Performance Study of Pulsed Plasma Thruster Using a New Kind of Electrode

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Abstract: To solve the problem of PPT's low efficiency, a new kind of electrode with microcrystal mica ceramic nozzles was designed. An experimental table was established to measure the operation parameters and the thrust of PPT. In order to investigate the effect of new electrodes, a series of experiments were conducted. The numerical simulation of the acceleration of neutral gas was also performed using commercial CFD software. The exhaust velocity change of neutral gas before and after using the new electrodes was obtained. The simulation results showed that the new electrodes can obviously enhance the acceleration of the neutral gas. As a result, the impulse bit and efficiency of PPT was also improved.

Nomenclature

F_{EM}	=	electromagnetic force
F_{ET}	=	aerodynamic force
f	=	pulsed frequency
μ_0	=	magnetic permeability of vacuum
t	=	discharge duration
h	=	gap of electrodes
w	=	width of electrodes
i	=	discharge current
Q_0	=	discharge caloric
r_{PTFE}	=	latent heat of vaporization
P, V, T	=	pressure, volume and temperature of neutral gas
R_g	=	gas constant
P^*, T^*	=	stagnation pressure and stagnation temperature

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C_p	=	Specific heat
γ	=	adiabatic exponent
v^*	=	stagnation specific volume
P_{out}	=	back pressure at outlet
E	=	discharge energy
m_s	=	propellant mass loss
I_{bit}	=	impulse bit
η	=	efficiency of thruster

I. Introduction

Pulsed plasma thruster (PPT) is a space propulsion approach using electromagnetic acceleration of plasma by a pulsed discharge (Ref. 1). Without moving parts, as well as distribute or toxic propellant systems, this new kind of electric thruster draws wide attention for its high stability, high reliability, small thrust level, high specific impulse, low power level and compact structure. PPT is one of the most promising propulsion devices for station-keeping, attitude control and orbit maintenance, precision positioning of small spacecrafts. As shown in Fig.1, a PPT system consists of a pair of rectangular electrodes, between which a bar of solid propellant is fed. Fluorocarbon polymer (PTFE) is the most typically employed solid propellant. The discharge energy is stored in a high-voltage capacitor, which is connected to the electrodes. Discharges are initiated by a spark plug located on the cathode. As discharges occur, the solid propellant is ablated and gasified with a high discharge temperature. A small amount of neutral gas particles are thus ionized, and then accelerated via the Lorenz force. The rest of the neutral gas particles are accelerated by the aerodynamic force. Due to the exhaust of the high-velocity ions and neutral particles, the thrust is generated along with continuous pulses. Compared with other electric propulsion systems, the main disadvantage of a PPT is its relatively low efficiency. The efficiency of a typical PPT is usually less than 10%, and the exhaust velocity is lower than 10km/s. By contrast, the efficiencies of other plasma propulsion systems are about 50% and the exhaust velocities are nearly 20–30km/s (Ref. 2). Great efforts have been made to improve the efficiency and thrust performance of PPTs. Kamhawi theoretically analyzed the acceleration process of a PPT using MACH2 magneto hydrodynamic computer code (Ref. 8). Gorshkov and Popov successfully improved the efficiency of a PPT by optimizing the parameters of discharge circuits (Ref. 3 and Ref. 9). Spanjers and McFall pointed out that the low performance is caused by low propellant utilization. The polymer propellant continues to be ablated even after the termination of discharge, which is known as late-time ablation (Ref. 10). The late-time ablation creates a large number of neutral gas particles with low velocities. This paper describes a new approach to enhance the acceleration process of neutral gas, and to improve the efficiency and thrust performance of a PPT.

