DESIGNING AND TESTING OF A 1.5 kW HALL EFFECT THRUSTER

[1] Erdal Bozkurt
Middle East Technical University
M.S. Student
Ankara, Turkey

[2] Nafiz Alemdaroğlu
Middle East Technical University
Ankara, Turkey

ABSTRACT

The main purpose of this paper is to introduce the design principles of a Hall Effect thruster and to explain how it is tested in terms of the main plasma parameters, such as the ion current density.

Hall Effect thrusters convert the electric power into thrust by the ionization of the propellant gas and acceleration of the ionized gas in the large electric potential gradient.

The thrust and the specific impulse of Hall Effect thrusters are well suited for the North-South station keeping of geosynchronous orbit telecommunication satellites. The French space agency, Centre National d'Etudes Spatiales launched an experimental telecom satellite Stentor with two Hall thrusters: PPS-1350 and SPT-100 [1]. The PPS-1350 Hall thruster was used for the Earth-Moon transfer in the SMART-1 ESA horizons scientific program [2].

INTRODUCTION

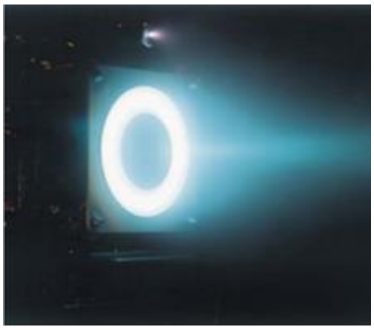

Figure 1: The Hall Thruster while it is functioning.

The main advantage of the high specific impulse is understood when it is looked at the rocket equation:

$$\frac{M_f}{M_i} = \exp\left(-\frac{\Delta V}{g I_{sp}}\right) \qquad (1)$$

----

[1] Graduate Student in the Aerospace Engineering Department in METU, Email: ladreboz@yahoo.com
[2] Prof Dr. in the Aerospace Engineering Department in METU, Email: nafiz@ae.metu.edu.tr

Where M_i and M_f are the initial and final spacecraft masses, respectively, ΔV is the required change in spacecraft velocity for the mission, g is the gravitational acceleration (at the Earth's surface), and I_{sp} is the specific impulse. Equation 1 shows that to maximize the useful payload, we want to maximize the specific impulse. The specific impulse of propulsion systems that depend on chemical propellants are limited to 200-400 sec. On the other hand, electric propulsion systems produce specific impulses in the range of several hundreds to several thousand seconds.

When Hall Effect thrusters are compared to other thrusters, they distinguish themselves with their simple structures as seen the Figure 2. In a conventional Hall Effect thruster, there is an anode that has positive electric potential. The anode is embedded into the inlet of an annular channel produced from a dielectric material, such as boron nitride. The plasma is created in this channel. At the same time, with the application of that dielectric material, this type of Hall Effect thrusters are called as Stationary Plasma Thrusters (SPT). At the anode there are holes where the propellant gas is injected into the annular channel. Around the discharge channel there is a magnetic field created which is axially symmetrical. At end of the discharge channel a cathode with negative electrical potential is placed in order to supply electrons to the thruster.

Although the mechanical structure of the Hall Effect thruster is simpler than other thrusters, its physical working principle is rather complicated. First of all, since the magnitude of the magnetic field is large enough, the electrons cannot approach to the anode, although there is much excessive positive electric potential gradient. On the other hand the ions are not affected from the magnetic field due to their relatively higher mass with respect to the mass of the electrons. Due to this cross electric and magnetic field configuration, electrons compose the Hall Current as seen in Figure 2 in the azimuthal direction shown with red circles and the motion of these electrons is known as the Hall Effect. In the exit plane of the thruster, these trapped electrons not only sustain the ionization by means of the collisions with the propellant gas atoms but they also sustain the sufficient potential drop through the exit plane of the discharge channel for the acceleration of the ions [3].

