A Novel Laser Ablation Magnetoplasmadynamic Thruster

Yu Zhang*, Jianjun Wu**

College of Aerospace Science and Engineering, National University of Defense Technology, 109 Deya Road, Changsha, Hunan, 410073 China

*****Corresponding author, E-mail: zhangyu_nudt@126.com (Yu Zhang);

**Corresponding author, E-mail: jjwu@nudt.edu.cn (Jianjun Wu).

Abstract: A novel laser ablation magnetoplasmadynamic thruster (LA-MPDT) is proposed by applying laser technology to the electromagnetic acceleration thruster. It can provide an efficient and advanced propulsion system for the future deep space exploration, manned lunar landing and Mars development. The design of thruster, experimental measurement of propulsion performance and analysis of influencing parameters are systematically investigated. Aiming at the operating characteristics of LA-MPDT, the scheme on multi-stage ignition and discharge power supply of LA-MPDT is proposed. The experimental study on the influence parameters of LA-MPDT propulsion performance is carried out. Based on the same laser parameters (1000W, 1ms), with increasing of discharge energy, the propulsion performance of the thruster is significantly improved. The specific impulse reaches 4800s and the thrust efficiency reaches 9.1% with the discharge energy of 78J. Based on the same discharge energy (50J), with increasing of laser energy, the specific impulse decreases gradually, and the thrust efficiency increases first and then decreases, the maximum thrust efficiency reaches at 18.5% with the laser energy of 2J. The mass loss of the propellant is mainly caused by laser ablation, while the thrust mainly comes from the electromagnetic acceleration of plasma.

Keywords: Laser ablation magnetoplasmadynamic thruster; Discharge characteristic; Specific impulse; Thrust efficiency.

0 Introduction

Because of the advantages of high thrust density, high specific impulse and low system quality, magnetoplasmadynamic (MPD) thrusters are considered as potentially suitable electric propulsion devices for a multiplicity of space applications from orbital maneuvering to interplanetary missions.

The concept of MPD thruster was proposed by Giannini Scientific Corporation (GSC) early in 1960s[1]. Afterwards, researchers have carried a lot of investigations on the effects of propellant type and flow rate, electrode configuration and material, thruster structure and size, applied-field strengthen and configuration on the specific impulse, thrust efficiency and life of MPD thruster[2-8]. Meanwhile, a large number of numerical models have been established to reveal the working mechanism and process of MPD thruster[9-15]. However, despite the simplicity of operating principle of MPD thruster, the complexity of the interlocking nature of the physics involved in MPD thruster acceleration has not been well identified. To date, there is no MPD thruster for space flight test, this mainly because of the following points: (1) The propellant of MPD thruster is gas, which is difficult to store. (2) The gas supply system of MPD thruster is complex, which leads to slow thrust response. (3) The cathode ablation of MPD thruster is serious, which limits the working life. (4) As the power of MPD thruster increasing, the discharge may be unstable, which reduces the thrust performance.

At present, the researches of MPD thruster have reached the "bottleneck", and it is urgent to combine with new technical means to further improve the performance of MPD thruster. With the advent and development of high-performance laser, the application of laser technology in aerospace field can provide new research approaches and methods for the development of electric propulsion. Laser-electromagnetic hybrid propulsion and laser-assisted pulsed plasma thruster have been developed, which verifies the feasibility of the combination of laser ablation and electromagnetic acceleration[16-20].

In this paper, a novel laser ablation magnetoplasmadynamic thruster (LA-MPDT) is developed and investigated. This thruster is expected to overcome the shortages of conventional MPD thruster in the above paragraph. And the discharge characteristics, specific impulse and thrust efficiency of the thruster are experimental studied.

1 Thruster Design

The schematic illustration of LA-MPDT is shown in Figure 1, the LA-MPDT system includes laser, PC, discharge power supply, supply device and thruster. The copper anode with an inner diameter of 52mm, a wall thickness of 2mm and length of 80mm is used. The tungsten cathode with an inner diameter of 10mm, a wall thickness of 1mm and length of 10mm is used. The solid propellant with the material of 20%Al80%PTFE is placed inside the cathode. Meanwhile, there is a isolated section with the material of BN between the cathode and anode, which has the characteristics of insulation and ablation resistance.

