Investigation of the Effect of Hollow Cathode Neutralizer Location on Hall Effect Thruster Efficiency

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***Abstract*—Neutralization of ions is important for all electric thruster types when considering thruster efficiency and life. Hollow cathode is responsible for both creating plasma discharge and neutralization of the beam ions for Hall Effect Thruster (HET). In this study, appropriate placement of the cathode is investigated by taking into account that the decrease in cathode coupling voltage increases thruster efficiency. Regarding this, the effects of mass flow rate of the cathode and keeper current on the coupling voltage are investigated, according to available experimental results from the literature.**

Keywords— hall effect thruster, ion beam neutralization, neutralizer cathode.

I. INTRODUCTION

Thrusters using electric energy were built as a practical alternative of chemical thrusters to meet demands related to increasing the possibilities of deep space exploration, reducing mass, and saving cost. After huge impulse requirement of the spacecraft to be launched was handled, simple solutions were investigated to utilize the excess onboard electric power. Electric propulsion systems became acceptable for planned long-term mission, and researchers focused on thrusters with electric propulsion broadly [1]. In 1964, on SERT I spacecraft, US flew its first electric propulsion thruster. It was a gridded ion thruster with hollow cathode neutralizer [2]. In 1970's, Soviet Union and United Stated started their research on Hall thruster independently. At the beginning of research, basic design parameters were tried to be optimized such as discharge chamber geometry, magnetic field topology and propellant type. Soviet studies achieved more suitable magnetic topology of Hall thruster for flight and Hall thrusters were used for the first time in 1971. In 1990's, after the end of the cold war, the Soviet researchers found the opportunity to bring their experience and knowledge to the western countries. In the US, Hall thruster research was conducted by universities, some government agencies and industry [3]. With improvements on Hall thruster systems, these systems became desirable propulsion alternatives for LEO to GEO orbit raising, north-south station keeping and GEO orbit topping applications [4]. European Space Agency (ESA) made contributions to the development of Hall thrusters by sending SMART-1 spacecraft that orbited the Moon in 2003 [5]. In the US, several companies such as Aerojet and Busek have conducted research and development of Hall effect thrusters [2].

Hall effect thrusters 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 and the created ions move through the exit while electrons are partially trapped in HET due to magnetic field. 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 compensate for the charge effects on thruster and to prevent the spacecraft from charging. This is done by placing the neutralizer on a mount near the thruster exit plane. By doing this, excessive charging is reduced and again quasi-neutral distribution in the beam plasma is obtained. After further enhancements are accomplished for reducing thruster discharge losses, another part of the power losses stem from the neutralizer power. Thus, the location of the neutralizer becomes significant because it should be protected from energetic ions as well as constantly emitting sufficient amount of electrons to the beam [6].

The cathode is located such that it interacts with the discharge plasma, and this interaction is based on a phenomenon called cathode coupling. Before introducing the concept, the understanding of electron and ion motion in HET should be discussed and then the importance of cathode coupling voltage could be explained.

Electron mass is much smaller compared to the ion mass, therefore, the effects of electric and magnetic fields are observed differently on those. Because of high acceleration of electrons, plasma interactions with the surroundings are dominated by the electrons. Besides, relatively low mass of electrons implies that they are affected by the fields with Lorentz Force, $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$, much more significantly. However, crossed field electric and magnetic field cause drift motion for both electrons and ions independent of mass. This could be seen contradictory to above prediction but Larmor radius calculated in uniform magnetic field shows how strongly magnetic field can trap a particle. Since Larmor radius is proportional to particle mass, ions have much larger Larmor radius than electrons. Therefore, ions could escape from the HET while electrons could not. Extracted ions now

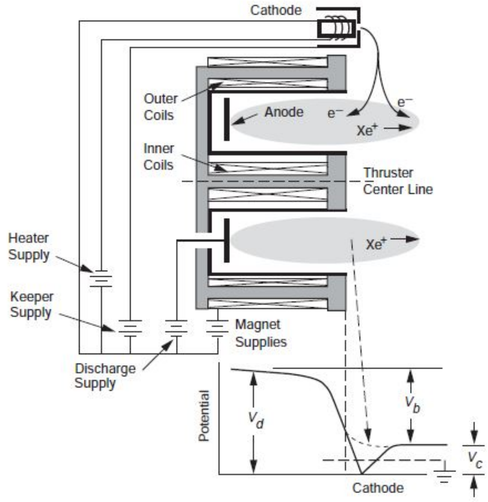

Fig. 1. Electrical schematic for Hall Thruster [7]

should be neutralized because thruster efficiency is strongly tied to neutralization in three ways: focusing ion beams to generate higher thrust, producing equal amount of electrons to ions, and adjusting cathode coupling voltage. All of the enhancements on efficiency will be explained by considering hollow cathode location, mass flow rate of gas in the cathode and keeper current.

