Effect of Propellant Flow Rate on a Cusped field thruster

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Abstract: The cusped field thruster is a unique concept in the electric propulsion which has the advantages of long lifetime, wide range of continuous throttle-ability and high thrust density. Current experiment results have provided that the anode flow rate is one of the key factors affecting the discharge characteristics, especially the ionization and accelerate processes, which have significant effects on the working performance. In this paper, a 2D-3V PIC-MCC model is built to reveal the electron conduction behavior in different flow rate conditions. And the variation tendencies of plasma potential and plasma density are also presented. It is found that the electron conduction behaviors are coincident with the experiment results in different flow rate conditions, and the analysis results show that higher flow rate could promote ratio of electron current travelling along the inner routes in the plume region and increase the electron current near the central axis region in the discharge channel. At the same time, the electric potential drop in the plume region is increased and the ionization region expands to the downstream along the central axis accordingly.

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Nomenclature

HEMP-T = Highly Efficient Multistage Plasma Thruster
DCFT = Divergent Cusped Field Thruster
CCFT = Cylindrical Cusped Field Thruster
PIC-MCC = Particle-in-cell plus Monte Carlo
LIF = Laser-induced fluorescence
U_d = Bias voltage of retarding potential analyzer
DADI = Dynamic Alternating Direction Implicit

I. Introduction

The cusped field thruster is a new concept in electric propulsion, which is first put forward by the THALES Electron Devices named as HEMPTs in 2000[1-3]. In contrast to traditional Hall thrusters and ion thrusters, the cusped field thruster employs alternating polarity permanent magnets to create periodic magnetic field. As shown in Figure1, a set of axial and para-radial cusps serve as the dominant electron confinement to enhance the propellant ionization and to protect the electrically insulating walls of the discharge chamber, thus the lifetime of the thruster is prolonged obviously compared with other types of electric thrusters[4-6]. In 2011, the excellent long-term behavior and unique reliability of HEMPT was fully verified by the 4000 h comprehensive endurance test. The confined electron provides a steep potential gradient at the exit, while the main ionization regions located in the discharge channel, thus a spatial separation of ionization and ion acceleration which results in high specific impulse.

Besides, the cusped field thruster also has many advantages such as the 3 decades continuous throttle-ability, high thrust density, lower mass and easier for integration. All those unique performances gain people's attention and favor, thus similar thrusters are developed such as the MIT's DCFT[4] and Stanford's CCFT[7] and relevant studies have been conducted with great rapidity. Daniel G. Courtney et al. found that there was an obvious transition of the plume occurred when the anode potential changed in different flow rates of the DCFT[4], the bulk of the ionizing plasma would be physically moved upstream in the low current mode[8]. The experiments results of Stanford DCFT also revealed the different changing trends when the flow rate changed while keeping the discharge voltage constant[9]. The laser-induced fluorescence (LIF) experiments validated that the potential distribution near the exit changed significantly when the DCFT operated in the different operating conditions[10].

