Evaluation of Exothermic Performance of Chemically Augmented Electrothermal Thrusters

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Abstract: In this study, an investigation and development of non-hazardous, low-cost, and stable liquid propellants including their mixtures under room temperature for arcjet thrusters were conducted. These materials should be energetic producing chemical exothermic energy when given an input energy density above certain thresholds, or namely only with electrical inputs (discharges). Numerical investigations based on chemical equilibrium calculations were conducted to understand the details of combustion reactions and products of the electrically augmented reactions for various liquids. In addition, a preliminary experimental study was conducted to evaluate thermal characteristics of the arcjet thruster employing novel water-based liquid propellants. To evaluate various liquids, variations of measured thermal output ratios of exhaust plumes from the arcjets with flow rates (0.3 ~ 1.0 mg/s) of various liquid propellants were compared. As a experimental results, HFE showed the highest outputs throughout various flow rates followed by acetic acid-ethanol mixture. Moreover, slight increases of output ratios with the increase of flow rate could also be seen. Although the output ratios of a pure argon propellant case was about 5.3%, those of HFE showed about 9 ~ 10%, 7.5 ~ 8.8% for acetic acid – ethanol mixture, and 6 ~ 7% for water.

I. Introduction

The current trend towards miniaturized satellites, which is not only mass limited but also power limited, has produced a strong interest in development of micropropulsion devices.1-4) Although in the past, all of those miniaturized satellites have lacked propulsion systems altogether, future micro-spacecraft will require significant propulsion capability to provide a high degree of maneuverability and capability. The benefit of using electric propulsion for the reduction of spacecraft mass will likely be even more significant for mass limited micro-spacecraft missions.

Various potential micropropulsion systems for micro-spacecraft applications, such as ion thrusters, field emission thrusters, pulsed plasma thrusters (PPTs), resistojets, arcjets, etc., have been proposed and are under significant development for primary and attitude control applications.

Through the use of an arc for direct heating of 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

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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.

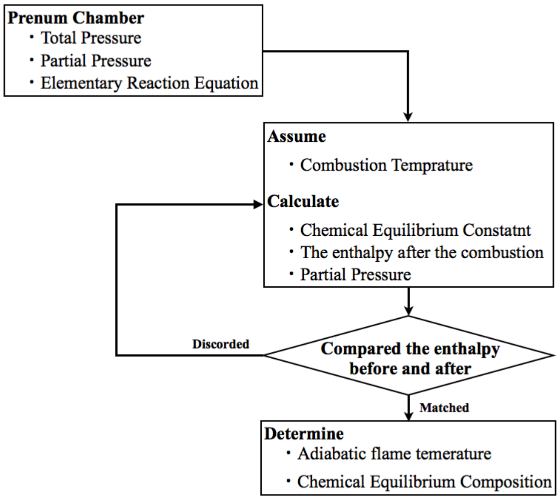

Figure 1. Flowchart of chemical equilibrium calculation.

In this study, an investigation and development of non-hazardous, low-cost, and stable liquid propellants including their mixtures under room temperature for arcjet thrusters were conducted. These materials should be energetic producing chemical exothermic energy when given an input energy density above certain thresholds, or namely only with electrical inputs (discharges). Since the objective of this study is an investigation of exothermic characteristics from the non-exothermic, stable, non-hazardous materials, these novel propellants must be "exotic propellants" with abnormally exothermic characteristics. Numerical investigations based on chemical equilibrium calculations were conducted to understand the details of combustion reactions and products of the electrically augmented reactions for various liquids. In addition, a preliminary experimental study was conducted to evaluate thermal characteristics of the arcjet thruster employing novel water-based liquid propellants.

Figs. 2 and 3 show the results for pure water, pure acetic acid, water solution of acetic acid (60mol%), HFE (Hydrofluoroether), water solution of HFE (60mol%), pure hydrogen peroxide, acetic acid and ethanol solution, CO_2, and hydrazine. Among them, hydrogen peroxide, acetic acid and ethanol solution, HFE solution and HFE (Hydrofluoroether) showed interesting characteristics.

