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Development and research of a coaxial microwave plasma thruster

Juan Yang,[1,a)] Yingqiao Xu,[1] Jinlan Tang,[1] Genwang Mao,[1] Tielian Yang,[1] and Xiaoquen Tan[2]

[1]*College of Astronautics, Northwestern Polytechnic University, Xi'an 710072, People's Republic of China*
[2]*School of Mechatronics, Northwestern Polytechnic University, Xi'an 710072, People's Republic of China*

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An overview of the research on a coaxial microwave plasma thruster at Northwestern Polytechnic University is presented. Emphasis is put on the development and research on key components of the thruster system, a microthrust balance, plasma plume diagnostics, and a numerical simulation of the plasma flow field inside the thruster cavity. The developed thruster cavity is chosen from a coaxial resonant cavity with concentrated capacitance, which can operate well in atmosphere and vacuum conditions. The development of a microwave source shows that a magnetron powered by a switch power supply has advantages in the power level and efficiency, but a solid state microwave source synthesized from the arsenide field effect transistor is superior in weight and volume. Through elimination of the effect of large gravity and resistance force induced by a gas pipe line and a microwave transmitting line on the microthrust, 15 mN and 340 s in the performance of the microwave plasma thruster at 70 W and with helium gas are measured. Diagnosing experiment shows that the plasma plume density is in the range of $(1-7.2)\times 10^{16}/\mathrm{m}^3$. Numerical simulation of the plasma flow field inside the coaxial thruster cavity shows that there is a good match between the microwave power and gas flow rate.
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I. INTRODUCTION

As Table I shows, there are typically three kinds of electric propulsion, of which the microwave plasma thruster (MPT) and the microwave ion engine belong to the electrodeless propulsion type. These can be designated as electric microwave thrusters. Space tests and ground experiments have shown that electric microwave propulsion has the advantage of a long life span, a simple system structure, a wide range of thrust, and less electromagnetic emissions.[1–5]

Inspired by the advantages of electric microwave propulsion and in keeping with the charter of the Northwestern Polytechnic University (NPU) to advance new types of propulsion, the government and National Natural Science Foundation of China in 1997 provided funding support for research on MPTs. Commencing with the successful experience of the USA,[6–8] we developed a cylindrical MPT at 1000 W power level, which is separated into two parts by a dielectric diaphragm. In addition, we investigated a coaxial cavity thruster with a concentrated capacitance running at less than 200 W because of its stable operation at low powers and application to small satellites.[9]

The MPT is called the microwave electrothermal thruster (MET) in the USA. At 30–2000 W input power, the MET produces 10–400 mN thrust and 450–650 s specific impulse, which are comparable to those of the arcjet.[10–14] MET investigations started in the 1960s and reached a high point in the 1980s. However, because of the low performance of microwave sources and the successful use of arcjets for north/south station keeping and altitude control of satellites,[15–17] MPT research was confined to the laboratory. However, work continues in this field on the MPT because of the MPT's advantage of having no cathodes and its simple structure.[18–20]

The MPT system is composed of a microwave source, a resonant cavity, and a propellant supply subsystem. The thruster cavity is a key component. It is where microwave energy is transferred to the gas to heat it. The heated gas is then converted to thrust into the nozzle. The cavity's resonant state affects the gas discharge, plasma stability, and efficiency of energy deposition. The microwave source, which consists of a power supply, microwave generator, and transmitting components, is important because it occupies most of the propulsion system's volume and accounts for most of its efficiency. Measuring the microthrust of MPT is difficult because the thrust will be affected severely by its large gravity force and resistance force caused by the hard-shelled microwave propagation line and propellant supply line, which take special work to overcome. In addition, the study of the plasma flow fields inside the thruster cavity helps optimize MPT parameters for efficient operation. The work in this article is focused on these coaxial MPT matters.

II. DEVELOPMENT OF THE COAXIAL THRUSTER CAVITY

The plasma must be formed in the thruster cavity near the entrance to the nozzle in order to heat the flowing gas. In order to deposit maximum microwave energy in the cavity, the propagating wave mode needs two strong electric fields, one is for wave coupling and the other overlaps with the gas discharge region. A coaxial microwave resonant cavity with a concentrated capacitance satisfies this requirement and has been chosen as the thruster cavity. The cavity is composed of an inner and an outer conductor and a coupling probe, as

a)Electronic mail: yangjuan@nwpu.edu.cn.