The focus of this paper is on the coupling voltage between discharge plasma and the cathode. All the electrical components in the thruster are adjusted with respect to a common voltage. This common voltage is spacecraft itself in space or vacuum chamber walls on the ground [7]. Fig.1 represents the electrical circuit of a typical HET.

In Fig.1, the cathode coupling voltage, V_c, is the required amount of potential for emitting electrons from the cathode [8], V_d is the cathode potential, and V_b is the beam voltage. The relation between V_c, V_d, and V_b is as follows:

$$V_b = V_d - V_c \tag{1}$$

The coupling voltage is close to 20 V and in laboratory testing it could be neglected [2].

$$V_b \approx V_d - V_{cg} \tag{2}$$

where V_{cg} is the cathode to ground voltage.

Larger negative coupling voltage implies that there is larger resistance between anode and cathode [8]. Therefore energy is lost when providing electrons to discharge chamber as can be seen in Fig.2. With the same discharge voltage (V in Fig.2), accelerated voltage is increased when coupling voltage approaches the ground.

Fig.2 shows that coupling voltage value should be lowered to ensure high thruster efficiency with increased acceleration voltage. The other fact is that coupling voltage is a factor that should be taken into consideration for other gridded ion thrusters as well. In Bechtel's study on electron bombardment ion thruster in 1973, keeper current, mass flow rate and

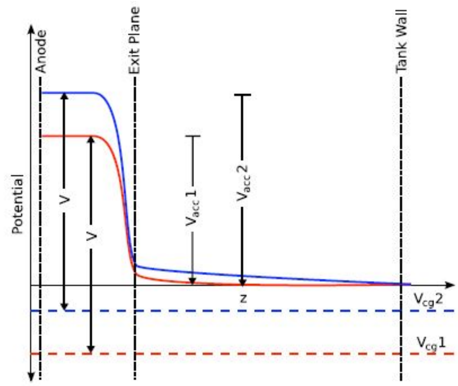

Fig. 2. The available acceleration voltages for low and high cathode coupling voltages [8]

coupling voltage were examined. It was shown that higher keeper current in hollow cathode does not increase coupling voltage significantly. An increase in the current reduces mass flow rate of the cathode, and creates self-heating by resulting in a decrease in power consumption [6]. In another study conducted by Nishiyama et al., it was demonstrated that the optimum position of microwave discharge neutralizer also decreases coupling voltage and mass flow rate [9]. From these different examples, it is clear that the location of any type of neutralizer is important to reduce coupling voltage and to increase efficiency of the thruster.

II. EXPERIMENTAL EQUIPMENT

For the experiments to investigate the cathode coupling, the placement effects of a LaB_6 hollow cathode designed and built at the Bogazici University Space Technologies Laboratory (BUSTLab) will be studied. For these tests, two different prototype Hall effect thrusters will be used. These thrusters, Cusped Field Hall Thruster (CFHT-40) and HK40 Hall effect thruster, are also designed and built at BUSTLab. The details of the cathode and the thrusters are presented in the following subsections.

A. Hollow Cathode

Dependence of the efficiency of HET on the location of the neutralizer will be assessed by utilizing the LaB_6 hollow cathode designed and built at BUSTLab. A 3D CAD design of the BUSTLab hollow cathode is shown in Fig.3.

