Recent progress of a helicon plasma thruster development

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Abstract: The thrust imparted by an electrodeless helicon plasma thruster having a magnetic nozzle is estimated for various cavity diameters with a very simple one-dimensional model. The plasma density and electron temperature are simply calculated from the particle and power balances in a global model; then the magnetic thrust component is calculated from the electron diamagnetic model with the known plasma injection into the nozzle. The thrust is also experimentally assessed for the 95-mm-diameter source cavity. The maximum thrust-over-power of ~18 mN/kW is obtained for 1 kW rf power. Furthermore, the rf power is increased up to ~ 6kW and the thrust of ~57 mN is obtained.

Nomenclature

T_e	=	electron temperature
n_p	=	plasma density
T_{total}	=	total thrust
T_s	=	force exerted to the axial source boundary
T_B	=	force exerted to the magnetic field
u_B	=	Bohm velocity
h_R	=	edge-to-center density ratio in the radial direction
h_L	=	edge-to-center density ratio in the axial direction
R	=	source radius
L	=	source length
B	=	magnetic field strength
K_{iz}	=	ionization rate constant

I. Introduction

OVER the past few decades, various electric propulsion devices such as ion gridded thrusters [1-3], hall effect thrusters [1,4,5], and magnetoplasmadynamic (MPD) thrusters [6-8] have been developed and some of them have been successfully tested in space. In such conventional electric propulsion devices, electrodes for the plasma generation and acceleration are exposed to the plasma discharges; then ion sputtering and thermal load significantly damage the electrodes. For further development of long-lived electric propulsion devices, various electrodeless plasma thrusters (e.g., the Variable Specific Impulse MagnetoPlasma Rocket [9], the helicon plasma thruster[10],

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and the electron cyclotron resonance plasma thrusters [11]) have been proposed and are now investigated vigorously. The helicon plasma thruster consists of only an insulator source cavity and an expanding magnetic field (magnetic nozzle). It is considered that the external magnetic field has two roles of the thruster operation: One is improvement of the power transfer efficiency from the rf generator to the plasma itself via a helicon wave discharge, and the other is the plasma acceleration along the axis via the magnetic expansion process. A number of the initial basic laboratory experiments have shown a spontaneous formation of a current-free helicon double layer or ambipolar electric fields [12-14]; then the source ions are subsequently and supersonically accelerated by the static electric field [15]. These supersonic ions have been sometimes observed to be detached from the external closed magnetic field lines [16,17], while the electrostatic ion acceleration process does not impart to the plasma since the kinetic energy of the electrons overcoming the potential drop is converted into the ion energy via the electrostatic acceleration [18-21]. Hence the presence of the internal electrostatic field does not increase the thrust. This fact has been suggested in theory [18] and verified in experiments [22]. Alternatively, the presence of the magnetic pressure thrust by the magnetic nozzle has been demonstrated by the individual measurements of the force components exerted on the physical boundaries and the magnetic nozzle [23], which can be performed by attaching only the source cavity or the solenoid providing the magnetic nozzle to the pendulum thrust balance. Theoretical models have shown that the magnetic force is equivalent to the Lorentz force arising from the radial magnetic field and the plasma-induced current [23,24]. In the simplest thruster model, the plasma-induced current is described by the electron diamagnetic drift current [23]. By inhibiting the plasm cross-field diffusion in the magnetic nozzle by the magnetic field strength, the magnetic thrust components are confirmed to be increased and approach to the theoretical thrust limit [25]. To further approach the ideal magnetic nozzle with no plasma loss from the magnetic nozzle, the pulsed and strong magnetic field has also been tested in the helicon plasma source [26].

The recent theory has shown that the simple two-dimensional electron diamagnetic model can be rewritten by a one-dimensional expression equivalent to the physical nozzle physics [27]. Under the condition of the ideal magnetic nozzle with no radial plasma loss, the plasma parameters in the nozzle can be estimated from the flux conservation. Once if the plasma parameters in the source cavity and at the nozzle entrance are obtained, the static pressure force exerted to the axial physical boundary and the magnetic thrust can be estimated, where the radial loss of the axial momentum is neglected although the recent experiment has clearly shown the presence of the radial loss term for the case that axial density gradient and electric field exists in the source [28].

