Effect of magnetic field configuration on discharge characteristics in permanent magnet thrusters with cusped field

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Abstract: Low power electric propulsion today has become a mature and well-established technology for small satellite propulsion system. For the low power thruster, the use of permanent magnets can significantly reduce the total power consumption and the mass of the thruster compared with the electromagnetic coils. The cylindrical Hall thruster with permanent magnet ring and the cusped field thruster are two typical permanent magnet thrusters based on the cusped field. However, the magnetic field configuration are significantly different between these two thrusters. This paper investigates the differences of discharge characteristics between these two thrusters based on the PIC/MCC simulation. The simulation result shows that the ionization regions of the cylindrical Hall thruster are located at the region near anode. However, the ionization regions are located at the near-axis region in the cusped field thruster. The cusped field thruster has additional ionization in the plume. The main potential drop of the cylindrical Hall thruster is also located at the region near anode, and the ionization region and the acceleration region are coupled together. The main potential drop is located at the plume region in the cusped field thruster, with an acceleration region separated from the ionization region. Under the same condition, the anode electron energy deposition of the cusped field thruster is less than that of the cylindrical Hall thruster. Therefore, the cusped field thruster shows larger-range thrust throttling ability according to the previous experimental research.

Nomenclature

B	=	magnetic field
E	=	electric field
X,Y	=	coordinates
$\dot{m}$	=	anode mass flow rate
ε_0	=	vacuum permittivity coefficient
U_a	=	anode voltage

I. Introduction

Low power electric propulsion today has been a mature and well-established technology in terms of small satellite propulsion system.[1] Hall thrusters have been researched through numerous experimental and theoretical works these years and can achieve high performances at kilowatt power levels. However, scaling down the hall

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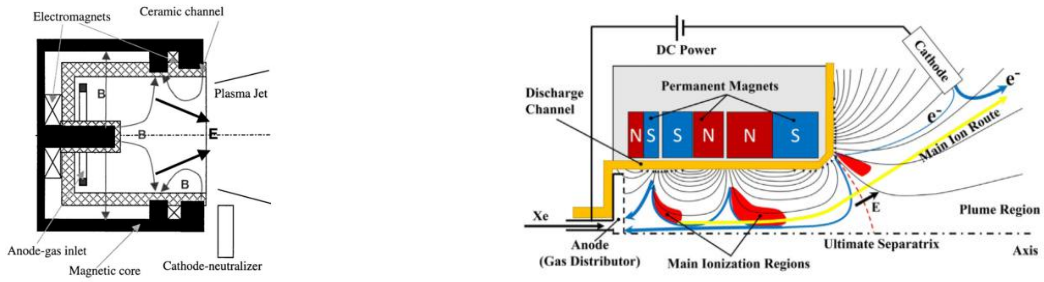
thrusters is facing many difficulties and challenges. In details, the Hall thrusters have large surface-to-volume ratio and have difficulty in miniaturizing the magnetic circuit, which would aggravate the channel wall erosion and limit the thruster lifetime. Therefore, some variants of the Hall thrusters have also been proposed in recent years, using the cylindrical channel configuration to replace the original annular discharge channel. The typical thruster variants include the cylindrical Hall thruster (CHT) and the cuspd field thruster (CFT).



(a) **(b)**

Figure 1. (a) CHT firstly raised in PPPL[2] and (b) CFT firstly raised in Germany

The CHT, which was proposed by Prof. Raitses and Prof. Fisch in Princeton Plasma Propulsion Laboratory (PPPL), can efficiently decrease the surface-to-volume ratio. Both theoretical and experimental studies have been conducted on the CHTs.[34] The magnetic field of the CHT has two types, including "direct-type" and "cusp-type". The magnetic field and can be generated by coils or permanent magnets. When the permanent magnet ring is used to produce the magnetic field of the CHT, the magnetic field exhibits typical "cusp-type" characteristics. Related experimental studies have been reported in the literature before.[5]