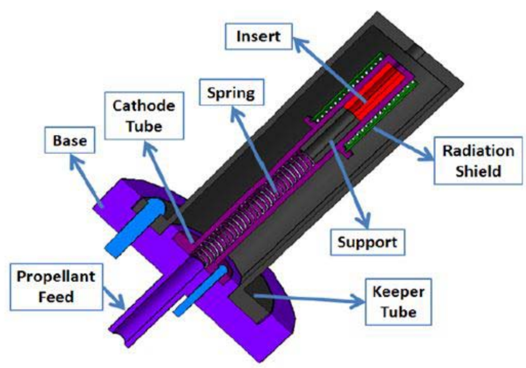

Fig. 3. Hollow cathode parts

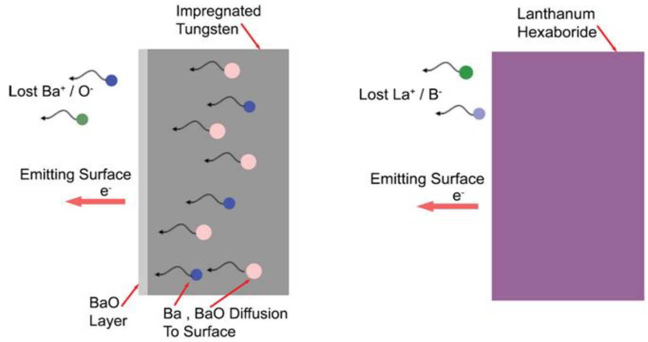

Fig. 4. Schematic of the emission mechanisms of BaO - W and LaB_6 [10]

In hollow cathode, thermionic emission is the mechanism to produce electrons. Insert material should be heated in order to obtain necessary electron current. For this reason, different heater designs and different insert materials in the literature are investigated.

For insert material, BaO-W and LaB_6 was compared and LaB_6 was chosen since it is not significantly affected by the impurities in the propellant gas [10]. Fig.4 shows the schematic of the emission mechanisms of these two thermionic materials. As an insert material BaO - W was the best option for many years, however new alternatives gave better results in terms of evaporation rate. As seen in Fig.5, LaB_6 has lower evaporation rate in comparison to BaO - W. Therefore, it is suitable for long lasting hollow cathode applications.

The other concern was the decision on a heater design among different designs in the literature. Three different heater designs can be seen in Fig.6.

Three options were evaluated by a COMSOL model and designs B and C with tantalum bare wire were found to be usable since they can distribute heat more uniformly. In the final design, graphite was chosen as the cathode and keeper tube material, and dielectric parts were made of boron nitride and alumina as appropriate.

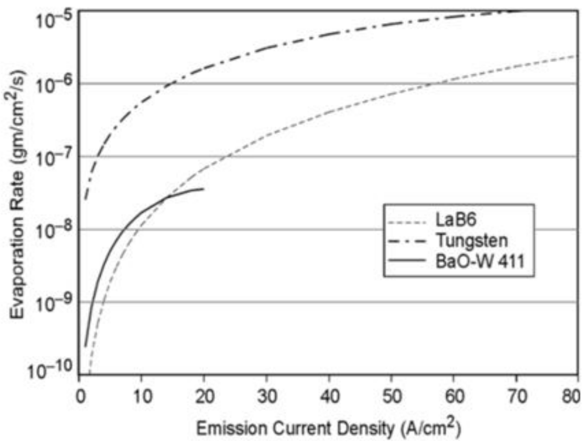

Fig. 5. Evaporation rate vs. emission current density [11]

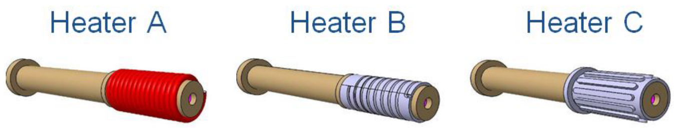

Fig. 6. Heater A: classical heater with sheathed tantalum wire wrapped around cathode tube. Heater B: Tantalum bare wire wrapped inside a helical shaped groove. Heater C: Tantalum bare wire wrapped inside a horizontal shaped groove [8]

Fig.7 shows images from the BUSTLab LaB_6 hollow cathode assembly process.

Fig. 7. LaB_6 hollow cathode during and after assembly

Effect of cathode mass flow rate on the coupling voltage was investigated in different studies [13, 14, 15]. A decrease in coupling voltage with decreasing mass flow rate is observed in all studies regardless of the type of the cathode used. In a similar manner, coupling voltage will be assessed at different cathode mass flow rates ranging from 0.2 mg/s to 0.7 mg/s of propellant considering low power thruster.

B. CFHT-40 : Cusped Field Hall Thruster

The CFHT-40 is a 40 mm diameter cylindrical cusped field Hall thruster that utilizes permanent magnets by creating three cusps inside the thruster channel for the generation of the desired magnetic field topology. This arrangement provides confinement of electron streaming from the cathode and reduction in wall erosion and ion losses [10]. The thruster was operated at a discharge voltage of 400 V and a discharge current of 1.2 A with high purity argon gas as the propellant.