Here the simple analysis is performed for the various diameters of the source cavity, where the ion velocity at the source exit is assumed to be supersonic. The analysis shows an increase in the thrust with the increase in the cavity diameter. To verify the qualitative analysis, the thrust imparted by the helicon plasma thruster is assessed by using a pendulum thrust balance immersed in vacuum, where a larger diameter source cavities than that used in the previous experiments are tested. Actually, the highest thrust-over-power of ~18 mN/kW to this date is obtained with only the magnetic nozzle for the larger diameter source cavity and 1 kW rf power, while the previously reported thrust-over-power of the helicon thruster were about 10 mN/kW with only the magnetic nozzle and 13 mN/kW even with both the magnetic and physical nozzles [29].

II. Model

Here the simple analysis connecting the plasma production in the cavity and the magnetic nozzle expansion are described. Since the actual expansion is more complex than we thought, the analysis is used only for qualitative discussion. The plasma production is analyzed by the well-known global model treating the balances between the ionization in the given volume and the particle loss to the given surface, and between the absorbed electric power and the energy lost from the system [30]. By incorporating the edge-to-center density ratio in the axial and radial directions (h_L and h_R) and the

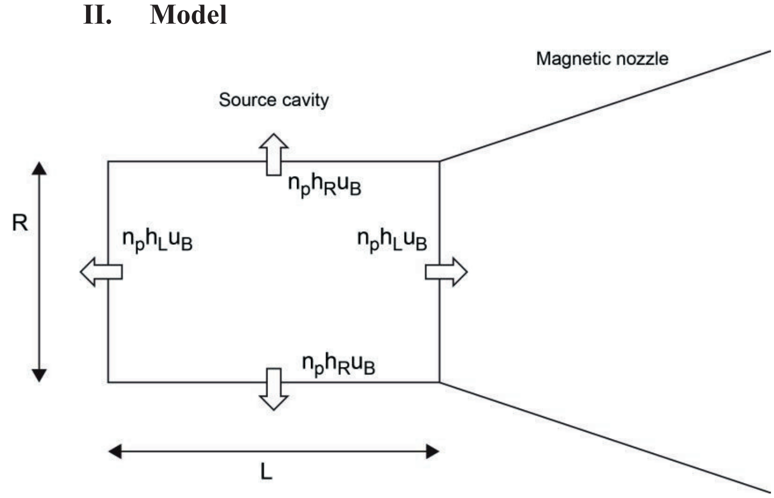

Figure 1. Schematic diagram of the thruster model.

