

Fundamental Study of Laser Micro Propulsion Using Powdered-Propellant

IEPC-2007-230

*Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007*

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Abstract: In this paper, a newly designed micro propulsion device with the powdered propellant is examined. To produce thrust the powdered propellant is ablated by a pulsed Nd:YAG laser beam in the energy range of 40 – 400 mJ. The radius of the particles, the effect of focus control, and the role of adhesive sheet, which the particle is attached on, are studied. As a result of fundamental experiments, 1 ~ 18 μN impulse bit was measured for various conditions. Specific impulse is obtained from the impulse bits and the propellant mass shot measurements. The results suggest that an adhesive sheet deteriorates the thrust performance due to the production of extra-ablated mass.

I. Introduction

LASER micro propulsion is a promising thruster candidate for the attitude control and the orbital transfer of small satellites¹² because it can optimize both the momentum and specific impulses to meet mission requirements by the control of laser beam conditions. On-board laser thruster which equips laser system on the spacecraft³ has many advantages compared with ground-based laser propulsion which irradiates with the laser beam from a laser station because it can transfer high quality laser beam without air turbulence and can change the orbits by a small thrust using moderate power of the laser beam.

For such laser ablation thrusters, powdered-propellant has never used. In comparison with conventional propellants such as gases, solid, and liquid materials, a powdered propellant is expected to be handled more easily because the storage and the propellant supply can be electrically controlled as in the case of 'toner' for laser printers and copy machines. In space missions, flexibility in choosing propellant is the great advantage because it can be stored in high density and can be supplied only when it is necessary for operation.

In this study, we propose a new laser ablation thruster concept using a powdered propellant. This paper presents the results of impulse bit and specific impulse measured for various configuration of propellant target. The most important issue is to fix powders to the focal point of the laser beam.

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II. Experimental Device and Method

A. Vacuum and Laser System

The major parts of the experimental facility are schematically summarized in Fig. 1. Two main constituents are a pulsed Q-switch type Nd:YAG laser (BM Industries 5022 DNS10, wave length 1064nm), a vacuum chamber with a pendulum mass target for impulse measurement. Maximum obtained pulse energy of the laser is 400 mJ and pulse width is 10 ns. The diameter of a beam of the YAG laser is extended from 10 mm to 25 mm by a beam expander; then the laser beam penetrates a silica glass window and is introduced to the vacuum chamber evacuated into 10^{-3} Pa. Within the chamber, laser light was focused to the surface of the propellant target using a convex lens with a focal length of 100 mm. On this occasion, the movable X-Y stage was used for a propellant to supply and to change its focal point at each laser-shot. The vacuum chamber inside is 600 mm in diameter and 750 mm high. The beam enters the vacuum chamber through a 35 mm diameter window.

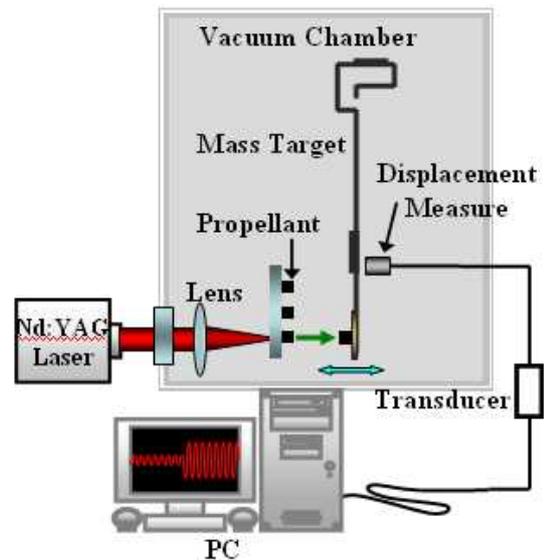


Fig.1 Schematic of experimental set up.

