Evaluation of Nontoxic Liquid Propellants for Chemically-augmented Electrothermal Thrusters

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In this study, an investigation and development of non-hazardous, low-cost, and stable water-based liquid propellants including their mixtures under room temperature were conducted for propellant of arcjet thrusters. From the results of numerical simulation, it was shown that HFE and HFE solution showed high temperature characteristics (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). In a wide range of specific powers (1-5, 20-40 kJ/g) except 10 kJ/g, HFE solution showed the highest values (260-350, 500-710 s), followed by hydrazine (230-330, 490-610 s). However, at 10 kJ/g, hydrazine showed higher value (410 s) than HFE solution (400 s). In addition, a preliminary investigation of operational tests of arcjet thruster was conducted employing various liquid propellants.

Key Words : Low power arcjet thruster, Exothermic propellant, Liquid propellant, Non-hazardous propellant

1. Introduction

Although 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]. With 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 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. Yanagida et al. proposed a mixture of aluminum (either solid or powder) and water[7]. 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.

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 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 thrust characteristics of the arcjet thruster employing novel water-based liquid propellants.

2. Prediction of Chemically-augmented Arcjet Thrusters

As for the numerical simulation, equilibrium calculations of chemical reactions of water-based liquids and mixtures to estimate thrust performances for a given nozzle condition of an arcjet thruster were conducted using a simulation code, NASA Chemical Equilibrium with Applications (CEA) developed by S. Gordon and B. J. McBride[13]. To include additional electrical 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.

To discover and investigate exothermal properties of various liquid propellants from chemically stable liquids in standard condition, some liquids and their combinations were examined. Moreover, calculation of hydrazine was conducted as a widely used, standard liquid propellant for comparison.

Figures 1 and 2 show the results for pure water, pure acetic acid, water solution of acetic acid (60 mol%), HFE (Hydrofluoroether), water solution of HFE (20 mol%), pure hydrogen peroxide, acetic acid and ethanol solution, 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 and hydrazine are plotted in Fig. 1. In all propellants, reaction temperatures increase monotonically with specific power. Especially, HFE and HFE solution show high temperature characteristics among them (i.e., HFE: 1,000-3,900 K, HFE solution: 800-3300 K) for a wide range of specific powers (1-40 kJ/g). Subsequently, hydrogen peroxide follows (1100-3100 K).

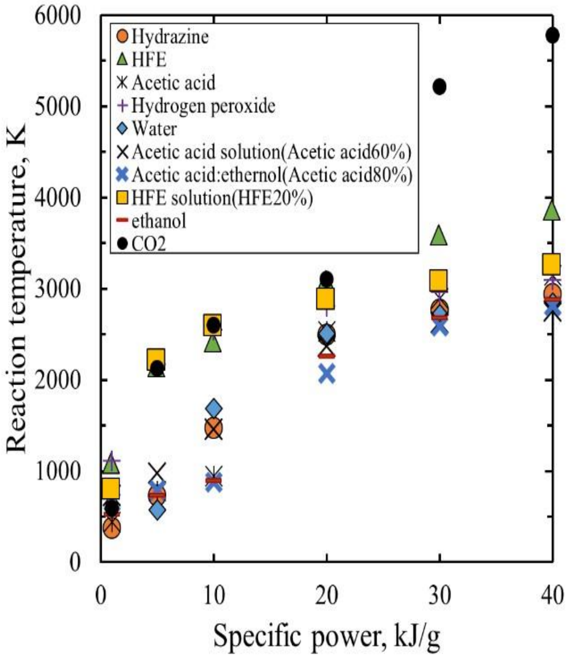

Figure 1. Variation of reaction temperatures vs specific powers for liquids.

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. 2. Similar to reaction temperature, specific impulses increase monotonically with specific power in all propellant cases. In a wide range of specific powers (1-5, 20-40 kJ/g) except 10 kJ/g, HFE solution shows the highest values (260-350, 500-710 s), followed by hydrazine (230-330, 490-610 s). However, at 10 kJ/g, although values are very close, hydrazine shows higher value (410 s) than HFE solution (400 s).

3. Preliminary Experiment

Although our final goal is to utilize water-based liquid propellants of an arcjet thruster, an objective of this part is to examine a newly developed arcjet thruster and its evaluation system.

