Study on discharge character of 200W Hall thruster with metal wall

IEPC-2017-159

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: One 200W annular channel permanent magnet Hall thruster was designed. The magnetic field intensity of section of channel outlet at pitch diameter position is 80% of the maximum magnetic field. An integrated structure of U-shaped shrunk anode/gas distributor is adopted, the whole discharge channel is made of Ti metal, and the channel and the anode are insulated by using BN ceramic. Under the conditions that the anode mass flow is 1, 1.1, 1.2 and 1.3mg/s, the voltage is 150-400V at the interval of 50V, and the power is 118-488W, the discharge properties of the condition under which the channel and shell are insulated or conductive are respectively tested, the results show that when the channel is insulated from the shell, the thrust is 6.2-22.2mN, the specific impulse is 635-1748s, the anode efficiency is 16.3-39.2%, which are slightly higher than the thrust, the specific impulse and the anode efficiency under the condition that the channel is conducted with the shell, and in addition, the potential of the channel and the shell is within 30-90V, which is related to discharge situation.

Nomenclature

$j(\theta)$	=	ion current density
I_b	=	ion current
θ_{div}	=	divergence angle of the plume
T	=	thrust
U_d	=	discharge voltage
I_d	=	discharge current
Isp	=	specific impulse
g	=	gravitational acceleration
η_a	=	anode efficiency
I_i	=	ion current

I. Introduction

Hall thrusters feature simple and compact structure, high specific impulse, high efficiency, and low propellant consumption, thus widely using in spacecraft. Improving the performance and service life of Hall thrusters are is a basic necessity for the continual development of space applications. Sputter erosion of discharge channel, which is caused by the bombardment of high-energy ions, is an important factor restricting the lifetime of a Hall thruster.[1] Moreover, secondary electrons emitted from BN wall significantly affect the overall thruster performance.[2] Considerable researches such as reducing the erosion of the wall by optimizing the magnetic field have been

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conducted to solve the problem. The magnetic shielding (MS) technology[3-8] and the wall-less technology[9-12] proposed by the Jet Propulsion Laboratory and CNRS (Toulouse, France) respectively have been proved to be effective methods to reduce wall erosion. Another method is to consider the geometry optimization of discharge channel, where the oblique channel is adopted to reduce the ion-wall interaction. The research on channel material optimization has also been conducted globally. Rosenberg and Wehner calculated the sputtering yields of different metals subject to He^+, Kr^+, and Xe^+ ion bombardments in 1961.[13] In 1994, Garcia-Rosales et al. presented, revised, and improved analytical formulae for calculating sputtering yields based on several calculations and experiments.[14] In 2003, Doerner et al. measured the sputtering yields of titanium (Ti), molybdenum, beryllium, and carbon under xenon ion bombardment.[15] Both the sputtering yields and secondary electron emission factor are significantly affected by the materials used.[2,16-20] Different materials for the insulating channel influence the discharge characteristics and the thruster service. Therefore, Barral et al. studied the effect of graphite channels on thrusters[21] and Gascon et al. performed comparative experiments on four types of materials: boron nitride (BN), alumina, silicon carbide, and graphite based on SPT-100 prototype.[2] The findings indicate that BN is the only material that benefits a low current and oscillation rate, and a high thrust efficiency of the thruster. Recently, Goebel et al. have conducted a survey relevant to the graphite channel for the H6 Hall thruster by adopting the MS technology;[22] it was found that the graphite channel leads to low thrust and efficiency but contributes to higher specific impulse compared with the BN channel.

So far, numerous materials have been considered to design the thruster wall, such as BN, silicon carbide, alumina, graphite, macor (glass ceramic, mainly SiO_2), and shapal (AlN ceramic).[23] However, there is still no report relevant to Hall thrusters with metallic walls. Compared with the commonly used BN and graphite materials, Ti, as a special metallic material, has an anti-sputtering capability, which is slightly lower than that of graphite, but markedly higher than that of BN. Furthermore, Ti has a lower gas emanation rate and a larger structural strength than BN and graphite. Therefore, taking the technology of pushing down the magnetic field with two permanent magnetic rings[24] as a prototype, we designed a 200 W Hall thruster. The magnetic field structure can push the ionization and acceleration zones effectively to the discharge channel exit. So the wall is only bombarded by low-energy electrons and ions, and the subsequent power deposition is small, reducing the plasma-wall interaction effectively. In this article, we adopted the Ti channel to study the discharge characteristics of Hall thruster. However, there is an essential difference between this design and the thruster with an anode layer (TAL),[25-27] i.e., in TAL, the metallic walls are usually biased to or close to the cathode potential to decrease the electron current. The thruster designed here is of similar structure to that of a traditional BN-wall Hall thruster, which is obviously different from TAL in terms of channel structure and magnetic field. The metal channel of our thruster is completely insulated. Considering a special case where the channel and cathode are connected in TAL, we compared the experimental conditions under which the channel and cathode are insulated or electrically connected, and the change rules of discharge parameters of the thruster with the Ti wall were analyzed.

