

Performance Characteristics of Low-Power Arcjet Thrusters Using Low Toxicity Propellant HAN Decomposed Gas

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Abstract: Although hydrazine (N_2H_4) is used as a propellant of spacecraft thrusters, it is high toxicity liquid. Spacecraft researchers need a low toxicity propellant. Hydroxyl Ammonium Nitrate (HAN: NH_3OHNO_3) is proposed as a low toxicity propellant. In this study, the possibility of HAN as a propellant of direct-current arcjet thrusters is examined. Using the HAN-simulated-decomposed gas of H_2O , CO_2 and N_2 mixture, the hydrazine- - simulated-decomposed gas of N_2 and H_2 mixture, and N_2 itself, an arcjet thruster was operated, and the basic characteristics were obtained and compared. The thrust and the thrust efficiency with the HAN decomposed gas were 182.6 mN and 10.3 %, respectively, at a specific impulse of 156.4 sec with 1.36 kW input power, although severely-eroded electrodes was observed, and their performance was slightly low compared with the hydrazine decomposed gas.

I. Introduction

Arcjet thruster that is one of electric propulsion is used in low-gravity space. Mainly it is used for satellite attitude control and transfer between the orbital and interplanetary. Propellant that was used in this case is hydrazine (N_2H_4), or hydrazine-based two liquid propulsion systems. However, hydrazine is a carcinogen that is difficult to manage safety. Furthermore, hydrazine is costly and time consuming. Therefore, study of chemical propulsion system using low toxic propellant has been made all over the world. Currently, Hydroxyl Ammonium Nitrate (HAN: NH_3OHNO_3) has been attracting attention. It has a combustion performance in excess of hydrazine, and the handling is very safe because it is a low toxicity. **Figure 1** shows the differences in the handling of hydrazine and HAN. It will be the main propulsion system for the next generation satellite. **Table 1** shows a comparison of the performance of hydrazine and HAN. Table 1 means thrust density ratio of HAN is 1.6 times compared to that of hydrazine. Furthermore, we can make a tank smaller because of the high density of HAN. We

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can also reduce the power of the heater, because the freezing point of HAN is lower than that of hydrazine. However, HAN has a rapid combustion performance. Therefore, it makes difficult to burn stably¹⁻⁵⁾.

In this study, we aimed at assessing the suitability of HAN (SHP163) to low-power (1-3 kW) arcjet thrusters.



Table 1. Comparison of chemical performance of hydrazine and HAN.

	Hydrazine	HAN
Density[g/cm ³]	1.008	1.435
Specific Impulse[s]	210~220	230
Freezing Point[degree]	2	-35

II. Experimental Apparatus

Figures 2, 3 and 4 show the image, the cross-sectional view and the photo, respectively, of the low-power arcjet thruster used for this study, in which because we use a propellant system with corrosive HAN, both an anode and a cathode holder are made of excellent antiseptic SUS304. A constrictor of a convergent-divergent nozzle throat, as shown in Fig. 5, has a diameter of 1.0 mm and a length of 1.0 or 1.5 mm. A divergent nozzle has an exit diameter of 21.5 mm and is inclined at an angle of 52 deg. A cylindrical cathode made of pure tungsten has a diameter of 2 or 3 mm. The shape of the cathode tip is conical shape. The gap between the electrodes is set to 0 mm.

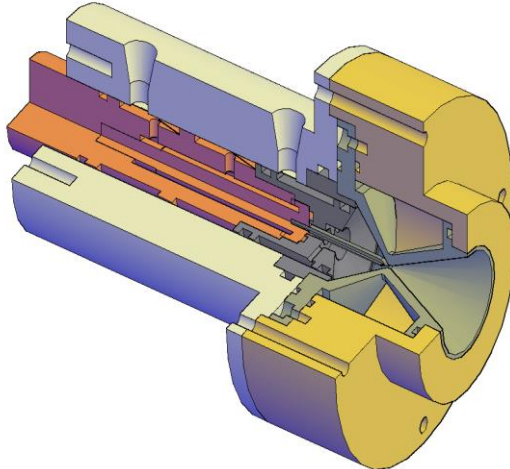


Figure 2. Image of low-power (1-3kW) direct-current arcjet thruster.

