Application of the Hollow Cathode to DC Arcjet

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Abstract: Lifetime enhancement is one of the main themes for DC arcjet to accomplish large-scale interplanetary missions in future. Applying hollow cathode is considered as the solution of lifetime limit issue. In this study, the capability and propellant injection dependence on hollow cathode is investigated. The hollow cathode used in this study has stepped section in its tip, designed to set the tip temperature the same as conical-shape tip of the rod cathode. As a result, the ignitionability of hollow cathode operation is poor, which means that the tip of the hollow cathode is hard to warm comparing that of the rod cathode.

I. Introduction

Electric propulsion enabled various space missions such as attitude control of satellites and deep space sailing. However, there still are some missions which have not been realized for instance large-scale interplanetary orbital transfer missions. Such missions are needed in international manned mission proposal by ISECG[1]. In order to accomplish these missions direct current (DC) arcjet is one of the considered candidates in JAXA's In-space Propulsion workshop[2].

DC arcjet, classified as electrothermal propulsion, has characteristics in its high thrust density, high thrust/power ratio and simple structure. The lifetime limit of DC arcjet is lower compared with other electric propulsion. It is regarded as about 1000 hour. To improve lifetime limit is one of the main problems. The primary life limiting factor is the erosion of the cathode material[3]. It is mainly affected by the temperature of the cathode material. In other words, low temperature operation is needed to prolong the lifetime of cathode. To accomplish this, application of the hollow cathode is strongly considered as the solution. There are some previous researches about the hollow cathode application in low-power DC arcjet[4,5,6]. However, in these researches the design of hollow cathode is not considered about its thermal condition but just the same diameter and length as rod cathode[5,7].

In this study, operation range and propellant injection dependence on hollow cathode is investigated. The final target is to apply the hollow cathode to middle power DC arcjet with appropriate cathode thermal design.

II. Experimental Setups

DC arcjet

Figure 1 and 2 show the cross section of the 15 kW-class DC arcjet used in this study. The anode is made of copper, which has convergent, constrictor and divergent nozzle part. The convergent part of the anode has an upstream diameter of 12 mm and an angle of 90°. The constrictor of the throat part has a diameter of 2 mm and a length of 4mm. The divergent nozzle part has an exit diameter of 22 mm and an angle of 64°. The cathode body is made of 2% ThO2-W or 2% La2O3-W and brazed to the cathode base, which is made of copper. The electrodes are water-cooled and isolated by two insulators which are made of boron nitride and macor respectively. The minimum gap between the electrodes is set to about 1 mm from the contact point both rod and hollow cathode cases. The error of electrodes distance is estimated at about 5 %.

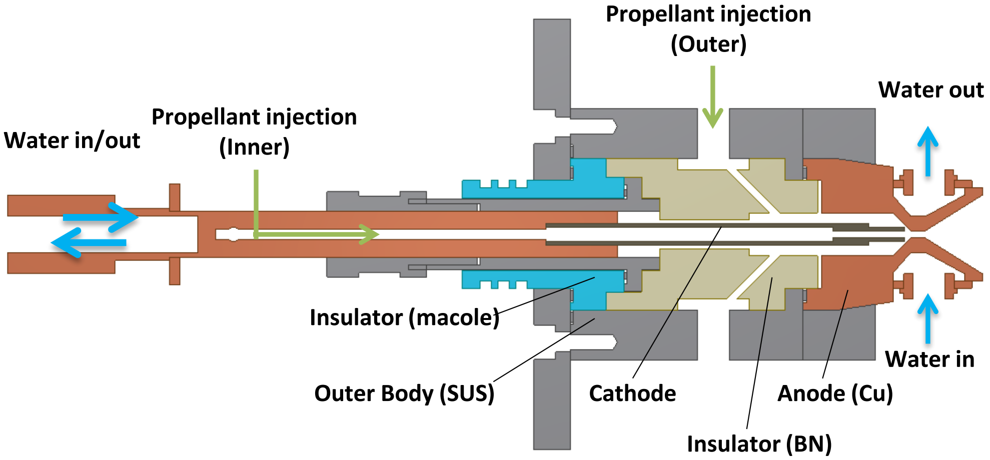
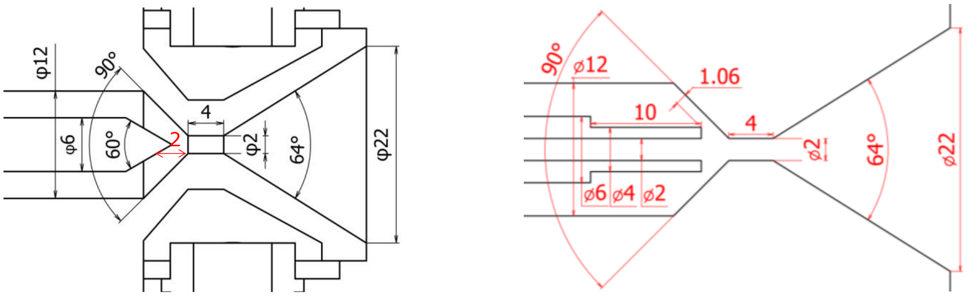


