19pD2-4

Thrust Measurement and Emission Spectroscopy of Radio Frequency Inductively Coupled Plasma Thruster
高周波誘導結合型プラズマ推進機の推力計測および発光分光計測

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The authors conducted a preliminary experiment for an inductively coupled plasma thruster. Thrust measurement was carried out to investigate the relation between thrust force and mass flow rate. Electron temperature of a plasma in the thruster was also obtained from emission spectroscopy. Electric power from an RF power source was set at 100W. Ar gas was used as a propellant. Thrust and specific impulse increased with a rise in mass flow rate. Electron temperature of the plasma in heating region ranged from 6000 to 9000 K at any mass flow rate. In this experiment, the input power to the thruster did not seem to be constant when the mass flow rate varied, because the plasma generated outside the nozzle and it consumed the electric power. Therefore, improvement of the apparatus is needed in order to prevent the external plasma from arising.

1. Introduction

Inductively coupled plasma thruster (ICP thruster) is an electrodeless electrothermal thruster utilizing radio frequency (RF) electric power for heating propellant. This thruster does not have electrode erosion, and it is expected that this thruster has longer lifetime than DC arcjet [1].

Thrust performance of ICP thruster is, however, inferior to that of DC arcjet. To improve the performance of ICP thruster, it is important to investigate the relation between the operating condition and the performance of the thruster, and also to clarify the plasma properties in the thruster.

As a preliminary experimental study, we measured thrust of an ICP thruster to investigate the relation between mass flow rate and thrust. We also conducted an emission spectroscopy to obtain electron temperature of a plasma in the thruster.

2. Experimental Setup

Figure 1 shows an apparatus for this experiment. A thruster was composed of a quartz tube nozzle and a copper coil. Dimensions of the nozzle and the coil are shown in Fig. 2. If a flow in the nozzle is isentropic, Mach number at the outlet of the nozzle is 3.12.

A pendulum-type thrust stand was assembled for thrust measurement. We obtained thrust force from the displacement of the arm using a laser displacement meter. When a displacement angle of the arm was much small, the relation between the thrust force and a signal voltage from the meter was given in $V = \alpha F$, where V: the voltage and F: thrust force. The constant α was determined by calibration. The stand was set inside a vacuum chamber, which was evacuated by a rotary pump and a mechanical booster pump. During the test time, we continued evacuating the chamber. Pressure in the chamber was measured by a pirani gauge.

Inlet of the nozzle was connected to a gas tank outside the chamber through a mass flow controller which regulated mass flow rate of the gas at the

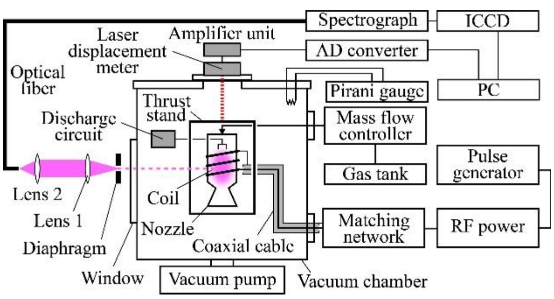


Fig. 1. Experimental apparatus

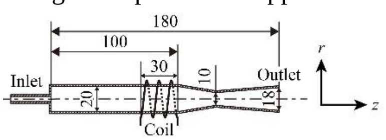


Fig. 2. Dimensions of the nozzle and the coil

range 0-0.56 g/sec. In this experiment, we used Ar gas as a propellant.

The coil was connected to an RF power source via a matching network. This source was triggered by a signal from a pulse generator. The power from the source was fixed at 100 W, and the frequency was 13.56 MHz. In order to trigger ionization of the propellant, pulsed discharge was generated by a Cockcroft–Walton circuit in the coil existing area.