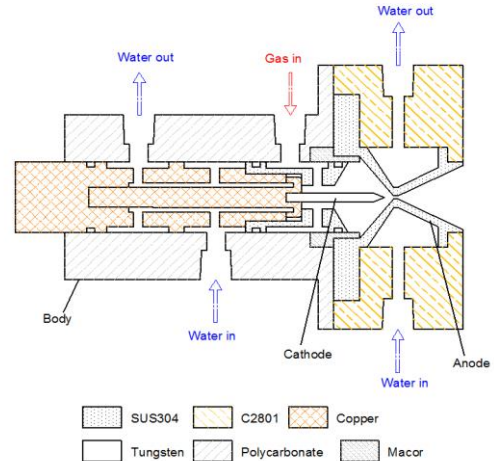


Figure 3. Cross-sectional view of low-power (1-3kW) direct-current arcjet thruster.



Figure 4. Photograph of low-power (1-3kW) direct-current arcjet thruster.

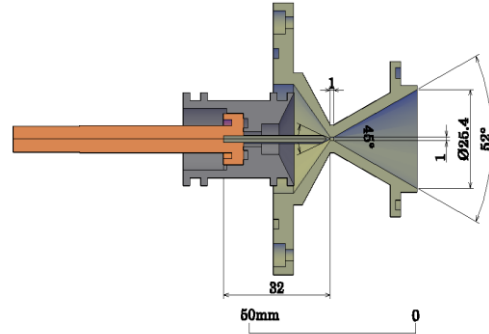


Figure 5. Electrode configuration.

The schematic diagram of the experimental system is shown in **Fig. 6**. The vacuum chamber used in this study is cylindrical one as shown in **Fig. 7**. The inner diameter of the vacuum chamber is 1.2 m, and the length is 2 m. The vacuum chamber is made of stainless steel. All experiments were carried out in the vacuum chamber. In order to realize a vacuum, a rotary pump (Osaka Vacuum Equipment Manufactory, exhaust speed 600 m³/h) and a mechanical booster (Osaka Vacuum Equipment Manufactory, exhaust speed 600m³/h) are used as shown in **Fig 8**. The vacuum pressure is kept below 1 Pa. Furthermore, in order to perform stable operation with quick response, the electric power unit was changed into a special 1-3kW-class PWM power supply, as shown in **Fig. 9**, from the commercially-available DC power source. The PWM power supply is equipped with current and voltage meters. As for propellant supply, nitrogen, carbon dioxide and hydrogen are supplied with flow regulations by mass flow controllers, and the gases are injected into the inside of the thruster. We used mass flow controllers for supplying propellant gases, and water was supplied with a micro tube pump (Tokyo Rikakikai Co., Ltd, MP100-typeA), as shown in **Fig. 10**, as a liquid. In this study, we used a new thrust stand with plate springs as shown in **Figs. 11 and 12**. Plate springs are stainless steel ones that are 270 mm in length, 25 mm in width and 0.4 mm in thickness. The arcjet thruster is attached below the plate spring. The load cell (Agent A & D Co., Ltd., U2X1-0.5LA) is settled on the same axis as the central axis of the thruster. The load cell is pushed by thrust. We take the calibration to measure thrust. We can calculate the actual thrust by substituting experimental values to the calibration equation. Calibration was taken by pulling the weights in the axial direction of the thruster. We gave a linear approximation to graph the relationship between the value of the load due to the weights and value of the Indicator. **Figure 13** shows a typical calibration data. It is very linear line.