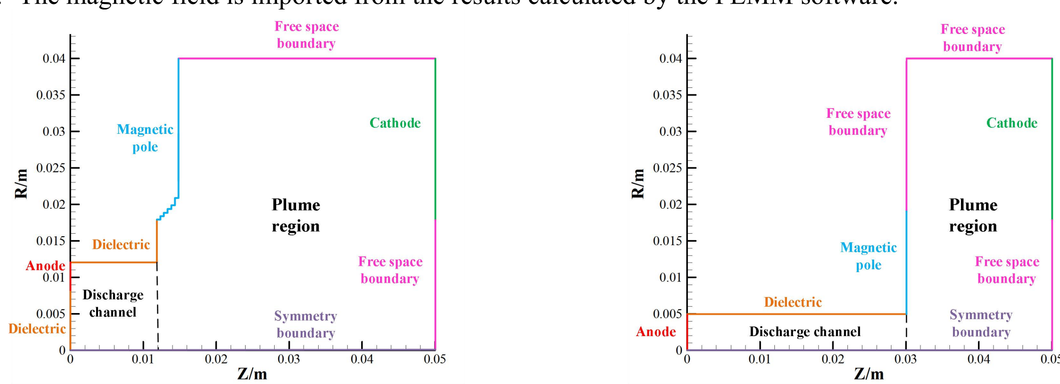
The CFT is a novel concept in electric propulsion, which was firstly rasearched in German. It is also named as the High Efficiency Multistage Plasma Thruster (HEMPT).[6] The specific magnetic field topology in the CFT is formed by a sequential arrangement of permanent magnets, which can form the cusped magnetic field to confine plasma and minimize plasma—wall interaction efficiently

The "cusp-type" CHT with permanent magnets and the CFT have certain similarities in the magnetic field. However, the magnetic field configuration are different between these two thrusters. Therefore, the experimental results of these two thrusters show the differences. For example, under the same working condition, the propellant utilization of the CHT is higher than that of the CFT, and the current utilization of the CFT is higher than that of the CHT. This paper investigates the differences of discharge characteristics between these two thrusters based on the PIC/MCC simulation.

II. Model and magnetic field description

A. Model description

The 2D-3V axial symmetrical PIC-MCC model employs the particle-in-cell method combined with Monte-Carlo techniques to simulate the position, velocity, and energy of the neutral gas, electrons, and ions. This model we developed has been used to study the near-wall conductivity, magnetic mirror effects, and double-stage Hall thrusters.[7] The magnetic field is imported from the results calculated by the FEMM software.



(a) CHT **(b) CFT**

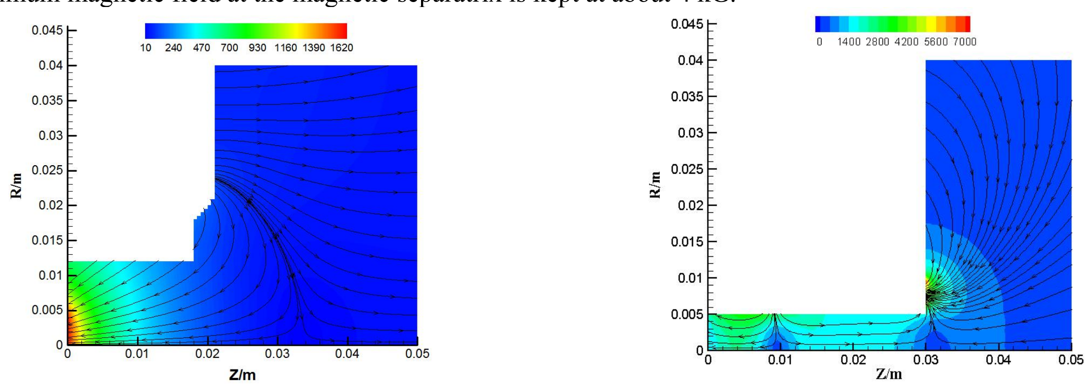
Figure 2. Boundary conditions (a) CHT, (b) CFT

The electron and ion densities are obtained via the simulation of their trajectories. The Boris's leapfrog method is used to resolve the particle movement. The initial speed of new particles is determined according to the half-Maxwell distribution, and the Poisson equation is solved using the dynamic alternating direct implicit method. The elastic scattering, excitation and single ionization between electron and neutral atoms are modeled by the MCC technique, while the ion-neutral, Coulomb collisions and three-body and radiative recombinations are neglected because of their small collision frequency. At the end of each electron loop, ions are created at the ionization locations. The initial ion velocity is set equal to the local neutral background velocity.

