Compatibility Study of Low Toxicity Propellant Gas "HAN" for DC Arcjet Thrusters

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Hirokazu Tahara[1], Yusuke Okamachi[2], Katsuya Fujita[3], Kazuya Nakagawa[4] and Masamichi Naka[5]
Osaka Institute of Technology
Asahi-Ku, Osaka, 535-8585, Japan

and

Taiichi Nagata[6] and Ideo Masuda[7]
Japan Aerospace Exploration Agency
Tsukuba, Ibaraki 305-8505, Japan

Abstract: Hydrazine is used as a propellant of spacecraft thruster. However, hydrazine is high toxicity liquid. Spacecraft researchers need a low toxicity propellant. Hydroxyl Ammonium Nitrate (HAN: NH_3OHNO_3) is proposed as low toxicity propellant. In this study, the capability of HAN as DC arcjet thruster propellant is examined. Using both the decomposed gas of H_2O, CO_2 and N_2, and HAN itself an arcjet thruster was operated, and the basic characteristics were obtained. As a result, a very severe condition of the electrodes was clarified. The thrust and the thrust efficiency with mixture of HAN and N_2 were 220.6 mN and 0.62 %, respectively, with 5 kW input power. As a result, the performance with HAN was very low for DC arcjet thrusters although the operation was relatively stable during 10 min.

I. Introduction

THE direct-current (DC) arc plasma jet generator is a promising plasma device suitable for aerospace applications to arcjet thrusters in space and arc heaters in high-enthalpy plasma chambers, and also for economically assisting material processing in which a high throughput of material is desired.

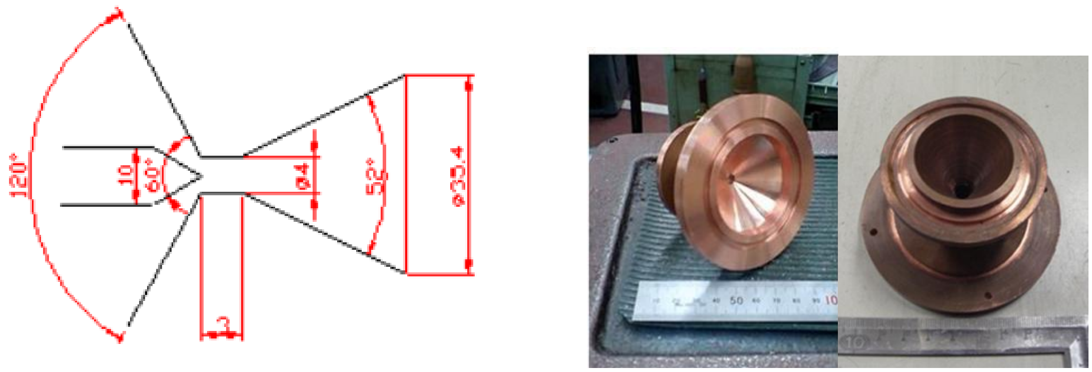
In aerospace applications, arcjet thrusters were developed for near-earth missions. A low power arcjet thruster is a commercial one with ammonia, and mixture of hydrogen and nitrogen, hydrazine decomposed gases, as propellants. The arcjet generator is also available as arc heaters for entry and reentry simulations into atmospheric gases around Mars, Venus and Earth etc, in which carbon dioxide and nitrogen are mainly used as working gases.

In low-pressure plasma spraying, a plasma jet generator with a supersonic expansion nozzle is useful for spraycoating hard and large-area films adhering strongly to substrates.[1,2] In surface treatment such as nitriding, a supersonic plasma jet in a low pressure environment also has benefits of efficient plasma treatment by using irradiation of highly excited and/or chemically active particles in the thermodynamical nonequilibrium plasma in

[1] Professor, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[2] Graduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[3] Graduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[4] Undergraduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[5] Graduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[6] Engineer, Aerospace Research and Development Directorate, and nagata.taiichi@jaxa.jp.
[7] Engineer, Aerospace Research and Development Directorate, and masuda.ideo@jaxa.jp.

a) b) c)

Figure 1. Configuration of water-cooled direct-current arcjet.
a) Cross-sectional view, b) photo, c) arrangement.



a) b)

Figure 2. Electrode configuration and anode part.
a) Electrode configuration, b) photos of anode nozzle.

a) b)

Figure 3. Cathode tip configuration.
a) Conical cathode, b) hemispherical cathode.

addition to large-area and uniform treatment.[3,4] In our previous study, ammonia and mixtures of nitrogen and hydrogen were used for nitriding processing.[3,4] Since these gases were chemically active, the processing efficiency was enhanced.

a)

b)

Figure 4. Photos of experimental facility for arcjet thruster.
a) Vacuum chamber, b) rotary pump and mechanical booster.

