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Effect of ceramic nozzle on performance of pulsed plasma thruster

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Abstract

Pulsed plasma thruster (PPT) is one of the most promising electric propulsions system. Its main drawback is the low thrust efficiency. A theoretical analysis is given in this paper for exploring the reasons. The low electrothermal acceleration efficiency is concluded as an important factor. For improving the electrothermal acceleration, a new electrode structure associated with a nozzle was designed and adopted. The experimental result shows that the new electrode impaired the electromagnetic acceleration slightly. But the overall thrust was improved significantly. It means that the electrothermal acceleration was enhanced distinctly. The thrust efficiency was also improved remarkably. The simple electrode structure with a nozzle implicates an efficient way to improve the performance of PPT.

Keywords: Pulsed plasma thruster (PPT); Nozzle; Impulse bit; Specific impulse; Thrust efficiency

1. Introduction

Pulsed plasma thruster (PPT) is an electric propulsion device which uses electric power to ionize and electromagnetically accelerate plasma to high exhaust velocities, attaining a high specific impulse. It is one of the most promising propulsion devices for station-keeping, attitude control and orbit raising of small spacecraft, since it is compact and light among electric propulsion systems [4]. However, the low thrust efficiency limited its use in some conditions. For examples, the thrust efficiencies for typical PPTs such as LES8/9 and EO-1 are 7% and 8% respectively. The efficiency of PPT reported in near years is rarely exceeding 10%. The crucial difficulty in PPT modeling is lacking of theoretically thorough understanding of the process of energy transfer from discharge to solid propellants and mass ablation. The electromagnetic and thermal phenomena involved in propellants acceleration are very complicated. There is still no ideal physical model to accurately predict the behavior of the thruster. This paper proposes a new approach for improving the acceleration effect.

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2. Fundamentals

The PPT systems are completely self-contained propulsion modules. Generally, it includes a power source, a power processing unit (PPU), an energy storage unit, and the thruster itself. Solar cells are generally used as power sources, since the thruster operates at a low power level. The main functions of the PPU are to provide the charging voltage for the energy storage unit and to provide the command and telemetry functions required to operate the PPT. The energy storage unit provides high-current pulses through the thruster to perform work. Capacitor is often used as an energy storage unit. Thruster typically consists of two electrodes, the propellant, a negater spring and a spark plug. The configuration of PPT is illustrated as in Fig. 1.

At the beginning of PPT operation, the capacitor is charged to the desired voltage. The spark plug is ignited to trigger the discharge. The energy stored in the capacitor powers a high current duration plasma discharge and produces an electromagnetic field. Then the molecules of propellant are ionized. Due to the actions of $\vec{J} \times \vec{B}$ electromagnetic Lorentz force and gas-expanding force, the plasma is accelerated to high exhaust velocities and thrust is generated.

Generally, there are two types of acceleration mechanisms employed in PPT which are electromagnetic acceleration and

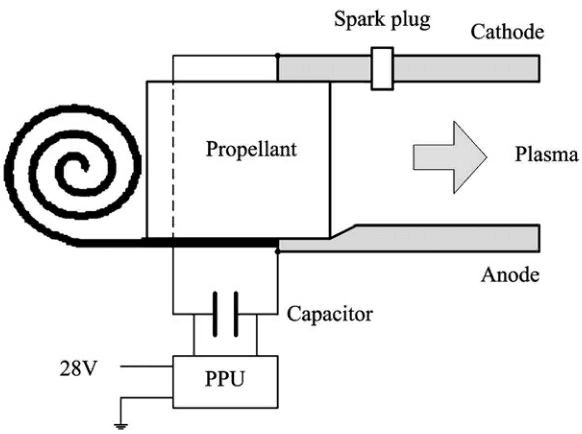


Fig. 1. Basic schematic of PPT.

electrothermal acceleration [6]. In the electrothermal acceleration stage, the thrust is produced by gas expansion which is caused by discharge. In the electromagnetic acceleration stage, a thrust is produced by accelerating ionized particles in the electric field and the self-induced magnetic field.

The thrust of PPT is defined as [3]

$$F = F_{\mathrm{EM}} + F_{\mathrm{ET}} \tag{1}$$

F_{EM} is the electromagnetic force and F_{ET} is the thrust contributed by the gas dynamic expansion, i.e. the electrothermal force. $F_{\mathrm{EM}}$is expressed by

$$F_{\mathrm{EM}} = f\frac{\mu_0}{2}\frac{h}{w}\int_0^t i^2\,\mathrm{d}t \tag{2}$$

where f is the pulse frequency, and i is the total current calculated by RLC circuit analysis. μ_0 is the magnetic permeability. h is the gap between the electrodes. w is the width of the electrodes and l is the length of the electrodes.

