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STUDY OF MAGNETIC FIELD CONFIGURATION EFFECTS ON COUPLING BETWEEN HALL EFFECT THRUSTER AND HOLLOW CATHODE

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ABSTRACT

Hall effect thrusters utilize electric and magnetic fields to extract ions from a plasma discharge. In Hall effect thrusters, the ionization of the propellant gas is achieved by collisions of the neutral propellant gas atoms with the emitted electrons from a cathode, typically a hollow cathode. Besides, the cathode is responsible for the neutralization of the ion beam by emitting an equal number of electrons to prevent spacecraft charging. Proper placement of the cathode strongly affects the neutralization of ions in addition to creating well coupled discharge plasma. Studies from the literature show that the cathode coupling voltage is a function of cathode placement and thruster efficiency. Cathode coupling voltage is related to the external magnetic field lines of the thruster. This study shows that depending on the external magnetic field topology of the thruster, there could be an optimum position for the cathode considering the separatrix region.

INTRODUCTION

Electric propulsion systems have been used as a practical alternative to chemical thrusters in propulsive applications such as orbit maintenance, orbit raising and in deep space missions due to their advantages in reducing required propellant mass and resulting cost savings. Hall effect thrusters (HET) use electric and magnetic fields to extract ions from plasma discharge. A significant component of HET is the cathode, since it emits electrons to ionize neutral atoms in the discharge channel. The second role of the cathode is completely different from the former in a way that equal amount of electrons to exiting ions should be emitted to neutralize the ion beam and to prevent the spacecraft from charging. This is generally done by placing the cathode on a mount near the thruster exit plane. Proper placement of the cathode is important for the efficient neutralization of ions in addition to creating well coupled discharge plasma.

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The location of the cathode determines the interaction between electrons and plasma discharge. A large distance between the cathode and discharge plasma causes higher magnetic obstacle for the electrons to overcome. For the electrons emitted from the cathode to pass this magnetic barrier, lower potential for the cathode or higher potential for plasma plume is needed. Depending on the placement of the cathode, it should be expected that there would be double layer formation between cathode and anode [Sommerville, 2009]. The conditions for the formation of double layer was first stated by Langmuir to explain space charge limit effects of ions and electrons. For two different plasmas which are in contact, electron current passing from the double layer is limited due to space charge effects between plasma plume and the cathode [Goebel and Katz, 2008].

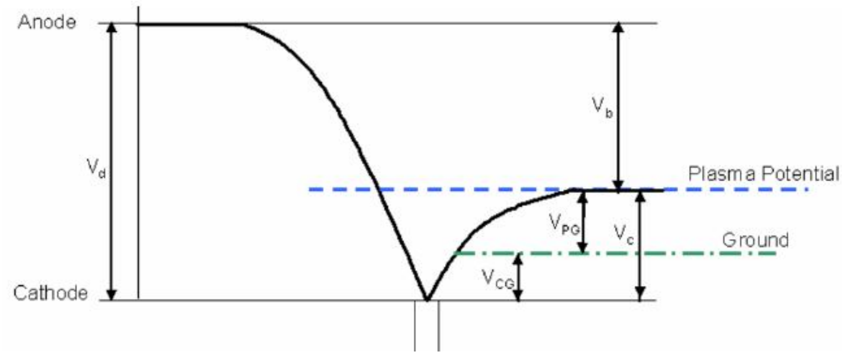


Figure 1: Hall effect thruster voltage schematic [Jameson, 2008]

Plasma potential increases due to magnetic field line restriction on electron motion from the cathode to ion beam and anode. If plasma potential (V_p) increases, cathode coupling voltage (V_{cg}) decreases, thus becoming more negative. So, potential difference between the anode and cathode becomes larger as could be seen in Figure 1. It could be concluded that the magnetic field topology of the thruster has an effect on the cathode coupling.

External magnetic field topology of a Hall effect thruster has an important characteristic called *magnetic field separatrix* that signifies the surface which forms the boundary between closed magnetic surfaces and open field lines. Inside the separatrix, magnetic field lines capture electrons near the anode and along the beam while the lines outside the separatrix orient electrons away from the beam. Therefore, it can be suggested that the cathode should be placed inside the region determined by the separatrix surfaces. However, the cathode should be protected from sputtering damage of the high energy ions exiting the thruster. Also, according to the experimental results of Sommerville [Sommerville, 2009], the thruster efficiency is observed to be the lowest when the cathode is positioned closest to the thruster. Considering these, there should be an optimum placement for the cathode to protect it from ion bombardment, to emit electrons without causing double layer formation, to reduce the plasma potential in the near plume region, and to increase the cathode coupling voltage.

