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ORIGINAL ARTICLE

Experimental Study on the Effects of Discharge Chamber Length on 5 cm Radio-Frequency Ion Thruster

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Abstract

For keeping microgravity level of microgravity and space science satellites, a kind of electric thruster, the radio-frequency ion thruster (RIT) has been designed and applied. The RIT produces thrust through ionizing neutral particles in the discharge chamber and extracting ions by the ion optics system. The length of discharge chamber affects the ionization of neutral particles as well as the performance of RIT. In this paper, an experimental study has been carried out for analyzing the influence of discharge chamber length. In the experiment, the RIT-5 with various discharge chamber lengths, 27.6 mm, 30.0 mm, 31.9 mm, 35.5 mm, 40.0 mm, has different performances under the same condition. With the same radio frequency power and propellant flow rate, the RIT-5 has the optimal performance in beam current and efficiency when the discharge chamber length is 30.0 mm or 31.9 mm.

Keywords Microgravity condition · Radio-frequency ion thruster · Discharge chamber length · Electron density

Introduction

With the rapid development of space science in recent decades, the science and technology instruments require the satellite platform to keep higher microgravity level on orbit such as SJ-10 (Hu et al. 2014). The dropping of microgravity level is caused by atmospheric resistance, solar pressure, attitude controlling, etc. The drag-free control is one of the most effective methods to maintain the satellite orbit and microgravity level by offsetting non-conservative forces (Zhang et al. 2019), and the propulsion of satellite is the actuator. There are multiple propulsion technologies used to maintain the microgravity level. Traditionally, the chemical propulsion system has to carry more propellant because of its low specific impulse characteristic, which is not the optimal choice for deep space detections or other space science missions. However, the electric propulsion systems which are advanced propulsion technologies have been applied in space missions extensively.

Compared with other electric propulsion technologies, the radio-frequency ion thruster (RIT) has characteristics of simple structure, low power, long lifetime and high specific impulse, etc. And the RIT has been selected as one of the propulsion systems for the drag-free control and the attitude adjustment of the "Taiji program" satellite, which aims to detect the gravitational wave in space (Liu et al. 2018). The RIT was invented at Giessen University in the 1960s firstly in the world, and the first RIT applied in the space mission was the RIT-10 on board EURECA in 1992 (Bassner et al. 2001a). The diameter of discharge chamber was 10 cm. A few years later, RIT-10EVO was invented at Giessen University with a better performance, 1–41 mN thrust range and 3400–3700 s specific impulse (Bassner et al. 2001b). In the 2000s, Britain and the USA began to study radio-frequency ion thrusters. For the Next Generation Gravity Mission, the μRIT-3.5 was invented by the University of Southampton (Feili et al. 2015). An iodine-fueled RF ion thruster was firstly reported by an American company Busek in 2015 (Tsay et al. 2015), and the fabrication and test of the miniaturized BIT-3 system were finished in 2017. The BIT-3 should have been applied in the 6 U CubeSats missions in 2019(Tsay et al. 2017). In

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China, the Institute of Mechanics (CAS) invented a serial of RITs with different sizes of discharge chamber in recent years, RIT-2, RIT-2.5, RIT-4 and RIT-5.

The thrust of RIT is generated through ionizing propellant gas in the discharge chamber which is surrounded by the induction coils, and the positive particles are accelerated and extracted out of the discharge chamber by the ion optics system (Fig. 1). Besides the discharge chamber and the ion optics system, other main components of the radio-frequency ion thruster system include gas propellant feed system, reducing valve and gas mass flow controller, gas inlet located at the back of the discharge chamber, power supply and control unit, and neutralizer that extracts electrons for neutralizing positive ions to keep the satellite in electric neutrality.

As one of the most important components, the geometry size of discharge chamber affects the performance of RITs. The influence of different diameters of discharge chamber on the thrust range of the RIT has been verified by scientists at Giessen University (Walther et al. 1975; Groh and Loeb 1991), and an empirical relation has been summarized through calculations and experiments (Loeb et al. 2004):

$$L_{opt} = (2R)^{0.66} + d \tag{1}$$

Where, L_{opt} is the optimized length of discharge chamber, which does not include the length d of gas distributor intruding into the discharge chamber, and R is the radius of discharge chamber.