Figure 1. Cross-sectional view of the 15 kW DC arcjet thruster with hollow cathode.



a) rod cathode. **b) hollow cathode.**

Figure 2. Electrodes setup.

Hollow Cathode Design

The cylindrical hollow cathode used in this experiment has a stepped-section 1 cm behind the cathode tip. The inner and outer diameters of the cathode tip are 2 and 4 mm, corresponding to the throat diameter of the anode. Outer diameter of the cathode before the stepped-section is set to 6 mm from the viewpoint of heat transfer and electrical conductivity. When comparing the characteristics of rod and hollow cathode equally, it is important to set both cathode tip temperature equal at the same power input. Conical-shape tip of the rod cathode plays an important role to keep high temperature and enhance thermionic electron emission. If the length and diameter of the hollow cathode are same to those of the rod cathode, the tip temperature will be lower than that of rod cathode. For this reason, designed hollow cathode has a stepped section in its tip region.

Figure 3 shows the analysis model of the rod/hollow cathode. Boundary conditions are summarized in Fig. 2. Heat input to the cathode is assumed to be 150 W at 150 A of the discharge current[8]. The root of the cathode was cooled by sufficient amount of water (> 2L/min). The difference of the heat transfer coefficient between the cathode root and the cooling water had little effect on the cathode tip temperature. This is because most part of heat (> 80% of the heat input) dissipates by radiation from the lateral side of the cathode. Temperature dependency of the material properties are considered for both of tungsten cathode and copper cathode base, especially on their thermal conductivities.

As shown in Fig. 5 and 6, designed hollow cathode keeps almost same tip temperature compared to the rod cathode used in our former experiment[8]. It was confirmed that the transient temperature rise of the hollow cathode was also similar to the rod cathode in this simulation.

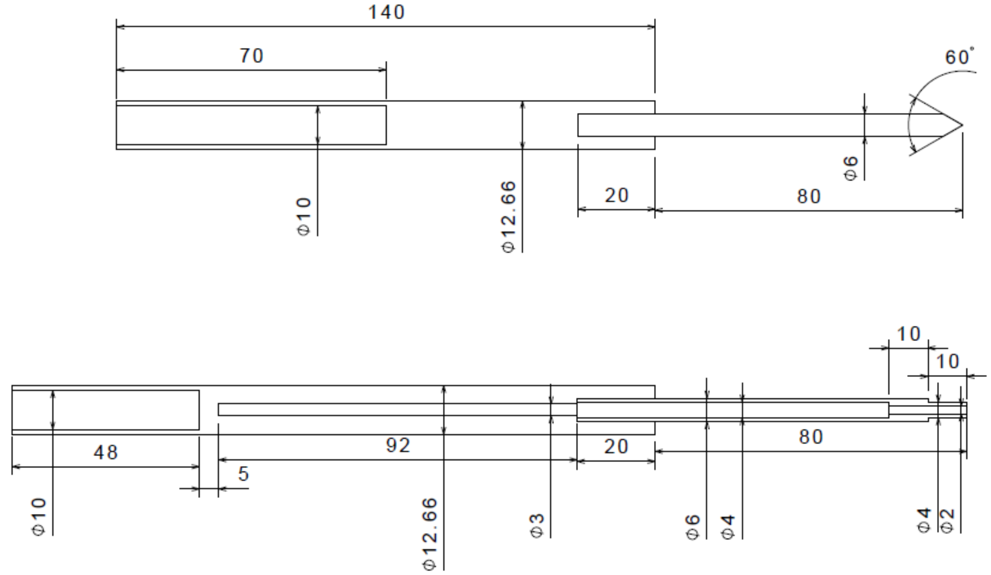


Figure 3. Analysis model of the rod/hollow cathode.

