Chemically-Augmented Laser Microthrusters

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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: *chemically stable liquid,* Chemical Equilibrium Calculation, Liquid propellant

Ⅰ. Introduction

Feasibility studies of micro-spacecraft are currently under significant development for a mass less than 100 kg with an available power level for propulsion of less than 100 watts.[1-4] The significance in reducing launch masses has attracted growing interests in regard to a decrease in mission cost and an increase in launch rate. The micro-spacecraft segments of the satellite launch industry have been growing rapidly in recent years. Development activity for a mass less than 50 kg range has been significantly exceeding that in the 50 ~ 100 kg range. In the smaller range alone, there were fewer than 15 satellites launched annually in 2000 to 2005, and 34 satellites in 2006. Then there were fewer than 30 launches annually during 2007 to 2011, and 34 satellites in 2012. The launch rate rapidly rose up to 92 satellites in 2013, and then 158 in 2014, which included some of more practical missions .[5-7]

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, many very small spacecraft lacked propulsion systems, 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.[2-4] Various potential propulsion systems for micro-spacecraft applications, such as ion thrusters, field emission thrusters (FEEPs), colloid thrusters, pulsed plasma thrusters (PPTs), etc., have been proposed and are under significant development for primary and attitude control applications .[4]

On the other hand, small-sized onboard laser plasma thrusters are also under significant development with rapid evolutions of novel compact laser systems.[8] One of the advantages of the laser thrusters is that they can induce high specific impulses. In addition, the system can be very simple and small with significant controllability of the thrust.

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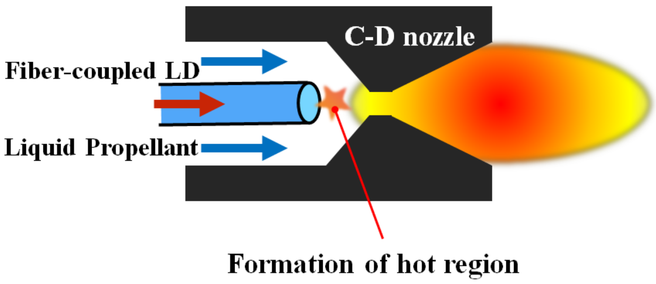
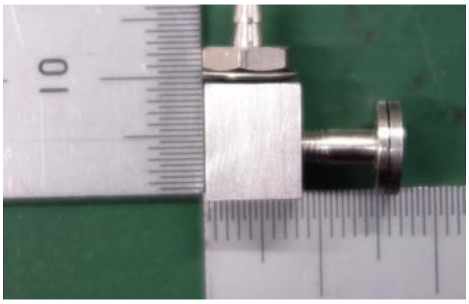
In our group at Tokai University, a laser-thermal microthruster (shown in Figs.1 (a) and (b)) employing a laser-diode (LD) coupled with an optical fiber, which can generate a fiber-tip heat source, is under development for novel laser-thermal microthruster applications. The LD-coupled fiber-tip heat source can generate a high temperature spot, and is currently used as a novel high-temperature heat source for skin surgery applications.[9,10]

The thrust performance of laser ablation thrusters mainly depends on lasers (i.e. average or peak power, fluence or intensity, wavelength, pulse duration, etc.)[8]. 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[8]. 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 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.



(a) Schematic illustration



(b) Photo

Fig.1. A schematic illustration and a photo of a laser microthruster with a LD-coupled fiber-tip heat source.

Ⅱ. Method of Calculation

A. Chemical Equilibrium Calculation

In this study, for chemical equilibrium calculation of chemical reactions, a widely-used simulation code, NASA hemical 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.2**.

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.

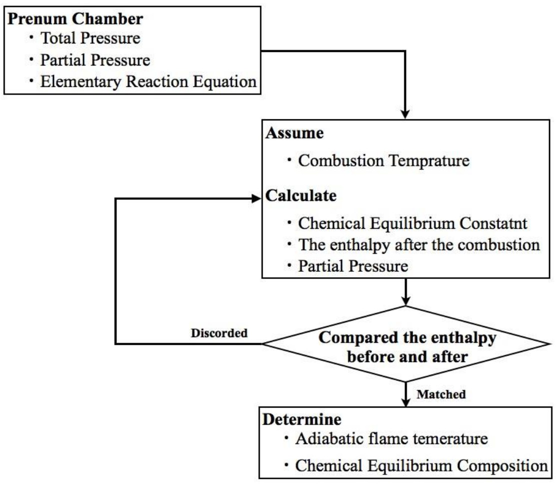


Fig.2 Flowchart of chemical equilibrium calculation.

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.

B. Verification of numerical simulation

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. 3 and 4**, respectively.