In the reference (Walther et al. 1975), R.J. Walther and J.E. Geisel found the discharge pressure and mean lifetime of a discharge ion are depended on the ionizer length under the same condition for RIT. And the optimum geometry size of discharge chamber can be theoretically calculated for RIT-5 according to the beam current (Walther et al. 1975). In addition, H.W. Loeb and K.H.Schartner found the discharge chamber length was also impacted by the mass of propellant (Groh and Loeb 1991). It's in agreement with the result of the reference (Walther et al. 1975), the optimum ratio of length to diameter increases when decreasing mass of propellant. For verifying the research of Gissen University, a series of experimental study with several discharge chamber lengths and diameters were in good agreement with the theory values (Walther 1974).

There are some other researches about the effect of discharge chamber length on the ion source. Kyoung-Jae Chung and Bong-Ki Jung (Chung et al. 2014) from South Korea studied the effects of discharge chamber length on the negative ion source with disc type RF discharge. Comparing with two kinds of lengths of discharge chamber, they found that short discharge chamber length would increase ion density and electron temperature with the same RF powers and discharge pressures (propellant rate). However, they only compared two discharge chamber lengths, which can not fully explain the effect of discharge chamber length on plasma characteristics. And Kong Ling-xuan and Gu Zuo studied the discharge chamber parameters on Kaufman ion thruster in 2016 (Kong et al. 2018). They found the optimum ratio of length to diameter of the discharge chamber by adjusting ionization length, and the thruster had the lowest discharge cost and the best propellant utilization efficiency .

For verifying the applicability of eq. (1) on the RIT-5 and further analyzing about the effect of discharge chamber length, the beam currents extracted from the discharge chamber with various discharge chamber lengths were diagnosed, and the optimal length was found through comparisons of the beam currents, the electric efficiencies and the propellant utilization efficiencies under the same conditions. From the experimental results, the RIT-5 with 30.0 mm and 31.9 mm discharge chamber length has the best performance.

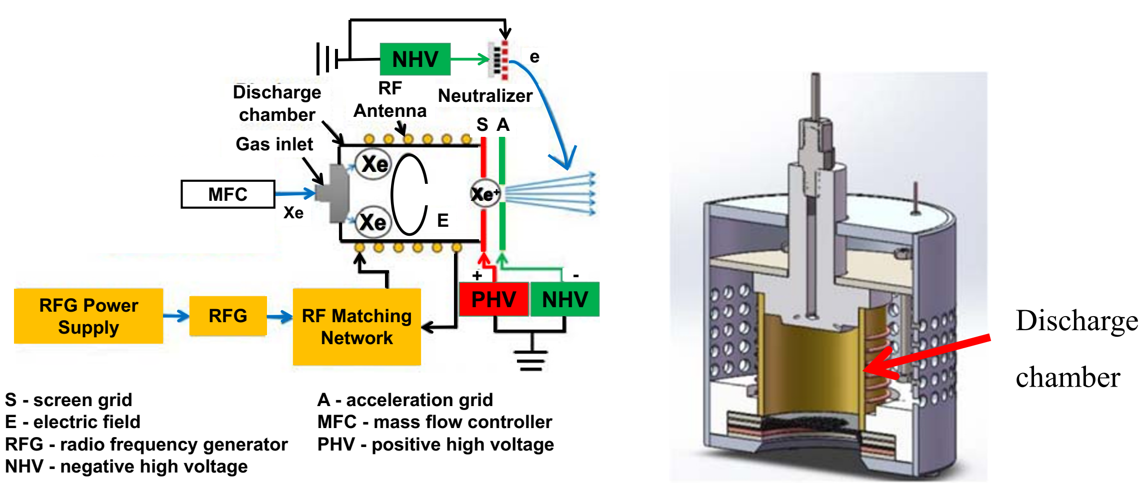

Fig. 1 The schematic diagram and components of the RIT

Fig. 2 The vacuum facility for electric propulsion at the Institute of Mechanics

Experimental Setup

Experimental Platform for RIT-5

The performance of the RIT-5 was tested in the vacuum facility at the Institute of Mechanics (Fig. 2). During the RIT-5 worked with 0.15 mg/s propellant gas Xe, the condition pressure was approximately 4×10^{-3} Pa which satisfied the stable working condition of RIT-5.

The vacuum system consists of 600 mm × 600 mm × 600 mm cube vacuum chamber and Φ400 mm × 400 mm cylinder vacuum chamber. The RIT-5 was installed in the cylinder vacuum chamber, then the RIT-5 was transported to the cube vacuum chamber by motorized positioning system to prevent discharging between the thruster and the vacuum chamber wall. The pump system consists of two mechanical pumps and three molecular pumps, one of the molecular pumps reaches 1600 L/s and the others are 2000 L/s at N_2.