Secondary electron emission (SEE) is considered at the dielectric walls. The SEE and electric field models we used at dielectric walls was proposed by Morozov. The electric field at the dielectric surface is $E_{\perp}=\sigma/\varepsilon_0$, here $E_{\perp}$ is the electric field perpendicular to the wall, and σ is the surface charge density collected by the wall. The ε_0 is the vacuum permittivity coefficient. To reduce the computation time, the ε_0 is increased by a factor of γ^2 to reduce the number of grids and iterations. However, the larger artificial permittivity can also lead to more serious charge unbalance. By testing the different values of γ^2, it is found that the charge unbalance degree changes little when $\gamma^2<1600$. So we set γ^2 to be 1600. The feasibility of this method has already been proved in our simulation work before.[8] The anode mass flow rate $\dot{m}$ is set at 0.3 *mg/s* and the voltage applied at the anode is 300 *V*. This 2D-3V PIC-MCC model is applied to study the discharge characteristics of the low-power CHT and CFT.

B. Magnetic field configuration

The magnetic circuit structure of the CHT and the CFT includes permanent magnets and porn. The CHT uses a permanent magnet ring to generate the magnetic field, and a magnetic screen is used to weaken the magnetic field in the plume. The magnetic field at the magnetic mirror is kept at 1.68 kG and there is a magnetic separatrix in the plume region. The CFT with two permanent magnet rings generating the magnetic field is shown in Figure 3 (b). The maximum magnetic field at the magnetic separatrix is kept at about 4 kG.

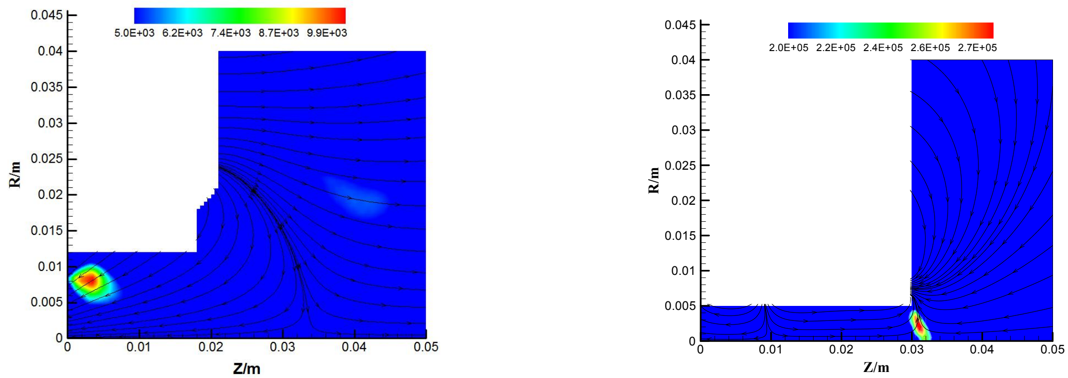


(a) CHT **(b) CFT**

Figure 3. Different magnetic field configuration of permanent magnet thrusters with cusped field (a) CHT, (b) CFT