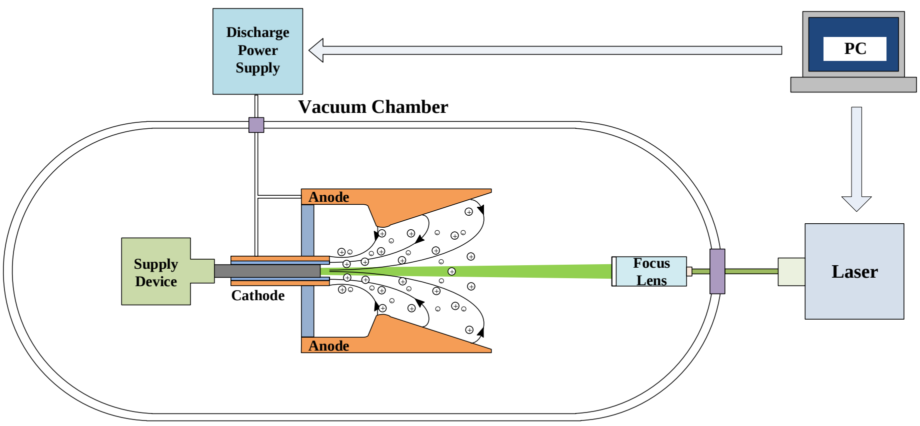


Figure 1. Schematic illustration of LA-MPDT

The working process of LA-MPDT can be divided into two stages: laser-induced ablation of propellant and plasma-induced discharge. In the first stage, the solid propellant inside the cathode is irradiated by a laser beam, decomposed into gas and plasmas, and injected into a vacuum between electrodes. In the second stage, the plasmas induce the breakdown discharge between the cathode and anode, and then the large current discharge arc is formed. As the discharge current increasing, the self-induced magnetic field becomes significant, and the interaction between the plasma and the electromagnetic field gets intensive. The ions in the plasma are then accelerated by the Lorentz force in the induced magnetic field. Moreover, the ionization of effluent matter can be enhanced by the arc discharge process.

The power supply of LA-MPDT includes discharge circuit and ignition circuit, as shown in Figure 2. The discharge circuit can provide a quasi-steady discharge power for the thruster, which consists of charging power supply, a sequence of capacitors and inductors, diode, protective resistor, electric relay and silicon controlled rectifier (SCR). The charging power supply is used to charging the capacitors in the circuit. A sequence of capacitors and inductors are twelve 0.7mF capacitors and 4.2μH inductors. The diode is used to prevent the high voltage charging from ignition circuit to discharge circuit. The protective resistor and electric relay are used to release the energy stored in the discharge circuit when the thruster discharge fails. The SCR is used to control the conduction between discharge circuit and thruster. Otherwise, the discharge circuit output a discharge passed through an adjustable ballast resistor to aid in load matching. The ignition circuit is connected in parallel to the thruster and isolated via high-voltage, high-current diode from the discharge circuit. This circuit use a 10μF capacitor charged to 2000V to initiate the discharge.

