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Resonant and Ground Experimental Study on Microwave Plasma Thruster

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Two types of microwave plasma thruster system setup, one operating at 1-kW power level and the other operating at 0.2-kW power level, are introduced. Only when their thruster cavities are in the resonant state can the microwave energy efficiently produce thrust. According to the test method on the return loss of passive microwave components, the resonance state of thruster cavity is experimented with the scalar network analyzer. The objects are to analyze the cavity efficiency and research the matching condition of the cavity dimension, microwave coupling probe position, and the medium within the cavity. The microwave plasma thruster systems are investigated under the condition of atmosphere. The propellant gas of argon and helium for 1-kW thruster will be ionized to produce thrust under the help of a vacuum pump, whereas the same gas for 0.2-kW thruster will be ionized directly because of the high volume power density. Reflected microwave power from 0.2-kW thruster cavity, mass flow rate, and total efficiency of microwave generation subsystem and cavity are measured, which explains that in order to improve microwave plasma thruster performance the parameters and gas must be chosen properly.

Nomenclature

f = frequency, GHz
I_a = anode current, mA
L = return loss, dB; length, mm
m = mass flow rate, mg/s
P = pressure, kPa; power, kW
P_r = reflected power, kW
V = volume, m^3
V_a = anode voltage, V
W = weight, kg
η = efficiency, %

I. Introduction

MICROWAVE plasma thruster (MPT) is one type of electric propulsion, which can be offered as a high-performance alternative for geosynchronous satellite altitude control and stationkeeping. Although it does not operate on satellite now, its electrodeless design, high efficiency, and simple electric power make it very attractive for future use.[1,2]

The microwave plasma thruster is composed of three parts: microwave generation subsystem, propellant supply subsystem, and resonant cavity (the thruster cavity). It is also called a microwave electrothermal thruster (MET) in the united states. Its investigation originated in the 1960s. At that time the cyclotron was used as the resonant cavity. Its efficiency was too low and the device weight too heavy to be competitive with other electric propulsion. In the 1980s with the advancement of electronics, the availability of lightweight and high-efficiency electroapparatus, and increased satellite electric power, MET studies reached a high point.[2–9] There are three groups carrying the work: a 0.5–2.2-kW device at Michigan University, a 30-kW device at NASA Lewis Research Center, and a 0.1–2.2-kW at Pennsylvania State University. After millennia the Aerospace Corporation measured the performance of a compact MET fed with water.[10]

Developed MET devices can be classified as noted in the following subsections.

A. More-Than-500-W-Power Device

This type of device uses an economic, industrial microwave generator, which can produce a continuous wave with standard frequency of 2.45 GHz. Earlier thruster cavity is rectangular, but experiment shows that plasma floats toward forepart of the cavity, causing low efficiency. Afterwards, a reliable design of cylinder cavity with TM_{011} mode is demonstrated, which uses swirl injection of propellant gas to create a favorable condition for gas breaking down.

B. Less-Than-500-W-Power Device

Although the typical microwave generator with a 2.45-GHz frequency can reduce the MET device cost, the bulky thruster cavity makes the volume power density too low for breakdown of the propellant gas at low power. M. M. Micci at Pennsylvania State University developed a minitype MET device at 7.5-GHz frequency.[11,12] The cylinder cavity, resonating at TM_{011} mode, used by this type of MET has a small volume and high volume power density, which makes it possible to operate MET at low power level.

In Northwestern Polytechnic University, Xi'an, People's Republic of China, two types of MPT systems with 2.45-GHz frequency are explored, one at 1 kW and the other at 0.2 kW.[13–15] The thruster cavity for 1 kW is similar to that in the United States. The 0.2-kW system is different and uses coaxial cavity, resonating at transverse electromagnetic mode (TEM), as thruster. The coaxial cavity is very small compared with the cylinder cavity. Section II gives the setups of the two systems.

Microwave source and thruster cavity of MPT constitute a loop, within which microwave is transferred and reflected. When the cavity is out of resonance condition, microwave energy can almost not be absorbed by the cavity. Therefore, it is very important to study the cavity resonance state for improving the device efficiency according to the method of microwave testing. Because of the comparability of MPT operation between the actual power and low signal level conditions, the energy absorbing efficiency of the thruster cavity can be deduced from the regulating research on the developed cylinder and coaxial cavities with a microwave network analyzer.

