An Al-water Fed DC Arcjet

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Abstract: **In this study, development of Al-water fed arcjet was conducted, in which water and aluminum were fed to the thruster as the propellant. The combustion of aluminum with water as an oxidizer can release a very high energy density with unit mass compared with fossil fuels. From the chemical equilibrium simulation, it was shown that thrust performance of the Al-water fed arcjet was as well as that of hydrazine arcjets at low specific power range. In addition, to observe behaviors of vaporized aluminum propellant fed as a solid state rod to the arcjet and then vaporized in the discharge plenum, a novel coaxial double cathode was developed and tested. It was shown that streams of vaporized aluminum were injected through the injection holes at a tip of the coaxial double cathode. From the spectroscopic measurement of the plasma in the plenum, spectra of atomic and ionic aluminum were observed at 200 nm to 400 nm. In addition, larger heat generation, probably due to exothermic chemical reactions of species, was confirmed with mixed propellant of Al and water. Since the heat exhausted from the nozzle was no longer measured after termination of discharges, this chemical reaction could be controlled only with discharges.**

Nomenclature

T_i = initial temperature
T_f = flame temperature

I. Introduction

Althought propulsion systems on the majority of spacecraft to date have consisted of chemical thrusters, an increasing number of spacecraft launched recently use arcjet thrusters as a high-performance alternative for north-south station keeping (NSSK) of geosynchronous satellites [1-4)]. Through the use of an arc for direct heating of

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the propellant stream to temperatures much higher than the wall temperatures, DC arcjet thrusters overcome the gas temperature and specific impulse limitation of the resistojet thrusters and can yield relatively high thrust power ratio among other electric propulsion systems. Regarding propellants, various kinds of gas have been applied to arcjet thrusters. Although relatively low molecular-mass gaseous propellants such as hydrogen generate a relatively high specific impulse, a need for a high-pressure tank and leakage problems through seals and valves are inevitable. These issues can be major disadvantages for the use of the propellant of this type for long-term missions [5)]. At present, hydrazine is the most common propellant because it is storable as a liquid phase and can be shared with chemical thrusters. However, due to its relatively high freezing point of 274 K, temperature management is still necessary for the storage in space environment. Since hydrazine is very reactive and toxic, the materials for tanks and valves must be compatible to the chemical properties.

For an alternative propellant, Kakami et al. proposed Dimethyl ether (DME)[6)]. Unlike hydrogen and hydrazine, DME can be stored as a liquid phase under a relatively low storage pressure without sophisticated temperature management system owing to a freezing point of 130 K, a boiling point of 119 K, and a vapor pressure of 6 atm at room temperature. Catalyst is not necessary for propellant gasification because DME is easily gasified or liquefied simply by adjusting pressure or temperature. They demonstrated that the DME arcjet thruster was comparable to the conventional thruster in discharge voltage, power and plenum chamber pressure. As for another alternative propellant, we propose a mixture of aluminum (either solid or powder) and water in this study. Since the combustion reaction of the mixture can release a very high energy, a thruster using this propellant can either be a chemically augmented arcjet thruster or an electrically augmented chemical thruster, in which much higher thrust performances can be expected than conventional chemical thrusters or even than hydrazine arcjets. Numerical investigations based on chemical equilibrium calculations are conducted to understand the details of combustion reactions and products of the electrically augmented aluminum and water reactions. In addition, to observe behaviors of vaporized aluminum propellant fed as a solid state rod to the arcjet and then vaporized in the discharge plenum, a novel coaxial double cathode was developed and its vaporization characteristics were experimentally exmined.

II. Advantages of use water and aluminum

Water is one of the handiest substances for a propellant in terms of the chemically stable, harmless characteristics for human body, and low-cost advantages for storage and delivery at room temperature compared with conventional propellants, such as hydrazine. Since it can be stored either in a liquid or solid state in space environment, any high-pressure tanks are not necessary. In addition, the water has superior thermochemical characteristics as a propellant. Due to large specific heat characteristics, the increase of plenum temperature can be suppressed under the increase of input power, or namely enthalpy, to the propellant. In particular, the suppressed plenum temperature characteristic will result in reduction of thermal losses of the thruster, which can be conductive, radiative and frozen flow losses, and also in improvement of thrust efficiency. In addition, the large specific heat characteristic will contribute to the increase of the plenum enthalpy which is a product of the specific heat and temperature of the plenum, or namely to the increase of the specific impulse, even under suppressed plenum temperature conditions.

