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Research Note

Rayleigh Scattering Measurement of Neutral Atom Number Density Downstream of a Hall Thruster under Cold Flow Conditions*

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1. Introduction

Electric propulsion systems show considerable promise for satellite station-keeping and orbital transfer applications; they offer an attractive combination of high thrust efficiency, exceeding 50%, and high specific impulse, as compared to chemical thrusters. The development of electric propulsion systems, however, will depend on the measurement of neutral atom density, since charge exchange collisions lead to sputtering on the satellite surface and ion engine grids.[1–4)] The measurement of neutral atom number density will also be crucial for the estimation of on-orbit performance from ground test data, since background neutral particles affect ionization and acceleration processes as well as the charge–exchange collisional processes. In fact, the presence of background neutral particles may lead to increased discharge current, thrust, and plume divergence, and cause differences in the oscillation characteristics of electric systems under testing conditions as opposed to on-orbit condition.[5)]

There has been considerable work[5–10)] on vacuum facility effects on Hall thrusters, including thrust measurements at various back pressures, numerical modeling, and direct measurement of neutral atom number density. These studies have shown that thrust performance depends on pressure, and there exists a critical back pressure for adequate evaluation of thrust performance, though the pressure is specific to the test facility. This is because the neutral number density distribution in the vacuum chamber is different in each facility, due to differences in thruster/pump/vacuum chamber geometries.[10–12)]

There are various techniques for measuring neutral atom number density: ionization gauge measurements,[12,13)] differential pressure gauge measurements,[14)] absorption spectroscopy,[15)] laser induced fluorescence (LIF),[16)] two-photon absorption LIF spectroscopy,[17)] electron beam excitation,[18)] and cavity ring-down spectroscopy.[19)] The use of LIF has proven to be effective for the measurement of relative number density and velocity, though it is difficult to use for quantitative number density measurements.

The approach presented here uses the laser Rayleigh scattering technique.[20,21)] This is a non-intrusive method; it does not disturb the plasma and neutral flow. Number densities can be measured quantitatively by calibration using 10^4 Pa nitrogen, so a complicated collisional-radiative model is not required. The Rayleigh scattering spectrum reflects the velocity distribution of the atoms, so propellant xenon atoms can be distinguished from the ambient xenon atoms. In addition, even when both ions and electrons are present, the neutral number density can be estimated, since the scattering spectrum is a convolution of Rayleigh and Thomson spectra.[22)] The contribution of scattering from metastable atoms can be addressed[23)] by measuring the population of metastable atoms by laser absorption spectroscopy.[15)]

Measurement of neutral atom density using Rayleigh scattering is not novel; it has been used in compressible turbulent-flow research,[21)] plasma process research,[22,23)] and other fields. The target range of our measurement, however, is below 10^{20} m^{-3}, at least one order of magnitude lower than previous studies. The aim of this study is to demonstrate the measurement of neutral atom number density in high vacuum (pressure less than 1 Pa) using the Rayleigh scattering technique, in order to understand the effect of neutral particles on thrust performance. First, we measure the nitrogen molecular number density in the absence of a thruster. Next, we measure the xenon neutral number density downstream of a miniature Hall thruster, without a plasma discharge.

2. Experimental Setup

Our laser Rayleigh scattering measurement setup is shown in Fig. 1. A 0.267 m diameter by 0.4 m long vacuum chamber with a turbo molecular pump (TMP, ULVAC, PT150, pumping speed 150 l/s with nitrogen gas) is used. Nitrogen gas is supplied from the upstream port and the pressure inside the chamber is controlled by changing the conductance of the needle valve upstream of the nitrogen port. The horizontal distance from the probe laser path to the N_2 port is 200 mm. The miniature Hall thruster is positioned 6 mm upstream of the probe laser path. Pressure is measured by means of a pressure sensor (Keyence, AP-C31) and an ion-

