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Effect of double-stage discharge on the performance of a multi-mode Hall thruster

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ABSTRACT

In order to develop multi-mode thrusters for all-electric propulsion spacecraft, a double-stage Hall thruster is designed and investigated experimentally. By applying two independent non-emissive electrodes and a double-peaked magnetic field in the double-stage Hall thruster, the propellant can be ionized in the first stage and then accelerated in the second stage. Experiment results revealed that double-stage discharge effectively improves thruster performance in high specific impulse working mode by reducing the electron current. A one-dimensional model is used to discuss the effects of discharge parameters on ionization distribution theoretically. As a conclusion, ionization distribution (in terms of position and length) in high specific impulse mode (mode I) is significantly different compared to high-thrust working mode (mode F). This double-stage Hall thruster provides a double-stage discharge in mode I to enhance the ionization in the channel and a single-stage discharge in mode F to reduce the ion wall-loss, achieving high efficiency in both working modes.

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1. Introduction

Hall thrusters, with high reliability and simple structure, are regularly applied electric propulsion devices nowadays [1,2]. Multi-mode Hall thrusters will be ideal propulsion devices for all-electric satellites or deep-space spacecraft because of the capability of generating a broad range of thrust and specific impulse [3–5]. However, as the ionization and acceleration processes of a conventional single-stage Hall thruster (SS-HET) are controlled by the same electromagnetic field, it is difficult for a SS-HET to work efficiently in a broad throttling range. Hence, its applicability is limited. Consequently, the double-stage Hall thruster (DS-HET) concept is proposed to separate the ionization and acceleration processes in space and optimize them independently, which makes developing high-efficiency multi-mode Hall thrusters possible.

A variety of DS-HET has been studied experimentally and numerically [6–15]. Kuwano developed a DS-HET by applying a microwave discharge ionization stage and reported the effect of microwave injection on thrust performance [11]. However, because of the power consumption of the microwave source, the efficiency of this type DS-HET is relatively low [11]. Bugrova [12] and Yu [16] investigated a potential well double-stage Hall thruster called SPT-MAG, and observed that more than 90% of the propellant ionized in the first stage. SPT-MAG can be operated in multiple working modes with relative high efficiency, demonstrating that the double-stage (DS) design concept is feasible. However, its complex structure impedes its engineering application. Rossetti designed a double-peaked magnetic field DS-HET and employed four commercial cathodes, which served both the role of intermediate anode for the acceleration stage and the role that a cathode traditionally serves in a Hall thruster for the ionization stage [13]. They believed the emissive anode played a key role on the effectiveness of the ionization process [14]. However, the low electron emission from the intermediate anode prevented the thruster from operating as DS discharge in the experiments. Perez-Luna studied this double-peaked magnetic field DS-HET numerically with a PIC code and reported that the ionization and acceleration processes were indeed partially separated [15] because the ion-wall recombination prevented a complete separation. Simulation results also showed that the electrode would neither act as an emissive electrode nor as a cathode. It indicates that the thruster does not really need an emissive intermediate electrode to operate in the configuration [15]. In conclusion, how to design a high reliability and high efficiency DS-HET for multiple working modes is still an open question. Ionization stage design and the effect of the ionization stage on Hall

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thruster performance are the most important problems for a DS-HET. Therefore, a new type non-emissive anode double-peaked magnetic field DS-HET was investigated experimentally in multiple working modes. The general organization of this paper is as follows: Section II gives the experimental set-up, Section III addresses experimental results, Section IV gives the discussion and physical analysis, and the conclusions are given in Section V.

2. Experimental apparatus

The main apparatus used in experiments includes a laboratory prototype DS-HET (hereafter called DSHT100), a set of vacuum systems, a thrust stand system, a data acquisition system, and diagnostic probes.

2.1. DSHT100 thruster

The DSHT100 thruster is a double-anode, double-peaked magnetic field DS-HET designed for multiple working modes. The maximum nominal power is 1500 W. The discharge chamber is made from boron nitride (BN) and outer diameter is 100 mm. A non-emissive anode made from stainless steel is installed between the gas distributor and outlet of the discharge channel, which divides the chamber into two regions as shown in Fig. 1. This wall-mounted anode is the primary anode, and the gas distributor serves as a secondary anode just for DS discharging. The region from wall-mounted anode to the cathode is an acceleration stage, where the acceleration process of the plasma mainly occurs. The region from the distributor to the wall-mounted anode is a complementary ionization stage. By applying an additional voltage on the gas distributor, based on the wall-mounted anode, an ionization stage voltage can be formed in this stage. Magnetic field configuration is significant in Hall thrusters [16,17]. A typical double-peaked magnetic field topology is specially configurated in the discharge chamber as shown in Fig. 2. The magnetic circuit is similar to the generic Hall thruster schematic in Refs. [18], Fig. 3; however, the external trim coil is omitted. An internal trim coil is employed to generate the double-peak magnetic field. It achieves the independent controlling of the magnetic field strength in each stage. An appropriate electromagnetic field in the ionization stage constrains and heats the electron backflow from the acceleration stage, and thus enhances the ionization here. The axial magnetic field strength along the channel centerline is small, as shown in Fig. 2, and the magnetic induction lines curve to the anode. Such a magnetic field configuration is beneficial for ion beam focusing [19]. The magnetic trap near the anode region retains the plasma; the potential here is close to the anode potential.