TABLE I. Types of electric propulsion and their characteristics.

	Electrothermal		Electrostatic				Electromagnetic	
				Ion engine				
Type	Arcjet	MPT	SPT	dc	Microwave	rf	PPT	MPD
F (mN)	100–300	10–400	40–80	15–40	8–25	15–35	2–10	0.2–2000
P (kW)	0.5–2	0.03–2	0.5–1.5	0.4–2	0.34–2.5	0.56–1.1	0.05–0.2	10–60
I_S (s)	450–600	450–650	~1600	~3000	2800–10000	3400–3700	500–1000	1000–7000

shown in Fig. 1(a). Radial and axial electric intensities E_r and E_z and tangential magnetic intensity H_Φ are present in the cavity. Near the end tip of the inner conductor, E_z becomes stronger, creating a favorable condition for gas breakdown. Around the end surface of the inner conductor, E_r becomes stronger, creating a favorable condition for microwave coupling. The gap between the end tip of the inner conductor and the inner side of the outer conductor forms a concentrated capacitance, which results in the cavity length being less than one-quarter wavelength. When gas is injected, it is ionized in the strong electric field zone and the resultant plasma jet is accelerated through the nozzle. The inside surface diameter of the outer conductor and outside surface diameter of the inner conductor are chosen to be 40 and 10 mm, respectively, based on the consideration that the structure must suppress the appearance of an inhomogeneous wave mode and support maximum power. Based on the resonant condition, the length of the cavity L is chosen to be 31 mm. The goal of the experiments on the thruster cavity is to find the best discharge gap and coupling probe position with a microwave network analyzer, and then to modify their dimensions according to measurements on gas discharges in atmosphere and vacuum environments. Afterwards, a combined inner conductor assembly consisting of a soft magnetic alloy, a NdFeB column magnet, and a brass column is used to produce a strong magnetic field of 0.5 T in the discharge gap. Experiments show that an applied magnetic field can increase the cavity coupling efficiency and induce a high degree of gas ionization in the thruster cavity. Figures 1(b) and 1(c) show the 100 W MPT operating in atmosphere and vacuum environments.

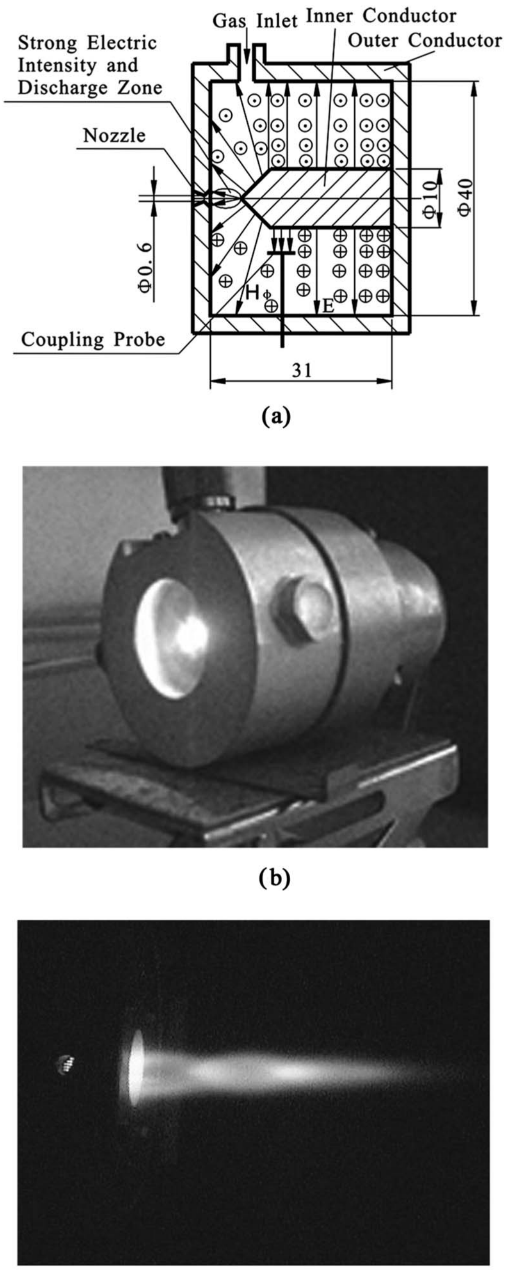
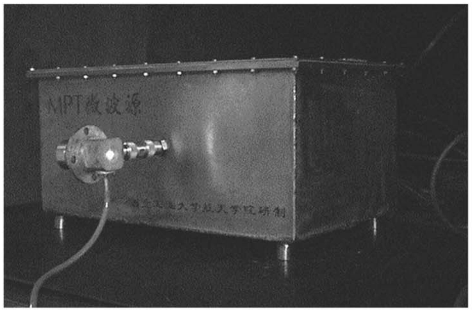


