Laser Ignition Microthruster Experiments on KKS-1

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(Received July 17th, 2009)

A laser ignition microthruster has been developed for microsatellites. Thruster performances such as impulse and ignition probability were measured, using boron potassium nitrate (B/KNO\(_3\)) solid propellant ignited by a 1 W CW laser diode. The measured impulses were 60 mNs ± 15 mNs with almost 100 % ignition probability. The effect of the mixture ratios of B/KNO\(_3\)/binder = 28/70/2 and 38/60/2 exhibited both high ignition probability and high impulse. Laser ignition thrusters designed and fabricated based on these data became the first non-conventional microthrusters on the Kouku Kousen Satellite No. 1 (KKS-1) microsatellite that was launched by a H2A rocket as one of six piggyback satellites in January 2009.

Key Words: Laser Ignition, Solid Propellant, Microthruster, KKS-1, Space Experiments

1. Introduction

Microspacecraft have increasingly attracted the interest of researchers as they make missions possible in a short period of time at extremely low cost. However, they currently lack a propulsion system that enables them to undertake more advanced and challenging missions that require them to change their attitude and perform positional maneuvering. Future mission requirements for microspacecraft will require more versatility, thus a wide range of propulsion systems might be needed onboard the same spacecraft.

After comparing the advantages and disadvantages of current micropropulsion systems, the authors have proposed a dual-mode micropropulsion system that operates in high-impulse chemical thruster mode by laser ignition, and in high-specific impulse operation mode by laser ablation as shown in Fig. 1\(^1\). The advantage of this thruster system is its compact size and low weight, achieved by sharing the same laser diode. In addition, it has no valves or pipes that could fail, unlike conventional gas-jet systems.

Laser ablation thrusters have been studied by our team members so that we have sufficient knowledge to develop laser ablation thrusters. However, we had little knowledge or experience of laser ignition. Thus, we started to research and develop laser ignition thrusters and to gain an understanding of the physics of laser ignition\(^3\).

After some basic experiments, we designed and fabricated a laser ignition thruster system that could be utilized by microsatellite users. Therefore, we planned demonstration experiments of this thruster system in space in order to verify its performance. This thruster was onboard the KKS-1 microsatellite that was launched by H2A rocket No. 16 as one of six piggyback satellites on January 23, 2009.

In the first half of this paper, we present the basic experiments and their results related to the design and development of the microthruster; and in the latter half, we show the details of space experiments of the laser ignition microthruster on the KKS-1 microsatellite.

2. Experimental Setups

2-1 Laser ignition thruster

One of the concerns of a laser-based propulsion system is contamination of the optical system. Therefore, we designed an acrylic propellant case that functions as a combustion chamber and nozzle, and also acts as a shield against the combustion gas as shown in Fig. 2. Through the transparent propellant case, the diode laser irradiates the surface of the propellant pellets. When the solid propellant is ignited by this irradiation, the gas generated by combustion expands through the nozzle to produce impulse. Acrylic resin was employed because it has a low thermal conductivity, which provides superior heat protection and some of the ablated mass can contribute to increase impulse.

![Fig. 1. Schematic of a dual-mode laser thruster.\(^3\)](image)

Same laser system

Solid propellant

Ablative material

Large impulse

Small impulse

Fig. 1. Schematic of a dual-mode laser thruster.\(^3\)
Boron potassium nitrate (B/KNO₃) was used as the propellant, which was supplied in the form of cylindrical pellets by Nichiyu Giken Kyogo Co. Ltd. B/KNO₃ was chosen from other pyrotechnics because it is easily ignited in a vacuum and it has proven reliability in space applications.

Impulse values were determined in view of space demonstration experiments onboard a microsatellite. Because it is not practical to detect the velocity change of a satellite moving at a velocity of 7.9 km/s, we planned to detect the rotational motion of the satellite. From the detection range of a typical gyro sensor, the change in the satellite’s rotational speed must be within ± several tens of degrees per second.