When the cathode is placed inside the separatrix, plasma potential at the thruster exit decreases and the cathode coupling voltage increases. It was observed in the experiments that the cathode coupling voltage increases as radial distance is reduced until the separatrix surface is crossed, after that the coupling voltage decreases [Sommerville, 2009]. Also, moving the cathode radially outward causes

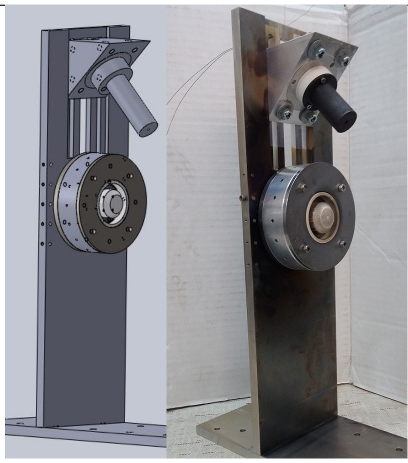


Figure 2: HK40 Hall effect thruster with LaB_6 hollow cathode

the electrons to pass a larger distance across the magnetic field lines between the cathode and the thruster exit, thus increasing the resistance. Inside the separatrix region, when the cathode is moved towards downstream of the thruster by increasing the axial distance, the efficiency is observed to be improved [Sommerville, 2009]. By determining the optimum axial position, sputtering damage is also reduced.

EXPERIMENTAL SETUP

In order to investigate the effects of the cathode placement on the cathode coupling voltage, tests on a prototype Hall effect thruster (HK40) and a prototype hollow cathode have been conducted. HK40 Hall effect thruster is a 40 mm diameter SPT type prototype Hall thruster designed and manufactured at the Bogazici University Space Technologies Laboratory (BUSTLab). This thruster operates at a discharge voltage of 260 V and discharge current of 1.2 A with Argon propellant. The prototype hollow cathode has a 6 mm diameter 48 mm long graphite cathode tube. It utilizes a 2 mm ID, 4 mm OD LaB_6 tube of 10 mm length. Figure 2 shows the picture of the HK40 Hall Effect Thruster with the prototype hollow cathode on the test stand along with the technical drawing of the same configuration.

The tests are being conducted inside the BUSTLab vacuum chamber. This vacuum chamber is a 1.5 m diameter 2.7 m long cylindrical tank. By using a mechanical pump and two cryogenic pumps, the pressure inside the vacuum chamber is maintained on the order of 3.2×10^{-5} Torr for 10 sccm Argon flow rate. In order to conduct the experiments, various gas and electrical feedthroughs have been used to provide gas flow and power to inside the chamber.

Before measuring the cathode coupling voltage, determining the location of the separatrix surface is important in terms of the proper placement of the cathode. In order to map the magnetic field topology and to determine the location of the separatrix region, magnetic field was measured with a gaussmeter as shown in Figure 3.

For the invariant fields, Hall effect provides a way to measure the magnetic field flux density. Hall probe works with a semiconductor standing in a magnetic field, B. An electrical current j, thus moving electrons, flowing perpendicular to this magnetic field in this semiconductor experiences a

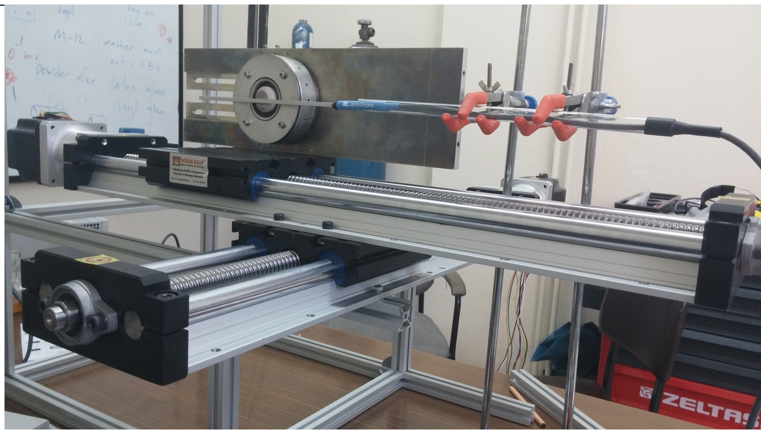


Figure 3: Magnetic field measurement at the center of the exit plane of the thruster by using gaussmeter