B. Thrust Stand

To measure impulse-bit at each laser shot, a lightweight target pendulum was developed and utilized. A schematic illustration of the pendulum is shown in Fig. 2. As shown in this figure, the plasma plume impinges on a 0.5 mm-thick brass target of 45 mm in diameter. The displacement was measured by an eddy-current displacement sensor (EMIC 503-F (amplifier) with NPA-010 (sensor), minimum displacement 100 nm, maximum displacement 1 mm) in vacuum. At each measurement, calibration of the pendulum was conducted by an inelastic collision of a steel-ball of 26.2 mg suspended with a thin string. To evaluate a mass shot per pulse a mass difference of the propellant before and after a laser-shot was measured with an electronic balance (SHIMAZU AUX220, minimum resolution 0.1 mg). From the mass shot and impulse bit, specific impulse for each case was estimated.

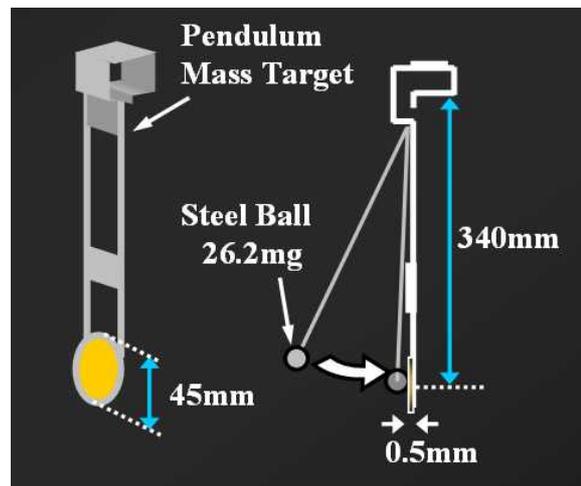


Fig.2 Pendulum mass target.

C. Propellant Target

In this section, four kinds of methods are shown.

1. Small Powders Pasted on Cellophane Tape

The most important problem is how to fix some powders on a focusing point of the laser beam. A schematic of the target is shown in Fig. 3. In this experiment, laser beam was irradiated from behind the OHP sheet and was focused at surface of the propellant. As for the propellant target, some silicon powders (99 % Si and diameter of particle, 1 μ m), are pasted on the cellophane tape, although the target tends to drop easily with this method. This propellant target is defined as case A the tape is fixed on a glass slide to prevent optical instruments from any

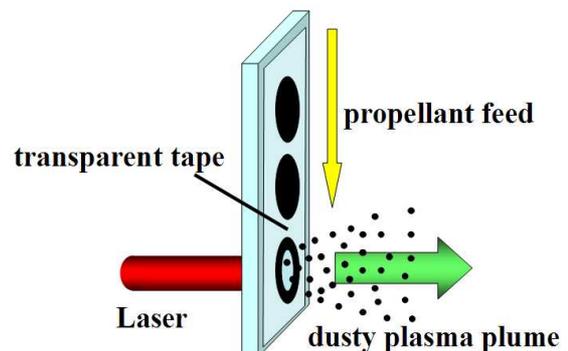


Fig.3 Propellant target construction of small particle pasted on cellophane tape.

contamination caused by the ablation plume, and the target was set on the X-Y stage to supply propellant repeatedly. The target was located to prevent any damage for the glass slide due to defocusing of the laser beam. If the silicon powders are mounted on the adhesive tape, it is possible that the particles are nearly uniformly mounted on the film surface. With this method the propellant density is expected to be uniform and to be handled easily. High reproducibility is also expected. The experiment was operated in vacuum (2.0×10^{-5} Torr) with laser pulse energy varied from 4.57×10^4 J/cm² to 1.14×10^6 J/cm².