III. Simulation results and discussion

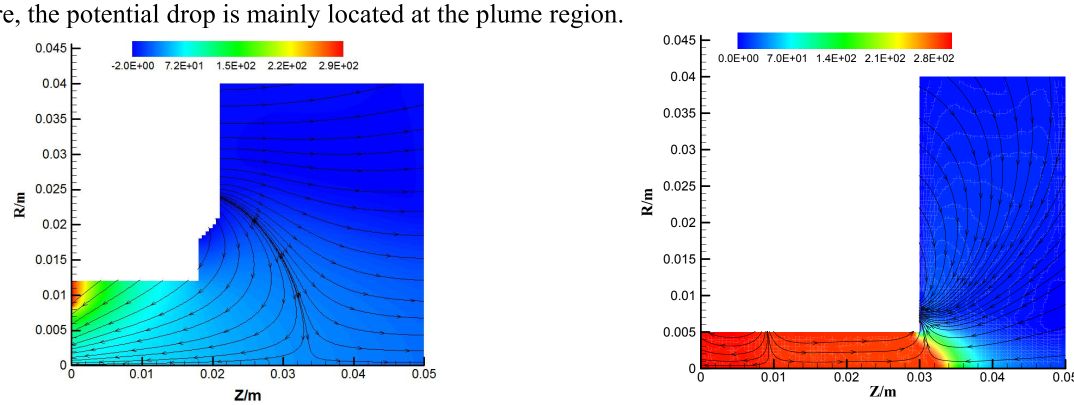
The azimuthal Hall drift current in Figure 4 shows the differences of electron bounding condition between the two magnetic field configurations. There is a strong magnetic mirror in the upstream region of the CHT, and the CFT has a strong magnetic field in the plume region, resulting in significant differences of the electron movement behaviors. The electrons are trapped by the magnetic mirror on the anode side and the electric field on the exit side, bouncing over the axial region. The electrons are conducted to the anode under the influence of the high potential of the anode. The Hall drift current reaches the maximum in the near anode region. The CFT plume region's strong magnetic field forms the strongest bounding on the electrons, so the Hall drift current reaches the maximum in the plume.



(a) **(b)**

Figure 4. Azimuthal Hall drift current density distribution (A/m^2) (a) CHT, (b) CFT

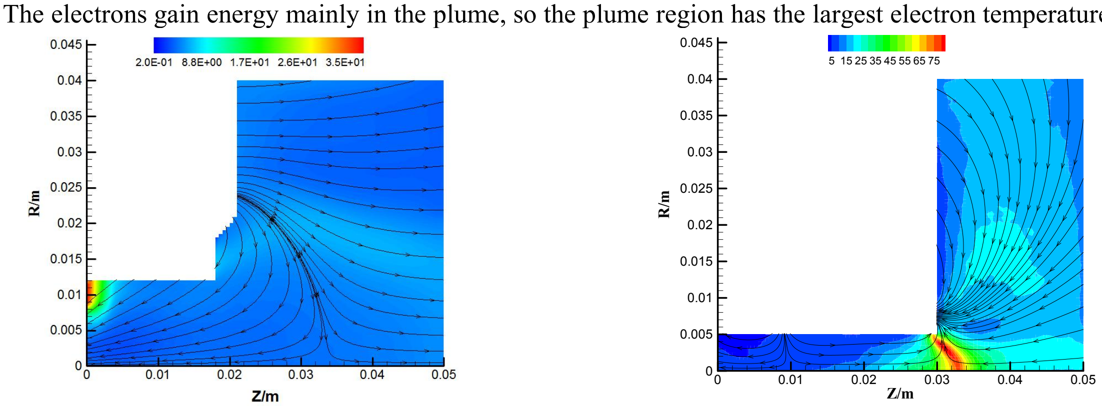
Figure 5 shows the potential distribution of the CHT and the CFT. For the CHT, the magnetic mirror in the upstream region has a stronger bounding effect on electrons, compared to the magnetic cusp in the plume region. The magnetic mirror field in the upstream region is the region with the lowest electron mobility in the channel. Thus the main potential drop is concentrated in the near-anode region of the channel. For CFT, the magnetic field in the plume is the place with the lowest electron mobility due to the absence of electron escape path inside the channel.[9] Therefore, the potential drop is mainly located at the plume region.