F_{ET} is given by

$$F_{\mathrm{ET}} = f\left[\frac{8(\gamma-1)}{\gamma^2(\gamma+1)}\cdot m\cdot E\right]^{\frac{1}{2}} \tag{3}$$

where m is the mass loss per impulse and γ is a constant decided by the propellant materials. For teflon, $\gamma = 1.3$. E is the total energy of PPT per discharge.

To achieve the best PPT performance, it's necessary to improve the electromagnetic force and the gas-expanding force.

Based on preceding study, the main reasons of low thrust efficiency are as follows. Firstly, PPT is inefficient when transfer of stored capacitor energy into acceleration of the ionized propellant. Secondly, mass utilization efficiency in PPT is low ($<50\%$) because of two performance robbing processes – late-time vaporization [7] and macro particles ejection. Many propellant particles wasted in the form of propellant vapor and large chunks. Generally, the thrusters have very low efficiency due to a combination of poor energy coupling into the propellant, late-time ablation, and inefficient acceleration [2].

The low electrothermal acceleration efficiency has concluded to be a major cause of the low thrust efficiency, since the slower neutral gas and macro particles can only be accelerated by electrothermal process. The electrothermal acceleration occurs near the propellant surface where the discharge happens. Once the plasma forms, the electrodes become conductive and main discharge occurs. The discharge ablates the propellant and produces more particles, which makes the pressure near the propellant surface increase greatly. A part of the power transfers into thermal energy and increases the temperature of plasma. This makes pressure of the PPT chamber increase rapidly. Then particles are accelerated by the high pressure in the chamber of the PPT. Late-time vaporization and macro particles ejection happens in this stage. Macro particles, mainly comprised by neutrals, only a part of them are accelerated by electrothermal acceleration because of uncharged. For the LES-6 PPT, it was estimated that more than 90% of exhaust was comprised of neutrals [9]. Thus, ameliorating the electrothermal acceleration will improve the thrust efficiency. The relation of the pressure, volume and temperature of plasma in this chamber is described by Clapeyron equation

$$PV = nR_0T \tag{4}$$

where P represents the pressure of plasma, V is the volume of PPT chamber, T is the temperature of plasma, n is the quantity of mole and R_0 is a constant expressed by

$$R_0 = 8.314\ \mathrm{J/mol\cdot K} \tag{5}$$

Up to 70% of propellant can reach acceleration channel of the thruster after the main discharge finish or at the moment of considerable discharge current drop [5]. In order to make more particles reach the acceleration channel, the pressure of plasma should be increased and reducing the volume of PPT chamber is an effective way from Eq. (4).

In general, parallel plate electrodes are suitable to electromagnetic acceleration and coaxial electrodes are suitable to electrothermal acceleration in PPTs. The electrothermal acceleration of parallel rail PPT is inefficient. In order to get high efficient PPT which combining the advantages of parallel plate electrodes and coaxial electrodes, a ceramic nozzle was designed to improve the electrothermal acceleration in this investigation.

3. Experimental system

To establish a foundation for the research, a parallel rail thruster was designed and fabricated. The PPT is flexible design which allows easy exchange of components for parametric study. The electrode gap, energy storage and discharge frequency can be adjusted easily. Energy storage is provided by a 10 μF capacitor. The discharge energy can be changed from 0 to 20 J by regulating the discharge voltage from 0 to 2000 V. The electrode length is 40 mm and the electrode width is 25 mm. The electrode gap can be changed from 30 to 50 mm. Fuel bars of fluorocarbon propellant are fed between the electrode pairs by springs held in position by retaining shoulders built into the electrodes. The fuel bars are removable so that they can be weighed to determine mass loss. The vacuum chamber is