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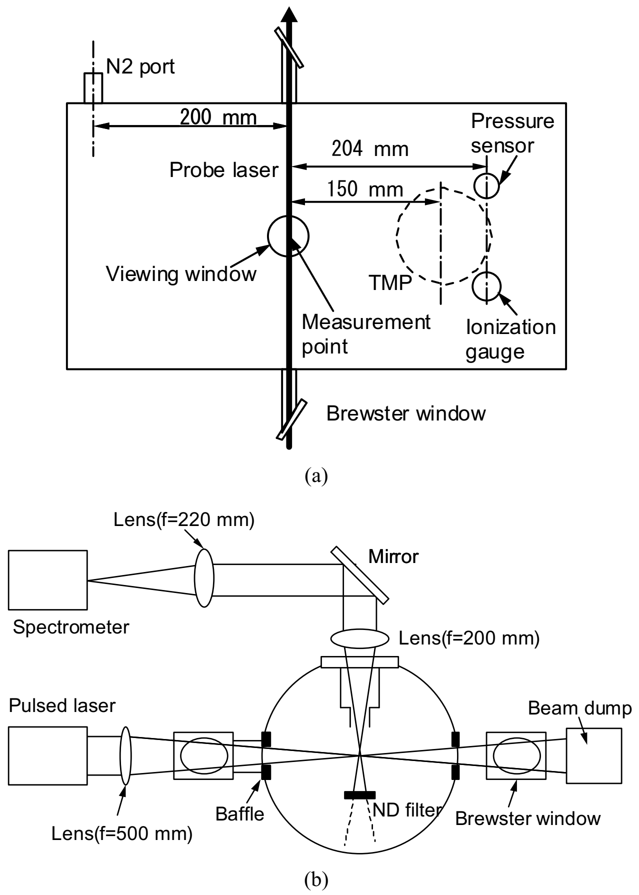

Fig. 1. Schematic of laser Rayleigh scattering system for Hall thruster, (a) top view, (b) side front view.

ization gauge (ULVAC WIT-18) on the chamber wall. The horizontal distance from the probe laser path to the ionization gauge is 204 mm. The chamber baseline pressure was below 3×10^{-3} Pa for these experiments, and the room temperature was 294 K. We assume that the nitrogen molecular temperature and xenon atom temperature in the vacuum chamber are the same as the room temperature (294 K).

Second harmonic beams of two Nd:YAG lasers, wavelength 532 nm, were used as the probe light source. The first laser has maximum energy 200 mJ, repetition rate 10 Hz, pulse width 6 ns, and nominal beam divergence 0.6 mrad (Continuum, Surelite II). The second has maximum energy 100 mJ, repetition rate 50 Hz, pulse width 3 ns, and nominal beam divergence 0.6 mrad (EKSPLA, NL231). Each beam is focused through a plano-convex focusing lens (focal length, *f*, 500 mm). The diameter of the focal spot for each beam was estimated by observing the spatial profile of Rayleigh scattering in 40 kPa air, and found to be 150 µm and 100 µm, respectively; the difference is due to differences in the actual beam divergence. Each beam is delivered through a Brewster window and passes through another Brewster window to a beam dump. Buffers are used in front of both entrance and exit windows to prevent light scattered on the windows from reaching the detector. The scattered radiation is observed at 90 degrees to both the Hall thruster axis and the probe laser beam. Scattered light is focused onto the entrance slit of a triple grating spectrometer (TGS) with two achromatic lenses

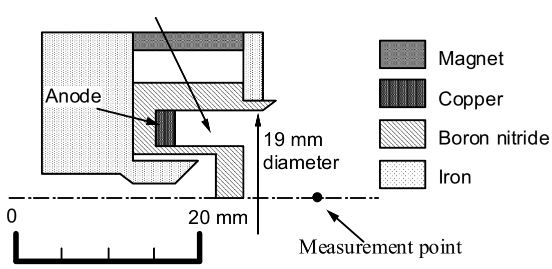

Fig. 2. Cross-section of miniature Hall thruster developed at Kyushu University.

of $f = 220$ mm and $f = 200$ mm. The TGS was used to obtain the scattering light spectrum, in order to distinguish the Rayleigh scattering signal from the Thomson scattering signal for future measurement of neutral atom density with plasma discharge.[23] The instrumental function of the detection system is 0.35 nm (full-width at half-maximum) and the linear dispersion is 1.66 nm/mm. In order to reduce the incidence of stray light (primarily from multiple wall reflected light), an absorptive neutral density (ND) filter with an anti-reflection coating (optical density 6) is set upstream of the observation direction as a viewing dump. The scattered light is dispersed using the TGS with dispersion subtraction,[24] and is detected by a photo-multiplier tube (PMT, Hamamatsu, R943-02).