Under the ground condition the experimental research on two types of the MPT device has been completed. Detailed measurements on the 0.2-kW MPT system show that the thruster cavity efficiency is more than 90%, and the total efficiency of the microwave generation subsystem and cavity will be affected by mass flow rate.

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II. MPT Experimental System Setup

Of the MPT subsystem microwave generation subsystem, which consists of the power supply, magnetron, and microwave transmitting section, is important because it defines MPT experimental system setup. Otherwise, thruster cavity is a key component, where microwave energy is deposited and is transferred to the hot energy of gas, which will be changed into thrust. Thruster cavity is chosen from microwave resonant cavities, which may be a cylinder or rectangular empty cavity with $TE_{0\,\mathrm{mn}}$ or $TM_{0\,\mathrm{mn}}$ resonant mode or coaxial cavity of quarter wavelength with TEM resonant mode. As a thruster cavity of MPT, plasma must be formed near the entrance of nozzle. According to the calculation of Ref. 16, the cylinder resonant cavity of TM_{011} resonant mode and coaxial cavity of TEM resonant mode can be chosen as thruster cavity. The cylinder cavity is appropriate to the 1-kW MPT system because the gas is broken down by high-power microwave to form high-temperature plasma, which will float within the cavity, and the wall will be kept from heating. The inside volume of coaxial cavity of quarter wavelength with TEM resonant mode is very small compared with cylinder cavity, which makes the volume power density high and creates a favorable condition for gas breaking down. Therefore, it will be appropriate for a 0.2-kW MPT system.

A. 1-kW MPT Formation

Figure 1 shows the sketch of 1-kW MPT system. In a microwave generation subsystem, the power supply providing the voltage for magnetron anode and current for filament is a commuting and nonfiltering linear power. Magnetron, with more than 0.5-kW power output, for an MPT system is chosen from that of a microwave oven. It transfers the electric energy into microwave, which is transmitted through coupling cavity, wave guide circular with three ports, bidirectional coupler, coaxial wave guide transducer, and coaxial line into cylinder resonant cavity. The load on one side of the wave guide circulator absorbs the reflected energy from cavity to protect the magnetron from influence and to keep the output power and frequency unchanged. A bidirectional coupler is used to test output and reflected power.

According to the characteristics of the cylinder cavity with TM_{011} resonant mode, strong intensity of axial electric fields E_z is positioned in the center area of the two end surfaces, and strong intensity of radial electric fields E_r is positioned at the middle wall, which allows the microwave to be coupled efficiently by a coupling probe inserted into the cavity from the center of the end surface on one side and permits the gas to be broken down at the center of end surface on the other side if gas is injected. The diameter of its inner round surface is chosen to be 101.5 mm, and the length is 157 ± 20 mm. The structure of this type of cavity is partitioned into two halves by a dielectric plate: the forepart is under the condition of atmosphere to avoid the air near the coupling probe to be broken down, and the second half is a sealed cavity, which contains the nozzle in the end plate. Gas will be injected tangentially into the sealed cavity and ionized easily when the microwave is coupled in and the pressure in cavity is below 5 kPa.

The actual setup of 1-kW MPT, using argon or helium propellant gas, is shown in Fig. 2. Power output can be adjusted from 0.3 to 1 kW, and operating frequency is 2.45 GHz.

B. 0.2-kW MPT Formation

The 0.2-kW MPT system sketch is shown in Fig. 3. Providing the magnetron with voltage and current is a commuting and filtering linear power supply. Microwave energy output by magnetron is transferred to coaxial resonance cavity through a coaxial circular with three ports. Its two ports are connected by the magnetron and the cavity. From the other port the reflected microwave energy from the cavity is transmitted to the attenuator and the detector for test. Different from 1-kW MPT system, the microwave output power is tested accurately by measureing the anode current of magnetron because the linearity between output power and the anode current is high.

