Chemically Augmented Laser-thermal Thrusters

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Abstract

In this study, evaluations of chemical exothermic energies of propellants, which were chosen from chemically stable liquids in room temperature except fuels, were conducted using chemical equilibrium calculation code, which were water, acetic acid, HFE (Hydrofluoroether), and hydrogen peroxide. Among them, HFE, HFE solution, and hydrogen peroxide showed high temperature characteristics. In a wide range of specific powers (1 ~ 40 kJ/g), reaction temperatures increased with HFE concentration in water solution. In a range of 0 ~ 20% of HFE concentration, specific impulses rapidly increased. Especially, at 40 kJ/g, specific impulse showed the highest value (710 s at 20%).

Keywords: Liquid propulsion, Chemical Equilibrium Calculation, LaserPropulsion

1. 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. In particular, small-sized onboard laser plasma thrusters are also under significant development with rapid evolution of novel compact high-power laser systems. The advantages of the laser thrusters are system simplicity and compactness with significant controllability of the thrust.

The thrust performance of laser ablation thrusters mainly depends on lasers (i.e. average or peak power, fluence or intensity, wavelength, pulse duration, etc.)[5]. It was shown in a recent work that the thrust performance was also dominated by chemical properties of the propellant such as reactivity, exothermic energy, etc. The use of energetic materials enabled high thrust-to-power ratios and high thrust efficiency, which could even be over 100% with additional energy release through exothermic chemical reactions.

Lippert et. al. achieved thrust efficiencies of over 100% with the use of energetic materials, such as GAP, PVN, etc., which could produce chemical exothermic energy in addition to the laser energy augmenting thrust performance[5].

However, most of those energetic materials are regarded as hazardous materials and thus hard to handle especially for small satellites. Regarding the convenience and simplicity of the miniaturized satellites, the use of those hazardous materials should be avoided. Therefore, in this study, an investigation and development of non-hazardous, low-cost, and stable materials under room temperature was conducted for the laser ablation thruster either in solid
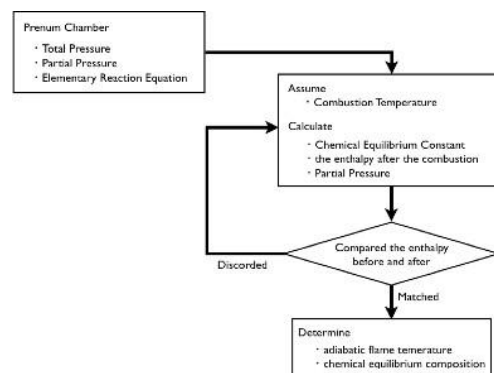

Fig. 1 Flowchart of chemical equilibrium calculation.

or liquid state, including their mixtures. These materials should be energetic producing chemical exothermic energy when given an input energy density above certain thresholds, or namely only with laser irradiation. 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.

2. Method of Calculation

2.1 Chemical Equilibrium Calculation

In this study, for chemical equilibrium calculation of chemical reactions, a widely-used simulation code, NASA Chemical Equilibrium with Applications (NASA-CEA) developed by S. Gordon and B. J. McBride at NASA Glenn Research Center was utilized[6].

The process of determination of the adiabatic flame temperature and chemical equilibrium composition is shown in **Fig.1**. In this process using energy balance method assuming isenthalpic conditions, first of all, an enthalpy before chemical reaction is determined by assuming chemical composition and temperature at plenum chamber. Secondly, assuming a temperature of reactant, an enthalpy, or a temperature, is calculated from chemical composition and then compared with that of before reaction. The iterative calculation continues until the value has reached a convergent value, in which the enthalpy, or temperature, has become consistent with that of former iteration.

The chemical composition in the reaction is calculated using equilibrium constants from JANAF thermochemical data. In addition, based on quasi-one dimensional nozzle flow theory, thrust performance (i.e., specific impulse, etc.) can be calculated from the adiabatic flame temperature and a given expansion ratio of a nozzle (=10).

