Design of a Microthruster using Laser-Sustained Solid Propellant Combustion

Akira Kakami[1], *Shinichiro Masaki*[2], *Hideyuki Horisawa*[3] *and Takeshi Tachibana*[2]
1) Satellite Venture Business Laboratory (SVBL), Kyushu Institute of Technology
2) Department of mechanical engineering, Kyushu Institute of Technology
1-1 Sensui-cho, Tobata-ku, Kitakyushu city, Fukuoka 804-0885, Japan

3) Department of Aeronautics and Astronautics, Tokai University
1117 Kitakaname, Hiratsuka-shi, Kanagawa 259-1292, Japan

E-mail: kakami@mech.kyutech.ac.jp

Keywords: Non-self-conbustible solid propellant, Laser-sustained combustion, Microthruster

Abstract

Solid propellants allow thrusters to be light-weight, compact and robust because they require neither tank nor valve. Moreover, the solid propellant will not leak, spill or slosh. Consequently, the solid propellant thruster is one of the potential candidates for the microthruster.

On the other hand, the control of the solid propellant combustion is difficult, since the conventional solid propellant continues to burn until all the stored propellant is consumed. Although particular devices like thrust reverser were designed to control the combustion, these devices were rarely used in the practical rocket motors. These devices rise thruster weight as well as complicate the thruster operation.

In this study, a solid propellant microthruster using laser sustained combustion was designed in order to develop a high-efficiency microthruster overcoming the previously-mentioned difficulty. This designed thruster has semiconductor lasers and non-self-combustible solid propellants in addition to the conventional solid propellant thruster. In this designed thruster, the semiconductor laser controls the combustion of the non-self-combustible solid propellant.

In order to demonstrate that the solid propellant combustion is controllable with laser, some non-self-combustible solid propellants were irradiated with the laser at a back-pressure of about 1kPa. A 40-W class Neodymium Yttrium Aluminum Garnet (ND:YAG) laser was used as a tentative alternate to the semiconductor laser. This experiment has shown that the solid propellant combustion was controllable with 10-W class laser irradiation.

Introduction

"Cheaper, faster and better" is required for the space development today. A solution to meet this requirement is to design a high efficiency small thruster, which is often called as "Microthruster." The solid propellant thruster would be one of the most promising propulsion devices for the microthruster, since the solid propellant allows the thrusters to be small and compact. Moreover, the solid propellant thruster is robust and cheap, since the thruster requires neither high pressure reservoir nor valve.

Nevertheless, the solid propellant thruster has a difficulty in active combustion control. It is difficult to start/stop the solid propellant combustion and to vary the thrust at desirable timing, since the solid propellant combustion proceeds until essentially all the stored propellant is consumed[1]. While the thrust is pre-programmable by change in shape or geometry of the propellant grain, the combustion is not actively controllable yet. For this reason, the solid propellant rockets produce only a single operation and has been used as an one-time thruster.

If the active and flexible combustion control is required, a special device like a thrust reverser is necessary. Nevertheless, this increases thruster weight increase and complicates thruster operation. Additionally, this would also affect the thruster performance since the combustion chamber pressure would vary from the designed pressure. Accordingly, installing these devices are not preferable for the microthrusters.

In order to overcome this difficulty, we propose a thruster using a laser and non-self-combustible solid propellants. The non-self-combustible solid propellant is a combustion controllable propellant. With this solid propellant, the combustion is sustained while the external energy is supplied to the propellant and is extinguished after stopping the energy supply. In our previous works, we have demonstrated that the combustion of the non-self-combustible propellant was controlled by the arc discharge[2].

Today, lasers are highly sophisticated and applicable to the propulsion devices. Moreover, laser can effectively generate heats in a desirable point on the solid propellant surface. Hence, in order to develop a microthruster, we propose that laser is used as energy source for the combustion control of the non-self-combustible solid propellant.

In order to demonstrate that the solid propellant combustion is controllable by the laser, preliminary combustion experiments were conducted in the vacuum using a continuous wave 40-W class Yttrium Aluminum Garnet (YAG) laser as a tentative laser. The combustion experiment shows that using some composite propellants with additives, the combustion was controllable at a back-pressure of 1-kPa with 10-W class laser irradiation.