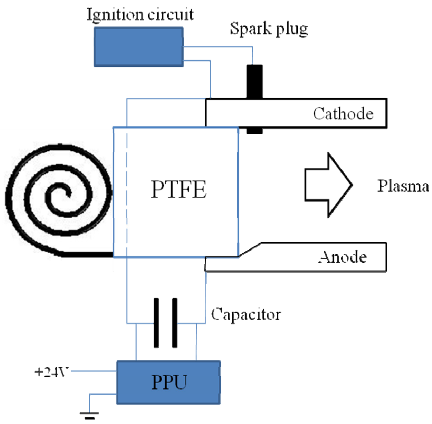


Figure 1. Basic schematic of PPT

II. Acceleration principle of pulsed plasma thruster

The acceleration principle of a PPT is consists of two parts, electromagnetic pressure acceleration and aerodynamic pressure acceleration (Ref. 11), which are imposed on high-velocity ions and slow neutral gas particles respectively. Compared with high-velocity ions, the neutral gas particles have a lower speed due to a higher mass. This is considered as the main reason of the low propellant utilization in PPTs. Fig2 depicts the whole acceleration process of high-velocity ions and neutral particles in a pulsed duration. Right upon the spark plug initiates, the fluorocarbon polymer (PTFE) is ablated and gasified, and then a small quantity of neutral gas is generated. According to the principle of diffusion, the gas pressure near the propellant surface is much higher than that in the downstream. As shown in Fig 2(a), the gas pressure at P1 is higher than that at P2. According to the Paschen's law, there is a minimum breakdown voltage of parallel plates in a gas, which can be described by a function of pressure and gap distance (Ref. 4). When the gap between the two electrodes is fixed, the electric breakdown voltage is mainly determined by the gas pressure between the electrodes. It is known that the electric breakdown is easier to occur in an area with a lower pressure. Due to the relatively higher pressure on the surface of PTFE, electric breakdowns generally take place at a region which is a certain distance from the surface of PTFE. Driven by the electric field force, a few electrons generated by the spark plug travelled along the electric field lines, which are vertical to the electrodes. These electrons are accelerated to a high speed and ejected into the neutral gas. Thus, a series of high-speed collisions occur, which causes an avalanche excitation as shown in Fig2 (b). These collisions result in the ionization of neutral gas, and more and more electrons and ions are generated in this process. Meanwhile, the electrons and ions also have a recombination effect. While the ionization and recombination effects achieved a dynamic equilibrium, a uniform current channel (current sheet) is formed across the cathode and the anode as shown in Fig 2(c). Generally, the current sheet accelerates to the downstream under the influence of the magnetic force. The electrons and ions between the electrodes are also accelerated in this process. Pulled back by the electromagnetic force, the ions and electrons after ionization travel a finite distance through the current sheet (Ref. 7). Due to the positive work done by the electric field force, the ions and electrons are accelerated obviously through the current sheet. After the speed reaches a certain level, the ions and electrons are reflected back by a strong electromagnetic repulsion force and ejected from the PPT as shown in Fig 2 (d).

On one hand, due to the low exhaust speed, the neutral gas stays near the PTFE surface during the discharge. On the other hand, the ions and electrons are quickly accelerated, leaving the neutral gas particles behind. Only a fraction of the neutral gas ablated by discharges participates in the ionization process and makes contribution to the electromagnetic acceleration (Ref. 2). Most of the neutral gas particles exhaust in a low speed. Furthermore, the current sheet makes the temperature of the PTFE surface rise much higher than needed, and gasifies and releases more neutral gas particles after the electromagnetic acceleration. This process is called the late-time ablation. These neutral gas particles have a larger weight but a lower speed, which is the main reason for low propellant utilization, as well as the low efficiency.

