

Effect of Applied Magnetic Field on a Microwave Plasma Thruster

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Theoretical analysis and calculation show that applying a magnetic field in a microwave plasma thruster operating at 2.45 GHz can improve the thruster performance, whereby an electron cyclotron resonant layer at thruster startup state contributes to the increase of microwave energy dissipated in plasma, and a strong magnetic field up to 0.5 T can increase the peak temperature of inside plasma when the thruster operates in steady state. Experimental measurements of the thruster with applied field and operating on argon gas show high coupling efficiency. Plasma plume diagnostics deduce a high degree of gas ionization in the thruster cavity. This shows the feasibility of operating a microwave plasma thruster with an applied magnetic field.

Key Words: Electrothermal thruster, Magnetic field, Numerical simulation, Plasma diagnostics

Nomenclature

B	: magnetic flux density
E	: electric intensity
F	: Lorentz force
h	: plasma enthalpy
J	: current density
L	: characteristic length
n_e	: electron density
P	: power
r	: radial distance
u	: velocity in axial direction
v	: velocity in radial direction
x	: axial distance
ν_e	: collision frequency
ω	: microwave frequency
ω_c	: electron cyclotron frequency
ω_{pe}	: plasma frequency
ω_{uh}	: upper hybrid frequency
λ_i	: mean free path of heavy particles

1. Introduction

To satisfy the requirements of both the low-thrust missions and the small-scale spacecraft, miniaturized propulsion systems are under development. Research is being conducted on a variety of microscale spacecraft propulsion systems¹⁻⁴. The low power microwave electrothermal thruster operates on the principle of transmitting microwave energy from an external source into a resonant cavity and then changing this energy into ionizing energy of the flowing propellant gas, which is accelerated through a converging-diverging nozzle to generate thrust. The ionized gas is isolated from the thruster's internal structures and, thus, does not erode any elements of the thruster. Thus, the microwave electrothermal thruster does not suffer from life limited produced by electrode erosion.

The microwave electrothermal thruster can also be called a microwave plasma thruster(MPT). The research on a low power (~ 100W), 7.5 GHz thruster was initiated at Penn State University in 1997. The thruster has a cylindrical resonant cavity, separated into two parts by a dielectric diaphragm. Microwaves are introduced into the cavity through an antenna positioned at the center of the upstream end plate to form TM₀₁₁ mode. Research is focused on characterizing the chamber conditions and obtaining thrust and specific impulse measurements using helium and simulated hydrazine propellants^{5,6}. In Northwestern Polytechnic University of China, motivated by the advantages of MPT and considering the fact that low cavity quality factor Q will have a wider resonance frequency band, low power MPT at 100 W and 2.45 GHz was developed from a microwave coaxial resonant cavity with concentrated capacitance. Its quality factor Q is lower than the cylindrical cavity⁷. The performance of coaxial MPT was measured by running it on a dynamic type thrust stand. Measured performance using helium gas propellant was 15 mN thrust and 370 s specific impulse.

According to theoretical predictions, the 100 W MPT operating on helium gas can produce 550 s specific impulse, but the measured value is lower than that. Part of the reason may be plasma instability and that its surface induces more reflected microwave energy. To overcome this problem, some theoretical work resulted in the development of a two-stage microwave plasma thruster, in which additional microwave energy was transmitted into the expanded and accelerated plasma flow region through the nozzle wall⁸. The work used a thermal equilibrium model to numerically simulate plasma expanded flow. The results show that when additional microwave power is 45% that of the energy in the thruster cavity, the specific impulse can only be increased by 3%. Heating the supersonic plasma region by additional microwave energy results in flow swirling and departure from the symmetry axis.