Since aluminum exists about 8wt% on the earth, its cost of utilization as a propellant can be inexpensive. In addition, a block of solid aluminum is chemically stable and harmless either to human body or to environment at room temperature. Even at elevated temperatures below the melting point, a block of solid aluminum mixed with water even at a stoichiometric ratio is still stable and safe without any combustion reactions. Therefore, under wide ranges of temperature and pressure, a mixture of water and aluminum can be a safe material. However, when the aluminum surface is stimulated with a significantly high energy density, a combustion reaction of water and aluminum additives will take place. The combustion of aluminum with water as an oxidizer can release a very high energy density with unit mass compared with fossil fuels, as follows,

$$2Al(s)+3H_2O(l) = Al_2O_3(cr)+ 3H_2 + 30\ kJ/g. \qquad (1)$$

Therefore, a mixture of aluminum and water can be very handy and superior material as a propellant for a thermal rocket engine, if any high-energy density sources are equipped. In this study, effects of use of arc discharges for the ignition of the aluminum (either in solid or powder state) and water mixture are investigated. Moreover, advantages of use of the mixture for a propellant of an arcjet thruster are also investigated for the improvement thrust performance, or efficiency.

For equilibrium calculations of combustion reactions of aluminum and water mixtures and further estimation of thrust performances for a given nozzle condition of an arcjet thruster, a simulation code, NASA Chemical

Equilibrium with Applications (CEA) developed by S. Gordon and B. J. McBride[7] was utilized. To include additional heating through arc discharges occurring in an arcjet thruster, an electrical input power was assumed and added to an enthalpy, or power, of formation of reactants, or propellant components.

Variations of mole fractions of reaction products and adiabatic flame temperatures with increase of initial temperature are shown in Fig. 1 for initial mass fractions of water and aluminum of 90% and 10%, respectively. It is shown that mole fractions of products, such as alumina and H_2, are kept almost constant values with initial temperatures below 2,000 K. On the other hand, at above 2,000 K, mole fractions of species, such as H_2, OH and H, increase and those of product (alumina) decrease with initial temperatures. Moreover, at initial temperature of 2,700 K, an amount of heat released from exothermic reactions and absorbed through endothermic reactions is balanced, or in equilibrium, and then a flame temperature stays at 2,700 K. At higher initial temperatures (T_i > 2,700 K), the endothermic reactions, producing H, OH and other radicals, become more dominant, and then $T_f < T_i$. Therefore, it is shown that, at higher initial temperature conditions, the electrical heating of propellant is not effective in inducing exothermic reactions.

Relations between input power and specific impulse are shown in Fig. 2 for various propellants, which are H_2O, N_2H_4, Ar and Al-water mixture (with equivalence ratio of unity) for mass flow rate of 108 mg/sec, assuming an expansion ratio of the nozzle of 100 and a plenum pressure of 0.1 MPa. As can be seen, the specific impulses of Al-water cases are as high as those of N_2H_4 cases with the maximum difference of about 8%. In particular, at input powers of below 200 W, higher specific impulses than N_2H_4 can be obtained with the Al-water propellant. Moreover, at input powers of over 2,000 W, the specific impulse of the Al-water propellant can also be higher than N_2H_2 propellant. Comparing these results with a pure water propellant case, an effect of addition of aluminum to water, inducing an additional enthalpy, is significant in increasing specific impulse.

Influences of equivalence ratios of the Al-water mixture on specific impulse with various input powers are shown in Fig. 3. It is shown that, among equivalence ratios of 0.5, 1.0 and 1.5 cases, the highest specific impulse can be obtained with that of 0.5 over wide range of input power conditions.

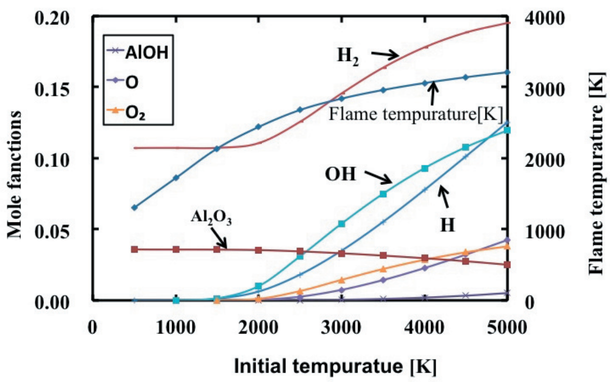


Figure.1 Variations of mole fractions of reaction products and adiabatic flame temperatures with initial temperature for initial mass fractions of water and aluminum of 90% and 10%.