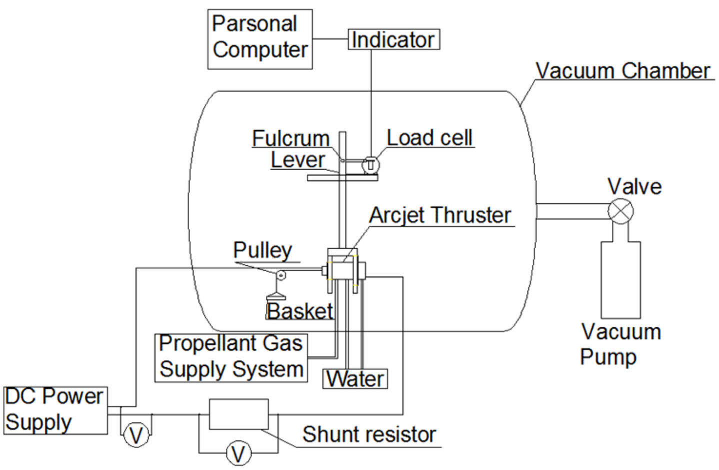


Figure 5. Experimental system for arcjet thruster.

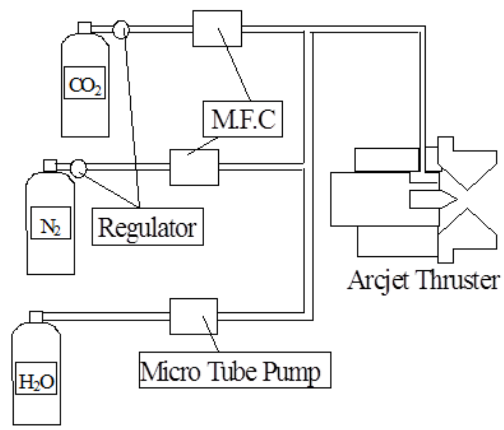


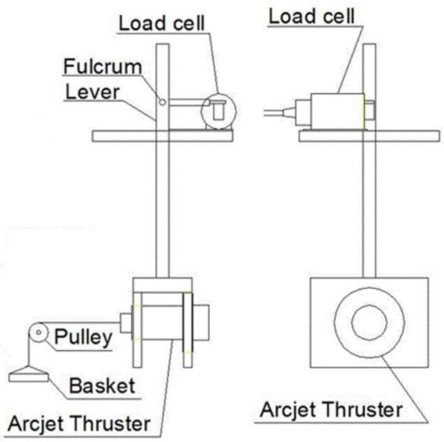
Figure 6. Propellant supply system.

In this study, a new propellant for arcjet thrusters is proposed instead of hydrazine because hydrazine is high toxicity liquid. Aerospace engineers and researchers need a low toxicity propellant. Hydroxyl Ammonium Nitrate (NH_3OHNO_3: HAN; decomposed gases: mainly mixture of carbon dioxide, vapor and nitrogen) is a measure up to the request. The capability of HAN is examined as DC arcjet thruster`s propellant.

II. Experimental Apparatus

Figures 1-3 show the configuration of the water-cooled DC arcjet thruster used for this study.[5-8] A constrictor of a convergent-divergent nozzle throat typically has a diameter of 4 mm and a length of 3 mm. A divergent nozzle has an exit diameter of 35.4 mm and is inclined at an angle of 52 deg. The ratio of the cross-sectional area of the nozzle exit to that of the constrictor is 32:1. A cylindrical cathode made of pure tungsten has a diameter of 10 mm. The shape of the cathode tip is changed to conical and hemispherical shapes as shown in Fig.3. The gap between the electrodes is set to 0 mm. The propellant gas is injected tangentially from the upstream end of the discharge chamber. The arcjet is operated with input powers of 5-12 kW. As shown in Figs.4 and 5, the arcjet is located in a vacuum tank 1.2 m in diameter and 2 m long, which is evacuated using a mechanical booster of 6000 m^3/h connected in series with a rotary pump of 600 m^3/h. The vacuum pressure is kept below 1 Pa.

The propellants are the decomposed gas of Hydroxyl Ammonium Nitrate (NH_3OHNO_3: HAN); that is, mainly mixture of carbon dioxide, vapor and nitrogen, pure HAN and pure nitrogen for comparison of performance. As shown in Fig.6, water is supplied with a micro tube pump into the propellant gas.



