Experimental Investigation of Influencing Factors for Reliable Startup and Steady Work of 100W Microwave Plasma Thruster

IEPC-2007-264

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

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Abstract: Microwave plasma thruster is one type of electrothermal propulsion devices. Its characteristics including electrodeless design, long lifetime, and slight plume contamination make it very attractive for future application. Making use of the vacuum experimental system, the factors which influence reliable startup and steady work of 100W coaxial resonant cavity MPT such as propellant kinds, coupling probe length, mass flow rate, incident microwave power, position of inner conductor, and sealed material selection of microwave connector were studied. The dependence of MPT performance such as thrust, specific impulse and efficiency on the parameters of propellant mass flow rate and incident microwave power were discussed and analyzed.

I. Introduction

THIS paper presents the results of research on the experimental investigation of influencing factors for reliable startup and steady work of 100W Microwave Plasma Thruster, conducted by the national key laboratory of combustion, flow and thermo-structure at Northwestern Polytechnical University in China.

Microwave Plasma Thruster (MPT) is one type of electrothermal thruster, which composes of microwave source, propellant supply subsystem and resonant cavity (thruster chamber). It is also called Microwave Electrothermal Thruster (MET) in USA[1]. The resonant cavity of MPT operates in transverse magnetic (TM_{011}) mode and transverse electromagnetic (TEM) mode, which are optimal for producing an axial, free-floating plasma. The operating principle is that microwave power at a given frequency propagates into the resonant cavity, within which cold propellant gas is heated to a high temperature. And then the plasma flow expands through a converging-diverging nozzle to produce thrust. Although MPT has not been used on spacecraft, its electrodeless design, long lifetime and slight plume contamination make it very attractive for future use. It can be offered as an alternative for geosynchronous satellite altitude control and station keeping[2].

The MET concept was first conceived in the 1960s. In 1982, researchers at Michigan State University proposed to use a microwave resonant cavity to produce plasma for propulsion device. And then a number of researchers at Michigan State University, Pennsylvania State University, Princeton University, NASA Glenn Research Center, the Aerospace Corporation, Research Support Instruments and Kennedy Space Center have developed a great deal of theoretical and experimental research with the propellant helium, nitrogen, ammonia, hydrogen, nitrous oxide or water vapor. MET has been scaled successfully to operate at 100W, 1kW, and 50kW using 7.5GHz, 2.45GHz, and

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0.915GHz microwave frequency respectively. And the measured specific impulse is greater than 8000N·s/kg using water vapor as the propellant[3].

In Northwestern Polytechnical University, Xi'an, China, two types of MPT with 2.45GHz microwave frequency are investigated, one at the power of 1kW and the other at 100W. The thruster cavity for 1kW is cylindrical cavity, similar to MET in USA. But 100W system is different and uses coaxial cavity, which resonates at TEM mode to produce microwave plasma. The cavity is very small compared with the cylinder one. In this paper, the studies on influencing factors for reliable startup and steady work are about this kind of MPT.

II. Vacuum Experimental System and 100W MPT

The vacuum experimental system is diagrammed in Fig. 1. It consists of the vacuum pumps and the vacuum chamber. The MPT is installed in the 1.2m diameter by 3.0m long vacuum chamber. The utmost chamber pressure is approximate 5.0×10^{-2} Pa and the operating pressure is typically in the range of 10^{-1} Pa to 10 Pa. The propellant supply subsystem composes of propellant gas tank, reducing valve, solenoid valve, mass flow controller (MFC), pressure transducer and several pipes. The measurement and control system of virtual instruments consists of the industrial computer, Labview software, data acquisition card and external transducers and sensors.

