Performance improvement of a magnetic nozzle plasma thruster

IEPC-2019-A855

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Kazunori Takahashi[1]
Department of Electrical Engineering, Tohoku University, Sendai, 980-8579, Japan

Yoshinori Takao[2]
Division of Systems Research, Yokohama National University, Yokohama 240-8501, Japan

and

Akira Ando[3]
Department of Electrical Engineering, Tohoku University, Sendai, 980-8579, Japan

Abstract: Thruster performance of a magnetic nozzle helicon plasma thruster is evaluated by measuring the thrust in a 1-m-diamter and 2-m-long vacuum chamber, which is evacuated by three 3000 L/s turbomolecular pumps. The thruster is attached to a pendulum thrust balance immersed in vacuum and the thruster has a 95-mm-inner diameter insulator source tube and the solenoid near the thruster exit. The rf antenna is powered by a 13.56 MHz rf generator and the rf power is increased up to about 6 kW. The thruster efficiency calculated from the measured thrust, the mass flow rate, and the rf power is approaching to about 20 percent, which seems to be highest up to this date.

[1] Associate Professor, Department of Electrical Engineering, Tohoku University, kazunori@ecei.tohoku.ac.jp
[2] Associate Professor, Division of Systems Research, Yokohama National University, takao@ynu.ac.jp
[3] Professor, Department of Electrical Engineering, Tohoku University, akira@ecei.tohoku.ac.jp

I. Introduction

HELICON plasma thruster consisting of a high-density helicon plasma source and a magnetic nozzle is one of the propulsion concept being studied vigorously in recent years [1-3]. The high density plasma produced in the helicon source is transported along the axial magnetic field lines to the source exit and exhausted from the thruster. Since the magnetic field lines inevitably expands downstream of the thruster exit, the plasma also expands there and spontaneous plasma acceleration processes would occur. It is crucial to understand the momentum gain/loss and conversion processes in the plasma source and in the expanding magnetic field (called a magnetic nozzle) for the performance improvement of the helicon plasma thruster [4,5].

The first direct measurement of the thrust imparted by the helicon plasma thruster has been performed in 2011 in two research groups [6,7]; the results showed the thrust of a few of mN for about 1kW rf power, which leads the thruster efficiency less than a percent. Subsequent experiment has demonstrated that the thrust is enhanced by the magnetic nozzle, where a Lorentz force due to the radial magnetic field and the electron diamagnetic drift current significantly contributes to the thrust enhancement [8]. Furthermore, the electron diamagnetic thrust is observed to increase with an increase in the magnetic field strength [9]. Although very strong magnetic field is applied to the helicon thruster by using the pulsed magnetic field technique [10], the experiment showed that the imparted thrust saturates for the magnetic field strength above a few of kG [11].

In addition to the physics in the magnetic nozzle, many aspects of physics underlies inside the plasma source. An individual measurement of the axial force imparted to the radial source wall has demonstrated that the axial momentum is lost to the radial wall when the axially accelerated ions are lost to the wall [12,13], while such a momentum loss process has been assumed to be negligible in the theoretical models [4,5,14]. This phenomenon gets conspicuous for the highly-ionized plasmas, where the axial profile of the plasma density has an upstream density peak due to the neutral depletion [12,15], which is consistent with theoretical prediction in a one-dimensional model [16,17]. To inhibit the formation of the upstream density peak, the propellant gas has been introduced near the thruster exit and the increase in the thrust by about a 10-20 percent has been observed [18].

Although the fundamental studies and the thruster development have been progressed over the last decades, the thruster performance is still low compared with the mature electric propulsion devices such as a Hall thruster and an ion gridded thruster. Moreover unclear physics such as a plasma detachment from the magnetic nozzle [19-25], an electron thermodynamics in the magnetic nozzle [26-29], and so on, are still there. Therefore, improvement of the thruster performance and exploration of the physics still remains further challenging issues.