FIG. 1. Coaxial thruster cavity and its operating images. (a) Structure sketch. (b) Operation in atmosphere. (c) Operation in vacuum.

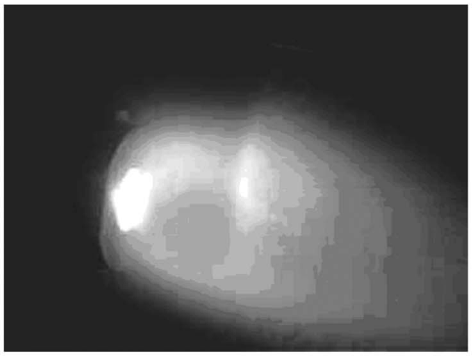
III. DEVELOPMENT OF THE MICROWAVE SOURCE

At the beginning of the MPT study, a heavy and bulky magnetron source powered by a commuting and filtering linear power supply was used for the coaxial MPT. It only operates in atmosphere because it is air cooled. In order to obtain the MPT vacuum performance, the thruster must be put in a vacuum chamber, with the microwave source positioned outside the chamber at atmospheric pressure. A coaxial cable connects the thruster and microwave source through a flange in the vacuum chamber. This leads to more microwave energy loss and introduces experimental uncertainty.

To resolve the problem, we developed two types of microwave sources. One is a 200 W magnetron microwave source, based on the technology of a switch power supply, with closed liquid cooling and virtual instrument measurement. It can operate in vacuum and at atmospheric pressure. Its efficiency, volume, and weight are a big improvement over those of the previous design. The other is a 100 W compact solid state microwave source, which is developed



(a)



(b)

(c)

FIG. 2. The developed microwave source. (a) Magnetron source with operation image in atmosphere. (b) Magnetron source with operation image in vacuum. (c) Solid state microwave source.

by the synthesizing technology of the arsenide field effect transistor (FET), the integration design of the attenuator, and the detector. It uses liquid cooling. Figure 2 shows these microwave sources and their operating images in atmosphere and vacuum environments. Table II presents the performance of the microwave sources. It shows that compared to a linear power supply microwave source, the switch powered source has higher efficiency, lower weight, and smaller size because of the switch power supply high performance. Although the efficiency of the solid state source is low, its weight and volume are only 15% and 6% of those of the switch power source. The reason the solid state source has a low efficiency is the arsenide FET. The efficiency of the solid source is $\eta=\eta_t(1-\varepsilon_s)(1-\varepsilon_e)$, where η_t is the efficiency of the arsenide FET. ε_s is the power lost in the synthesizer and distributor, and ε_e is power lost in the electrical circuit. In the developed solid state source, η_t=48%, ε_s=10%, and ε_e=20%, so η=34.6%. This shows that if the efficiency of the FET is improved, the total efficiency is increased also.

IV. THRUST MEASUREMENTS AND PLUME DIAGNOSTICS

Experiments are carried out in a 1.2 m diameter, 3 m long vacuum chamber. The chamber is pumped by two sets of Lobe-type vacuum pumps. They maintain a background pressure of less than 10 Pa throughout the experiments.

