Ignition Characteristics of 15 kW Arcjet with Hollow Cathode

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Koki Yoshida
The University of Tokyo, Bunkyo-ku, Tokyo, 113-8656, Japan

Abstract: Improvement of lifetime limit is one of the main themes for DC arcjet to accomplish large-scale interplanetary missions in future. Hollow cathode is expected as the solution of this problem. However, hollow cathode operation makes the initial phase of arc discharge so instable. Thus the improvement of this initial instability is required. In this paper, the results of the operation using swirl-injector and the analysis of the propellant flow in the plenum chamber are shown.

I. Introduction

Direct current (DC) arcjet thrusters, classified as electrothermal propulsion, is one of the electric propulsion which has some advantages of high thrust density, high thrust/power ratio and simple structure. On the other hand, DC arcjet suffers from its short limit of lifetime. The primary factor of this limit is the erosion of the cathode tip at very high temperature. Improvement of this lifetime limit is required.

Hollow cathode composed of a tungsten tube is expected to be effective to improve lifetime limit[1, 2]. In the previous researches, experimental results showed that the internal plasma column was formed in a hollow cathode and the cathode-tip temperature was decreased compared to the case of the rod cathode[3]. Lower temperature at the cathode tip is considered to reduce the erosion of the cathode material. However, hollow cathode operation made the initial phase of arc discharge instable. Thus the cathode was eroded extremely at this initial condition and the anode was eroded considerably at its long low-mode operation.

The aim of this research is an improvement of the initial discharge characteristics by changing the way of the propellant injection. In the previous research, the ignition characteristics became better by the injection from not only inside of the hollow cathode but also outside[3]. Furthermore, swirl injection is expected to improve the initial discharge characteristics[4]. In this paper, results of the experiment with swirl injector for outer injection are shown. The swirl injector is expected to make the propellant flow in plenum chamber into the rotational flow around the cathode coaxially. Moreover the propellant flow in the plenum chamber was analyzed with hot-wire anemometer.

II. Experimental Setup

A. DC Arcjet Thruster

Figure 1 shows the cross section of the 15 kW-class DC arcjet used in this research and Fig. 2 shows enlarged view of electrodes. The anode was made of copper which had convergent constrictor and divergent nozzle part. The material of cathode was 2 % La_2O_3-W and it was brazed to the cathode base, which was made of copper. The minimum gap between the electrodes was set to about 1 mm. The error of distance between anode and cathode was about $\pm$0.1 mm and this error provided about 1 % of error to discharge voltage.

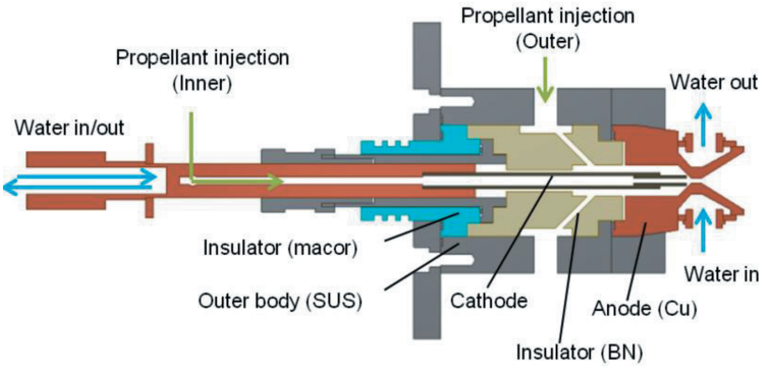

Fig. 1 The cross section of the 15 kW-class DC arcjet. The electrodes were water-cooled and isolated by two insulators which were made of boron nitride which has the propellant gas port (Ø2 mm) and macor respectively.