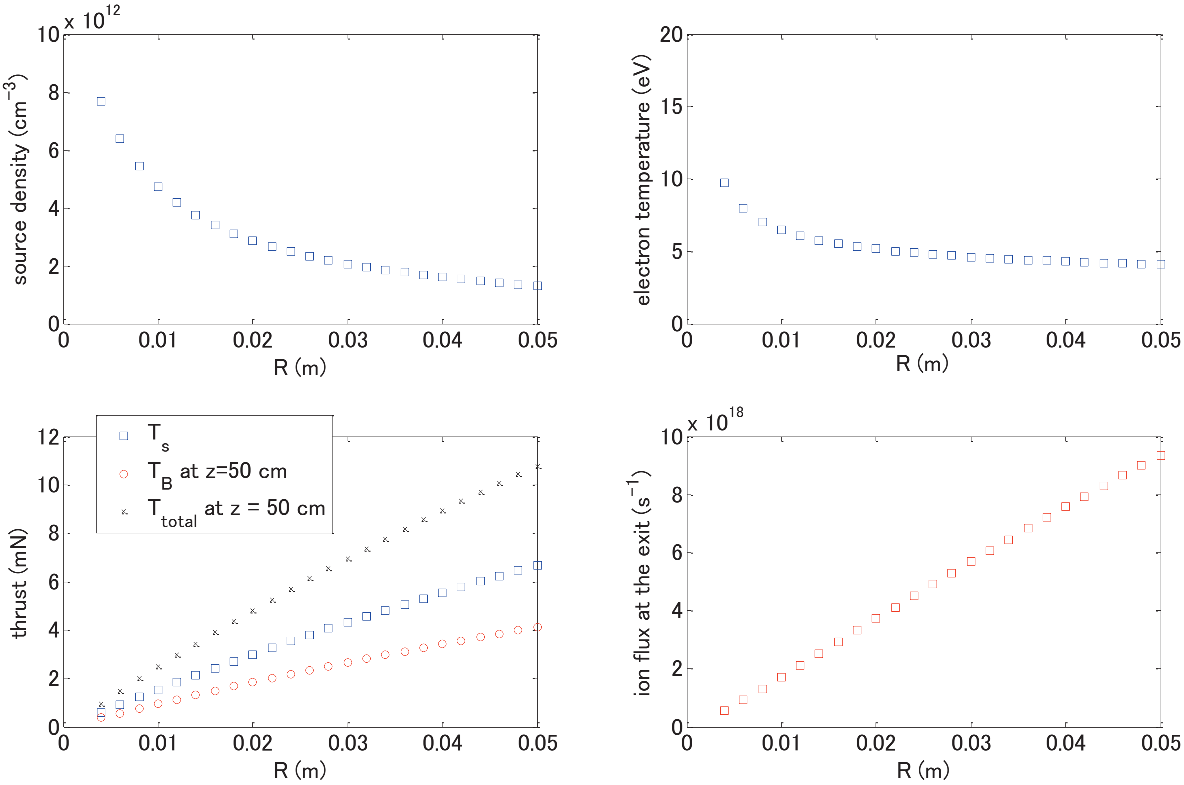

Figure 2. Analyzed results on the source plasma density, the electron temperature, the thrust components, and the ion flux exhausted from the source exit (nozzle entrance). The argon pressure in the source and the rf power are chosen as 2 mTorr and 1 kW.

approximated ionization rate constant $K_{iz}(T_e)$, the electron temperature is obtained from the former balance. Once the electron temperature is known, the plasma density is calculated from the power balance. When neglecting the loss of the axial momentum to the radial boundary, the pressure force to the source cavity can be given as T_s, where the detailed expression can be found in Ref. [25]. When using the paraxial approximation, the magnetic pressure force exerted by the magnetic nozzle can be given by T_B as found in Ref. [27], which can be calculated once if the electron pressure is known. Neglecting the radial loss of the axial momentum, which has been discovered recently [28], for simplicity, the total thrust can be given as $T_{total} = T_s + T_B$. By assuming no radial loss from the magnetic nozzle, the ion flow velocity and the local plasma density can be obtained.

Figure 2 shows the local plasma density and electron temperature in the source, the thrust components T_s and T_B, the total thrust T_{total}, and the ion flux at the source exit (i.e., the nozzle entrance) for the source length of 17.5 cm and 2 mTorr argon in the source. It is found that both the local plasma density and electron temperature in the source decrease with the increase in the diameter. On the other hand, all the thrust components (T_s, T_B, and T_{total}) increase due to the increased cross section of the source and the plasma volume in the magnetic nozzle. Actually, the flux of the ion exhausted from the open source exit is found to be increased by the cavity diameter, which seems to be due to the loss-surface to ionization-volume ratio decreased by the larger diameter cavity. This fact is consistent with the recently reported helicon thruster model, where the most of the energy is suggested to be deposited at the radial source wall [31,32].

III. Experiment

To verify the simplified and qualitative model described in the previous section, the experiments are performed in Mega-HPT machine (Fig.3) at Tohoku University. The machine has a 1-m-diameter and 2-m-long vacuum chamber evacuated by a 3000 L/sec turbomolecular pumping system to the base pressure below 10^{-6} Torr. The

