

Performance and Thermal Characteristics of High-Power Hydrogen Arcjet Thrusters with Radiation-Cooled Anodes for In-Space Propulsion

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Abstract: The arcjet thruster is one of electric propulsion for satellite attitude control, orbital transfer and interplanetary flight. In this study, a high-power arcjet thruster with a radiation-cooled anode made of carbon and a water-cooled cathode was investigated. The propellant is hydrogen with a mass flow rate of 4.0 mg/s. Stable operations during 10 minutes were carried out with a discharge current of 144 A, a discharge voltage of 46 V and an input power of 6.62 kW. Furthermore, the surface temperature of the carbon anode, which has thermal emissivity with 0.89, was measured to be 1,098 K by a radiation thermometer. Accordingly, the radiation heat loss to the anode was roughly calculated to be 13.18% on the total input power to the arcjet thruster.

Nomenclature

Q	=	heat energy of anode nozzle
σ	=	Stefan-Boltzmann's constant
ε	=	thermal emissivity
T	=	surface temperature of anode
S	=	surface area of anode
η	=	energy loss rate
P	=	input power

I. Introduction

ARCJET thrusters are one of the electrical propulsion systems for spacecraft. In low-power arcjet thrusters case, they are used for satellite attitude and orbit control. And in high-power arcjet thrusters case, they are used for transfer between the orbital and interplanetary¹⁻⁵⁾. Since hydrazine can be identified with monopropellant and bipropellant system, it is used as a propellant for arcjet thrusters. On the other hand, hydrogen and ammonia are investigated for a long time. In our study, the performance goals of arcjet thrusters are 1,000-1,200 s in specific impulse and 35-40 % in thrust efficiency at 10 kW in input power for hydrogen^{6,7)}.

In this study, a high-power arcjet thruster with a radiation-cooled anode made of carbon and a water-cooled cathode was investigated. Stable operation by using hydrogen was demonstrated. Furthermore, the radiation heat loss to the anode was measured.

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II. Experimental Equipment

A. High-Power DC Arcjet Thruster

The high-power DC arcjet thruster and the cross-section are shown in Figs. 1-3. The high-power arcjet thruster is composed of an anode nozzle, an anode holder to fix the anode, a cathode with a conical tip, a cathode holder and an insulator to isolate between the electrodes.



Figure 1. High-power DC arcjet thruster with radiation-cooled anode.

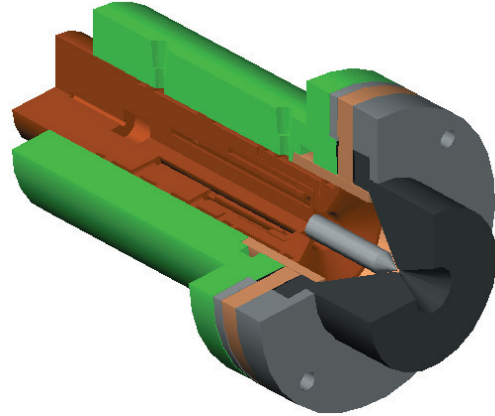


Figure 2. Three-dimensional cross-section of arcjet thruster with radiation-cooled anode.