2. Toner Printed on OHP Sheet

The experiment using toner powder (FUJI XEROX CT200611) as a propellant was conducted (case B). Since the toner is magnetic powder in small diameter ($< 1 \mu\text{m}$), it can be stored in high-density and can be supplied by precise electrical control. The toner was welded on the OHP sheet by laser print in order to avoid drop of the powders. To make the propellant layer uniform, it was printed four times (Fig. 4). Therefore it was expected that the mass shots would be reduced, and larger specific impulse could be obtained than the previous case. In this case (case A), the laser beam with the energy of 60 to 330 mJ is introduced to the target.

3. Particle Pasted on Cellophane Tape

A carbon particle (500 μm in diameter) pasted on a cellophane tape was used as propellant target (case C, Fig. 5) to reduce extra mass loss. The laser beam was irradiated on a particle through the adhesive tape, and is focused on the target precisely. It has to be noted that the transparent material (cellophane tape) on which the propellant was mounted is also ablated with propellant in this method, because the laser energy density on the target is larger than that of case A. The propellant was feed by the X-Y stage and it was ablated with the adhesive tape by the laser irradiation for the energy from 40 to 300 mJ.

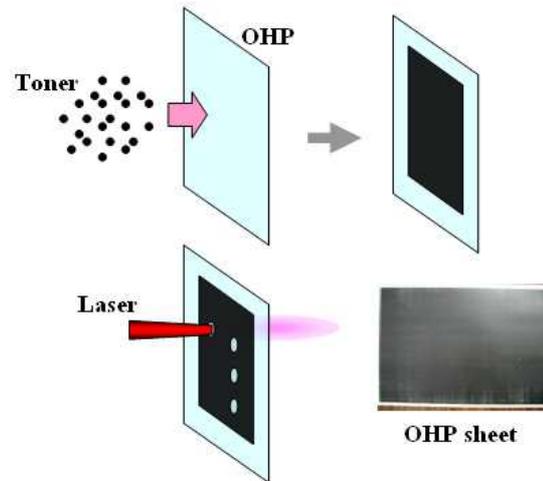


Fig. 4 Toner-OHP propellant target.

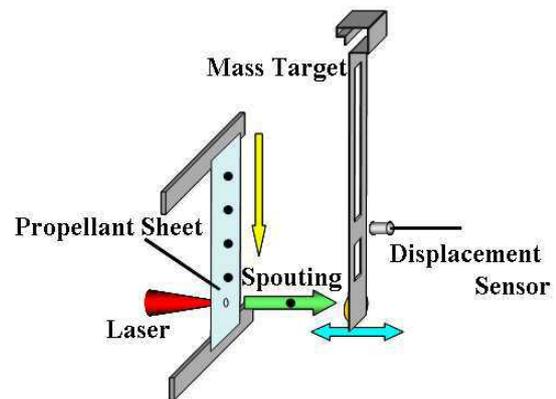
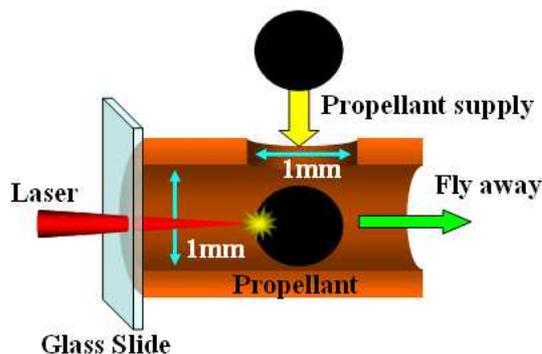
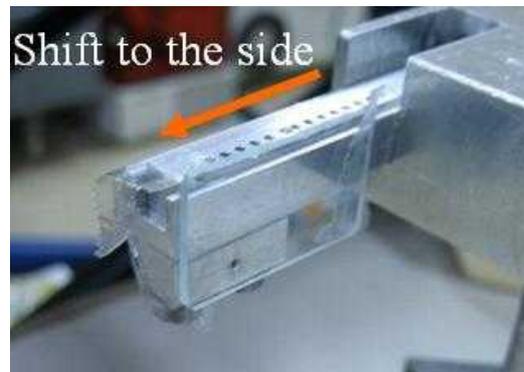


Fig. 5 Schematic of laser micro thruster using carbon particles of sub millimeter in diameter.



a)



b)

Fig. 6 Test model thruster using carbon; a) inner structure, and b) prototype for experiment.

