Vacuum 143 (2017) 251–261

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Influence of hollow anode position on the performance of a hall-effect thruster with double-peak magnetic field

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ARTICLE INFO

Article history:
Received 11 May 2017
Received in revised form
18 June 2017
Accepted 19 June 2017
Available online 20 June 2017

Keywords:
Hall-effect thruster
Permanent magnet
Anode position

ABSTRACT

A low-power Hall-effect thruster was designed with two permanent magnet rings. This Hall-effect thruster contains a symmetrical double-peak magnetic field with a gradient larger than that of conventional Hall-effect thrusters. The matching of the anode position with the magnetic field determines the performance of the thruster to a very large extent. This study investigates the laws and mechanisms that govern the front end of a U-shaped hollow anode at the inner magnetic separatrix, the outer magnetic separatrix, and the area between them and influence the discharge characteristics of the thruster. The study shows that with the increase of anode length, the ionization and acceleration zones are pushed down toward the channel outlet and even into the plume region. At the same operating point, both the thrust and the efficiency are the largest when the anode is placed between the inner and outer magnetic separatrices. When the anode is placed at the inner magnetic separatrix, both the thrust and the efficiency are small because of the heavy energy loss on the walls, despite the high degree of ionization. Finally, when the anode is at the outer magnetic separatrix, the performance of the Hall-effect thruster is the poorest because of the lower degree of ionization and larger divergence angle of the plume upon the shift of the ionization zone toward the plume region.

1. Introduction

Hall-effect thrusters (HETs) are widely used in spacecraft owing to their advantages, such as high specific impulse, simple structure, high efficiency, and low consumption of propellant [1–3]. The main drawback of conventional HETs is their relatively short operational lifetime. The primary factor limiting their lifetime is the erosion of the dielectric annular channel walls resulting from high-energy ion bombardment [4–6]. Wall-less (WL) technology [7–10], proposed by CNRS, and magnetic shielding (MS) technology [11–15],suggested by the Jet Propulsion Laboratory, can effectively reduce the wall erosion caused by ions. MS prevents the magnetic field lines from crossing the walls in the acceleration region. Such a topology strongly reduces the magnitude of the radial electric field component, thereby minimizing wall material sputtering. In a WL thruster, the channel erosion rate is significantly reduced by moving the anode to the exit plane of the discharge channel, thereby shifting the region where ionization and acceleration occur entirely outside the channel.

The findings of WL thruster studies show that the anode position significantly influences the potential distribution in a channel and greatly influences the performance and lifetime of the thruster. To date, many researchers performed several studies on the influence of the anode structure, material, and position on the discharge characteristics of the thruster. By changing the anode location and the near-anode channel cross section, Raitses et al. observed that if the near-anode channel cross section is narrowed, the density of electrons that diffuse toward the anode is expected to increase. This would result in an increase in the ionization probability because of the increased rate of ionizing collisions [16]. Yamamoto et al. studied the discharge stability of a thruster with a hollow annular anode and determined that the anode width and location affect the discharge stability of a thruster [17]. Carl et al. studied the influence of the anode temperature on the performance of an HET and observed that a drop in the anode temperature can increase the anode efficiency and thrust–power ratio [18]. Kapulkin et al.

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http://dx.doi.org/10.1016/j.vacuum.2017.06.030

proposed a new low-power Hall thruster called CAMILA (Co-Axial Magneto-Isolated Anode) HT where a longitudinal magnetic field in an anode cavity is created by special anode coils and found that the optimal length of the anode cavity of the CAMILA Hall thruster depends on a discharge voltage [19,20]. In addition, Courtney et al. studied a diverging cusped-field thruster and concluded that the anode position influences electron flow and stability [21]. It can be observed that the previous studies related to this do not consider the relative relationship between anode and magnetic field. Moreover, all studies are performed for single-peak magnetic field Hall thrusters.

Recently, our team proposed a method for pushing the location of the maximum magnetic field to plume area from the channel outlet position [22–24]. The magnetic field morphology can be formed by optimizing the dimensions and positions of the inner and outer permanent magnetic rings. The magnetic field formed only by the two permanent magnetic rings has double magnetic peaks and inner and outer magnetic separatrices. There are no other magnetic conductors. This magnetic field is comparable to the magnetic field formed by four coils in a study reported by Matticari et al. [25–27]. However, Matticari et al. positioned an anode near the magnetic peak at the channel bottom and an intermediate electrode at the zero-magnetic point to study the double-stage discharge. In this paper, single-stage discharge with a U-shaped anode is studied. In contrast to conventional HETs, the thruster designed by us uses a magnetic field with symmetrical double-peak characteristics and a large gradient. The matching of the anode position with the magnetic field determines the performance of the thruster to a large extent. In view of this significant influence of the anode on the physical process of the HET, in this study, we examine the influence of the anode position in a double-peak magnetic field on the discharge characteristics of the thruster.