In this study, to evaluate chemical exothermic energies of the propellant, prediction of the temperature after the reaction and specific impulse was conducted. A laser energy is assumed as an initial heat to the target which is added to an enthalpy of formation of reactants, or propellant components. Although, absorption coefficients of materials vary with combination of the laser and material, it is assumed that all the laser energy is absorbed to the target for simplicity. Moreover, in this study, since a thrust, or an impulse, generated through the laser ablation of the solid material is considered, an expansion ratio of 10 for a nozzle, which is namely a laser-ablation crater, was assumed, considering the geometry of the laser-ablation crater.

2.2 Chemical Equilibrium Calculation

To verify our simulation procedure and results, some previous experimental results, employing PTFE (Polytetrafluoroethylene, or Teflon®) and POM (Polyoxymethylene, or polyacetal)7) for the propellants, were compared with our numerical prediction.

Variations of specific impulse with specific input energy for PTFE and POM propellants are plotted in **Fig. 2 and 3**, respectively. Although relatively large scatters of experimental data for PTFE in **Fig. 2**, results from the numerical prediction are within those scatters and then consistent with experimental results.
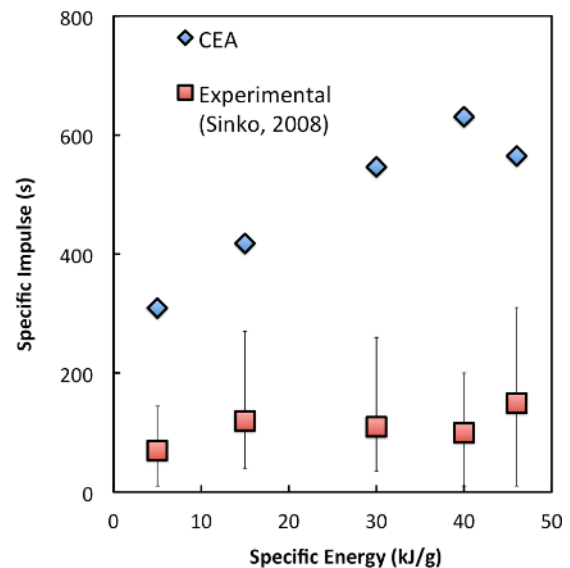

Fig. 2 Verification of calculation for PTFE.

On the other hand, for POM in **Fig. 3**, results from simulation are significantly large and overestimating the experimental results, i.e., 3 ~ 6 times larger than those obtained in the experiment. Since an energy absorption rate of an incident laser beam by the material surface in the simulation is assumed 100% for simplicity, some overestimated predictions must be inevitable.
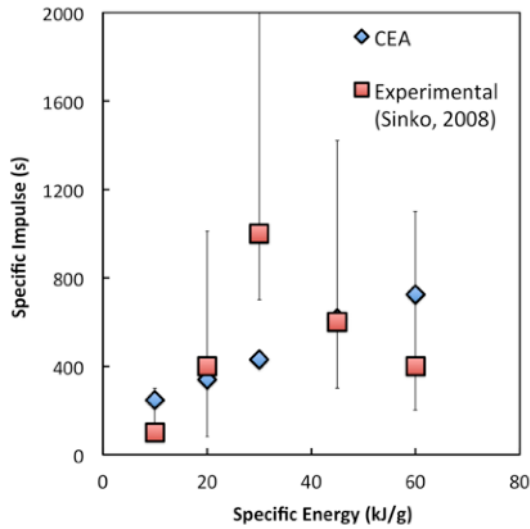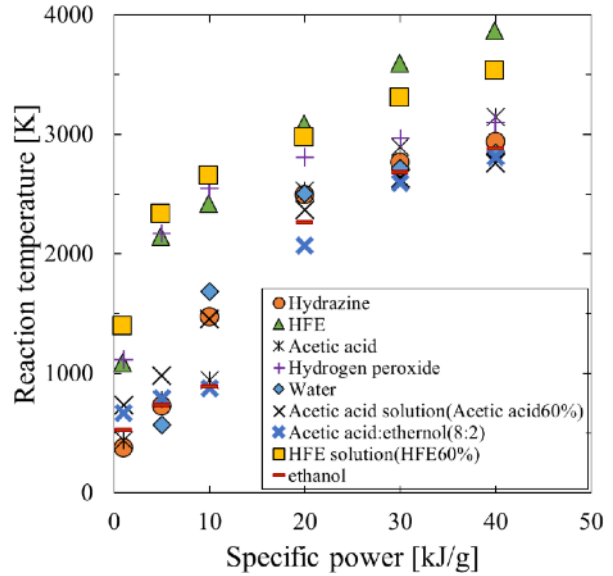
Fig. 3 Verification of calculation for POM.