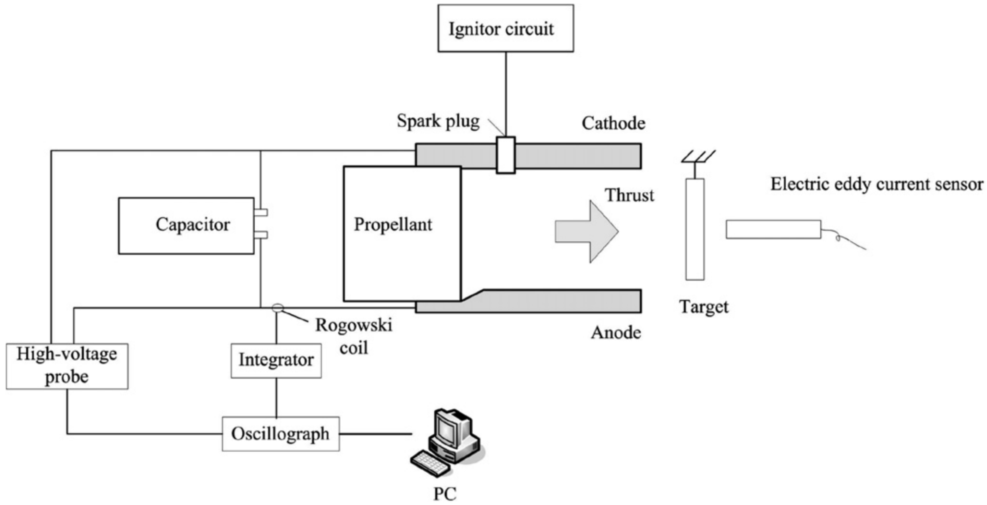


Fig. 2. The experimental system.

evacuated to a pressure of 4×10^{-5} Torr by a mechanical pump and a turbo molecular pump.

The experimental setup and facilities are described in Fig. 2.

To measure the discharge current, the Rogowski coil designed by Power Electronic Measurements Ltd in UK was used. Its output sensitivity is 0.2 mV/A with a maximum current rating of 30 kA. The P5100 100 × voltage probe was used to measure the capacitor voltage. A target-type thrust stand was used to measure the magnitude of impulse bit. It consists of a target and an electric eddy current sensor. When PPT runs, thrust is produced and pushes the target. The displacement of target is measured by the electric eddy current sensor. The relation between the impact force on the target and displacement is expressed by

$$P_{\text{impact}} = \frac{4m\pi^2}{T_{\text{cycle}}^2} a \tag{6}$$

where P_{impact} represents the impact force on the target, m is the mass of target, T_{cycle} is the period of target, a is the displacement of target. Based on dynamics of gas jets, impact force of jet is defined by this equation

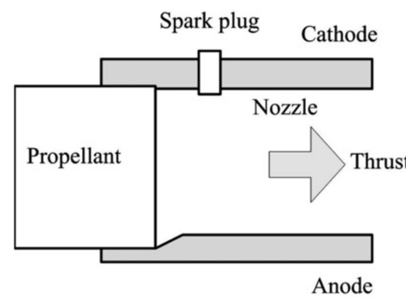
$$P_{\text{impact}} = F \cdot \left(\sin\beta + 0.0225 \frac{1}{\sin\beta}\right) \tag{7}$$

where F is the thrust of PPT, β is the angle that the force impacts on target. From Eqs. (6) and (7), the thrust is given by

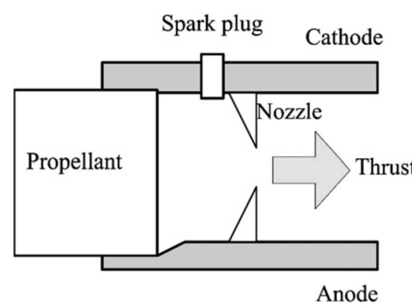
$$F = \frac{4m\pi^2}{(\sin\beta + 0.0225\frac{1}{\sin\beta})T_{\text{cycle}}^2} a \tag{8}$$

Thrust is determined as a function of displacement, period, mass of target and the impact angle. The maximal error of this thrust measurement is the energy loss when the target is impacted. When processing the experimental data, the error is considered. Some ways such as designing new type target and data processing method were adopted to reduce errors. The thrust stand has been calibrated. Experiments showed that the results were reliable.

The electrode with ceramic nozzle is described in Fig. 3(b). The nozzle should be insulated; otherwise discharge will happen between the two nozzles wedges. The nozzles should also be thermal isolated since the high temperature during the discharge. It should keep working in bad thermal environments. Considering of all the facts, ceramics is the best choice for producing the nozzles. In order to ensuring the effects of electromagnetic acceleration, the nozzle should be as narrow as possible. The height and width of the triangular nozzle are 10 mm and 6 mm. The distance between the nozzle and the spark plug is 5 mm.