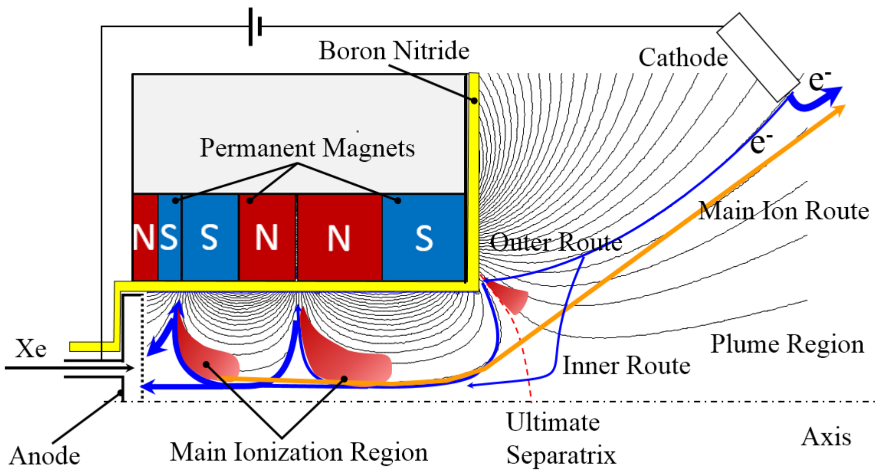


Figure 1. Schematic of the Multi-cusped Field Thruster

It can be found from the above experiment results that the anode flow rate is one of the key factors of affecting the discharge characteristics, especially the ionization and accelerate processes, which have significant effects on the working performance. However, due to its complicated physical processes in the thruster, the detailed description and analysis of its inner behaviors have not been achieved yet. The numerical simulation is regarded as a convenient tool to reveal the influence of the anode flow rate in a cusped field thruster. Since the periodic magnetic field and the strong electric field will make electrons deviate from Maxwell distribution, the particle-in-cell plus Monte Carlo (PIC-MCC) method based on the micro mechanism is a more suitable method to study the physical mechanism in a cusped field thruster. Some works concerning the cusped field thrusters have already been done. Konstantin Matyash's PIC-MCC simulated results demonstrated that the HEMPT-type cusped field thruster allows for a high thermal efficiency due to both minimal energy dissipation and high acceleration efficiency[11]. R. Schneider et.al used the PIC-MCC method to compare the plasma properties and the results indicated that the PIC is a powerful tool to provide important insight into the basic physics of the different thruster concepts[12]. Besides, a 2D PIC model was built by O. Kalentev and the potential, densities and plasma species temperatures of the HEMPT were calculated[13]. The PIC-MCC method could provide a fully self-consistent microscopic description of a plasma and is able to involve complicated atomic and plasma-surface interactions.

As the specific study on the influence mechanism of the anode flow rate is not fully clear yet. In this paper, the movement paths of electrons is analyzed, and a 2D-3V PIC-MCC model is built to reveal the electron conduction behavior in different flow rate conditions and the variation tendencies of plasma properties are also analyzed to identify the consistency between the electron conduction behavior and experiment results in different flow rate conditions.

II. PIC-MCC model

According to the structural features of the cusped field thruster, a PIC-MCC model is applied in this paper. The length of each stages are 8, 16 and 24mm separately, the inner diameter of permanent magnets is 40mm， and the thickness of BN discharge channel is 2.5mm. The axial and radial length of the whole calculation region are 100mm and 50mm, as shown in figure 2. The whole simulation region is composed of discharge channel and plume region. The length of the discharge channel is 50 mm, and the diameter is 34 mm. The Xe atoms are injected to the discharge channel through the stainless steel anode located at the left lateral boundary. The lower and upper boundaries of the discharge channel are the symmetric axis (particles are specularly reflected at this boundary) and a boron nitride dielectric wall. Both the axial and radial length of the plume region are 50mm.The cathode is set at the top of the right boundary of the plume zone, and the injected electrons meet the half Maxwell distribution with an initial temperature of 2 eV. The left boundary of the plume zone is the boron nitride dielectric wall while the upper and right boundaries except the cathode are the free space boundaries (all particles moving across these boundaries would be removed). The discharge voltage U_d of 300 V is applied at the anode, and 0 V is applied at the cathode. The magnetic field is generated by the FEMM externally. The elastic scattering, excitation, and single ionization between electrons and neutral atoms are modeled by the MCC technique[14], and the leapfrog method of Boris is used to solve the particle movement. The Dynamic Alternating Direction Implicit (DADI) method is used to solve the Poisson equation. Besides, anomalous cross-field electron diffusion (Bohm conductivity) is also considered in this model and the Bohm coefficient is set as 1/64. Other parameters of the discharge channel are the same as the former work[15]. The step time is, both the grid length and width are 0.5mm, total number of macroparticles is 1.5×106， and the weight of each macroparticle is 10^5.