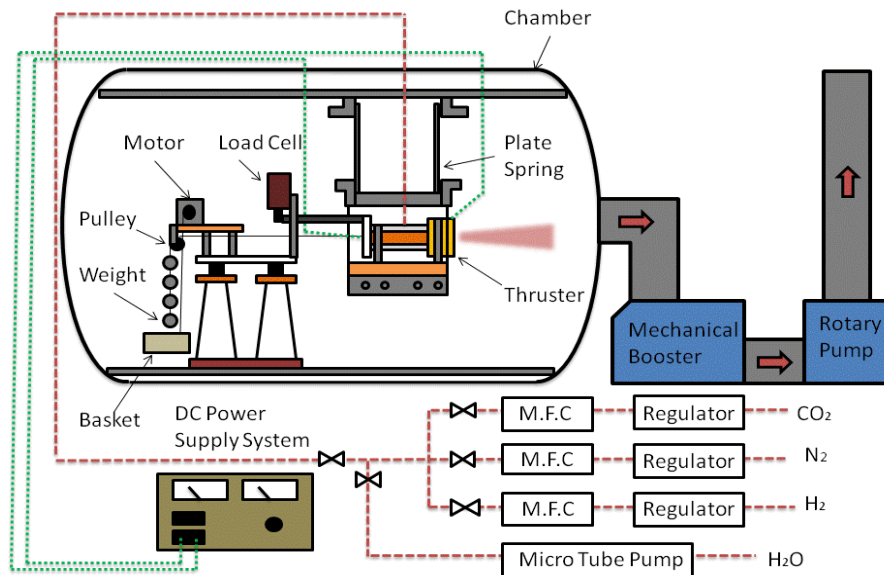


Figure 6. Schematic diagram of experimental system.



Figure 7. Vacuum chamber.



Figure 8. Vacuum exhaust pump.



Figure 9. PWM power supply.



Figure 10. Micro tube pump.

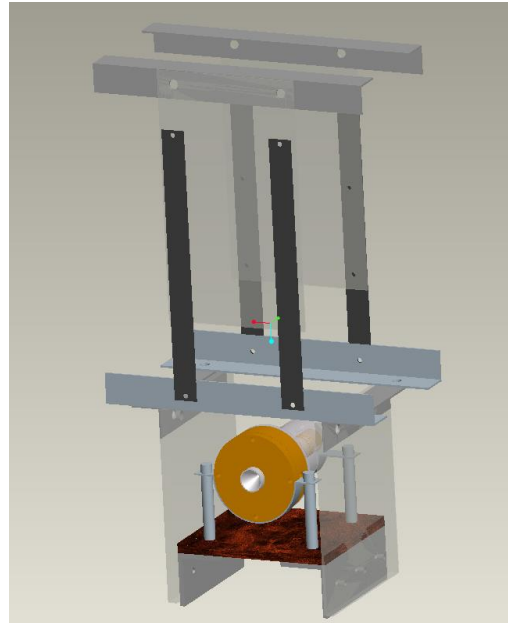


Figure 11. Thrust measurement system.



Figure 12. Photograph of thruster stand.

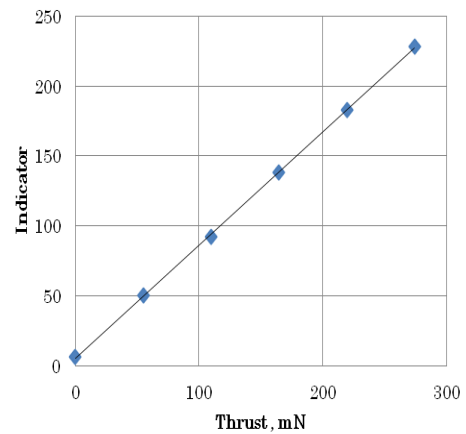


Figure 13. Typical calibration line.

Table 2. Configuration conditions for high-power arcjet.

Electrode Distance, mm	0
Cathode Material	Pure Tungsten
Cathode Shape	45°
Constrictor Diameter, mm	6.0
Flow Rate	N ₂ :7.0SLM

Table 3. Configuration conditions for low-power arcjet.

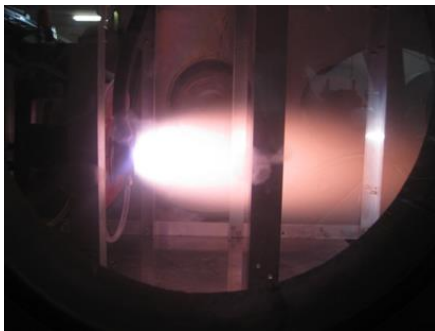
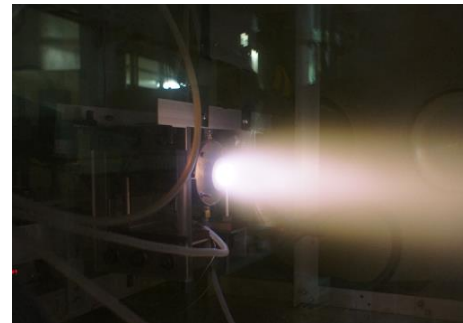
Electrode Distance, mm	0
Cathode Material	Pure Tungsten
Cathode Shape	45°
Constrictor Diameter, mm	1.0
Flow Rate	N ₂ :7.0SLM

Table 4. Experimental conditions with decomposed HAN(SHP163) gas, decomposed hydrazine gas and pure nitrogen for thrust measurement.