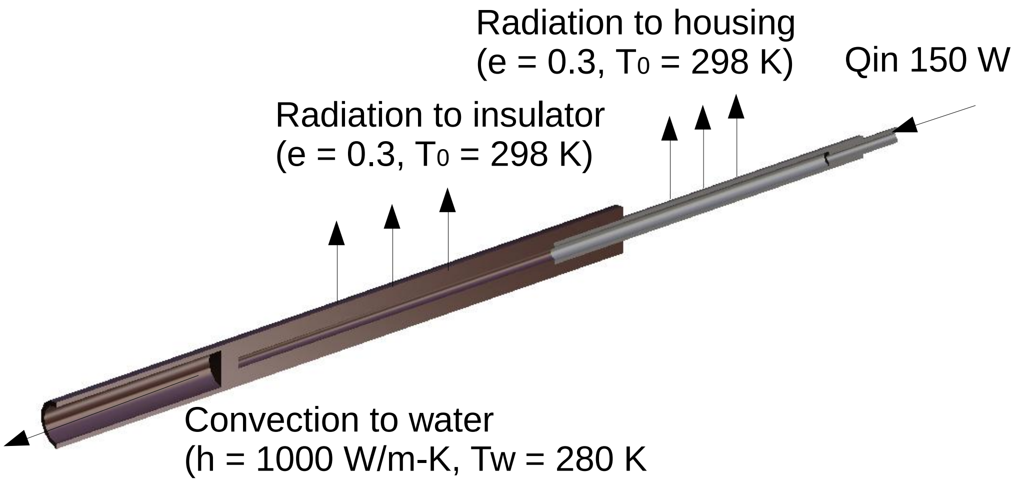


Figure 4. Boundary conditions of thermal analysis model.

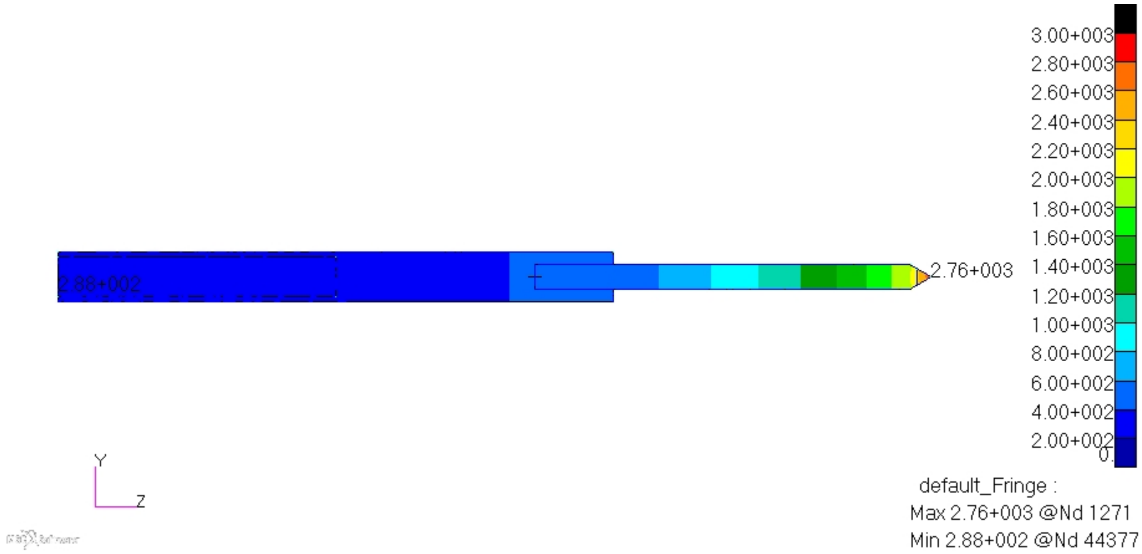


Figure 5. Calculated temperature profile of rod cathode.