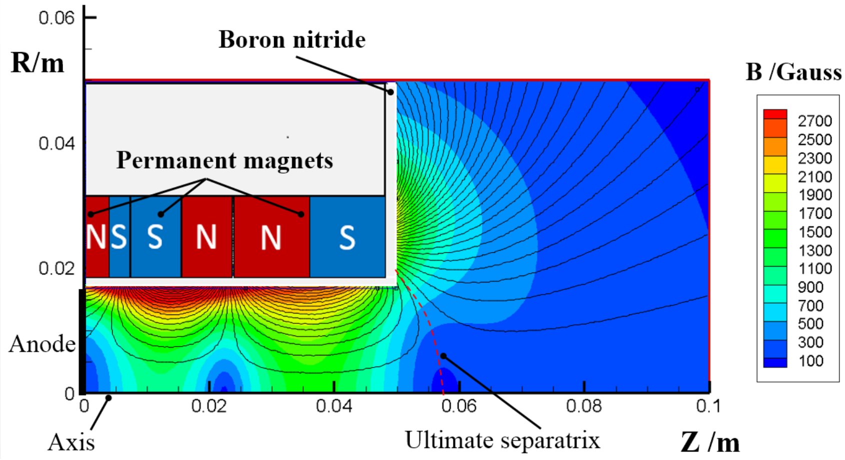
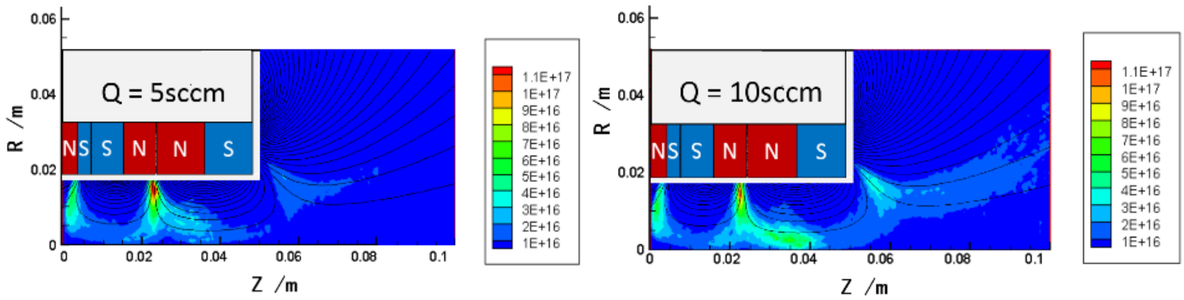


Figure 2. The calculation regions and boundaries set up of a Multi-cusped Field Thruster

III. The simulation results on the plasma properties

In the different flow rate conditions, characteristics of the plasma density distribution can be summarized as follows: As shown in Figure 3, in the discharge channel, the ionization mainly occurs in the upstream of each cusp region, in the other region, with mostly axial magnetic-field component, most plasma distribute near the central axis. While this is antipodal in the plume region, that the peak value of plasma density located at the outer region, not near the axis region. The location of ionization zones in the discharge channel are consistent with theories and experiment results[2] , as the electrons are well confined in the cusp mirror configuration and the gas density is higher inside the discharge channel, the ionization region mainly located in the upstream of each cusp under the influence of applied axial electric field. In the plume region, the characteristics of the plasma density distribution is coincident with the collective observance of hollow plume structure of the cusped field thrusters[16].

Compare the results in different flow rate conditions, we can find that as the flow rate increased to 15sccm, plasma density raised in different levels: the ionization regions in each cusp expand to the downstream along the magnetic field lines, while the extension perpendicular to the magnetic field is not obvious relatively. Intuitively, the increase of anode flow rate could increase the atom density equidistantly along the radius in the discharge channel, while the increase of radial difference with flow rate can be attributed to the change of electron current. The increase of anode flow rate could lead to higher electron current injected the discharge channel, and the radial difference of electron current density could be enlarged. This is because there is a central leak path in the discharge channel that the resistance near the axis is much smaller than the outer region (the position away from the channel central line) for the weak electron confinement of the magnetic field, therefore, the increase of electron current along the axis is much higher than the outer region, the ionization process is promoted significantly, and as a result, there is a noticeable expansion of plasma density to the downstream along the central axis.



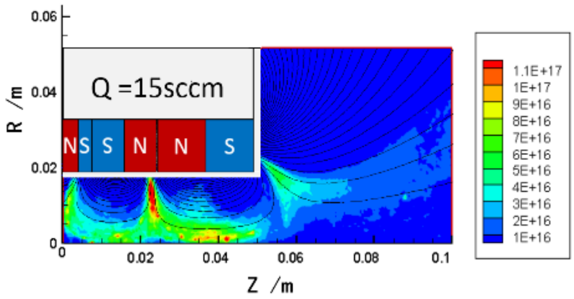


Figure 3. The plasma density distribution (m-3) in the anode flow rate conditions of 5sccm, 10sccm and 15sccm respectively.

The potential distribution in different flow rate conditions are shown in Figure 4. In the lower anode flow rate condition (Q=5sccm case), the potential drop mainly occurred near the exit region while the potential drop in the plume region approximates to zero. Thus a strong axial electric field is formed near the exit. The potential drop in this region is about 200V, and its length is about 10mm, so the average electric intensity can reach about 2×104V/m, which is coincided with the LIF experiment results[10]. In the higher anode flow rate condition, the sharp potential drop could not well maintained near the ultimate separatrix region, and spread to the plume region. It seems to be consistent that the more diffuse plasma plume may occur in the weaker electric field in the high current mode with higher anode flow rate, which is certificated in Ref. 12.