II. Magnetic Field Characteristics

The 200 W Hall thruster we designed based on the aforementioned technology of pushing down the magnetic field with two permanent magnetic rings, as shown in Fig. 1. Such a magnetic structure can effectively push the ionization and acceleration zones to the exit of the discharge channel. The wall is bombarded only by low-energy electrons and ions, and hence, the power deposition caused by this bombardment is small, which effectively reduces the channel wall erosion. The magnetic field in the channel is formed by two permanent magnetic rings (inner and outer), and the magnetic strength at the channel outlet is approximately 80% of the maximum magnetic field intensity. The structural and support members are fabricated using Ti. The external surface is 50% hollow. This will further improve the heat dissipation to realize a long stable operation. The anode, which is fabricated from nonmagnetic stainless steel, is integrated with the gas distributor. An oblique structure is adopted for the anode, and the tilt angle is consistent with that of the internal magnetic separatrix. The wall material for the discharge channel of the thruster is Ti. BN is adopted for insulation between the channel and the anode, and between the channel and the base plate. The on-off control between the channel and the cathode is realized by a switch. (see Fig. 2 for the 200 W Hall thruster with Ti walls)

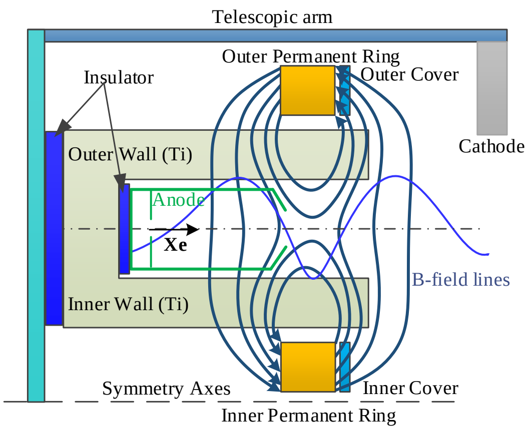


Figure 1. Schematic diagram for magnetic field configuration.

Figure 2. Experimental prototype of 200 W Hall thruster

III. General Guidelines

A self-heated hollow cathode with a lanthanum hexaboride (LaB_6) insert is mounted 40 mm away from the channel exit and 60 mm away from the channel central axis. The mass flow rate of xenon (Xe) propellant is 0.3 mg/s and the background pressure is (2.5-3.0) $\times 10^{-3}$ Pa (for Xe) during the test process. A combined Faraday probe with -50 V bias voltage and arc measurement method is applied to measure the ion current density. The probe diameter is 5 mm and is installed on a rotating arm with a rotational radius of 220 (90 °scanning); surface integral is performed for the ion current within the 90 °scanned area in the semi-spherical surface and the position of 90% of the total ion current is taken as the boundary of the divergence half-angle of the plume. The ion current is obtained as

$$I_b = 2\pi r^2 \int_0^{\frac{\pi}{2}} j(\theta) \sin\theta d\theta \,. \tag{1}$$

According to the measured ion current density $j(\theta)$ and ion current I_b, the divergence angle of the plume θ_{div} satisfies the condition Eq. (2) $0.9 I_b = 2\pi r^2 \int_0^{\theta_{div}} j(\theta) \sin\theta d\theta$. The thrust is measured with a torsion balance,[28] which transforms the thruster force to an equivalent linear displacement with the accuracy of ±0.1 mN. The balance should be calibrated with standard weights before using. A Yokogawa DL850E recorder is used to monitor the discharge current and oscillating peak value. The anode efficiency is defined as

$$\eta_a = \frac{T^2}{2\dot{m} U_d I_d}, \tag{2}$$

where T is the thrust, U_d is the discharge voltage, and I_d is the discharge current. The specific impulse is the thrust produced by a unit weight propellant in unit time, which is calculated as

$$Isp = \frac{T}{\dot{m} g}, \tag{3}$$

where g is the gravitational acceleration.