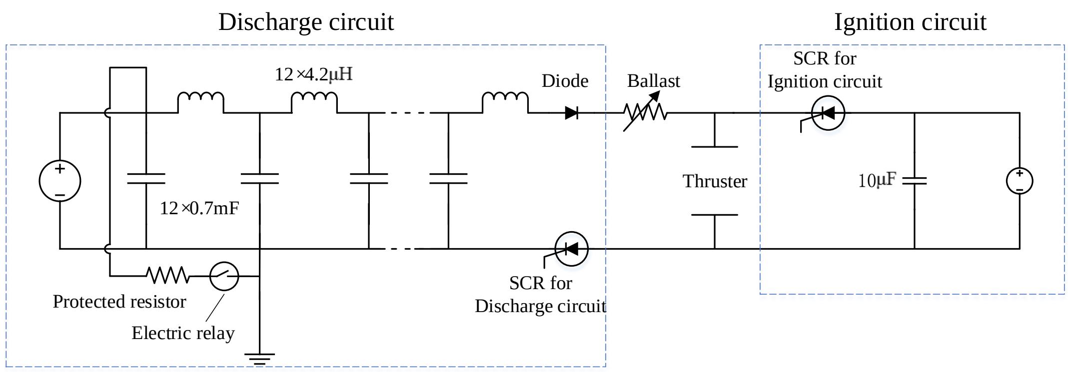


Figure 2. Schematic of the power supply

2 Results and Discussion

Figure 3 shows the discharge curves and discharge image of LA-MPDT. It can be seen from Figure 3 that the discharge voltage decreases from 300V to 50V when the discharge starts. The discharge current increases rapidly to the highest value of 3000A and then decreases to zero. It can be inferred from the variation of discharge voltage and current that the changing process of discharge arc is from weak to strong and then gradually extinguishing. At the beginning of discharge, the voltage between the electrodes is high, the discharge current is small, and the discharge arc is weak. Then more capacitive energy deposits in the discharge arc, the strength of discharge arc increases gradually, more neutral gases are ionized into plasmas, and the impedance of discharge arc decreases gradually. This represents the decrease of voltage and the increase of current in Figure 3. Afterwards, the plasmas eject from the thruster due to the acceleration with electromagnetic field. This results in the decrease of plasma density in the discharge area, the discharge arc gradually weakens, which represents the decrease of discharge current in Figure 3.

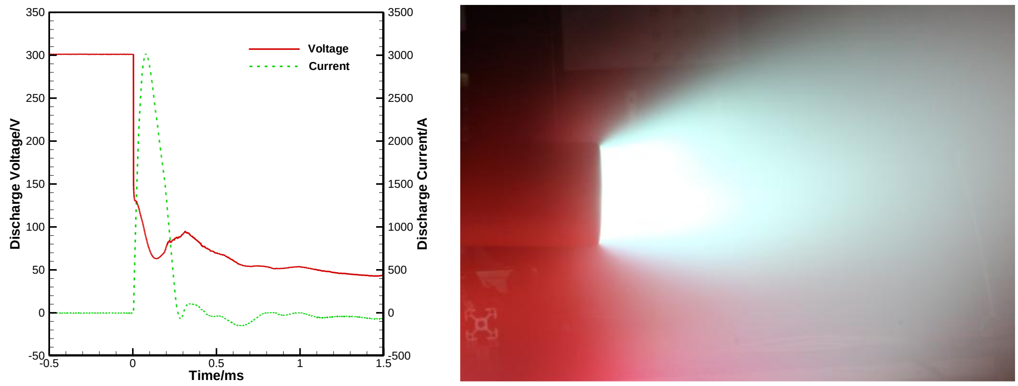


Figure 3. (a) Discharge waveforms and (b) Discharge image of LA-MPDT

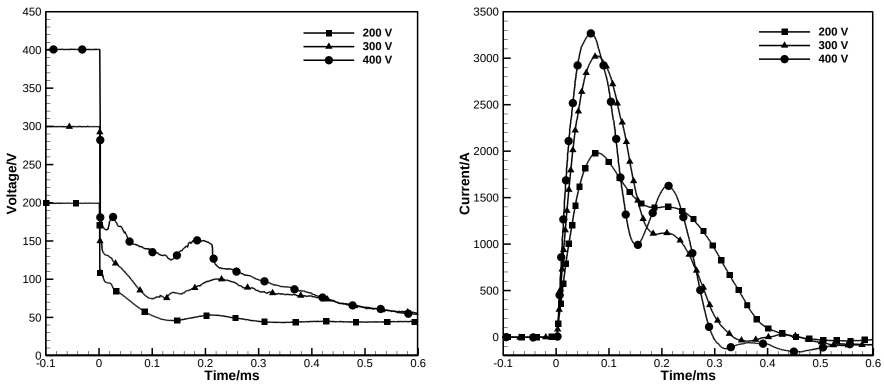


Figure 4. (a) Discharge voltages and (b) Discharge currents under different initial voltage conditions

According to the principle of capacitive energy storage, the discharge energy is proportional to the square of the initial voltage. Figure 4 shows the variations of discharge voltages and discharge current under different initial voltage. It can be known from Figure 4(a), the voltage between the electrodes decrease rapidly when the discharge starts, which means the energy deposition from capacitors to the discharge arc. But the energy stored in capacitors can not be completely deposited in the discharge arc, the discharge voltage decreases to a low value, and the lower the initial voltage the smaller the low value. We can seen from the Figure 4(b), there is oscillation in the discharge current curves. This is because of the dramatic changes of plasma during the discharge process. Otherwise, the discharge pulse width is almost independent with the initial voltage, and the values of peak discharge current increases with the increase of initial voltage.