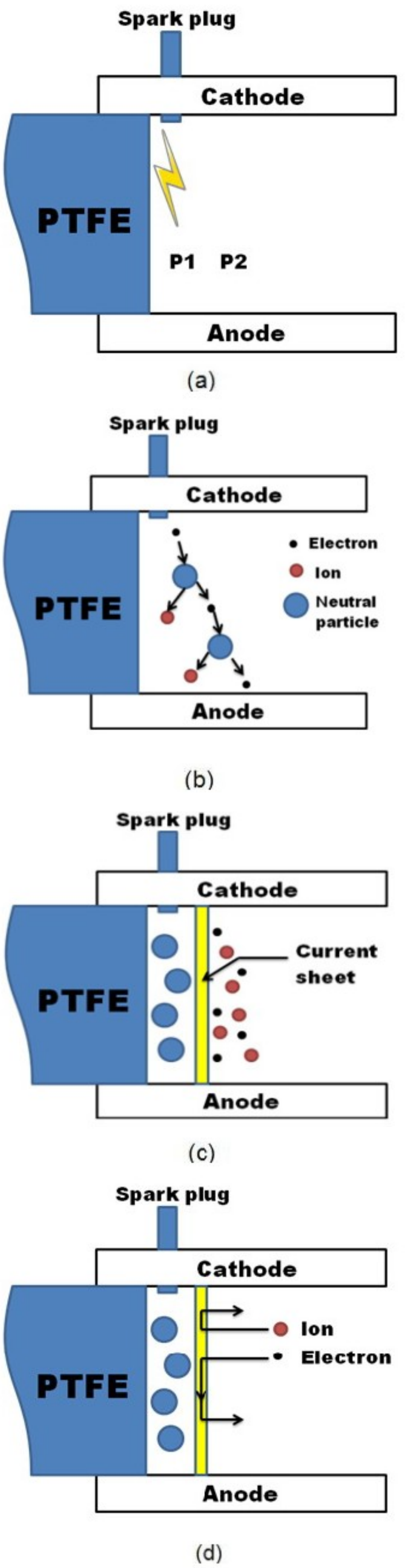


Figure 2. Acceleration processes of charged particles

III. The new ceramic nozzles and experiments

In order to increase the exhaust velocity of the neutral gas generated by the late-time ablation, Hou Dali from SJTU (Ref. 5) developed a new PPT electrode with ceramic nozzles as shown in Fig 3. Two wedge-shaped nozzles were installed on the electrodes. Considering the requirements for thermal isolation, mica ceramic was used as the nozzle material.

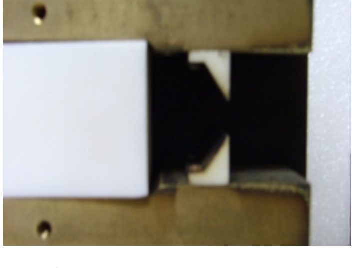


Figure 3. New electrodes with ceramic nozzles

To investigate the effect of new ceramic nozzles on the exhaust velocity of neutral gas as well as the efficiency and thrust of a PPT, an experimental system was established (Ref. 5). Several operational parameters of the PPT, including the discharge current, total thrust and efficiency, were tested on the system to compare the performance of two types of electrodes (with and without ceramic nozzles). The PPT consists of a pair of rectangular electrodes, a 10μF capacitor, a spark plug and a PTFE solid propellant rod. The electrodes were made of two parallel brass plates with an inter-electrode space of 50mm, a length of 40mm, and a width of 25mm. The voltage applied to the capacitor was adjustable and the maximum value was 2000V (energy stored in the capacitor was 20J). Rogowski coil was used here to test the discharge current. A target-type thrust stand was employed to measure the magnitude of the impulse bit, which consists of a target and an electric eddy current sensor. The displacement of the target is measured by the electric eddy current sensor. The vacuum chamber is evacuated to a pressure of 4×10^{-5} Torr by a mechanical pump and a turbo molecular pump. The schematic diagram of this experimental system is shown in Fig 4. A series of tests under various discharge energy levels, ranging from 4J to 20J, were conducted, and the thrust and efficiency of the PPT under each operation condition were also calculated.