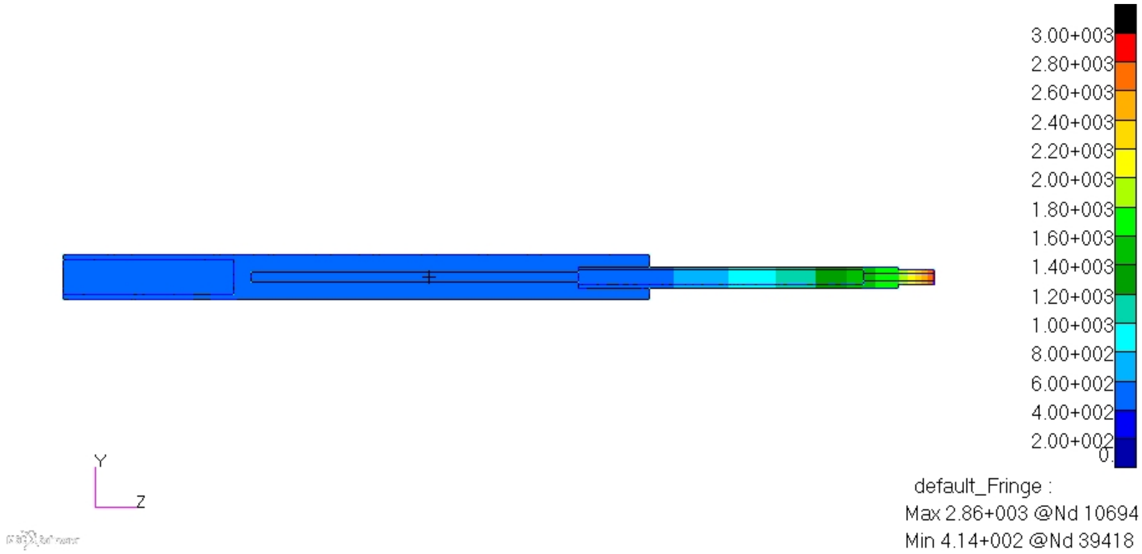


Figure 6. Calculated temperature profile of the hollow cathode.

Experimental Setup

Figure 7 shows a schematic of the experimental apparatus. All the experiments were carried out in a vacuum chamber which has diameter 1.0 m and length 2.0 m. the chamber is kept in the ground potential reference and the back pressure measured by pirani gauge. Direct current power supply (NW-300ASR) supplies electricity to the DC arcjet in the range of up to 300 A. This power supply has 60 V of voltage limit. Therefore we limited the electrode distance not to exceed this voltage limit. Because of this, the performance of DC arcjet in this study is relatively lower than in previous researches, but it is not a problem. This study focused on the characteristics of operation with hollow cathode.

Figure 8 shows the thrust measurement system. The thrust is measured by flat spring method with LED displacement meter. The DC arcjet is supported by two thin metal plates. The thrust calibration was carried out with a pulley and weight system, and a typical calibration curve was almost linear as shown in Fig.9.

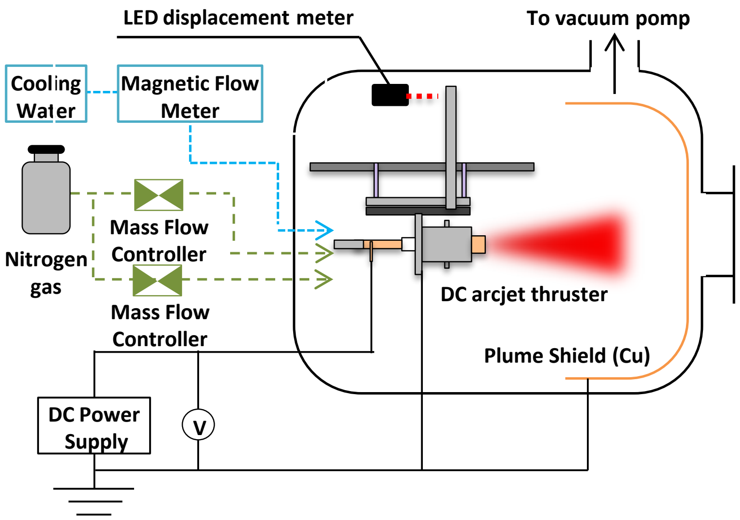


Figure 7. Experimental setup for arcjet thruster.

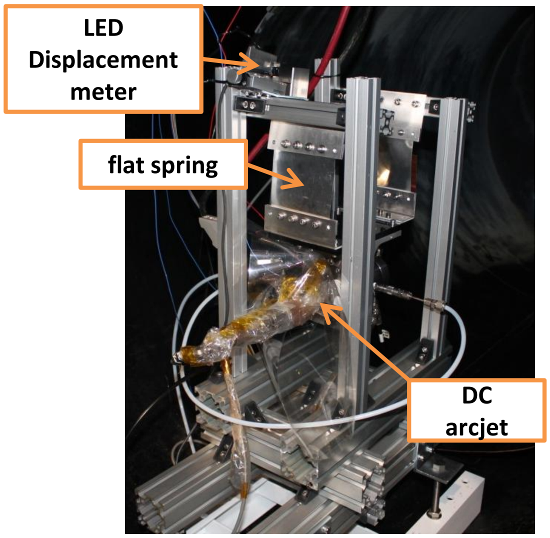


Figure 8. Thrust measurement system.