	Decomposed HAN (SHP163) Gas	Decomposed Hydrazine Gas	Pure Nitrogen
Electrode Distance, mm	0	0	0
Cathode Material	Pure Tungsten	Pure Tungsten	Pure Tungsten
Cathode Shape	45°	45°	45°
Constrictor Diameter, mm	1.0	1.0	1.0
Flow Rate	N ₂ :1.6SLM, CO ₂ :1.6SLM H ₂ O:180ml/h	N ₂ :2.3SLM H ₂ :4.6SLM	N ₂ :7.0SLM

Table 5. High-power and low-power arcjet performance data.

Thrust [mN]	205.6	144.11
Input Power [kW]	4.73	0.8
Specific Impulse [s]	392.6	201.52
Thrust Efficiency [%]	11.4	11.96

**Figure 14. Photo of high-power arcjet plasma plume with pure nitrogen.****Figure 15. Photo of low-power arcjet plasma plume with pure nitrogen.**

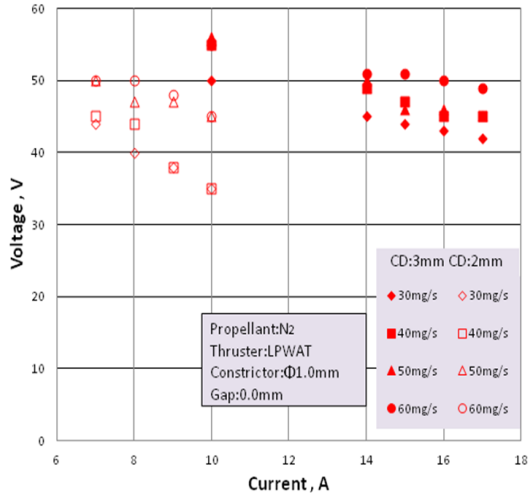
III. Results and Discussion

A. Operational conditions

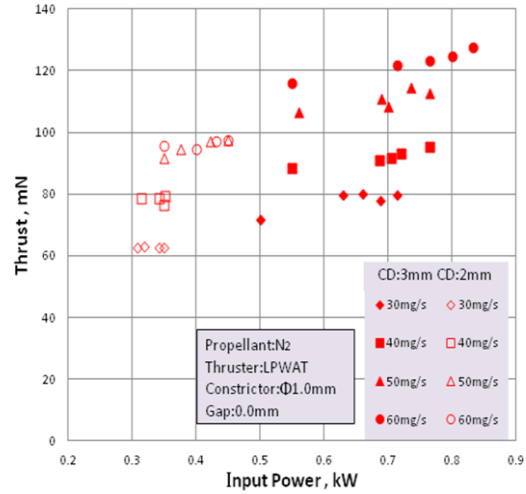
Tables 2 and 3 show the configuration conditions for the low-power thruster and another thruster operated previously with high powers. Table 4 shows the experimental conditions for thrust measurement.

B. Comparison between performances of high-power and low-power arcjet thrusters

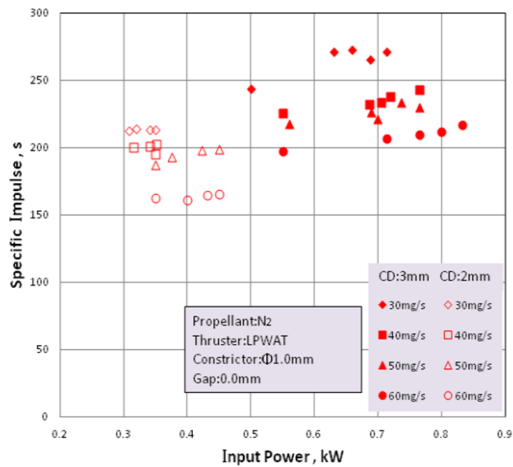
The performance comparison between a high-power (5-10 kW) arcjet thruster and the low-power arcjet thruster is performed as shown in Figs. 14 and 15. As the propellant, pure nitrogen is used.