A coaxial cavity of quarter wavelength with TEM resonant mode consists of an outer conductor, as cavity, and an inner conductor. As Fig. 4 shows, only radial intensity E_r of electric fields and tangential intensity H_Φ of magnetic fields exist in this cavity. Near the end of inner conductor, E_r becomes stronger, and in the gap between the

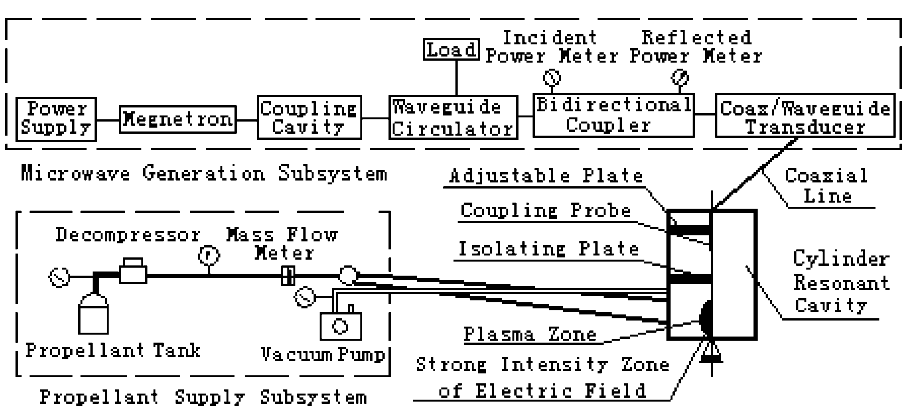

Fig. 1 The 1-kW MPT system.

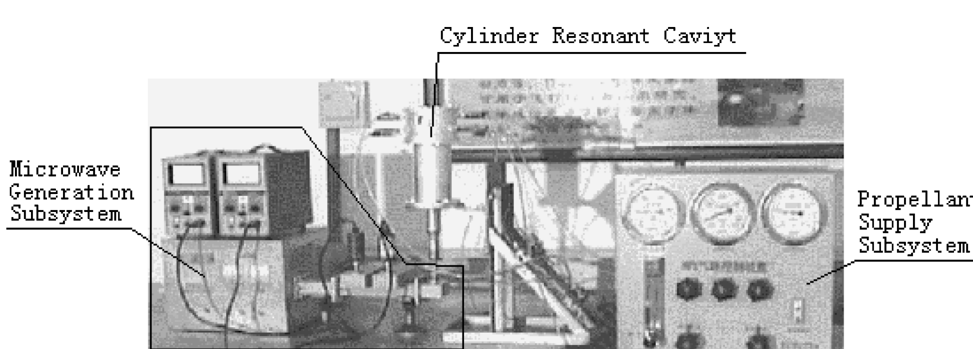

Fig. 2 The 1-kW MPT system setup.

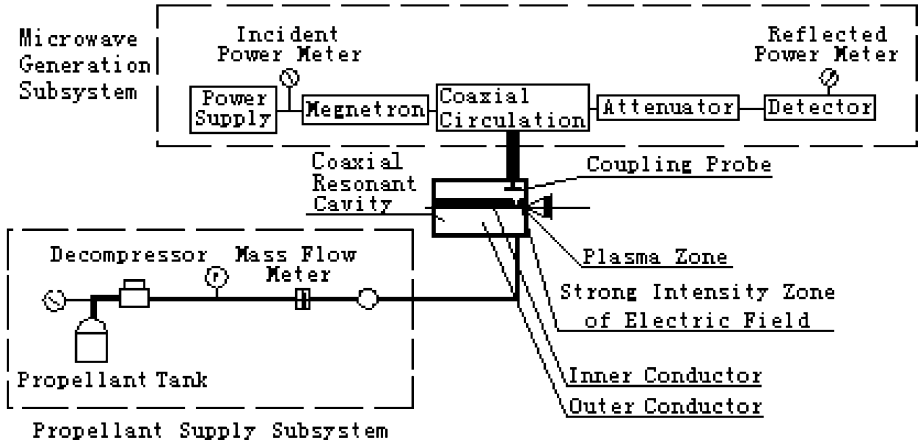

Fig. 3 The 0.2-kW MPT system.

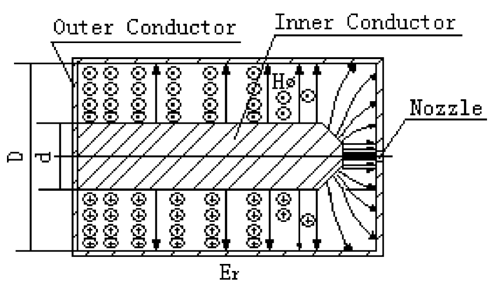

Fig. 4 Distribution of electromagnetic fields.