Variations of reaction temperatures with specific power (or specific energy) for water, acetic acid, acetic acid solution, HFE, HFE solution, hydrogen peroxide, acetic acid and ethanol solution, CO_2 and hydrazine are plotted in Fig.2. In all propellants, reaction temperatures increase monotonically with specific power. Especially, CO_2, HFE and HFE solution show high temperature characteristics among them (i.e., CO_2:500 ~ 6,800 K, HFE: 1,000 ~ 3,900 K, HFE solution: 1,500 ~ 3,500 K) for a wide range of specific powers (1 ~ 40 kJ/g). Subsequently, hydrogen peroxide follows (1,100 ~ 3,100 K).

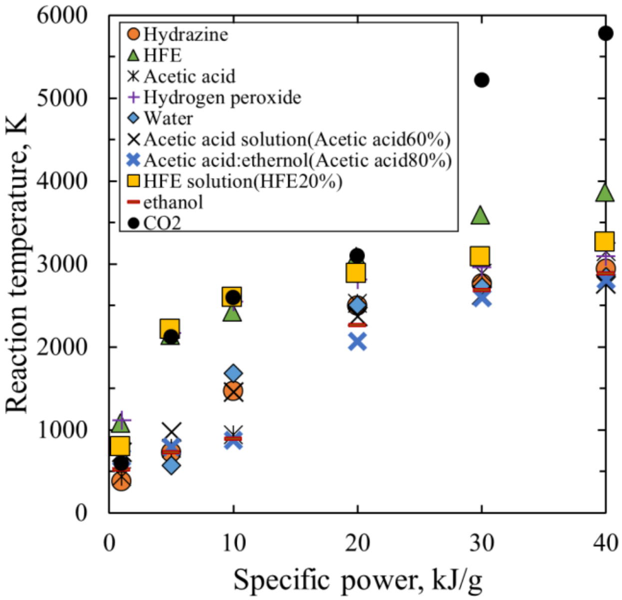

Figure 2. Variation of reaction temperatures vs specific powers for liquids.

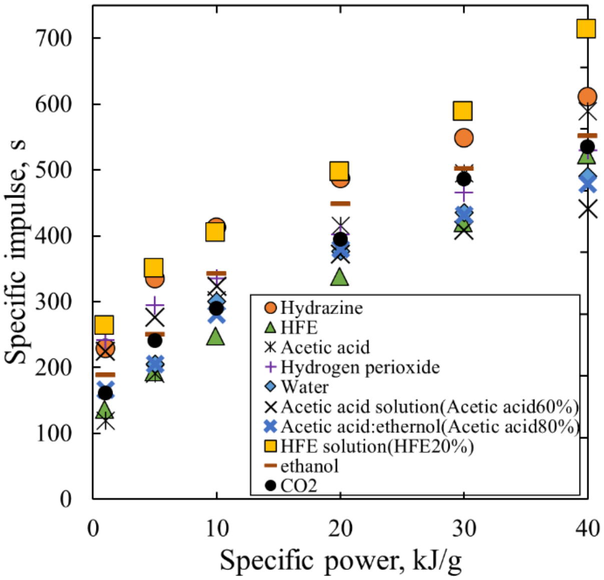

Figure 3. Variation of specific impulse vs specific powers for liquids.

Variations of specific impulses with specific power (or specific energy) for water, acetic acid, acetic acid solution, HFE, HFE solution, hydrogen peroxide, acetic acid and ethanol solution and hydrazine are plotted in Fig.3. Similar to reaction temperature, specific impulses increase monotonically with specific power in all propellant cases. In a wide range of specific powers (5 ~ 40 kJ/g) except 10 kJ/g, HFE solution (HFE20%) shows the highest values (380 ~ 710 s), followed by Hydrazine (230 ~ 610 s).

II. Experimental

In this study, to evaluate thermal characteristics of plasma plumes from arcjet, a water-cooled arcjet with a convergent nozzle (without divergent nozzle) was employed and operated in atmosphere, as shown in Fig.4.

As for the power source of the arcjet, a DC power source (maximum voltage 500 V, maximum current 40 A) and a high-frequency igniter, shown in Fig.5, were employed.

