Numerical Investigation of an External Discharge Hall Thruster Design Utilizing Plasma-lens Magnetic Field

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ABSTRACT An external discharge Hall thruster utilizing plasma-lens magnetic field, in which there are no physical walls to confine neutrals, was designed to address the technical problems encountered in designing low power (10-300 Watts), dual mode (High Thrust/High Isp) , and near infinite lifetime (Zero-erosion) Hall thrusters. To validate this conceptual design, a comprehensive numerical investigation was conducted. Design of this thruster was described, and numerical results were discussed. One particular problem with such Hall thruster may be considered as low neutral utilization efficiency in that high neutral density necessary to form plasma could not be obtained. However, our fully kinetic simulation results indicate that the external discharge Hall thruster can achieve neutral propellant utilization efficiency as much as conventional Hall thrusters by its plasma lens magnetic field topography.

1. Introduction

Hall thrusters are preferable for many on-orbit maneuvers and space missions due to several advantages such as high thrust density, moderate specific impulse, and outstanding in-space experience. However, although Hall thruster technology dates back to 1960s, development of an efficient low power (10-300 Watts) Hall thruster for micro/nano-satellites, operation at high voltages (Over 1 kV) for dual mode[1] (High Thrust/High Isp) operation, and achievement of long lifetime (Zero-erosion[2]) for deep space missions, today still remains a major technical challenge. The reason is that complex physical processes such as anomalous electron transport and plasma wall interactions are not completely understood in spite of numerous papers are being published each year by the electric propulsion (EP) community.

Plasma-wall interactions have substantial effects on discharge characteristics as well as on thruster performance. Discarding wall effects (e.g. near wall conductivity, plasma sheath of dielectric walls, secondary electron emission) not only would let us develop a better understanding on interaction between quasi-neutral plasma and magnetic field (e.g. the Bohm diffusion) but also would simplify numerical simulation as codes require certain parameters as an input such as thermal accommodation coefficient and wall temperature, which are quite difficult to be measured by experiments. Furthermore, a design without wall effects may let us understand channel wall's effect on the anomalous electron mobility, and present a solution to the technical problems encountered in designing low power, dual mode, and near infinite lifetime Hall thrusters.

There are many efforts to control ion acceleration region and to minimize the wall erosion to extend the thruster lifetime in the EP community[3, 4, 5, and 6]. A fully external discharge Hall thruster with an annular channel, in which there are no physical walls to confine neutrals, was numerically designed. Figure 1 shows a schematic of the external discharge Hall thruster and its plasma-lens magnetic field profile. Magnetic flux density varies spatially and its strength decreases from the anode having a maximum B_r of 0.15 Tesla. As for the design parameters, magnetized plasma depth is 8 mm, electron Larmor radius is 0.15 mm, square of electron Hall parameter is 400. Hall current is 5 A, and the ionization mean free path is 0.8 mm.

Mirror ratio, r_{mirror} is:

$$r_{mirror} = \frac{B_{max}}{B_{min}} \cong 2 - 10$$

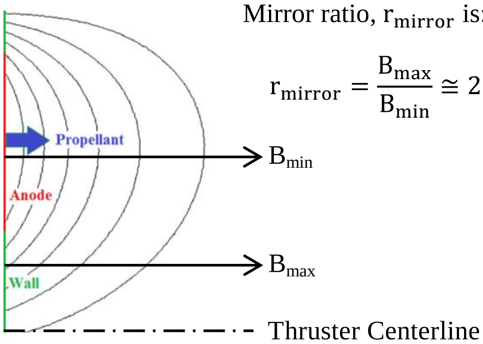

Figure 1: The External Discharge Hall Thruster Schematic

To validate this conceptual design, the external discharge Hall thruster was simulated for different input parameters through a fully kinetic code[7]. In this code, the semi-implicit field solver and an artificial mass ratio is employed to reduce the computational time.

2. Results and Discussion

The external discharge Hall thruster was simulated with various input parameters so as to determine a numerical error range to the results. Discharge voltage was set to 300 V, and Xenon mass flow rate was set to 1 1.36 mg/s for all the simulation conditions. LB, N, UB,T, Id, P, Ib1, Ib2, In, Δ, and ηA symbols means lower bound, nominal, upper bound thrust, discharge current, power, singly charged ion current, doubly charged ion current, neutral current, discharge current oscillation amplitude, and anode efficiency respectively. Simulations for each case were run for 0.8 million time steps corresponding to 0.4 milliseconds. Furthermore, all the data and plasma distribution plots were time-averaged. Table 1 shows simulation conditions.