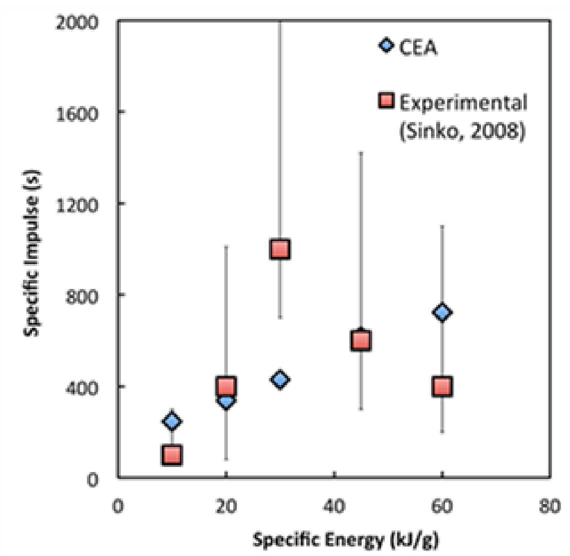


Fig. 3 Verification of calculation for PTFE.

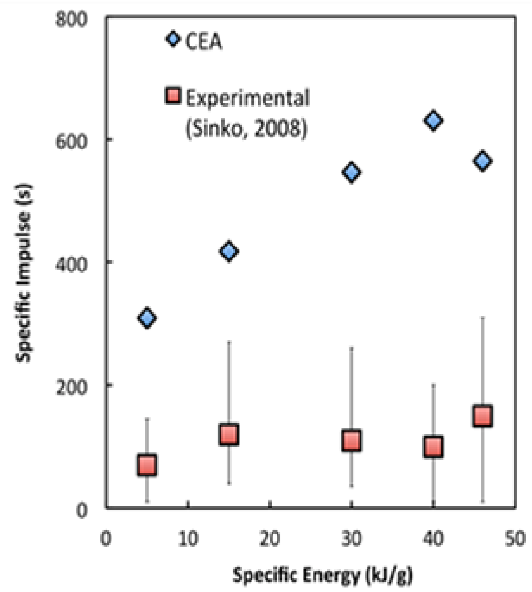


Fig.4 Verification of calculation for POM.

Although relatively large scatters of experimental data for PTFE in **Fig. 3**, results from the numerical prediction are within those scatters and then consistent with experimental results.

On the other hand, for POM in **Fig. 4**, 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.

Ⅲ. 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.

Fig. 5 and 6 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, and hydrazine. Among them, hydrogen peroxide, acetic acid and ethanol solution, HFE solution and HFE (Hydrofluoroether) showed interesting characteristics.

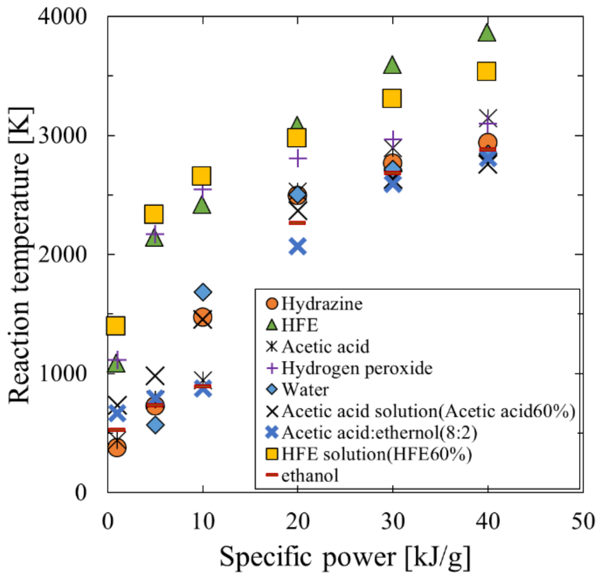


Fig. 5 Variation of reaction temperatures vs specific powers for liquids.

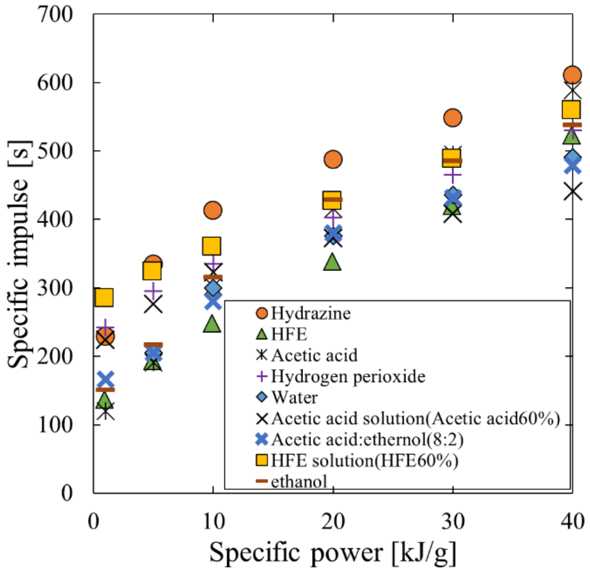


Fig. 6 Variation of specific impulses vs specific powers for liquids.

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.5**. 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.6**. 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).

Relations of reaction temperatures versus mole-concentrations of HFE solutions are plotted in **Fig.7**. Then, Relations of specific impulses and mole-concentrations of HFE solutions are plotted in **Fig.8**.