In collaboration with the First Metrology and Measurement Institute of China Aerospace Science and Technology Corporation, a set of microthrust measurement stands was developed for the MPT. As showed in Fig. 3 this apparatus eliminates the effect of thruster gravity force on the microthrust stand by adjusting the gravity center of the system on the knife edge. At the same time, it eliminates the resistance effect of the gas pipe line and microwave transmitting line on microthrust measurements by using perfect elastic lines, of which the resistance force can be compensated by counterweights. With this microthrust measurement stand, we succeeded in measuring thrust from 20 to 120 mN. The measurements demonstrate that the repetitive error is less than 2.7% and the measuring stability is about 1.6%, and we found that the MPT operating at 70 W with helium gas can produce a thrust of 15 mN and specific impulse of 340 s. Figure 4 shows a typical experimental result of a 100 W MPT.

The electron density of the MPT plasma plume is measured using an emission/Langmuir probe. A scanning power supply is used to measure the plasma space potential and *I-V* property. The electron density can be measured precisely by the saturated current of the *I-V* curve. Using the theory of the Langmuir probe, the typical electron density distributions of the argon plasma plume are interpreted from the *I-V* curve, as shown in Fig. 5. They show that at a microwave power less than 60 W and background pressure ranging from 2 to 6 Pa, the electron density in an MPT plume is in the range of $(1-7.2)\times 10^{16}/\mathrm{m}^3$.

TABLE II. Performance of the microwave source.

Source	Performance			
	W (kg)	V (mm^3)	η (%)	P (W)
Existing source with linear power supply	40	$230\times 250\times 400$	30	64
Magnetron with switch power supply	16	$190\times 260\times 400$	50	210
Solid state source	2.5	$35\times 120\times 280$	34.6	110

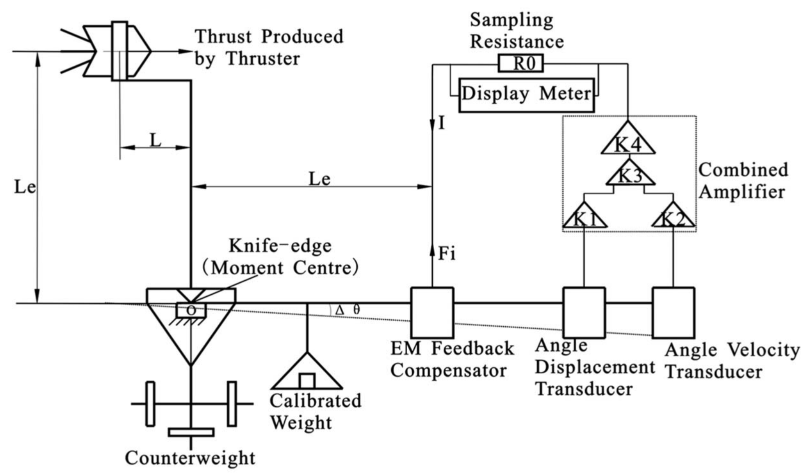


FIG. 3. Illustration of the microthrust measurement stand.

Diagnostic experiments have also been completed on the MPT with an applied axial magnetic field in determining an approach for increasing specific impulse. Results show that the field can augment the electron density in the plasma plume by about 2.1–3.5 times compared to the nonfield case, resulting in a high degree of gas ionization in the thruster cavity.

V. NUMERICAL SIMULATION

In order to analyze the influence of the microwave power on thruster parameters, the plasma flow fields inside the coaxial thruster cavity were numerically modeled.