(a) Without nozzle

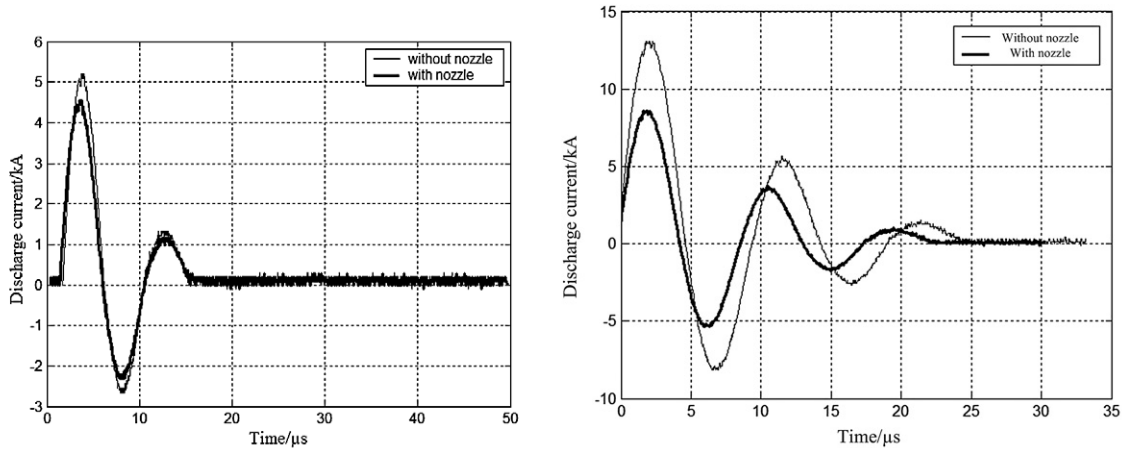


(b) With nozzle

Fig. 3. Structures of electrode.

4. Experiments result and analysis

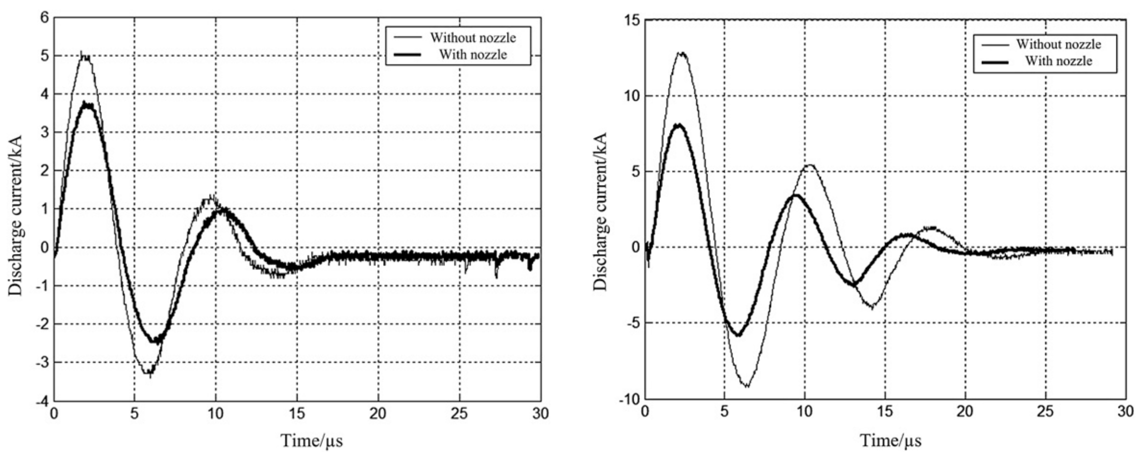
The experimental results and comparisons between the two kinds of electrode structural designs are shown as follows. Figs. 4, 5 present the discharge current waveforms for different structural design.



(a) discharge energy = 5 J

(b) discharge energy = 20 J

Fig. 4. Comparison of discharge current with different electrode structures (electrode gap = 50 mm).



(a) discharge energy = 5 J

(b) discharge energy = 20 J

Fig. 5. Comparison of discharge current with different electrode structural design (electrode gap = 30 mm).

