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Numerical Investigation of Thermal Accommodation Coefficient and Temperature Sensitivity in a Hall Thruster
数値解析によるホールスラスタにおける熱適応係数と壁面温度の感度解析

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ABSTRACT Understanding of neutral and plasma-wall interactions is important in order to develop plasma thrusters with more efficiency and long lifetime. In this study, a laboratory model Hall thruster with different thermal accommodation coefficients and anode/discharge channel wall temperatures were numerically simulated by using a fully kinetic 2D3V Particle-in-Cell (PIC)/Direct Simulation Monte Carlo (DSMC) code. The effects of thermal accommodation coefficient and anode/wall temperature on the thruster performance were investigated and discussed. Following conclusions were obtained: (1) Ion thermal accommodation coefficient is more determining over the thruster performance than neutral accommodation coefficient and anode/wall temperature; (2) Anode/wall temperature does not have significant effect on the thruster performance; (3) Uncertainties in the thruster performance arising from neutral particles' interaction with plasma and the walls, neutral uncertainties, are increased when higher magnetic fields were applied to the thruster by means of an electromagnetic coil.

1. Introduction

The neutral and plasma interactions with walls play an important role in designing better plasma devices such as Hall thrusters. Hall thruster is a type of electric propulsion system used for satellite missions like station keeping, orbit transfer or deep space exploration. Propellant residence time, ionization collisions and electron transport in a Hall thruster discharge channel contribute to the thruster performance and those mechanisms are affected by neutral particle's behaviors. There are many studies in the literature conclude that neutral flow dynamics in a Hall thruster have considerable impact on thruster performance, lifetime, and operation stability[1] Numerical simulations are important in order to optimize performance parameters of Hall thrusters and understand discharge chamber plasma physics. However, numerical codes require certain parameters as an input such as thermal accommodation coefficient and wall temperature, which are quite difficult to be measured by experiments. In order to display the confidence range of the numerical result for predictive simulation, it is necessary to determine lower and upper boundaries to those parameters. This paper serves to that purpose.

In our previous study, we simulated a Hall thruster of IHI Corporation, Japan with and without a Bohm diffusion coefficient and characterized the uncertainty caused by the Bohm diffusion model in our paper[2]. In the context of presenting better picture of the uncertainty of our simulation, in this paper, a Hall thruster of University of Tokyo's performance sensitivity to ion energy accommodation, neutral energy accommodation, anode temperature, and wall temperature were investigated for different operation conditions through a fully kinetic code. The details of the simulation methodology and the experimental results can be found at S. Cho's paper[3]. A laboratory model magnetic layer type Hall thruster with outer channel diameter of 62 mm[3] was chosen as the Hall thruster. In the kinetic code, there are two kinds of thermal accommodation coefficients: ion energy accommodation, E_{co}, and neutral energy accommodation, T_{co}. Velocity components of the ions hitting the discharge chamber walls are assigned according to a half-range Maxwellian distribution. Velocity components of the neutrals reaching the walls are assigned according to either a diffuse reflection or specular reflection, which is decided by randomly. At the anode region, both ions and neutrals' velocity components are assigned according to a half-range Maxwellian. As for the momentum accommodation, ions are fully accommodated, whereas T_{co} is also used as transverse momentum accommodation coefficient (TMAC) for the neutral particles.

2. Results and Discussion

Discharge voltage is set to 300 V for all the simulation conditions. E_{co} = 0.9, T_{co} = 0.9, T_{anode} = 500 K, and T_{wall} = 700 K (T_{anode} is anode temperature, and T_{wall} is inner and outer wall temperature) case is defined as the nominal configuration (N). 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 are time-averaged. Experimental work of V. Kim et al.[4] suggests a Xenon accommodation coefficient on Boron Nitride between 0.6 and 0.8 for ion energies between 100 and 400 eV. Therefore, an accommodation coefficient of 0.5 is chosen as lower bound, and of 1.0 as upper bound.

The simulation result has good consistency with the experimental result. As it can be seen from Table 1, increased ion energy accommodation resulted in enhanced thrust (T), discharge current (I_d), power (P), and anode efficiency (η_A), whereas increased neutral energy accommodation affected those parameters slightly. The alteration of the thermal accommodation coefficients mostly affected the neutral leakage (I_n), which means amount of neutral particles leaving the thruster exit without getting ionized. Increasing ion/neutral thermal accommodation also decreased neutral leakage. Magnetic flux density varies spatially and its strength increases from the anode toward the thruster exit.