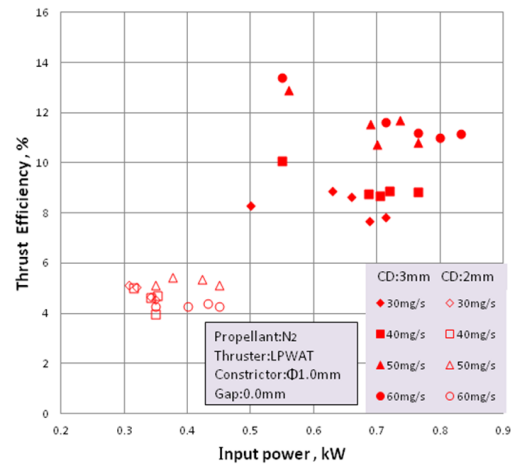
(a) Discharge voltage vs current.



(b) Thrust vs input power.

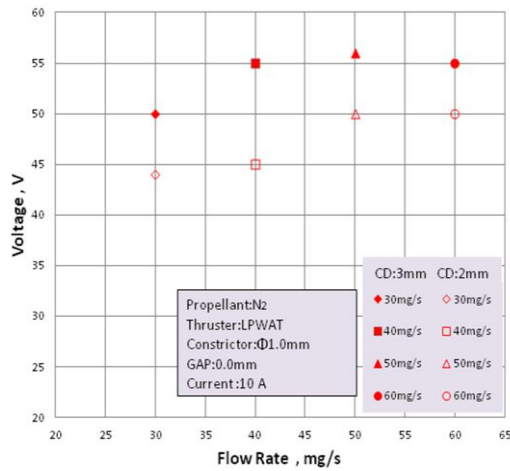


(c) Specific impulse vs input power.

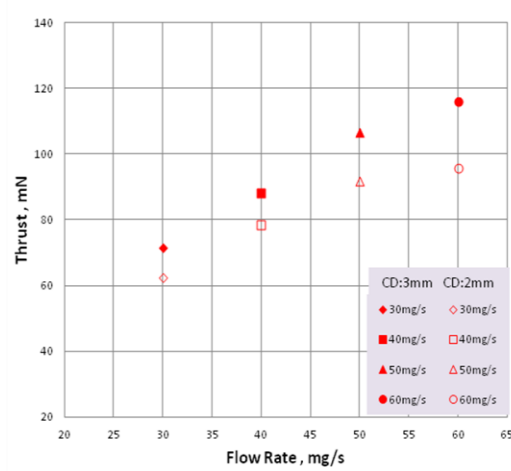


(d) Thrust efficiency vs input power.

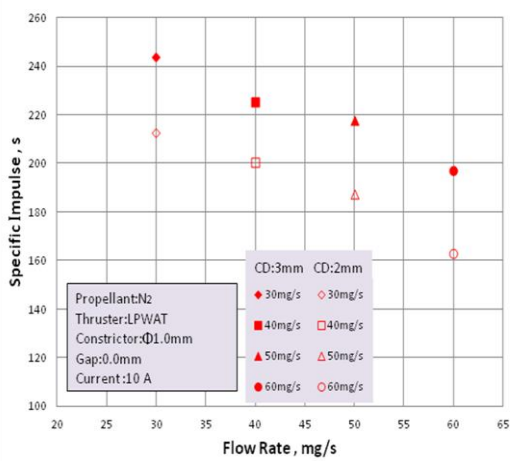
Figure 16. Performance characteristics of low-power arcjet thruster using pure nitrogen with constrictor diameter of 1.0 mm changing cathode diameters of 2 and 3 mm.



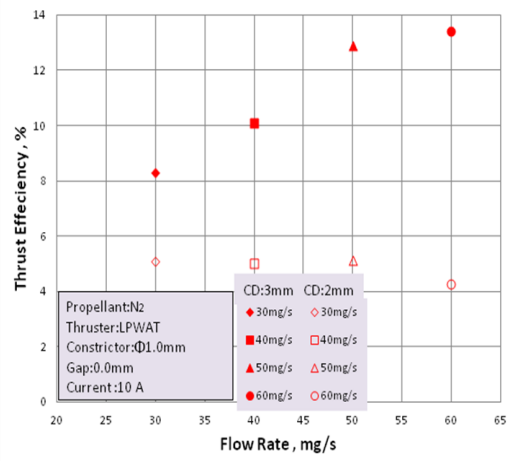
(a) Discharge voltage vs mass flow rate.