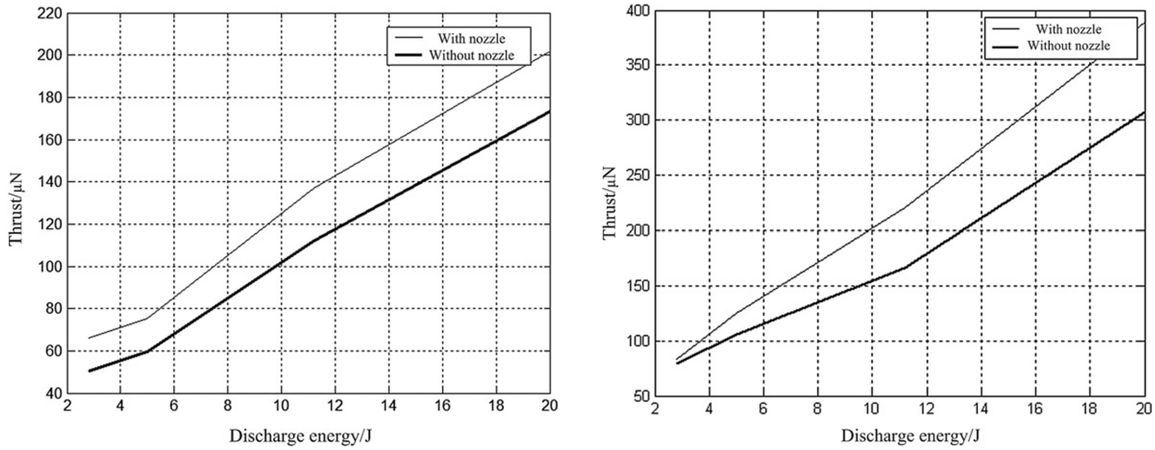
In Fig. 4, when the electrode gap was 50 mm, the discharge current peak values of PPT with ceramic nozzle were less than the PPT without ceramic nozzle. When discharge energy was selected to be 5 J and 20 J respectively, the peak current dropped from 5.2 kA and 13.1 kA to 4.6 kA and 8.6 kA after applying the ceramic nozzle.

In Fig. 5, the electrode gap was configured to be 30 mm. Similar to the above mentioned example, when discharge energy was set to be 5 J and 20 J respectively, the discharge current peak values dropped from 5.1 kA and 12.7 kA to 3.8 kA and 8.0 kA after applying the ceramic nozzle. The discharge current is related to the electromagnetic force. From Eq. (2), the thrust changes with the discharge current. The ceramic nozzle impaired the electromagnetic acceleration slightly for the reason that the ceramic nozzle narrows the discharge chamber partly which induces the decrease of electromagnetic force.

Comparisons of thrust are indicated in Fig. 6. The thrust scales roughly linearly with energy. After applying the ceramic nozzle, the thrust increased greatly significantly. Based on preceding analysis, the electromagnetic thrust decreased due to the reduction of discharge current. The thrust increase owning to the elevated electrothermal acceleration.

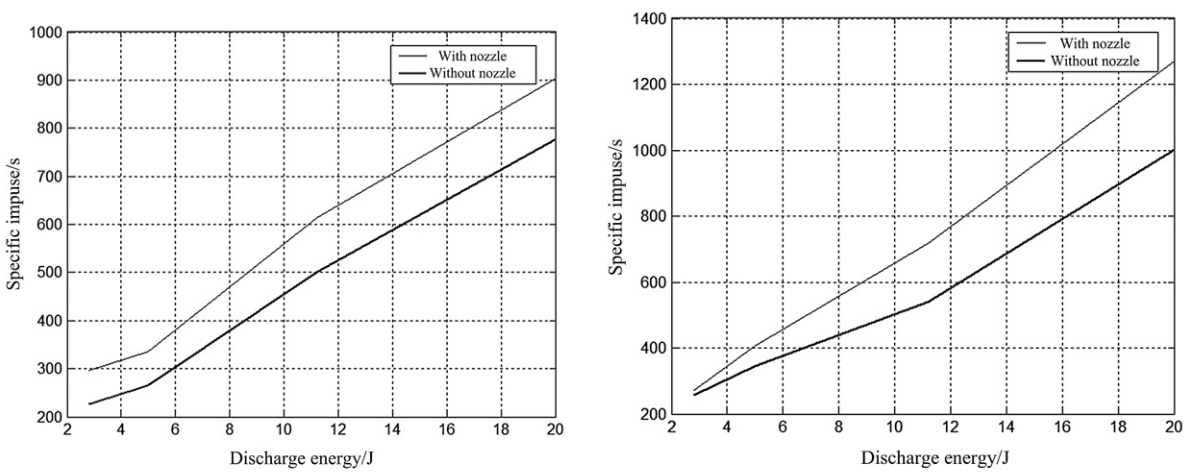
Previous PPT researches [8,10] showed that the existence of a high velocity plasma (~40 km/s) and a slower neutral component (~3 km/s) in the discharge. The high velocity particles have less mass but contribute most of the thrust. These slower neutral components produce a negligible thrust because of the low particle velocity. The existence of slower neutral particles is one of the reasons that PPT has low thrust efficiency. Due to uncharged, it could only be accelerated by electrothermal process. Ceramic nozzles improve the pressure of electrothermal area and then ameliorated the electrothermal acceleration. The improvement of the electrothermal force is larger than the reduction of electromagnetic force. Generally, the thrust gets improved in total.