4. Particle Set in Test Model Thruster

Based on the previous method (case C), we made a test model thruster (case D). The schematic illustration and the photograph of prototype thruster are shown in Figs.6 a) and b) respectively. The thruster is 1 mm in diameter, and it has a side tunnel to supply the propellant (500 μm diameter carbon particle). One side of this thruster is blocked by a glass slide of 1.2 mm in thickness to converge the propellant flow to the forward direction, and the laser beam irradiates through the glass in the energy range of 40 mJ to 300 mJ. Experimental conditions such as barometric pressure and laser energy were the same as that of case C. The propellant is dropped into the hole from a bar (in Fig.6b)) that stored some propellant powders, and flows away from the thruster exit

In this experiment, the laser beam was irradiated at 5 laser pulse energies in the range of 40 to 300 mJ.

III. Experimental Result and Discussion

A Small Powders Pasted on Cellophane Tape

The photograph of the target after experiments is shown in Fig. 7. Strong light emissions were clearly confirmed when the laser was irradiated, and all the particles inside the circular marks, which corresponding to the laser-spot sizes at the surface, were emitted. The picture of laser ablation plume is shown in Fig. 8. Orange plume was observed in the direction of the laser optical axis, and the plume axis was perpendicular to the glass slide. One can see that the plume is relatively converged even though there is no nozzle. This good collimation will make it possible to control the direction of thrust by changing the laser axis. In addition, since the laser ablation plume is emitted only in the direction of the laser beam, it is able to prevent any contamination for the optical system, which is located behind the ablation target mounted on a glass plate.

Measured impulse-bits for six laser fluencies are plotted in Fig. 9 a), and plots of specific impulses estimated

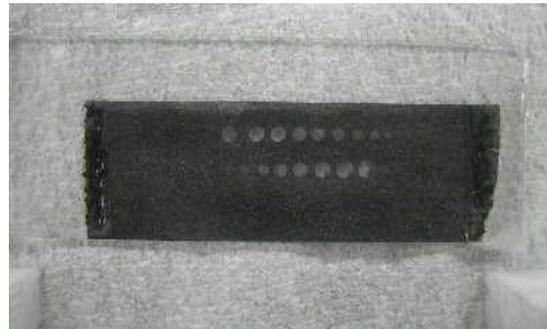


Fig. 7 The propellant target of small powder after laser ablation.

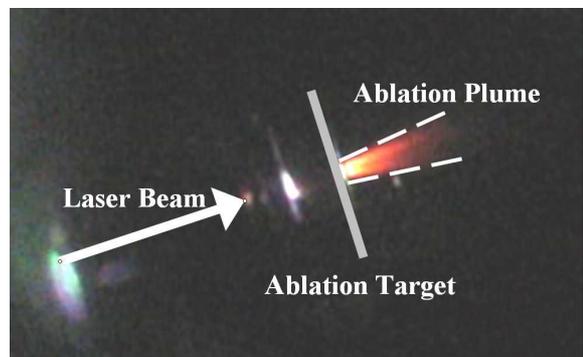
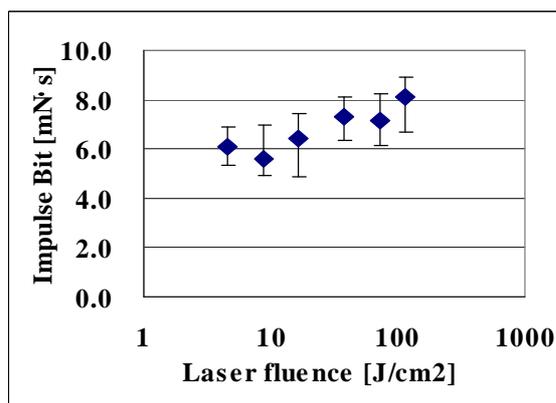
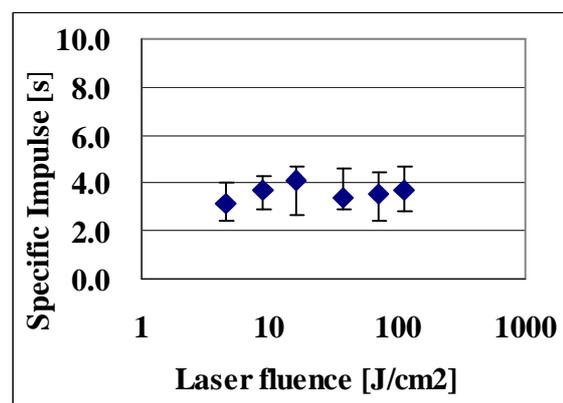