Emission spectrum of the plasma in the nozzle was obtained by a spectrometer and an ICCD detector. Period of the grating in the spectrometer was 300 grooves per mm. We calibrated the apparatus for the experiment with a standard halogen light source. To evaluate electric temperature T_e, we used the following equation;

$$\ln\left(\frac{I_{21}\lambda_{21}}{g_2 A_{21}}\right) = -\frac{E_2}{k_b T_e} + K \qquad (1)$$

where I: intensity, λ: wavelength, g: degeneracy, A: transition probability, E: electron energy of upper level, k_b: Boltzmann coefficient, K: fixed constant, subscript 1: lower level, and 2: upper level of atomic state. I_{21} and λ_{21} were obtained from the experiment, and g_2, A_{21}, and E_2 were taken from the database of NIST [2].

3. Results and Discussions

3.1 *Thrust force measurement*

Figure 3 and 4 show thrust and specific impulse, respectively, for mass flow rate of 29.3-62.8 mg/sec when the power from the source was 0 W and 100 W. Calculation results of quasi-1-dimensional (Q1d) isentropic flow are also shown on each graph. Thrust and specific impulse with no RF power were roughly equivalent to those under the assumption of the isentropic flow. Propellant was heated by the electric power, and thrust and specific impulse at the power 100 W were higher than 0 W. Those increased with mass flow rate.

Figure 5 shows photos of the plasma at the mass flow rates: (a) 40.5 mg/sec and (b) 62.8 mg/sec. In this experiment, plasma of residual gas in the chamber was generated outside the nozzle at both flow rates. When the external plasma is generated, the input power to the thruster declines because it consumed the electric power, and the input power to the thruster did not seem to be constant in the experiment.

3.2 *Emission spectroscopy*

Figure 6 shows axial distribution of the intensity of 811 nm Ar-I line at the ICCD detector gain of 100, the gate width of 500 μsec, and the accumulation number of 150. The intensity had a maximum value at the coil area, and it declined at all the area (z = -110 ~ -80 mm) with increasing mass flow rate.

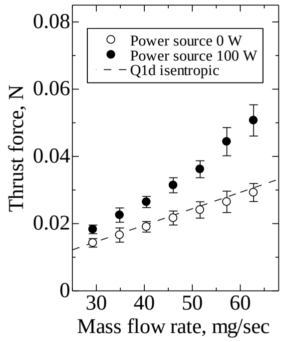


Fig. 3. Thrust force for various mass flow rate

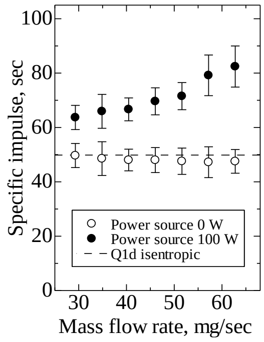
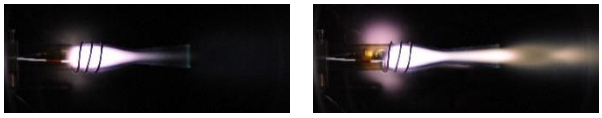


Fig. 4. Specific impulse for various mass flow rate



(a) 40.5 mg/sec (b) 62.8 mg.sec

Fig. 5. Photo of the plasma in the thruster

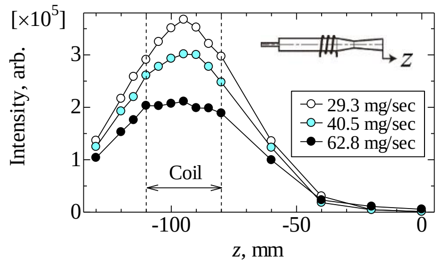


Fig.6. Axial distribution of the intensity of Ar-I line

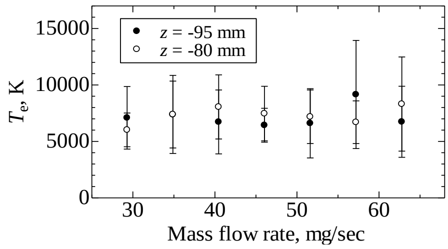


Fig. 7. T_e for various mass flow rate on the axis line

Figure 7 shows T_e for mass flow rate of 29.3-62.8 mg/sec at z = -95, -80 mm. T_e in the heating area ranged from 6000 to 9000 K at any mass flow rate. As we mentioned before, the input power to the thruster did not seem to be constant because of the plasma outside the nozzle. Therefore, improvement of the apparatus is needed in order to prevent the external plasma from arising.

References

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