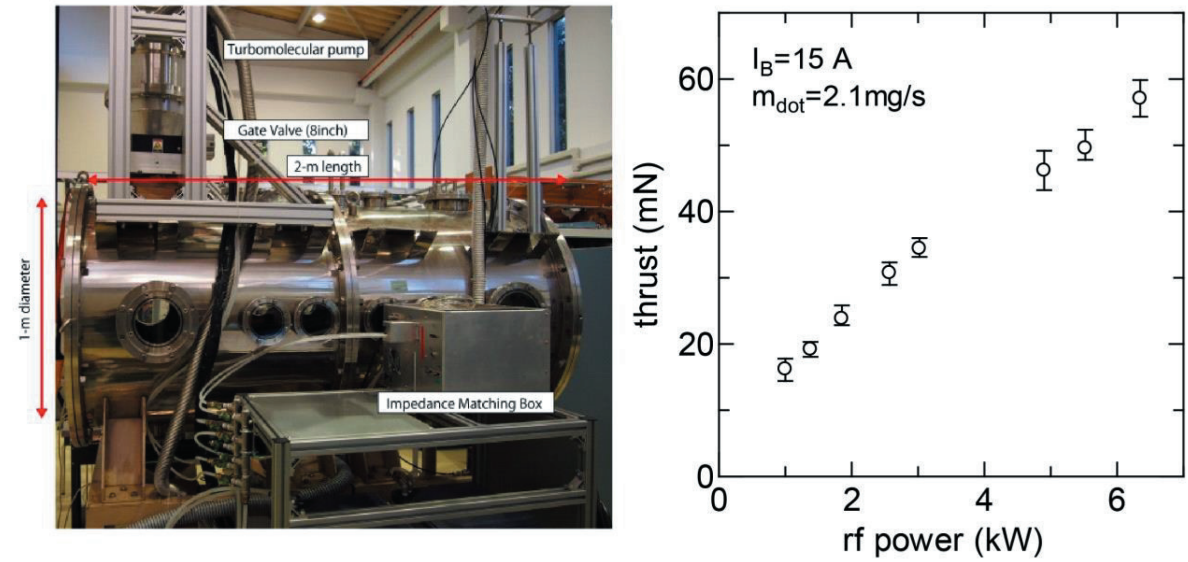

Figure 3. Photograph of Mega-HPT machine at Tohoku University and the measured thrust as a function of the rf power for the solenoid current of 15 A and the argon mass flow rate of 2.1 mg/s.

helicon plasma thruster attached to a pendulum thrust balance is immersed in the vacuum chamber. The thrust head has a 95-mm-diameter ceramic source tube surrounded by a double-turn rf loop antenna. Argon gas is introduced upstream of the thruster head and the mass flow rate is chosen as 2.1 mg/s (70 sccm). A dc current of 15 A is supplied to a solenoid located near the open source exit; then the maximum magnetic field strength of 980 Gauss exist within the source and decrease to 40 Gauss at 20 cm downstream of the source exit. The rf antenna is continuously powered from a 13.56 MHz rf generator through an impedance matching circuit.

Simultaneously with the continuous plasma production, the displacement of the thrust balance is measured by a laser displacement sensor and the absolute value of the total thrust is obtained by multiplying the calibration coefficient, which is obtained before pumping down and confirmed to be unchanged after venting the chamber.

The measured total thrust is plotted as a function of the rf power in Fig.3 by open circles. The thrust for the rf power of 1 kW is about 18 mN. It should be noted once again that the highest thrust for the 1 kW rf power was about 11 mN with only the magnetic nozzle and was improved up to 13 mN with both the magnetic and physical nozzles [29], where the cavity diameter was chosen as 6.5 cm. Therefore, the larger thrust in the present experiment seems to be due to enlarging the cavity diameter and consistent with the model described in the previous section. Fortunately, the rf power can be increased up to 6-7 kW (maximum power of the generator is 10 kW, but the anomalous discharge is often observed for above 7 kW). The maximum thrust of ~57 mN can be obtained for the rf power of 6.3 kW as seen in Fig. 3. Hence the thrust-to-power of 9 mN/kW is still sustained even for the high power operation. The performance improvement and the investigation on the underlying physics will be more progressed hereafter.

IV. Summary

The helicon plasma thruster having the magnetic nozzle is operated with the source cavity of 95 mm in diameter. The thrust-over-power of 18 mN/kW is successfully obtained by enlarging the cavity diameter. This result is qualitatively consistent with the analytical, simple, and one-dimensional model connecting the plasma production model in the cavity and the one-dimensional magnetic nozzle expansion. When increasing the rf power up to ~ 6 kW, the thrust of 57 mN is obtained; then the thrust-over-power of 9 mN/kW is still sustained. Since the neutral depletion effect appears when increasing the rf power and the resultant ionization rate, its effect on the propulsive performance will also be investigated hereafter.

Acknowledgements

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