The discharge energy is obtained by integrating the discharge voltage and current, meanwhile, the impulse bits of the thruster under different initial voltage conditions are experimentally measured, as shown in Figure 5(a). The ablation mass of solid propellant under different initial voltage conditions are also obtained by experiments. Then the specific impulse and thrust efficiency can be calculated, as shown in Figure 5(b). The discharge energy and impulse bit increase linearly with the initial voltage, and the specific impulse and thrust efficiency increase linearly with the discharge energy, which represents the thruster can obtain better performance under high power condition.

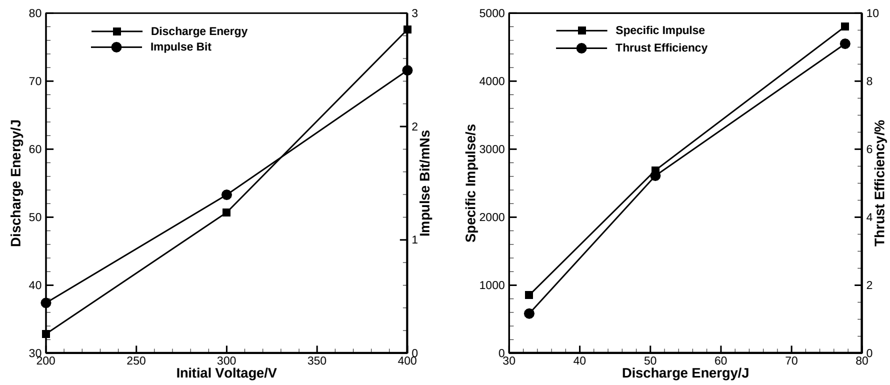
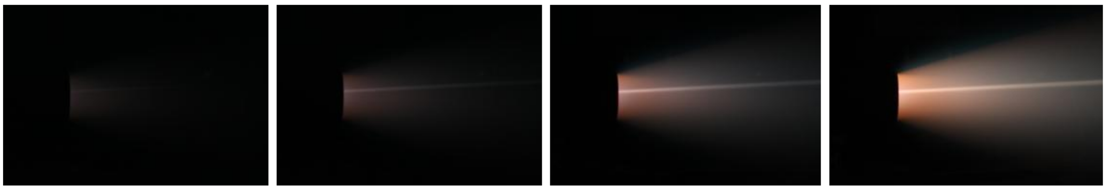


Figure 5. (a) Discharge energy and Impulse bit, (b) Specific impulse and Thrust efficiency under different initial voltage conditions



(a) 1 J (b) 2 J (c) 5 J (d) 10 J

Figure 6. Ablation images with different laser energy conditions

In order to study the effect of laser energy on propulsion performance of LA-MPDT, pure laser ablation experiments are carried out with laser energies of 1, 2, 5 and 10 J, respectively. Figure 6 shows the ablation images with different laser energy conditions. It can be obviously observed that with the increase of laser energy, the brightness of ablation plume increases, indicating the increase of plasma density. Figure 7 shows the variation of propulsion performance with laser energy without discharge. As the laser energy increasing, both the impulse bit and ablation mass increase, but the impulse bit is still small, as shown in Figure 7(a). When the laser energy is 10J, the impulse bit is about 0.7mNs, but the ablation mass reaches 1700μg at this time. This indicates that the impulse bit of laser ablation is produced by the ablation plume escaping from solid propellant. Because the velocity of ablation plume is relatively small, the specific impulse and thrust efficiency of laser ablating solid propellant is low, as shown in Figure 7(b).