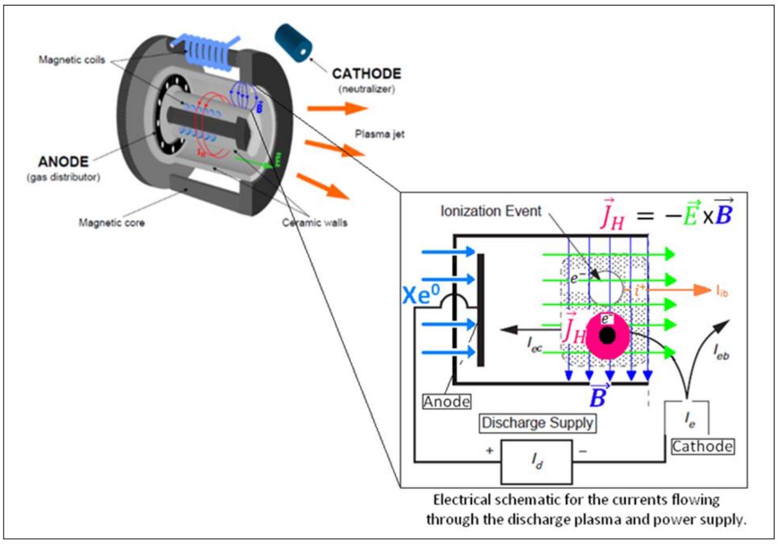

Figure 2: The fundamental structures of the Hall Thruster, electric and magnetic fields, and corresponding Hall current are shown.

DESIGN PROCEDURE FOR THE 1.5 kW HALL EFFECT THRUSTER

The design of a Hall Effect thruster is generally performed based on experimental results since it is not possible to develop a thruster with a sufficient performance level based only on the theoretical principles. Instead, we take advantage of the accumulated know-how by the scientists and researchers. This know-how has brought up a couple of design rules given by the following equations [4]:

$$b_m = 0.3 d_{ch} \qquad [mm] \qquad (2a)$$
$$b_{ch} = 6 + 0.375 b_m \qquad [mm] \qquad (2b)$$
$$L_c = 0.32 b_m \qquad [mm] \qquad (2c)$$
$$L_a = 2 L_c \qquad [mm] \qquad (2d)$$
$$L_{ch} \geq 1.1 L_a \qquad [mm] \qquad (2e)$$
$$\delta_w \approx 0.1\mathrm{d} \qquad [mm] \qquad (2f)$$

For the equation set 2, the parameters are shown in Figure 3. Where d_{ch} is the outer diameter of the discharge chamber, b_m is the separation distance of the front magnetic pole pieces around discharge channel, b_{ch} is the channel width, L_c is the distance from the maximum of the magnetic field to the location where the magnetic field intensity is half of the maximum, and L_a is the distance from the front of the magnetic pole to the anode. δ_{win}, δ_{wout} are inner and outer discharge channel thicknesses respectively. When these equations are put together with the discharge chamber outer diameter "d_{ch}", they provide a principal basis for designing a Hall Effect thruster.