Fig. 7 shows that the specific impulses increase almost linearly with the energy level. Comparison of data shows that the specific impulse values are higher for the design with nozzles than that of design without nozzle for all the energy levels.



(a) electrode gap = 30 mm (b) electrode gap = 50 mm

Fig. 6. Comparison of thrust with different electrode structural design.



(a) electrode gap = 30 mm (b) electrode gap = 50 mm

Fig. 7. Comparison of specific impulse with different electrode structural design.

These elevated specific impulses are mainly due to the increased thrust.

The kinetic energy of ejected particles is expressed by [1]

$$E_k = \frac{1}{2}mv^2 = \frac{(mv)^2}{2m} = \frac{(Ft)^2}{2m} = \frac{(F/f)^2}{2m} \tag{9}$$

where m is the mass loss per impulse in kg, v is the effective exhaust velocity of propellant particles, F is the thrust including electromagnetic force and electrothermal force in N, t is the time of acting force and f is the discharge frequency. The thrust efficiency which is the ratio of total kinetic energy to the discharge energy is calculated by Eq. (10)

$$\eta = \frac{E_k}{E} = \frac{(F/f)^2}{2mE} \tag{10}$$

where E is the total discharge energy in J. If the discharge energy and mass loss are constant, thrust efficiency will be improved by adding the ceramic nozzle as the increase of thrust. In this experiment, when the discharge energy was 20 J, the thrust efficiency of this PPT was improved from 7.5% to 12% (electrode gap = 50 mm). I.e. the total kinetic energy per pulse improved from 1.5 J to 2.4 J. Fig. 8 presents a comparison of the thrust efficiency between two structures with and without nozzle for the 50 mm electrode gap at different energy level.

5. Conclusion

The effect of the ceramic nozzle on the discharge current, thrust, specific impulse and thrust efficiency of a parallel rail PPT was investigated. The experimental results showed that the ceramic nozzle reduces the discharge current slightly. But the thrust is still improved significantly because of the increase of electrothermal force. The low electrothermal acceleration efficiency has concluded to be a major cause of the low thrust efficiency, since the slower neutral gas and macro particles can only be accelerated by electrothermal process. The experimental results also indicated that the increase of pressure in electrothermal acceleration area increases the thrust remarkably. Applying a ceramic nozzle is an efficient approach to ame-

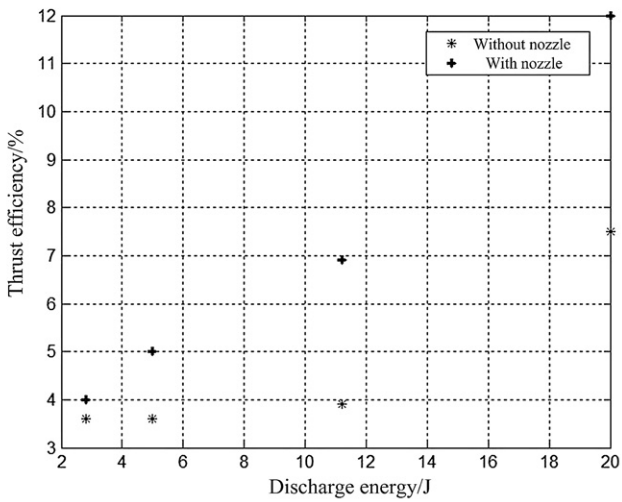


Fig. 8. Thrust efficiencies for at 50 mm gap width at different energy levels.

liorate electrothermal acceleration and hence improve the PPT performance remarkably.

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