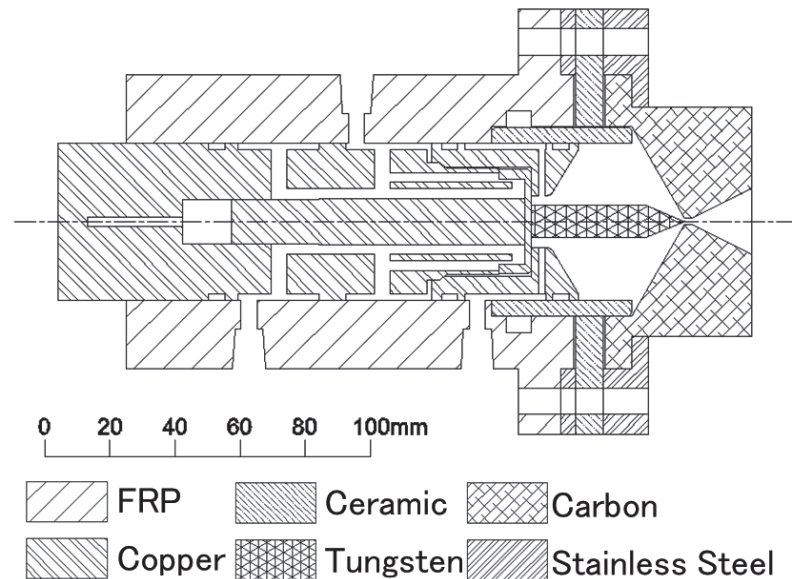


Figure 3. Cross-sectional view of arcjet thruster with radiation-cooled anode.

B. Vacuum System

The vacuum system is shown in Figs. 4 and 5. The experiments were carried out in a stainless steel vacuum chamber which has 0.6 m in inner diameter and 4.75 m in length. It has a window for observation. The chamber is evacuated by using an oil diffusion pump of 13,000 l/s, KPR-3000 made by DIAVAC LIMITED, connected in series with a rotary pump of 180 m³/h, DMB-1500 made by DIAVAC LIMITED, and a mechanical booster of 1,630 m³/h, SD-22 made by SHOWA SHINKU CO., LTD. The oil diffusion pump, the rotary pump and the mechanical booster are shown in Figs. 6-8. The pressure of the vacuum tank was measured by a Pirani gauge and an ionization gauge. A tank pressure is kept to 1.2×10^{-3} Pa by using the pumping system⁸⁾.

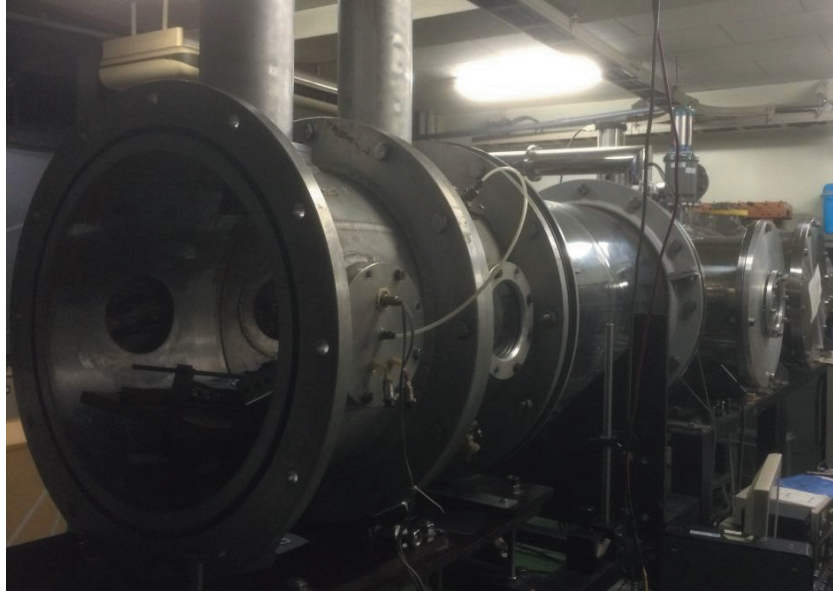


Figure 4. Large vacuum chamber with high-speed pumps.