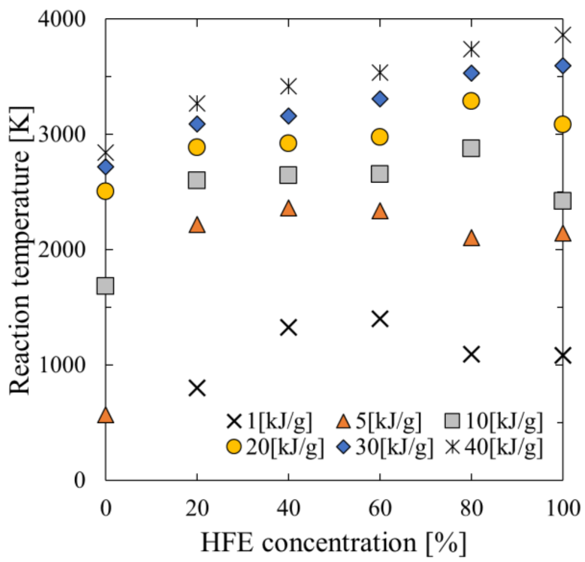


Fig.7 Variation of reaction temperatures vs HFE concentrations.

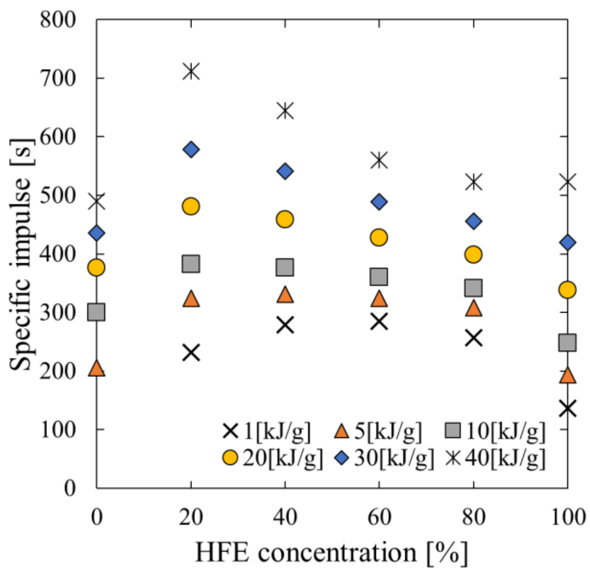


Fig.8 Variation of specific impulses vs HFE concentrations.

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.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.9 and 10**. In all range of specific powers (1 ~ 40 kJ/g), pure HFE showed high reaction temperatures.

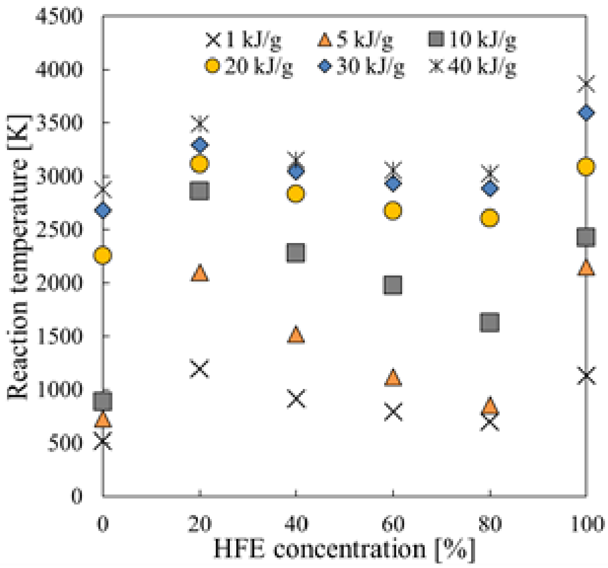


Fig. 9 The reaction temperature for the ratio of HFE in ethanol and HFE solution.

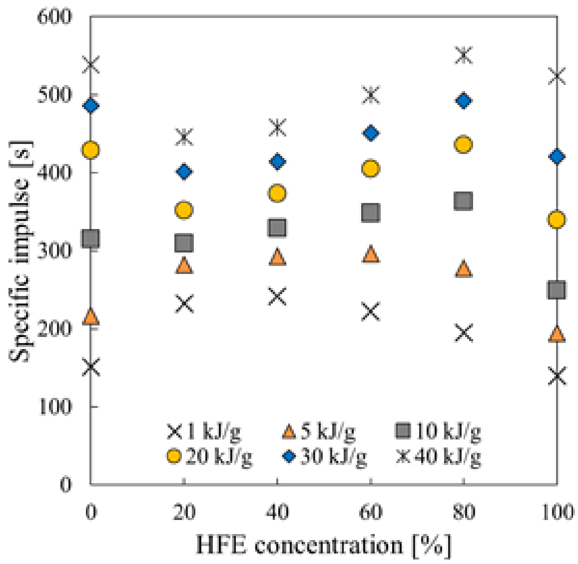


Fig. 10 The specific impulse for the ratio of HFE in ethanol and HFE solution

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. 10**, 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 concentratin 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.

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