Thrust estimation for HTS-magnet based Magneto Plasma Dynamic Thrusters (MPDT)

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Abstract. At present time, electric propulsion is being considered for outer deep space missions. Magneto Plasma Dynamic Thrusters are capable of accelerating semi-neutral plasma gas (Xenon, Iodine, Argon, Ammonia, or Lithium) to a high exhaust velocity using combination of RF power & high magnetic fields. High Temperature Superconducting (HTS) coils can generate high magnetic field due to high operating current density at temperatures below its critical temperature (Tc). These superconducting coils can be cooled by using the cold of outer dark space. The use of 2nd Generation (2G) HTS coils can increase thrust, by increasing high magnetic field with very low power consumption. Thus, specific impulse due to the combination of RF plasma and HTS based superconducting high magnetic field is increased drastically. In this paper, the thrust calculation are carried out for MPDT for varying magnetic fields produced by superconducting coils. The estimation of exhaust velocity and thrust generated by plasma for an MPDT is of great challenge and is required to determine for calculating the life of mission as well as the distance of travel. These estimations are required to support the indigenous development of MPDT.

1. Introduction
At present time, electric propulsion is being considered for outer deep space missions. Magneto Plasma Dynamic Thrusters (MPDT) are capable of accelerating semi-neutral gas (Xenon, Iodine, Argon, Ammonia, or Lithium) to achieve high exhaust velocity using combination of DC biased, RF power & high magnetic fields. High temperature superconducting (HTS) coils can generate a high magnetic field due to high operating current density at temperatures below its critical temperature (Tc). These superconducting coils can be cooled by using the cold of outer dark space. The use of 2nd Generation (2G) HTS coils can increase thrust, by increasing high magnetic field with very low power consumption due to its usage in persistent mode. Thus, specific impulse due to the combination of RF plasma and HTS based superconducting high magnetic field is increased drastically. [1, 2]

Magneto Plasma Dynamic Thruster (MPDT) utilizes externally generated magnetic field to accelerate plasma with high velocity using Lorentz force. The magnetic field can be generated using either permanent magnet or copper based electromagnet. Replacing this with a 2G HTS superconductor can significantly reduce the mass of the thruster, as the superconductor is having multiple fold increases in current carrying capacity below its critical temperature. HTS magnet coils can generate high field with reduced mass.

Ducati et. al. first discovered that electromagnetic acceleration can be used in propulsion [3]. In early research on MPDT, copper based solenoid coil or permanent magnet [4, 5] was
used for acceleration [6]. Most AF-MPDT had the applied field in the range of 0.01-0.6 T [7]. The ReBCO based superconducting 2G tapes are recently developed and are being considered for many applications related to electric space propulsion [8-10]. Glowacki et al. presented theoretical design and benefit of using superconductor based AF-MPDT [11]. 25 kW AF-MPDT is developed and tested (thrust, specific impulse and efficiency) experimentally by Voronov et al. using 2G superconducting magnet coil with 1 T magnetic field density while operating at 100 A and 77 K. This is first experiment that has been reported which utilizes 2G HTS [12].

In section-2 describes the plasma generation simulation used in this paper along with geometry and governing equations. Section-3 discusses the dimension of 2G HTS superconducting coil. In section-4, thrust is computed using governing equations. Section-5 describes the ion distribution along with magnetic flux density, electric field profile, the magnetic flux density profile and section-6 concludes the paper.

2. Plasma generation

Plasma is generated in AF-MPDT by arc created between anode and cathode by application of RF and high voltage. This arc heats up the cathode and ejected electrons from the heated cathode ionize the gas at very low pressure (0.993 Torr). The continuous arc completes the circuit with high flowing current. These currents also create a magnetic field, termed as self field, which is primarily responsible for thrust in SF-MPDT. In case of AF-MPDT, the major contribution for thrust comes from externally excited magnetic coils. To calculate the thrust due to externally excited coil, plasma is generated here using a pre-existing DC discharge model in COMSOL. The model can be seen in Figure 1 and applied biased RF voltage is also mentioned. This model provides us the ion density, ion current that can be utilized to calculate the thrust component due to the externally excited magnetic coil.
2.1. **Geometry used for simulation**

The 3D drawing of geometry used here is shown in Figure 2. The cathode and anode diameter is 10 mm and (ID-50, OD-75) mm respectively. The ID of the external 2G HTS coil is 85 mm. The other details of 2G HTS coil are discussed in the following section. Due to axis symmetric nature of this geometry, the model used for simulation is axis-symmetric as shown in Figure 3. Figure 3 also shows the mesh distribution used for simulation. For plasma generation, the external coil magnetic field is excluded.