The remainder of this paper is organized as follows: Section 2 presents the experimental setup, Section 3 describes the experimental results, and Section 4 presents the numerical simulation results and discussion. Finally, the conclusions are provided in Section 4.

2. Experimental setup

We designed a low-power HET based on the aforementioned technology that pushes the maximum magnetic intensity to the plume area with two permanent magnetic rings, as shown in Fig. 1. The magnetic field in the channel was formed by two permanent magnetic rings (inner and outer), and the magnetic strength at the channel outlet position was 85% of the maximum magnetic field intensity. The average magnetic field gradient from zero to the largest axial magnetic field was 23.4 G/mm—larger than the average magnetic field gradient of traditional HETs, which is approximately 10 G/mm. The structural and support members of the HET were made of titanium, and 50% of the external surface was hollow to further enhance heat dissipation and achieve stable long-term operation. As the zero magnetic field was forced considerably closer to the channel outlet, the distance was insufficient for gas homogenization. Therefore, a U-shaped hollow anode, which was integrated with a gas distributor and constructed from nonmagnetic stainless steel, was adopted. The front end of the anode was placed at the inner magnetic separatrix, between the inner and outer magnetic separatrices, and at the outer magnetic separatrix; the three cases are denoted as Anode 1, 2, and 3, respectively. The relationship between the anode position and magnetic field configuration is shown in Fig. 2.

The material of the wall of the discharge channel was BN. The thruster was operated over a broad range of parameters: discharge voltage U_d from 150 V to 350 V and anode flow rate between 1.2 mg/s and 1.3 mg/s of xenon. A heated hollow cathode with a LaB_6 insert was used with a constant xenon mass flow rate of 0.3 mg/s. The cathode and the thruster body were floating and unbound. The vacuum pressure was 2.6×10^{-3}–2.8×10^{-3} Pa (for Xe) during the entire test process.

The ion current density in the plume area determines the divergence angle of the plume and the utilization ratio of the working medium. Therefore, a guarded planar Faraday probe which the diameter of the collecting disk and the width of the ring are 10 mm and 1 mm and an arc measurement were combined to measure the ion current density $j(\theta)$. The measured bias voltage was −50 V, the probe diameter was 5 mm, and the probe was installed on a rotating arm (with rotational radius 30 mm). The probe center moved from the position facing the outer edge of the thruster to the position facing the center of the thruster (90° scanning). The surface integral was determined within the 90° scanned area for the ion current of half of the semi-spherical surface. The position of 90% of the total ion current was considered as the boundary of the divergence half-angle of the plume; see Equation (1) for the specific calculation process.

$$0.9I_b = 2\pi r^2 \int_0^{\theta_{div}} j(\theta)\sin\theta d\theta, \tag{1}$$

where $I_b = 2\pi r^2 \int_0^{\frac{\pi}{2}} j(\theta)\sin\theta d\theta$ is the ion beam current and θ_{div} is the divergence half-angle of the plume.

Propellant utilization can be described by Equation (2):

$$\eta_i = \frac{m_i I_b}{e\dot{m}}, \tag{2}$$

where $\dot{m}$ is the anode flow rate, m_i is the ion mass, and e is the elementary charge. The beam here is assumed to be solely composed of singly-charged Xe ions, for the discharge voltage was kept below 350 V during the whole test process.

The anode efficiency is determined using Equation (3):

$$\eta_a = \frac{T^2}{2\dot{m}U_d I_d}, \tag{3}$$

where T is the thrust, U_d is the discharge voltage, and I_d is the

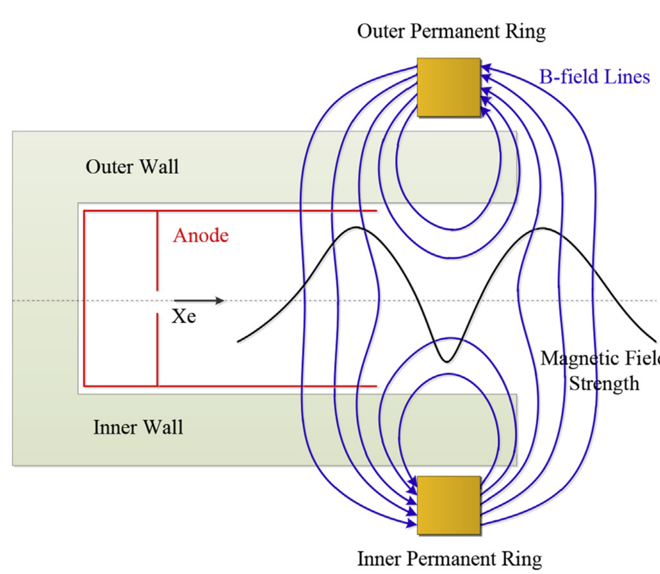

Fig. 1. Schematic of the magnetic field configuration.