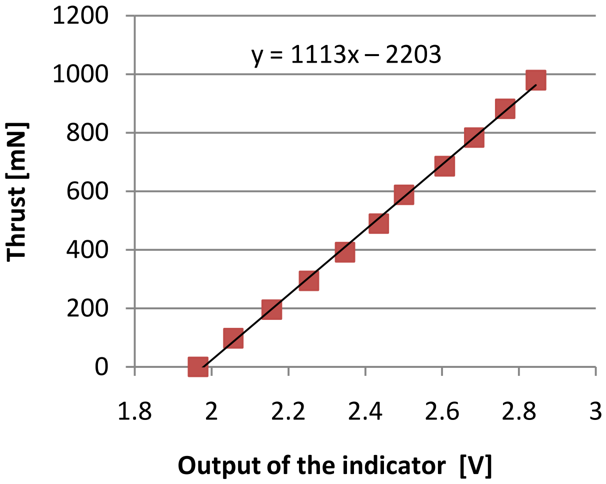


Figure 9. Thrust calibration curve.

III. Results and Discussion

At first, we tried to start the operation of the arcjet supplying the propellant from the inside of the hollow cathode. However, the arcjet was hard to ignite. Then we changed the propellant path from inner injection to outer injection. In this case, the propellant was fed through the insulator as well as the case of rod cathode arcjet. As shown in Table 1 and 2, the discharge voltage with rod cathode was 32 V at a discharge current of 210 A, and that with hollow cathode was 39.4 V. In the hollow cathode operation with outer injection, the plume of arcjet was stable and similar to that of rod cathode, shown in Fig. 10 and 11. It takes about 3 sec from the ignition to reach the high voltage mode with rod cathode operation, and about 10 sec with hollow cathode operation with outer injection. The thrust and the specific impulse of the operation of rod cathode are 445 mN and 465 sec respectively, and those of hollow cathode with outer injection are 370 mN and 377 sec. The performance of the hollow cathode with outer injection was inferior to that of the rod cathode. Besides, it takes longer time to be stable than the operation of the rod cathode. The longer transient time leads much erosion. Therefore this operation condition is not preferable to prolonging lifetime of DC arcjet. Furthermore, the discharge crater was formed at the tip of hollow cathode in outer injection operation. It is necessary to find an adequate operation point to reduce the erosion having the similar thrust performance with rod cathode.

Table 1. Experimental conditions and results of rod cathode operation.

Cathode material	ThO2-W
Electrodes minimum gap, mm	1
N_2 mass flow rate, g/s	0.1
Discharge current, A	210
Discharge voltage, V	32
Input power, kW	6.72
Thrust, mN	445
Specific impulse, sec	465

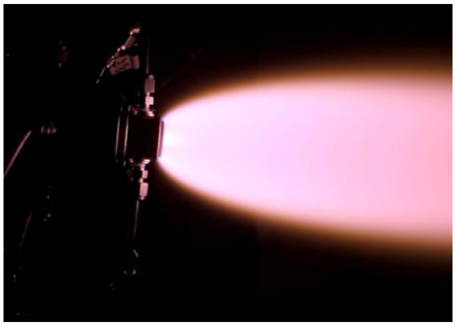


Figure 10. Picture of rod cathode operation.

Table 2. Experimental conditions and results of hollow cathode operation with outer injection.

Cathode material	ThO2-W
Electrodes minimum gap, mm	1
N_2 mass flow rate, g/s	0.1
Propellant injection	Outer
Discharge current, A	210
Discharge voltage, V	39.4
Input power, kW	8.27
Thrust, mN	370
Specific impulse, sec	377

Figure 11. Picture of hollow cathode operation with outer injection.

Next, we tried accomplishing the discharge with inner propellant injection and surveyed the performance. After the ignition and transition to the high voltage mode with 100% outer propellant injection, the mass flow rate to the outer port was reduced and inner port was increased simultaneously. By this operation technique, we accomplished successful discharge up to 100% ratio of inner injection.

