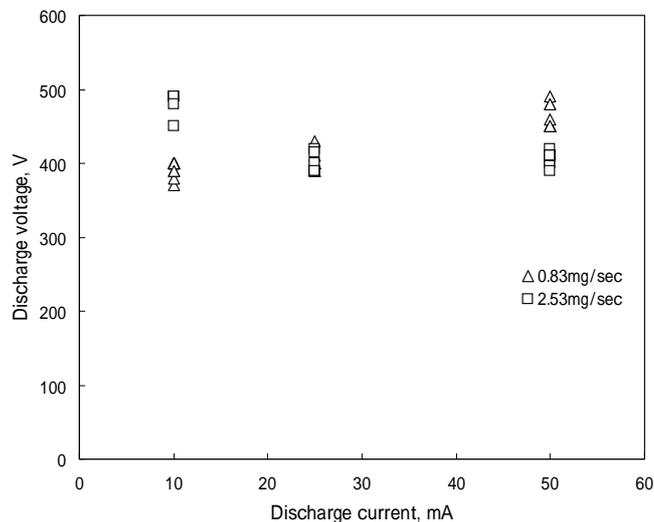


Fig.4 Discharge current vs. discharge voltage for very low-power gas-propellant plasma-jet.

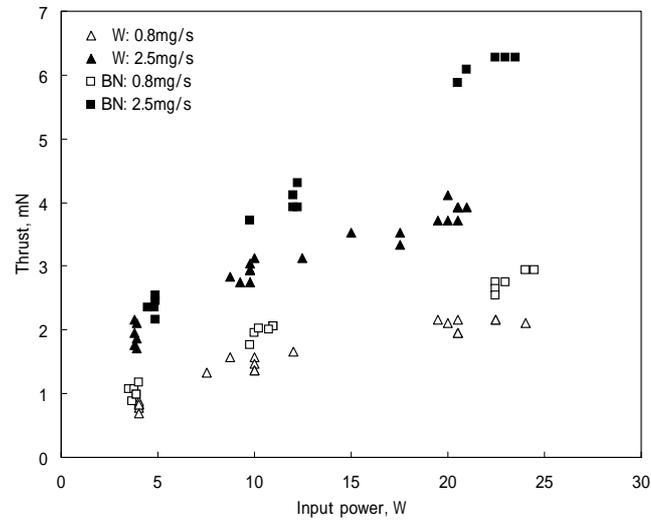


Fig.5 Input power vs thrust for very low-power gas-propellant plasma-jet.

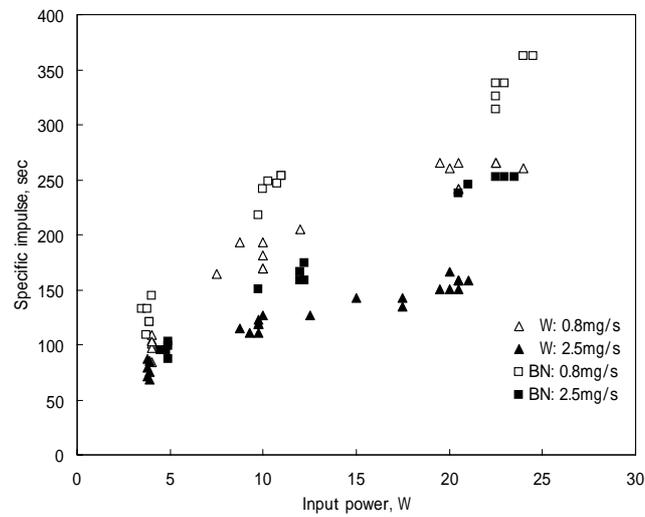


Fig.6 Input power vs specific impulse.

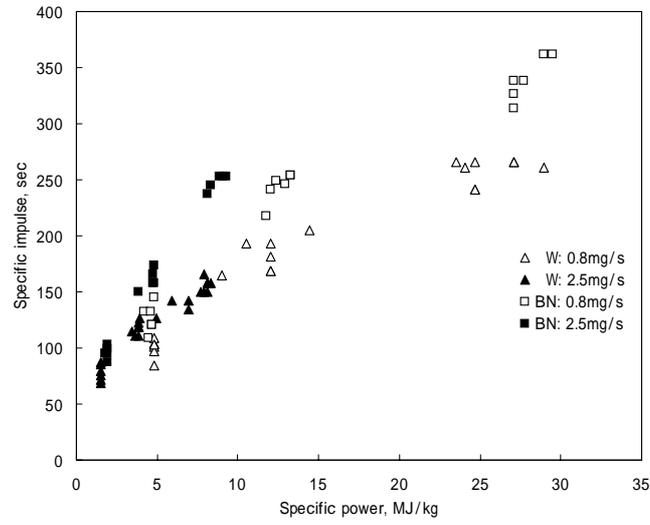


Fig.7 Specific power vs specific impulse.