Microthruster design using laser-sustained combustion of solid propellant

Figure 1 shows a simplified diagram of a solid propellant microthruster using laser-assisted combustion. This thruster uses a light-weight and compact laser like semiconductor laser and non-self-combustible solid propellant in addition to conventional solid propellant thruster elements: a combustion chamber, a casing, a nozzle, etc. In this thruster, the combustion starts when the stored propellant surface is irradiated with the laser. The combustion on the solid propellant surface is sustained during the laser irradiation. After required impulse is gained, the laser is interrupted, and then the combustion stops. When the thrust is necessary again, the solid propellant is irradiated with the laser to restart the combustion.

This thruster should have the following advantages:

1. Active combustion control
2. Robust, light weight and small volume
3. Low cost and excellent availability
4. Enhanced performance and thrust power ratio

The first advantage is owing to the combination of the laser and the non-self-combustible solid propellant. As well as the start/stop control of the combustion, the thrust level would be variable by the laser power.

The second advantage would be gained, since the thruster has no or few moving parts. The solid propellant and the semiconductor laser generally requires no moving part, whereas the other lasers require reaction tanks or discharge tubes. Owing to the recent development, the power level of the semiconductor laser is comparable with the power required for the propulsion device. Hence, the semiconductor laser is applicable to the propulsion device.

The third advantage is owing to the mass production of the semiconductor laser. The semiconductor lasers are frequently used today, and then the cost performance and the availability of the semiconductor laser are excellent among the lasers.

The fourth advantage is owing to both chemical potential of the solid propellant and effective laser-power transmission to the solid propellant. The laser generates heat in any point on the solid propellant surface effectively, and the heat loss would be lower than that of the other energy sources like heating wire and electrical discharge. Moreover, the chemical potential of the solid propellant enhances the thrust power ratio in comparison with the conventional electric propulsion. The higher thrust power ratio reduces the power supply weight and contributes to the propulsion-device downsizing.

Non self-combustible solid propellant

The non-self-combustible solid propellant is a combustion controllable solid propellant. Ingredients of typical non-self-combustible solid propellants are almost the same as that of the conventional solid propellants, while the mixture ratio is different from the conventional propellant.

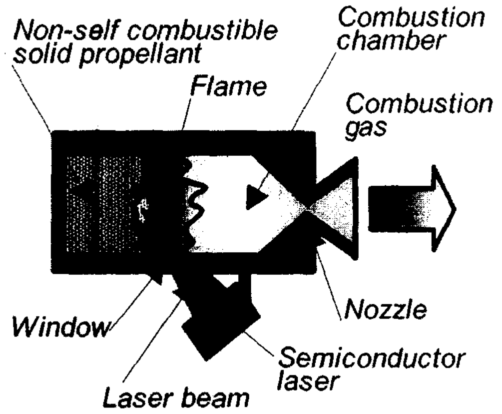

Figure 1: Schematic of Laser controlled solid propellant microthruster. The combustion is sustained only when laser was radiated on the non self-combustible solid propellant.

Change in the mixture ratio from stoichiometric ratio reduces the energy released in the combustion, and then the heat feedback from the combustion surface to the solid propellant surface is lower than that by the conventional solid propellant. Hence, with the non-self-combustible solid propellant, the combustion is autonomously terminated, since the heat feedback is insufficient to sustain the combustion. On the other hand, if the external energy source compensates the energy-feedback insufficiency, the combustion proceeds and is autonomously terminated by interrupting the energy supply.