Schematic illustrations of the experimental setup, thrust stand, and a photo of the arcjet thruster installed on the thrust stand are shown in Figs. 3 to 5. The thruster consists of a copper-tungsten anode and a thoriated tungsten cathode. A boron-nitride (BN) insulator (body) was employed for insulation of the cathodes and anode.

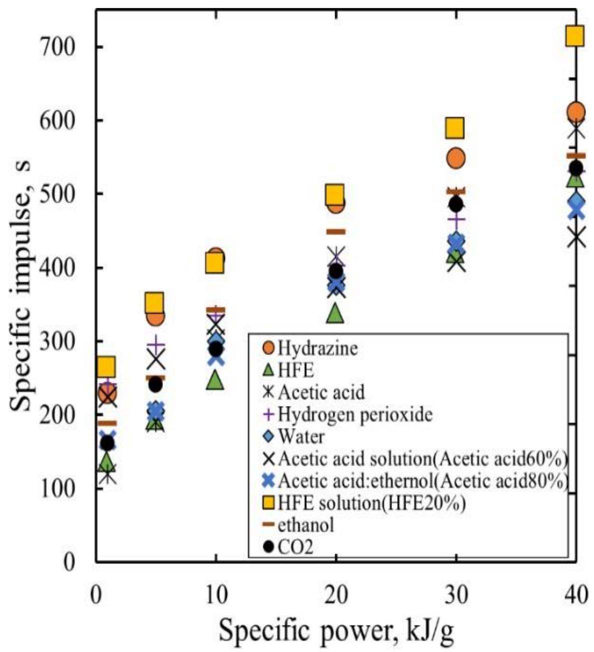

Figure 2. Variation of specific impulses vs specific powers for liquids.

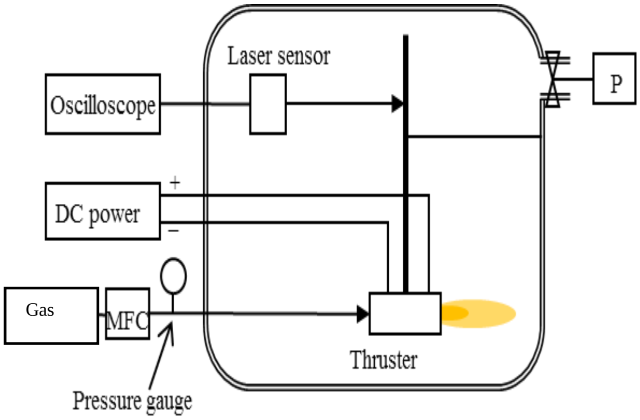

Figure 3. Experimental setup.

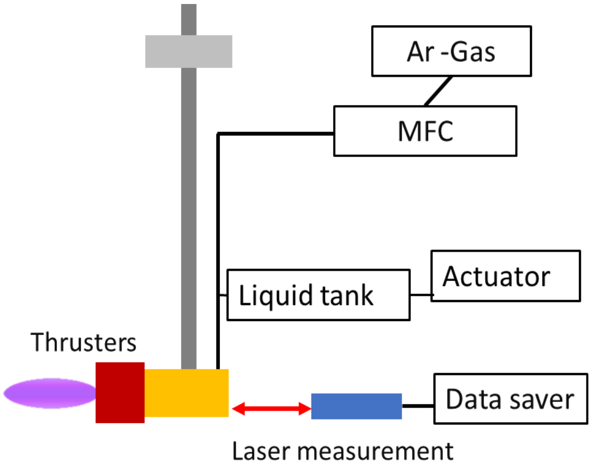

Figure 4. Schematic of Calibration method.

Figure 5. Photo of An Arcjet with Thrust Stand.

As an example of the operational experiment of an arcjet thruster with Ar gas propellant, a photo of the plasma plume exhausted from the arcjet is shown in Fig. 6. In this experiment, Ar gas was employed for the propellant operated with an average discharge voltage of 50 V and an average discharge current of 11 A.

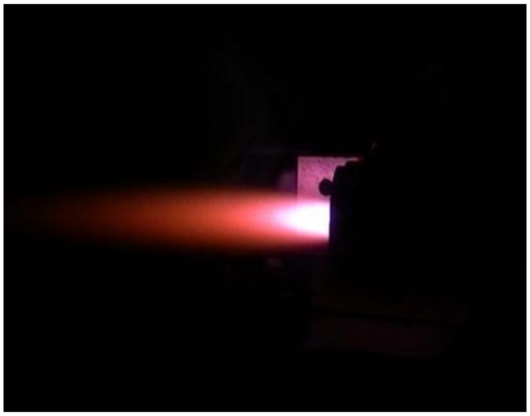

Figure 6. Photo of plasma plume exhausted from a Ar- arcjet thruster.