Here the thruster efficiency approaching about 20 percent is reported, where a 95-mm-inner dimeter ceramic tube is employed and the propellant gas is introduced near the thruster exit.

II. Model

Here the simple analysis connecting the plasma production in the cavity and the magnetic nozzle expansion are described again although it has been described before [30]. The analysis is used only for qualitative discussion since it is very simplified model. 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 [31]. By incorporating the edge-to-center density ratio in the axial and radial directions (h_L and h_R) and the 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.

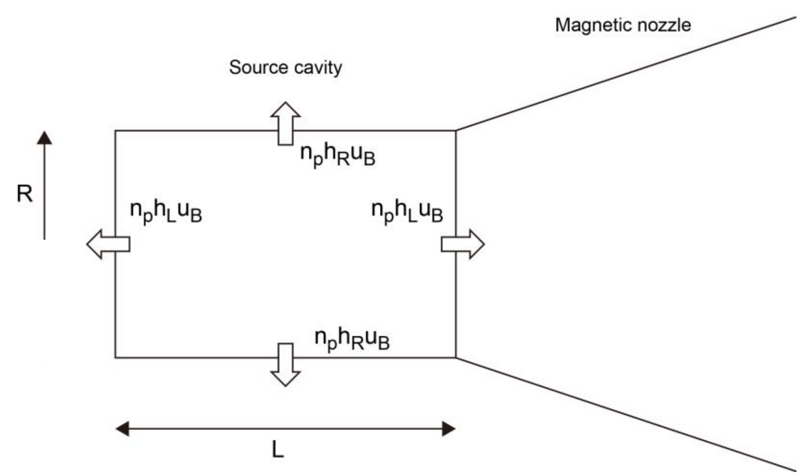

Figure 1. Schematic diagram of the thruster model.