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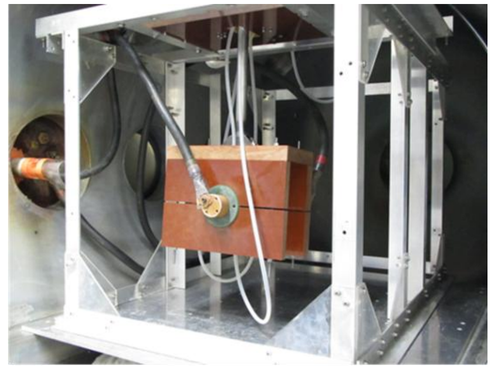


b)

Figure 7. Thrust measurement system.
a) Pendulum system, b) photo.

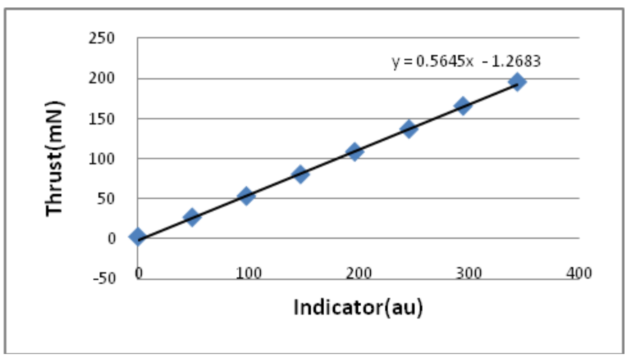


Figure 8. Thrust calibration curve.

Figure 7 shows the thrust measurement system. Thrust is measured by pendulum method with a load cell. Thrust calibration is carried out with a pulley and weight system, and a typical calibration curve, as shown in Fig.8, is almost linear.

Tables 1 and 2 show the operational conditions with the two cathodes. Tables 3 and 4 show the experimental conditions for thrust measurement.

Table 1. Experimental condition and results with conical cathode.

H_2O Liquid Flow Rate Dial scale , ml/h	100.5
Dial scale	5.2
N_2 Gas Flow Rate , SLM	2.5
CO_2 Gas Flow Rate , SLM	2.6
Discharge Current , A	115
Discharge Voltage , V	104
Plasma Input Power , kW	11.96

Table 2. Experimental condition and results with hemispherical cathode.

H_2O Liquid Flow Rate Dial scale , ml/h	100.5
Dial scale	5.2
N_2 Gas Flow Rate , SLM	2.5
CO_2 Gas Flow Rate , SLM	2.6
Discharge Current , A	110
Discharge Voltage , V	90
Plasma Input Power , kW	9.9

III. Results and Discussion

As shown in Tables 1 and 2, the discharge voltage with the conical cathode is 104 V at a discharge current of 115 A; the input power reaches 11.96 kW, and that with the hemispherical cathode is 90 V at 110 A with 9.9 kW. As a result, the discharge voltage with the conical cathode is higher than that with the hemispherical cathode. Furthermore, the discharge voltages are very high compared with those with hydrazine decomposed gases, resulting in the high input powers.

Figure 9 shows photographs of cathodes before and after operations. All cathodes were severely eroded even with short operational times. This is expected because drastic oxidation and current concentration with molecular gases occur. The eroded mass of the conical cathode is about 3 g with 10-sec operation and that of the hemispherical

Table 3. Experimental conditions with decomposed gas and pure nitrogen for thrust measurement.

	Decomposed Gas	Nitrogen
Electrode Distance , mm	-1	-1
Cathode Material	Pure Tungsten	Pure Tungsten
Cathode Shape	45°	45°
Constrictor Diameter , mm	6	6
Flow Rate	CO_2: 0.6[SLM] N_2 : 0.6 [SLM] H_2O: 180[ml/h]	N_2 : 7.0 [SLM]

Table 4. Experimental conditions with mixture of HAN and N_2 for thrust measurement.

Electrode Distance , mm	-1
Cathode Material	Pure Tungsten
Cathode Shape	45°
Constrictor Diameter , mm	6
Flow Rate	HAN: 33.0[ml/h] N_2 : 7.0[SLM]

Table 5. Performance date with decomposed gas and pure nitrogen.

	Decomposed Gas	Nitrogen
Thrust[mN] (45V,105A)	72.7	205.6
Input Power[kW]	4.73	
Thrust[mN] (0V,0A)	0.96	106.9
Specific Impulse[s]	54.9	143.7
Thrust Efficiency[%]	0.41	3.0

Table 6. Performance date with mixture of HAN and N_2.