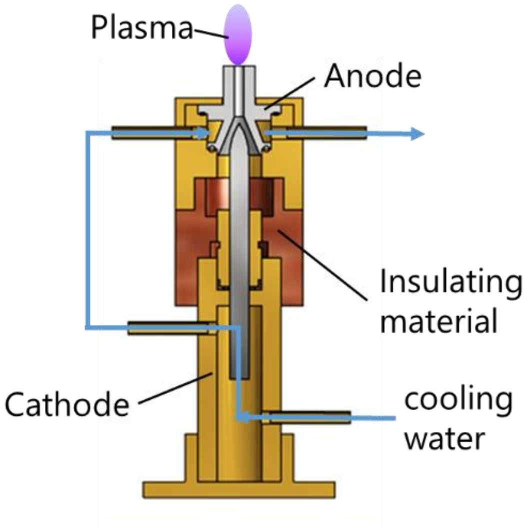

Figure 4. Cross section of water-cooled arcjet.

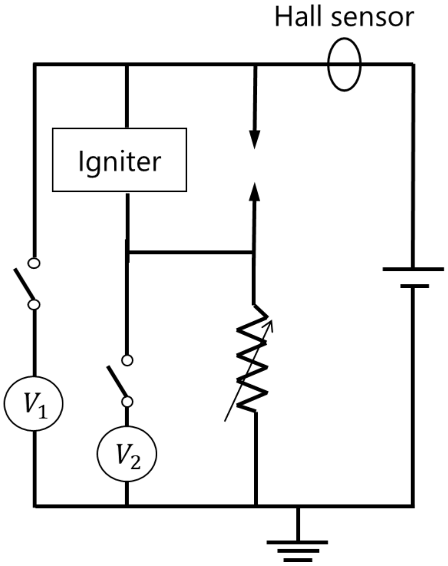

Figure 5. Schematic of DC power source.

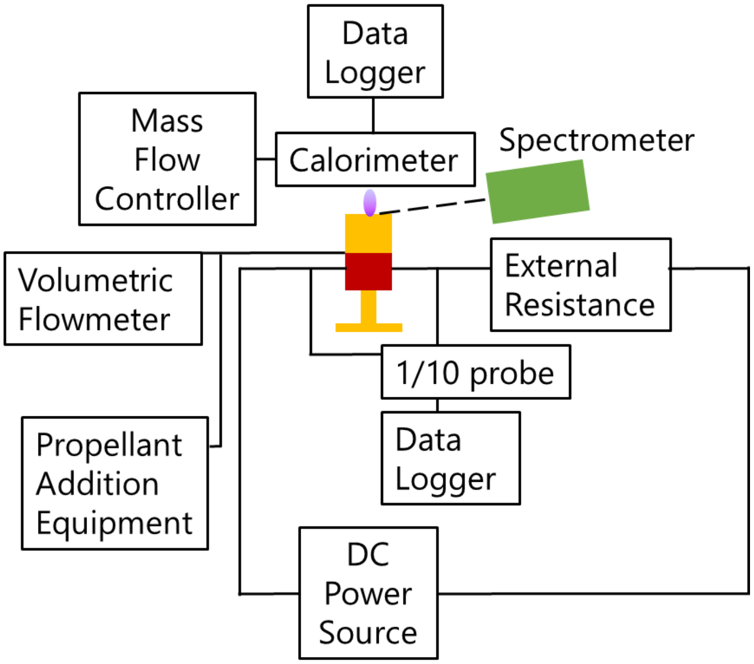

Figure 6. Schematic of experimental setup.