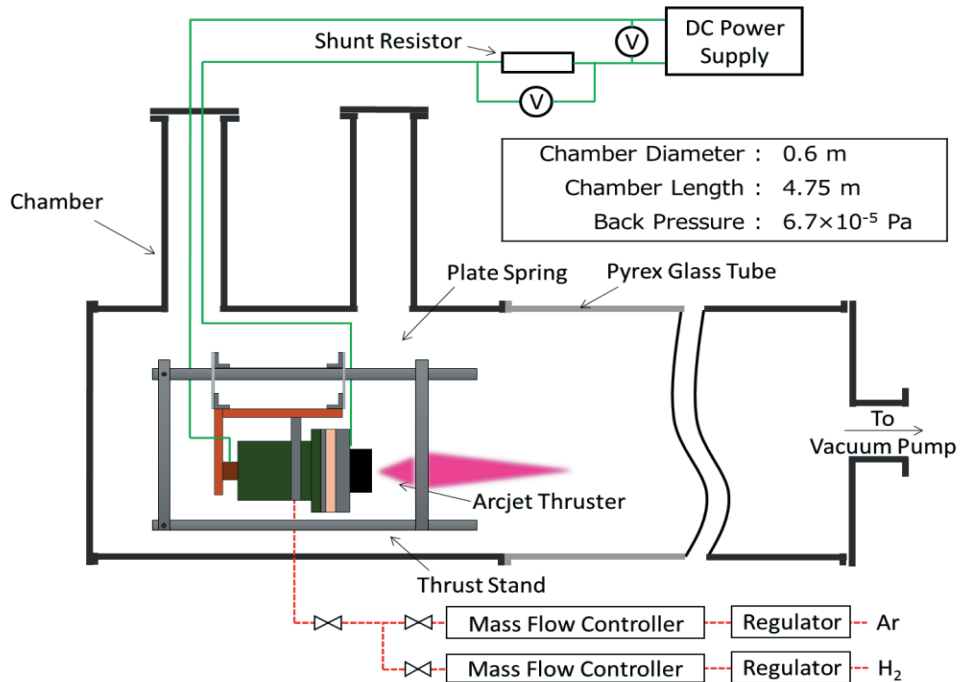


Figure 5. Schematic of vacuum system.



Figure 6. Photo of oil diffusion pump.



Figure 7. Photo of rotary pump.



Figure 8. Photo of mechanical booster.

C. Propellant Supply System

Hydrogen, argon and nitrogen were used as a propellant. These are fed to the thruster with a regulator and a mass flow controller ($20\text{SLM} \pm 1.0\%$). The volume flow rate is controlled by an input voltage to the mass flow controller.

D. Power Supply System

Discharge current and discharge voltage during operation are measured by an ammeter ($150\text{ A} \pm 0.5\%\text{F.S.}$) and a voltmeter ($30/100/300/1,000\text{ V} \pm 0.5\%\text{F.S.}$). Due to high current, a shunt resistor is used for the ammeter.

E. Radiation Thermometer

Surface temperature of the radiation-cooled anode was measured by a radiation thermometer, as shown in Fig. 9, THI-800 made by Tasco Japan CO., Ltd ($2000^\circ\text{C} \pm 1\%\text{F.S.}$), to acquire thermal characteristics of the arcjet thruster.



Figure 9. Photo of radiation thermometer.

III. Theory

The energy loss to the anode was evaluated from anode temperatures measured with the radiation thermometer to examine thermal characteristics of the arcjet thruster. The heat transferred to the anode Q is calculated as follows:

$$Q = \sigma T^4 S \quad (1)$$

where σ denotes Stefan-Boltzmann's constant. The thermal emissivity of carbon ε is assumed to be 0.89. The surface temperature of the anode T was measured by the radiation thermometer. S denotes surface area of the anode.

The energy loss rate η is calculated, as shown in Eq. (2):

$$\eta = \frac{Q}{P} \quad (2)$$

where P denotes input power to the arcjet thruster.

IV. Experimental Condition and Results

In this study, a radiation-cooled anode was developed to acquire thermal characteristics. The arcjet thruster was attached on the thrust stand. The electrode condition and the operating condition are shown in Tables 1 and 2.

Table 1. Dimension at electrode.