Our previous study has shown that the combustion of the non-self-combustible solid propellant was controllable with arc discharges3). An arc-controlled solid propellant thruster, which is named Solid Propellant Arcjet Thruster (SPAT), was designed to develop a high-thrust-power-ratio electric propulsion device. Figure 2 shows a simplified diagram of the SPAT. In the SPAT, the non-self-combustible solid propellant is placed opposite to the electrodes. In the inter-electrode region, the SPAT has the non-energetic polymer, which is named Pilot charge, in order to sustain the arc discharge stably. In the operation, an arc plasma is generated between the electrodes, and Joule heat is produced and delivered to the non-self-combustible solid propellant surface. This arc plasma assists the combustion of the non-self-combustible solid propellant. The product gases are heated by the combustion and is finally accelerated in the nozzle. By interrupting the discharge current, the flame began to diminish, and then the combustion is completely terminated.

The experiments with the designed SPAT have shown that the combustion of the solid propellant is controllable using some solid propellants: Hydroxyl-terminated polybutadiene (HTPB) / ammonia perchlorate (AP) or

HTPB/ ammonia nitrate (AN) propellants. Some propellants contained additives such as Titanium, Aluminum, etc. Figure 3 shows a picture of the SPAT operation.

The thrust and the combustion-chamber pressure of the thruster were measured with a thrust stand and a water-cooled pressure gauge, respectively. After producing the arc plasma, the combustion chamber pressure gradually rose and then reached the maximum of about 0.5 MPa within 10 seconds after producing the arc plasma. After the chamber pressure reached the maximum, the combustion chamber pressure was relatively stable with some propellant such as Ti-added propellant, while the chamber pressure tended to be oscillatory with the other propellants. By interrupting the discharge current, the chamber pressure dropped to zero rapidly and the combustion stopped. The thrust stand measurement showed that the thrust was produced with the SPAT and the thrust power ratio of the SPAT is larger than the conventional arcjet thruster.

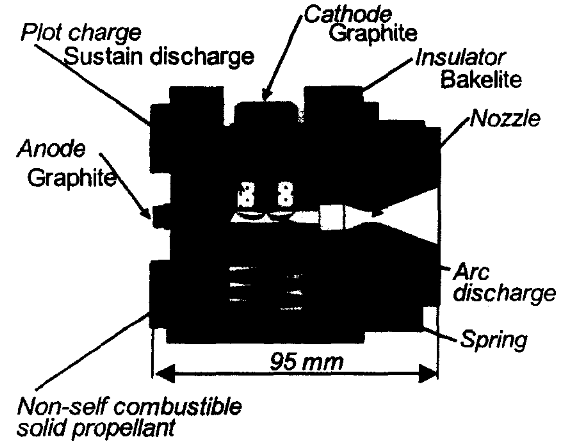

Figure 2: Schematic diagram of Solid Propellant Arcjet Thruster (SPAT).

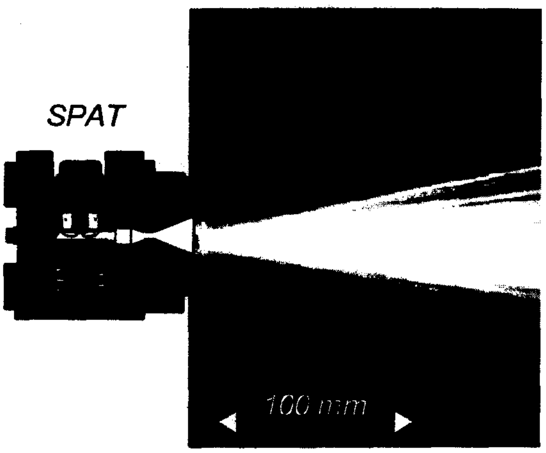

Figure 3: A plume of 1kW-class SPAT plume.

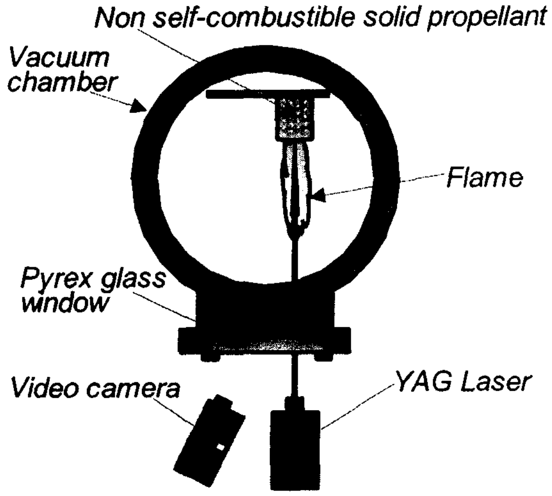

Figure 4: Schematic diagram of Experimental apparatus for laser-sustained solid propellant combustion.