2.2. **Plasma chemistry**

Table 1 shows the plasma chemistry and energy involved in respective reactions [13] [14]. The collision type and related energy is also mentioned. These equations are given to describe the behavior of the electron at different atmospheric gas plasma discharge condition.
Table 1: Reaction type and involved energy in plasma formation

| Reaction | Formula       | Type               | Energy loss(eV) | Reaction Rate coefficient |
|----------|---------------|--------------------|-----------------|---------------------------|
| 1        | e+Ar=\rightarrow e+Ar | Elastic            | 0              | 0                         |
| 2        | e+Ar=\rightarrow e+Ars | Excitation         | 11.5            | 5*E-9                     |
| 3        | e+Ars=\rightarrow e+Ar | Superelastic       | -11.5           | 1*E-11                    |
| 4        | e+Ar=\rightarrow 2e+Ar+ | Ionization         | 15.8            | 1*E-8                     |
| 5        | e+Ars=\rightarrow 2e+Ar+ | Ionization         | 4.24            | 4*E-8                     |
| 6        | Ars+Ars=\rightarrow e+Ar+Ar+ | Penning ionisation | -              | 6.2*E-10                  |
| 7        | Ars+Ar=\rightarrow Ar+Ar | Metastable quenching | -              | 3*E-15                    |

2.3. Governing differential equation

The governing differential equation involved in this plasma generation is given by equation 1 to equation 9. The governing differential equation 1 and equation 3 describe the electron number density and electron energy is changing with space and time.

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = R_e - (\mathbf{u} \cdot \nabla) n_e \tag{1}
\]

\[
\Gamma_e = - (\mu_e \cdot \mathbf{E}) n_e - D_e \cdot \nabla n_e \tag{2}
\]

\[
R_e = \sum_{j=1}^{M} x_j \alpha_j N_n \Gamma_e \tag{3}
\]

In equation 1, the first term shows the rate of change of electron number density with time, second term shows the electron number density change with space. Third term is electron flux vector, fourth term is described about electrons loss, due to random motion within the a few mean free paths.

Rate of change of the electron energy density is described by:

\[
\frac{\partial n_\varepsilon}{\partial t} + \nabla \cdot \Gamma_\varepsilon + \mathbf{E} \cdot \Gamma_\varepsilon = s_{en} - (\mathbf{u} \cdot \nabla) n_\varepsilon + (Q + Q_{gen}) / q \tag{4}
\]

\[
\Gamma_\varepsilon = - (\mu_\varepsilon \cdot \mathbf{E}) n_\varepsilon - D_\varepsilon \cdot \nabla n_\varepsilon \tag{5}
\]

\[
\mathbf{E} = -\nabla V \tag{6}
\]

Plasma acts like bulk fluid, because it also follows mass conservation and energy conservation. In the equation 4, the first term shows the rate of change of electron energy with time, second term shows the electron energy change with space, third term is joule heating and forth and fifth term describes about energy gain or loss during the elastic and inelastic collision and last term describes heat generation per unit charge.

\[
\nabla \cdot (\varepsilon_0 \varepsilon_r \mathbf{E}) = \rho_q \tag{7}
\]

Electron energy distribution function is given by:

\[
f(\varepsilon) = \phi^{-3/2} \beta_1 \exp \left( - \left( \varepsilon \beta_2 / \phi \right) \right) \tag{8}
\]
\[ \beta_1 = \Gamma(5/2)^{(3/2)}\Gamma(3/2)^{(-5/2)} \]  
\[ \beta_2 = \Gamma(5/2)\Gamma(3/2)^{-1} \]  

3. HTS coil design

The magnetic field used here in AF MPDT is created using a superconducting coil. The property of superconducting tape [15] used to make this is given in table 2. It consists of 6 coils with an inner diameter of 85 mm and outer diameter of 113 mm. The number of turns in each coil is 200. The operating current of this coil is 120 Amp and the magnetic field profile of this coil produced is given in figure 6. The magnetic field at the center is 0.404 T.

| Table 2: Specification of 2G HTS tape | Table 3: Details of HTS coil |
|--------------------------------------|-----------------------------|
| Parameter                            | Value                       | Parameter                        | Value                  |
| Manufacturer                         | SuNAM                       | Number of turns                  | 200                    |
| Model Number                         | SCN04200                    | Operating current                | 120 A                  |
| Width of tape                        | 4 mm                        | B_{prep} max                     | 0.673 T                |
| Thickness of tape                    | 0.14 mm                     | B at center                      | 0.404 T                |
| critical current at self filed@77 K  | 200 A                       | Number of coils                  | 6                      |
| Critical temperature                 | 90 K                        | distance between coils           | 8 mm                   |