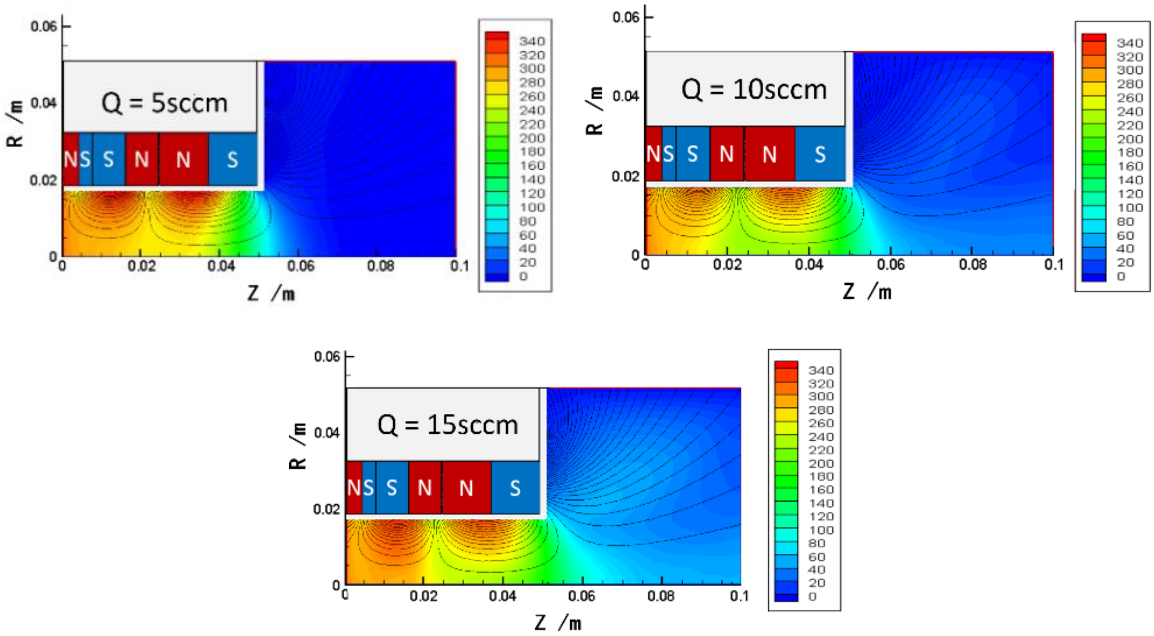


Figure 4. Simulation results of potential distribution (V) in different operation conditions (with magnetic field lines superimposed), the anode flow rates are 5sccm, 10sccm and 15sccm.

Moreover, it should be noted that there is a significant change in the direction of the electric field in the plume region and the potential distribution shows two obvious branches, and two ridge lines of potential occurred: one extends to the cathode along the outer magnetic field lines, the other extend to the downstream along the axis. The variation trend is quite obvious, especially in the 15 sccm condition, as shown in Figure 4. This indicates that the movement characteristics of plasma in the plume region changed a lot with the change of anode flow rate.

As we all know, in Hall thrusters and cusped field thrusters, the magnetic field can influence the movement of electrons, and the electron conduction behavior plays an important role in the formation mechanism of potential distribution. After being emitted by cathode, some electrons will enter the discharge channel, and some other electrons will flow into the plume region to neutralize the ions and keep quasi-neutral condition there. The two typical electron trajectories are shown in Figure 5. The experiment results indicate that some electrons tend to move along the outer magnetic field lines to the last cusp region near the wall. While some other electrons can move across the magnetic field lines along the inner routes.

In order to understand the effect of flow rate more explicitly, a parameter named leak ratio α is defined at the ultimate cusp, as we have defined in Reference18 at the inner cusp, is used here to describe the ratio of the number of the electrons move along the inner routes to the total amount of electrons injected to the discharge channel. By counting on 1000 electrons, it is found that α at the last separatrix increased from 0.12 to 0.25 with the increase of anode flow rate from 5 sccm to 15 sccm.

As the magnetic field in the plume region is strong and mainly axial, the radial electron current is strongly confined, the electrons tend to move along the outer routes, especially in the lower flow rate condition. In the higher flow rate condition, when the density of xenon atoms in the plume region is increased, the radial electron current is enhanced accordingly, and this lead to an increase of electron current conducting along the inner routes. This means that the anode flow rate plays a critical role in adjusting the relative electron current proportion of the two routes in the plume region. Higher anode flow rate can bring about an increase of electron current conducted along the inner routes, and the total electron current injected to the discharge channel.