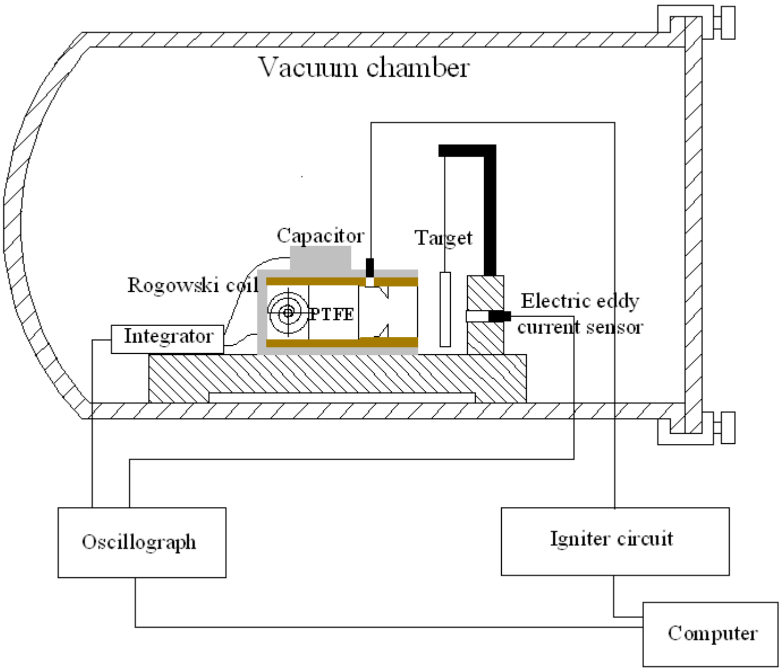


Figure 4. Schematic diagram of the experimental system

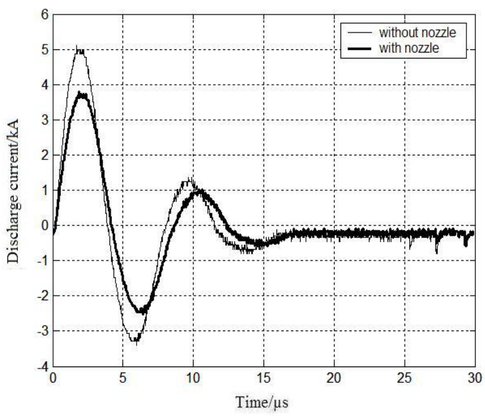


Figure 5. The variation of discharge current with and without nozzle (5J)

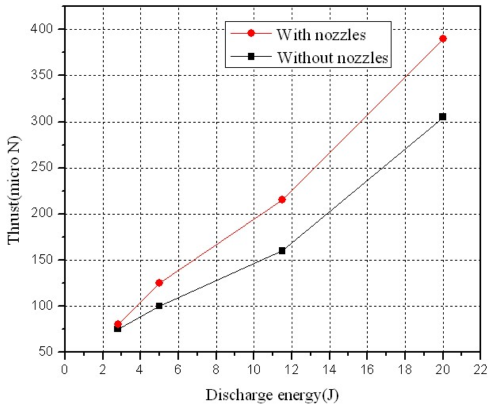


Figure 6. Profile of the thrust in different energy level

The experiment results showed that the ceramic nozzles decreased the discharge current in each capacitor energy level. The profile of the discharge current with capacitor energy of 5J was illustrated in Fig 5. Since the ceramic nozzles are electric insulating, interference occurs between the current sheet and the ceramic nozzles, as the current sheet moving to the outlet in the discharge duration. This process increases the electrical resistance of the main discharge circuit, and results in a decrease in the discharge current. However, after installing the ceramic nozzles on the electrodes, the total thrust measured by the experiment system is increased in each discharge energy level. The thrust comparison before and after using the ceramic nozzles are shown in Fig 6.

IV. Numerical simulation and discussion

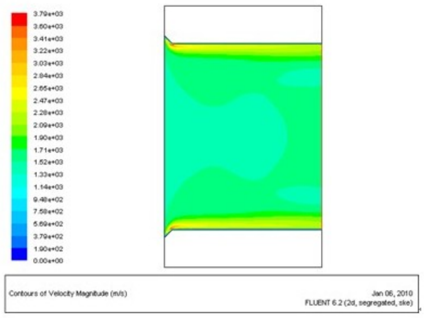
Since the acceleration process of a PPT is consists of the electromagnetic pressure acceleration and the aerodynamic pressure acceleration, the total thrust of PPT is given by

$$T_{total} = F_{EM} + F_{ET} \quad (1)$$

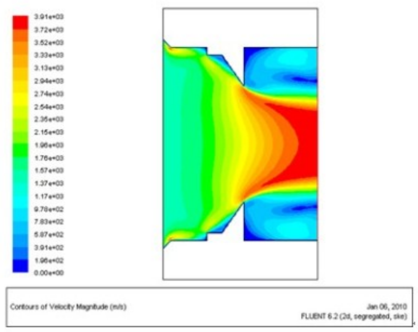
The thrust F_{EM} generated by the electromagnetic force is given by

$$F_{\mathrm{EM}} = f\frac{\mu_0}{2}\frac{h}{w}\int_0^t i^2 \mathrm{d}t \quad (2)$$

