Extraction of explosive characteristics from stable materials irradiated by low-power laser diodes

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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 alcohols, were conducted using chemical equilibrium calculation code. Among liquid propellants, HFE indicated over 1000 K increase of reaction temperature than pure water cases even with low specific energy inputs (5 kJ/g). In a low specific power range (1 ~ 10 kJ/g), specific impulse of acetic acid solution showed the highest values compared to the other materials. Effects of mole-concentration of acetic acid to water on the characteristics, which were reaction temperature and specific impulse, were compared. At high specific powers over 20 kJ/g, higher temperatures of 2,100 ~ 3,150 K could be obtained and specific impulses rapidly increased resulting in the highest value at 100% for each specific power cases.

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 .[5,6] 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.

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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 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.

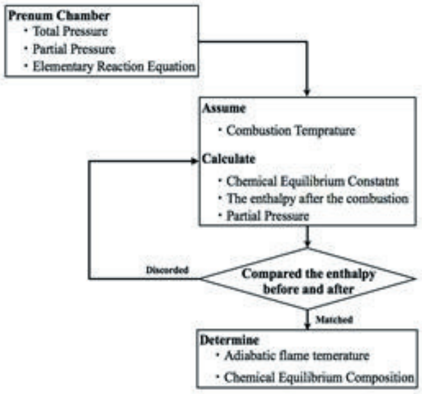

Figure 1. Flowchart of chemical equilibrium calculation

II. Principle of Chemical Equilibrium Calculation

A. 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 Figure.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.

B. Verification of Calculation through Prediction of Thrust Performance

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 Figure. 2 and 3, respectively. Although relatively large scatters of experimental data for PTFE in Figure. 2, results from the numerical prediction are within those scatters and then consistent with experimental results.

On the other hand for POM in Figure. 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.

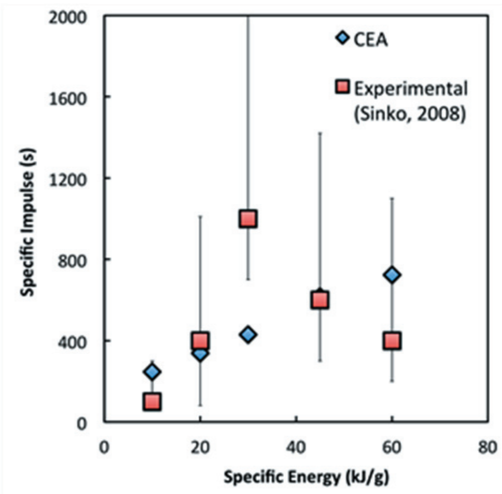

Figure 2. Verification of calculation for PTFE

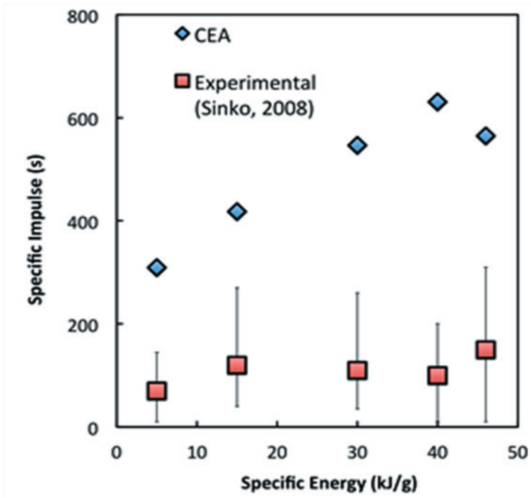

Figure 3. Verification of calculation for POM

III. Results and Discussion

To discover and investigate undiscovered properties of liquid propellants including their combinations with significant characteristics from chemically stable liquids in standard condition (excluding liquid fuels), over 30 liquids and their combinations were evaluated. Among them, water, acetic acid and HFE (Hydrofluoroether) showed interesting characteristics. Figure 4 and 5 show the results for pure water, pure acetic acid, water solution of acetic acid (60mol%), and HFE (Hydrofluoroether).