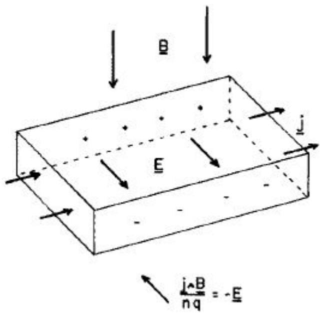


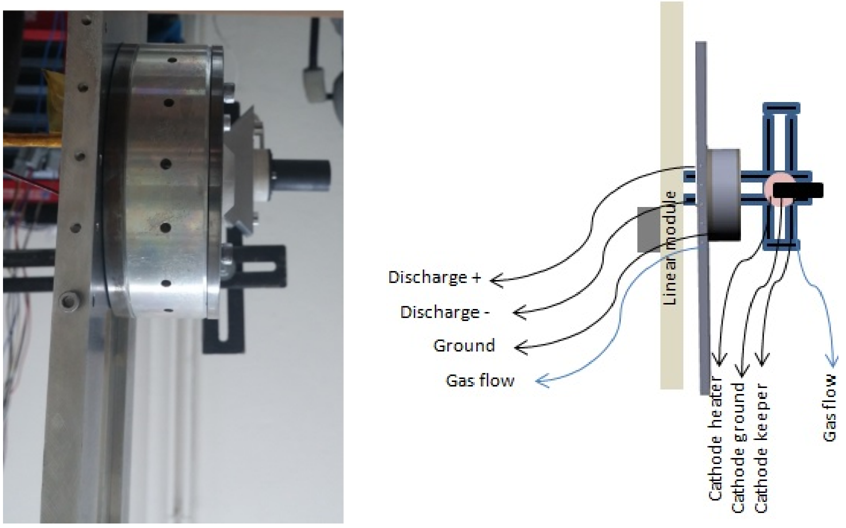
Figure 4: Schematic illustration of the operation of a Hall probe [Hutchinson(2005)]

Lorentz force perpendicular to both j (motion of electrons) and B as in Figure 4. As a result, there is a net charge build up on the side faces of this probe surface, and that causes an electric potential to form to oppose the magnetic force. This additional potential is measured from the faces by electrodes to deduce the magnetic field flux density.

In the current experiments a 2-D translational stage was used to move the hollow cathode with respect to the thruster. The stages are moved independently using a PLC controller. The currently used stepper motors, attached to the translational stages, are not vacuum rated and thus certain precautions were needed to be taken to use them inside the vacuum chamber. For the initial tests, the stages were only tested outside the vacuum chamber and the vacuum tests have not yet been carried out. As shown in Figure 5, the cathode is placed in a parallel orientation with respect to the thruster axis and moved radially. During the movement of the cathode, special attention is paid to ensure the unrestricted motion of the electrical cables and gas flow connections to the cathode.

NUMERICAL ANALYSIS

To observe the separatrix surface, a finite element model of the HK40 Hall effect thruster was constructed over a 2D domain which was obtained from the cross-section of the 3D CAD drawing of the thruster. The numerical simulations was done using COMSOL, a finite element software. The



(a) (b)

Figure 5: Photograph and schematic of the translational stages with the cathode and the thruster