The gas propellant mass flow controller is LF-400, which controls the mass rate of gas flow by a mechanical valve. The maximum rate of gas mass flow is 0.5 mg/s and the accuracy of the controller is 1%. The positive high voltage power and the negative high voltage power are provided by WISMAN. The positive high voltage range is 0 V - 2000 V and the negative high voltage range is −500 V - 0 V with less than 1% accuracy. The currents of the screen grid and the acceleration grid were also measured by the positive high voltage power and the negative high voltage power, the measurement current accuracy is less than 1%. The radio frequency generator is R&S SMC100A signal generator, the frequency range is from 9 kHz to 1.1 GHz and the voltage peak range is from 0 V to 10 V. The power amplifier can provide 150 W power maximally and the power stability is ±0.5%. The matching network was made of two capacitors (C_1 and C_2), the capacitors and coil L_x made up "L" type matching (Fig. 3). This kind of matching network can match the impedance of coil L_x and plasma resistance R_x. In order to ensure that the RF power absorbed by the plasma in the discharge chamber kept the same, through adjusting the value of RF match net capacitance (C2), the RF power reflecting into the RF circuit was controlled less than 0.2 W. The total RF power and reflecting power were measured by a power meter.

Parameters of RIT-5

According to the requirement of thrust range for low-earth orbit satellites (Goebel and Katz 2008), the thrust range of RIT-5 is designed to be 0.5 mN - 5 mN. Based on the experience of Giessen University and the Institute of Mechanics, the material of discharge chamber is quartz and the diameter was designed to be 50 mm (the actual diameter of discharge chamber was 49.0 mm). The length of discharge chamber was designed as 27.6 mm, 30 .0 mm, 31.9 mm, 35.5 mm, 40 .0 mm (Fig. 4). For studying the influence of discharge chamber

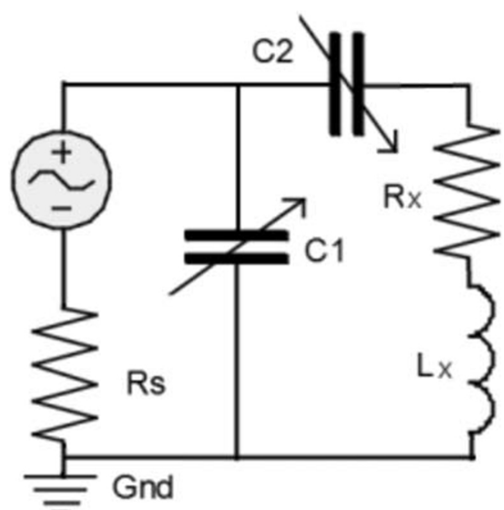

Fig. 3 Matching network of RIT-5

Fig. 4 The discharge chamber with different length quartz tubes

length, other parameters of RIT-5 were kept constant when RIT-5 worked. The length of gas distributor intruding into the discharge chamber was 10.0 mm. At 1.5 MHz RF frequency, the RF power was controlled as 50 W and 60 W respectively, and the RF power was delivered to the copper coils. The propellant flow rate Q was 0.11 mg/s - 0.15 mg/s which was controlled by the gas mass flow controller. The ion optics system consisted of the screen grid and the acceleration grid. The screen grid connected to the positive high voltage power of 1550 V and the acceleration grid connected to the negative high voltage power of −150 V. The materials of screen grid was molybdenum and acceleration grid was graphite.

The beam current, the electric efficiency and the propellant utilization efficiency of RIT-5 are discussed in this paper, and they are also the factors of evaluating the performance of RIT-5. The beam currents were measured through the positive voltage power and the negative voltage power. And the electric efficiency and the propellant utilization efficiency are defined as eqs. (2) and (3): (Goebel and Katz 2008)

$$\eta_e = \frac{V_b I_b}{V_s I_s + V_a I_a + P_{RF}} \tag{2}$$

$$n_m = \frac{\dot{m}_i}{\dot{m}_p} = \frac{I_b m_i}{e\,\dot{m}_p} \tag{3}$$

$$\eta_t = \eta_e \times \eta_m \tag{4}$$

Where, η_e is the electric efficiency, $V_b I_b$ is the beam power with net voltage V_b and beam current I_b, $V_s I_s$ is the positive voltage power with screen voltage V_s and screen grid current I_s, $V_a I_a$ is the negative voltage power with acceleration voltage V_a and acceleration grid current I_a, and P_{RF} is the radio frequency generator power, and η_m is the propellant utilization efficiency, η_t is the total efficiency of the thruster, m_i is the ion mass, e is the electron charge, $\dot{m}_i$ is gas ionization rate and $\dot{m}_p$ is the propellant mass flow rate.