Cathode Diameter	10mm
Cathode Tip Angle	45 deg
Constrictor Diameter	2mm
Constrictor Length	2mm
Convergent Nozzle Angle	120 deg
Divergent Nozzle Angle	50 deg
Electrode Distance	0 mm

Table 2. Operating condition.

Propellant	Mass Flow Rate, mg/s	Discharge Current, A
Hydrogen	4.0	54, 80, 97, 116, 144
Nitrogen	20	90, 103, 121, 152, 170

Firstly, the arcjet thruster was operated to confirm stable operations by using 20 mg/s with a mass flow rate of nitrogen, as shown in Fig. 10. In the next experiments, as a propellant 4.0 mg/s of hydrogen was supplied to the arcjet thruster. Furthermore, argon was mixed with hydrogen to easily ignite at initial operation. Stable operations with hydrogen are shown in Figs. 11 and 12.

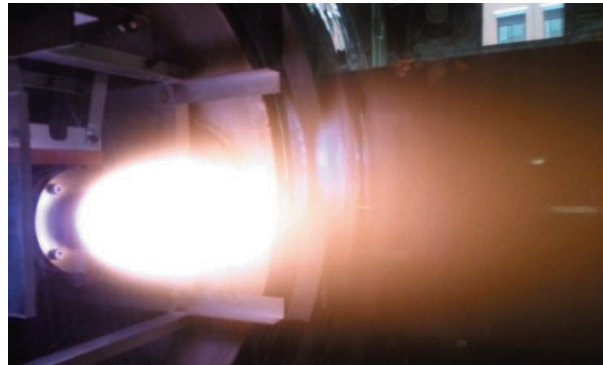


Figure 10. Plasma plume with nitrogen.

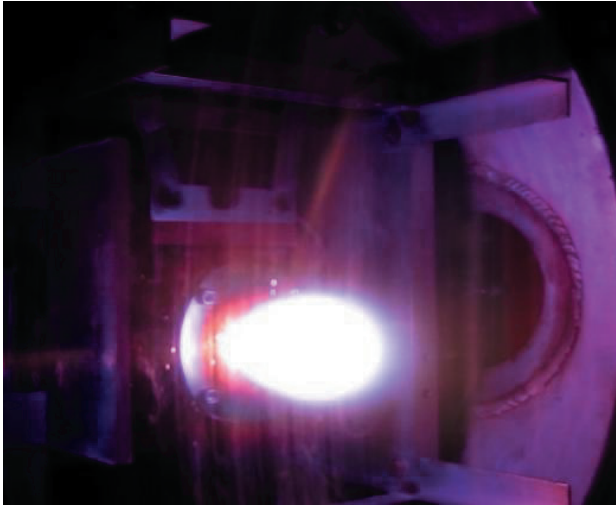


Figure 11. Plasma plume with hydrogen at 4.0mg/s in mass flow rate.

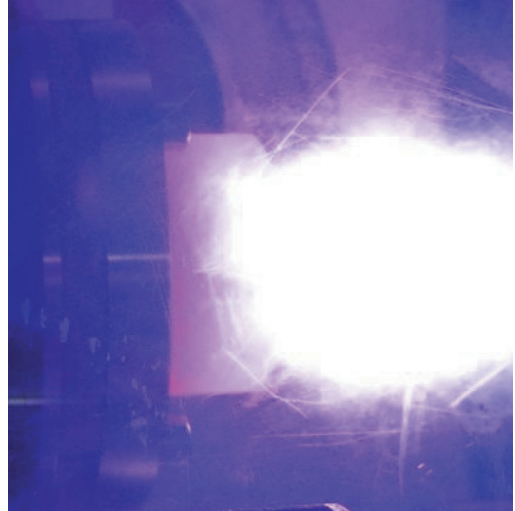


Figure 12. Red hot portion on carbon anode with hydrogen.