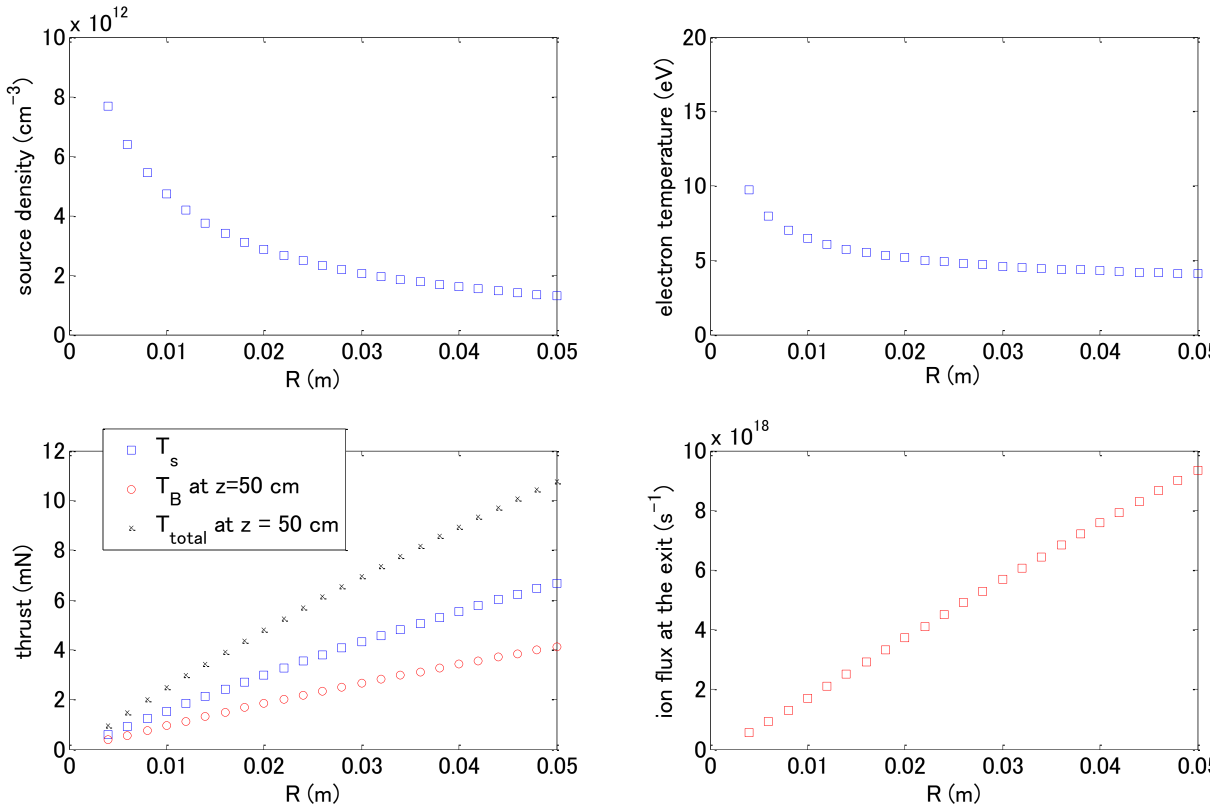

Figure 2. Analyzed results on the source plasma density, the electron temperature, the thrust components, and the ion flux exhausted from the source exit (nozzle entrance). The argon pressure in the source and the rf power are chosen as 2 mTorr and 1 kW.

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. [31]. When using the paraxial approximation, the magnetic pressure force exerted by the magnetic nozzle can be given by T_B as found in Ref. [32], which can be calculated once if the electron pressure is known. Neglecting the radial loss of the axial momentum 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 [14,33]. According to the analysis and the fact that the highest performance has been obtained with the 95-mm-inner diameter source tube, the present experiment is conducted with the 95-mm-diameter source tube. Furthermore, the gas is introduced near the thruster exit based on the result that the thrust is increased with the downstream gas injection configuration, where the previous experiment on the gas injection location used the 65-mm-diameter source tube [18].

III. Experimental setup and result

Experiment is performed in a 1-m-diameter and 2-m-long vacuum chamber evacuated by three turbomolecular pumps connected to the chamber via gate valves, where each pump has a pumping speed of 3000 L/s. The thruster has very similar configuration to the previous experiment, which has shown a maximum thrust of about 60 mN for about 6 kW rf power. However, the propellant argon is introduced near the thruster exit via a 1-mm-innner and 2-mm-outer diameters ceramic tube. It should be mentioned again that the thrust is increased by introducing the gas near the thruster exit. The rf antenna, which is shielded by thick insulator parts and grounded metallic parts as in Ref.[34], is powered from the 13.56 MHz rf generator via an impedance matching circuit consisting of two variable capacitors. The rf power can be increased up to 6 kW.

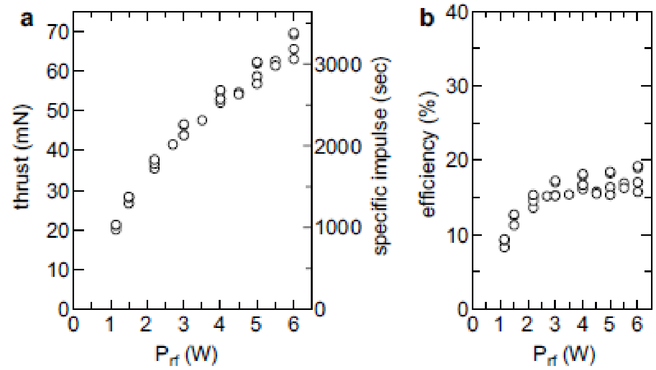

Figure 3. (a) Measured thrust and estimated specific impulse. (b) Thruster efficiency calculated from the thrust, the mass flow rate, and the rf power, where the power for the solenoid coil is not taken into account. The data is taken from [3].

The thrust is measured by a pendulum thrust balance immersed in the vacuum chamber, where the displacement induced by the force when generating the plasma is measured by a laser displacement sensor [35]. By multiplying the calibration coefficient relating the displacement to the force, the absolute value of the thrust can be obtained.