(b) Thrust vs mass flow rate.

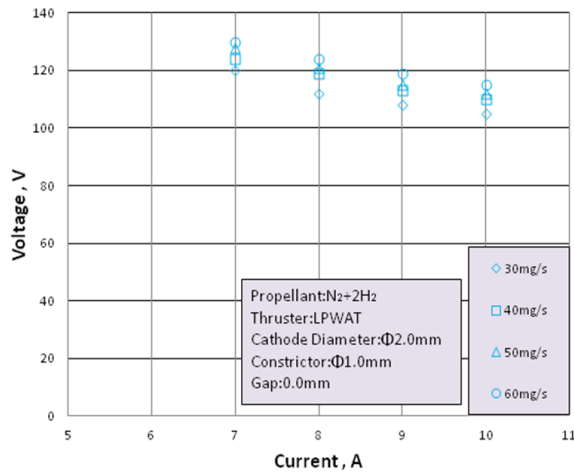


(c) Specific impulse vs mass flow rate.

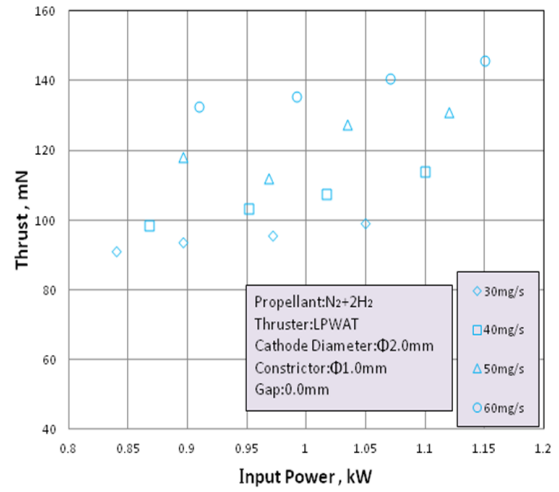


(d) Thrust efficiency vs mass flow rate.

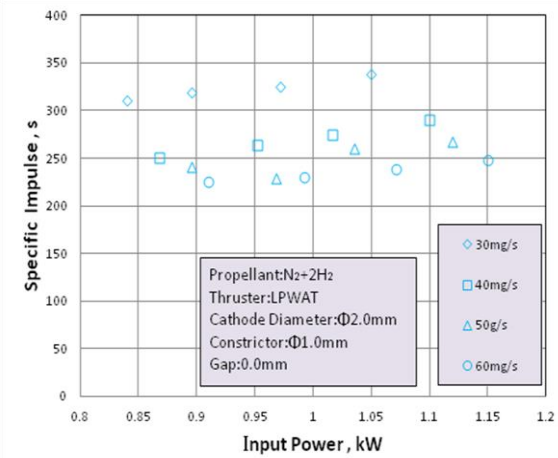
Figure 17. Performance characteristics of low-power arcjet thruster using pure nitrogen with constrictor diameter of 1.0 mm and cathode diameters of 2 and 3 mm at discharge current of 10 A changing mass flow rate.



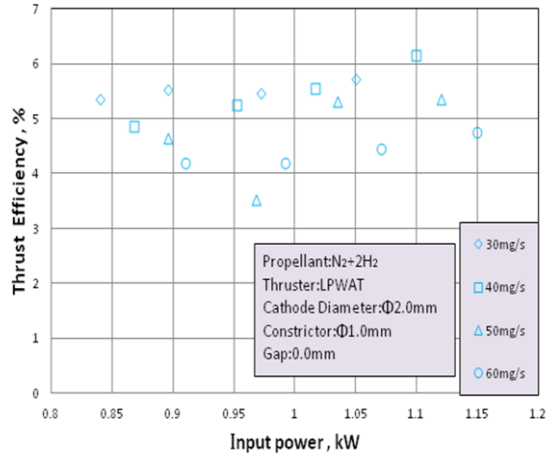
(a) Discharge voltage vs current.



(b) Thrust vs input power.



(c) Specific impulse vs input power.