Although the onboard satellite and its specifications had not been precisely determined when we developed the thruster, the impulse value was determined from the estimated inertia momentum of a microsatellite, which was obtained assuming the mass of the satellite to be 1~2 kg and its size to be 10~20 cm₂ from typical microsatellite data. The determined value of the impulse was between 50 and 100 mNs.

From this impulse value and the theoretical exhaust velocity of B/KNO₃ calculated using the NASA Computer program known as Chemical Equilibrium with Applications (CEA), the mass of the propellant was set at 0.06 g using two B/KNO₃ pellets. Each pellet weighs 0.03 g and measures 3.2 mm in diameter and 2.0 mm in axial length. The mass fractions of the components of the B/KNO₃ pellets are boron 28%, KNO₃ 70%, and binder 2%.

The pellets are placed inside a combustion chamber with a two-dimensional nozzle that has a 1 mm throat. The expansion ratio of the nozzle was determined to be 4.2 by numerical simulations, so that the thrust head would fit within a 10 mm × 10 mm square.

For quick and effective measurements, we designed the propellant case shown in Fig. 3. The propellant case has five single-shot disposable thrusters. Figure 4 shows a side-cut view of the thruster using this propellant case. The thruster consists of a diode laser system, the propellant case, and a stepper motor to rotate the case. A laser beam from the diode laser focuses on the surface of the B/KNO₃ pellet through two plastic lenses having a focal length of 3.3 mm. Two different 1 W CW diode lasers with a wavelength of 808 nm and 980 nm were used for ignition of the B/KNO₃ pellets.

All the experiments were conducted in a 0.9 × 0.9 × 0.9 m³ cubic vacuum chamber at an ambient pressure between 3 × 10⁻⁴ and 9 × 10⁻⁴ Torr.

### 2-2 Ignition probabilities and impulse measurements

Ignition probabilities and impulses were measured using the thruster shown in Fig. 4. Preliminary experiments showed that laser beam power and the throat area have a significant effect on laser ignition performance. Therefore, the throat area was chosen as a parameter, which was varied from 0.5 to 1.0 mm². Laser beam power was set 1 W to achieve perfect ignition because the least laser beam power for ignition is estimated to be around 300 mW from ignition probability measurements using bare B/KNO₃ pellets and a numerical study.

The impulses were measured by means of a thrust stand, using a horizontally swinging torsional balance with a 30-cm-long arm. The ignition delay time was defined as the time between the input voltage of laser irradiation and the detection voltage of movement of the thrust stand arm. The thrust stand was calibrated by striking a force transducer attached to the thrust stand with an impact pendulum.

### 2-3 Propellant mixtures

Ignition probabilities and impulses for different B/KNO₃ compositions were investigated using the same size B/KNO₃ pellet and propellant case, in order to enhance performance by determining the optimal component ratio of the propellant mixture. The mixture ratios tested were: B/KNO₃/binder=8/90/2, 18/80/2, 28/70/2 (normal), and 38/60/2, 48/50/2.

### 2-4 Measurement of B/KNO₃ burning rates

The burning rates of B/KNO₃ under different pressures were measured to develop a numerical model to predict laser ignition microthruster performance. B/KNO₃ pellets with φ3.2 × 4.0 mm, φ3.2 × 8.0 mm (two φ3.2 × 4.0 mm pellets connected by nitrocellulose lacquer) and φ3.2 × 10.0 mm (five φ3.2 × 2.0 mm pellets connected by nitrocellulose lacquer) were employed for measurements.

