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A 200-W permanent magnet Hall thruster discharge with graphite channel wall

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ABSTRACT

A 200-W Hall thruster was designed using permanent magnets placing the axial maximum magnetic field outside of the channel, and the anode/gas distributor as an integrated U-shaped structure. A split structure is adopted for the discharge channel to conveniently change the wall material. With the initial conditions that the anode mass flow is maintained at 0.8 mg/s, 1.0 mg/s and 1.2 mg/s over a voltage range of 150–400 V (at 50 V intervals), the discharge properties were determined for the two thruster models with the channel walls composed of graphite and boron nitride (BN). The results demonstrate that under identical operating parameters, the properties of the thruster with the graphite channel walls are similar to the properties of the thruster with the BN channel walls. The maximum difference of the discharge current between the two wall materials is 6.2%; the maximum difference of the thrust and the specific impulse is 3.3%, and that of the anode efficiency is 1.7% (absolute value). These differences are smaller than the corresponding parameter differences observed from changing wall materials in other common Hall thrusters.

The Hall thruster, known for its high specific impulse, large thrust density, and high efficiency, has been widely applied to north–south station-keeping maneuvers for orbital satellites as well as for the orbital lift of satellites [1,2]. The development of spaceflight has placed a greater emphasis on the service life and performance requirements of the Hall thruster. These requirements are primarily focused on the interaction between the plasma and the wall, in the following two situations: (1) high-energy ions bombard and erode the wall, consequently shortening the service life of the thruster; (2) secondary electrons generated by the bombardment of high-energy electrons on the wall can participate in conduction and affect the discharge characteristics [3]. The sputtering yield characteristic and secondary electron emission characteristic of the material comprising the wall directly influence the service life and discharge characteristics of a thruster. Due to the small dimensions, which imply a large surface-to-volume ratio, these effects can have drastic consequences for low power Hall thrusters. There have been multiple studies on the interaction between the plasma and the channel wall. On one hand, the sputtering yield characteristic of the channel wall is increased using composite material technology [4], on the other hand, the erosion of the wall by high-energy ions is reduced primarily by magnetic shielding (MS) technology [2,5–8] and wall-less technology [9–12] to prolong the service life. The different channel materials cause not only different sputtering yields but also different secondary electron emission yields [13,14], which improve performance; this is indicative of the influence of the discharge characteristic of the thruster. Gascon et al. performed a comparative study on four types of materials including boron nitride (BN), alumina, silicon carbide, and graphite on a prototype of SPT-100 [5]; their results demonstrated that the secondary electrons generated by the wall bombardment of high-energy electrons influence the near-wall conductivity and space-charge saturation of the wall sheath. This suggests a maximum difference of up to 50% in the discharge currents under identical operating conditions and an efficiency difference of 20% (50% for BN and 30% for graphite). The electrically insulating BN, with low secondary electron emission and high efficiency at lower current oscillations, was selected as the most appropriate material for the wall. Recently, Goebel et al. studied the graphite channel on an H6 Hall thruster that uses MS technology [15], and determined that the combination of the local magnetic field topology and channel outlet chamfer significantly reduces the plasma contact with the wall in the acceleration zone,

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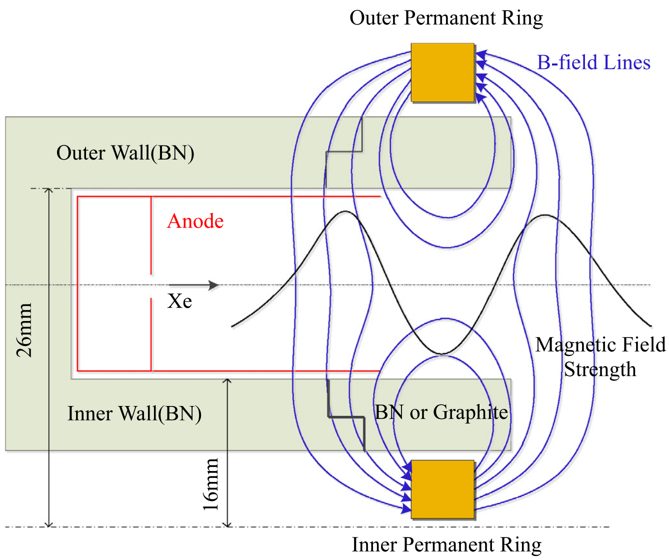

Fig. 1. Diagram for magnetic field configuration.

where erosion typically occurs; the graphite channel, compared with the BN channel, increases the specific impulse, but slightly decreases the thrust and efficiency. The work of Grimaud et al. proved that the effect of the wall material on the discharge characteristic is different based on different magnetic fields in the channel [16].

