Effect of Propellant Species on Thrust Imparted by a Helicon Plasma Thruster

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A. Chiba[1], K. Takahashi[2], A. Komuro[3], and A. Ando[4]
Tohoku University, Sendai 980-8579, Japan

Abstract: **The thrust imparted by a helicon plasma thruster and pressure dependence are directly measured in various propellants, neon, argon, krypton, and xenon, respectively. Both the thrust and the RF power transfer efficiency in neon are smaller than those in the other gas species. The measured thrust for argon, krypton, and xenon saturates when increasing the pressure, while being reduced for the low operating pressure condition in spite of the constant power transfer efficiency. The presence of the threshold decreasing the thrust and the saturation are qualitatively understood by the simple thrust model connecting the global model in the source cavity and the magnetic nozzle expansion.**

Nomenclature

η_p	=	power transfer efficiency between the RF antenna and the plasma
P_{abs}	=	RF power absorbed by the plasma
P_{RF}	=	output RF power
R_p	=	plasma resistance
$R_{antenna}$	=	antenna resistance

I. Introduction

VARIOUS electric propulsion devices, e.g., hall thrusters[1, 2], ion thrusters[3, 4], and magnetoplasmadynamic thrusters[5, 6], have been well developed so far. Such mature thrusters have a common problem that the metallic electrodes for the plasma production and/or acceleration are exposed to the plasma and are sputtered by the energetic ions hitting the electrodes. This critical problem is the one of the factors that determines the lifetime of propulsion systems. Therefore electrodeless propulsion devices such as a variable specific impulse magnetoplasma rocket (VASIMR)[7] and a helicon plasma thruster[8-10] have been studied recently for long-lived propulsion devices. The external magnetic field is typically applied to these propulsion devices to improve the radio frequency (RF) plasma production efficiency and to accelerate the plasma along the magnetic nozzle. Clarifying an interaction between the magnetic field and the current-free plasma is a key issue to improve the thruster performance.

In the helicon plasma thruster, the effects of the magnetic nozzle on the imparted thrust have been investigated. According to the previously reported simple model, the thrust is mainly given by sum of the electron pressure force within the source cavity and the Lorentz force arising from the radial magnetic field and the electron diamagnetic drift current[11]. Since the thrust can be decomposed into the forces exerted on the physical boundaries and the magnetic nozzle, the individual measurement of the thrust components has been performed[11]. The measurement has shown that increasing the magnetic field strength inhibits cross-field diffusion within the magnetic nozzle; then both

[1] Graduate Student, Department of Electrical Engineering, chiba@ecei.tohoku.ac.jp
[2] Associate Professor, Department of Electrical Engineering, kazunori@ecei.tohoku.ac.jp
[3] Assistant Professor, Department of Electrical Engineering, komuro@ecei.tohoku.ac.jp
[4] Professor, Department of Electrical Engineering, akira@ecei.tohoku.ac.jp

the Lorentz force term and the imparted total thrust are increased[12]. These results also seem to be consistent with the one- and two- dimensional theoretical studies[13, 14]. It is also reported that modifying the source cavity[15] and attaching the physical nozzle on the thruster exit[16] contribute to increasing the thrust. Some of previously experiments have tested on the various propellant gas species[11, 15, 17-19]. However these experiments have been tested by using differently designed helicon plasma thrusters. As a result, the effects of the propellant species on the thruster performance have not been fully characterized yet. The recent experiment has shown that total thrust for the various rare gas species are similar[20]. The measurement with the various propellant species has implied that the axial momentum lost to the radial wall increases with increasing the ionization rate by changing the propellant species[21].

The plasma production inside the source cavity is one of the critical issues to determine the thruster performance, which can be simply modeled with particle and power balance equations[22], where not the mass flow rate but the working pressure determines the plasma density and the electron temperature. Here, the helicon plasma thruster is operated with the various rare gas species (neon, argon, krypton, and xenon) and the imparted thrust is evaluated with the various propellant pressures. The results are also discussed with the simple model connecting the global model inside the source cavity[22] and the one-dimensional magnetic nozzle model[23].