Variations of reaction temperatures with specific power (or specific energy) for water, acetic acid, acetic acid solution, and HFE are plotted in Figure.4. In all propellants, reaction temperatures increase monotonically with specific power. From the figure, HFE shows the highest temperatures among them, i.e., 1,000 ~ 3,900 K, for a wide range of specific powers (1 ~ 40 kJ/g). Acetic acid shows the second highest temperatures (2,500 ~ 3,150 K) in a high specific power range (20 ~ 40 kJ/g). On the other hand, in a low specific power range (1 ~ 10 kJ/g), temperatures of acetic acid are lowest (430 ~ 950 K), and those of water and acetic acid solution show higher values (water: 500 ~ 1,600 K, acetic acid solution: 730 ~ 1,460 K).

Variations of specific impulses with specific power (or specific energy) for water, acetic acid, acetic acid solution, and HFE are plotted in Figure.5. Similar to reaction temperature, specific impulses increase monotonically with specific power in all propellant cases. In a low specific power range (1 ~ 10 kJ/g), acetic acid solution shows the highest values (220 ~ 324 s), followed by HFE (140 ~ 260 s), water (205 ~ 300 s), and acetic acid (110 ~ 303 s).

On the other hand, in high specific powers (20 ~ 40 kJ/g), specific impulses of acetic acid increase most rapidly and show the highest values (410 ~ 590 s). Then HFE and water follows (HFE: 340 ~ 524 s, water: 376 ~ 490 s, and acetic acid solution: 372 ~ 441 s).

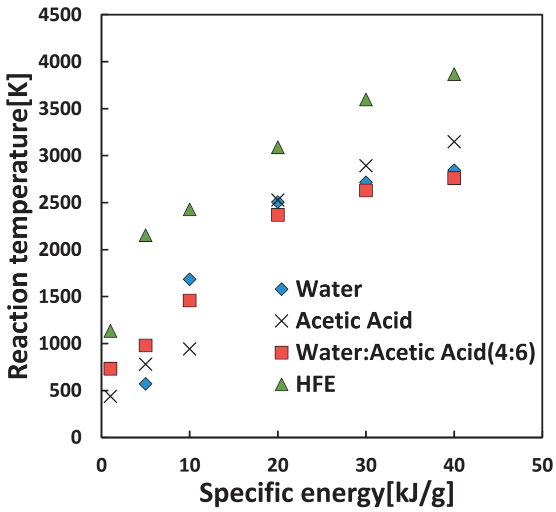

Figure 4. Comparison of reaction temperatures for liquid propellants

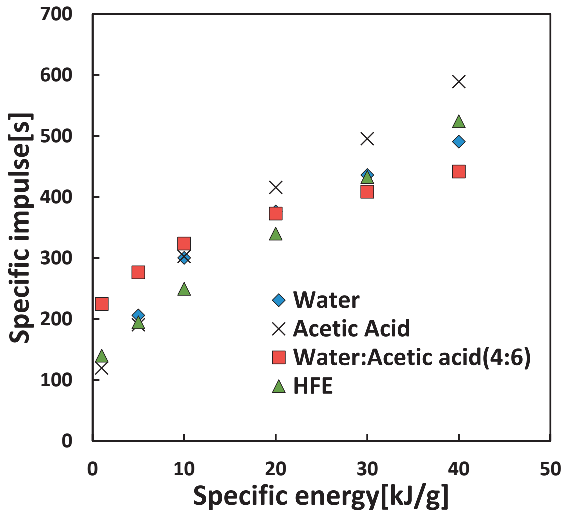

Figure 5. Comparison of specific impulses liquid propellants

Since water, acetic acid and, its solution show interesting characteristics, effects of mole-concentration of acetic acid to water on the characteristics, which are reaction temperature and specific impulse, are compared and discussed.