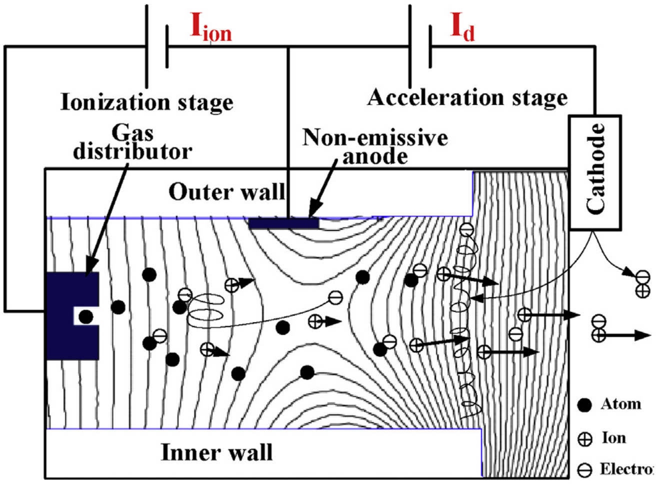

Fig. 1. Schematic diagram of the DSHT100 discharge chamber.

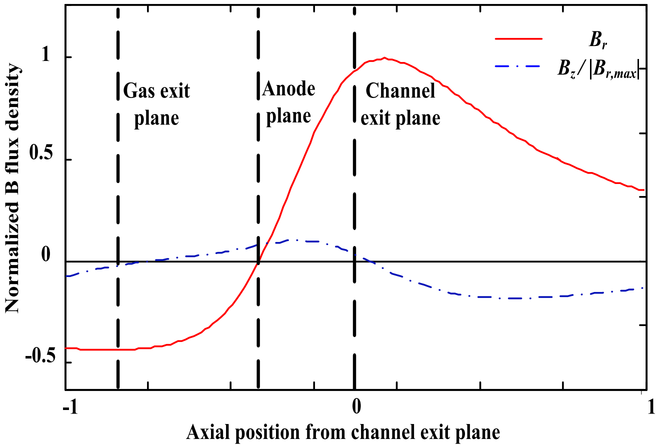

Fig. 2. Magnetic flux density distribution on the center line of the discharge channel. X-axis is normalized by the discharge channel length.

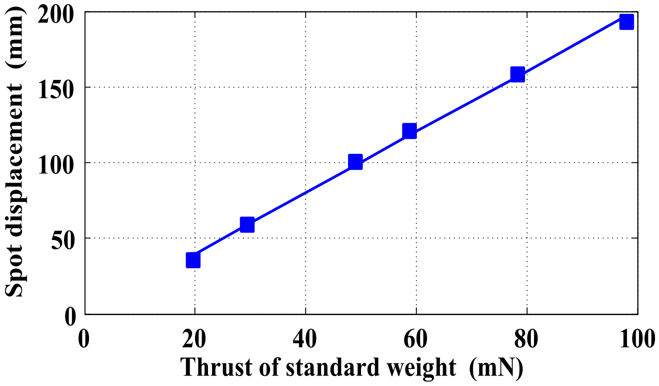

Fig. 3. Characteristics of the thrust measurement system.

DSHT100 is designed to work at two nominal-operation modes: mode F for high thrust at rated power P_t and discharge voltage 350 V; and mode I for high specific impulse at rated power $P_t/2$ and discharge voltage 500 V. Mode F is used for the orbital transfer task in order to get more thrust, and mode I is used for maintaining attitude in order to save propellant (to increase satellite lifetime) and power consumption (for other satellite electric devices). The ionization stage is designed to enhance the ionization and improve the thrust performance mainly for mode I.

The thruster is powered with commercial power supplies. A 10-μF capacitor is parallel connected with the main discharge supply, and used as a discharge filter. A laboratory-model hollow cathode is used to supply electrons. Xenon (99.995% pure) is supplied with commercial mass flow controllers. The uncertainty of the mass flow calibrations are on average ± 1.0%. Thruster telemetry is acquired using a digital oscilloscope with uncertainties of ±0.05% for voltage and ±0.2% for current. The magnetic field is optimized in every experiment condition to achieve the minimal discharge current accordingly.

2.2. Vacuum facility

All experimental trials were performed in the vacuum chamber at Harbin Institute of Technology, Lab of Plasma Propulsion [20].

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