II. Experimental Setup and Method

The previously described helicon plasma thruster and the pendulum thrust balance[12] shown in Fig. 1(a) are used here. A vacuum chamber is a stainless cylinder (60-cm-diameter and 140-cm-length), and the plasma source is attached to the pendulum thrust balance immersed in the vacuum. The chamber is evacuated to a base pressure less than 5 × 10^{-6} Torr by a turbomolecular pump and a rotary pump. The source cavity is composed of a ceramic tube (64-mm-inner-diameter) and the upstream insulator back plate located at z = -19 cm, where the downstream open source exit is defined as z = 0 cm. The back plate has a center hole (6-mm-diameter) and the one of the propellant gases (neon, argon, krypton, and xenon) are injected through a stainless-steel tube (2-mm-inner-diameter) passing the center hole. The mass flow rate of the propellant gases is maintained by a mass flow controller. The operating pressure is measured by a Baratron gauge connected to a side port of the chamber, where the chamber pressure for the mass flow rate of 1 mg/s are 1.6 mTorr for neon, 0.9 mTorr for argon 0.65 mTorr for krypton and 0.5 mTorr for xenon. A magnetic nozzle is provided by supplying dc current of 7 A to a solenoid centered at z = -3.5 cm. The calculated magnetic field strength on z-axis is shown in Fig. 1(b). A configuration of the magnetic nozzle is a convergent-divergent nozzle and has a maximum magnetic field strength is about 350 Gauss. It should be noted that a current-free double layer is sometimes formed near the source exit when applying a uniform field within the source, which is a complex nonlinear phenomenon. To investigate the simple current-free magnetic nozzle thruster, the convergent-divergent magnetic nozzle is chosen here. A double-turn RF loop antenna is situated at z = -11 cm and powered from a 13.56 MHz RF power generator. The output RF power from the generator for the steady-state plasma production is maintained at 1 kW, where the

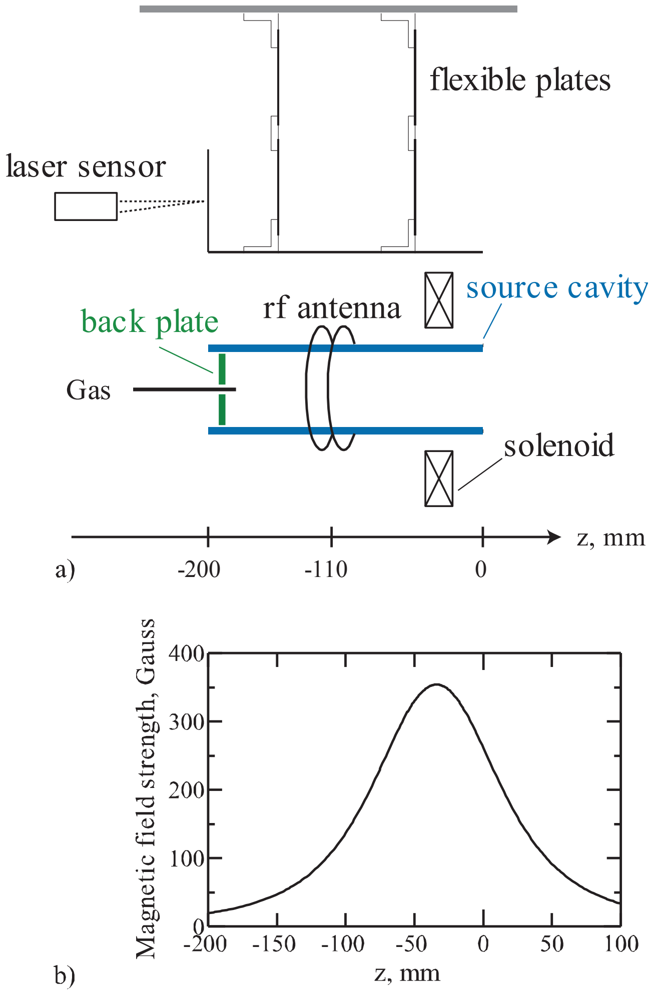

Figure 1. a) Schematic diagram of the experimental setup. b) Magnetic field configuration on z-axis for the solenoid current of 7 A.

reflected RF power is minimized to less than a few percent by turning the impedance matching circuit

The thrust is measured by a similar method to the previously experiments[16]. The thrust is estimated from a displacement of the thrust balance which is measured by a laser displacement sensor while producing the plasma. A calibration coefficient relating the displacement to the force is obtained by adding a known force to the thrust balance. The displacement is calculated by the laser signal with only turning on magnetic field and the signal with both the magnetic field and the plasma.