Fig. 4 Variation of reaction temperatures vs specific powers for liquids.

3. Results and Discussion

To discover and investigate exothermal properties of 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.

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.4**. 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: 1500 ~ 3500 K) for a wide range of specific powers (1 ~ 40 kJ/g). Subsequently, hydrogen peroxide follows (1100 ~ 3100 K).

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.5**. 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 1 kJ/g, hydrazine shows the highest values (330 ~ 610 s), followed by HFE solution (320 ~ 560 s). However, at 1kJ/g, HFE solution shows higher value (280 s) than hydrazine (230 s).
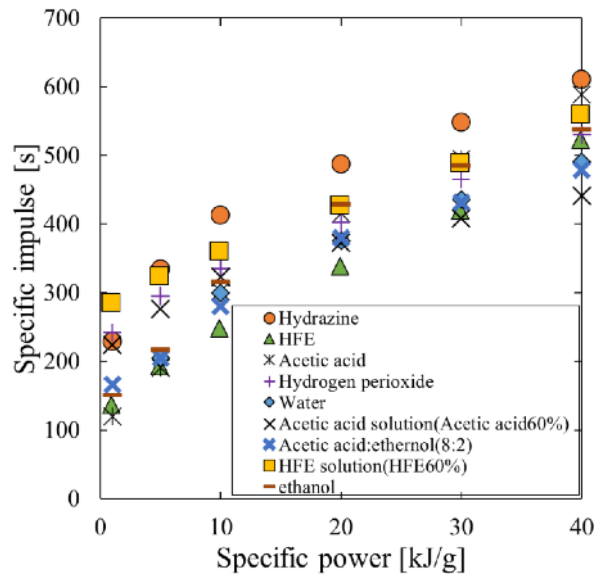

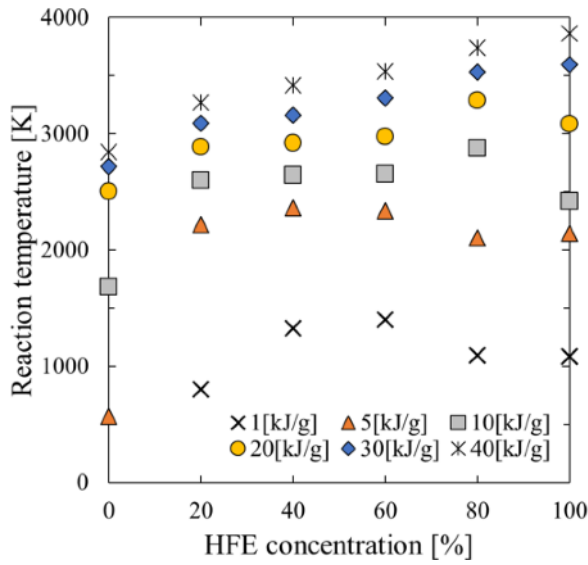**Fig. 5** Variation of specifc impulses vs specific powers for liquids.

