Thrust Characteristics of a Coaxial Laser-Electromagnetic Hybrid Thruster

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An experimental study on coaxial laser-electromagnetic hybrid thrusters was conducted. The laser-electromagnetic hybrid thruster, consisting of a coaxial electrode configuration with an annular copper anode and carbon fiber rod cathode was used to produce laser-induced plasmas, which were further accelerated by electromagnetic force to improve thrust performance. Experimental measurement of impulse bit and mass shot was conducted. From the measurement, thrust performance showed impulse-bit of 2 ~ 45 μNsec, momentum coupling coefficient of 5 ~ 14 μNsec/J, specific impulse of 1000 ~ 1400 sec and thrust efficiency of 3 ~ 5 % for charge energies 0 ~ 8.6 J and a laser pulse energy of 120 mJ. In addition, a significant improvement of thrust performance, could be obtained with the use of alumina propellant, which were an impulse-bit (I_{bit}) of 60 μNsec, a specific impulse (I_{sp}) of 6,000 sec, and a thrust efficiency of 20% at charge energy of 8.6 J.

Key Words: Laser-Electric Hybrid Propulsion, Electromagnetic Acceleration, Coaxial Pulsed Plasma Thruster

1. Introduction

Small onboard laser plasma thrusters are under significant development along with the rapid evolution of novel compact laser systems1-4). One of the advantages of such laser thrusters is that they can use any solid materials as their propellant. Therefore, the system can be very simple and small with significant controllability of thrust. In order to improve the thrust performance and system simplicity of conventional electric and laser propulsion systems, preliminary studies of a laser-electric hybrid acceleration system have been conducted by the authors5-10). In this paper, we describe some of typical electromagnetic acceleration characteristics of the propulsion system of this type.

2. Laser-Electric Hybrid Thruster

A schematic of laser-electric hybrid acceleration system is illustrated in Fig. 15-10). A basic idea of the system is that laser-ablation plasma induced through laser irradiation on a solid target is additionally accelerated by electrical means. Since any solid materials can be used as propellants in this case, no tanks, valves, or piping systems are required for the propulsion system. Therefore, the system employing this technique can be significantly simple and compact. Because laser-ablation plasma has a directed initial velocity of tens of km/sec, which will be further accelerated by electrical means, significantly high specific impulses can also be expected.

In the above hybrid cases, depending on different factors such as electrode configuration, plasma density, and electrical input power (voltage x current), acceleration mechanisms for the laser-ablation plasma can be classified into three types, i.e., i) electrostatic acceleration, ii) electrothermal acceleration, and iii) electromagnetic acceleration, although ii) usually occurs simultaneously with iii). Especially for laser-ablation plasma, depending on laser conditions such as pulse energy, fluence, etc., plasma density and velocity distributions can be widely controlled. Moreover, they can also be controlled through additional electric discharges.

Properly controlling a power source, or voltage and current, with optimized electrode configuration for additional electric acceleration, each acceleration mechanism can be adopted. Therefore, propulsion system that is able to satisfy all the above acceleration schemes through i) to iii) will be achieved with one thruster configuration. Namely, this system enables a robust conversion between high-specific-impulse operation and high-thrust-density operation in regard to mission requirements. Each of two typical acceleration modes, a electrostatic mode and a electromagnetic mode, is currently under investigation in our group.
Table 1. Sizes of thrusters.

<table>
<thead>
<tr>
<th>Thruster</th>
<th>Anode (mm)</th>
<th>Cathode (mm)</th>
<th>Channel length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>II</td>
<td>13</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

2.1. Electrostatic acceleration

One of the laser-electric hybrid acceleration regimes employed in our studies is laser-electrostatic hybrid acceleration, in which laser-ablation plasma is further accelerated by an electrostatic field\(^9\). In the laser-ablation, first, electrons are accelerated from the surface, and then, ions are accelerated through ambipolar diffusion and Coulomb explosion. In the hybrid accelerator, such ions are further accelerated with an additional acceleration electrode. Because laser-induced plasma generated from the target surface having a directed initial velocity is further accelerated by an electrostatic field, fast ion emission and high specific-impulses can be expected.