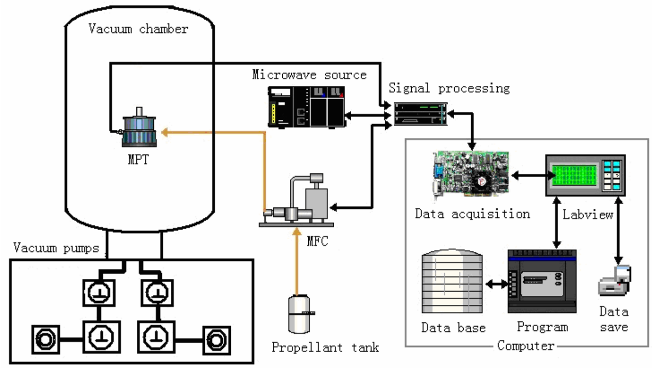

Figure 1. Schematics of MPT vacuum experimental system

In experiment, the electromagnetic dynamic balance system is used for precise measurement of small thrust. It consists of the thrust stand and the measuring-controlling instrument. The thrust stand composes of the indifferent equilibrium system, the mounting components and the measurement calibration system. When the thrust measurement balance operates in the indifferent equilibrium state (or near to the indifferent equilibrium state), the thrust is separated from the thruster weight. Flexible connections of the gas pipe and the microwave transmission circuitry are used to eliminate the measurement influence of the thruster accessories. Then the electromagnetic torque apparatus feeds back the electromagnetic force for compensation the thrust of the thruster. The thrust value is directly shown on the measuring-controlling instrument. Since the axial thrust measurement range of the device is 0 ~1000 mN, it can be applied for both 100W and 1kW MPT. The static state measurement uncertainty is 1%FS and the dynamic change uncertainty of zero output is 5%FS. When MPT operates steadily, the thrust value is recorded immediately to reduce the influence of the shift.

The cavity of 100W MPT is in the mode of coaxial resonant cavity with concentrated capacitance, which is resonated at 2.45GHz. The coaxial resonant cavity structure is shown in Fig. 2A, while the photograph of 100W MPT is shown in Fig. 2B. It consists of adjustable subassembly, inner and outer conductor, microwave coupling probe, propellant injector, viewing window and converging-diverging nozzle. The propellant gas flows into the resonant cavity in radial direction, and the microwave excites by the radial coupling probe in another 90 degrees side of the circumferential direction. The head shape of the coupling probe is like a disc which avoids discharging at the probe, destroying the resonance and eroding the probe. The inner wall of the resonant cavity uses silver-plating for reducing microwave loss and enhancing the quality factor of the resonant cavity.

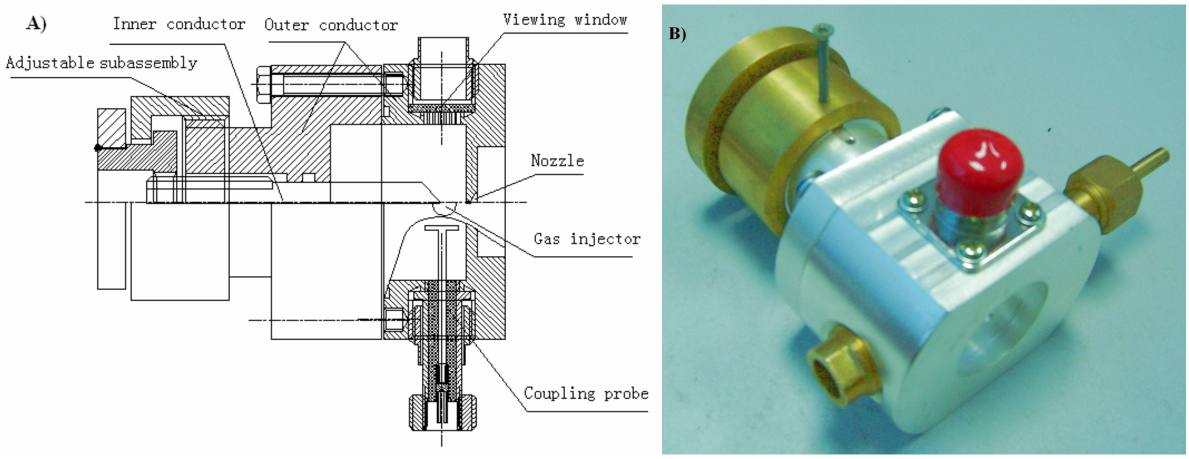

Figure 2. A) Coaxial resonant cavity structure of 100W MPT and B) the photograph of 100W MPT

III. Experimental investigation of influencing factors for reliable startup and steady work

Making use of the vacuum experimental system, the factors which influence reliable startup and steady work of 100W coaxial resonant cavity MPT such as propellant kinds, position of inner conductor, sealed materials of microwave connector, coupling probe length, mass flow rate and incident microwave power were studied.