The electrical characteristics of the arcjet thruster with hydrogen and nitrogen are shown in Figs. 13 and 14. Stable operations during 10 minutes were achieved at a discharge current of 144 A, a discharge voltage of 46 V and an input power of 6.62 kW with hydrogen; 4.0 mg/s, and at a discharge current of 170 A, a discharge voltage of 36 V and an input power of 6.12 kW with nitrogen; 20 mg/s.

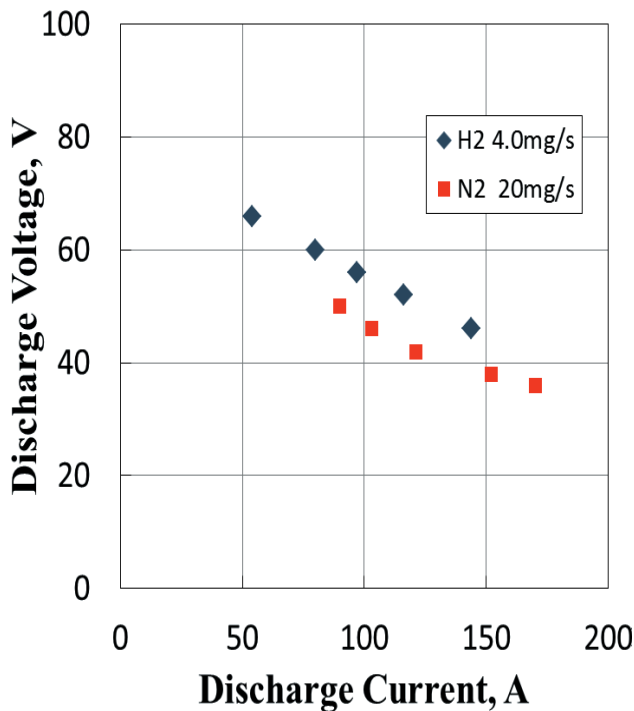


Figure 13. Discharge current vs. discharge voltage operated by hydrogen.

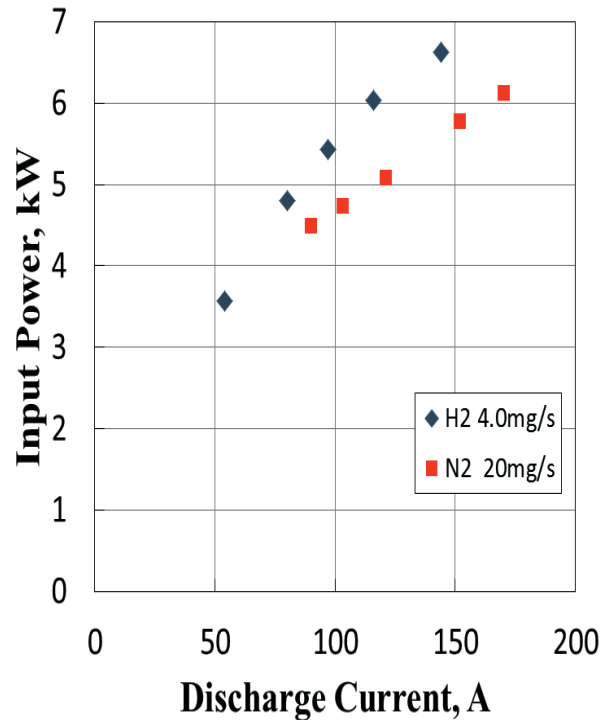


Figure 14. Discharge current vs. input power operated by hydrogen.

A red-hot heating portion was seen on the anode. It is shown in Fig. 15. Accordingly, the radiation heat loss to the anode was calculated to be 13.18 % on the total input power to the arcjet thruster. Since the water-cooled low-power DC arcjet thruster developed at Osaka Institute of Technology has 55.2 % of water-cooling loss to the anode^{9,10)}. The performance characteristics of the arcjet thruster with radiation-cooled is expected to be improved compared to water-cooled.