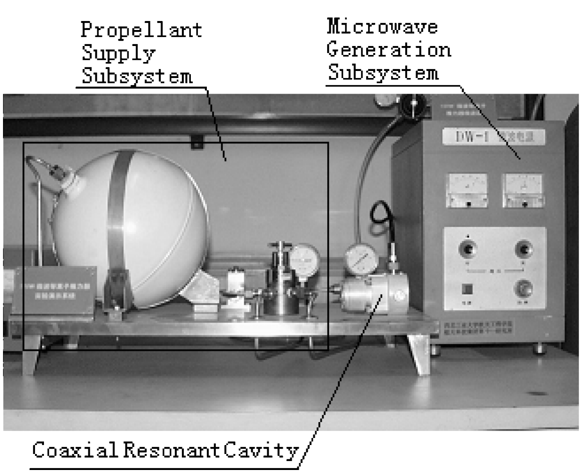

Fig. 5 The 0.2-kW MPT system setup.

inner and outer conductors E_r is maximum, which creates favorable conditions for microwave coupling and gas breaking down, respectively.

The diameter D and d of the outer and inner conductors are chosen to be 30 and 10 mm, respectively.[16] Near the entrance of the nozzle, the microwave is coupled in with a round disk connected by a coaxial connector. Gas breakdown is taking place in the gap between the tip of inner conductor and the nozzle entrance. The only strong electric intensity zone in this cavity is high enough to break down the gas without any assistance, which makes it unnecessary to apply the vacuum pump.

The setup of 0.2-kW MPT, with argon or helium propellant gas, is depicted in Fig. 5; its output power can be adjusted within the range of 0.03–0.2 kW, and frequency is 2.45 GHz.

C. Comparison of the Two Systems

The parameters of the two developed MPT systems are tabulated in Tables 1 and 2. It can be concluded that the low-power MPT system constructed with coaxial structure will be compact and lightweight.

Table 1 Parameters of different microwave generation subsystems

Type of parameter, kW	V, m^3	W, kg	V_a, V	I_a, mA
1	0.075	30	4000	358
0.2	0.020	20	1750	220

Table 2 Parameters of different resonance cavities

Type	Length, mm	Outer diameter, mm	W, kg
Cylinder with TM_{011} mode	200	110	1.5
Coaxial with TEM mode	103	70	0.9

III. Regulation on Thruster Cavity

A. Conditions and Requirements of Cavity Resonance

A section of closed wave guide or coaxial cavity applied as thruster cavity is composed of inductance and capacitance impedance in parallel or series. It will deposit electric and magnetic energy when the microwave is transferring along it. If its length is appropriate, the cavity state will be in resonance, and stored energy will be maximum. Now the closed wave guide or coaxial cavity is called resonance cavity, which absorbs energy most efficiently. According to microwave theory, the resonance conditions of the thruster cavity are as follows:

The maximum electricity and magnetism energy are equal.

Stationary waves with the wave number of $1/4 + n/2$ or $1/2 + n/2$ exist in the closed cavity ($n = 1, 2, 3, \ldots$).

Inductance impedance is equal to capacitance impedance.

The resonance state of thruster cavity will be affected by the structure, medium within the cavity, manufacture technology, and assembly condition. It is necessary to develop the thruster cavity under the following requirements: 1) highest energy-absorbing efficiency to form powerful electric intensity, 2) the widest resonance frequency band for regulating cavity to a steady state easily, 3) appropriate distribution of electric fields, which is favorable for propellant gas breakdown near the entrance of nozzle, and 4) compact size and lightweight.

Changing the cavity state will lead to different changes of the energy-absorbing efficiency and the resonance frequency band. High efficiency will result in a narrow frequency band, which ought to be compromised when developing thruster cavity.

B. Cavity Regulating Method

According to the return loss testing method of passive parts of microwave apparatus,[17,18] the thruster cavity of MPT will be resonated accurately with a microwave scalar network analyzer. Return loss is

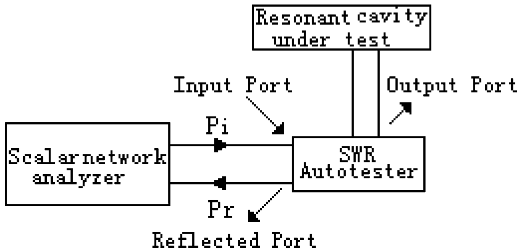

Fig. 6 Sketch of testing apparatus.

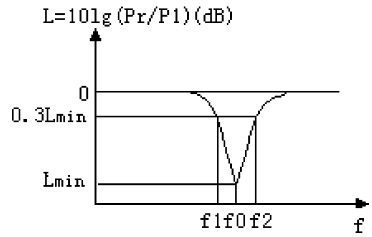

Fig. 7 Relation between return loss and frequency.