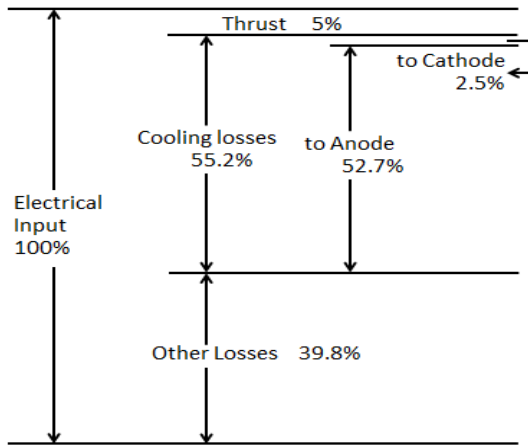
(d) Thrust efficiency vs input power.

Figure 18. Performance characteristics of low-power arcjet thruster using hydrazine decomposed gas with constrictor diameter of 1.0 mm and cathode diameter of 2.0 mm.

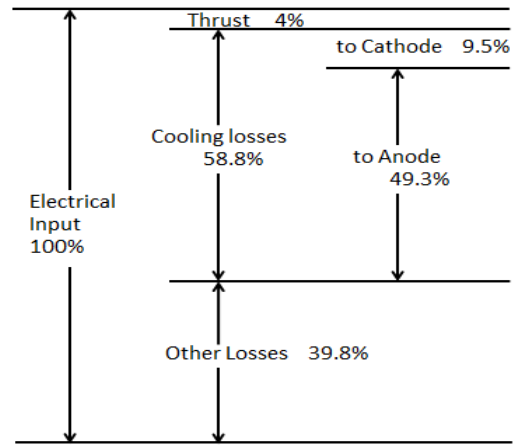
The flow rate is 7.0SLM. **Table 5** shows typical performances with the high-power and low-power arcjet thrusters, respectively. Both the specific impulse and the thrust with the high-power arcjet are higher than those with the low-power arcjet thruster. However, the thrust efficiency with the low-power arcjet is slightly high compared with that with the high-power arcjet thruster. This is inferred because of a longer constrictor of 1.5 mm of the low-power arcjet thruster.

We optimized constrictor configuration of the low-power arcjet thruster to a constrictor with 1.0 mm in length and 1.0 mm in diameter with a cathode with 3.0 mm in diameter. **Figures 16-18** show performance characteristics of the optimized low-power arcjet thruster with cathode diameters of 2 and 3 mm. With hydrazine decomposed gas, the thrust and specific impulse reaches about 140 mN and 300 sec at input powers around 1.0 kW.

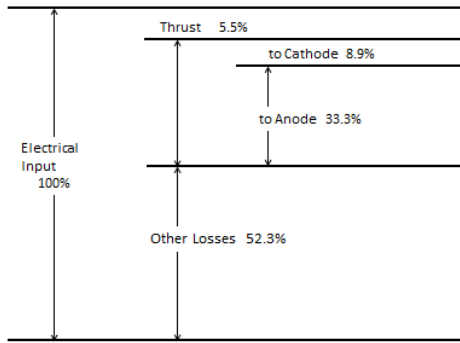
Furthermore, we performed heat balance measurements. We measured temperatures of cooling-water at some points using K-type thermo-couples, and heats were evaluated from differences of the temperatures under operation. A steady-state operation was performed until it reached the temperature equilibrium. **Figure 19** shows results of energy balance with a cathode diameter of 2 mm. The anode occupies most cooling losses because of water-cooled anode.



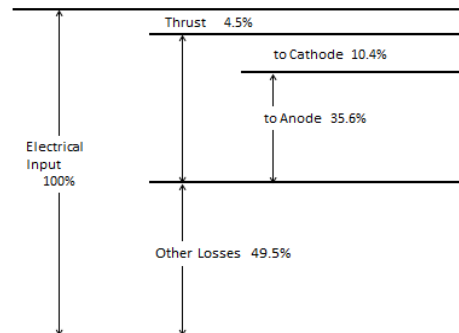
(a) With pure N_2 at mass flow rate of 30mg/s.



(b) With pure N_2 at mass flow rate of 60mg/s.



(c) With hydrazine decomposed gas at mass flow rate 30mg/s.



(d) With hydrazine decomposed gas at mass flow rate of 60mg/s.

Figure 19. Energy balance characteristics with cathode diameter of 2 mm.



Figure 20. Photo of low-power arcjet plasma plume with HAN (SHP163) decomposed gas.