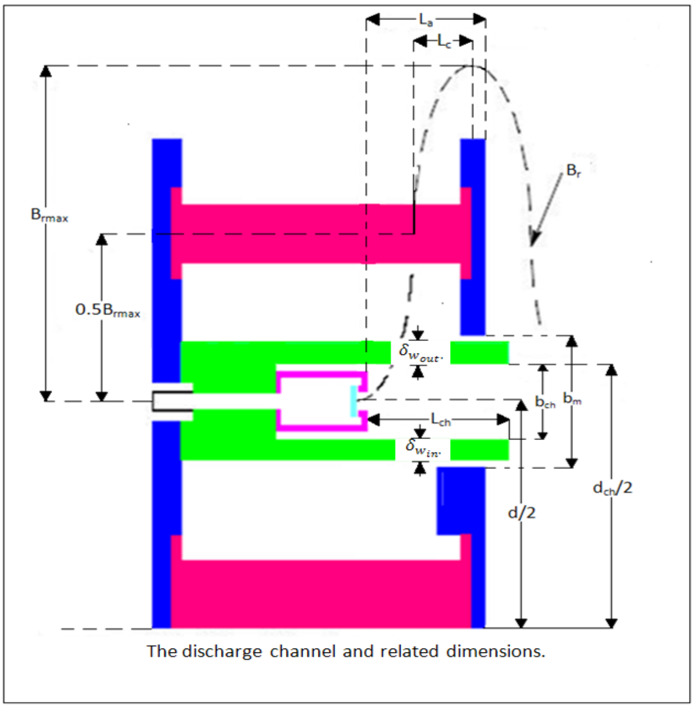

Figure 3: Fundamental design dimensions of a Hall Effect thruster

In order to determine the outer diameter of the discharge chamber, first of all the specific impulse must be known for the mission of the satellite. In the light of the experimental works for the Hall Effect thrusters, it is known that a given specific impulse corresponds to a minimum power level that the thruster operates and that relation between these two quantities is shown in the Figure 4 [4]. In our Hall thruster it is aimed to 1660 sec. of specific impulse. As seen the Figure 4, 1660 sec. specific impulse corresponds to approximately 1.5 kW electric power. At the same time, in order to sustain this power level, from experimental works it is known that the discharge outer diameter "d_{ch}" should be 100 mm [4]. This dimension as well as other parameters are taken from the well-known Russian SPT-100 Hall Effect thruster. In the second step for determining other dimensions of the Hall Effect thruster, equation set given in eq (2) is used.

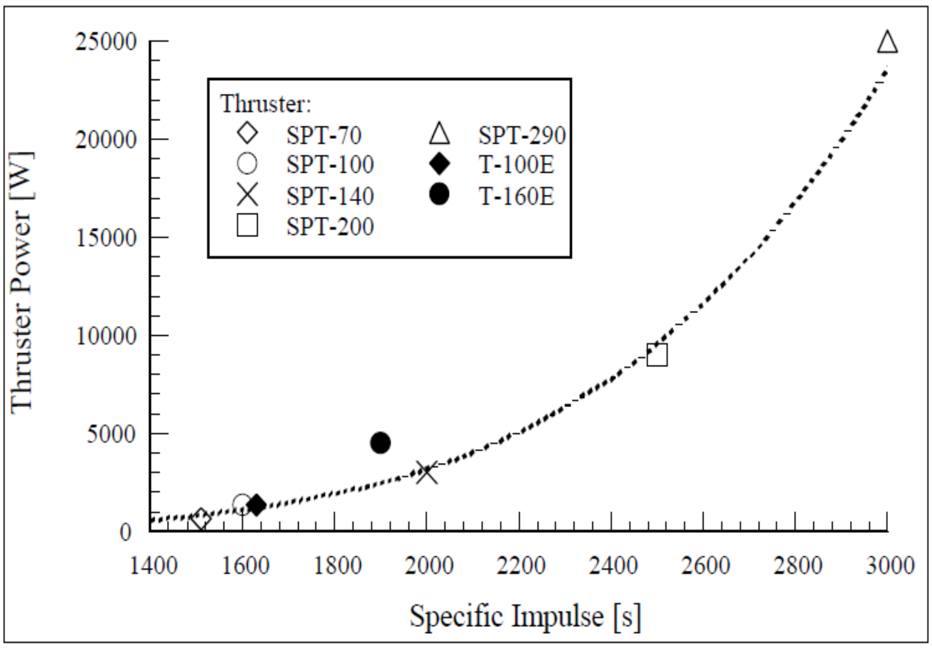

Figure 4: Experimentally determined, specific impulse vs. power table for Hall Effect thrusters.

In the second step of the design, in order to sustain the plasma by means of the accelerated ions, the propellant mass flow rate through discharge channel must be determined. In our design, it is decided to get 70 mN thrust from our Hall Effect thruster. Required mass flow rate is calculated by using Equation 3 by replacing the required specific impulse and the desired thrust values into eq (3) and we obtain a mass flow rate of 4.29 mg/s.

$$\dot{m}_p = \frac{T}{Isp.g} \qquad (3)$$

T (mN)	70
U_d (Volt)	350
Isp (second)	1660
P (kWatt)	1.5
Expected Lifetime (hour)	3500
B_{max} (Gauss)	305
Propellant	Xenon
Total mass flow rate (mg/s)	4.29
Anode mass flow rate (mg/s)	3.9
Cathode mass flow rate (mg/s)	0.39

Table1: After design process Hall Effect thruster operating parameters expected.