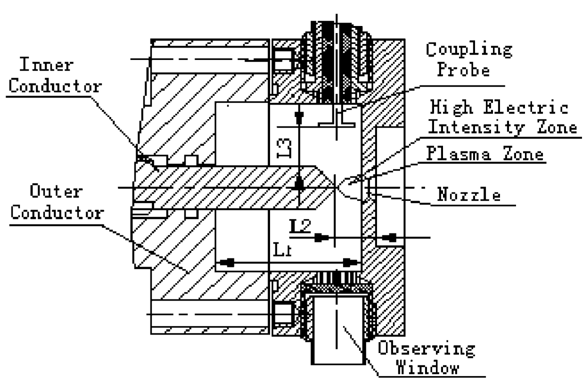

Fig. 8 Structure of coaxial resonant cavity.

defined as $L = 10lg(P_r/P_i)(dB)$. The relation between the return loss and efficiency of cavity is as $L = 10lg(1-\eta)(dB)$.

The test equipment, shown in Fig. 6, consisted of scalar network, Anritsu54147A, which can produce a low power level of microwave, standing wave ratio (SWR) autotester, which actually is a coupler with high directional property, and the resonance cavity under test. When the output port of SWR is shorted, the power will be reflected entirely to the scalar network analyzer, and the return loss will be 0 dB. After the cavity is connected to the output port of SWR, the screen of scalar network analyzer will show the return loss curve changing as a function of frequency as shown in Fig. 7. The point B on the curve denotes the resonance state of cavity, and the resonance frequency band is defined as $\Delta f = f_2 - f_1$. Changing the cavity state or altering the media material within cavity will change point B forward and backward. If the changing is appropriate, the frequency of point B will be invariable.

C. Resonance Study on Two Types of MPT Cavity

1. Coaxial Cavity

Figure 8 shows the detailed structure of coaxial cavity. Its two states are regulated. One is cavity length L_1, gap L_2, and L_3 adjustable. The other is that L_2 and L_3 are adjustable at fixed L_1. The results of resonance test are tabulated in Table 3.

Table 3 Test results of coaxial cavity resonating

L_1, mm	L_2, mm	L_3, mm	f_0, GHz	Δf, GHz	Lmin, dB	η, %
11	0.05	2	2.47	0.056	−6.95	80
13.5	0.2	2	2.44	0.058	−8.36	85
18	0.8	2	2.45	0.076	−20.83	99.2
18	0.8	3.2	2.46	0.017	−19.98	98.9
18	2.5	3.2	3.71	0.052	−12.11	94
18	1.1	2.1	2.44	0.113	−3.55	56
18	3.1	2.1	3.70	0.159	−3.20	52

Analyses for the table are as follows:

1) No matter how L_1 changes at a given range, which means changing inductance impedance, resonance states with same frequency can always be captured by changing L_2, which means changing capacitance impedance. This kind of cavity has many resonance states, provided that the inductance impedance and capacitance impedance are equal.

2) When the value of L_1 is greater, corresponding large volume for absorbing microwave energy, the value of return loss is less; moreover, the resonance frequency bandwidth is wider. Compared, the cavity with this state will operate more stably and efficiently under a practical power level.

3) When inductance impedance, or the cavity length L_1, is fixed, a small value of L_3 leads to greater value of L_2 to keep a resonant state with unchanged frequency. The reason for that is the shorter L_3 is equivalent to greater capacitance impedance; longer L_2 means smaller capacitance impedance. When $L_2$and L_3 are matching, the capacitance impedance of cavity will be unchanged.

4) High resonant frequency will be obtained by increase the gap L_2.

5) The lowest return loss of −20.83 dB tabulated in Table 1 shows that the highest efficiency of cavity will be 99.2%.

Table 4 Cylinder resonance cavity test

State parameter	Teflon plate			State[a]	State[b]	State[c]
L_1, mm	98	94	92	111	107	98
L_2, mm	10.3	7.8	4.8	5	5	5
Lmin, dB	−3	−4	−13	−14.2	−9	−5.5
η, %	49.9	60	95	96.2	87.4	71.8
Δf, GHz	0.007	0.005	0.005	0.005	0.0065	0.006

[a]Without isolate plate. [b]Teflon isolate plate. [c]Quartz glass isolate plate.