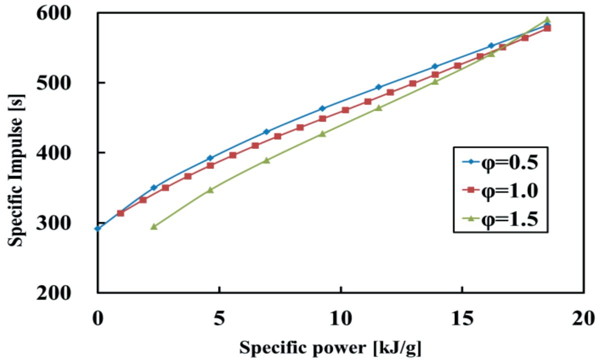


Figure.2 Relations between input power and specific impulse for various propellants.

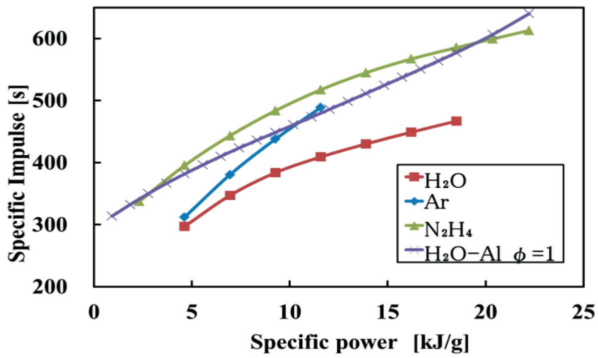


Figure.3 Influences of equivalence ratios on specific impulse with various input power.

III. Experimental

Although our final goal is to utilize aluminum and water to the propellant of an arcjet thruster, an objective of this part is to examine a newly developed coaxial double cathode designed to vaporize the aluminum propellant fed as a solid state rod to the arcjet and then vaporized in the discharge plenum. Optical observations of behaviors of the vaporized aluminum propellant were conducted.

A photo and a schematic of a coaxial double cathode are shown in Fig.4. The cathode consists of an inner aluminum rod (diameter 2 mm) propellant inserted in a hollow tungsten cathode (outer diameter 3 mm, inner diameter 2 mm). On a tip of the hollow cathode, there are two propellant injection holes of 0.2 mm in each diameter. From the injection holes, vaporized aluminum propellant, which is heated, melted and vaporized by the arc heating of the cathode tip, is injected to the discharge plenum and then mixed and to be reacted with oxidizing propellant (i.e. air, water, etc.). A schematic of an arcjet employing the coaxial double cathode is illustrated in Fig.5. To observe behaviors the aluminum vapor from the injectors, a wall of the discharge plenum is made of a quartz tube and therefore is transparent. A body of the arcjet is made of boron-nitride (BN), and an anode made of brass with a throat of 3 mm in diameter. A schematic of experimental setup for plasma behavior observation is illustrated in Fig.6. To observe the aluminum vapor behaviors, a digital HD camera (30 fps) and a multichannel spectrum analyzer were employed. To drive the arcjet, a direct current (DC) power supply (capable of maximum voltage of 500 V, current of 40 A) and an igniter to initiate arc discharges were used. As shown in this figure, temporal variations of discharge voltages and currents were monitored. An amount of heat exhausted from the nozzle of the arcjet was measured with a calorimeter.

Although our final goal is to utilize aluminum and water to the propellant, an objective of this study is to observe behaviors of aluminum vapor during discharges. To simplify the phenomena, non-reactive argon gas is firstly utilized for the gaseous propellant for comparison. In addition, effects of vaporized water for the propellant is also tested. Mass of the gas or liquid propellant were controlled with mass flow controllers.