An electrical igniter was attached on the surface of the pellet for ignition. The combustion process of the B/KNO₃ pellet was recorded by a high-speed CCD camera using frame rates between 50 and 200 fps. The uncertainties of the start and end of the combustion are estimated to be around 5 frames.
\[ P_c = \frac{mRT_c}{V} \]
\[ \frac{dm}{dt} = A_b \rho_b - \frac{P_c A_b}{c} \]
\[ r = r(P_c) \]
\[ V = V_0 + \int_0^t A_b r(P_c) dt \]

where \( P_c \) and \( T_c \) are the combustion pressure and temperature, \( V \) is the combustion volume, \( m \) is the gas mass of the propellant, \( R \) is a gas constant, \( A_b \) is the throat area, \( \rho_b \) is the density of the propellant, \( r \) is the speed of the combustion surface, \( A_b \) is the burning area, and \( c^* \) is the characteristic exhaust velocity. The gas constant, characteristic exhaust velocity and the combustion temperature of B/KNO₃ are calculated using NASA CEA. The burning area \( A_b \) is determined in such a way that ignition started at the focus point and spread spherically, which is expressed as

\[ A_b = \begin{cases} 
2\pi r_0^2 \left[ 1 - \cos \left( \sin^{-1} \left( \frac{R}{r_0} \right) \right) \right] & (0 \leq r_0 \leq R) \\
2\pi r_0^2 \left[ \frac{R}{r_0} - \cos \left( \sin^{-1} \left( \frac{R}{r_0} \right) \right) \right] & (R \leq r_0 \leq L) \\
2\pi \left[ \frac{R}{r_0} - \sqrt{R^2 + L^2} \right] & (L \leq r_0 \leq \sqrt{R^2 + L^2})
\end{cases} \]

where \( r_0 \) is the distance from the focus point, \( R \) and \( L \) are the radius and axial length of the pellet.

3. Results and Discussions
3-1 Ignition probability and impulse

Figure 5 shows the relation between throat area and ignition probability. The ignition probability increases along with a decrease in the throat area, becomes 90% with a throat area of 1 mm², and reaches 100% with a throat area less than 0.65 mm². From experience, ignition probabilities of second-time laser irradiation are very low due to the change of the irradiated surface after we failed ignition by first-time laser irradiation. Therefore, we determined to use a smaller size throat area (less than 0.65 mm²) to achieve 100% ignition.

Figure 6 shows the relation between impulse and ignition delay time. The average impulse is around 60 mNs (±15 mNs) and its specific impulse is calculated to be around 100 s. This impulse is three to four orders of magnitude higher than those of pulsed plasma thrusters and laser ablation thrusters and can provide large ΔV maneuvers to microsatellites.

In Fig. 6, a large variation in ignition time delay is observed, which peaks around 100 ms after the start of laser irradiation. However, this large variation has little effect on impulse performance by the following evaluations:

1) The absorbed laser power by B/KNO₃ pellets is less than 0.4 J (= 1 W × 400 ms) because all the ignitions started within 400 ms. 2) The exhaust gas energy calculated from 60 mNs average impulse and the propellant mass of 0.06 mg is around 30 J. Therefore, impulse increase by laser irradiation is less than ΔI/I = 0.5×ΔE/E = 0.5×0.4/30 = 0.7%.

Although Fig. 6 showed that the ignition probability of B/KNO₃ pellets greatly depends on the throat area of the combustion chamber, impulse has little dependence on the throat area. No differences were found between the wavelengths of 808 nm and 980 nm regarding laser ignition and impulse performance.

From these results, we have established a technique for laser ignition using CW diode lasers. The problem remaining is to decrease the laser beam power needed for ignition as the numerical study showed that minimum laser ignition power is around 300 mW.
3-2 Propellant mixture

Figure 7 shows the impulses for five different component propellants. Propellants with smaller boron fractions (8/90/2 and 18/80/2) failed to ignite under 1 W laser beam irradiation both in vacuum and air. By contrast, propellants with higher boron fractions (28/70/2, 38/60/2 and 48/50/2) showed 100% ignition. The measured impulses of B/KNO$_3$/binder ratios of 28/70/2 and 38/60/2 were around 60 mNs and higher than the other mixture ratios. These results indicate that too low and too high boron fractions deteriorate propulsion performance. From these results, we decided to use B/KNO$_3$/binder=28/70/2 (nominal mixture ratio) for our laser ignition microthrusters.