Fig.8 Laser Ablation plume.



a)



b)

Fig. 9 Result of experiment using small powdered propellant pasted on cellophane tape; a) impulse bits, and b) specific impulse.

from the impulse bit and the mass shot are shown in Fig. 9 b). It can be seen that impulse-bits are in the range of 5 μNsec to 8 μNsec . This result shows that impulse bit goes up with increasing laser fluency, although it seems that the laser power does not have an significant effect to obtained larger impulse bit using this thruster. On the other hand, specific impulses are around 4 sec. It is considered that specific impulses did not vary with increasing laser fluency, because the some powdered propellant that pasted on the cellophane tape was dropped by the shock of the laser ablation. In addition, the propellant that does not contribute to thrust production become larger as the laser energy is increased. Actually, the useless propellant mass is larger than the mass converted into the impulse bit, which leads to the low specific impulses.

B Toner Printed on OHP Sheet

Measured thrust performances are shown in Fig. 10. By increasing the laser energy, impulse bit become larger. Specific impulse ranges from 2 sec to 5 sec. The light emission of laser ablation and thrust production was confirmed in the experiment. By the laser irradiation, the filmed toner was broken into some fragments and scattered. The toners around the focal spot are also ripped up by the laser irradiation, which means the ripped region was larger than laser focal spot. In addition, the OHP sheet was also ablated, thus it also contributes to the mass shot. The mass of ablated OHP is larger than the propellant mass.

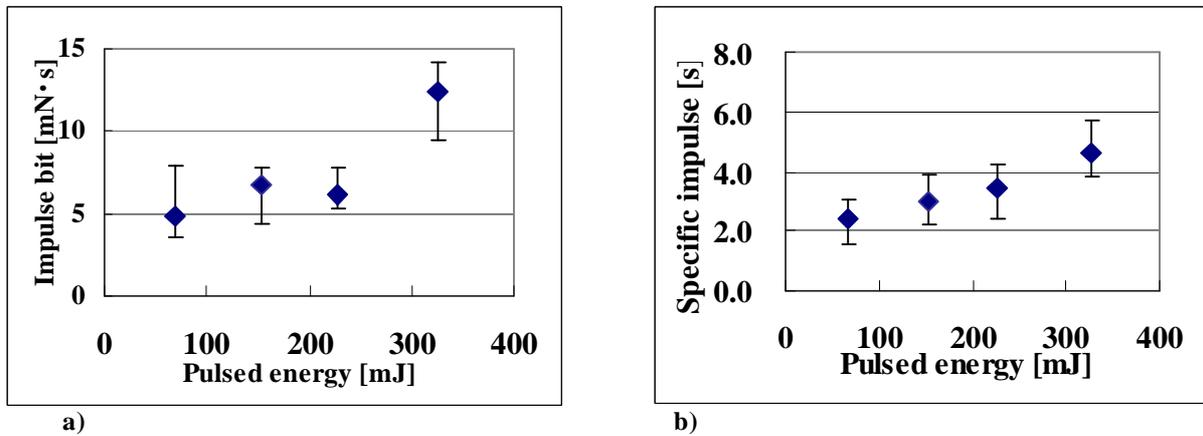


Fig. 10 Result of experiment using toner propellant printed on OHP; a) impulse bits and, b) specific impulse