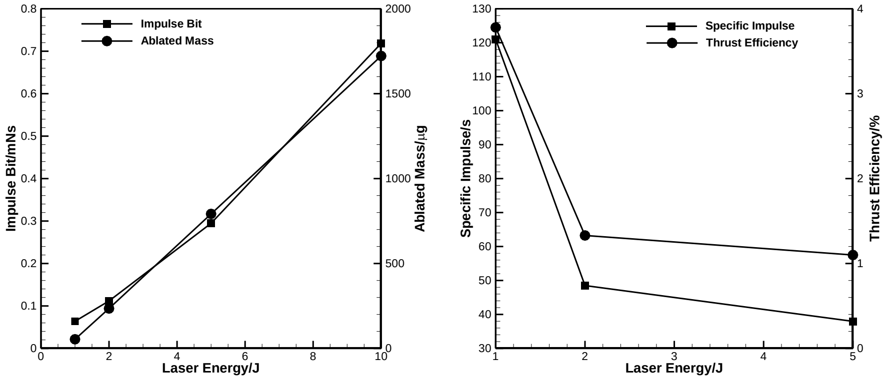


Figure 7. Variations of (a) Impulse bit and Ablation mass, (b) Specific impulse and Thrust efficiency with laser energy without discharge

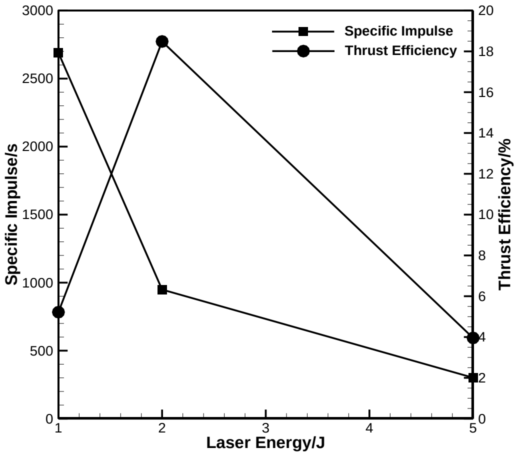


Figure 8. Variations of specific impulse and thrust efficiency with laser energy with the discharge energy of 50J

In addition, the effect of laser energy on propulsion performance with the discharge energy of 50J is studied experimentally, as shown in Figure 8. Because the solid propellant is placed inside the cathode, the ablation mass of solid propellant caused by discharge arc can be neglected, the ablation mass of solid propellant is only produced by laser irradiation. Hence the ablation mass is affected by laser parameters rather than discharge parameters. It can be concluded from Figure 8, the specific impulse decreases gradually with the increase of laser energy, due to the increase of ablation mass caused by the increase of laser energy. However, the thrust efficiency reaches the highest when the laser energy is 2J, which indicates that to improve the thrust efficiency, enough plasmas should be provided for electromagnetic acceleration. Compared with Figure 7 and Figure

8, the discharge has obvious effects on improving the propulsion performance of the thruster, and the thrust is mainly contributed by electromagnetic acceleration.

3 Conclusion

In summary, a novel laser ablation magnetoplasmadynamic thruster (LA-MPDT) is presented, and preliminary experiments on the discharge characteristics and thrust performance are conducted and analyzed. Following conclusions are achieved and summarized.

(1) The feasibility of LA-MPDT is verified by experiments. The physical process of discharge between the electrodes is obtained from the variation of discharge voltage and current.

(2) The effects of discharge energy and laser energy on the propulsion performance of thruster are experimentally studied. The specific impulse and thrust efficiency linearly increase with discharge energy, which indicates that the thruster can obtain better propulsion performance under high power condition. When the discharge energy is 78J, the specific impulse of LA-MPDT is 4800s, and the thrust efficiency is 9.1%. With the increase of laser energy, the specific impulse gradually decreases, but the thrust efficiency increases first and then decreases. When the laser energy is 2J, the thrust efficiency reaches 18.5%.

(3) Compared with the propulsion performance of thruster with and without discharge, the ablation mass of solid propellant is mainly caused by laser irradiation, and the thrust mainly contributed by electromagnetic acceleration.

Acknowledgments

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