The experimental condition is shown in Table 3. Total propellant volume flow rate is constant during the discharge sequence. Figure 12 shows the behavior of the discharge voltage and plenum pressures against the mass flow rate distribution ratio-from the inner injection. Figure 10 shows the behavior of thrust, specific impulse, and efficiency against the distribution ratio from inner injection. The performance at the 100% of ratio of inner injection, 108 mN of thrust and 105 sec of the specific impulse were achieved. This is quite inferior to those of rod cathode operation. The discharge voltage gradually decreases with increasing of the distribution ratio of the inner injection to the total flow rate. Plenum pressure, thrust, specific impulse and efficiency are also showed the same tendency. Overexpansion was observed in the operations more than 40% of the distribution ratio of the inner injection, as shown in Fig.14. The backpressure during operation of the vacuum chamber was 55 Pa regardless of the distribution ratio. Figure 15 and 16 show the picture of the inner channel of the hollow cathode before and after operation taken by fiberscope. A change of color of discharge crater is observed in the pictures of after operation. It indicates some arc attachment occurred during inner propellant injection.

Operation with hollow cathode resulted severe erosion. Sometimes the tip melting was observed. It is considered that this severe erosion might be occurred in the transition time from the ignition to reach the high voltage mode. Since the transient time of hollow cathode was longer than that of the rod cathode, there is a possibility that the original thermal design was not adequate. As a future work, we try the hollow cathode with a tapered tip in order to heat up the cathode tip rapidly and reduce the transient time.

Table 2. Experimental condition of propellant distribution operation with hollow cathode.

Cathode material	La2O3-W
Electrodes minimum gap, mm	1
N_2 total mass flow rate, g/s	0.1
Discharge current, A	160

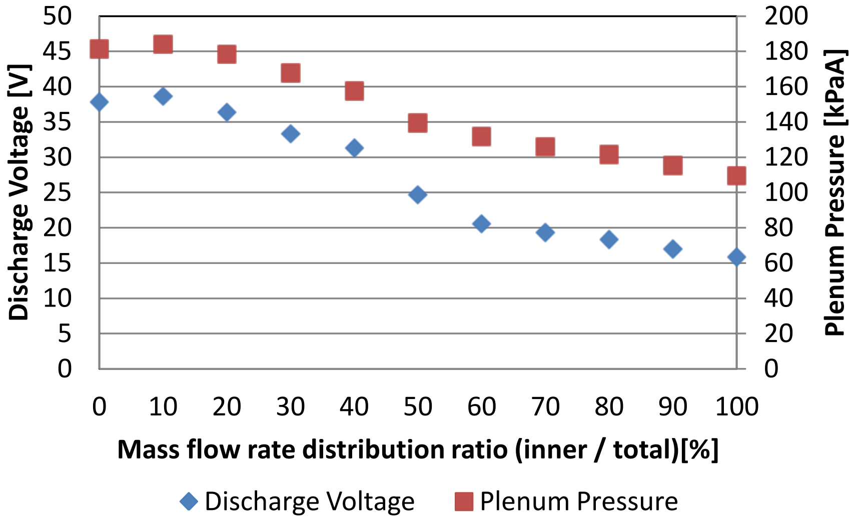


Figure 12. Discharge voltage and plenum pressure vs mass flow rate distribution ratio of inner injection to total flow rate.