IV. Results and Discussion

A test with the voltage varying from 200 to 400 V at 50 V intervals and the anode flow rates 1.1 and 1.3 mg/s is performed on Hall thruster with the Ti wall, and in the power range of 190–500 W. Figure 5 shows the variation tendencies of discharge current, thrust, specific impulse, anode efficiency, divergence angle of the plume, and thrust-to-power ratio as the discharge voltage changes. Figure 3 displays an image of the discharge plume under the following conditions: anode flow rate = 1.1 mg/s, cathode flow rate = 0.3 mg/s, and discharge voltage = 250 V. We

can see that the thruster with the Ti channel can discharge stably for a long time. Then, a bright area appears at the channel outlet. The ionization zone is pushed to the channel outlet, and partial ionization occurs in the plume region. This further verifies the technology of pushing down the magnetic field proposed previously. The half of the plume divergence angle is about 46 °,which clearly originates from the downstream shift of the electric field to the channel exhaust, thereby decreasing the focusing efficiency of the electrostatic lens. According to Fig. 5, the thrust and specific impulse increase with the discharge voltage and anode flow rate. When the discharge voltage is 400 V, the anode flow rate is 1.3 mg/s, the power is 500 W, the thrust can reach 21 mN at maximum, and the specific impulse may reach 1590 s. When the discharge voltage is 200–400 V and the discharge current is relatively stable, the anode efficiency begins to increase, and then decreases as the voltage increases. When the discharge voltage is 300 V and the anode flow rate is 1.3 mg/s, the anode efficiency may reach 34% at maximum. Moreover, the thrust-to-power ratio gradually decreases ranging from about 60 to 40 mN/kW as the voltage increases.. In terms of overall performance, the thruster is not as good as the BHT-200 thruster produced by the Busek company.[29-34] The BHT-200 thruster exhibits a thrust of 12.8 mN and a specific impulse of 1,390 s when the nominal discharge power and the
nominal voltage is 200 W and 250 V, respectively. At the same discharge voltage, the thrust of the thruster can reach 12.8 mN, but the specific impulse is only 1,148 s, and the discharge power reaches 235 W. However, experiments show that operational times between 1,300 and 1,500 h will lead to the failure of the nose cone of the BHT-200 thruster, exposing the centerline pole pieces to ion bombardment.[33] The technology of pushing down the magnetic field with two permanent magnetic rings can reduce the channel wall erosion. In addition, the Ti channel wall has the capability of anti-sputtering and structural strength, which guarantees the long service time of thrusters.

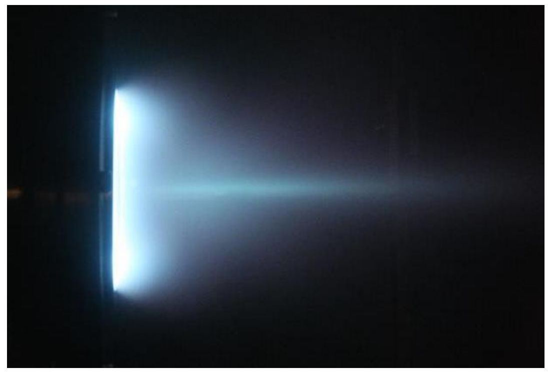
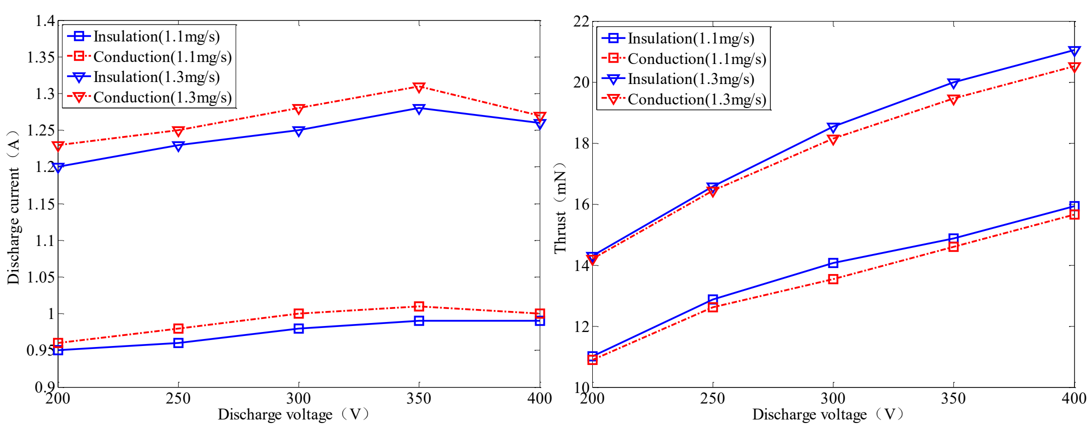


Figure 3. Photo graph of discharge plume.