A. Propellant Gas

The experiments demonstrate that in the same operating conditions for 100W MPT, the specific energy (defined as the ratio of incident microwave power to mass flow rate) of reliable startup is greater than 120 MJ/kg using helium as propellant gas, while using argon it is greater than 15 MJ/kg, and using nitrogen it is greater than 30 MJ/kg[5]. This is mainly because the ionization energy of helium, nitrogen and argon is 24.6eV, 15.6eV and 15.8eV respectively[6]. And since helium and argon are monatomic gas, while nitrogen is diatomic molecule, there are fewer internal energy modes in monatomic gas, and the free electron with high energy ionizes gas more easily through inelastic collisions. Therefore, in the same operating conditions, it's much easier for reliable startup using argon, then nitrogen, and last helium.

Using both helium and argon can form stable, compact discharges, and the plasma can be sustained over a broad range of pressure in the resonant cavity. The experiments demonstrate that using helium and argon can obtain better coupling with microwave and higher efficiency. The advantages of propellant argon contain the smaller ionization energy, easy to startup and steady work, so it's very useful for research and exploration in laboratory. And the advantages of propellant helium include the little molecular weight, low reflected power and high plasma temperature, so it can get high performance parameter[7].

The average temperature in the resonant cavity of MPT is calculated on the hypotheses of zero-dimensional model, isentropic flow of a perfect gas with constant specific heat, and supposing the average temperature of plasma in the nozzle is equal to the central temperature of the plasma in the resonant cavity which determined as average temperature in the resonant cavity[8]. The performance parameters of 100W MPT including plasma average temperature, specific impulse and thermal efficiency are computed through experimental data such as thrust, discharge pressure, mass flow rate, incident microwave power and reflected power. Table 1 shows the configuration and performance parameters of 100W MPT.

B. Position of Inner Conductor

The experiments show that when the spacing between the tip of the inner conductor and the outer conductor is smaller, the electric field strength is higher, and it's easier to startup for MPT in the vacuum environment in spite of using helium or argon as propellant[9]. In order to stabilize the operation of MPT, it should be selected the minimum reflected microwave power by turning the adjustable subassembly and the corresponding spacing will be as the optimal spacing between the tip of the inner conductor and the outer conductor. If the spacing is too small, erosion of the tip of the inner conductor and nozzle inlet will occur. However, if the spacing is too large, the discharge will be shaking and unstable[10].

Table 1 Configuration and performance parameters of 100W MPT

Content	Symbol, Unit	Parameter	
Propellant		Ar	He
Incident power	P_{in}, W	120	120
Nozzle throat diameter	d_t, mm	0.25	
Nozzle area ratio	ε	151	
Mass flow rate	q_m, mg/s	28.10	4.42
Plasma average temperature	T, K	703.8	3200
Discharge pressure	p_{re}, Pa	320000	
Pressure at nozzle exit	p_e, Pa	50	
Thrust	F, mN	28.82	25.45
Specific impulse	I_{sp}, N·s/kg	1 025.56	5 758.29
Thermal efficiency	η, %	12.33	55.43

C. Sealed Materials of Microwave Connector

There are two kinds of sealed materials of microwave connector in recent experiments: teflon and glass. The advantage of teflon is the possession of little loss of microwave power and it's better for the research on low power (30W-100W) MPT, but it has much erosion and will affect gas tightness of the resonant cavity for long time use. Glass has little erosion for long time use and the experimental iteration is better, but it has much loss of microwave power. As to helium, in the same condition of mass flow rate, it needs much higher microwave power using glass instead of teflon for startup of MPT. And as to argon with lower ionization energy, it does not obviously affect on startup of MPT using glass as sealed materials.

D. Coupling Probe Length

The length of the coupling probe or the spacing of coupling probe and inner conductor affects the startup of MPT obviously. The complex microwave electromagnetic field exists in the resonant cavity of MPT, and the coupling mechanism of microwave and propellant gas determines that the coupling probe needs an appropriate length[11]. When the spacing of coupling probe and inner conductor is optimal, the strong point of microwave and gas coupling will be situated at the formation point of plasma. Here, it's very useful to ionize and produce the stable plasma. If the spacing is too large, the coupling strength of microwave and gas will descend sharply. However, if the spacing is too small, the discharge will be shaking and unstable and the erosion of the coupling probe will occur. The experiments demonstrate when the spacing of the coupling probe and the inner conductor is 0.3mm-0.6mm, it's easier for reliable startup and steady work.

E. Mass Flow Rate

In a given vacuum environment (0.05Pa-10Pa), when the microwave power conforms to the requirement of the specific energy to startup, the mass flow rate of propellant gas is still demanded in a certain range. Using helium as propellant, when the microwave power is 40W, the range of mass flow rate for reliable startup is 0.1mg/s-0.42mg/s. Using argon as propellant, when the microwave power is 30W, the range of mass flow rate for reliable startup is 1mg/s-4mg/s[12]. If the mass flow rate is too small, it does not produce stable plasma. However, if the mass flow rate is too large, the incident microwave power will not sustain the enough energy to ionize the gas.