However, the performance of MPT can be improved in another way such as applying magnetic field to improve the coupling efficiency between microwave and plasma. This increases the peak plasma temperature and specific impulse. This idea comes from the physical phenomenon of microwave propagation in plasma. Microwave energy dissipated in cold plasma is limited by the microwave and plasma frequencies. When the plasma frequency is greater than the microwave frequency, most of the microwave energy is reflected. An applied magnetic field can force electrons to gyrate around the magnetic flux lines, creating more collision opportunities with other particles. As a result more microwave energy is deposited in the plasma. In this case when the electron gyration frequency is equal to the microwave, the plasma is in the state of electron cyclotron resonance (ECR) and energy absorbed by plasma will approach maximum. For thermal equilibrium plasma, even though the ECR phenomenon is eliminated by strong particle collisions, energy absorbed by the plasma with strong applied field will be increased because of the augmented Joule heating.

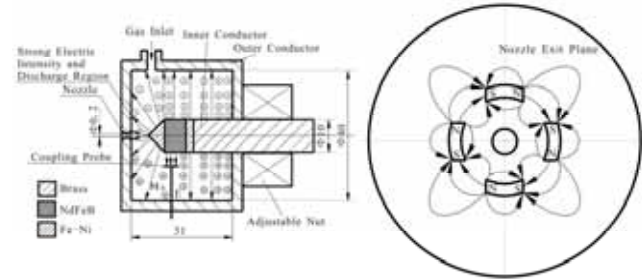
We study the effects of magnetic field topology on startup and steady operation state, and the plasma plume characteristics of coaxial MPT operating. Through theoretical analysis, it is found that in the startup phase of MPT operation, the applied magnetic field can create electron cyclotron resonant wave even at fields less than 0.0875 T. Through resolving N-S equations with SIMPLE⁹⁾ and coupled resolving Maxwell equations with FDTD¹⁰⁾, the plasma peak temperature varying with applied field is obtained. When MPT is in steady operation state, a strong field up to 0.5 T can increase the peak temperature of the plasma. Thruster operation is investigated in two cases: With and without applied magnetic field. Reflected microwave powers from the MPT cavity and related diagnostic electron densities of the plasma plume are obtained by experiments in a vacuum quartz container and utilizing a static electric probe system. Data show an obvious effect of the applied magnetic field on MPT operation.

2. Coaxial MPT with Applied Magnetic Field and its Characteristics

2.1 Coaxial MPT with applied magnetic field

The coaxial cavity of the MPT with power less than 100 W and operating at 2.45 GHz frequency has been previously described in detail¹⁰⁾. Hence, only the thruster cavity with the applied magnetic field will be described. The cavity is composed of inner and outer conductor, coupling probe and adjustable nut. It can facilitate studies of thruster operation under different configurations, with and without magnetic field. Two possible magnetic field topologies are shown in Fig. 1. The first magnetic field is from an axial magnetic mirror, which is formed by a combined inner conductor composed of a NdFeB column magnet, Fe-Ni soft magnetic alloy and brass column as shown in Fig. 1a). The second is an azimuthal magnetic field induced by NdFeB magnets stuck on the outside surface of the end plane as shown in Fig. 1b). The inside surface diameter of the outer conductor and the 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. The length of cavity is chosen as 31 mm, which is less than a quarter wavelength at 2.45 GHz. The nozzle throat diameter is chosen as 0.2 mm in order to sustain appropriate gas pressure in the cavity and appropriate mass flow rate.



(a) Axial field

(b) Circumferential field

Fig. 1. Sketch of Coaxial Cavity with Applied Magnetic Field

When gas is injected, it is ionized in the region of strong electric field intensity to form plasma, which exits through the nozzle. Experiments showed that the discharge can be held at power level of 40 W, pressure range from 0.1 Pa to 100 kPa and gas flow rate less than 5 L/min. At the moment of MPT startup, the pressure in the cavity is less than 1 Pa. However, in steady operation state, the plasma will be stabilized at pressures up to 100 kPa. Therefore, the plasma state will be changed from cold non-equilibrium to thermal equilibrium, corresponding with MPT operation from startup to steady state.