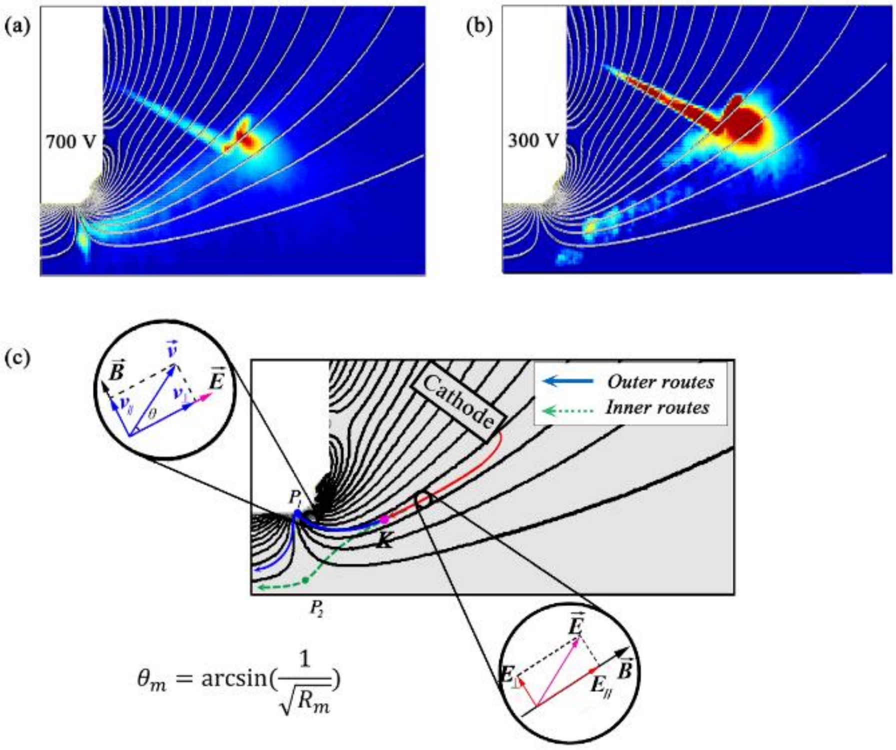


Figure 5. Electron conduction routes in plume region[17]. (a) Light intensity distributions of plasma bridge for the outer electron conduction route. (b) Light intensity distributions of plasma bridge for the inner electron conduction route. (c) Schematic diagram for two types of electron conduction routes.

Based on the analysis above, the variation of potential distribution in the plume region in different flow rate conditions can be briefly analyzed as follow: Firstly, as the total resistance inside the discharge channel is much smaller compared with that the ultimate separatrix and plume region for the low resistance of a central leak path, the variation of potential distribution with the different flow rate is mainly occurred near the exit and plume region. On the other hand, as we have analyzed, in the lower flow rate condition, most electrons in the plume region tend to move along the outer routes, they are well confined by the magnetic mirror force and strongly resisted by the radial magnetic near the ultimate separatrix region. As a result, a main resistance with small electron mobility is formed, and a sharp potential drop occurred near the exit region with a good agreement with the magnetic surfaces near the ultimate separatrix. However, this phenomenon becomes less obvious in higher anode flow rate conditions, which is attributed to the increase of electron current along the inner routes. It's clear in Figure 1 that the inner route bypass the strong magnetic field region and turn to the weaker magnetic field near the central axis region (especially the region near the zero magnetic flux point). In this path, electrons cannot be well confined near the ultimate separatrix region, the main resistance occurred as the electrons move across the mainly radial magnetic lines in the plume region and the potential distribution is consistent with the magnetic surfaces there. Therefore, the electron current in inner routes tend to form a large radial potential drop in the plume region, while the electron current in outer routes tend to form a mainly axial potential drop near the exit plane.

IV. Conclusions

In conclusion, the PIC-MCC model is built and the influence mechanism of the anode flow rate is studied in this paper. It is found that the anode flow rate plays a critical role in adjusting the electron conduction behavior, and higher flow rate could promote the electron current along the inner routes in the plume region and the potential drop in the plume region increased accordingly. Besides, in the discharge channel, as the existence of central leak path, the ionization regions expand to the downstream along the central axis with the increase of flow rate and the ionization process is also promoted in the outer region with the increment of atom density. The formation mechanism of hollow plume in the cusped field thruster and the influence of the anode flow rate should be studied further.

Acknowledgments

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