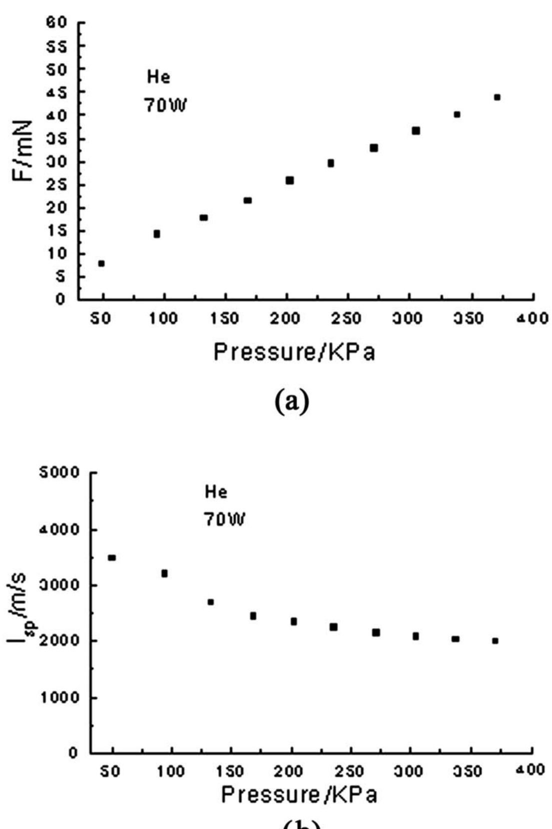


FIG. 4. Typical experimental results of a 100 W MPT. (a) Thrust measurement results. (b) Specific impulse measurement results.

In MPT steady state operation, the pressure inside the cavity is greater than 1 atm, so the plasma can be regarded as a continuous fluid, in which there is local thermal equilibrium and the temperature of the heavy particles is equal to

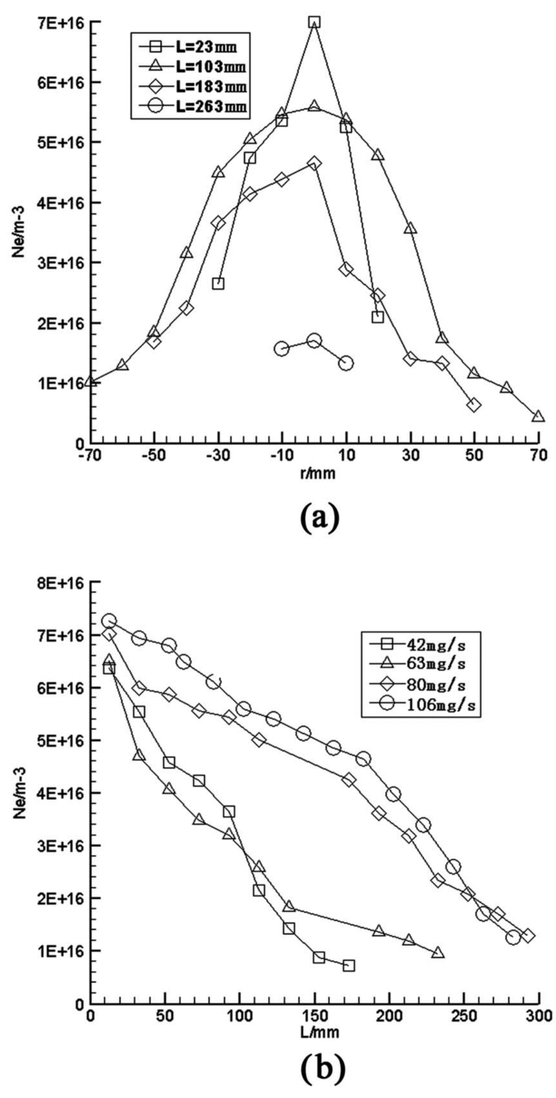


FIG. 5. Plasma plume diagnostic results. (a) Electron density distributions along the radius at 105 mg/s and 60 W. (b) Electron density distributions along the axis at 60 W.