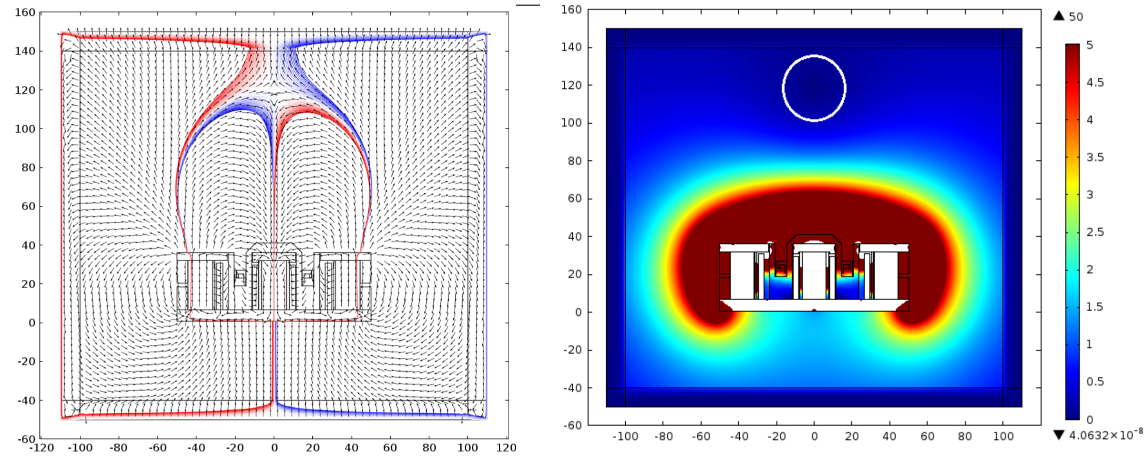
thruster head has an inner permanent magnet pole at the center and four outer permanent magnet poles that are 90 degrees apart, so they obey axial symmetry. The cross-section plane passes through the center of the thruster head and the centers of two of the outer pole permanent magnets, as shown in Figure 6a. The arrows represent the direction of the magnetic field in a normalized manner, whereas the colored contours show the z-component of the vector potential with values very close to zero, that stands for the separatrix surface. Since the magnetic field is planar, the vector potential has only z-component according to Gauss's Law for magnetic fields. The relation between the magnetic field and the magnetic vector potential is given by:

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{1}$$

$$\mathbf{B} = \frac{\partial A_z}{\partial y}\hat{x} - \frac{\partial A_z}{\partial x}\hat{y} \tag{2}$$

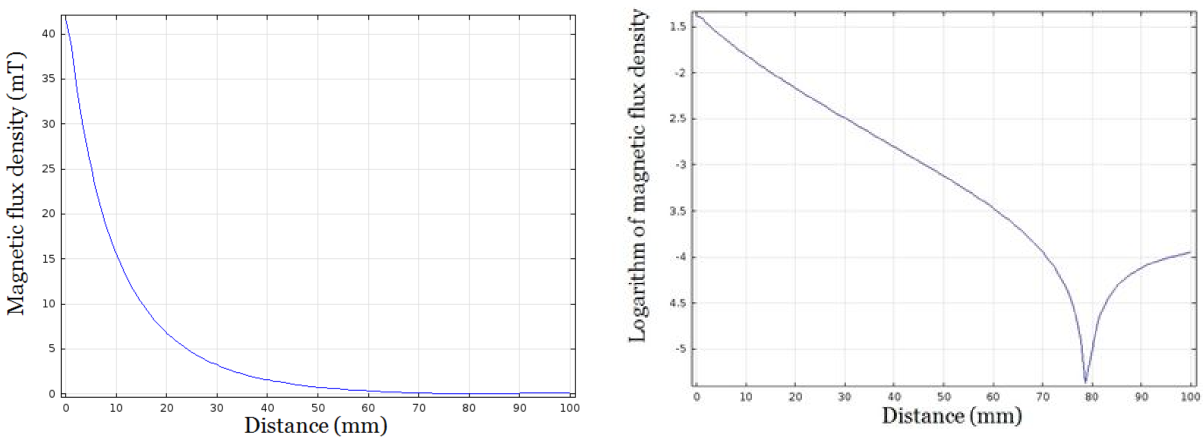
Figure 6b shows the modeled magnetic field topology of the thruster. In this figure the dark blue region, indicated by a circle, shows the separatrix region. It can be concluded that magnetic lines are closed at some point and the lowest magnetic flux density is observed after that point. In the figure, the described dark blue region is located at a certain distance from the center of the thruster exit. Comparing the results in Figure 6, it could be claimed that the separatrix region between 100-120 mm axial distance from the back of the thruster identifies the boundary of the minimum magnetic flux density region.

In numerical analysis, the change in magnetic flux density with respect to the center of the thruster exit is obtained as shown in Figure 7. To determine the location of the minimum value, logarithmic scale is a good approach to observe the change as shown in Figure 7b. It is clear that the minimum magnetic flux density is detected on 70-80 mm axial distance from the center of the thruster exit. It is also in accordance with Figure 6a when determining the location of the separatrix region by considering the thruster length of roughly 40 mm.