Figure 3 shows the measured thrust, the specific impulse, and the thruster efficiency, the latter two of which are calculated using the rf output power from the generator and the mass flow rate. The maximum thrust exceed the previous value of 60 mN and the thruster efficiency of 17.5 percent is obtained, approaching to 20 percent. This seems to be the highest thruster efficiency to this date [3].

Conclusion

The thruster performance of the magnetic nozzle rf plasma thruster is evaluated by the direct measurement of the thrust, where the 95-mm-inner diameter source tube and the downstream gas injection are employed in the thruster. The maximum thruster efficiency approaching 20 percent is obtained and further improvement and the fundamental physics researches will be progressed hereafter. In the presentation, the auto-tuning rf system will also be presented for future development of compact rf system.

Acknowledgments

This work is partially supported by grant-in-aid for scientific research (Grants No.18K18764, and 19H00663) from the Japan Society for the Promotion of Science, Research Foundation for the Electrotechnology of Chubu, and JAXA.

References

[1]Charles C., "Plasmas for spacecraft propulsion", *J. Phys. D: Appl. Phys.* **42** 163001 (2009).

[2]Bathgate S.N., Bilek M.M.M., and Mckenzie D.R., "Electrodeless plasma thrusters for spacecraft: a review", *Plasma Sci. Technol.* **19** 083001 (2017).

[3]Takahashi K., "Helicon-type radiofrequency plasma thrusters and magnetic plasma nozzles", *Rev. Mod. Plasma Phys.* **3** 3 (2019).

[4]Fruchtman A., "Electric field in a double layer and the imparted momentum", *Phys. Rev. Lett.* **96** 065002 (2006).

[5]Ahedo E. and Merino M., "Two-dimensional supersonic plasma acceleration in a magnetic nozzle", *Phys. Plsamas* **17** 073501 (2010).

[6]Pottinger S., Lappas V., Charles C., and Boswell R., "Performance characterization of a helicon double layer thruster using direct thrust measurements", *J. Phys. D: Appl. Phys.* **44** 235201 (2011).

[7]Takahashi K., Lafleur T., Charles C., Alexander P., Boswell R.W., Perren M., Laine R., Pottinger S., Lappas V., Harle T., and Lamprou D., "Direct thrust measurement of a permanent magnet helicon double layer thruster", *Appl. Phys. Lett.* **98** 141503 (2011).