3-3 Burning rate measurements and numerical model

Figure 8 shows the plots of burning rates and pressures. A line calculated from the empirical formula of Vieille’s law of burning ($r=24\times P^{0.08}$) and the data from Reference 5 are shown for comparison. The burning rate increases from 100 kPa to 1 kPa, however, it becomes almost constant at a background pressure less than 1 kPa. This result agrees well with the fact that the reaction of B/KNO$_3$ occurs in melted KNO$_3$ and thus pressure dependency is small.

Figure 9 shows the calculated histories of combustion pressure for different throat areas as a function of time from the start of laser irradiation, where the measured burning rates in Fig. 8 were employed.

Regarding the throat area of 0.5 mm$^2$, the combustion pressure increased very sharply around 70 ms and has a peak value of 5.8 MPa. From Fig. 6, impulses were measured with delay times. The average of the delay times was around 100 ms and it coincides with that obtained by this calculation. In addition, the reactions continued around 100 ms, which agreed very well with that measured by digital video camera measurement in Fig. 4 in Reference 2.

4. Demonstration Experiments on Microsatellite

Figure 10 shows a laser ignition microthruster unit for the KKS-1 microsatellite$^6$. The KKS-1 is a 15 × 15 × 15 cm$^3$ microsatellite developed by Tokyo Metropolitan
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College of Industrial Technology as an educational engineering satellite. Its specifications are summarized in Table 1. Two individual laser ignition thrusters were installed in each thruster unit, and a pair of thruster units was attached to two corners of the KKS-1 to enable it to change its rotational speed (Ω). It is calculated from the moment of inertia around the roll axis of the KKS-1 and the impulses of the two thrusters, which is given as Ω = 60 mNs×2×0.075 m / 0.0125 kgm² = 0.72 rad/s (37.9 deg/s). This angular velocity change can be detected by the KKS-1’s gyro sensor. Its detection range is ±100 deg/s.

The thruster was designed without moving parts, and the total amount of B/KNO₃ was limited to 0.24 g (8 pellets) due to safety requirements. A nontransparent safety plate for the diode laser is inserted into a slit between the laser and the propellant case to block unintentional laser irradiation of the solid propellant pellets during launch. The slit is located 2 mm upstream from the focus where the laser beam intensity is low enough to be blocked easily.

Under the law controlling explosives, the demonstration experiments of laser ignition thrusters on the KKS-1 required permission from the Kagoshima Prefectural governor. After several adjustments, the experiments were permitted as scientific experiments as described in Article 25 of the Explosives Control Law.

The KKS-1 was launched on January 23 atop a Japanese H2A rocket and separated successfully. Beacon signals from the KKS-1 were received during the first pass of its orbit. However, a serious communications problem occurred between the ground station and the KKS-1, and demonstration experiments of the thrusters were suspended. Currently, we are waiting for the recovery of the communications system of the KKS-1.

It should be emphasized that this laser ignition microthruster became the first non-conventional microthruster system on orbit.

5. Summary

A laser ignition microthruster was developed for a microspacecraft. The microthruster uses a CW diode laser to ignite small solid-propellant pellets to produce high impulse. Basic experiments were performed to investigate the laser ignition characteristics of a B/KNO₃ propellant. The ignition probabilities of B/KNO₃ pellets using 1 W laser irradiation reached 100 % and an impulse of around 60 mNs with 100 s specific impulse was measured. The optimum mixture of the propellant was found to be B/KNO₃/binder=28/70/2. A numerical model using measured burning rates of B/KNO₃ successfully predicted the ignition delay time experienced in the basic experiments.

Laser ignition microthrusters designed and fabricated based on these basic data were launched into space on the KKS-1 microsatellite. Although the demonstration experiments of the thruster were suspended due to the communications troubles of the KKS-1, we successfully developed and launched the laser ignition microthrusters for microsatellites.

Acknowledgement

This work was supported by a Grant-in-Aid for Young Scientists (B) No.20760550 from Japan Society for the Promotion of Science.

References

6) http://www.kouku-k.ac.jp/~kks-1/

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