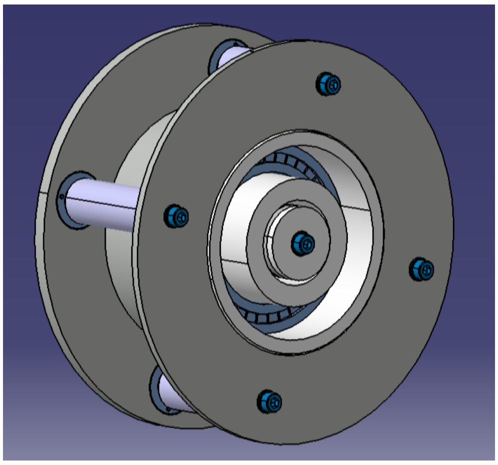

Figure 5: CAD model of the designed 1.5 kW Hall Effect thruster.

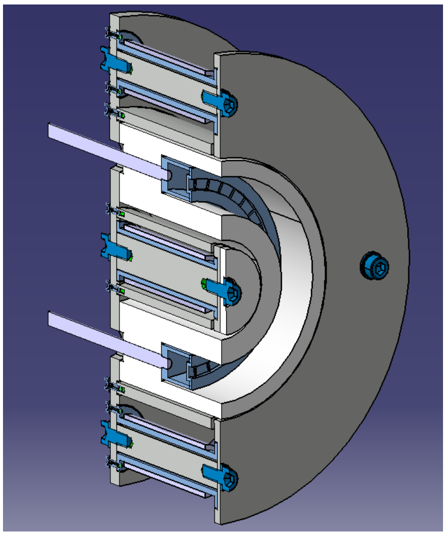

Figure 6: CAD model of the designed 1.5 kW Hall Effect thruster in the cut view.

TESTING OF THE 1.5 kW HALL EFFECT THRUSTER WHILE IT WORKS

After manufacturing the Hall Effect thruster, it is necessary to determine the performance parameters of the plasma thruster by performing measurements. While accelerated ions are moving away from the thruster, the ion beam diverges in a certain angle due to non-uniform magnetic field (or in other words due to magnetic lens effect). That highly energetic ion beam effect the spacecraft. First of all, it is vital to know the angle of the ion beam divergence, since the spacecraft is much more electric sensitive as an electronic device. Secondly, by measuring the ion current density it is possible to experimentally predict the thrust that Hall Effect thruster generates. For this purpose, a device called, Faraday probe is used to measure the total ion beam current. In Figure 7, a typical Faraday probe is shown.

Figure 7: A typical Faraday probe (ref: Yassir Azziz, "Experimental *and Theoretical Characterization of a Hall Thruster Plume"*, PhD. Dissertation, MIT, June 2007.

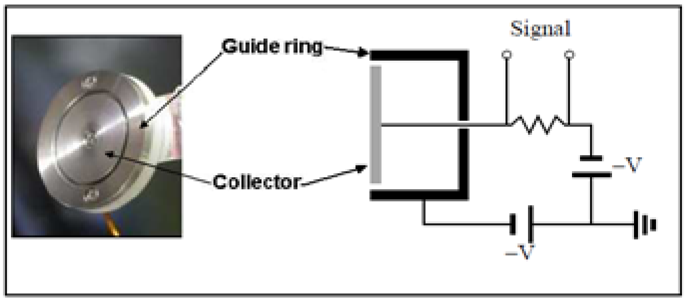

Figure 8: A typical Faraday probe

A Faraday Probe consists of a collector metal disc and a cylindrical hallow tube called the "guided ring". The collector is biased with electrically negative to collect the ions and repel the plasma electrons. The guard (guide) ring which surrounds the collector is biased with the same potential of the collector. The collector and the guard ring is separated from each other with a dielectric material.