Relations of reaction temperatures versus mole-concentrations of acetic acid solutions are plotted in Figure 6. Although tendencies of increase of reaction temperatures at 0% and 100% can be seen, reaction temperatures gradually increase with concentration in a 20 ~ 80 % range. In particular, at higher specific power over 20 kJ/g, higher temperatures of 2,100 ~ 3,150 K can be obtained. On the other hand, in low specific powers below 5 kJ/g, temperature are relatively lower (< 1,000 K), and temperature increase is smaller (about 400 K).

Relations of specific impulses and mole-concentrations of acetic acid solutions are plotted in Figure 7. Although tendencies of increase of specific impulses at 0% and 100% can be seen, specific impulses gradually increase with concentration in a 20 ~ 80 % range. In particular, at over 80% and at higher specific power over 20 kJ/g, specific impulses rapidly increase and the highest values can be obtained at 100% for each specific power cases.

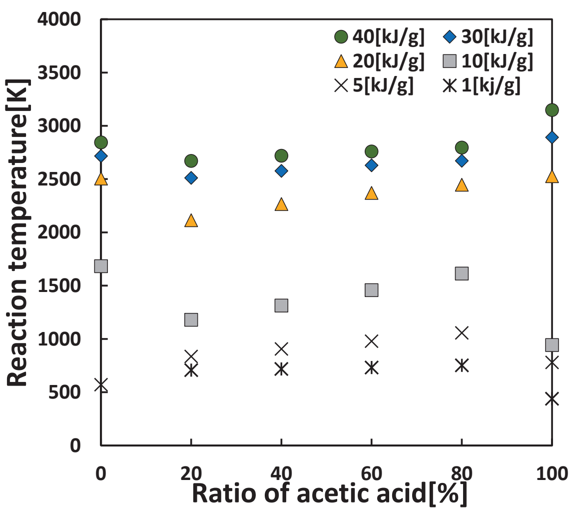

Figure 6. The reaction temperature for the ratio of acetic acid

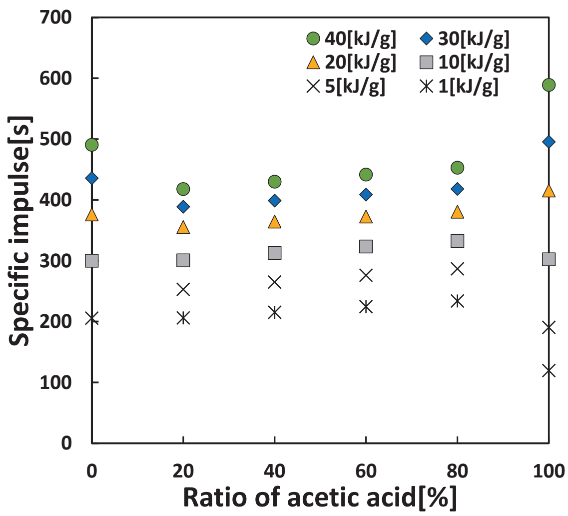

Figure 7. The specific impulse for the ratio of acetic acid

On the other hand in this concentration range, for specific powers of less than 10 kJ/g, specific impulses are decreasing with increase of concentration. In particular, at < 5 kJ/g, from 20% they gradually increase and then decrease in a high concentration range > 80%.

Currently, to verify the influence of chemical effects on thrust performance, thrust measurement for various propellants are being conducted. Since our equilibrium calculation in this study assumed 100% absorption of laser energy in the materials, our future work will include effect of absorption coefficient on both theoretical and experimental studies.

IV. Conclusion

In this study, evaluations of chemical exothermic energies of propellants, which were chosen from chemically stable liquids in room temperature except alcohols, were conducted using chemical equilibrium calculation code. Among liquid propellants, HFE indicated over 1000 K increase of reaction temperature than pure water cases even with low specific energy inputs (5 kJ/g). In a low specific power range (1 ~ 10 kJ/g), specific impulse of acetic acid solution showed the highest values compared to the other materials.

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