Design of Magnetic Circuit for Stationary Plasma Thruster

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Abstract. SPT-100 electrostatic thruster is considered, and the effects of magnetic circuit is studied by introducing magnetic screen. The magnetic flux density in the discharge channel is generated with the help of one inner coil and four outer coils. The radial magnetic field has to be maximum near the exit plane of the thruster to trap the electrons in acceleration region which are emitted from an external hollow cathode. These electrons help in increasing the ionization rate of the propellant gas. This is obtained by placing magnetic poles near exit plane. It helps to trap the electrons emitted from the external hollow cathode. The magnetic circuit should be designed such that the magnetic flux density is near to zero at the anode plane to reduce interaction of electrons with channel walls. To arrive at such better design, magnetic screens are used. Computational simulations are performed to quantify the magnetic flux density distribution along the channel using COMSOL Multiphysics software. The simulation results show that the obtained radial magnetic flux density is maximum near the exit plane, and the magnetic screens help in reducing the magnetic field at the anode region while maintaining the maximum magnetic field at the exit plane.

1. Introduction:
Satellite propulsion systems are required for orbit control, change of orbit, and de-orbit after its lifetime. Stationary Plasma Thrusters (SPTs) are one of the most important propulsion systems among electric propulsion which are useful for orbit control and station keeping of satellites. The advantages of using SPTs is that they provide a thrust of 80-100 mN and specific impulse of 1500-2000 s. The lifetime of SPTs is around few thousand hours with efficiency of 50%. They require less propellant mass and are cost effective when compared to chemical propulsion systems. Mostly the propellant used is Xenon (Xe). The SPTs are closed-drift plasma thrusters which have extended acceleration region [1]. The schematic of an SPT-100 is shown in Figure 1. The discharge channel is cylindrical shape for SPTs. Radial magnetic field is established at the exit region of the thruster using a magnetic circuit. Magnetic circuit consists of solenoid coils, one at the center and others outside surrounding the discharge channel. An axial electric field is developed due to anode and cathode. The cathode used is an external hollow cathode and the anode is ring shaped which is placed at the bottom of the discharge channel.

Figure 1. Schematic representation of SPT-100 [2]
The electrons liberated from the hollow cathode accelerate towards anode and encounter magnetic field when they enter the discharge channel. These electrons are caught in the magnetic field lines and are not accelerated directly towards the anode region, which reduces the axial electron mobility. Also, they move along ExB azimuthal direction due to Lorentz force. Thus, a local electric field is induced due to these electrons. Few electrons escape into outer space without entering the discharge channel.

The Xe gas is injected into the discharge channel from the anode with the help of gas injector and flow controller. The flow rate is maintained at 5mg/s for SPT-100 (where 100 denotes the diameter of the cylindrical discharge channel). Plasma is generated due to the ionization of Xe gas by the electrons. The rate of ionization increases due to the increase of collision frequency of electrons with ions since they curl along the thruster axis in the discharge channel. The ions are accelerated due to the local electric field [3]. Later these ions are neutralized by the electrons in the outer space liberated by hollow cathode.

Thus, the magnetic field plays important role to increase the thruster performance. The field should be radial and also maximum at the thruster exit. Parametric investigation of magnetic field is studied by Rossi et al [4]. Many studies have been done to increase the lifetime of thruster and are discussed in various studies [5–9]. The purpose of this study is to design the magnetic circuit and study the influence of magnetic screens on the field variation. SPT-100 is considered for the design aspects.

2. Methodology

The magnetic circuit with necessary boundary conditions is modelled using COMSOL Multiphysics simulation software. COMSOL is a simulation software which is equipped with different physics interfaces and differential equations [10]. The equations solved in the simulations are Maxwell’s equations which are

\[ \nabla \times B = \mu J \]

The total current density J is given by

\[ J = \sigma (E_{ext} + v \times B_{ext}) + J_e \]

Where J_e is the external current density due to coils which is given by

\[ J_e = \frac{N I_{ext}}{A} \]

The geometry of SPT-100 is modelled, different materials are specified and appropriate boundary conditions are applied. The number of coil turns, area of the coil wire and coil current are specified to obtain desired magnetic flux density values.