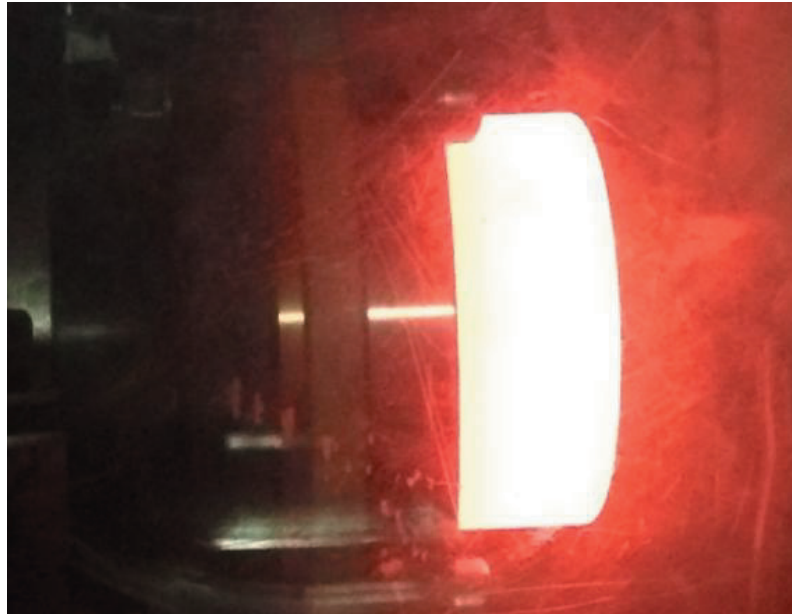


Figure 15. Red hot portion at carbon anode after operation with hydrogen.

The original anode is shown in Fig. 16. Eroded anodes after operations with hydrogen and nitrogen are shown in Figs. 17 and 18. The erosion of the carbon anode with hydrogen was severe compared with that with nitrogen. The constrictor diameter of the anode after operations with hydrogen increased to 3.9 mm from 2 mm. It is inferred that the erosion at the constrictor was caused that methane gas was generated by chemically combining hydrogen gas with carbon anode under high pressure and temperature. We will change anode material from carbon to tungsten

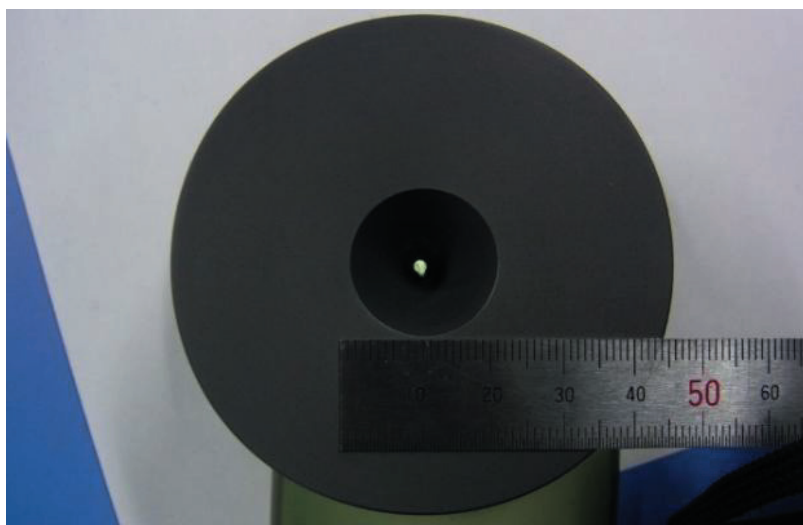


Figure 16. Carbon anode before operation with 2.0mm in constrictor diameter.