The Cusped Field Hall Thruster (CFHT-40) and hollow cathode designed and manufactured at BUSTLab will be used in experimental investigation of the relationships between cathode coupling voltage, cathode mass flow rate, keeper current and neutralizer location. Fig.8 shows the CFHT-40 thruster placed on a platform inside BUSTLab vacuum chamber which is 1.5 m in diameter and 2.7 m in length. Fig.9 shows CFHT-40 thruster in operation.

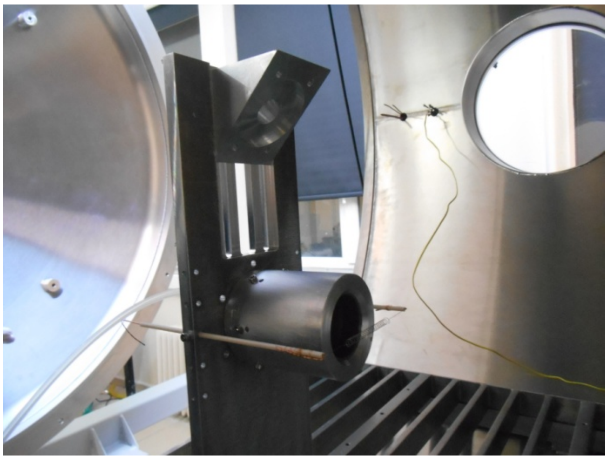

Fig. 8. Cusped Field Hall Thruster in BUSTLab Vacuum Chamber

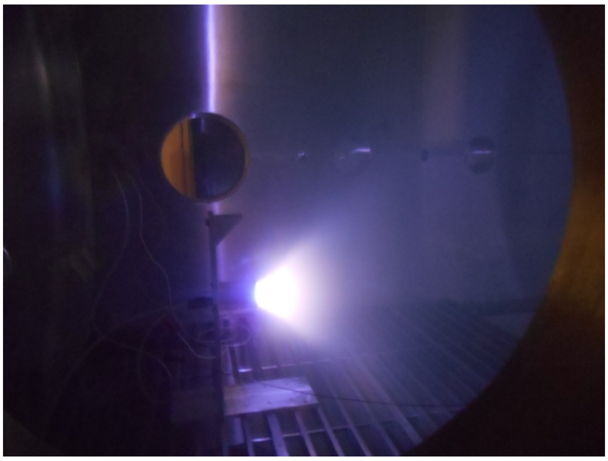

Fig. 9. Cusped Field Hall Thruster in operation

C. HK40 : SPT type Hall Effect Thruster

HK40 Hall effect thruster is a 40 mm diameter SPT type prototype Hall thruster designed and manufactured at BUSTLab. This thruster was tested inside the BUSTLab vacuum chamber. The thruster was operated at a discharge voltage of 260 V and discharge current of 1.2 A with Argon propellant for the initial tests. A picture from the first testing of the HK40 thruster is seen in Fig.10.

The HK40 Hall effect thruster is going to be tested with the prototype LaB_6 hollow cathode. Fig.11 shows the picture of the HK40 Hall Effect Thruster with the prototype hollow cathode on the test stand along with the rendered technical drawing of the same thruster-cathode configuration.

III. THE EFFECT OF THE CATHODE LOCATION

The location of the cathode directly affects cathode coupling voltage between the thruster and the cathode. The other parameters such as mass flow rate of the cathode and keeper current change as a consequence of variation in cathode coupling voltage.

In experiments, the location is altered both axially and radially and coupling voltage which should be small in magnitude is measured.

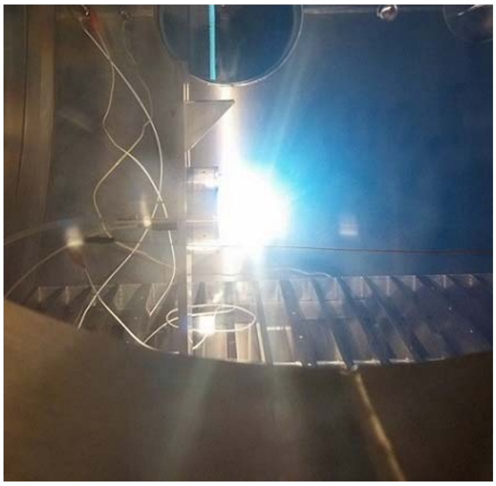

Fig. 10. The first testing of the HK40 Hall effect thruster inside the BUSTLab vacuum chamber