The results in section 3 are all calculated by eqs. (2)–(4). The propellant gas used in the experiment was Xe and the parameters of Xe are taken in eqs. (3)–(4).

The ion optics system is close to the discharge chamber that can be seen in Fig. 1. There is a potential difference between the plasma and the screen grid, so that the ions are extracted from the holes of ion optics system. And the potential difference between the ion optics system grids will focus and accelerate the ions. In the RIT-5, a two-grid ion optics system was applied and the structure of ion optics system was shown in Fig. 5. There are 241 holes on the screen gird and the accelerating grid, which was designed for milliNewtons thrust.

Results

The ignition of RIT-5 is caused by the discharge of ion optics system by a pulse high gas pressure, and generates a large number of electrons between the ion optics system grids. When the electron enters the thruster discharge chamber and are captured by the electromagnetic field, the neutral particle will collide with the high-energy electrons and ionize, and the thruster enters the working state. Once RIT-5 ignites successfully, the RF power and the propellant flow rate are adjusted to keep the plasma discharge stable (Fig. 6). When the ionization and heat transfer stabilize, the RF power is maintained at

Fig. 5 Structure of the ion optics system (a) the ion optics system with 241 holes, (b) Cross-section of the ion optics system

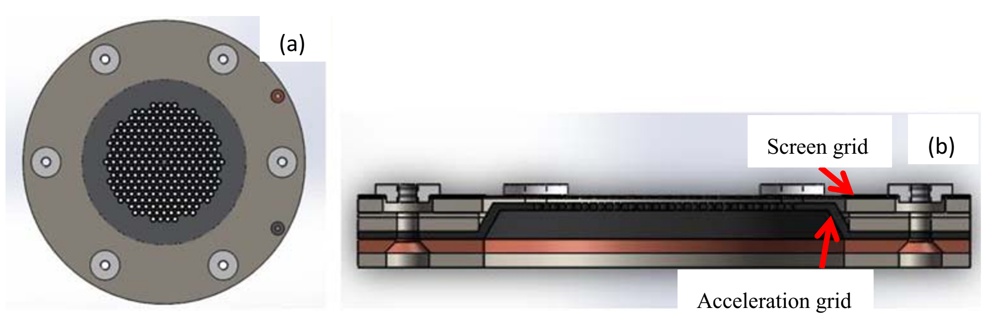

Fig. 6 The discharge in RIT-5

50 W and 60 W respectively, and the propellant flow rate is adjusted from 0.11 mg/s - 0.15 mg/s. Recording the current collected by the ion optics system to obtain the thruster ion beam current value. Comparing the difference performances of the thruster with difference discharge chambers lengths. The lengths of discharge chamber were 27.6 mm, 30.0 mm, 31.9 mm, 35.5 mm and 40.0 mm. The relation between the RF power, the propellant flow rate and the beam current are showed in Fig. 7.

As shown in Fig. 7, beam currents are almost increasing linearly as the propellant flow rate increases from 0.11 mg/s - 0.15 mg/s at the same RF power. But with different discharge chamber lengths, the increase of beam current is not in proportion to the discharge chamber length, and the beam current values are higher at lengths of 30.0 mm and 31.9 mm relatively. The beam current at length 27.6 mm is lower than the beam currents at lengths 30.0 mm and 31.9 mm, but higher than the beam currents at lengths 35.5 mm and