Experimental apparatus

Vacuum chamber

In order to demonstrate the solid propellant combustion is controllable with the laser, combustion experiments were conducted in a vacuum chamber shown in Fig 4. The solid propellant was fixed to a stand in the vacuum chamber, which was evacuated at a back pressure of about 1-kPa by a rotary pump. The solid propellants were neither pre-heated nor pre-cooled, and the initial temperature was the same as the room temperature of about 300 K. The solid propellant surface was irradiated with laser beams generated by a 40-W class YAG laser, which was placed outside of the vacuum chamber. Through a Pyrex glass window, the laser beam went to the solid propellant surface. This Pyrex glass transmits about 70 % of the laser beam, and then the laser power on the solid propellant surface is about 30 W at the maximum. The YAG laser was placed out of the vacuum chamber in order to protect the laser and the optics from the high-temperature smoky plume.

In the combustion experiments, the solid propellant was irradiated with the laser for the period of 30 seconds after the combustion started. During the combustion experiments, the flame on the propellant surface was observed with a digital video camera, which is placed next to the YAG laser. With this observation, the some combustion properties like ignition delay were evaluated as well as observing the flame structure. Burning rates was also evaluated for each propellant. The burning rate was calculated by measuring the propellant weight before and after the combustion.

Laser

In this study, a continuos-wave ND:YAG laser (Lee Laser Inc., 7150M-200) was used as a tentative alternate to the semiconductor laser. This laser is a flash lamp pumped YAG laser and emits a 6 mm in diameter, 1064 nm in wavelength, multitransverse-mode beam. The experimental results using the YAG laser would not differ from that using the semiconductor laser, since both the YAG lasers and the Watt-class semiconductor laser emit near-infrared rays. Among various interactions of laser beam with the solid, thermal process is dominant in near infrared band. Moreover, optical properties of the materials such as transmission factor and reflectance ratio are almost the same in the wavelength range. Hence, both lasers are equivalent to a heat source on the propellant surface.

Solid propellant

In this study, frequently-used fuels such as HTPB, PPG, BAMO-NIMO are utilized, and two kinds of the oxidizer were used. One oxidizer is ammonium perchlorate (AP). AP is frequently used in a variety of rocket motors, since AP oxidizer has good properties: good performance, quality, uniformity and availability. Moreover, the SPAT experiment yields a good performance and stable operation with AP.

The other oxidizer is ammonium nitrate (AN). While the performance of the AN-added propellant is lower than that of the AP-added propellant, the AN-added propellant has the following advantages: low cost and smokeless. The smokeless enables this designed thruster to reduce the contamination on solar cells of the spacecraft and on the laser optics for this thruster itself. This results in enhancing the thruster robustness. Additionally, while AP contains chlorine, the plume of AN-added propellant is relatively clean.

Moreover, while the AN based propellant has the difficulty in starting and sustaining the combustion, this property would be favorable for the solid propellant microthruster using laser sustained combustion. This is because the combustion of the AN propellant would be laser controllable when the stoichiometrically balanced propellant is used.

Results and Discussion

Combustion experiment result

The combustion of the non-self-combustible solid propellant was successfully controlled with the 10-W class laser irradiation. Figure 5 illustrates a timing chart of the combustion and the laser irradiation using a propellant (30 % HTPB, 50 % AP and 20 % Ti). In the beginning of the laser irradiation, nothing occurred. A few seconds after the laser irradiation, smoke was produced from the laser-heated surface of the solid propellant. At $t \approx 10$ seconds, flame appeared on the solid propellant surface. Then, this flame was gradually enlarged and reached its maximum size within 2 seconds after the start of the combustion. The combustion was sustained during the laser irradiation as shown in Fig.6. When the laser was interrupted, the flame began to shrink, and finally extinguished at about 5 seconds after stopping laser irradiation. After the combustion, a cavity developed on the initially flat propellant surface around the laser-irradiated region of 6 mm in diameter(Fig.7). When the solid propellant was irradiated again, the flame appeared again and extinguished by interrupting laser.