2.2 Plasma characteristics at startup

Taking argon or helium as propellant, the collision frequency ν_e of plasma inside cavity without applied magnetic field can be deduced¹¹⁾. It ranges from 1.6 to 60 MHz when the MPT is in startup state. It is much less than the frequencies of microwave and plasma. The microwave mode inside the coaxial cavity can be decomposed into longitudinal and transverse electromagnetic wave modes propagating along the axial direction of the cavity, while the latter can also be decomposed into different line polarized microwaves.

For the axial magnetic field as shown in Fig. 1a), magnetic flux lines in the discharge region are mainly in axial direction, which characterizes polarized microwaves by left and right-hand rotation waves. Only right-hand rotation waves can interfere with electron movement and transmit more energy to the plasma. In this case, electrons in the cold plasma not only collide with other particles but also gyrate around the magnetic flux lines, enlarging the effective distance that the electron travels before reaching the wall and increasing the collision opportunity with other particles. If the magnetic flux density is set to $B=0.0875$ T, then the electron cyclotron frequency $\omega_c=eB/m_e$ is equal to the 2.45 GHz frequency of the MPT. The electron gyrating motion resonates with microwave and an ECR layer is formed in the discharge region. The energy absorbing mechanism of this plasma is controlled by ECR motion. The ECR absorbed power¹²⁾ is

$$P = \frac{n_e e^2 v_e}{4m_e} \left(\frac{1}{v_e^2 + (\omega - \omega_c)^2} + \frac{1}{v_e^2 + (\omega + \omega_c)^2} \right) E^2 \quad (1)$$

At MPT startup state, $v_e \ll \omega$. When $\omega_c = \omega$, it thus yields $P \rightarrow$ even at low microwave energy or E.

For the azimuthal magnetic field, magnetic flux lines in the discharge region are mainly in the circumferential direction, which characterizes the microwaves as abnormal waves. The magnetic field changes the electron orbit from a straight line along the electric field direction to an ellipse, and the electron gyration frequency approaches the upper hybrid frequency

$$\omega_{uh} = (\omega_{pe}^2 + \omega_c^2)^{1/2} \quad (2)$$

Therefore, even at magnetic fields lower than 0.0875 T, microwaves with frequency of $\omega = \omega_{uh} = 2.45$ GHz will become upper hybrid resonant waves, by which the plasma can be heated efficiently compared with unmagnetized plasma¹³).

2.3 Plasma characteristics at Steady Operating State

At steady operating state, the background pressure inside the MPT cavity is greater than 1 atm. With the nonfield case, the argon and helium plasma collision frequency can be estimated in the range of $3.6 \times 10^1 \sim 2 \times 10^2$ GHz¹³). The plasma inside of the MPT cavity with applied field exhibits the following behaviors: (1) ECR motion will disappear because electron collisions counteract their gyrating motion at the condition of $v_e > 2.45$ GHz. However, strong magnetic field up to 0.5 T enables gyromotion up to 1.4×10^1 GHz, which is close to v_e . (2) Plasma frequency $\omega_{pe} \ll v_e$, the plasma is in a local thermal equilibrium state and can be described by Saha equations. (3) $\lambda_i \ll L$, the plasma can be regarded as a continuous fluid. In this case, the energy absorbing mechanism of plasma will be controlled by electron collision and gyration together due to the comparative frequencies of the two motions. The microwave power density absorbed by plasma is Joule heating $\vec{J} \cdot \vec{E}$, where current density $\vec{J} = \sigma(\vec{E} + \vec{u} \times \vec{B})$.

In axial symmetrical cylindrical coordinates (r, x), the equations controlling plasma continuous flow fields are N-S ones,

$$\begin{aligned} \frac{\partial(\rho u)}{\partial x} + \frac{\partial(r\rho v)}{r\partial r} &= 0 \\ \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(r\rho uv)}{r\partial r} &= \frac{\partial(\mu \partial u / \partial x)}{\partial x} + \frac{\partial(\mu r \partial u / \partial r)}{r\partial r} - \frac{\partial p}{\partial x} + F_x \\ \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(r\rho v^2)}{r\partial r} &= \frac{\partial(\mu \partial v / \partial x)}{\partial x} + \frac{\partial(\mu r \partial v / \partial r)}{r\partial r} - \frac{\partial p}{\partial r} - \frac{2\mu v}{r^2} + F_r \\ \frac{\partial(\rho hu)}{\partial x} + \frac{\partial(r\rho hv)}{r\partial r} &= \frac{\partial[(\lambda \partial h) / (C_p \partial x)]}{\partial x} + \frac{\partial[(\lambda r \partial h) / (C_p \partial r)]}{r\partial r} + \vec{J} \cdot \vec{E} \end{aligned} \quad (3)$$