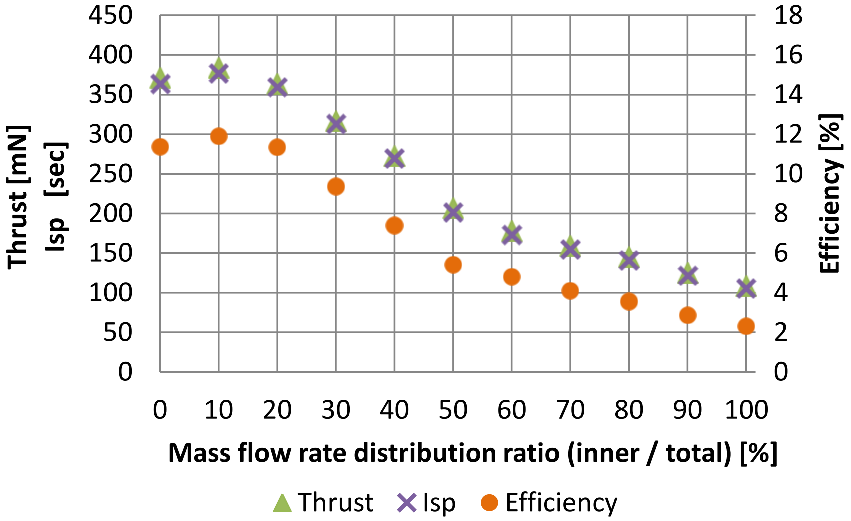
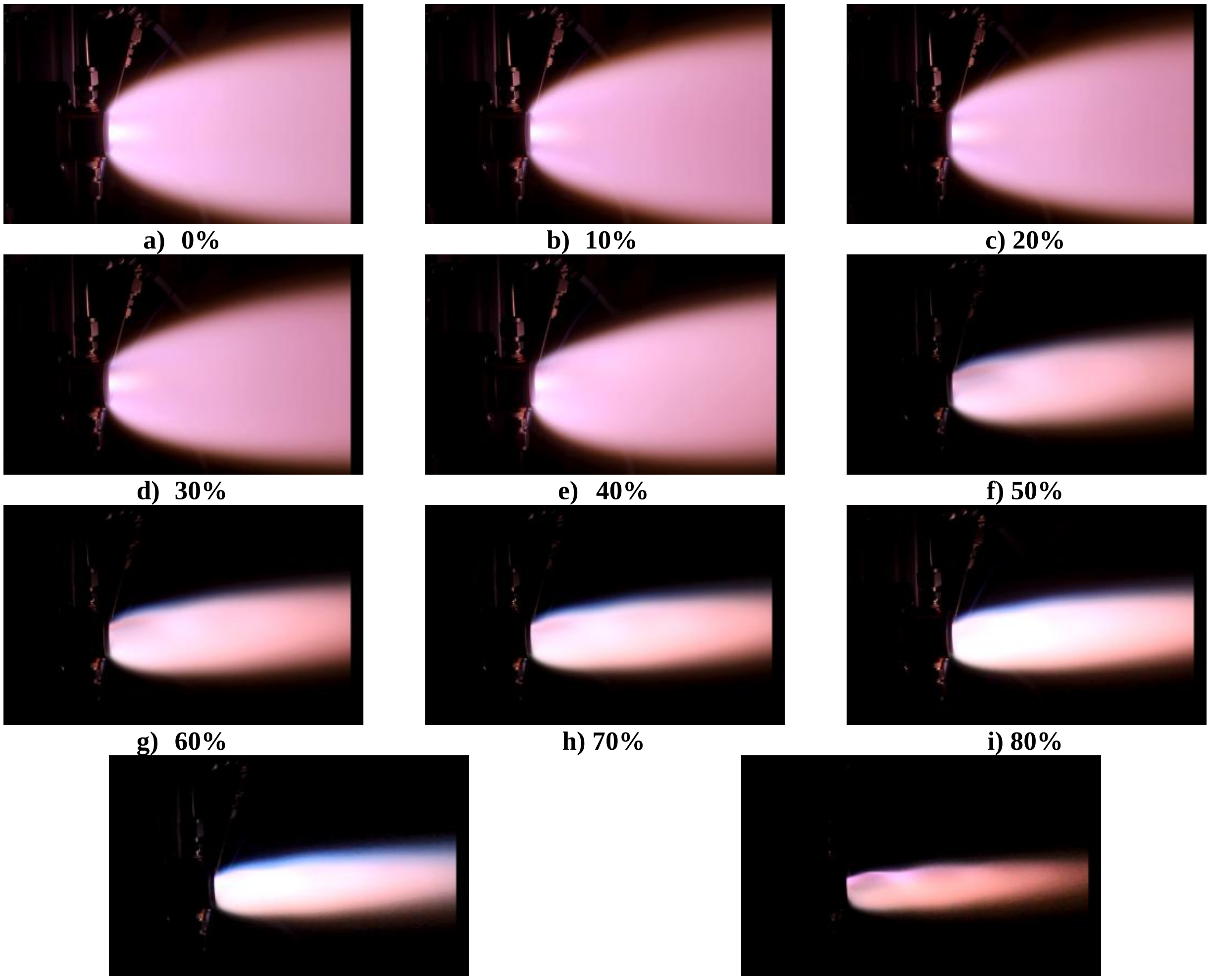


Figure 13. Thrust, Specific impulse, and efficiency vs mass flow rate distribution ratio of inner injection to total flow rate.