(a) CHT **(b) CFT**

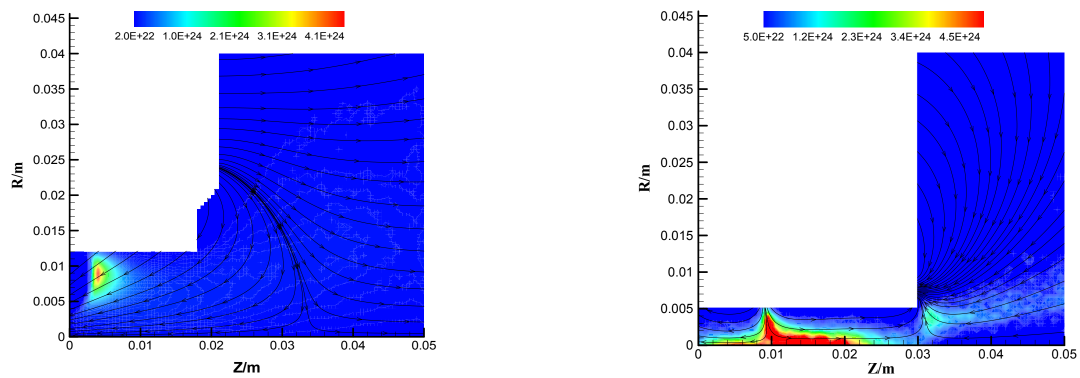
Figure 5. Potential distribution (V) (a) CHT, (b) CFT

As shown in Figure 6, the peak of electron temperature is mainly concentrated in the near-anode region in the CHT, and the electron temperature peak of the CFT is mainly concentrated in the plume region, which is closely related to the potential distribution. The potential drop of the CHT is located at the near-anode region. Thus, the electrons mainly get heated in the near-anode region. The potential drop of the CFT is concentrated in the plume region. The electrons gain energy mainly in the plume, so the plume region has the largest electron temperature.



(a) CHT **(b) CFT**

Figure 6. Electron temperature distribution (eV) (a) CHT, (b) CFT



(a) CHT **(b) CFT**

Figure 7. Ionization rate distributions (a) CHT, (b) CFT

The distributions of the ionization rate are shown in Figure 7. The ionization region of the CHT is located at the near-anode region. The ionization and acceleration regions are coupled together. The ionization region of the CFT is located at the near-axis region inside the channel. The ionization region and the acceleration region are almost separated. There is also additional ionization of the propellant in the CFT's plume. The simulation results are consistent with previous experiments results.[10]

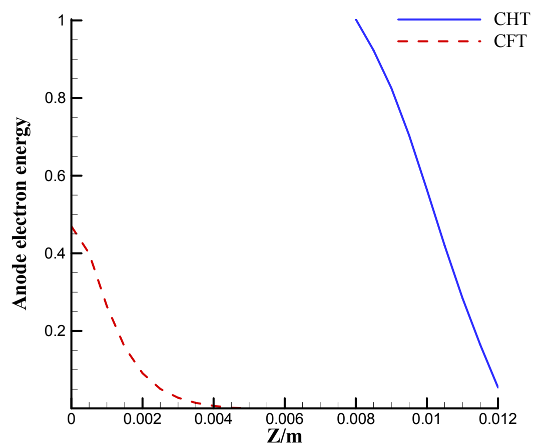


Figure 8. Normalized anode electron energy

Figure 8 shows the mormalized anode electron energy distribution for the CHT and the CFT. It can be seen that the electron energy deposition of CHT is significantly higher than that of CFT under the same operating conditions. The CHT ionization region and the electron temperature peak are mainly concentrated in the near-anode area. Thus, the anode is more likely to overheat in the CHT, so it is difficult to work at a high voltage. The electron temperature of the CFT is the largest in the plume region, and the anode electron energy deposition is low, so it can has a higher voltage regulation range.

IV. Conclusion

This paper investigates the differences of discharge characteristics between the CHT and the CFT. The research results shows that the ionization regions of the two thrusters are significantly different.The ionization regions of the CHT are located at the region near anode. However, the ionization regions are located at the near-axis region in the CFT. Mainwhile, the CFT has the additional ionization region in the plume. The main potential drop of the CHT is also located at the region near anode. Thus, the ionization region and the acceleration region are coupled together. The main potential drop is located at the plume in the CFT, with an acceleration region separated from the ionization region. The simulation results also show that the anode energy deposition is smaller in the CFT, indicating that the CFT can achieve a better confinement for eletron.

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