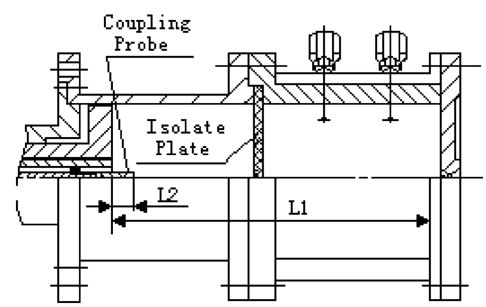

Fig. 9 Structure of cylinder resonant cavity.

2. Cylinder Cavity

The detailed structure of cylinder cavity is illustrated in Fig. 9. Changing cavity length L_1, the insertion depth L_2 of the coupling probe and the plate material or removing the plate to find out the cavity resonate state can make clear how these factors affect the return loss and resonance frequency band. Testing results for different resonance states are tabulated in Table 4.

Analyses for the table are as follows:

1) At a fixed range, when the insertion depth L_2 of coupling probe changed, the resonance state with same frequency can be captured by adjusting the cavity length L_1. The greater the space between the outside surface of coupling probe and the inside surface of cavity structures is, which means greater L_2 or greater inductance impedance, the smaller the room is between the end surface of coupling probe and the opposite surface of cavity, which means smaller L_1–L_2, which forms greater capacitance impedance. Therefore, when L_1 and L_2 are all decreased properly, inductance impedance will be equal to capacitance impedance, which leads to resonance state as original.

2) When L_2 is decreased, the value of return loss will be small, but the frequency band will be narrow.

3) The material of the separating plate will decrease the cavity length in order to make the resonance frequency unchanged. The reduced value of cavity length when using Teflon® plate is smaller than that of quartz glass.

4) The lowest return loss of -14.2 dB, tabulated in Table 2, explains that the highest efficiency of cavity will be 96.2%.

3. Comparison

The data shown in Tables 3 and 4 indicate that the resonance frequency bandwidth of coaxial cavity is 0.017–0.15 GHz, whereas the one of the cylinder cavity is no more than 0.01 GHz. Therefore, the coaxial cavity can easily be adjusted to a stable resonance state, but adjusting the cylinder cavity to a stable resonance state is not easy. The efficiency of the cylinder cavity is less than that of the coaxial cavity.

IV. Experimental Study Under the Ground Condition

A. 1-kW MPT

After regulating cylinder thruster cavity to the resonance state of 2.45-GHz frequency on scalar network analyzer, cavity is resonated again on microwave generation subsystem at the minimum power output on account of the output frequency difference of two equipments. Blocked with jam, pressure of the cylinder resonant cavity is reduced to 5 kPa below by a machine pump. After increasing pressure to 100 kPa by feeding propellant gas in, it is vacuumed again to 5 kPa below. Then a plasma zone will be formed at nozzle entrance after tuning output power to 0.9 kW. As Fig. 10 shows, plasma will exit out of the cavity after propellant gas is injected tangentially to increase pressure to 100 kPa upwards. Steady plasma flow from the thruster cavity nozzle will be maintained after the pump is turned off.

B. 0.2-kW MPT

The thruster cavity must be resonated on a scalar network analyzer and the microwave generation subsystem of 0.2-kW MPT system separately. When starting plasma, propellant gas with absolute pressure of 200 kPa is fed into coaxial cavity in the radial direction. Plasma can be formed within the cavity and exit from nozzle after slowly tuning output power to 0.030 kW. Plasma exit speed will be higher if gas inlet pressure is increased. Because the energy needed to break down gas is increased with the increasing of gas density, gas pressure must be appropriate to avoid plasma disappearing. The image of plasma flow is shown in Fig. 11. Figures 12 and 13 show the reflected power change of the cavity with the variation of argon and helium mass flow rate, respectively. Figures 14 and 15 show the total efficiency change of the microwave generation subsystem and coaxial resonant cavity with the variation of argon and helium mass flow rate, respectively. On the figures the data range of mass flow rate is the scope when plasma steadily ejects from the nozzle. The different shapes of nodes on the figures are experimental

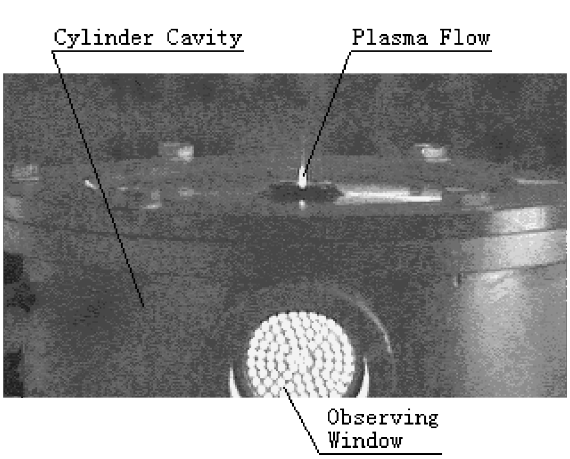

Fig. 10 Plasma generation by the cylinder cavity of 1-kW MPT.