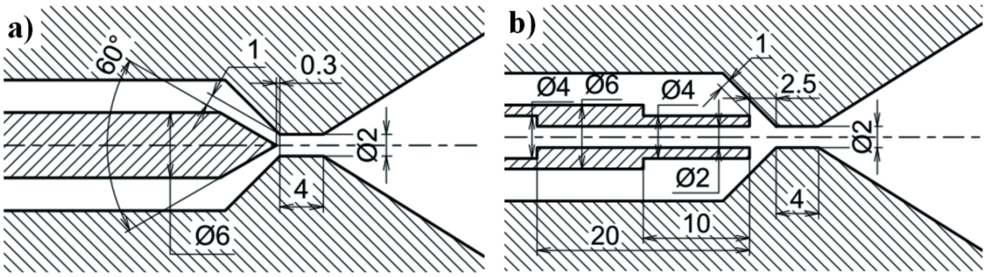

Fig. 2 The enlarged view of electrodes. Figure a) shows rod cathode and Fig. b) shows hollow cathode. The convergent part of the anode had an upstream diameter of 12 mm and an angle of 90°. The constrictor of the throat part had a diameter of 2 mm and a length of 4 mm. The divergent nozzle part had an exit diameter of 22 mm and an angle of 64°.

B. Experimental Equipments

Figure 3 shows a schematic image of the experimental equipments. Arcjet thruster operation was carried out in a vacuum chamber which has diameter of 1.0 m and length of 2.0 m and it was grounded. The back pressure was measured by pirani gauge and it was kept at 10 Pa before thruster operation. Direct current power supply (NW-300ASR) was used as main power supply for DC arcjet and it had the ability to supply up to 300 A of current and 60 V of voltage limit. Propellant mass flow rate was controlled with mass flow controller.

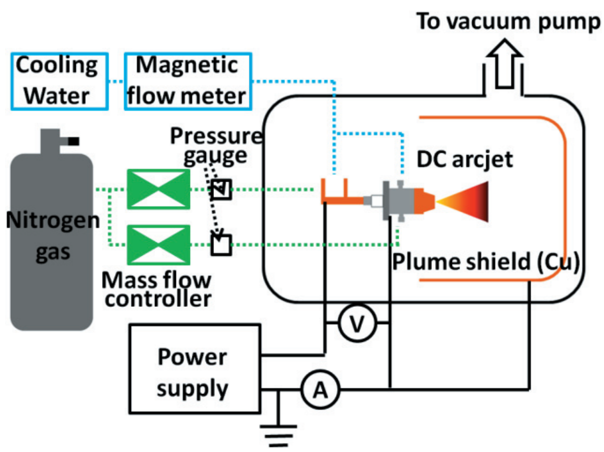

Fig. 3 A schematic image of the experimental equipments. Main propellant was Nitrogen. The plenum pressure was measured by the pressure sensor at the downstream of mass flow controller.

Figure 4 shows the thrust measurement system. The thruster was supported by two thin SUS plates. The LED displacement meter detects the displacement of thrust stand. The thrust calibration was carried out with a pulley and weight. Figure 5 shows the typical thrust calibration data. This measurement system has about 5 % of error.