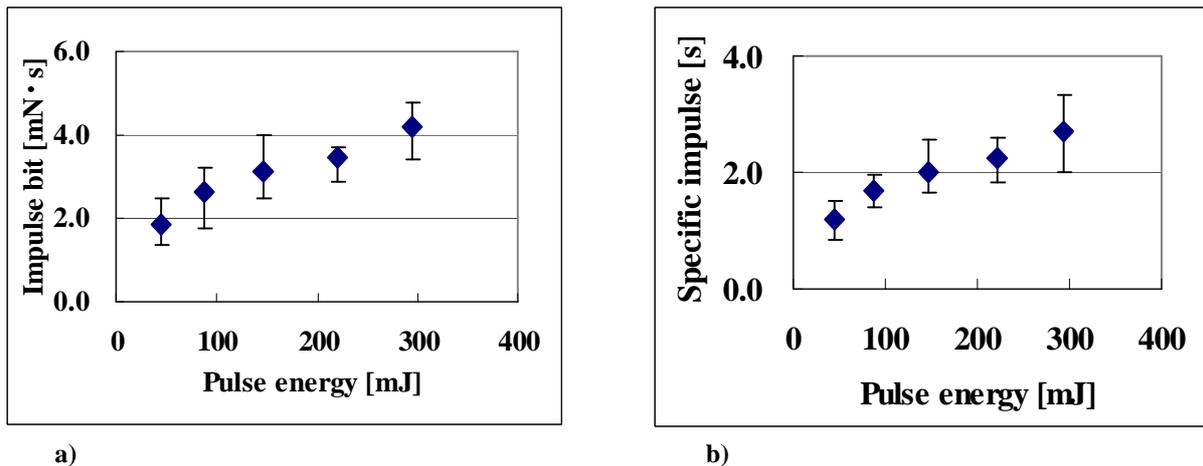


Fig.11. Result of experiment using a carbon propellant pasted on cellophane tape; a) impulse bits, and b) specific impulse.

C Particle Pasted on Cellophane Tape

The propellant and cellophane tape were ablated with light emission. The carbon particles were broken by thermal shock when the laser beam was irradiated. Then propellant was ejected in all directions. Therefore some parts of the ablated propellant did not contribute to impulse bit. Thrust performances are shown in Figs. 11a) and b). The impulse bit is enlarged with increasing laser energy. The impulse bit and specific impulse are too small because the laser energy was consumed to break the particles.

D Particle Set in Test Model Thruster

The photograph of the plume is shown in Fig.12. The white emission was observed with good collimation because the hole of this thruster acted as a nozzle. Measured thrust performances are shown in Fig. 13. Due to the effect of the hole, thrust of this case is higher than the case C.