(a) (b)

Figure 6: a) Separatrix surfaces b) Magnetic field topology of the thruster



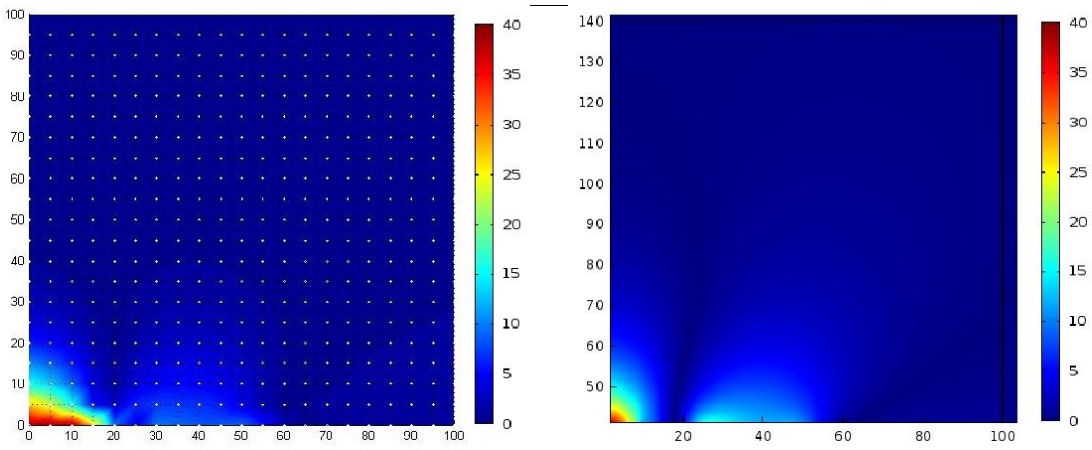
(a) (b)

Figure 7: a) Magnetic flux density at the center of the thruster from numerical analysis b) Logarithmic change in magnetic flux density

RESULTS AND DISCUSSIONS

To verify the numerical model with experimental results, magnetic flux density has been measured with the Hall probe, and the experimental measurement results are compared with the COMSOL modeling results as shown in Figure 8. The measurements are carried out for the 100 mm by 100 mm region in front of the thruster that started from the center of the thruster exit and extended parallel to the thruster axis. Measurements are conducted by Hall probe on the points represented by white dots shown in Figure 8a. As described before in Figure 6, the center of the region inspected is located at the center of the thruster exit which is located at 40 mm in that model. It could be seen in the figure that there is a good match between the model and the measured data.

The region investigated starts at the center of the thruster exit. There are four outer permanent magnets those are assembled 90 degrees apart. The cross-section plane for the magnetic probe measurements, shown in Figure 8, does not pass through the outer magnets as could be seen in Figure 9, but instead the magnets are positioned at an angle of 22.5 degrees with respect to the plane of



(a) measured (b) model

Figure 8: Comparison of the modelled and measured magnetic fields

magnetic probe measurements.

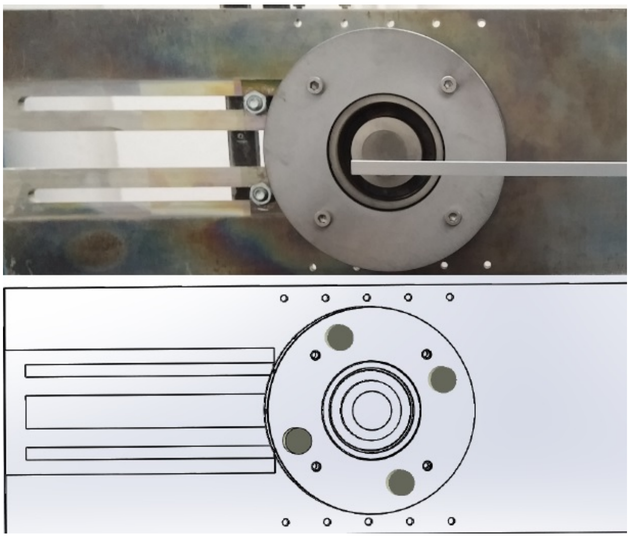


Figure 9: Photograph and schematic of thruster showing the placement of the permanent magnets

Experimental measurements from the center of the thruster exit through an axial line has yielded similar results to those of the numerical model. Magnetic flux density decreases as the probe moves away from the thruster as in Figure 10a. There should be a point with minimum magnetic flux density as expected from numerical results. Again, logarithm of the values clearly shows the minimum point.