A typical output signal of the thrust stand at the preliminary test is shown in Fig. 7. Following a thrust of 0.08 N with a cold gas jet of nitrogen, a thrust of 0.16 N was obtained during discharge operation.

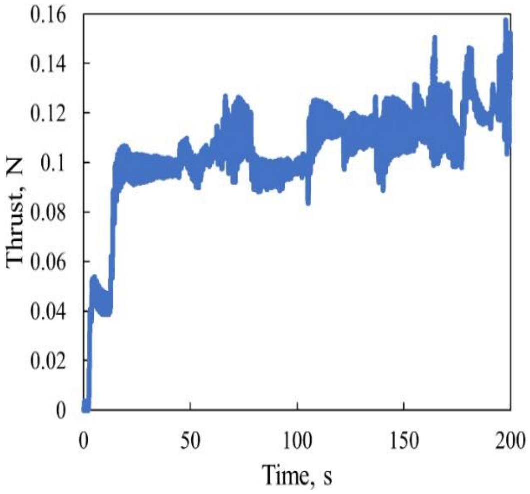

Figure 7. Results of thrust (At water 8 mg/s).

Output signals of normalized thrusts for HFE, acetic acid, and water propellants, mixed to Ar gas, in which values of thrust are normalized with that of pure Ar case, are shown in Fig.8. As shown in the figure, comparing to the thrust of pure Ar operation, the addition of those liquids to Ar propellant is effective for augmentation of thrust.

Table 1 shows average increased values of thrusts compared to the thrusts of pure Ar operation for various propellant mass flow conditions. From the Table, it is shown that the highest thrust can be obtained with a flow rate of 6 mg of acetic acid, in which the value of thrust was about twice as much as pure Ar conditions.

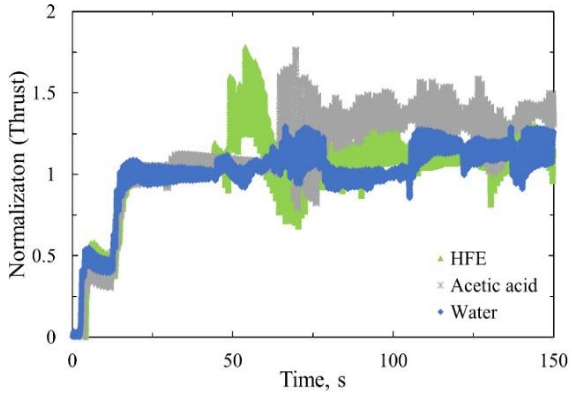

Figure 8. Results of normalization thrust for various propellants.

Table. 1 Results of normalization thrust performance for various propellants.

Flow rate[mg/s]	H2O	HFE	Acetic Acid
2	1.57	1.08	1.30
4	1.13	1.23	1.13
6	1.14	1.53	1.93
8	1.28	1.10	1.34
10	1.20	1.04	1.20

2. Conclusion

In this study, an investigation and development of non-hazardous, low-cost, and stable water-based liquid propellants including their mixtures under room temperature were conducted for propellant of arcjet thrusters. Following results were obtained.

1) From the results of numerical simulation, it was shown that HFE and HFE solution showed high temperature characteristics (i.e., HFE: 1,000-3,900 K, HFE solution: 800-3300 K) for a wide range of specific powers (1-40 kJ/g). Subsequently, hydrogen peroxide followed (1100-3100 K).
2) In a wide range of specific powers (1-5, 20-40 kJ/g) except 10 kJ/g, HFE solution showed the highest specific impulses (260-350, 500-710 s), followed by hydrazine (230-330, 490-610 s). However, at 10 kJ/g, hydrazine showed higher value (410 s) than HFE solution (400 s).
3) A preliminary investigation of operational tests of arcjet thruster was conducted employing various liquid propellants. Examinations of thrust performances of various potential liquid propellants are currently being conducted.
4) As shown in the figure, comparing to the thrust of pure Ar operation, the addition of those liquids to Ar propellant is effective for augmentation of thrust.
5) From the Table, it is shown that the highest thrust can be obtained with a flow rate of 6 mg of acetic acid, in which the value of thrust was about twice as much as pure Ar conditions.

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