2.2. Electromagnetic acceleration

Another acceleration regime considered in this study is laser-electromagnetic hybrid acceleration. It utilizes laser-beam irradiation to induce plasma ionized from a solid propellant between electrodes, and then an electric discharge is induced in this conductive region. As the current running between the anode and cathode is increased, the plasma can be heated and further ionized through Joule heating. Thus, the electrothermal acceleration effect becomes significant. When current exceeds more than one thousand amperes, an electromagnetic acceleration effect becomes significant. Since a primary current concentrates on the cathode center running in axial direction, a self-induced magnetic field is induced in azimuthal direction. Then a streamwise acceleration is provided through the interaction of the radial current and the azimuthal magnetic field, or Lorentz force. In addition, there is an electromagnetic pumping process wherein axial components of current cross with the azimuthal magnetic field to establish a radial gradient in the gas dynamic pressure which provides a reaction force on the cathode surface\(^{11-13}\).

Because the use of a shorter laser pulse enables a shorter pulsed-plasma generation, a significantly high peak current can be induced. Since the force induced in the accelerator is dependent on the square of the current, significant improvements in acceleration characteristics can be expected\(^{11-13}\). In addition, depending on laser power, laser-induced plasma produced from a solid propellant usually has a directed initial velocity, and this can also contribute to an improvement in the acceleration performance.

3. Experimental Setup

In this study, two different sizes of the thrusters were examined. Sizes of the thrusters are listed in Table 1. For the thruster (Fig.1), a coaxial electrode configuration with an annular copper anode (5 and 13 mm in diameters for thrusters I and II, respectively) and a carbon fiber rod cathode (3 and 6 mm in diameters for the I and II), which is also the solid propellant, was used, in which channel lengths between the cathode edge and the anode exit were set 3 and 6 mm for the I and II, respectively. A schematic of experimental setup is given in Fig.2. A Q-sw Nd: YAG laser (BMI, 5022DNS10, wavelength: \(\lambda =1064\) nm, pulse energy: 120 mJ and 0.7 J/pulse, pulse width: 10 nsec) was used for a plasma source. The laser pulse was irradiated into a vacuum chamber (10\(^{-3}\)).
Pb_35

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Pa) through a quartz window and focused on a target, or a propellant, with a focusing lens (f = 100 mm). Discharge current was monitored with a current probe (Pearson Electronics, Model-7355, maximum current: 10 kA, minimum risetime: 5 nsec) and an oscilloscope (Tektronix TDS3034B, range: 1 nsec/div ~ 50 sec/div). Moreover, in order to estimate \( \mu \text{nsec-class impulses, a calibrated torsion-balance-type thrust-stand was developed and tested}^{(10)} \). Schematic of experimental setup for impulse-bit measurement is given in Fig.3. The balance is 450 mm long made of aluminum. Distance between the pivot and thruster is set 437 mm. For the pivots, the Flexural Pivot (SDP/SI) was used. A torsional spring rate of the pivot estimated in this case is \( k = 4.7 \times 10^7 \text{ Nm/rad} \). As for the displacement sensor, a non-contacting displacement sensor of eddy current type (EMIC, 503-F, NPA-010, maximum range: 1 mm, minimum displacement: 0.5 \( \mu \text{m} \)) located at 450 mm from the pivots was used.

4. Results and Discussion

4.1. Discharge characteristics

Temporal variations of discharge current for charged voltage conditions from 500 to 2,000 V and laser pulse energies of 120 mJ and 0.7 J for thruster II are shown in Fig.4, in which the maximum charge energy is 8.65 J. In the 500 V case, a single pulse discharge peaking up to 500 A at 1.7 \( \mu \text{sec} \) with a pulse width of 4 \( \mu \text{sec} \) is observed. In the figure, positive values on an ordinate mean a positive current from anode to cathode. It is confirmed that electric discharges can be achieved even under low voltage conditions (~ 500 V). Also, it can be seen that the higher the voltages, the higher currents are induced. Although one positive wave of the current of about 4 \( \mu \text{sec} \) duration is observed in low-voltage cases, the current oscillation with longer duration is occurring in higher voltage conditions. At 2,000 V (8.65 J), the current abruptly rises and reaches the maximum value of + 2,340 A at 1.9 \( \mu \text{sec} \), after which it falls down to a minimum value (−1,150 A) at 5.9 \( \mu \text{sec} \) and converges zero at about 12 \( \mu \text{sec} \). Although not shown, the current waveform of the different thrusters was approximately the same.