As shown in Eq. (2), the thrust generated by the electromagnetic force is directly related to the discharge current i (Ref. 11). As a result, the decrease in the discharge current by installing ceramic nozzles will reduce the electromagnetic force. However, as shown in Fig 6, the total thrust is increased in each discharge level after installing the ceramic nozzles. To explain the experimental results, numerical simulation was conducted to investigate the flowing condition of neutral gas between the electrodes using commercial CFD software FLUENT. The length and width of the electrodes in the geometry model were 40mm and 25mm respectively, and the electrode gap was set at 50mm. The height and width of the wedge-shaped nozzle were 10mm and 6mm respectively. FLUENT's coupled implicit solver was adopted in this numerical simulation. Steady-state solution and k-epsilon model were both selected to simplify the flow condition of the neutral gas generated by the late-time ablation. The neutral gas in the flow field was considered as an ideal gas. The inlet condition was set according to the experimental results reported by Erik Antonsen (Ref. 6). The gas pressure on the surface of PTFE was set at 100Torr, and the temperature was 800K. The initial velocity of the neutral gas was 1.5km/h. To be consistent with the environment of the vacuum chamber，the outlet pressure of the flow field was set to be 3×10^{-5}Tor, and the temperature was 293K.



(a) PPT without nozzle



(b) PPT with nozzle

Figure 7. The velocity distribution of neutral gas

The velocity field of the neutral gas before and after the installation of the mica ceramic nozzles was presented in Fig 7. In Fig 7 (a), due to the rectangular and inerratic flow channel between the electrodes of the PPT, the neutral gas was flowing at a low velocity, which caused the reduction in the thrust level and efficiency. In Fig 7 (b), the flow channel was changed by installing the nozzles. During the process of aerodynamic acceleration, the exhaust velocity of the neutral gas was obviously increased. The comparison of the exhaust velocity at the outlet of PPT was illustrated in Fig 8. The simulation results showed that the exhaust velocity of the neutral gas before and after using the ceramic nozzle was 1.7km/s and 3.9km/s respectively. The increase in exhaust velocity is able to provide a higher thrust and an improvement of efficiency. The pressure on the surface of PTFE after using the ceramic nozzles was also increased, which was shown in Fig 9.

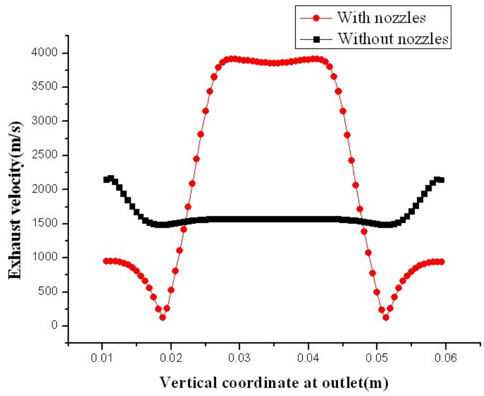


Figure 8. The comparison of the velocity on outlet

The simulation results showed that the ceramic nozzles made a large contribution to the aerodynamic acceleration of the neutral gas. While the PPT worked at a stationary discharge energy level, the caloric generated by the spark plug and the current sheet was a fixed value. The mass of the neutral gas generated during the discharge and late-time ablation is given by

$$m = \frac{Q_0}{r_{PTFE}} \tag{3}$$

Therefore the mass of neutral gas generated from the surface of PTFE is mainly determined by the discharge energy. According to the state equation of ideal gas, the relationship between the pressure and volume of the neutral gas is given by