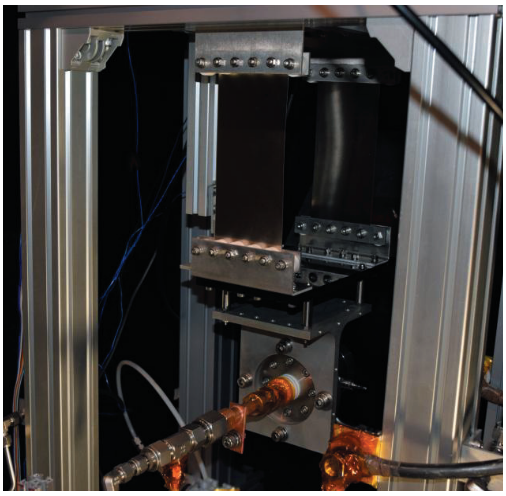

Fig. 4 Thrust measurement system

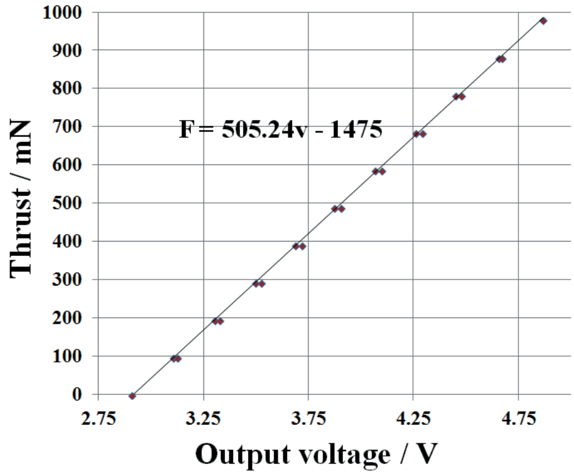

Fig. 5 One of the calibration data

III. Swirl Injection

Empirically it is known that swirl injection helps stable discharge at its initial phase[5, 6, 7, 8]. In the previous research[3], low-voltage mode continued long and sometimes the transition to the high-voltage mode did not occur.

In this research, rotational flow was generated by using of "swirl insulator". Swirl insulator has propellant gas port which is tilted from the nominal front insulator. Figure 6 shows the images of two front insulators which were used in this research. The propellant gas through this swirl insulator was expected to become rotational flow in the plenum chamber.

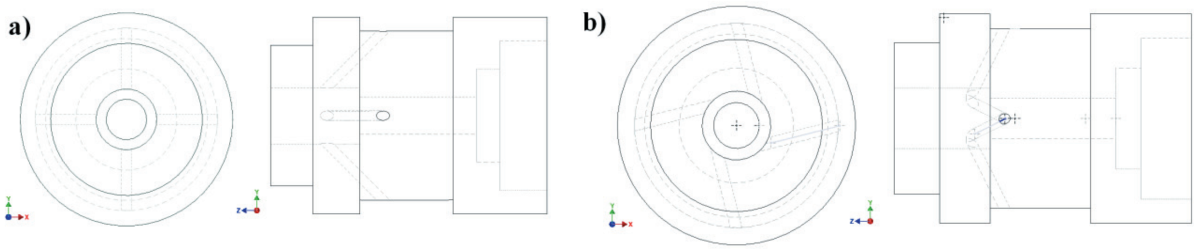

Fig. 6 The image of front insulators. a) shows nominal straight insulator. b) shows swirl insulator. When the z axis is the cathode axial direction, the direction vector of gas ports are (x y z) = (1 0 1) and (4 1 2) respectively.

At first, results of the operations using straight and swirl insulator under the condition shown by Table1 were compared. This experiment was to investigate the influence of swirl injector with rod cathode. Figure 7 shows the results and pictures of operations.

Table1 The experiment condition at swirl injection	
Cathode	Rod
Cathode material	2 % La_2O_3-W
Electrodes minimum gap, mm	1.0
Discharge current, A	150
Propellant gas	Nitrogen
Mass flow rate, g/s	0.05, 0.10, 0.15