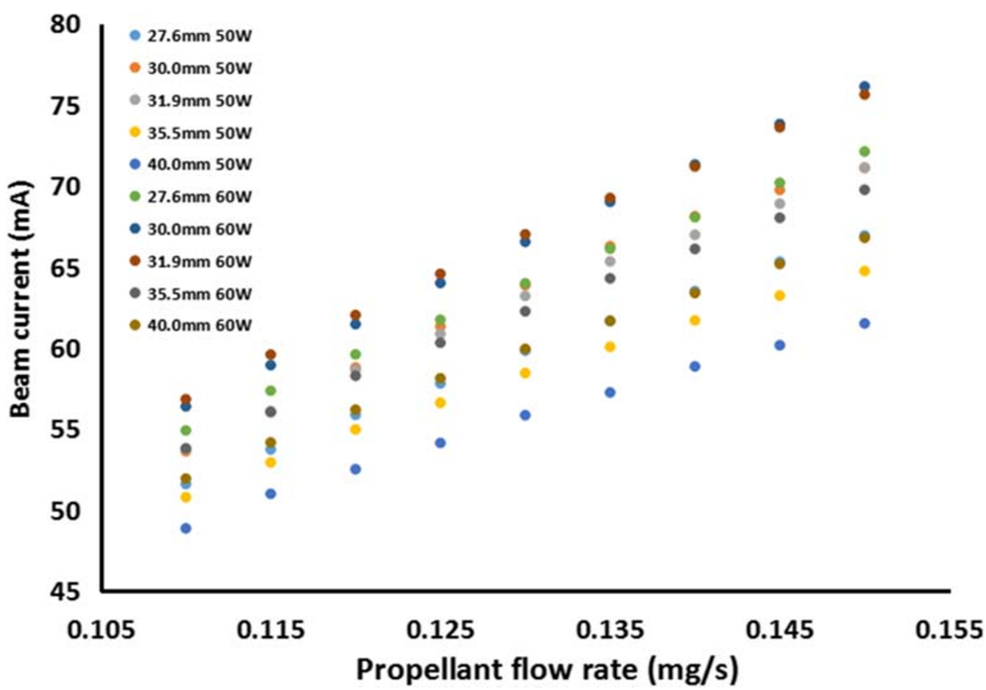

Fig. 7 Beam currents at various propellant flow rates and discharge chamber lengths with the RF power 50 W and 60 W

40.0 mm. According to eq. 5 (Goebel and Katz 2008), the beam current of RIT-5 extracted by the electric field of ion optics system mainly depends on the plasma density in the discharge chamber.

$$I_b = n_i e v_i A_a \tag{5}$$

Where n_i is density of plasma, v_i is ion velocity and A_a is the beamlet area in the grid aperture. And another key parameter of obtaining high ion current is the electron temperature between the heating region and the extraction region. The electron temperature can be controlled by plasma length (Pascal et al. 2011). The gas ionization rate is inversely proportional to the neutral density n_g and effective plasma size d_{eff} according to eq. (6) (Lieberman and Lichtengerg 2005):

$$\frac{K_{iz}}{u_B} = \frac{1}{n_g d_{eff}} \tag{6}$$

Where K_{iz} is gas ionization rate and u_B is the Bohm speed.

Therefore, it is evident that the discharge chamber length has an essential effect on plasma density, electron temperature and beam current, and excessive long length of discharge chamber is adverse for generating higher plasma density. In addition, the plasma density and the beam current also depend on the propellant flow rate and the RF power as shown in Fig. 7. Under the same of discharge chamber length, the beam current also increases with the increase of the propellant flow rate and the RF power respectively. And the beam currents of 30.0 mm and 31.9 mm are still the largest. Consequently, comparing beam currents with the changes of three parameters: propellant flow rate, RF power and discharge chamber length, we can see that they affect the beam current and the plasma density crucially.

The effects of discharge chamber length on ion source have been studied briefly by Kyoung-Jae Chung (Chung et al. 2014). But they researched the effects of discharge chamber length on negative hydrogen ion source and they just verified that the short discharge chamber length could increase electron temperature with two size discharge chambers. They also researched the effects of the RF power and the propellant flow rate on plasma density and electron temperature by Langmuir probes. But we found that the excessive short discharge chamber length can't obtain more extracted current from Fig. 7.

Other essential parameters that illustrates the performance of RITs are efficiencies, the propellant utilization efficiency and the electric efficiency. They are calculated in the experiment of RIT-5 and shown in Figs. 8 and 9.

In Fig. 8, with the increase of propellant flow rate 0.11 mg/s - 0.15 mg/s, the propellant utilization efficiencies gradually decrease at various discharge chamber lengths and the same RF power. According to eq. (3), the propellant utilization efficiency is the ratio of ionization rate to propellant mass flow rate. When the propellant utilization efficiency decreases, the propellant gas ionization rate K_{iz} reduces which is defined as eq. (7):

$$K_{iz} = \sigma_{iz}\overline{v}_e\left(1+\frac{e\varepsilon_{iz}}{kT_e}\right)\exp\left(-\frac{e\varepsilon_{iz}}{kT_e}\right) \tag{7}$$

Where σ_{iz} is collision cross section, $\overline{v_e}$ is average speed of electron, kT_e is electron energy and ε_{iz} is ionization energy threshold. When the propellant flow rate increases, the gas density in the discharge chamber will increase, and the elastic collision frequency and inelastic collision frequency of electrons and other particles also increase, which leads to the decrease in electron energy and low ionization rate.