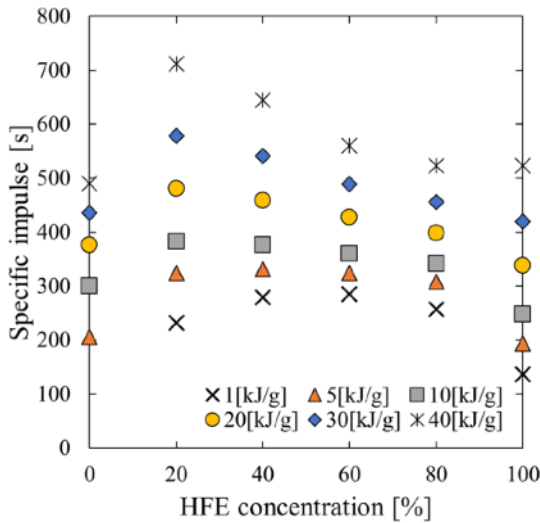Fig · .6 Variation of reaction temperatures vs HFE concentrations.

Fig. 8 The reaction temperature for the ratio of HFE in ethanol and HFE solution.

Fig. 7 Variation of specific impulses vs HFE concentrations.
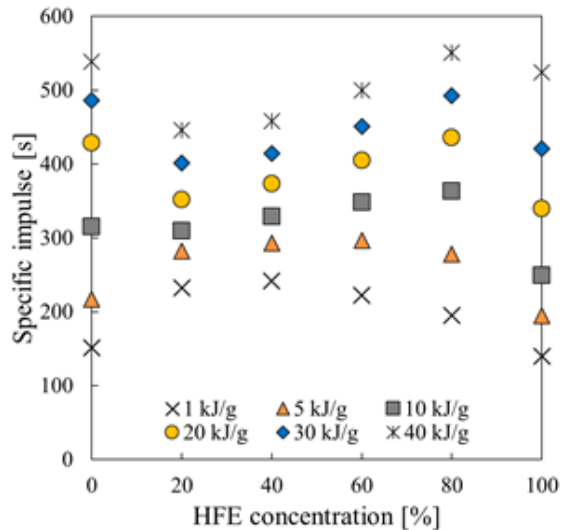
Fig. 9 The specific impulse for the ratio of HFE in ethanol and HFE solution

Relations of reaction temperatures versus mole-concentrations of HFE solutions are plotted in **Fig.6**. In a wide range of specific powers (1 ~ 40 kJ/g), reaction temperatures increase with HFE concentration. In particular, at higher specific power over 30 kJ/g, reaction temperatures increase monotonically with HFE concentration.

Relations of specific impulses and mole-concentrations of HFE solutions are plotted in **Fig.7**. In a range of 0 ~ 20% of HFE concentration, specific impulses rapidly increase. Especially, at 40 kJ/g, specific impulse shows the highest value (710 s at 20%). This value is higher than that of pure hydrazine, which is 610 s at 40 kJ/g.
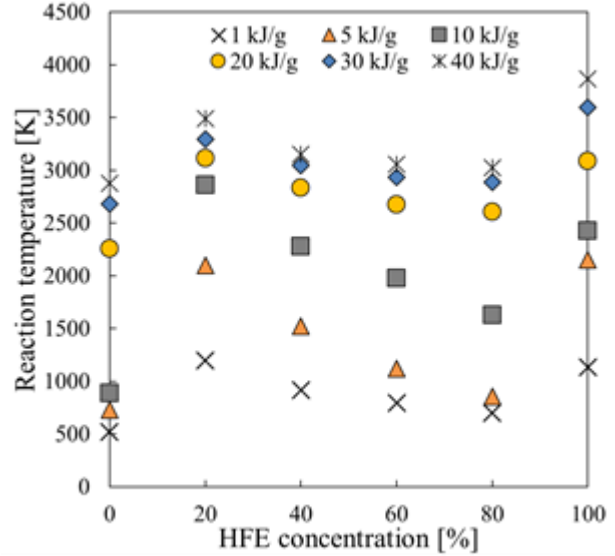
At 1 kJ/g, it shows the maximum value (about 190 s) at the ethanol concentration of 60%.