3. Modelling of SPT-100 magnetic circuit

SPT-100 parameters are chosen for the design. The schematic representation of SPT-100 is shown in Figure 1. The important components of the magnetic circuit are coils to produce the magnetic flux density and is guided by ferromagnetic material such as soft-iron. There are five coils made of copper wire among which four are placed at the corners of a square base and one coil is at the center. The discharge channel is an annular region with 25mm height and 15mm width. It is surrounded by a ceramic wall made of Boron Nitride (BN). The diameter of the annular discharge region is 100mm. The 3D geometrical model designed to perform computational simulations is represented in Figure 2.

Figure 2. 3D model of SPT-100
The magnetic flux density should be maximum at the exit plane of the discharge channel. Inner and outer poles placed at the exit to get maximum field. The field lines have the shape of the lens at the exit symmetrical with respect to channel axis. The opposite poles at the exit are obtained by passing current in opposite direction for inner and outer coils.

3.1 Simplifying 3D model
3D geometries and meshing require more system memory and has high computational time. 2D axisymmetric modelling makes simpler modelling configuration and offers faster computation compared to 3D model. If coordinate system with the z direction along the symmetry axis is used, all partial derivatives with respect to \( \Phi \) vanish. Thus, a two-dimensional problem in the rz-plane is remained. Thus, equations are easier to solve than the one in the Cartesian coordinate system. The 2D axisymmetric geometrical model built to perform computational simulations is represented in Figure 3.

![Figure 3. 2D axisymmetric model of SPT-100](image)

The different components of the 2D axisymmetric model are represented in Table 1.

| Material   | Component                  |
|------------|----------------------------|
| Soft-Iron  | 1. Inner coil core         |
|            | 2. Outer coil core         |
|            | 3. Inner pole              |
|            | 4. Outer pole              |
| BN         | 6. Channel walls           |
| Stainless steel | 7. Anode                |
| Copper     | 8. Inner coil              |
|            | 9. Outer coil              |
| Air        | 10. Air medium             |

Table 1. Components of 2D axisymmetric model

3.2 Importance of magnetic screens
The efficiency of the thruster is reduced by the erosion of the channel wall. The erosion is caused due to the surface interactions with plasma and electron wall collision. Thus, to reduce these interactions the magnetic field should be designed in such a way that the magnetic flux density is near to zero from the anode (located at the bottom of the discharge channel) till the exit region and field is maximum at the exit plane (15-20mT in the case of SPT-100). Thus, the magnetic flux density should be almost zero and increase to maximum at the exit. To obtain such field magnetic screens play an important role. Two annular screens made up of soft-iron are placed on the either side of the discharge channel. These screens do not allow the magnetic field to enter the discharge channel there by reducing the magnetic flux density to zero. The 2D axisymmetric model with magnetic screens is represented in Figure 4.
4. Results and discussions

The required magnetic field for SPT-100 is 15-20 mT at the exit plane [2]. The result of magnetic flux density obtained from the 3D model is shown in the Figure 5. In the discharge channel the maximum magnetic field obtained is 19.2 mT and the lowest is 2.59 mT. The maximum magnetic field is near the exit plane of the thruster (5 mm below the simulated region). It can be noted that there is non-zero magnetic field at the anode plane. This non-zero field would reduce the thruster efficiency. The magnetic flux density results of 2D axisymmetric model are represented in Figure 6.

From Figure 6 it can be seen that the maximum value of magnetic flux density is 16.5 mT and the lowest is 2.37 mT. The maximum magnetic field is near the exit plane of the acceleration region and is near to the inner pole. It can be noted that maximum and minimum values for 2D is 14% and 8.5% lower than 3D quantification. This difference is because of the modelling limitations of number of outer poles.
Figure 6. Plot of magnetic flux density of 2D axisymmetric model

The magnetic flux density can be visualised by the plot of magnetic field lines in Figure 7.