In addition, propellant utilization efficiencies are the highest at discharge chamber lengths 30.0 mm and 31.9 mm. The propellant utilization efficiency at length 30.0 mm exceeds 67% which is 9.7% - 15.6% higher than that at length 40.0 mm. Because the ion optics system is close to the

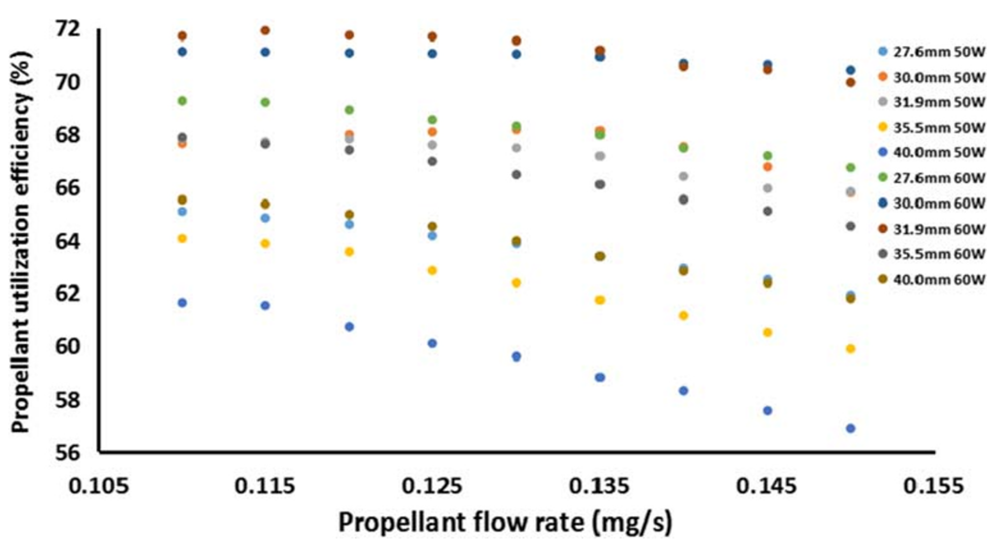

Fig. 8 The propellant utilization efficiency at various propellant flow rates and discharge chamber lengths with the RF power 50 W and 60 W

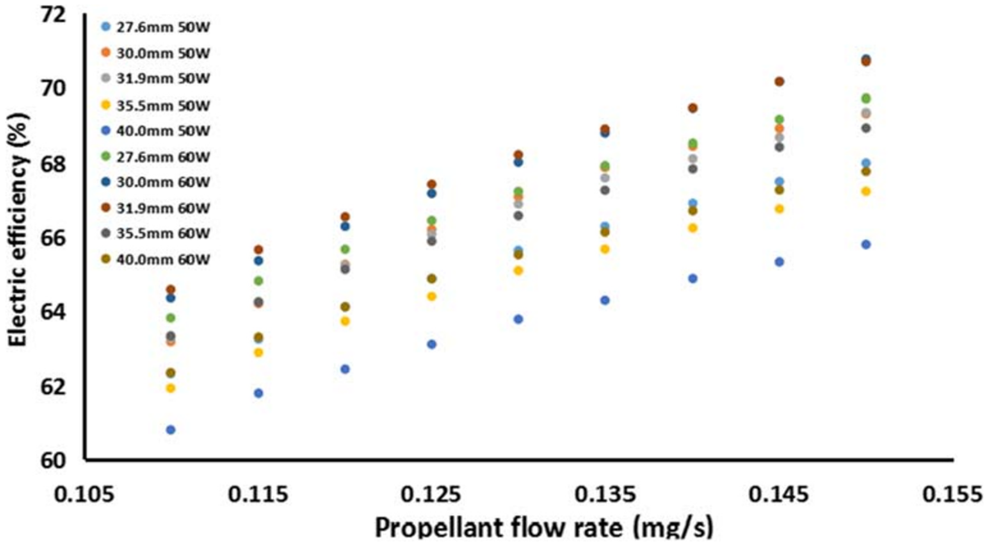

Fig. 9 The electric efficiency at various propellant flow rates and discharge chamber lengths with the RF power 50 W and 60 W

discharge chamber, neutral particles will be extracted out of the short discharge chamber directly by the pressure gradient. At 27.6 mm discharge chamber length, propellant loss increases and the propellant utilization efficiency reduces. And at longer discharge chamber lengths 35.5 mm and 40.0 mm, the energy that the electron obtains from the RF power reduces, which results in a low ionization rate.