Considering the constant circumferential component of magnetic flux density, single ionization process, and local thermal equilibrium state, assuming plasma as isotropy and the end shape of the inner conductor as a column, equations (3) can be resolved with SIMPLE. Electric intensity of microwave

can be obtained by coupled resolving Maxwell equations with FDTD. Taking argon as propellant, at the conditions of 0.0, 0.5, 1.0, and 2.0 T magnetic flux density, 100 W microwave power, and gas inlet velocity of 10 cm/s, the peak temperature T_c of plasma inside the thruster cavity can be calculated as Fig. 2 showing. It can be seen that T_c will increase with increasing magnetic flux density and will tend to a saturation value. When the magnetic flux density is greater than 0.5 T, T_c will be increased by more than 24% compared with zero magnetic flux density.

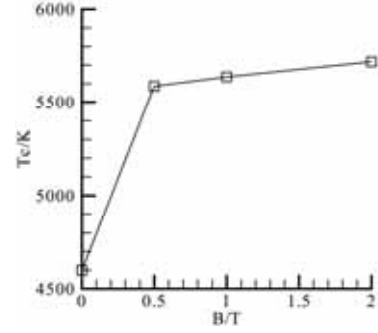


Fig.2. Peak Temperature in Discharge Region vs. Magnetic Flux Density

3. Experiments on MPT with and without Applied Magnetic Field

3.1 Experimental setup

As Fig. 3 showed, the experiment is conducted in a quartz bell container, $\Phi 380\text{mm} \times 600\text{mm}$. At argon flow rate of 105 mg/s, background pressure less than 10 Pa can be maintained by one set of lobe-type vacuum pumps. The cavity is designed with two types of inner conductor assemblies: A full brass inner conductor without magnetic field and a combined inner conductor consisting of conic Fe-Ni soft magnetic alloy, NdFeB column magnet 20 mm in length, column of Fe-Ni soft magnetic alloy 5 mm in length, and brass column as shown in Fig. 1a) to produce an axial magnetic field. As shown in Fig. 4, the axial magnetic field distribution near the combined inner conductor is numerically simulated by using commercial electromagnetic software package and measured by Gauss meter, where x is the axial distance from the end tip of the inner conductor. Another measurement of radial magnetic flux density on the centerline shows that it can be ignored compared with the axial component. Fig. 4 shows that ECR layer can be formed at the strong magnetic field region near the end tip of the inner conductor when the MPT is at startup state. The cavity, running on argon and powered by a solid state microwave source, is installed on the metal flange of a quartz vacuum chamber. All the assembly parts are enclosed in vacuum except for the adjustable nut, which is maintained at atmospheric pressure to facilitate adjusting the insertion depth of the inner conductor and reducing the reflected microwave power from the cavity to a minimum. The reflected power is detected by a power meter, and auxiliary parts consisting of a circular and attenuator. A gas flow controller with 5SLM upper limit controls the flow rate and a pressure sensor measures gas pressure inside the cavity up to 1 atm. A commercial software package controls and acquires the

signals from the flow rate controller and sensor.

Fig. 3 shows two bent static probes, which function not only as an emission probe but also as a Langmuir probe, hermetically penetrate the container flange to diagnose the electron density of plasma plume. The bent length has two values for measuring the electron density distributions on the centerline of the plasma plume and 30 mm off the centerline. Each probe is heated and biased from negative to positive voltage by a heating power supply and a scanning power supply, respectively. The space potential and the I-V plot of the plasma are measured by a semicircular tungsten filament, 0.0635 mm in radius. The saturated electron current on the I-V plot of the plasma can be precisely obtained from the plasma space potential. It is used to estimate the electron density¹⁴.