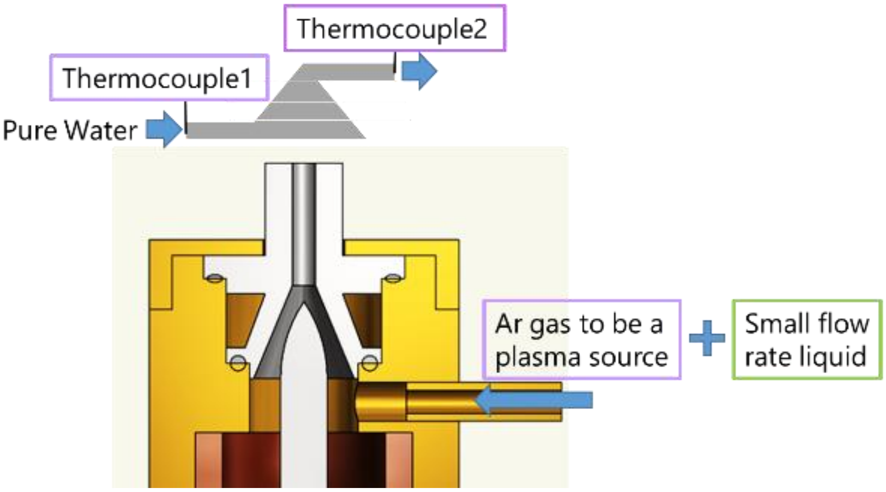

Figure 7. Schematic of calorimeter to measure evaluate thermal characteristics of the plasma plume from the arcjet.

A schematic of experimental setup is shown in Fig.6. To evaluate thermal characteristics of the exhaust plume of the arcjet, a calorimeter was developed and used in this experiment.

A schematic of the calorimeter is illustrated in Fig.7. As shown in this figure, the conical calorimeter consists of a helical tube made of aluminum. Differences of water temperatures of outlet and inlet of the tube in the calorimeter, which captures a plasma plume exhausted from the arcjet, namely receiving a heat flux from the arcjet, were measured with thermocouples and recorded with a data logger.

The heat received with the calorimeter was estimated as a product of the difference of water temperature, specific heat of water, and a mass flow rate of water (0.3 g/s). The mass flow rate of the water was controlled with a mass flow controller.

For the propellant of the arcjet, argon gas of a flow rate of 8 slm was used as a standard, main propellant.
With the main propellant, liquid propellants, such as water, HFE, and acetic acid solution, were added with the flow rate of 0.3 to 1.0 mg/s.

III. Results and discussion

Temporal variations of thermal outputs measured from exhaust plumes of the arcjet for various water-based liquid propellants are shown in Fig.8.

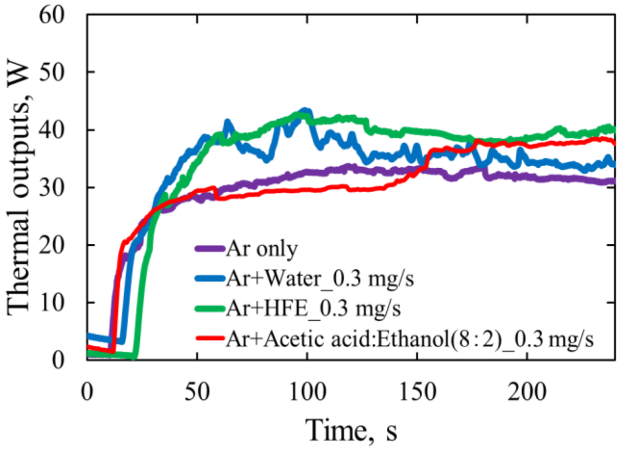

Figure 8. Results of thermal outputs from arcjet exhaust plumes for various propellants.

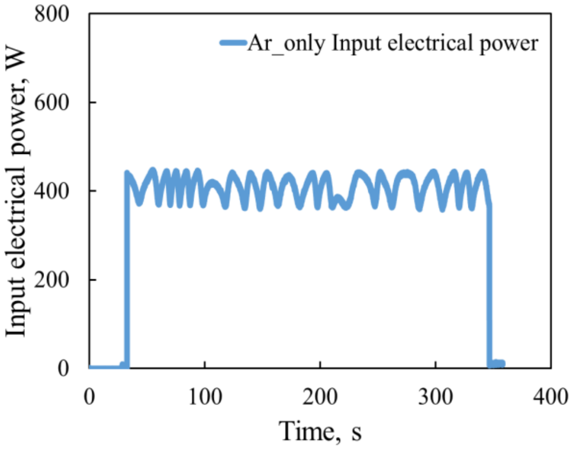

Figure 9. Temporal variation of input power of the arcjet in operation.

A typical output signal of temporal variation of input electrical power of the arcjet in operation for argon propellant is shown in Fig.9.

In Fig.8, the flow rate of the liquid propellant added to the primary propellant (argon gas) was controlled to a constant value of 0.3 mg/s for water, HFE, and a mixture of acetic acid and ethanol.