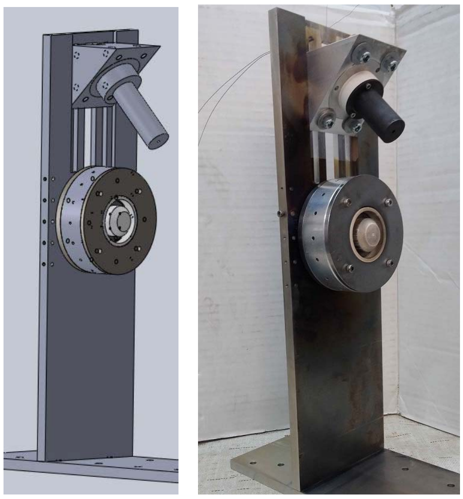

Fig. 11. HK40 Hall effect thruster with LaB_6 hollow cathode

Hollow cathode could be used with different ion engines. Bechtel reported in his studies on electron bombardment ion thruster that radial direction affects coupling voltage more than changes in axial direction [6]. On the other hand microwave discharge neutralizer is affected by the changes in location more severely, and higher coupling voltage is measured [9]. Cathode coupling was investigated with alternative HET designs with the examination of keeper current variations of hollow cathode in past studies [10].

As stated in Bechtel's work, increase in keeper current causes more heating in emitter and the potential difference is reduced at the exit of HET while the voltage of the discharge chamber remains the same. The parameters of the cathode including keeper current and mass flow rate of the cathode affects the discharge of the thruster. Regarding this, in the study of Raitses, it was suggested that cylindrical Hall thruster provides better thrust by eliminating radial deviations and reducing beam divergence with cylindrical geometry. This could be explained by causing more accelerated ions in axial direction for cylindrical Hall thruster [16].

Considering both radial and axial changes in hollow cathode location, there is a relation between the cathode coupling voltage and thruster efficiency. The voltage that accelerates the ions is calculated by the sum of the applied discharge voltage and the coupling voltage [8].

$$V_{accel} = V + V_{cg} \tag{3}$$

Thrust is defined as:

$$T = \dot{m} v_{avg} \tag{4}$$

where $\dot{m}$ is total propellant mass flow rate including both anode and cathode and υ_{avg} is the average exit velocity of ions and neutrals given by:

$$\upsilon_{avg} = a\sqrt{\frac{2q_{avg}e\left(V + V_{cg}\right)}{m_i}} \tag{5}$$

where m_i represents ion mass, a is a constant coming from cosine losses, e is electron charge and q_{avg} is the average charge with all species of the propellant. For the case of Xenon propellant:

$$q_{avg} = \frac{\sum_{q=0}^{54} q n_q}{\sum_{q=0}^{54} n_q} \tag{6}$$

Thruster efficiency is calculated by:

$$\eta = \frac{a^2 q_{avg} e \dot{m}\left(V + V_{cg}\right)}{m_i I V} \tag{7}$$

and thus,

$$\eta = \left(1 + V_{cg}/V\right)\left(a^2 \frac{q_{avg} e \dot{m}}{m_i I}\right) \tag{8}$$

where I is anode supply current.

First term represents the efficiency that comes from cathode coupling, while the second term is assumed as the efficiency of other terms [17]. Thus, the total efficiency becomes:

$$\eta = \eta_{cg}\eta_{other} \tag{9}$$

Theoretical effects of cathode coupling on efficiency is calculated by above equations. The relation between cathode's radial and axial position and efficiency with cathode coupling voltage was compared in the study of Sommerville [8].

Axial changes affect the coupling voltage and efficiency more severely than radial changes in location of hollow cathode as can be seen in Fig.12 and Fig.13.