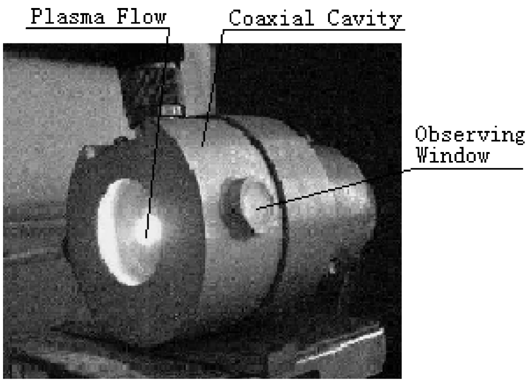

Fig. 11 Plasma generation by the coaxial cavity of 0.2-kW MPT.

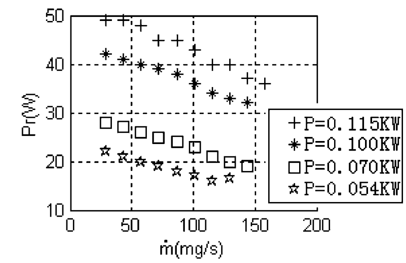

Fig. 12 Reflected power of coaxial resonant cavity vs argon mass flow rate.

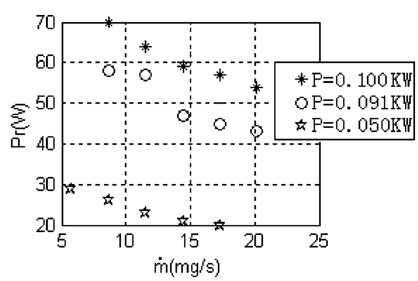

Fig. 13 Reflected power of coaxial resonant cavity vs helium mass flow rate.

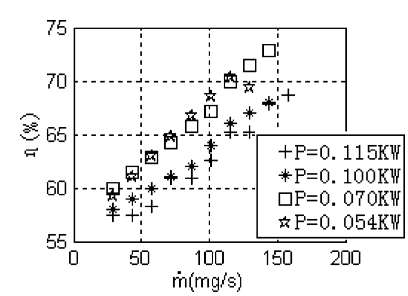

Fig. 14 Total efficiency vs argon mass flow rate.

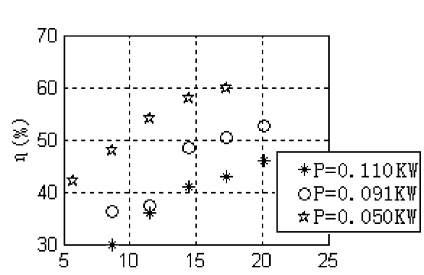

Fig. 15 Total efficiency vs helium mass flow rate.

measurements under different unchanged microwave output power from the magnetron.

Analyses for the figures are as follows:

1) At the fixing output power from the magnetron, reflected power from the cavity decreases as the mass flow rate is increased, when the propellant gas is argon or helium, whereas the total efficiency of the microwave generation subsystem and cavity changes contrarily.

2) At the fixing output power reflected power from the cavity when argon plasma is generated is smaller than helium, but the total efficiency is reverse.

3) At the fixing mass flow rate reflected power is increased as output power is increased, when propellant gas is argon or helium, but the total efficiency changes contrarily.

The experiments explain that the greatest total efficiency of the microwave generation subsystem and coaxial cavity is 73% for argon and 60% for helium. Although increasing output power can increase power absorbed by cavity, the total efficiency will be decreased.

V. Summary

The designed thruster cavity ought to be adjusted for finding the resonance state, which will improve the cavity efficiency and stabilize the operational state under the practical output power.