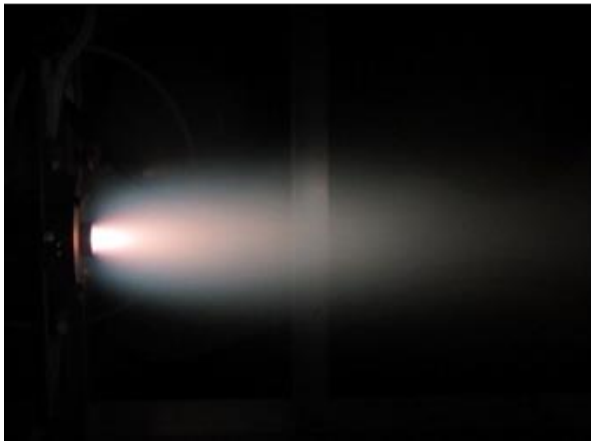


Figure 21. Photo of low-power arcjet plasma plume with hydrazine decomposed gas.

Table 6. Performance data with HAN (SHP163) decomposed gas and hydrazine decomposed gas.

Discharge Current [A]	17	17
Discharge Voltage [V]	80	78
Input Power [kW]	1.36	1.33
Thrust [mN]	182.62	116.64
Specific Impulse [s]	156.41	217.10
Thrust Efficiency [%]	10.30	9.36

C. Performance with HAN decomposed gas

We performed experiments using the HAN (SHP163) decomposed gas. The ratio of mixture was set from the mole fraction of combustion products of SHP163. **Table 6** shows the performances with the HAN decomposed gas and the hydrazine decomposed gas, respectively. The thrusts with the HAN decomposed gas, the hydrazine decomposed gas and pure nitrogen are 182.62 mN, 116.64 mN and 144.11 mN, respectively, with specific impulses of 156.41 s, 217.10 s and 201.52 s at input powers of 1.36 kW, 1.33 kW and 0.8 kW, and the thrust efficiencies are 10.30 %, 9.36 % and 11.96 %. As a result, the performance with the HAN composed gas is acceptable compared with those with the hydrazine decomposed gas and pure nitrogen for the low-power arcjet thruster although the specific impulse is slightly lower. **Figures 20 and 21** show typical photographs of plasma plumes with the HAN decomposed gas and hydrazine decomposed gas, respectively. With all conditions of the both decomposed gases, the plasma with intensive emission is stably expanded axially and radially. Specially, even with mixture of HAN (SHP163) itself and N_2 , the plasma plume is very stable during 10-min operation although with severe cathode erosion.

IV. Discussion

In this experiment, we could confirm operations with HAN decomposed gas. However, the operations were very short. As a result, we consider that a decrease in thrust efficiency and specific impulse and an increase in the input power required for ionization have happened. We infer that the cathode cooled by room-temperature water, the soot adhering to the cathode and possibility of oxidation of the cathode by oxygen are causing slightly-unstable operation. **Figure 22** shows the photo of the heated cathodes with severe erosion after operations with HAN decomposed gas. There is a need to improve cathode itself and electrode configuration in the future.



Figure 22. Photo of cathodes after operations with HAN (SHP163) decomposed gas.

V. Conclusion

We mainly investigated basic performances of a low-power (1-3 kW) arcjet thruster with the HAN decomposed gas.

In these experiments, the thrusts with the HAN decomposed gas, the hydrazine decomposed gas and pure nitrogen were 182.62 mN, 116.64 mN and 144.11 mN, respectively, with specific impulses of 156.41 s, 217.10 s and 201.52 s at input powers of 1.36 kW, 1.33 kW and 0.8 kW, and the thrust efficiencies were 10.30 %, 9.36 % and 11.96 %. As a result, the performance with the HAN composed gas is acceptable compared with those with the hydrazine decomposed gas and pure nitrogen for the low-power arcjet thruster although the specific impulse was slightly lower. With all conditions of the both decomposed gases, the plasma with intensive emission was stably expanded axially and radially. Specially, even with mixture of HAN itself and N_2 , the plasma plume was very stable during 10-min operation although with severe cathode erosion.

As for the hydrazine decomposed gas, after optimization of constrictor configuration of the low-power arcjet thruster the thrust and specific impulse reached about 140 mN and 300 sec at input powers around 1.0 kW.

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