As shown in Fig. 9, when the propellant flow rate gradually increases, the electric efficiency also increases at the same RF power 50 W and 60 W, and the changing trend of the electric efficiency is similar with the beam current. From eq. (2) and Fig. 7, the beam current I_b gradually increases with the increase of the propellant flow rate when the RF power is kept constant, which results in the uptrend of the electric efficiency when the propellant flow rate increases 0.11 mg/s - 0.15 mg/s. Due to the increase of the plasma density, the beam current increases with the increase of the propellant flow rate, although the ionization rate decreases. When the length of discharge chamber increases, the ratio of area to volume of discharge chamber decreases, which leads to the lower recombination of ions and electrons.

As same as the propellant utilization efficiency, the electric efficiency has the highest values at the discharge chamber lengths 30.0 mm and 31.9 mm. And the electric efficiencies at lengths of 30.0 mm and 31.9 mm are more than 63%, which is 3.2% - 5.5% higher than that at length 40.0 mm.

The result demonstrates that the discharge chamber length affects the propellant utilization efficiency and the electric efficiency, the length of discharge chamber mainly affects the discharge process of plasma. In order to comprehensively summarize the best performance of RIT-5 at which one discharge chamber length, we discuss the total efficiency as shown in Fig. 10.

When the others conditions remain the same and the propellant flow rate increases, the propellant utilization efficiencies decreases, and the electric efficiencies increases, as shown in Figs. 8 and 9. According to eq. (4), the total

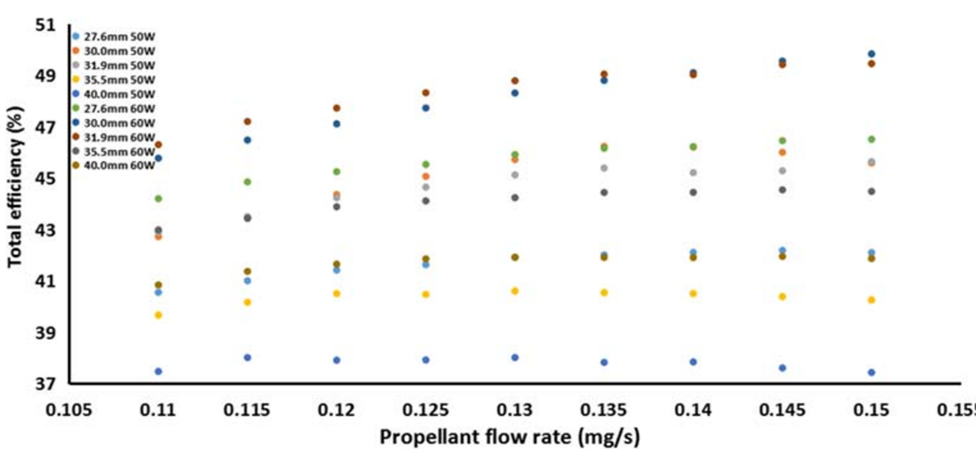

Fig. 10 The total efficiency at various propellant flow rates and discharge chamber lengths with the RF power 50 W and 60 W

efficiency of RIT-5 is the product of the propellant utilization efficiency and the electric efficiency, and the relationship between the total efficiency and the propellant flow rate is non-linear, as shown in Fig. 10. The main reason is that the ionization rate of the neutral particle decreases at a large propellant flow rate, and the propellant utilization efficiency limits the total efficiency of the thruster. The pressure in the discharge chamber is higher at a greater propellant flow rate, so that electrons need more energy from the induction coil for ionizing neutral particle. When the RF power increase, the total efficiency and performance of RIT-5 improve, as shown in Fig. 10 $P_{RF} = 50$ W and $P_{RF} = 60$ W. It means that the propellant flow rate and the RF power are main parameters for adjusting the beam current of RITs. According to Fig. 10, it can be confirmed that the best performances of RIT-5 are at the discharge chamber lengths 30.0 mm and 31.9 mm. Considering the size and weight of the thruster, the optimal length of discharge chamber is 30.0 mm for RIT-5.