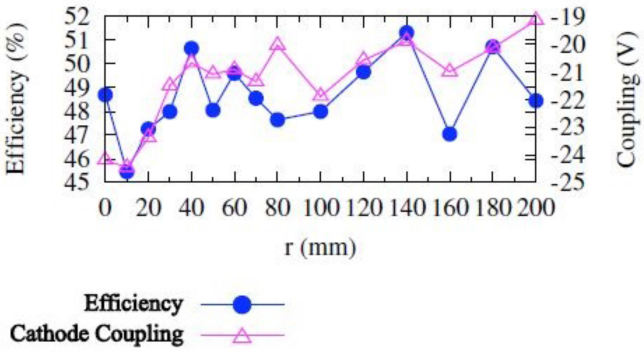

Fig. 12. Effects of radial position changes on efficiency and coupling voltage for V=250 V, $\dot{m}$ =4.0 mg/s [8]

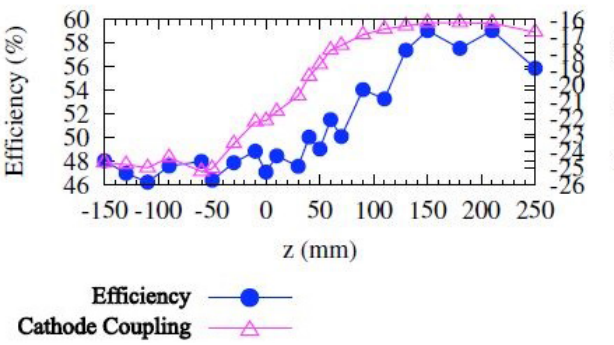

Fig. 13. Effects of axial position changes on efficiency and coupling voltage for V = 250 V, $\dot{m}$ = 4.0 mg/s [8]

For cylindrical Hall thruster (CHT), increase in keeper current was discussed in a study of Raitses [16]. It was observed that keeper current increases the discharge current as can be seen in Fig.14.

As implied in Bechtel's study, high keeper current decreases mass flow rate of the cathode slightly and does not affect the coupling voltage dramatically [6]. From the outcomes of that study and from Fig.14 it could be suggested that the relation between cathode coupling voltage and keeper current provides a way to associate the discharge current with the location of the neutralizer. Thruster efficiency also depends on what fraction of the discharge current and voltage are converted to beam current and voltage, and those effects are included into η_{other} term in "(9)". It can be seen that discharge current, keeper current and cathode coupling voltage are correlated with thruster efficiency. Therefore understanding each term becomes important to increase the efficiency of the thruster.

Mass flow rate of the cathode should be changed keeping other parameters constant, however the relation is based on an increase or decrease in cathode coupling voltage proportionally as suggested in the literature. Therefore, location changes affect the reduction of mass flow rate indirectly.

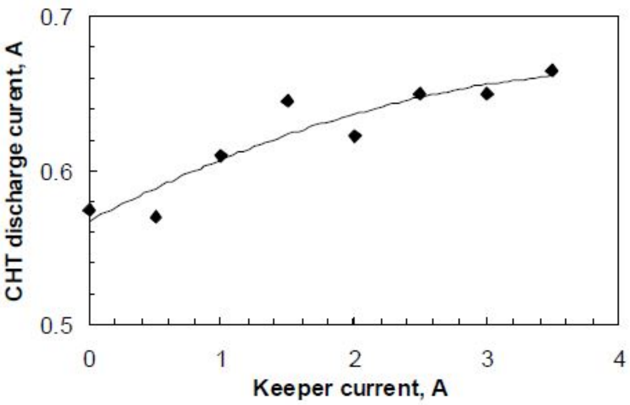

Fig. 14. Keeper current vs. discharge current [16]

IV. CONCLUSION

In this study, different research attempts in the literature regarding the location of hollow cathode neutralizer and its effect on thruster efficiency are investigated. The studies point out that neutralizer location directly affects cathode coupling voltage. Hall thruster efficiency can be increased by decreasing cathode coupling voltage. In order to achieve this, hollow cathode location needs to be optimized. Rather than hollow cathode location, cathode coupling voltage can be reduced by decreasing cathode mass flow rate as well.

As a future work, total efficiency of Hall effect thrusters designed at BUSTLab will be calculated with "(8)" theoretically. Moreover, efficiency of these thrusters will be assessed, using the hollow cathode designed and developed at BUSTLab, at different neutralizer locations for different cathode mass flow rate and keeper current experimentally. Eventually, the results of these theoretical and experimental investigations will be compared.

Acknowledgment

The authors would like to thank Turkish Scientific and Technological Research Council (TUBITAK) for their partial support to this work under project numbers 112M862 and 113M244. The authors also acknowledge the financial support from Bogazici University Scientific Projects Office (BAP) under project number BAP-6184 and BAP-8960. The authors would like to thank Ali Enes Ozturk for his contributions to this study.

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