Fig. 3 and Fig. 4 show the relationship between mass flow rate and reflected power. The experiments demonstrate that for a given microwave power level, when increasing mass flow rate, the reflected power decreases, the discharge pressure and thrust increase, the plume is lighter and longer. And then the reflected power tends to be constant, the average temperature in the resonant cavity increases to maximum level and MPT is in the optimal steady work state.

Fig. 5 and Fig. 6 show the relationship between specific impulse and specific energy of two different propellant gases. In the two figures, specific impulse is calculated by thrust and mass flow rate. As to helium, the optimal specific energy is 30MJ/kg. While as to argon, the optimal specific energy is 4.0MJ/kg. When the specific energy is too high, the MPT does not work normally in the vacuum condition. This is because the mass flow rate is too small, and the discharge pressure is too low, then the density of electron and neutral particle is too low, there are not enough particles for ionization collision, and it is difficult to form high temperature plasma zone. When the specific energy is too low, namely, as a given incident power, the mass flow rate is too big, and then the plasma discharge and the thruster plume are unstable observed through the viewing window. This is because the gas flow takes too much energy to sustain the stable plasma discharge. On the other hand, the increase of gas exhaust velocity results in the fluctuation of resonant characteristic, impedance and affects the stability of plasma discharge zone[13]. The experiments demonstrate that in the stable operating condition, the reflected power of argon is obviously higher than that of helium, thus this is a reason of low efficiency when using argon.