Figure 7. Plot of magnetic field lines for 2D axisymmetric model

It can be seen that inner and outer poles are responsible for the magnetic field in the discharge channel. The concentration of field lines is more at the exit plane and gradually reduces till anode. This is the reason magnetic flux density is maximum near the exit plane.

4.1 Results of magnetic flux density due to application of magnetic screens

The result of magnetic flux density after application of magnetic screens for 3D model are represented in Figure 8. In the discharge channel the maximum magnetic field obtained is 18.3 mT and the lowest is 0.06 mT. The maximum magnetic field is near the exit plane of the thruster (5 mm below the simulated region). It can be seen that the magnetic field near the anode plane is reduced to near 0 whereas maximum value remains almost same.
Figure 8. Plot of magnetic flux density of 3D model with magnetic screens
The result of magnetic flux density with magnetic screens for 2D axisymmetric model is represented in Figure 9. It can be seen that the maximum value of magnetic flux density is 16.5 mT and the lowest is 0.19 mT. The maximum magnetic field is near the exit plane of the acceleration region and is near to the inner pole. The maximum magnetic field remains the same whereas the minimum value at the anode plane is reduced by 99%. This helps in increasing the efficiency of the thruster.

Figure 9. Plot of magnetic flux density of 2D axisymmetric model with magnetic screens
The magnetic flux density can be visualised by the plot of magnetic field lines in Figure 10.

Figure 10. Plot of magnetic field lines for 2D axisymmetric model with magnetic screens
It can be seen that inner and outer poles are responsible for the magnetic field in the discharge channel. The concentration of field lines is more at the exit plane and the field lines end at the magnetic screens. This is the reason the magnetic flux density is reduced near the anode region.

![Figure 11. Effect of magnetic screens on magnetic flux density](image)

Figure 11 represents the effect of magnetic screens on magnetic flux density. It can be seen that the maximum magnetic field for both the cases is same near the exit plane but at the anode region the magnetic field is reduced to a value close to zero.

5. Conclusions

- The 3D and 2D axisymmetric geometrical models of the SPT-100 have been built in COMSOL Multiphysics software.
- Computational simulations of magnetic flux density for both the models have been performed.
- The maximum magnetic flux density is near the exit plane of the thruster.
- The maximum magnetic field at the exit plane is due to the inner and outer poles present at the channel exit.
- The magnetic screens help in reducing the magnetic flux density near the anode plane.

References

[1] Clauss C W, Tilley D L and Barnhart D A 1995 Benefits of Low-Power Stationary Plasma Thruster Propulsion for Small Satellites
[2] Boeuf J P 2017 Tutorial: Physics and modeling of Hall thrusters J. Appl. Phys. 121
[3] Gawron D, Mazouffre S, Sadeghi N and Héron A 2008 Influence of magnetic field and discharge voltage on the acceleration layer features in a Hall effect thruster Plasma Sources Sci. Technol. 17 2–12
[4] Rossi A, Messine F and Henaux C 2016 Parametric Optimization of a Hall Effect Thruster Magnetic Circuit Trans. Japan Soc. Aeronaut. Sp. Sci. Aerosp. Technol. Japan 14 Pb_197-Pb_202
[5] Kim V 1998 Main physical features and processes determining the performance of stationary plasma thrusters J. Propuls. Power 14 736–43
[6] Zhurin V V., Kaufman H R and Robinson R S 1999 Physics of closed drift thrusters Plasma Sources Sci. Technol. 8 R1-20
[7] Morozov A I and Savelyev V V 2000 Fundamentals of Stationary Plasma Thruster Theory Reviews of Plasma Physics (Springer, Boston, MA) pp 203–391

[8] Choueiri E Y 2001 Fundamental difference between the two Hall thruster variants Phys. Plasmas 8 5025–33

[9] Gascon N, Dudeck M and Barral S 2003 Wall material effects in stationary plasma thrusters. I. Parametric studies of an SPT-100 Phys. Plasmas 10 4123–36

[10] https://www.comsol.com/company