$$PV = mR_g T \tag{4}$$

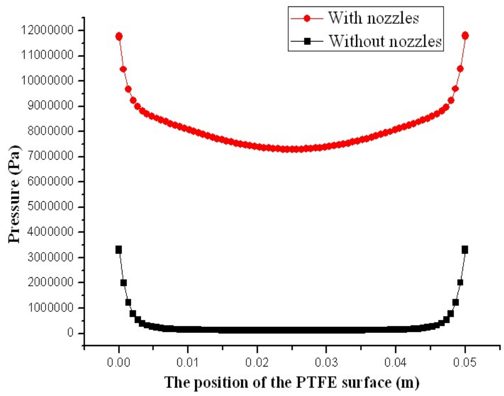


Figure 9. The comparison of pressure on the surface of PTFE

When the temperature and mass of the neutral gas between the electrodes is constant, the pressure is inversely proportional to the volume between the electrodes of PPT. The ceramic nozzles reduce the space surrounded by the electrodes and the surface of PTFE, which is equivalent to compress the neutral gas generated by discharge and late-time ablation between the electrodes. As a result, the ceramic nozzles can increase the pressure of the neutral gas on the surface of PTFE to a certain extent. Because the heat transfer between the neutral gas and the inner wall of a PPT is negligibly small, the whole aerodynamic acceleration process of the neutral gas can be regard as a constant entropy process. Generally, the aerodynamic acceleration of the neutral gas is simplified as a process initiated from a stationary state. The relationship between stagnation parameters and initial flowing parameters is given by

$$T^* = T + \frac{V_{in}^2}{c_p} \tag{5}$$

$$p^* = p\left(\frac{T^*}{T}\right)^{\frac{\gamma}{\gamma-1}} \tag{6}$$

And the exhaust velocity at the outlet of constant entropy acceleration process is given by

$$V_{out} = \sqrt{2\frac{\gamma}{\gamma-1}p^*v^*\left[1-\left(\frac{p_{out}}{p^*}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{7}$$

Eq. (6) and Eq. (7) indicate that the exhaust velocity at the outlet is directly related to P, the pressure on the surface of PTFE. Thus the ceramic nozzles can obviously enhance the exhaust velocity of neutral gas by increasing the pressure on the surface of PTFE. During the aerodynamic pressure acceleration process, the aerodynamic force F_{ET} is directly proportional to the exhaust velocity of neutral gas and the propellant mass loss of each pulse. Therefore, the exhaust velocity of neutral gas increasing obviously increases the aerodynamic force F_{ET}.Comparing with ions and electrons generated by the discharge, the neutral gas particles have larger mass but a lower speed. As mentioned before, the total thrust of a PPT consists of two parts, electromagnetic force and aerodynamic force. Although the electromagnetic force is reduced to a certain extent, the effective acceleration of neutral gas particles supplies a higher aerodynamic force. Therefore the total thrust was still increased in each discharge energy level. The efficiency of PPT is calculated by

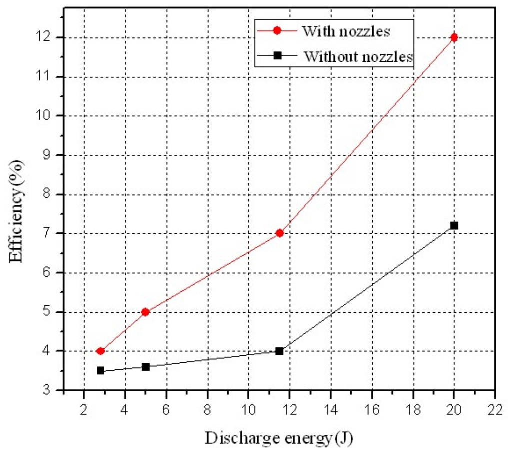


Figure 10. The profile of PPT efficiency in different energy level

$$I_{bit} = m_s V_{out} \tag{8}$$

$$\eta = \frac{w}{E} = \frac{I_{bit}^2}{2m_s E} \tag{9}$$

As shown in Eq. (8) and Eq. (9), the impulse bit I_{bit} increases with the increase of exhaust velocity, and the efficiency is directly proportional to the square of the impulse bit. Therefore, the new mica ceramic nozzles not only enhance the exhaust velocity of neutral gas generated by discharge and late-time ablation, but also significantly increase the impulse bit and the efficiency of PPT. The efficiency comparison before and after using the ceramic nozzles is shown in Fig 10.

V. Conclusion

A new kind of electrode with mica ceramic nozzles was used in a PPT prototype to improve the propellant utilization, thrust and the efficiency of the PPT. A series of experiments and numerical simulation were conducted on the prototype. The simulation and experimental results showed that the ceramic nozzles can obviously enhance the exhaust velocity of neutral gas. Although the electromagnetic force is reduced to a certain extent, the effective acceleration of neutral gas particles increase the total thrust, as well as the efficiency of PPT.

Acknowledgments

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