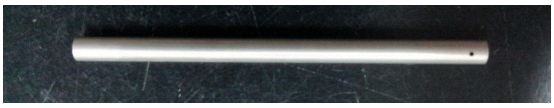
IV. Results and Discussion

Although our final goal is to utilize aluminum and water to the propellant of an arcjet thruster, an Images of aluminum vapor injection from a tip of a coaxial double cathode captured by digital HD camera are shown in Fig. 7 (a) and (b), respectively. In this case at Fig. 7 (a), discharge current and voltage were 13 A and 17 V, respectively, and, namely, the input power was 221 W. In addition, a flow rate of the gaseous propellant, argon in this case, was 208 mg/s. A flow rate, or consumption rate, of the aluminum vapor propellant was estimated from the difference of the mass of the coaxial double cathode before and after discharges and its duration, which was 5.4 mg/s. In Fig. 7 (b), discharge current and voltage were 11 A and 34 V, respectively, and, namely, the input power was 374 W. In addition, a flow rate of the gaseous propellant, H_2O in this case, was 50 mg/s. A flow rate, or consumption rate, of the aluminum vapor propellant was 10.7 mg/s.

From the images, it was shown that streams of vaporized aluminum were injected through the injection holes at a tip of the coaxial double cathode

Typical spontaneous spectra from the plasma in the plenum are shown in Fig. 8. As can be seen, spectra of atomic and ionic aluminum were observed at 200 nm to 400 nm and spectra of atomic and ionic argon were observed at 600 nm to 900 nm. From these results, it was confirmed that injected vapor from the injectors shown in Figs. 7 (a) and (b) was mainly vaporized aluminum. From argon spectra, the maximum temperatures of the plasma are roughly estimated, 9000 ~ 30000 K.

From these results, the successful feed of the vaporized aluminum propellant to the discharge plenum was demonstrated by employing the coaxial dual cathode.