In order to perform the measurements, the Faraday probe should be placed approximately 1 meter away from the Hall Effect thruster. Along the axis on the thruster, the probe would be swept in an arc within 180 degree with that 1 meter radius circle and the data are taken. By means of the negative collector potential which is about -20 Volts the ions from the plume are collected on the probe surface.

When ions are collected on the probe, an ion on the probe takes an electron and a Xe ion transform into a neutral gas atom. The electron taken from the collector is measured as a potential increase in the resistor which is the part of the circuit. The potential rise is read with a voltmeter attached to the resistor in parallel. Then by using Equation 4, the current on the resistor is calculated. In Equation 4, R is the resistance value in Ohm, V is the potential of the resistance in Volts and I_{probe} is the probe current in mA.

$$I_{probe} = \frac{V.1000}{R} \quad [mA] \qquad (4)$$

After measurement of the ion current, by using Equation 5, the ion current density is calculated. Where A_{probe} is the surface area of the probe.

$$j(\theta)_{probe} = \frac{I_{probe}}{A_{probe}} \quad [mA/cm^2] \qquad (5)$$

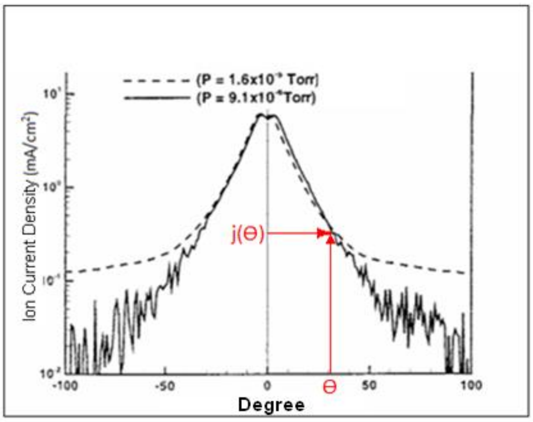

Figure 9: Degree vs. Ion current density data

After obtaining the ion current density at each θ, angular probe position, all of the data is represented in a graph like shown in Figure 9.
To obtain the total beam current, the integral in the Equation 6 must be calculated numerically.

$$I_B = (\pi) r^2 \int_{-\pi/2}^{\pi/2} j(\theta) \sin\theta d\theta \qquad (6)$$

Where "r" is the radial distance of the probe in cm and in our system it is equal 100 cm. Equation 6 yields the total beam current in mA.

CONCLUSION

Hall Effect thrusters have extensive benefits over chemical propulsion systems for both the near-Earth orbit and deep space planetary missions. In order to assess the effectiveness of this propulsion technology for Turkey's future space missions, a 1.5 kW Hall Effect thuster has been designed and the dimensions of its plasma channel has been determined..In future works, this Hall Effect thruster and a Faraday probe, one of the main plasma diagnostic device, will be manufactured and tested in cooperation with the HALE team of the TUBITAK Space Institute [5]. After the establishment of the test facilities in TUBITAK Space Institute, including vacuum chambers of different dimensions, the indigenous Hall Effect thruster, designed and manufactured through this research work will be tested and its performance parameters will be measured.

References

[1] Cadiou, Dudeck, Lyszyk, and M., "Research and Development on Plasma Thrusters in France," International Electric Propulsion Conf., IEPC Paper 99-007, Oct. 1999.
[2] Saccoccia, G., "European Electric Propulsion Activities," AIAA Paper 99-2158, June 1999.
[3] D.M. Goebel, I. Katz, book: Fundamentals of Electric Propulsion: Ion and Hall Thrusters.
[4] Frank Stanley Gulczinski, Examination of the Structure and Evolution of Ion Energy Properties of a 5 kW Class Laboratory Hall Effect Thruster at Various Operational Conditions, the PhD Dissertation 1999.
[5] Demet Uluşen, Banu Ç. Aydın, İ. Sedat Gülle, Erdal Bozkurt, Hasan Özkaya, Suat Ontaç, Mustafa Türkmenoğlu, "Overview of TUBITAK UZAY's Electric Propulsion Development Project (HALE)", 6th International Conference on Recent Advances in Space Technologies-RAST 2013 Paper.