On the other hand, at 5 kJ/g, the maximum value (about 223 s) can be obtained at 80%.

Moreover, reaction temperatures and specific impulses for various mixtures HFE to ethanol are shown in **Fig.8 and 9**. In all range of specific powers (1 ~ 40 kJ/g), pure HFE showed high reaction temperatures. Following that, a high reaction temperature of about 3500 K can be obtained at 20% concentration at 40 kJ/g. Also, as shown in **Fig. 9**, at over 10 kJ/g (to 40 kJ/g), higher specific impulses (360 to 550 s) can be obtained for HFE concentratin of 80%.On the other hand, the maximum values for 5 kJ/g and 1 kJ/g are 350 s (at 60%) and 240 s (at 40%), respectively.

4. Conclusions

To discover exothermal properties of liquid propellants including their combinations with significant characteristics from chemically stable liquids in standard conditions (excluding liquid fuels), some liquids and their combinations were examined, which were pure water, pure acetic acid, water solution of acetic acid, HFE (Hydrofluoroether), water solution of HFE, acetic acid and ethanol solution, ethanol and HFE solution, pure hydrogen peroxide and hydeazine. Primary results are as follows;

1. In all propellants, reaction temperatures increased monotonically with specific power. 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). Then, hydrogen peroxide followed (1100 ~ 3100 K).

2. Specific impulses increased monotonically with specific power in all propellants. In a wide range of specific powers (5 ~ 40 kJ/g) except 1 kJ/g, hydrazine showed the highest values (330 ~ 610 s), followed by HFE solution (320 ~ 560 s). However, at 1kJ/g, HFE solution showed higher value (280 s) than hydrazine (230 s).

3. In a wide range of specific powers (1 ~ 40 kJ/g), reaction temperatures increased with HFE concentration in water solution. In particular, at higher specific power over 30 kJ/g, reaction temperatures increased monotonically with HFE concentration.

4. In a range of 0 ~ 20% of HFE concentration, specific impulses rapidly increased. Especially, at 40 kJ/g, specific impulse showed the highest value (710 s at 20%).

5. For HFE and ethanol mixtures, higher specific impulses (360 to 550 s) can be obtained for HFE concentration of 80% at over 10 kJ/g (to 40 kJ/g). On the other hand, the maximum values for 5 kJ/g and 1 kJ/g are 350 s (at 60%) and 240 s (at 40%), respectively.

References

1) Myers, R.M, Oleson, S.R., Curren, F.M., and Schneider, "S.J. : Small Satellite Propulsion Options", *AIAA Paper*, June 1994, 94-2997.

2) Mueller. J, "Thruster Options for Microspacecraft: A Review and Evaluation of Existing Hardware and Emerging Technologies", *AIAA Paper,* July 1997, 97-3058.

3) Micci, M. M., and Ketsdever, A. D. (ed.), "A Micropropulsion for Small Spacecraft (Prog. Astronautics and Aeronautics 187)", *American Institute of Aeronautics and Astronautics,* 2000.

4) Martinez-Sanchez, M., and Pollard, J.E., : Spacecraft Electric propulsion-An Overview, *Journal of Propulsion and Power,* **14** (1998), pp.688-699.

5) Claude Phipps et al, "Review: Laser-ablation propulsion", *Journal of Propulsion and Power*, **26**-4 (2010), 609-637.

6) S. Gordon and B. J. McBride, "Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications", *NASA Reference Publication 1311*, 1996.

7) Sinko, J. E, "Vaporization and Shock Wave Dynamics for Impulse Generation in Laser Propulsion", *Ph.D. Dissertation, Univ. of Alabama in Huntsville*, Huntsville, (2008)