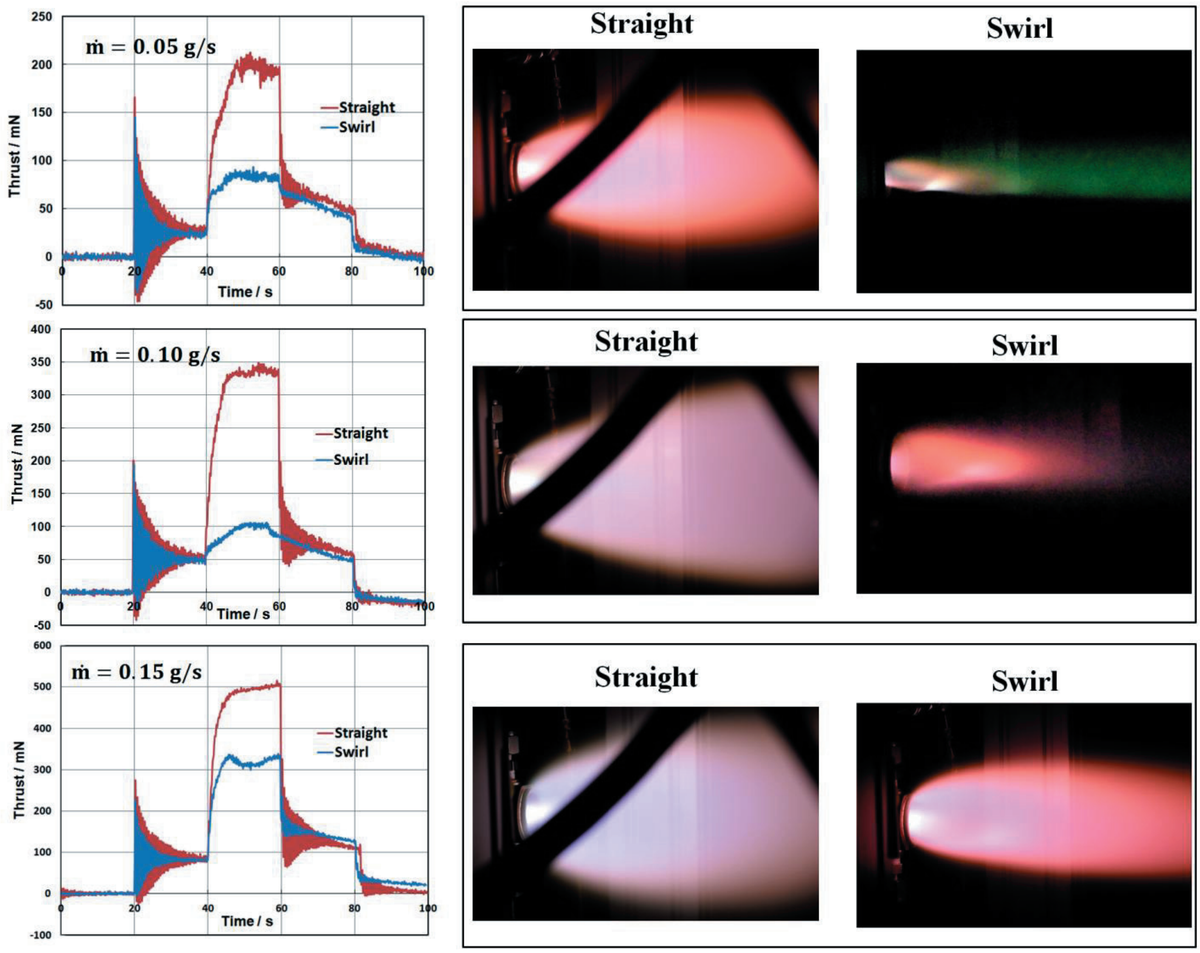

Fig. 7 Left graph shows thrust data for 20 s arcjet operations. The bottom axis represents operation time , and left axis represents thrust value / mN. Red line represents data using straight insulator and blue is swirl one. Right pictures shows arc plume under the each conditions. The upper, middle and bottom column are under the condition of which mass flow rate is 0.05 g/s, 0.10 g/s and 0.15 g/s respectively.

Under the condition of which mass flow rate was 0.05 g/s and 0.10 g/s, the discharge mode did not shift to high-voltage mode. Only at 0.15 g/s, high-voltage mode shift was observed. However the thruster performance of straight insulator was better than that of swirl insulator at any mass flow rate.

IV. Propellant Gas Flow Measurement

The thruster performance with the swirl insulator was found to be poor. Here the result of the propellant gas flow measurement was described. In this research, hot-wire anemometer was adopted for the measurement of gas flow because it has good resolution both for location and time. Hot-wire anemometer (0252R-T5, KANOMAX) is X form probe, it has two tungsten wires which diameter is 5 μm and length is 2 mm. Dummy anode made of acrylic was prepared for flow analysis, anemometer was inserted to its plenum chamber directly. The picture of acrylic anode setting is shown by Fig. 8.