From these results, the combustion of the solid propellant is controllable with the 10-W class laser irradiation at 1-kPa back pressure. On the other hand, the combustion chamber pressure of the thruster is generally higher than 1-kPa by an order of magnitude in order to enhance the performance and reduce the nozzle size, whereas at the higher pressure, the combustion would be autonomously sustained until all the propellant is consumed. Nevertheless, the combustion would be still controllable with the laser radiation at the higher pressure level. From the previous study, the combustion was controllable with the arc discharge when the combustion chamber pressure was over 0.5 MPa. As a consequence, at the higher back pressure, the combustion should be controllable with the laser since both the laser and the arc plasma is equivalent to a heat source to the solid propellant.

Combustion controllability for each propellant

Tables 1 a) shows results for combustion experiment using AP-added propellants. The combustion of the propellant with some additives such as carbon, Titanium or Aluminum are controlled with the laser irradiation. The burning rate was 10 mg/s for HTPB/AP/Ti and 20 mg/s for HTPB/AP/Al. The ignition time and the quenching time for HTPB/AP/Al were almost the same as those for the HTPB/Ti/AP, whereas the ignition delay for the PPG/AP/C propellant was as large as 40 seconds.

The mark × indicates that the corresponding solid propellants were never ignited while the solid propellants were irradiated for 60 seconds. The solid propellant weight was not reduced from the initial weight, and the solid propellant surface color on the irradiated point was not different from the initial color.

Comparing the ignited propellants with the non-ignited propellants, the ignited propellants had cool colors such as black, dark green and gray, whereas the non-ignited propellants had warm color. Seeing the results for the propellants (80 % HTPB, 20 % AP and some additives), the Al-added propellant, which was only cool color propellant, was only ignited. As for PPG/AP propellants, the propellant changed the color from white to black by adding only 3 % carbon, and the black propellant was ignited.

This would result from the relation of the absorption ratio with the color. In general, black or grayish materials absorb the infra-red rays well. Then, the grayish or black solid propellants absorb the laser well, and the combustion was successfully started and sustained. Hence, the solid propellant color would be an index for the combustion control.

The propellant color is dependent on the propellant ingredients and the mixture ratio. In particular, the ad-

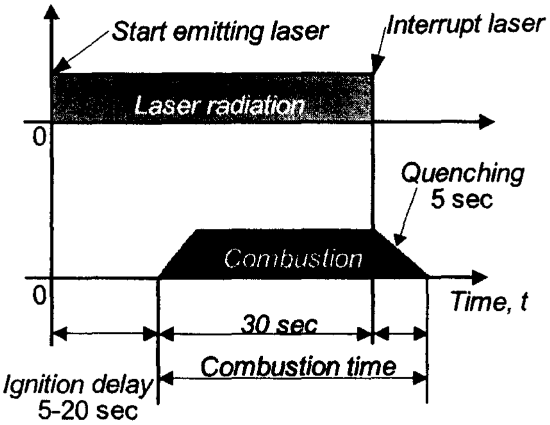

Figure 5: A diagram of laser irradiating and combustion timing. The time origin $t = 0$ is defined as the moment when the YAG laser start to emit beam.

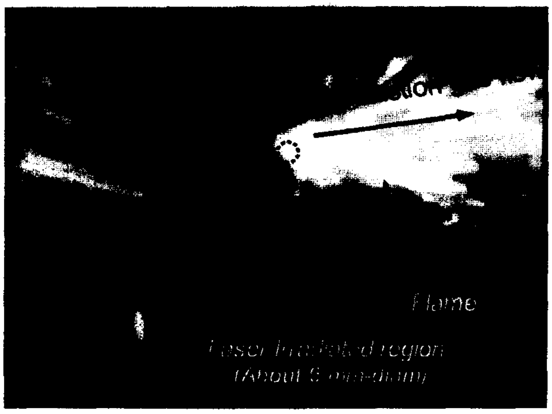

Figure 6: A photograph of the combustion. The average laser power was 15 W. The solid propellant (30 % HTPB, 50 % AP and 20 % Ti) was used in this combustion test.