	HAN
Thrust[mN] (55V,107A)	220.6
Input Power[kW]	5.9
Specific Impulse[s]	33.7
Thrust Efficiency[%]	0.62

cathode is about 2 g. The erosion with the conical cathode is intensively severe compared with that with the hemispherical cathode.

We measured thrust in typical conditions with a conical cathode as shown in Tables 3 and 4. Tables 5 and 6 show the performances with the decomposed gas, pure nitrogen, and mixture of HAN and nitrogen. The thrusts with the decomposed gas and pure nitrogen are 72.7 mN and 205.6 mN, respectively, and the thrust efficiencies are 0.41 % and 3.0 %, respectively. Accordingly, the performance with pure nitrogen is higher than that with the decomposed gas. As shown in Table 6, the thrust with mixture of HAN and N_2 is 220.6 mN and the thrust efficiency is 0.62 %. As a result, the performance with HAN is very low for DC arcjet thrusters although the operation is relatively stable.

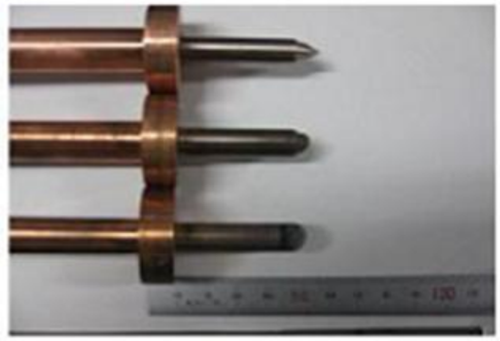
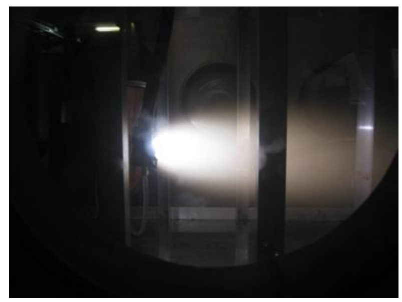


Figure 9. Photos of eroded cathodes.



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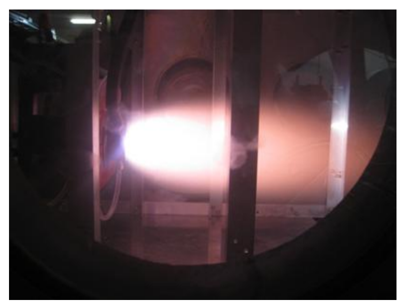

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Figure 10. Photos of plasma plumes. a) Decomposed gas, b) nitrogen.

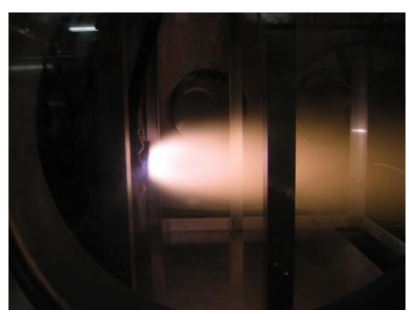

Figure 11. Photos of plasma plume with mixture of HAN and N_2.

Figures 10 and 11 show typical photographs of plasma plumes. With all conditions the plasma with intensive emission is stably expanded axially and radially. Specially, even with mixture of HAN and N_2, the plasma plume is very stable during 10-min operation although with a severe eroded cathode.

IV. Conclusion

The performance characteristics of a 10-kW-class arcjet were investigated with a low toxicity propellant of Hydroxyl Ammonium Nitrate (HAN: NH_3OHNO_3). The capability of HAN as arcjet thruster's propellant was examined. Using the decomposed gas of H_2O, CO_2 and N_2, the arcjet was operated. As a result, the discharge voltage with the conical cathode was higher than that with the hemispherical cathode, and the discharge voltages were very high compared with those with hydrazine decomposed gases, resulting in the high input powers. All cathodes were severely eroded even with short operational times. This is expected because drastic oxidation and current concentration with molecular gases occur. The erosion with the conical cathode was intensively severe compared with that with the hemispherical cathode.

From thrust measurement, the thrusts with the decomposed gas and pure nitrogen were 72.7 mN and 205.6 mN, respectively, and the thrust efficiencies were 0.41 % and 3.0 %, respectively. Accordingly, the performance with pure nitrogen was higher than that with the decomposed gas. Furthermore, the thrust with mixture of HAN and N_2 was 220.6 mN and the thrust efficiency was 0.62 %. As a result, the performance with HAN was very low for DC arcjet thrusters although the operation was relatively stable. With all experimental conditions the plasma with intensive emission was stably expanded axially and radially. Specially, even with mixture of HAN and N_2, the plasma plume was very stable during 10-min operation although with a severe eroded cathode.

Acknowledgments

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