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A novel laser ablation plasma thruster with electromagnetic acceleration

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ABSTRACT

A novel laser ablation plasma thruster accelerated by electromagnetic means was proposed and investigated. The discharge characteristics and thrust performance were tested with different charged energy, structural parameters and propellants. The thrust performance was proven to be improved by electromagnetic acceleration. In contrast with the pure laser propulsion mode, the thrust performance in electromagnetic acceleration modes was much better. The effects of electrodes distance and the off-axis distance between ceramic tube and cathode were tested, and it's found that there were optimal structural parameters for achieving optimal thrust performance. It's indicated that the impulse bit and specific impulse increased with increasing charged energy. In our experiments, the thrust performance of the thruster was optimal in large charged energy modes. With the charged energy 25 J and the use of metal aluminum, a maximal impulse bit of 600 μNs, a specific impulse of approximate 8000 s and thrust efficiency of about 90% were obtained. For the PTFE propellant, a maximal impulse bit of about 350 μNs, a specific impulse of about 2400 s, and thrust efficiency of about 16% were obtained. Besides, the metal aluminum was proven to be the better propellant than PTFE for the thruster.

1. Introduction

Because of the advantages of low-cost, low-mass, and high specific impulse, electric propulsion thrusters(EPTs) for spacecraft orbit correction and interplanetary spacecraft acceleration have recently become the front subject and focal point in space propulsion fields [1,2]. As a member of EPTs, pulsed plasma thruster(PPT) has a broad prospect on small satellites for its small, compact, and low mass [3–5]. PPT has been studied decades on its performance and lifetime, and has been successfully applied to a number of satellites [6–8]. However, the problem of low efficiency and ignition failure still restricts the development of PPT.

Professor A. Kantrowitz proposed the concept of laser propulsion for launching a payload into near-earth orbit early in the 1970s [9]. And the investigation of laser ablation typed thrusters made laser propulsion a potential method to produce thrust [10,11,11–15]. Recently, the laser-electric hybrid acceleration systems were proposed and investigated, considering the combination of laser propulsion and electric propulsion may produce a new method to improve the performance and system efficiency of thrusters. The basic idea is that the laser-ablation plasma induced by laser irradiation of a solid target is additionally accelerated by magnetic or electrical means [15]. In the early work of Choueiri et al. [16,17], they tested the gas-fed pulsed plasma thruster (GFPPT) and used an IR laser pulse to replace the plug and to ignite the thruster. However, the gas-tank and valves were needed by the thrusters with gas propellants. In addition, the ablation rates of propellants were mostly decided by the arc

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Nomenclature

A	coefficient in calibration procedure, Eq. (4).
A_0	coefficient in calibration procedure, Eq. (1).
B	coefficient in calibration procedure, Eq. (4).
B_0	coefficient in calibration procedure, Eq. (1).
$\boldsymbol{B}$	magnetic induction, T, Fig. 4.
d_1	distance between cathode and anode, mm
d_2	distance between cathode and the axis of ceramic tube, mm
E	electric field intensity, V/m
E_{charge}	charged energy of capacitors, J
$E_{kinetic}$	kinetic energy of plasma plume, J
E_{laser}	single pulse energy of laser, J
E_{total}	total energy imported by the thruster, J
f	focal length, mm
$\boldsymbol{F}$	Ampere force generated by magnetic field (vector), μN, Fig. 4.
F	Ampere force generated by magnetic field (scalar quantity), μN
I	current of calibration circuit, A
I_b	impulse bit of thruster, μN·s
m	mass ablated per shot, μg
S	voltage of PSD signal, V
t	duration of Ampere force, s
v	mean velocity of plume, m/s
V_0	charged voltage of capacitors, V
X	volts d.c. output of the function generator, V
η	thrust efficiency, %

discharge processes, and the “late ablation” phenomenon existed. Early in the year 2000, novel laser-assisted plasma thrusters were developed and tested, and from then on, a series of fundamental studies of laser-electric hybrid acceleration systems were conducted by Horisawa, Kawakami and Tomohisa et al. [18–34]. Wherein, the laser ablation plasma was enhanced and accelerated by the electromagnetic means. In addition to the electrical means of accelerating the plasma, the theory of magnetically guided laser ablation for high specific impulse thrusters was also proposed by Zaidi et al. [35].

Because laser-ablation plasma can have a directed initial velocity of tens of kilometers per second, which will be further accelerated by electrical means, a significant specific impulse can be expected [18]. However, several shortages were found in the laser-electric hybrid acceleration systems listed above. Firstly, the “late ablation” or “late-time vaporization” [23] of propellant in discharge may weaken the ionization of propellants and decrease the specific impulse or thrust efficiency. Secondly, considering the electrical insulation between the anode and cathode in almost all the conventional laser-electric hybrid acceleration systems, the propellants are limited to nonconductors, except that the cathode is used as propellant.

M.V.Silnikov described a novel charged plasma sources of EPTs in literature [1], which utilized the effects of “runaway” electrons and the formation of an electron beam in a nanosecond surface discharge plasma. The example of electrostatic EPT in literature [1] presented more optimal performance than current EPT prototypes, for the separation of production and acceleration of plasmas effectively overcame the shortage of “late ablation”. In this paper, a novel laser ablation plasma thruster with a ceramic tube is developed and investigated. This thruster is expected to overcome the shortages of conventional laser-electric hybrid acceleration systems in the above paragraph. And the ionization rate, specific impulse and thrust efficiency of the thruster are expected to be increased.

2. Laser ablation plasma thruster accelerated by electromagnetic field

Schematics of the laser ablation plasma thruster accelerated by electromagnetic field are illustrated in Fig. 1. A rectangular electrode configuration with four capacitors (capacitance: 3 μF per capacitor, peak charged voltage: 2000 V) and a ceramic nozzle (labeled a ceramic tube in Figs. 1 and 2, material: BN, inside diameter: 6 mm, length: 30 mm) is used. The electrodes are made of two parallel plates of non-oxide copper with an inter-electrode space (labeled as d_1 in Fig. 2) of 20–40 mm, length of 35 mm, width of 15 mm, and thickness of 3 mm. The distance between the anode and the axis of ceramic tube is labeled as d_2 in Fig. 2. The propellant is placed inside the ceramic tube. Because of the unique structure of this thruster, almost all types of solid matter can be applied as the propellant, such as metals, polymers and so on. The propellants metal aluminum and Polytetrafluoroethylene (PTFE) were tested in the experiments.

The working processes of the thruster can be divided into two stages: laser-induced ablation of propellant and plasma-induced discharge. In the first stage, the solid propellant placed inside the ceramic tube is irradiated by a laser beam, decomposed into gas or solid particles, and injected into a vacuum between electrodes. In the second stage, the effluent matter induces discharge arcs across the pair of electrodes. In the second stage, the plasma is enhanced by the electric discharge. 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 larger particles may be broken into smaller pieces by particle collision processes and chemical reactions. The ionization of effluent matter may be enhanced by the arc discharge process, i.e., a high specific impulse may be obtained by the thruster. The sequent two stages of the working processes of the thruster are isolated spatially by the ceramic tube and the insulator, as shown in Fig. 1. The mass consumed per shot in the working processes equals approximately the mass