Numerical Parameters	LB	N	UB
tu [s]	$2x10^{-10}$	$3x10^{-10}$	$5x10^{-10}$
Electron current [Aeq]	1	4	6
Macro-particle number	$2x10^{7}$	$4x10^{7}$	$1x10^{8}$
Mass ratio	1600	2500	3600
Grid size [mm]	0.1	0.2	0.4
Bohm diffusion	0	1/16	1/8

Table 1: Simulation Conditions

As it can be seen from Table 2, the external Hall thruster can achieve high neutral propellant utilization efficiency as much as conventional Hall thrusters even though there are not any physical walls to confine the neutrals.

T [mN]	Id [A]	P [W]	Ib1[A]
18.1	0.94	281	0.80
Ib2 [A]	**In [Aeq]**	**ηA [%]**	**Isp [s]**
0.13	0.13	43	1355

Table 2: Simulation results for the nominal condition

Parametric investigation results suggest an anode efficiency of 43 with a maximum error of +5%/-21 %, and thrust with a maximum error of +1%/-16 %. Upper bound on the overall numerical error was determined by the error with respect to the grid size, yielding to an anode efficiency of 34% and a thrust of 15.1 mN.

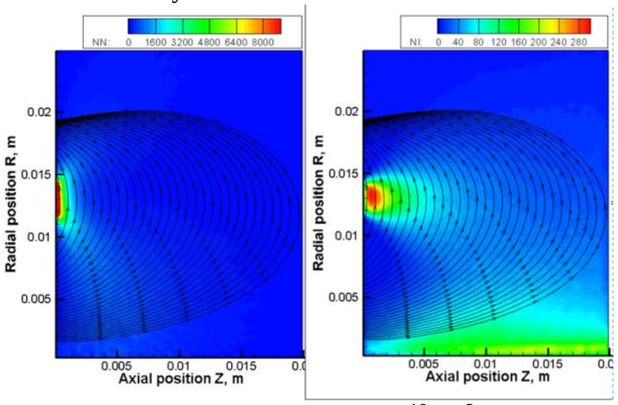

Figure 2: Neutral density (NN, 10^{16} m^{-3}) and plasma ion density (NI, 10^{16} m^{-3})

Figure 2 and Figure 3 shows plasma properties of the external discharge Hall thruster for the simulation nominal.

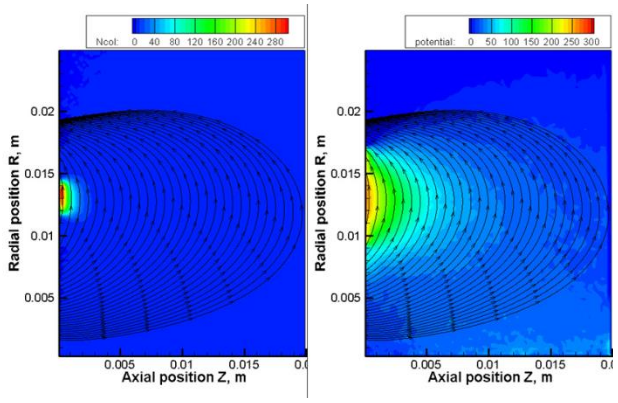

Figure 3: Time-resolved total collision number (Ncol) and potential distribution

As seen from Figure 2, it may be said that plume divergence is low as ion velocity components are mostly parallel to the thruster axial direction. However, considering the potential distribution given in Figure 3, voltage utilization may be expected to be low.

3. Conclusion

Unlike the common thought, it was numerically shown that the external discharge Hall thruster can achieve neutral propellant utilization efficiency as much as conventional Hall thrusters through its plasma lens magnetic field topography. The external discharge approach has the potential to lead us to simpler, lighter, low-cost, more efficient, and zero-erosion Hall thrusters at both low power and high power/Isp levels. In addition, the external discharge Hall thruster may help us to take better picture of plasma-wall interactions and the Bohm diffusion.

Acknowledgements

B. Karadag thanks Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) for his scholarship.

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