The RF power transfer efficiency η_p (between the RF antenna and the plasma) is also simultaneously measured with the thrust measurement. The transfer efficiency is estimated as a ratio of the plasma resistance to the total resistance as[24],

$$\eta_p = \frac{P_{abs}}{P_{RF}} = \frac{R_p}{R_p + R_{antenna}} \tag{1}$$

where P_{abs}, P_{RF}, R_p, and $R_{antenna}$, are the RF power absorbed by the plasma, the RF output power from the generator, the plasma resistance, and the antenna resistance, respectively. The values of $R_{antenna}$ and $R_p + R_{antenna}$ are estimated from the RF antenna current and the RF power with no plasma (no gas) and with the plasma.

III. Experimental Results and Discussion

The thrust measured for neon (crosses), argon (open squares), krypton (filled circles), and xenon (open triangles) are plotted in Fig. 2(a), where the solenoid current is chosen to be 7 A. Beyond the pressure ranges where the data are plotted, the stable plasma production could not be made, In other words, the operational pressure range is changed by the propellant gas species due to the collisional cross section, ionization energy, and so on. Here it should be noted that the unstable plasma production for the higher pressure range is due to the anomalous discharge around the RF feedthrough and the RF antenna, both are located outside of the source cavity. This is only a technical issue for the experimental setup and beyond the scope of this paper. Interestingly, the thrust drastically decrease at the low operating pressure even when the stable plasma is produced, which will be discussed later. The measured thrust for neon is significantly lower than that for the other propellant species. Here, the measured power transfer efficiency η_p is shown in Fig. 2(b) for the same conditions as in Fig. 2(a). η_p for neon is found to be smaller than the other propellant species. Therefore it appears that the small thrust for neon is caused by the poor coupling between the RF power and the plasma. This result has been also described in Ref. 20. On the other hand, the measured thrust for argon, krypton, and xenon are very close, whereas η_p for argon, krypton, and xenon are maintained at about 80%. Therefore the thrust cannot be drastically improved by the propellant species. In the helicon plasma thruster, the source of the plasma momentum is mainly electron pressure even if incorporating the magnetic nozzle effects[12]. Since the almost of the RF power is coupled with plasma electrons and their pressure is converted into the thrust via electrostatic and electromagnetic acceleration, the thrust unchanged by the propellant species under the constant power