A switch was used for the on-off control between the channel and cathode, and a comparative experiment was performed. According to Fig. 4, the trend of performance parameters is consistent with that whether the channel and cathode are insulated or not. As mentioned before, Goebel et al. also conducted research relevant to the electrically conducting, floating walls made of graphite for the H6 Hall thruster,[22] and found that, compared with the BN channel, the graphite channel leads to lower thrust and efficiency but higher specific impulse. However, there are no comparative experiments for the channel and cathode that are electrically connected or insulated. Also, the structural strength of Ti is larger than that of graphite. Our experimental results show that the discharge current obtained when the channel and cathode are insulated is slightly lower than that when the channel and cathode are electrically connected. Furthermore, the performance obtained for a connected method between channel and cathode is slightly higher than that of a disconnected one. The absolute value of efficiency increases by 3% at maximum, and the thrust increases by about 0.5 mN. Furthermore, the plume divergence angle also decreases significantly.



a) **b)**

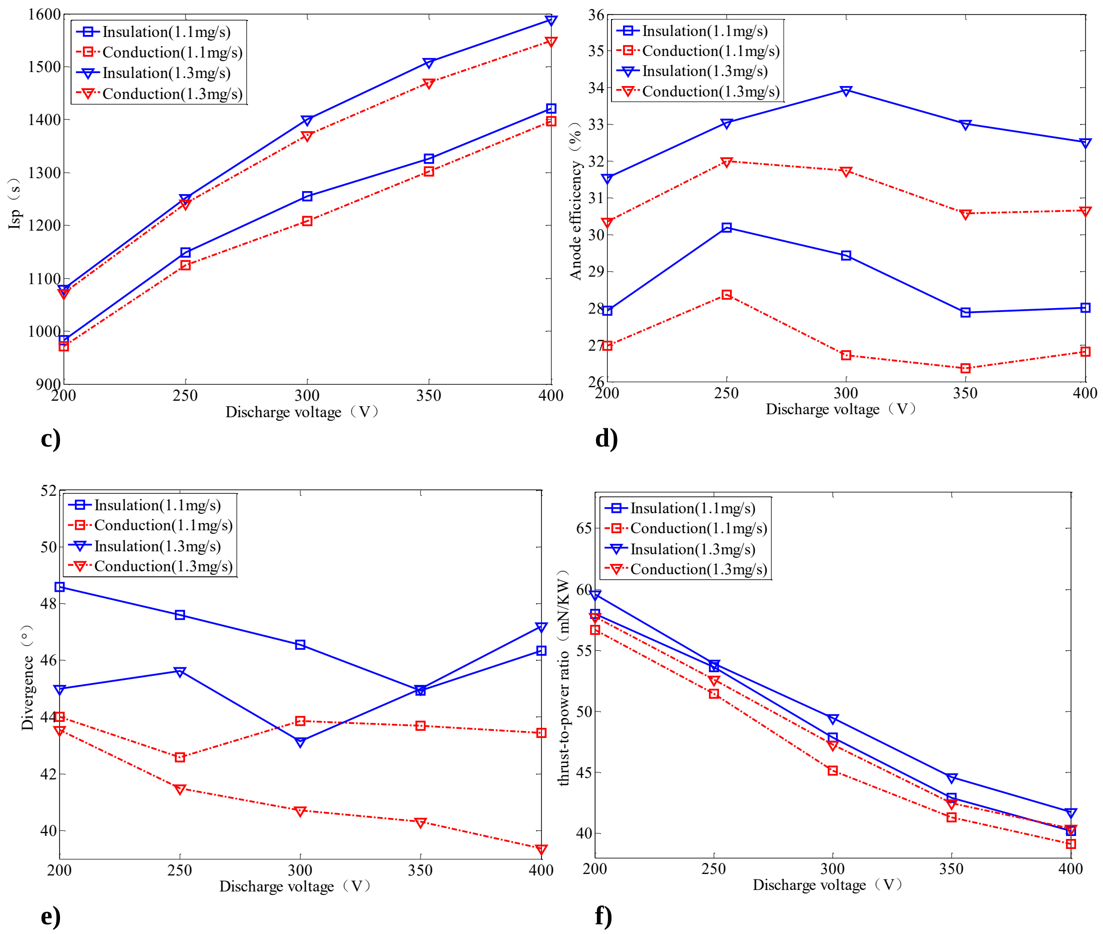


Figure 4. Performance comparison when the channel and cathode are insulated or electrically connected.