For cylinder thruster cavity its length, the position of the coupling probe, and the dielectric material will affect the resonance state. For coaxial thruster cavity, its length and the position of the inner conductor and coupling probe are the factors that influence the resonance state. Microwave coupling probe position has the reverse effect on efficiency and resonance state. Compared with the cylinder cavity, the coaxial cavity has higher efficiency and a more stable operation state.

At the atmosphere condition the microwave power per unit volume of cylinder cavity is too low to start the 1-kW MPT system with argon or helium propellant, but the electric intensity within the coaxial cavity of 0.2-kW MPT is high enough to break down the gas. Detailed experiments on the 0.2-kW MPT system show that output power, mass flow rate, and propellant gas all affect the reflected output power from cavity and the total efficiency of microwave generation subsystem and coaxial cavity. To improve MPT performance, the parameters and propellant gas must be considered properly.

References

[1] Micci, M. M., "Prospects for Microwave Heated Propulsion," AIAA Paper 84-1390, June 1984.

[2] Whitehair, S., and Asmusse, J., "Recently Experimental with a Microwave Electrothermal Thrusters," AIAA Paper 85-2051, Sept.–Oct. 1985.

[3] Hawley, M. C., and Morimand, T. J., "Review of Research and Development of Microwave Electrothermal Truster," AIAA Paper 89-5620, July 1989.

[4] Mueller, P., "Microwave Electrothermal Thrusters Using Waveguide Heated Plasmas," AIAA Paper 90-2562, July 1990.

[5] Balaam, P., and Micci, M. M., "Performance Measurements of a Resonant Cavity Electrothermal Thruster," IEPC-91-031, Oct. 1991.

[6] Micci, M. M., and Balaam, P., "Investigation of Free-Floating Resonant Cavity Microwave Plasma for Propulsion," *Journal of Propulsion and Power*, Vol. 8, No. 1, 1992, pp. 103–109.

[7] Power, J. L., "Microwave Electrothermal Propulsion for Space," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 40, No. 6, 1992, pp. 1179–1191.

[8] Power, J. L., and Sullivan, D. J., "Preliminary Investigation of High Power Microwave Plasma for Electrothermal Thruster Use," AIAA Paper 93-2106, July 1993.

[9] Balaam, P., and Micci, M. M., "Investigation of Stabilized Resonant Cavity Microwave Plasma for Propulsion," *Journal of Propulsion and Power*, Vol. 11, No. 5, 1995, pp. 1021–1027.

[10] Diamant, J. E., Brandenburg, J. E., Cohen, R. B., and Kline, J. F., "Performance Measurement of a Water Fed Microwave Electrothermal Thruster," AIAA Paper 2001-3900, July 2001.

[11] Nordling, D., and Micci, M. M., "Low Power Microwave Arcjet Testing: Plasma and Plume Diagnostics and performance Evaluation," AIAA Paper 99-2717, June 1999.

[12] Souliez, F. J., Chianese, S. G., Dizac, G. H., and Micci, M. M., "Low-Power Microwave Arcjet Testing: Plasma and Plume Diagnostic and Performance Evaluation," *Micropropulsion for Small Spacecraft*, edited by M. M. Micci and A. D. Ketsdever, Vol. 187, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2000, pp. 199–214.

[13] Genwang, Mao, Hongya, Ma, and Hongqing, He, "Coupling Between Plasma and Microwave," *Journal of Propulsion Technology*," Vol. 19, No. 4, 1998, pp. 14–17.

[14] Juan, Yang, Hongqing, He, and Genwang, Mao, "Optimum Choice of Microwave Mode for Microwave Plasma Thruster," *Journal of Propulsion Technology*, Vol. 20, No. 1, 1999, pp. 76–79.

[15] Juan, Yang, Hongqing, He, and Genwang, Mao, "Engineering Calculation of Microwave Plasma Thruster Performance," *Journal of Propulsion Technology*, Vol. 19, No. 6, 1998, pp. 58–60.

[16] Juan, Yang, "Theoretical and Experimental Investigation of Microwave Plasma Thruster," Ph.D. Dissertation, Northwestern Polytechnical Univ., Xi'an, PRC, Oct. 2001, pp. 24–33.

[17] Chunhui, Zhao, and Xinyuan, Yang, *The Course of Microwave Test and Experiment*, Harbin Polytechnical Univ. Press, Harbin, PRC, 2000, pp. 44–54.

[18] Shiyi, Dong, *Microwave Testing Technology*, Beijing Inst. of Technology Press, Beijing, 1990, pp. 180–187.

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