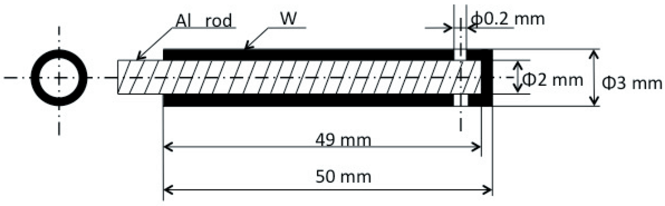


Figure.4 Photo (left) and schematic (right) of coaxial double cathode

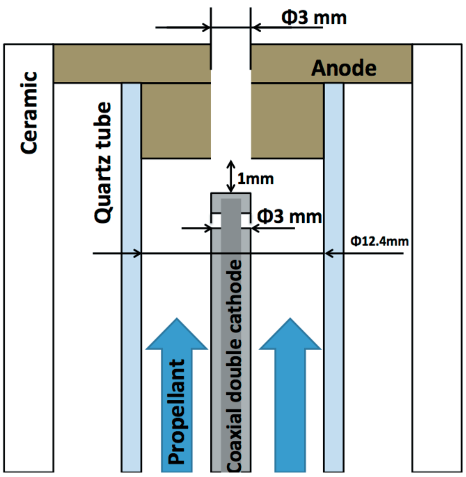


Figure. 5 Schematic of an arcjet

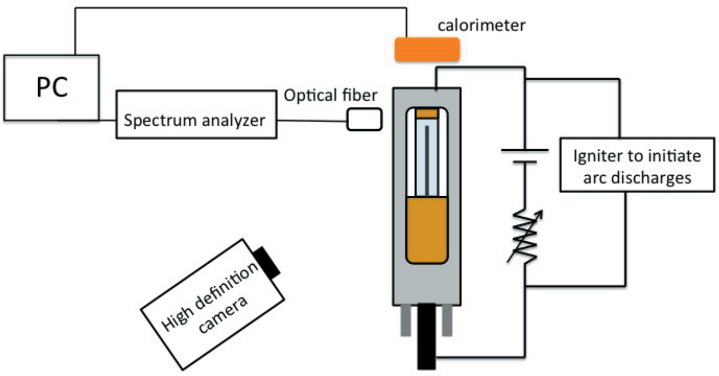


Figure. 6 Schematic of experimental setup

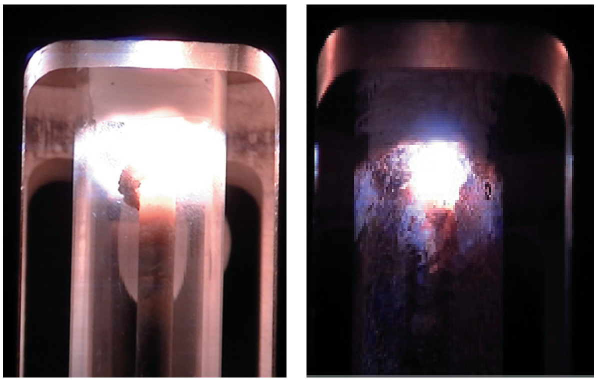


Figure.7 Images captured by digital HD camera ((a) left: discharge current 13 A, discharge voltage 17 V, mass flow rate 208mg/s (Ar), 5.4 mg/s (Al)) and ((b) right: discharge current 11 A, discharge voltage 34 V, mass flow rate 50mg/s (H_2O), 10.7 mg/s (Al))

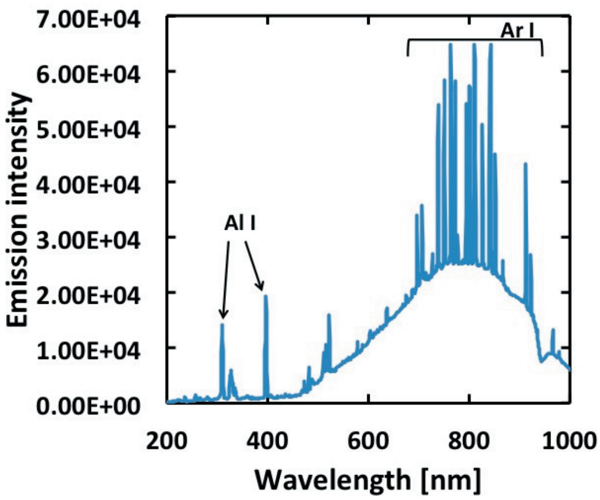


Figure.8 Typical spontaneous spectra (discharge current 13A, discharge voltage 17V, mass flow rate 208mg/s (Ar), 5.4mg/s (Al))

Table 1. Discharge characteristics of typical operation.

	Ar	H_2O
I [A]	13	11
V [V]	17	34
P [W]	221	369
Operating duration Δt [s]	10	5
m (gas) [mg/s]	208	50
m (Al) [mg/s]	5.4	10.7
Q [J]	6.0	164.4
$Q/(P\Delta t)$ [%]	0.2	2.2

Discharge characteristics of an arcjet in operation obtained from the experiments with argon and water propellants employing a coaxial double cathode are listed in Table 1. In this table, mass flow rates of aluminum (m (Al)) were estimated from the differences of the masses of the cathode by measuring the cathode mass before and after operation. Moreover, estimated amount of heats Q measured at exhaust orifice of the arcjet, and ratios of those to input energies ($Q/(P\Delta t)$) are also listed. Although, measured exhausted heats are very low, there is clear difference in exhaust energy outputs between argon and water propellants. Namely, larger heat generation, probably due to exothermic chemical reactions of species, is confirmed with mixed propellant of water and Al. Since the heat exhausted from the nozzle was no longer measured after termination of discharges, this chemical reaction can be controlled only with discharges. Therefore, the aluminum combustion with water can be ignited and sustained with discharges.

V. Conclusion

In this study, development of Al-water fed arcjet was conducted, in which water and aluminum were fed to the thruster as the propellant. Numerical investigations based on chemical equilibrium calculations were conducted to understand the details of combustion reactions and products of the electrically augmented aluminum and water reactions.

From the chemical equilibrium simulation, it was shown that thrust performance of the Al-water fed arcjet was as well as that of hydrazine arcjets at low specific power range. In addition, to observe behaviors of vaporized aluminum propellant fed as a solid state rod to the arcjet and then vaporized in the discharge plenum, a novel coaxial double cathode was developed and tested. From hispeed camera images, it was shown that streams of vaporized aluminum were injected through the injection holes at a tip of the coaxial double cathode.

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From these results, it was confirmed that injected vapor from the injectors of the coaxial double cathode was mainly vaporized aluminum.

In addition, larger heat generation, probably due to exothermic chemical reactions of species, was confirmed with mixed propellant of water and Al. Since the heat exhausted from the nozzle was no longer measured after termination of discharges, this chemical reaction could be controlled only with discharges. Therefore, the aluminum combustion with water could be ignited and sustained with discharges.

VI. References

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