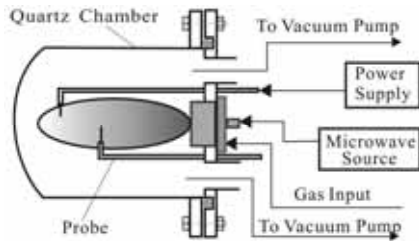
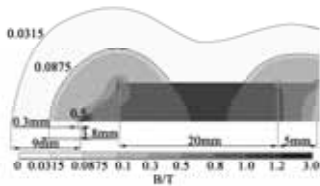
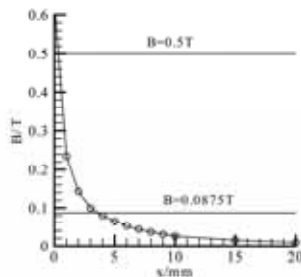


Fig. 3. Experimental Setup



(a) Calculated Contours



(b) Measured Value

Fig. 4. Axial Magnetic Field Generated by Combined Inner Conductor.

3.2 Startup and Steady Operation

The microwave source is turned on first. If the output power is high enough to ionize the gas, the plasma will start up inside the cavity at the moment of propellant injection. Table 1 presents the pressure inside the cavity versus MPT startup flow rate. It shows that the pressure increases with the increasing of flow rate from the initial background value of the vacuum container to 100 kPa above. At each flow rate value shown in Table 1, it is found that cavity pressure increases to the value in the table within 0.5s. From this, it can be concluded that when the gas flow rate is greater than 21 mg/s, the plasma inside the cavity can be transformed from cold non-equilibrium to thermal equilibrium state as MPT operation transitions from startup to steady state. This is based on the fact that when the background pressure in the plasma is greater than 20 kPa, collisions between plasma particles are so strong that the kinetic energy of heavy particles will be balanced by electrons.

Table 1. Pressure in the Cavity vs. Gas Flow Rate

\dot{m} (mg/s)	0	10	21	31	41	52	63	73	84
p(kPa)	0.001	10	20	30	40	60	80	100	115

In order to study how the applied magnetic field affects microwave propagation in the plasma, the cavity coupling efficiency is introduced, defined as $eff = (P_{out} - P_r) / P_{out}$. Fig. 5a) shows data points of cavity coupling efficiency at the startup for different configurations of the inner conductor. It is noted that for the full brass inner conductor, the maximum flow rate for MPT startup is computed to be 52 mg/s. However, it reaches 105 mg/s for the combined inner conductor. The cavity coupling efficiency with the magnet is larger than that without magnetic field by about 10%–23% at the given power range when flow rate is less than 41 mg/s. This is anticipated because ECR motion at startup of MPT increases the energy absorbed by the plasma, which in turn increases the cavity coupling efficiency and enlarges gas flow rate of MPT startup.

Fig. 5b) shows the cavity coupling efficiency versus gas flow rate when MPT is in steady operating state. For the given power and gas flow rate range, it can be shown that an applied magnetic field increases cavity coupling efficiency by about 3% to 23%. It is speculated that because the strong magnetic field up to 0.5 T creates gyromotion at frequencies close to the electron-neutral collision frequency, an increase in Joule heating results an increase in microwave power absorption and an increase in microwave coupling efficiency.