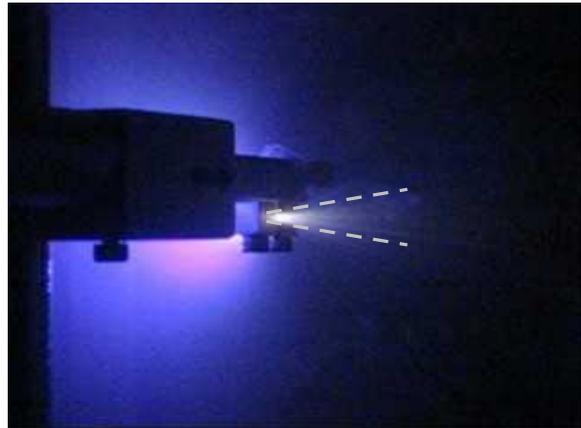
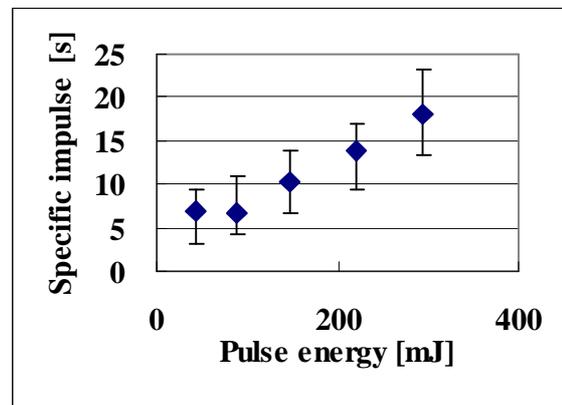
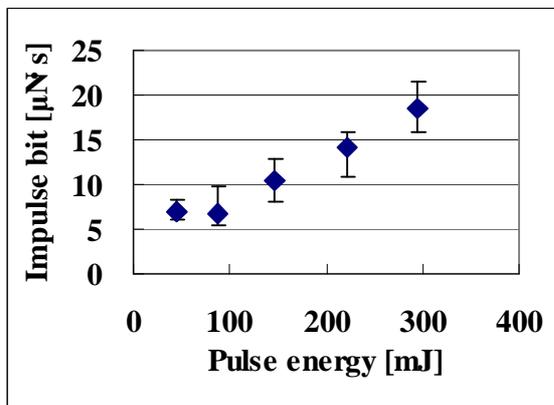


Fig.12 Emission when laser is irradiated to a particle set in the test model thruster.

The minimum impulse bit is 6.6 μNsec at 88 mJ per pulse, and the maximum impulse bit is 18.1 μNsec at 294 mJ. By increasing the laser pulse energy, impulse bits are enlarged. Specific impulses are in the 7 sec to 18 sec range. In this experiment, only propellant is ablated by laser irradiation unlike the case C, where the cellophane tape is employed and does not contribute to the mass shot. Since there is no extra mass that does not contribute to the thrust, the mass shot was reduced, which results in large specific impulse. It is considered that specific impulse may be further improved by using smaller particles for this thruster, because specific impulse is inversely proportional to the mass shot. In addition, the ejection velocity can be enlarged by decreasing the propellant mass and increasing the energy supply per mass. We expect to realize high specific impulse in this thruster. We will use the test model thruster available for a particle smaller than 100 μm in diameter, and examine characteristics in the future.



a)

b)

Fig.13 Result of experiment using a carbon propellant using test model thruster; a) impulse bits and, b) specific impulse.

IV. Conclusion

We proposed various laser ablation thrusters using powdered propellant. In this paper, four concepts of the laser ablated micro thruster are discussed, and characterization of the thrusters for various laser pulse energies, which are supplied by a pulsed Nd:YAG laser (~ 10 ns) with moderate energies in the range of 40 to 400 mJ, is conducted.

The method to mount the propellants on the transparent material (cellophane tape, and OHP sheet), was not preferable to apply for the laser micro thruster. It's because the material is ablated with propellant. It is found that, although the transparent material is also ablated, the extra-ablated mass does not contribute to the thrust. The reason for this may be that the ablated transparent material is reflected from the propellant. Thus, the mass shot becomes larger than the ablation of propellant. Hence, we made a test model thruster without using the transparent material. The thruster allows supplying laser energy only to propellant by focusing the laser beam. As a result, it can provide better performances than other concepts. According to our results, the ejection velocity and specific impulse may be increased by decreasing the propellant mass and increasing the supply energy per mass. In the future, how to supply the propellant in space has to be solved.

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