Figure 7: A photograph of the non-self combustible solid propellant before and after the combustion. The average laser power was 15 W. A HTPB-based solid propellant (30 % HTPB, 50 % AP and 20 % Ti) was used in this combustion test.

ditives have a significant influence the propellant color. By doping the particular additives, the propellant colors drastically change from the warm color to gray or black, while the change in the mixture ratio has a slight influence on the color and the propellants still have the warm color. Hence, the additive is an important ingredients for the laser absorption. As a consequent, the additive has an influence on the combustion controllability and would influence the thrust power ratio.

Table 1 b) shows the experimental results using AN-oxidizer propellant with 30-W laser irradiation. AN oxidizer results are the same in ignition dependency on the propellant color as the AP oxidizer propellants. The grayish propellant (Titanium added propellant) was only ignited, and the others were never ignited. The ignition delay was also the same as that of the AP-oxidizer propellant, while a quenching time of 2 seconds is a little shorter than that of the AN-oxidizer.

Table 1: Experimental result for each propellant
a) AP oxidizer propellants with 15-W laser irradiation

Propellant		Mixture ratio*	Color†	Result*
Fuel	Additive			
HTPB	Ti	40/60/20	Dark green	○
		37/63/5		○
		35/65/0	Orange	×
HTPB	Al	20/80/20	Gray	○
	LiF	20/80/1	Bright yellow	×
		20/80/3		
	Oxam	20/80/5	Yellow	×
		20/80/1		
	PTFE	20/80/10	White	×
PPG	C	20/80/3	Black	○
		20/80/0	White	×

b) AN oxidizer propellants with 30-W laser irradiation

Propellant		Mixture ratio*	Color†	Result*
Fuel	Additive			
HTPB		10/90 20/80	Brown	×
BAMO NIMO	Ti	40/60/25	Gray	○
	PTFE	40/60/25	White	×
		20/80/0	White	×

*A mixture ratio 20/80/10 indicates that the propellant has 20 % AP (or AN), 80 % HTPB and some additives. The mass of the additive is 10 % of the fuel and binder weight.

†The color of the solid propellant surface

*The mark ○ indicates that the combustion was controllable with corresponding solid propellant. The mark × indicates that the combustion of the corresponding propellant is never ignited while the propellant was irradiated with the YAG laser for 60 seconds.

Summary

In order to develop a high performance, robust, compact and light-weight microthruster, we propose a solid propellant microthruster using laser sustained combustion. This designed thruster uses the non-self-combustible solid propellant and the semiconductor laser as combustion control energy source. This thruster would be compact and small, since it has no moving parts such as valves. Moreover, by utilizing energetic material as the solid propellant the thrust power ratio would be enhanced.

This study has demonstrated that the combustion of the non-self-combustible solid propellant was controllable with the 10-W class laser irradiation. The HTPB/AP/Al or Ti, PPG/AP/C and BAMO-NIMO/AN/Ti propellants were combustion controllable and had a time lag in the ignition and the quench, whereas the other propellants were never ignited.

Comparing the ignited propellant with the non-ignited propellant, the combustion controllability depends on the propellant color. The combustion controllable propellants were dark, grayish or black, whereas the warm color propellants were never ignited. From this result, the ignition would be influenced by the absorption ratio. In general, the grayish or black solid absorbs the infrared rays effectively and the warm colored solid not effectively. Hence, the color would be an index for selecting the solid propellant ingredients.

REFERENCES

[1] George P. Sutton and Oscar Biblarz. *Rocket Propulsion Elements*. John Wiley & Sons, Inc., 2001.

[2] H.Ohisa T.Tachibana. Electrical Combustion Control of AP- and AN-based Propellants for Upper Stage Applications. *Journal of Propulsion And Power*, 11(2), 1999.