In Fig.4 (b), where laser pulse energy of 0.7 J, the current at 2000 V (8.65 J) abruptly rises and reaches the maximum value of + 2,440 A at 1.9 \( \mu \text{sec} \), after which it falls down to a minimum value (−1,100 A) at 5.9 \( \mu \text{sec} \) and converges zero at about 12 \( \mu \text{sec} \). It is confirmed that discharge current patterns did not depend on the laser pulse energy.

4.2. Thrust performance measurements

Thrust performance of pure laser propulsion mode for laser pulse energies of 120 mJ and 0.7 J is listed in Table 2. The case of laser pulse energy for 120 mJ showed higher thrust performance than 0.7 J case.

Plots of impulse-bit measured with a torsion-balance type thrust stand for various energies charged to capacitors for laser pulse energies of 120 mJ and 0.7 J for two types of thrusters I and II are shown in Fig.5. As shown in this figure, impulse-bit of each thruster increases with energy of up to 8.65 J. Impulse-bits for two laser pulse energies were approximately the same. The thruster II with the larger diameter of the anode (Ø13 mm) showed higher impulse-bits than thruster I (Ø5 mm).

While in terms of thrust density, the maximum value of 1.2 Nsec/m² for smaller thruster (thruster I) was larger than that of 0.3 Nsec/m² for larger thruster II. Deviations of the plots are probably due to those of laser pulse energies and misalignments of mechanical and optical elements at each operation.

Relationship between momentum coupling coefficient \( C_m \) and charge energy for laser pulse energies of 120 mJ and 0.7 J are shown in Fig.6 for thrusters I and II. From the figure the momentum coupling coefficient of each thruster gradually decreases with energy showing maximum value in the pure laser propulsion mode (Table 2). Moreover, values of the coupling coefficient for different laser energies were about the same. Regardless of the laser energies, larger coupling coefficients could be obtained with the larger thruster.

For the mass measurement of the propellant consumption rate we used an electronic precision balance (Shimazu AUX220, minimum mass 0.1 mg). The typical number of pulse-shots to measure the mass shot was 500 times. The mass in this case was 2.3 mg for a charge energy of 8.65 J and a laser pulse energy of 120 mJ with thruster II. Mass shots with charge energy 2.2 ~ 8.6 J for thrusters I and II are listed in Table 3. It is apparent that the mass shots of two thrusters I and II for a laser pulse energy of 120 mJ were approximately the same (Table 3). From these results, specific impulse for each plot of impulse-bit was estimated. In Fig.7, specific impulse variations with charge energy for laser pulse energies of 120 mJ and 0.7 J for two types of thrusters are plotted.
Table 2. Thrust performance of pure laser propulsion mode.

<table>
<thead>
<tr>
<th>Thruster II</th>
<th>Laser pulse energy</th>
<th>Charged energy</th>
<th>Mass shot</th>
<th>Impulse-bit</th>
<th>momentum coupling coefficient</th>
<th>Specific impulse</th>
<th>Thrust efficiency</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>120 mJ</td>
<td>0 J</td>
<td>0.04 μg</td>
<td>2 μNsec</td>
<td>14 μNsec/J</td>
<td>4400 sec</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td>0.7 J</td>
<td></td>
<td>0.76 μg</td>
<td>7 μNsec</td>
<td>9 μNsec/J</td>
<td>900 sec</td>
<td>4%</td>
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Table 3. Mass shot measurements.

<table>
<thead>
<tr>
<th>Thruster I</th>
<th>Laser pulse energy</th>
<th>Charge energy</th>
<th>Mass shot</th>
<th>Thruster II</th>
<th>Laser pulse energy</th>
<th>Charge energy</th>
<th>Mass shot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120 mJ</td>
<td>2.2 J</td>
<td>1.6 μg</td>
<td></td>
<td>120 mJ</td>
<td>2.2 J</td>
<td>1.6 μg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.9 J</td>
<td>2.7 μg</td>
<td></td>
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<tr>
<td></td>
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<td>8.6 J</td>
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<td>8.6 J</td>
<td>5.4 μg</td>
<td></td>
<td>8.6 J</td>
<td>5.4 μg</td>
</tr>
</tbody>
</table>

Fig. 5. Impulse bit vs. charged energy.

Fig. 6. $C_a$ vs. charged energy.

Fig. 7. Specific impulse vs. charged energy.