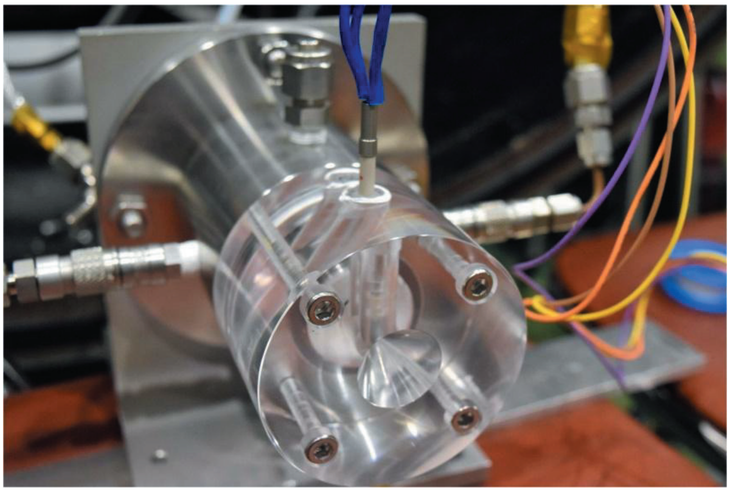

Fig. 8 The picture of acrylic dummy anode setting the anemometer. The measurement points are 5 mm and 30 mm upstream from the tip of the cathode.

Under the atmospheric pressure, mass flow rate was gradually changed from 0.029 g/s to 0.049 g/s and measured the output voltage from anemometer using straight and swirl insulator and compared that both data. Figure 8 shows the result of this experiment.

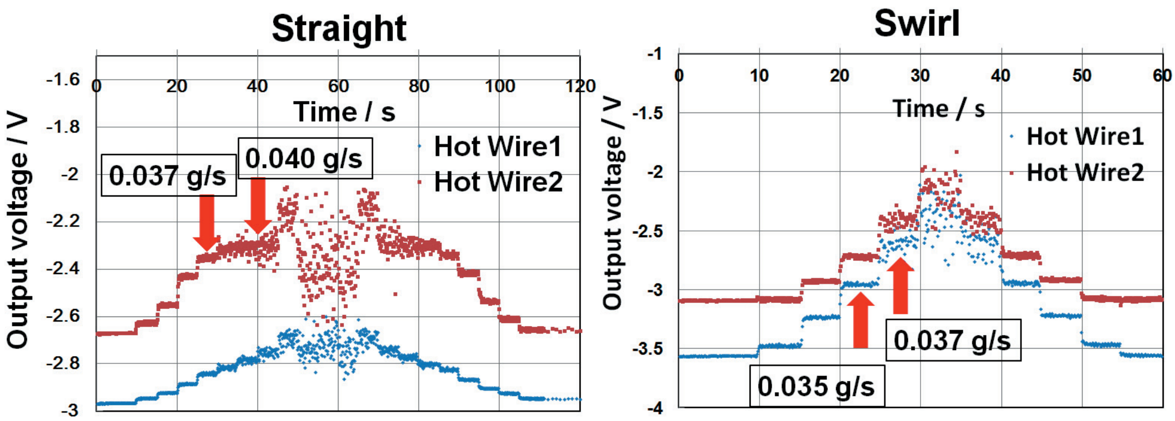

Fig. 8 Comparison of two data which are output voltage from anemometer with straight and swirl insulator. The upper axis represents measurement time/s and left axis represents output voltage/V. Red and blue dot are output from hot-wire1 and 2 respectively.

With straight insulator, it seems that propellant gas flow became turbulent between 0.037 g/s to 0.040 g/s of mass flow rate. On the other hand, it seems that the gas flow changed turbulent between 0.035 g/s to 0.037 g/s with swirl insulator.

V. Conclusion

In order to have stable discharge at initial phase of DC arcjet with hollow cathode, swirl injection was attempted. The result of the experimental thruster operation with rod cathode revealed that the low-voltage mode with swirl insulator continued longer than with straight insulator.

In order to investigate the reason of this problem, the propellant gas flow in plenum chamber was measured by hot-wire anemometer. As a result, it was found that the gas flow with swirl insulator became turbulent flow at the operational condition. The new swirl insulator, which has widen gas ports in order to reduce the flow speed and make a laminar swirl flow, is under development.

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