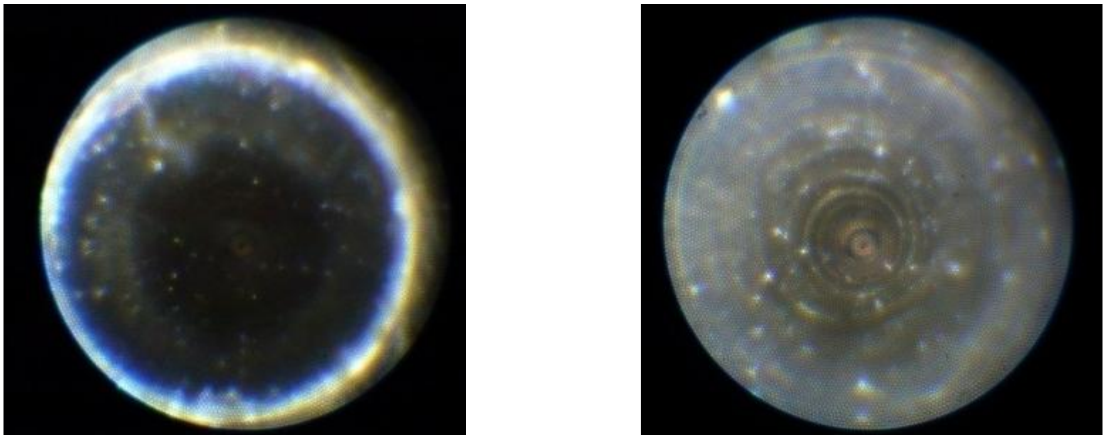
a) 0% **b) 10%** **c) 20%**

d) 30% **e) 40%** **f) 50%**

g) 60% **h) 70%** **i) 80%**

j) 90% **k) 100%**

Figure 14. Photos of operation with propellant distribution.
Each number indicates the volume flow rate distribution with ratio of inner injection to total flow rate.



(a **(b**

Figure 15. Photos of inner channel of the hollow cathode before the volume flow rate distribution operation.
a) From the tip of the hollow cathode, b) From 3 mm inside of the tip of the hollow cathode.

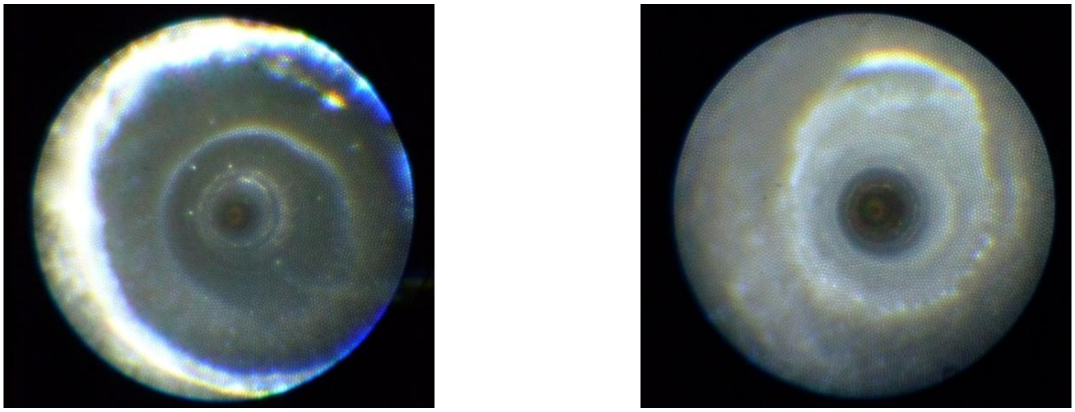

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Figure 16. Photos of inner channel of the hollow cathode after the volume flow rate distribution operation. a) From the tip of the hollow cathode, b) From 3 mm inside of the tip of the hollow cathode.

IV. Conclusion

In this study, basic operation characteristics and propellant injection effect of the hollow cathode arcjet was investigated with nitrogen as a propellant.

1. The hollow cathode was designed to have the same tip temperature as the rod cathode at the same thermal input.
2. The arcjet was hard to ignite with supplying the propellant from the inside of the hollow cathode. We accomplished successful discharge 100% ratio of inner propellant injection by igniting the arcjet with 100% outer injection and gradually varying the mass flow rate distribution ratio of outer and inner injection simultaneously.
3. The best performance of the hollow cathode operation was observed with 100% ratio of outer injection, and the performance get inferior with decreasing the ratio of inner propellant injection. The operation with hollow cathode resulted severe erosion.
4. As a future work, we try changing the hollow cathode tip design, and investigate appropriate operating condition as the hollow cathode.

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