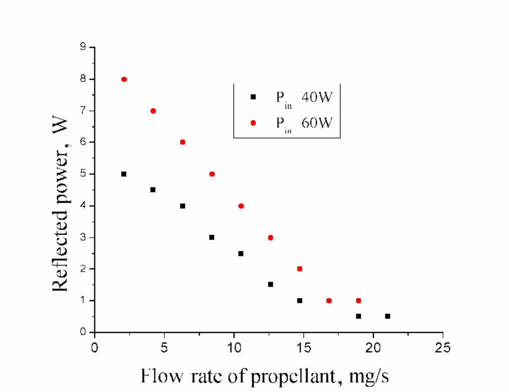

Figure 3. Reflected power vs. He mass flow rate

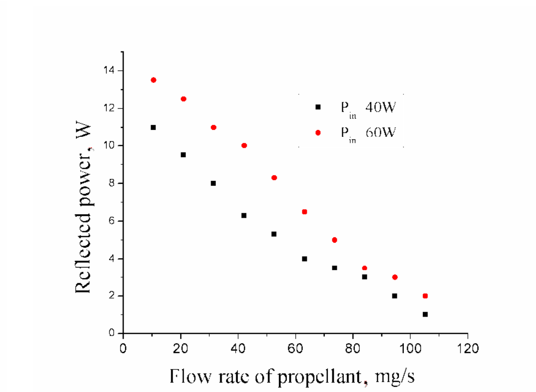

Figure 4. Reflected power vs. Ar mass flow rate

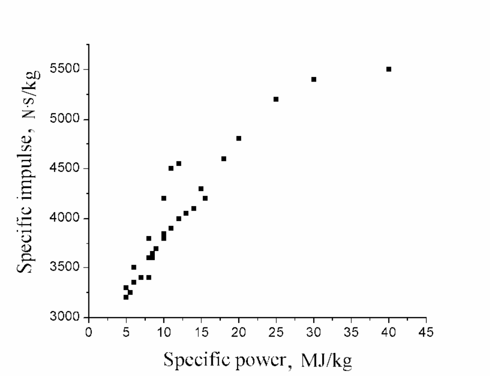

Figure 5. He specific impulse vs. specific power

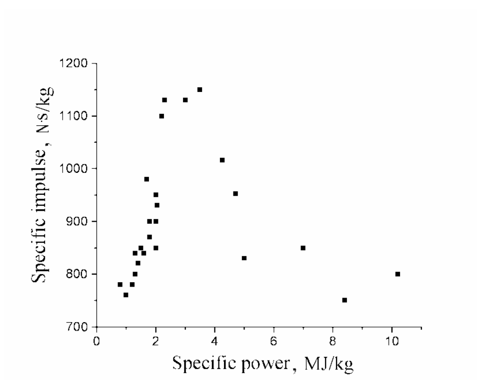

Figure 6. Ar specific impulse vs. specific power

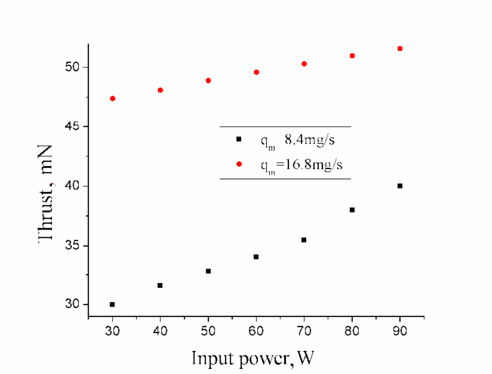

Figure 7. He thrust vs. input power

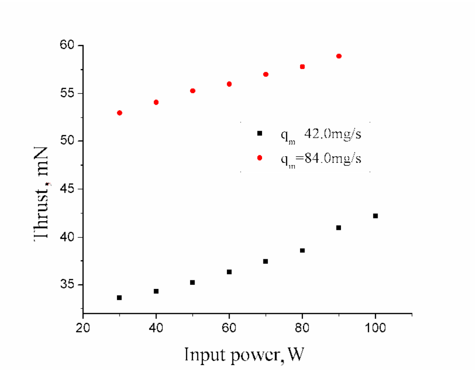

Figure 8. Ar thrust vs. input power

F. Microwave power

The experiments show that in a given vacuum environment, when the mass flow rate is constant, it's easier to startup with the higher incident microwave power. It is the same for both helium and argon. The power magnitude obviously affects the thruster startup especially for the helium gas with high ionization energy[14]. As thruster starts up successfully, then decreasing microwave power, the MPT still operates steadily. This is mainly because, here, the diffusion coefficient is smaller than the electron diffusion coefficient on the restriction effect of electric field. Thus the electric field of stable discharge is smaller than the breakdown electric field[15].

Fig. 7 and Fig. 8 show the relationship between thrust and incident microwave power. Under the steady work experiment, the pressure in the resonant cavity and thrust of MPT will increase with increasing the incident microwave power. This is because much more microwave energy couples with electrons, the ionization improves and the plasma temperature increases[16].

IV. Conclusion

Based on the ground experiments, making use of the vacuum experimental system, the factors which influence reliable startup and steady work of low power (30W-100W) coaxial resonant cavity MPT such as propellant kinds, coupling probe length, mass flow rate, incident microwave power, position of inner conductor and sealed material selection of microwave connector were studied. Experimental research demonstrates that it's easy to startup using argon as propellant than nitrogen and helium in the vacuum environment, but the specific impulse of helium is higher than argon. And when the spacing between the tip of the inner conductor and the outer conductor is smaller, it's easier to startup. With respect to steady work of MPT, it should be selected the minimum reflected microwave power by turning the adjustable subassembly and the corresponding spacing will be as the optimal spacing between the tip of the inner conductor and the outer one. For sealed material of microwave connector, using teflon or glass has its advantage and disadvantage respectively. The former has little loss of microwave power and it's better for the research on low power MPT, but it has much erosion. The latter has little erosion and the experimental iteration is better, but it has much loss of microwave power. Moreover, when the spacing of the coupling probe and the inner conductor is 0.3mm-0.6mm, it's easier for reliable startup and steady work. Furthermore, using helium as propellant, when the microwave power is 40W, the range of mass flow rate for reliable startup is 0.1mg/s-0.42mg/s. Using argon as propellant, when the microwave power is 30W, the range of mass flow rate for reliable startup is 1mg/s-4mg/s. In a given vacuum environment, when the mass flow rate is constant, it's easier to startup with the higher incident microwave power. Under the steady work experiment, the pressure in the resonant cavity and the thrust of MPT will increase with increasing the incident microwave power.

Acknowledgments

The authors thank Prof. ZHAO Bao-rui in the First Metrology and Measurement Institute of CASC for providing the small thrust measurement system and the contributions of all graduate students in our research group.

This work was sponsored by the National Natural Science Foundation of China (Grant No. 10575081).

The author, XIA Guang-qing was financed by the State Scholarship Fund of the Program Collège Doctoral Franco-Chinois to pursue the study in the Université Joseph Fourier (Grenoble I, France) and greatly acknowledged China Scholarship Council.

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