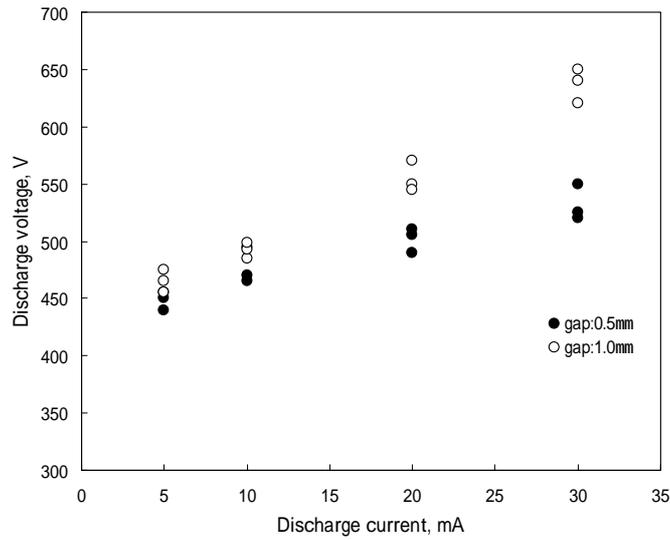


Fig.8 Discharge current vs. discharge voltage for very low-power solid-propellant plasma-jet.

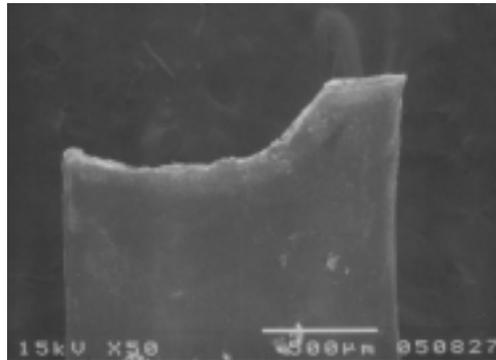


Fig.9 SEM micrograph of an used propellant on which electric discharge was applied.

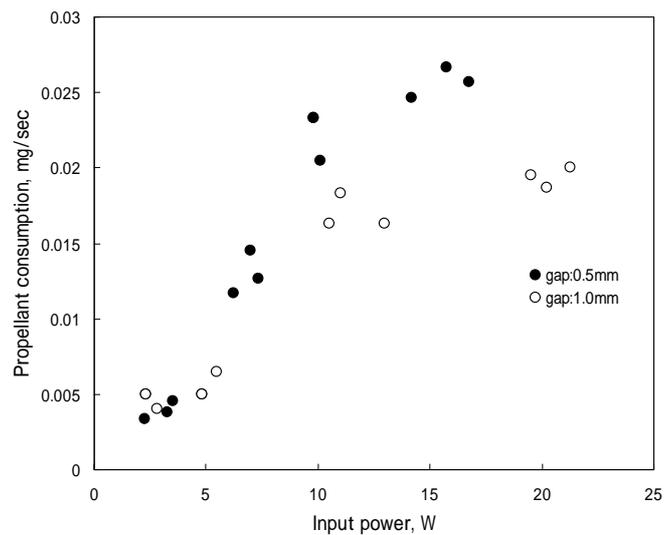


Fig.10 Input power vs. propellant consumption rate of very low-power solid-propellant plasma-jet.

4. Conclusions

An experimental study was performed to evaluate the feasibility of plasma-jet microthrusters operation at very low power levels ranging 2 ~ 20 watts. Two types of the very low-power plasma-jet microthrusters ((a) gas-propellant type, and (b) solid-propellant type) were fabricated and tested. The following results were obtained.

- 1) Stable operations at very low-power levels ranging from 2 ~ 20 watts were confirmed for each type of the thrusters.
- 2) With the utilization of partially insulated constrictors for the gas-propellant plasma-jet microthruster, specific impulse and thrust efficiency can be significantly improved compared to the conventional nozzle cases. This fact indicates that the

partially insulated nozzles may efficiently contribute to the reduction of electrode losses.

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