	T [mN]	I_d [A]	P [W]	I_n [mg/s]	η_A [%]
Simulation (N)	17.3	1.18	353	0.29	31.4
Experiment	16.4	1.00	302	-	33.2
Cases	**Percentage Difference (%)**				
E_{co} = 0.5	-1	-3	-3	21	0
E_{co} = 1.0	8	11	11	-58	4
T_{co} = 0.5	-1	-1	-1	14	-2
T_{co} = 1.0	0	1	1	-3	0
T_{anode} = 700 K	1	0	0	3	0
T_{anode} = 900 K	0	0	0	5	0
T_{wall} = 500 K	0	1	1	-8	1
T_{wall} = 900 K	0	0	0	8	-1

Table 1: Performance data for 0.03 T Magnetic Flux Density, and 1.361 mg/s mass flow rate

The first two rows of Table-1 shows experimental and simulation, while the rest rows list percentage difference (%) between each case and the nominal configuration (N). The reason for the decrease in neutral leakage with increased thermal accommodation coefficient is neutral's decreased velocity. When thermal accommodation coefficient is increased, kinetic energy or velocity of the neutrals is decreased. As a result of lower neutral velocity, the residence time that neutrals pass in the discharge chamber is increased, which yields to higher electron-neutral collision probability, and therefore higher ionization rate. Enhanced frequency of collisions between electrons and neutrals in the plasma due to the higher energy accommodation coefficient increases the ion number density and discharge current in the discharge chamber. As for the temperature effect, both increased anode temperature, and wall temperature had only considerable effect on neutral leakage. The thruster's insensitivity to anode temperature is consistent with C. F. Book and M. L. R. Walker's experimental work[5]. The magnetic flux densities shown are sampled from the center point of the thruster exit.

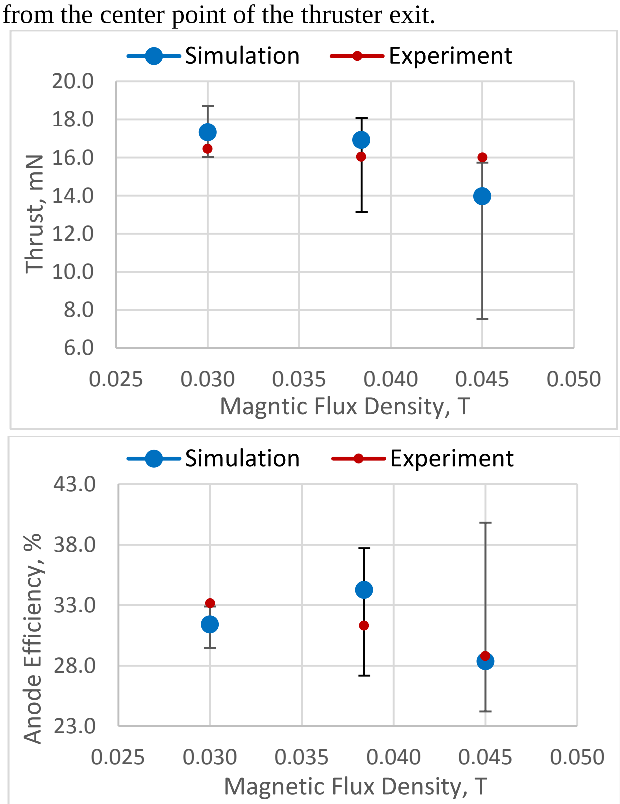

Figure 1: Thrust and anode efficiency uncertainty for 1.361 mg/s mass flow rate

Figure 1 makes a comparison between experimental thrust/efficiency and simulational thrust/efficiency for three different coil current cases and gives a neutral uncertainty range. Blue markers show simulation results for the nominal configuration (N). Error bars indicate the uncertainty between upper bound (T_{co} = 1.0, E_{co} = 1.0, T_{anode} = 500 K, T_{wall} = 500 K) and lower bound (T_{co} = 0.5, E_{co} = 0.5, T_{anode} = 900 K, T_{wall} = 900 K). For all the accommodation coefficient values between 0.5 and 1.0, numerical results are expected to lie within those intervals. It is obvious from Figure 4 that neutral uncertainties are increased along with the increased magnetic field strength. It can also be inferred from Figure 4 that neutral uncertainty generally may explain the discrepancy between numerical results and experimental data.

3. Conclusion

Effects of thermal accommodation coefficients and anode/discharge channel wall temperatures on a Hall thruster's performance parameters were examined through a fully kinetic PIC code. A range of influence regarding the thruster performance parameters was determined. It's been found that ion energy accommodation is more effective than the anode/wall temperature, and neutral accommodation coefficient on the thruster performance. An increase in ion/neutral accommodation coefficient increases residence time of neutral particles yielding to higher efficiency and thrust. For lower bound E_{co}/T_{co}, recombined ions creates neutrals with higher kinetic energies compared to upper bound E_{co}/T_{co} and causing to more unionized neutral molecules to leave the thruster exit without contributing to thrust and efficiency. In addition, it was found that although anode/wall temperature is related to thruster performance, the overall effect is less than 2 %, and it was concluded that a thruster with high propellant utilization efficiency was insensitive to anode/wall temperature. Finally, it was observed that neutral uncertainties are increased as the magnetic field strength increases.

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