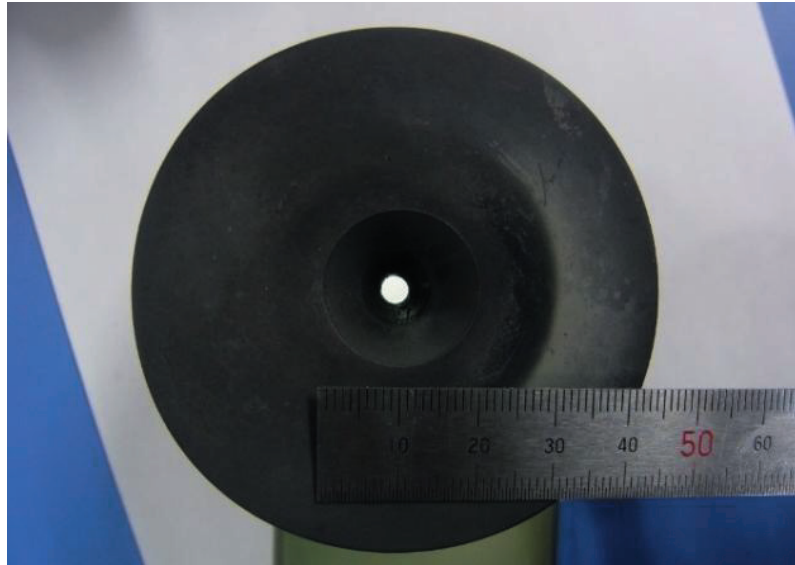


Figure 17. Carbon anode after operation with hydrogen.

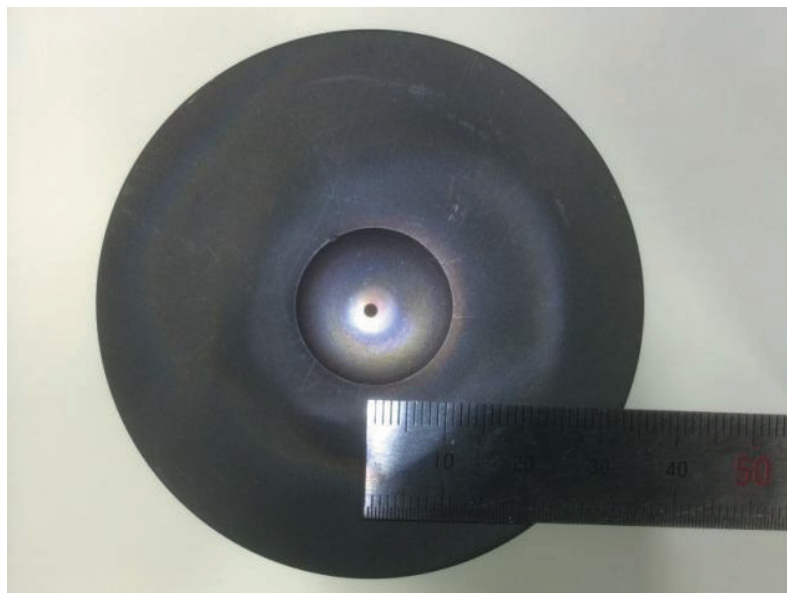


Figure 18. Carbon anode after operation with nitrogen.

V. Conclusion

In this study, the high-power arcjet thruster with a radiation-cooled anode was developed. The stable operation with only hydrogen was confirmed, and thermal characteristics were measured.

(1) Stable operations during 10 minutes were confirmed. Argon was mixed to hydrogen to easily ignite at initial operation.

(2) The steady-state surface temperature of the radiation-cooled anode made of carbon was 1,098 K with 6.62 kW in input power. As a result, the radiation heat loss to the anode was calculated to be 13.18 % on the total input power to the arcjet thruster. The performance characteristics of the arcjet thruster with radiation-cooled is expected to be improved compared to water-cooled.

(3) Severe erosion was seen after operation with hydrogen at the constrictor of the anode. This is inferred because methane gas was generated by chemically combining carbon with hydrogen under high pressure and high temperature; that is, the constrictor diameter was increased to 3.9 mm from 2 mm. We will change anode material from carbon to tungsten

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