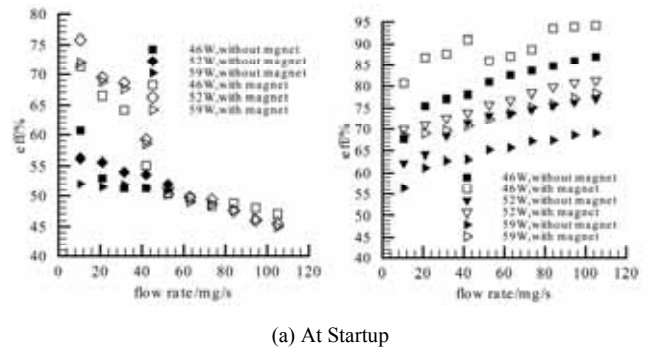


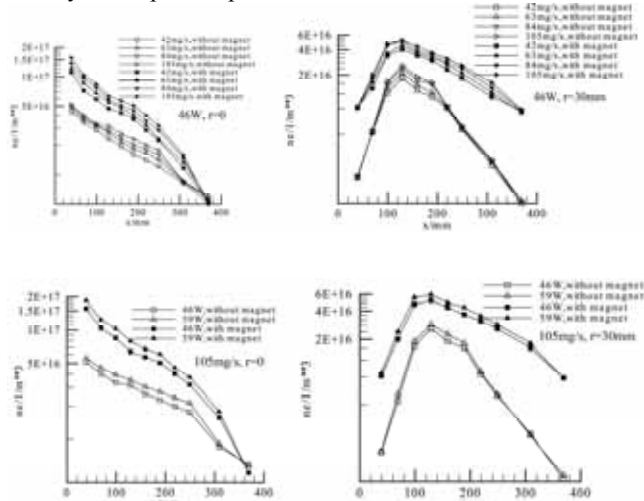
Fig. 5 Cavity Coupling Efficiency vs. Flow Rate., (a) At Startup (b) At Steady State

3.3 Plasma plume diagnostics during steady state operation

Plume diagnostics start near the nozzle exit plane, the first diagnostic point is 39 mm from the tip of inner conductor. In Fig. 4b), it can be seen that the axial magnetic flux density at this point is about 50 G. According to the calculation of the radial electron velocity distribution¹⁵, the electron cyclotron radius is greater than the probe tungsten filament radius of 0.0635 mm. Otherwise, by estimating the temperature and density magnitude of the MPT plasma plume, near the nozzle exit plane the radius of the tungsten filament is less than the mean free path of electrons and ions, but greater than the Debye length. Therefore, the applied magnetic field and high pressure inside the cavity do not interfere with plume diagnostics by Langmuir probe.

Diagnostic results during MPT steady operating with full brass and combined inner conductor are shown in Figs. 6 and 7. In Fig. 6a) it can be seen from the centerline profiles that near the nozzle exit plane the electron density is greatly affected by the field. The difference between the two families of plots, with and without magnetic fields, tends to disappear at the far end of the nozzle exit plane. As shown in Fig. 6b),

the applied magnetic field increases electron density mostly by $3 \times 10^{16}/\text{m}^3$ at the position $x=159$ mm. The curvilinear trend in Fig. 7 is the same as Fig. 6. The two figures show applied magnetic field can augment the electron density in plasma plume by about 2.1 to 3.5 times compared with the non-field case. The explanation of the diagnostic result corresponds to the steady state experiments. Strong Joule heating increases the gas ionizing degree inside the cavity and the electron density in the plasma plume.



4. Conclusions

Theoretical analysis of coaxial MPT has demonstrated that more microwave energy can be absorbed by the plasma inside the cavity when axial and azimuthal magnetic fields are applied separately in the discharge gap. The benefit comes from the ECR layer and the upper hybrid resonant wave appeared at MPT startup state. Numerical calculating shows that strong magnetic field up to 0.5 T can increase the peak temperature of plasma inside cavity when MPT operates in steady state.

Experimental measurements of the reflected power from the thruster cavity have clearly displayed the effect of an axial magnetic field on MPT. This contribution increases the gas flow rate of the MPT startup to 105 mg/s, twice of that without applied field, and increases the cavity coupling efficiency by about 23% when thruster is operating in steady state.

Diagnostic experiments with static electric probe have shown that axial magnetic field can augment the electron density in plasma plume by about 2.1 to 3.5 times compared with non-field case. This demonstrates, using another approach, that the magnetic field can improve the performance of the MPT.

Acknowledgments

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