Fig. 8. Thrust efficiency vs. charged energy.
It is found that the thruster II for a laser pulse energy 120 mJ showed higher specific impulse than thruster I. Since the thruster II for laser pulse energy 0.7 J showed a larger mass shot than that of 120 mJ, it showed a lower specific impulse than the case of 120 mJ. This is probably due to the thermal loss of a propellant. Specific impulse of lower laser energy case gradually decreases with increasing charge energy. On the other hand, specific impulse of higher laser pulse energy case is almost constant with charge energy. The values of specific impulse of thruster II for charge energy 2 ~ 5 J are higher than those of conventional PPTs operated under similar energy levels\(^{23}\). For a higher charge energy, it is hence confirmed that part of propellant is consumed by the discharge, which may not effectively contribute to impulse-bit.

Relationship between thrust efficiency \((= (\text{kinetic energy}) / ([\text{charged energy}] + (\text{laser energy})))\) and charged energy for laser pulse energies of 120 mJ and 0.7 J for two types of thrusters are given in Fig.8. As shown in this figure, thrust efficiency decreases with increasing charged energy for each thruster. At charge energies of 5 to 9 J for thruster II, there are no big differences in the efficiencies between different laser energies. Some values of the thrust efficiency obtained in this study for input energy ranging 5 ~ 9 J are lower than those of conventional PPTs\(^{23}\). This is probably due to structure of the thruster. When the channel length of the thruster is not long enough, all the charged energy may not be discharged. Some fraction of the mass shot may not be able to receive an acceleration force and namely not contributing to induction of the impulse resulting in the mass loss.

### 4.3. Comparison of thrust performance between different sets of cathode and propellant

To improve the mass loss and namely thrust performance of the use of carbon-resin cathode and propellant, different sets of cathode and propellant, which were molybdenum and alumina, respectively, were examined, as shown in Fig.9 (thruster IV). Since the propellant is not conductive material in this case, it was used as an insulator between the cathode and anode, and an incident laser beam was irradiated on the propellant surface. Size of the thruster is identical to that of thruster II. In this subsection, thrust performance of these two thrusters was compared.

Temporal variations of discharge current of thruster IV are shown in Fig.10 for various charge voltages and laser pulse energy of 120 mJ. Comparing with the similar size thruster II with different set of cathode and propellant shown in Fig.4, i.e., with the improved conductivity of the cathode, the peak current became larger from 2,200 to 3,500 A, and the pulse width was reduced from 4 \(\mu\)sec to 3 \(\mu\)sec. Comparison of impulse-bit variations between thruster II and IV is shown in Fig.11. From the figure, it is shown that slightly higher impulse bits can be obtained in low energy cases of thruster II, while in high energy cases, similar values of impulse bit can be obtained in each thruster. Variations of mass shot of each thruster are plotted in Fig.12. A significant reduction of the mass shot can be obtained with the use of alumina propellant.

From these results, specific impulse and thrust efficiency were estimated and plotted in Figs.13 and 14, respectively. From Fig.13, the specific impulse increases from about 5,000 to 6,000 sec with charge energy for alumina propellant thruster, while in carbon-resin propellant thruster, the value decreases from 2,000 to 1,300 sec. It is shown that a very high specific impulse can be obtained with alumina propellant. Similar tendency can be seen for thrust efficiency shown in Fig.14. The improvement of the thrust efficiency can be seen from 17 to 19% with the increase of charge energy for alumina thruster. On the other hand, for carbon-resin propellant case, the value decreased from 10 to 5%. As can be
seen, a significant improvement of thrust efficiency was achieved with the alumina propellant thruster. Since configuration of the alumina propellant thruster is still not optimized, our future work will be focused on this point.

5. Conclusions

A fundamental study on laser-electric hybrid thruster was conducted, in which laser-induced plasmas were generated through laser-beam irradiation on to a solid target and accelerated by electrical means instead of direct acceleration using only a laser beam. For two different sizes of the thruster, a feasibility study on electromagnetic acceleration mode of the laser ablation plasma was conducted. Following results were obtained.

1) Electric discharges could be achieved even under low voltage conditions (~ 500 V).
2) Impulse-bit of two cases of laser pulse energy (120 mJ and 0.7 J) were almost equal.
3) Specific impulse and thrust efficiency were higher for relatively low charge energies below 5 J.
4) A significant improvement of thrust performance could be obtained with the use of alumina propellant, which were Ibit of 60 μNsec, Isp of 6,000 sec, and thrust efficiency of 20% at charge energy of 8.6 J. Possibility of further improvement with the increase of charge energy was also demonstrated.

References