If Figure 7b and Figure 10b are compared, it is observed that there is a difference between the location of the minimum point. The minimum magnetic flux density is observed at 60-65 mm range in the experimental measurement results. On the other hand, the numerical results point to 70-80 mm distance for the minimum value. There is almost 10 mm difference between the numerical and experimental results while finding the end of the separatrix surfaces. The reason for this discrepancy could

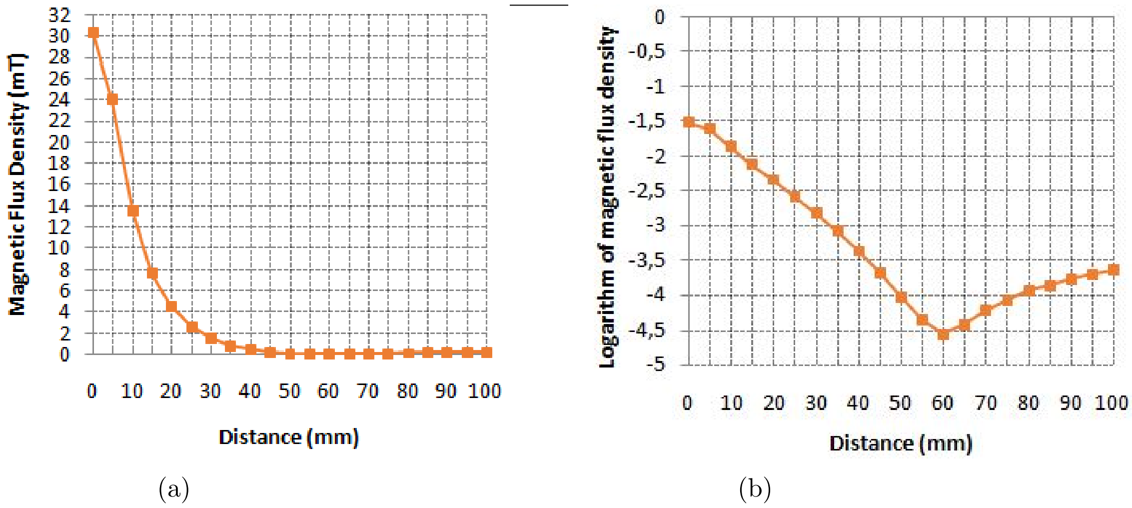


Figure 10: a) Magnetic flux density at the center of the thruster exit b) magnetic flux density in logarithmic scale

be due to the differences in actual and tabulated material properties information, such as magnetic permeability, entered into the COMSOL model regarding the SmCo ring magnets and the magnetic materials (in this case 1018 stainless steel) used in the construction of the thruster.

CONCLUSION

In this study experimental measurements and numerical modeling of the external magnetic field of a prototype Hall effect thruster have been conducted in order to study the placement of the cathode. It is proposed that depending on the external magnetic field topology of the thruster, there could be an optimum position for the cathode considering the separatrix region. The comparison between the experimental results and the numerical solutions obtained from the finite element model shows that the the modeling and experimental results agree to a great extend. The location of the separatrix region could be determined as the minimum magnetic flux density region on the thruster axis away from thruster exit.

Future plan is to conduct experiments with different cathode positions to observe changes in cathode coupling voltage and comparing the results with those of the numerical simulations. To investigate magnetic field effects on the cathode coupling process, simulations will include an electron emitting cathode.

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References

Goebel, D. M. and Katz, I.(2008)*Fundamentals of Electric Propulsion: Hall Thrusters*, JPL Space Science and Technology Series, New York, USA, 2008.

Hutchinson, I. H. (2005), *Principles of Plasma Diagnostics*, Cambridge University Press, 2005.

Jameson, K.(2008)*Investigation of Hollow Cathode Effects on Total Thruster Efficiency in a 6 kW Hall Thruster*, Ph.D. Thesis, University of California, Los Angeles, CA, USA, 2008.

Sommerville, J. D.(2009)*Hall-Effect Thruster Cathode Coupling: The Effect of Cathode Position and Magnetic Field Topology*, Ph.D. Thesis, Michigan Technological University, Houghton, MI, USA, 2009.