We have previously conducted studies on the reduction of sputtering of high-energy ions to the channel wall [17,18]. Based on the double-ring magnetic field pushdown technology, a 200W permanent magnet Hall thruster was designed with a magnetic field structure effectively pushing the location of the maximum magnetic field to plume area from the channel outlet potion, so that the ionization zone and the acceleration zone were closer to the outlet of the discharge channel, resulting in a decrease in the interaction between the high-energy ions and the wall since the wall is only bombarded by low-energy ions and electrons. In order to prolong the service life of the thruster, we also studied the discharge channel of graphite with a lower sputtering yield. We chose to study graphite as a material for the wall because it possesses multiple useful properties. These include a low secondary electron yield with high crossover energy (with a secondary electron yield $\geq$1), a higher plasma erosion resistance [13], and a superior structural strength to mass ratio when compared with that of stainless steel. A primary motivation for our work was to compare the effective use of BN and graphite as materials for the wall when using the designed 200-W permanent magnet Hall thruster and to observe the discharge characteristics of graphite as a wall material.

We designed a non-wall-loss-Hall-thruster-200W (NWLHT-200W) based on the technology of pushing down the magnetic field using two permanent magnetic rings [17,18], as shown in Fig. 1. This magnetic field configuration can effectively push down the ionization zone and the acceleration zone to a location near the outlet of the discharge channel; thus, the wall is bombarded by only low-energy ions and electrons possessing less power deposition, which effectively reduces the erosion of the channel wall. The magnetic field in the channel is formed by two permanent magnetic rings (inner and outer) yielding a magnetic strength at the channel outlet position which is 80% of the maximum magnetic field intensity. The material of the magnets is Sm_2Co_{17}. The typical characteristic of this thruster is that there are no other magnetic components except for two magnetic rings which leads to a simple structure. The structural and support components (including magnets covers) are constructed from titanium (Ti), which

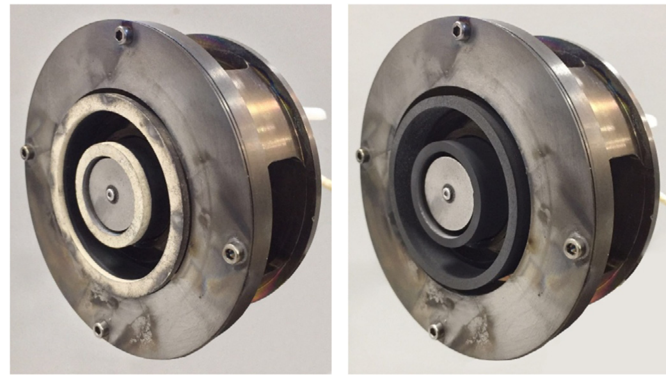

Fig. 2. Picture of NWLHT-200W with wall materials of BN and graphite.

has a lower sputtering yield than pure iron or stainless steel [13]. Here, the thruster shell has a hollow surface allowing improved heat dissipation and an extended stable operation time. In order to facilitate the replacement of the material of the wall, the discharge channel adopts a split-type structure, as shown in Fig. 1, the rear part of the channel is made of BN. The U-shaped anode is integrated with the gas distributor surrounding the rear part of the discharge channel, which is constructed from nonmagnetic stainless steel. Since the magnetic field gradient of designed thruster is larger than the magnetic field intensity of traditional Hall thruster, the U-shaped anode is helpful for the gas homogenization. And the outer radius of the anode is 1 mm smaller than that of the channel, so the anode has no contact with the discharge channel (graphite). The 200-W Hall thruster prototype with a wall constructed from graphite and BN is shown in Fig. 2.

The replacement materials of the wall discharge channel are BN and graphite. According to the related Reference [19], the secondary electron emission yield of BN is larger than that of graphite while working within the electron temperature range of the Hall thruster. The thruster was operated over a broad range of parameters: a discharge voltage, U_d, varied from 150 V to 400 V with an anode flow rate between 0.8 mg/s, 1.0 mg/s and 1.2 mg/s of Xenon. A heated hollow cathode with a LaB_6 insert, which was placed above the channel, was used with a constant xenon mass flow rate of 0.3 mg/s. The cathode and the thruster body were isolated and both were floating. The vacuum pressure was maintained at 2.4–2.8 $\times$ 10^{-3} Pa (for Xe) for the duration of the test process.

The thrust was measured using a torsion balance [20]. It transformed the thruster force into a rotation angle equivalent to a linear displacement in the case of a third medium. The third medium used here was a laser spot reflected by a mirror fixed on the balance. The balance was calibrated using standard weights before each trial. The accuracy of the thrust measurement is $\pm$0.2 mN. The discharge current and the peak-to-peak value of the oscillations were monitored using an oscilloscope. The anode efficiency was calculated by measuring the thrust, discharge current, and mass flow rate. The measurement for the thruster in the contrast test was performed under thermal balance conditions, and the measurement was performed 3 h after ignition.

Fig. 3 shows the plume pictures for the wall materials, BN and graphite, at a discharge voltage of 250 V and an anode mass flow rate of 1 mg/s. From the pictures, the plume does not differ significantly for the two types of materials used for the wall, the ionization zones (white and bright regions) of both are at the channel outlet, and a fraction of the plasma discharge appears to be located inside the channel.

Fig. 4 shows the performance parameters for the discharge voltages from 150 to 400 V, the anode mass flow rate of 0.8 mg/s,