Conclusions

For optimizing the performance of RIT-5, the influence of discharge chamber length on discharging has been studied by experiment. The optimal performance of RIT-5 has been obtained through comparison of the beam currents extracted from the discharge chamber, the propellant utilization efficiencies and the electric efficiencies at the discharge chamber lengths 27.6–40.0 mm. According to the experimental results, the performance of plasma in the RIT-5 is non-linear with the change of discharge chamber length and the optimal performance is decided to be at length 30.0 mm. At this discharge chamber length, the RIT-5 is capable of producing the largest plasma density and in the best performance. On the other hand, according to the results, the discharge chamber length has to be considered when designing RITs due to its influence on the plasma performance.

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References

Bassner, H., Killinger, R., Leiter, H., Muller, J.: Development Steps of the RF-Ion Thrusters RIT. 27th International Electric Propulsion Conference. (2001a)

Bassner, H., Killinger, R., Leiter, H., Muller, J., GmbH, A.: Advantages and Applications of the RF-Ion Thruster RIT. 37th AIAA Joint Propulsion Conference and Exhibit. (2001b). https://doi.org/10.2514/6.2001-3494

Chung, K.J., Jung, B.K., An, Y.H., Dang, J.J., Hwang, Y.S.: Effects of Discharge Chamber Length on the Negative Ion Generation in Volume-Produced Negative Hydrogen Ion Source. Review of Scientific Instruments. **85**(2), 02B119 (2014)

Feili, D., Smirnova, M., Dobkevicius, M. Design.: Construction and Testing of a Radio Frequency Mini Ion Engine According to the Propulsion Requirements of the Next Generation Gravity Missions "NGGM". 34th International Electric Propulsion Conference. (2015)

Goebel, D.M., Katz, I.: Fundamentals of Electric Propulsion: Ion and Hall Thrusters, National Aeronautics and Space Administration, California, the United State. (2008). https://doi.org/10.1002/9780470436448.ch7

Groh, K.H., Loeb, H.W.: State-of-the-Art of Radio-Frequency Ion Thrusters. Journal of Propulsion. **7**(4), 573–579 (1991). https://doi.org/10.2514/3.23364

Hu, W.R., Zhao, J.F., Long, M., et al.: Space Program SJ-10 of Microgravity Research. Microgravity Science and Technology. **26**(3), 159–169 (2014). https://doi.org/10.1007/s12217-014-9390-0

Kong, L.X., Gu, Z., Wu, C.C., Guo, N., Wang, M., Guo, D.Z.: On-Line Adjustments Based Optimization of Discharge Chamber Parameters on Ion Thruster. Journal of Propulsion Technology. **39**(3), 709–714 (2018). https://doi.org/10.13675/j.cnki.tjjs.2018.03.027

Lieberman, M.A. Lichtengerg, A.J.: Principles of plasma discharges and materials processing, John Wiley and Sons, Inc. the United State. (2005). https://doi.org/10.1097/01.NNN.0000475911.94610.63

Liu, H.S., Luo, Z.R., Jin, G.: The Development of Phasemeter for Taiji Space Gravitational Wave Detection. Microgravity Science and Technology. **30**(6), 775–781 (2018). https://doi.org/10.1007/s12217-018-9625-6

Loeb, H.W., Schartner, K.H., Weis, S., Feili, D., Meyer, B.L.: Development of RIT-Microthrusters. 55th International Astronautical Congress (2004)

Pascal, C., Nicholas B: Physics of Radio-Frequency Plasmas, Cambridge University Press, New York, the United State. (2011)

Tsay, M., Frongillo, J., Hohman, K.: Iodine-Fueled Mini RF Ion Thruster for CubeSat Applications. 34th International Electric Propulsion Conference. (2015)

Tsay, M., Model, J., Barcroft, C., Frongillo, J., Zwahlen, J., Feng, C.: Integrated Testing of Iodine BIT-3 RF Ion Propulsion System for 6U CubeSat Applications. 35th International Electric Propulsion Conference. (2017)

Walther R J.: RF-Ion Engine Plasma Analysis. 3rd European Electric Propulsion Conference (1974)

Walther, R.J., Geisel, J.E., Pinks, W.F., Rothermel, K.H., Trojan, F.M., Loeb, H.W.: Scaling Laws of Radio-Frequency Ion Thrusters. AIAA 11th Electric Propulsion Conference. (1975). https://doi.org/10.2514/6.1975-367

Zhang, C., He, J.W., Duan, L., Kang, Q.: Design of an Active Disturbance Rejection Control for Drag-Free Satellite. Microgravity Science and Technology. **31**(1), 31–48 (2019). https://doi.org/10.1007/s12217-018-9662-1