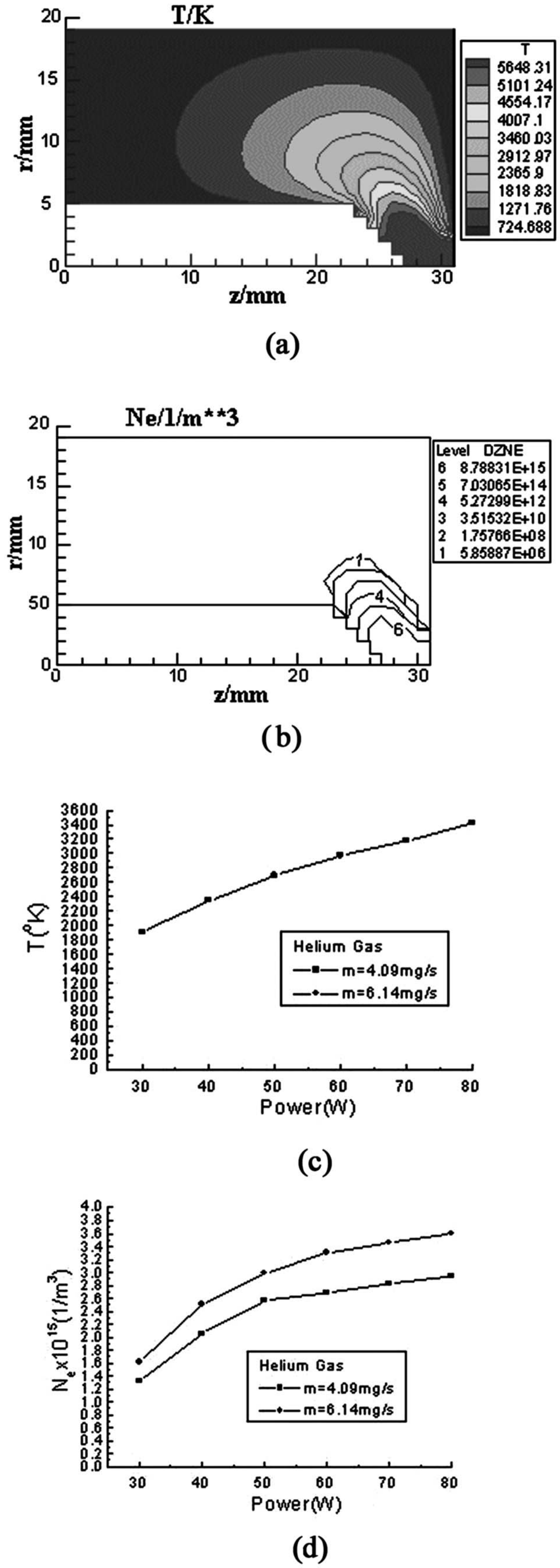


FIG. 6. Numerical simulation of the plasma flow field inside the coaxial cavity. (a) Temperature distribution at 60 W. (b) Electron density distribution at 60 W. (c) Average temperature varies with power. (d) Average electron density varies with power.

that of the electrons. In the fluid, the microwave energy affects the plasma through Joule heating, whereas the microwave electric field is influenced by the plasma conductance. A numerical simulation was developed by solving the Navier–Stokes and Maxwell equations with the semi-implicit method for pressure linked equations (SIMPLE) and the finite-difference time-domain (FDTD) method.[20,21] Staggered grids are used in the FDTD to calculate the electric and magnetic field intensities, and also in SIMPLE to detect unreasonable pressure values. In addition, the Saha[22] equation was also solved to obtain the electron numerical density at a given temperature and pressure in the fluid.

Figure 6 presents the calculated distributions of plasma temperature and density inside the cavity and the changes in average temperature and electron density with microwave power.

The following conclusions are drawn from Fig. 6: (1) the gas temperature and electron density are highest near the centerline of the nozzle entrance, (2) the average gas temperature is increased with increasing microwave power, and (3) when the microwave power is increased, the electron density increases gradually to a fixed value, at which point only a small part of the microwave energy is absorbed by the plasma. These conclusions are consistent with experimental observations.

Furthermore the effect of an applied magnetic field on the coaxial MPT is also studied numerically. An applied magnetic field with a magnetic flux density up to 0.5 T increases the peak temperature in the discharge region by more than 24%.

VI. CONCLUSIONS

The coaxial MPT has been studied and developed at the NPU. Its feasibility and reliability have been proven in ground-based experiments. A magnetron microwave source developed by using the technology of the switch power supply and using closed liquid cooling has greatly improved the system performance. The developed 100 W solid microwave source combined with a coaxial cavity forms a compact and miniaturized thruster system. With the use of a microthrust measurement stand in a vacuum chamber, we found that the MPT operating at 70 W on helium gas produces a thrust of 15 mN and specific impulse of 340 s. The plasma plume density using argon as the propellant is in the range of $(1-7.2)\times 10^{16}/\mathrm{m}^3$. Numerical simulation of the plasma flow field inside the coaxial thruster cavity shows that there is a good match between the microwave power and gas flow rate when the MPT is operating in a steady state mode. Also, an applied magnetic field with a magnetic flux density up to 0.5 T increases the peak temperature in the discharge region by more than 24%.

ACKNOWLEDGMENTS

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