The potential difference between the channel and the cathode was measured under "off" condition in order to explain the difference in the previously mentioned comparative experiment. As indicated in Fig. 5, the value measured for the channel is about 60–90 V higher than that measured for the cathode under the following conditions: anode flow rates of 1.1 and 1.3 mg/s, voltage varying from 200 to 400 V and insulated channel and cathode. Figure 6 shows the ratio of ion current to total discharge current (I_i/I_d) when the channel and cathode are insulated or electrically connected; it is clear that I_i/I_d is lower when the metal channel and cathode are electrically connected. Further analysis is that, the channel and cathode are of the same negative potential when they are electrically connected; such a negative potential allows partial ions to directly bombard the wall, causing ion energy loss. A negative potential also repels electrons, make the anode collect more electron current, causing the reduction in Ii/Id. Therefore, compared with insulated metal channel and cathode, the performance parameters such as thrust and specific impulse suffer from certain reduction.

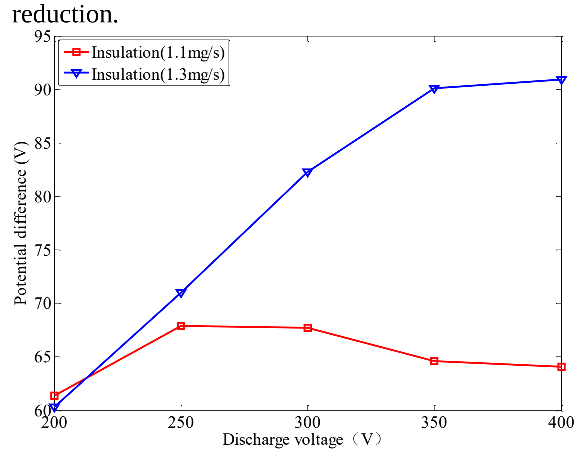


Figure 5. Potential difference when the channel and cathode are insulated.

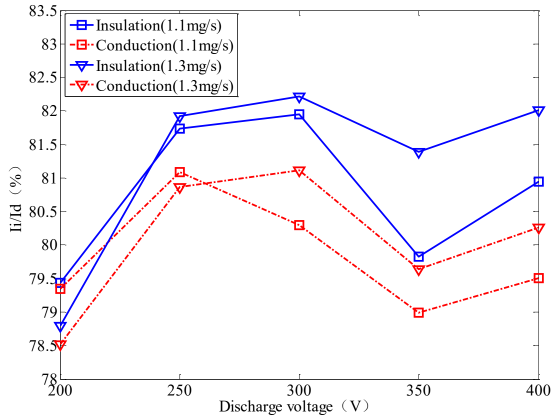


Figure 6. I_i/I_d comparison when the channel and cathode are insulated or electrically connected.

According to the comprehensive analysis of the obtained experimental results, the thruster with Ti metal channel is able to operate stably for a long time. From the comparative experiments we can find that when the channel and cathode are insulated, the angle of plume divergence increases, and other performance parameters including discharge current, thrust, specific impulse, and anode efficiency increase slightly compared with the case in which the channel and cathode are electrically connected.

V. Conclusion

We designed a 200 W Hall thruster based on the aforementioned technology of pushing down the magnetic field with two permanent magnetic rings. Since Ti has a powerful anti-sputtering capability, a low emanation rate of gas, and a large structural strength, we adopted the Ti channel to study the discharge characteristics. Experimental results show that the thruster with the Ti channel can work under stable condition for a long time, and the ignition shock is also small. The half the plume divergence angle is about 46° when the anode flow rates is 1.1 and 1.3 mg/s, the voltage varying from 200 to 400 V and in the power range of 190-500 W; the thrust is 11-21 mN; the specific impulse is 982–1591 s; the anode efficiency is 26.9-33.9%; and the thrust-to-power ratio is 40-60 mN/kW. Furthermore, a comparative experiment was performed when the channel and thruster cathode are insulated or electrically connected. Experimental results show that when the metal channel and cathode are electrically connected, the negative potential of the metal channel causes partial ions to bombard the wall directly, resulting in ion energy loss, and also repels electrons to make the anode collect more electron current. Compared with the case that the channel and cathode are electrically connected, when the channel and cathode are insulated, performance parameters such as thrust, specific impulse, and anode efficiency are improved; the discharge current decreases; the absolute value of efficiency increases by 3% at maximum and the thrust increase is about 0.5 mN. Ti has a powerful anti-sputtering capability, a low emanation rate of gas, and a large structural strength, which provides a new choice for a wall material design of low-power Hall thrusters.

Acknowledgments

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (Grant Nos. 51777045 and 51477035).

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