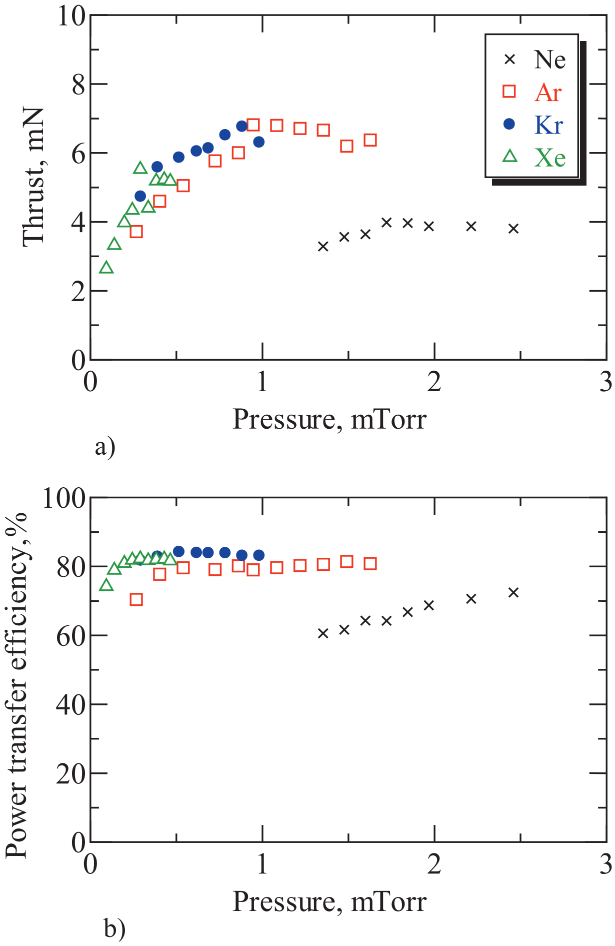

Figure 2. Measured a) thrust and b) power transfer efficiency as a function of propellant pressure.

transfer efficiency is understandable. Furthermore the recent work has shown that the axial plasma momentum is lost to the lateral wall for the highly ionized and heavy gas species[21]. By understanding the detailed physics underlying the thruster performance, further improvement of the performance will be progressed. It is interesting to mention that the thrust saturates when increasing the gas pressure, while it starts to decrease when decreasing the pressure in spite of the constant power transfer efficiency. This might be understood by the energy loss to the sheath for the higher gas pressure and by the fact that the origin of the thrust imparted by the helicon plasma thruster is the electron pressure in the source.

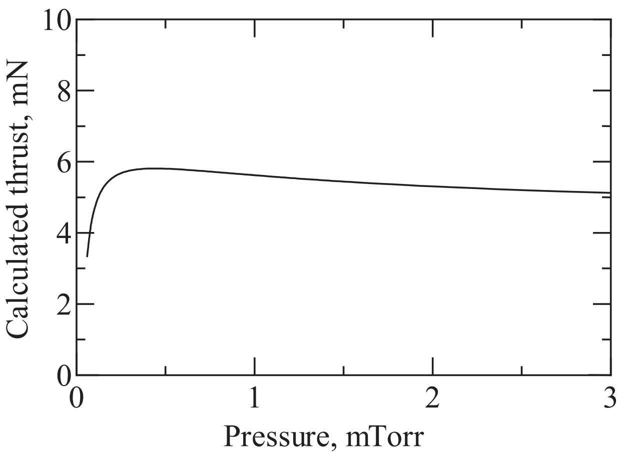

Figure 3. Calculated thrust for argon as a function of pressure, where the calculated condition is the same as the experiment but η_D is assumed to be constant and set as 80%.

To qualitatively understand such data showing the decrease in the thrust at the low pressure and the saturation at the high pressure, the theoretical thrust for argon as a function of a source cavity pressure is estimated by the simple thruster model, where a simple global model[22] in the source cavity and a magnetic nozzle model in one-dimension[13] are connected at the open source exit. It is assumed that the ion flow velocity corresponds to the Bohm velocity power balances in the source cavity and the edge-to-center density ratio in free fall model is incorporated in the particle and power balances in the source cavity. The calculated thrust for the same condition as the experiment is shown in Fig. 3 as a function of the gas pressure, where the power transfer efficiency is assumed to be constant and set as 80%. The result clearly reproduces the drastic decrease in the thrust at the low gas pressure (< 0.5 mTorr) even when the power transfer efficiency is maintained at constant. This is probably due to the increase in the plasma loss to the wall boundaries for the higher electron temperature at the low pressure condition. For the higher gas pressure (> 0.5 mTorr), the thrust gradually decreases with the increase in the pressure, which seems to be due to the energy consumption for the inelastic collisions and the reduction of the particle flux exhausted from the source cavity. The latter effect seems to be included in the edge-to-center density ratio depending on the gas pressure[22]. These facts qualitatively correspond to the result in Fig. 2(a).

IV. Conclusion

The helicon plasma thruster is operated, for the different species of neon, argon, krypton, and xenon, and the thrust is measured with the various pressures. The measurements for any propellant species show the saturated thrust when increasing the operating gas pressure, which is measured at the chamber side port. The measured thrust saturates at the high pressure, whereas drastically decreased at the low gas pressure in spite of the constant power transfer efficiency. The thruster model incorporating the source model and the magnetic nozzle model qualitatively explains these features.

Acknowledgments

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