[8]Takahashi K., Lafleur T., Charles C., Alexander P., and Boswell R.W., "Electron diamagnetic effect on axial force in an expanding plasma: experiments and theory", *Phys. Rev. Lett.* **107** 235001 (2011).
[9]Takahashi K., Charles C., and Boswell R.W., "Approaching the theoretical limit of diamagnetic-induced momentum in a rapidly diverging magnetic nozzle", *Phys. Rev. Lett.* **110** 195003 (2013).
[10]Takahashi K., Sato D., Takaki K., and Ando A., "Development of a compact magnetically expanding plasma source with a strong magnetic field", *Plasma Sources Sci. Technol.* **22** 055002 (2013).
[11]Takahashi K., Komuro A., and Ando A., "Operating a magnetic nozzle helicon thruster with strong magnetic field", *Phys. Plasmas* **23** 033505 (2016).
[12]Takahashi K., Chiba A., Komuro A., and Ando A., "Axial momentum lost to a lateral wall of a helicon plasma source", *Phys. Rev. Lett.* **114** 195001 (2015).
[13]Takahashi K. and Ando A., "Enhancement of axial momentum lost to the radial wall by the upstream magnetic field in a helicon source", *Plasma Phys. Control. Fusion* **59** 054007 (2017).
[14]Ahedo E. and Navarro-Caballe J., "Helicon thruster plasma modeling: Two-dimensional fluid dynamics and propulsive performances", *Phys. Plasmas* **20** 043512 (2013).
[15]Takahashi K., Takao Y., and Ando A., "Neutral-depletion-induced axially asymmetric density in a helicon source and imparted thrust", *Appl. Phys. Lett.* **108** 074103 (2016).
[16]Fruchtman A., "Neutral depletion in a collisionless plasma", *IEEE Trans. Plasma Sci.* **36** 403 (2008).
[17]Fruchtman A., "Neutral gas depletion in low temperature plasma", *J. Phys. D: Appl. Phys.* **50** 473002 (2017).
[18]Takahashi K., Takao Y., and Ando A., "Modifications of plasma density profile and thrust by neutral injection in a helicon plasma thruster", *Appl. Phys. Lett.* **109** 194101 (2016).
[19]Arefiev A.V. and Breizman B.N., "Magnetohydrodynamic scenario of plasma detachment in a magnetic nozzle", *Phys. Plasmas* **12** 043504 (2005).
[20]Terasaka K., Yoshimura S., Ogiwara K., Aramaki M., and Tanaka M.Y., "Experimental studies on ion acceleration and stream line detachment in a diverging magnetic field", *Phys. Plasmas* **17** 072106 (2010).
[21]Takahashi K., Itoh Y, and Fujiwara T., "Operation of a permanent-magnets-expanding plasma source connected to a large-volume diffusion chamber", *J. Phys. D: Appl. Phys.* **44** 015204 (2011).
[22]Deline C.A. *et al.*, "Plume detachment from a magnetic nozzle", *Phys. Plasmas* **16** 033502 (2009).
[23]Ahedo E. and Merino M., "On plasma detachment in propulsive magnetic nozzle", *Phys. Plasmas* **18** 053504 (2011).
[24]Olsen C.S. *et al.*, "Investigation of plasma detachment from a magnetic nozzle in the plume of the VX-200 magnetoplasma thruster", *IEEE Trans. Plasma Sci.* **43** 252 (2015).
[25]Takahashi K. and Ando A., "Laboratory observation of a plasma-flow-state transition from diverging to stretching a magnetic nozzle", *Phys. Rev. Lett.* **118** 225002 (2017).
[26]Zhang Y., Charles C., and Boswell R., "A polytropic model for space and laboratory plasmas described by bi-maxwellian electron distributions", *Astrophys. J.* **829** 10 (2016).
[27]Little J.M. and Choueiri E.Y., "Electron cooling in a magnetically expanding plasma", *Phys. Rev. Lett.* **117** 225003 (2016).
[28]Takahashi K., Charles C., Boswell R., and Ando A., "Adiabatic expansion of electron gas in a magnetic nozzle", *Phys. Rev. Lett.* **120** 045001 (2018).
[29]Kim J.Y., Chung K.S., Kim S., Ryu J.H., Chung K-J, and Hwang Y.S., "Thermodynamics of a magnetically expanding plasma with isothermally behaving confined electrons", *New J. Phys.* **20** 063033 (2018).
[30]Takahashi K., Komuro A, and Ando A., "Effect of source dimeter on helicon plasma thruster performance and its high power operation", *Plasma Sources Sci. Technol.* **24** 055004 (2015).
[31]Lieberman M.A. and Lichtenberg A.J., *Principles of plasma discharges and materials processing, 2nd edn.* (John Wiley & Sons, Hoboken, New Jersey, 2005)
[32]Fruchtman A., Takahashi K., Charles C., and Boswell R.W., "A magnetic nozzle calculation of the force on a plasma", *Phys. Plasmas*, **19** 033507 (2012).
[33]Lafleur T., "Helicon plasma thruster discharge model", *Phys. Plasmas*, **21** 043507 (2014).
[34]Takahashi K., "Radiofrequency antenna for suppression of parasitic discharges in a helicon plasma thruster experiment", *Rev. Sci. Instrum.*, **83** 083508 (2012).
[35]Takahashi K., Komuro A., and Ando A., "Measurement of plasma momentum exerted on target by a small helicon plasma thruster and comparison with direct thrust measurement", *Rev. Sci. Instrum.*, **86** 023505 (2015).