4. Thrust calculation for varying coil current

In this paper thrust produced by MPDT is due to the self field, gas dynamics, electric field and applied magnetic field component as given in table 4. In gas dynamic thrust is calculated using pressure difference and momentum of ions, which is calculated by newton’s second law. Thrust due to applied field is calculated by Fradkin’s [16] and self field is calculated by Maeker equation [17].

\[ T_{Fradian} = J B_{A} \frac{r_{a}^{2} - r_{c}^{2}}{\sqrt{2} \left( r_{a}^{2} + r_{c}^{2} \right)} \]  
\[ T_{maeker} = \mu_{0} \frac{I^{2}}{4\pi} \left\{ \ln\left( \frac{r_{a}}{r_{c}} \right) + 0.75 \right\} \]  

| Table 4: Contribution of each forces in MPDT |
|---------------------------------------------|
| Sr. No. | Type          | Thrust(mN) | % contribution |
|--------|---------------|------------|----------------|
| 1      | Self field    | 4.43E-03   | 0.007479137    |
| 2      | Applied field | 4.77E+01   | 80.53156913    |
| 3      | Gas dynamics  | 1.14E+01   | 19.28030439    |
| 4      | Electric field| 1.07E-01   | 0.180647335    |
|        | Total         | 5.92E+01   | 100            |
Figure 4a shows the variation of magnetic flux density with increasing current. Figure 4b shows the linear variation of total thrust with magnetic field density. According to table 4, major contribution of thrust is due to the external magnetic field of HTS coil. The minimum thrust is 39 mN and maximum thrust is 150 mN.

![Magnetic field density vs Coil current](image1.png)  ![Total thrust vs Magnetic field density](image2.png)

(a) Operating current vs axial magnetic field  (b) Magnetic field vs thrust

Figure 4: Variation of magnetic flux density and thrust with respect to coil current

5. Results and discussions

Figure 5 shows the argon ion density and figure 6 shows the electric field profile due to generated plasma. This also contributes to thrust as it can be seen from the field line directions. Increase in the number density of positive ions causes an increase in the Lorentz force. Higher the number of positive ions within the Debye length, collision frequency and interaction time of ions are higher which leads to thrust.

![Plasma density of argon ion](image3.png)  ![Electric field in plasma chamber](image4.png)

Figure 5: Plasma density of argon ion  Figure 6: Electric field in plasma chamber

In figure 5, it is shown that intensity of ions at the surface of the cathode is high and decreasing in the radial direction. Non-ionized gas molecules near the cathode surface are ionized first. Thrust at the center is the highest. The plasma is formed near the Radio frequency electrode(cathode) with low radius of curvature due to the corona effect.
The electric field formed between RF electrodes moves the ionized species towards the RF ground electrode. These ions collide with neutral gas molecules and electrons transferring momentum and thus creating a flow between the RF electrodes. The plasma gas consists of Ar$^{2+}$, Ar$^+$ ions and Ars (metastable state). These ions depend on the oscillating frequency ($\omega$), contact time($\tau$) and debye length($\lambda_d$). These three parameters will decide number of ions for a particular power input.

In the figure 7 and 8, the effect of second generation High temperature superconductor can be observed. There is high magnetic field density (0.55 T) at the edge of the chamber and it lowers towards the center of the chamber (0.40 T) at 120 A operating c. Because of this, repulsive force acts and forces plasma toward the center of the chamber. Due to the effect of magnetic field, the plasma is moving circularly around the Z-axis. Swirl motion (kinetic energy) of plasma comes out at the end of nozzle with high velocity.

6. Conclusions
In this paper, model has been created to show the capability of radio frequency high voltage in MPDT, which helps to create high ion density and the stream lines of plasma. Plasma stream lines is almost parallel to the center line of thruster in the ion chamber. 2G based superconducting magnet coil is used in MPDT to increase the thrust. The coil is in single pancake configuration and the magnetic field produced (0.40 T) . As the applied magnetic field is high, the plasma density is higher toward the center axis of the chamber. The value of thrust is increasing linearly with increasing current and magnetic field density similar to copper based coil. Maximum magnetic field considered at the edge of the chamber for this analysis, is 0.55 T and 0.404 T at center with 120 A as operating current. Thrust depends on the discharge current and magnetic field strength. The discharge current depends on the number of positive ions produced per unit time. By application high RF voltage, number density can be increased. This MPDT model will help to reduce weight, be less compact, reduce fuel consumption and increase the life of the mission.

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