As shown in this figure, HFE showed the highest average value of about 40 W, followed by a mixture (8:2) of acetic acid and ethanol (37 W at 250 s), and water (36 W at 250 s).

Fig. 10 shows variations of measured thermal output ratios of exhaust plumes from the arcjets with flow rates (0.3 ~ 1.0 mg/s) of various liquid propellants. The thermal output ratio is defined as a ratio of an average thermal output to an electrical input power of the arcjet. Plots in Fig. 10 are average values of 3 runs of operation.

From the figure, it can be seen that results of HFE show the highest outputs throughout various flow rates followed by acetic acid-ethanol mixture. Moreover, slight increases of output ratios with the increase of flow rate can also be seen.

Although the output ratios of a pure argon propellant case is about 5.3%, those of HFE show about 9 ~ 10%, 7.5 ~ 8.8% for acetic acid – ethanol mixture, and 6 ~ 7% for water.

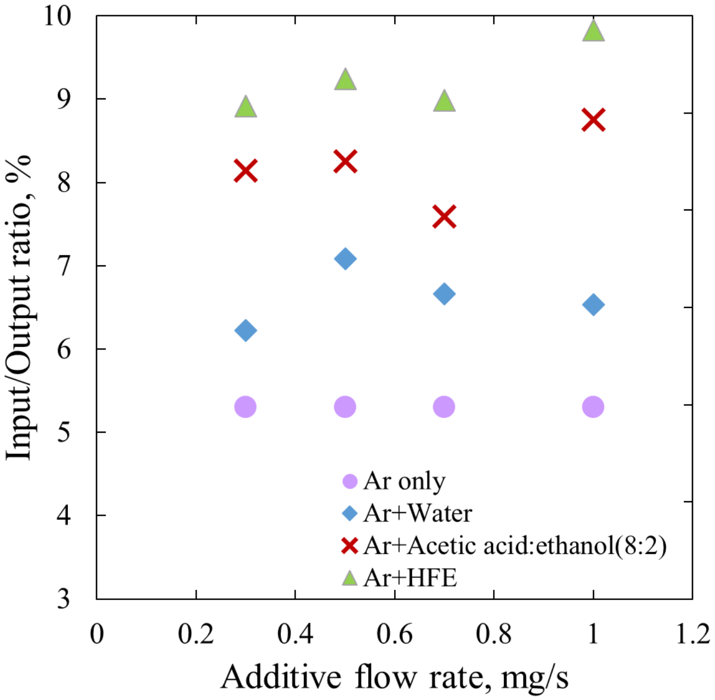

Figure 10. Variations of measured thermal output ratios of exhaust plumes from the arcjets with flow rates of various liquid propellants.

IV. Conclusion

In this study, numerical investigations based on chemical equilibrium calculations were conducted to understand the details of combustion reactions and products of the electrically augmented reactions for various liquids. In addition, a preliminary experimental study was conducted to evaluate thermal characteristics of the arcjet thruster employing novel water-based liquid propellants. To evaluate thermal characteristics of plasma plumes from arcjet, a water-cooled arcjet with a convergent nozzle (without divergent nozzle) was employed and operated in atmosphere.

1) From the simulation, it was found that HFE and HFE solution show high temperature characteristics among them (i.e., HFE: 1,000 ~ 3,900 K, HFE solution: 1500 ~ 3500 K) for a wide range of specific powers (1 ~ 40 kJ/g). Subsequently, hydrogen peroxide followed (1100 ~ 3100 K).
2) At 1kJ/g, HFE solution showed higher specific impulse value (280 s) than hydrazine (230 s).
3) From the experiment, HFE showed the highest average value of about 40 W, followed by a mixture (8:2) of acetic acid and ethanol (37 W at 250 s), and water (36 W at 250 s).
4) HFE showed the highest outputs throughout various flow rates followed by acetic acid-ethanol mixture. Moreover, slight increases of output ratios with the increase of flow rate was also shown. Although the output ratios of a pure argon propellant case was about 5.3%, those of HFE showed about 9 ~ 10%, 7.5 ~ 8.8% for acetic acid – ethanol mixture, and 6 ~ 7% for water.

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