The estimated Rayleigh scattered photon number is so small that we use a photon counting method. The detected Rayleigh scattered signals are analyzed by a photon counting device (SR430, Stanford Research Systems) after more than 5,000 laser shots. The measurement periods per pulse with the 6 ns pulse width laser and 3 ns laser are 10 ns (5 ns $\times$ 2 bin) and 5 ns (5 ns $\times$ 1 bin), respectively. A high-speed photo diode is used for detection of laser firing and triggering the PMT signal. The incident laser is fixed at 10 mJ, to avoid double counting. We confirmed that an increase in laser energy does not contribute to improvement of the signal to noise (SN) ratio. The experimental uncertainty for each point was determined primarily from the statistical fluctuation in the number of detected photons.[25]

Absolute calibration was performed by Rayleigh scattering measurement through the ND filter (optical density of 4) at 3, 6, 9, and 12 kPa nitrogen gas. The ratio of the xenon cross section to the nitrogen cross section was assumed to be 1.83, following Ref. 26).

Figure 2 shows the miniature Hall thruster developed at Kyushu University.[27] The anode is located 9 mm upstream of the thruster exit face, and the outer acceleration channel diameter is 19 mm. Details and performance are presented in Ref. 27). For the present experiments, the thruster was positioned on the axis of the chamber and the thruster exit face was set 6 mm upstream of the probe beam. Xenon atom number density was measured without discharge; the gas was supplied to the thruster using a thermal mass flow controller (Brooks Instrument, 5850S, full scale of 3 sccm). The background pressure detected using an ionization gauge on the chamber was 0.05 Pa at xenon mass flow rate of 0.2 mg/s.

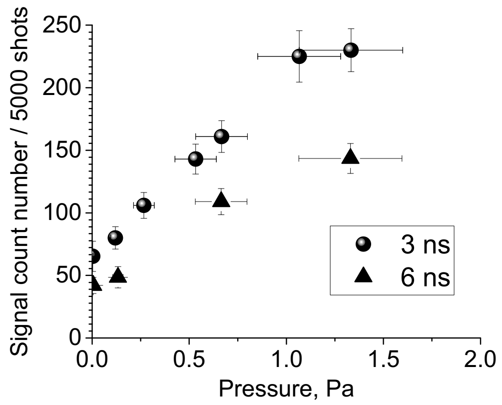

Fig. 3. Rayleigh scattering signal count number per 5,000 laser shots for various pressures.

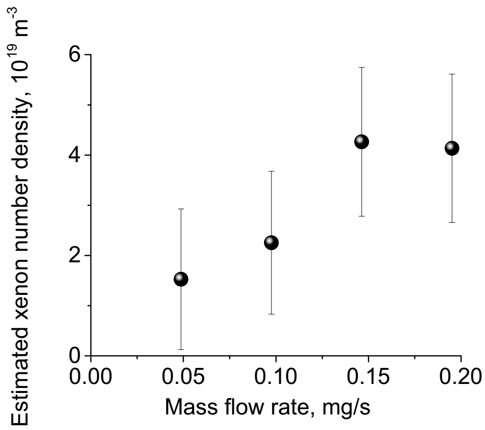

Fig. 4. Xenon number density vs. mass flow rate on axis 6 mm downstream of thruster exit.

3. Results and Discussion

Figure 3 shows the Rayleigh scattering signal count number per 5,000 laser shots for various pressures. Both signals have a linear relation to the pressure measured by the ionization gauge. The estimated number of photons at 1 Pa pressure nitrogen with 10 mJ incident laser per shot is about 0.06, considering the Rayleigh scattering cross section of 6×10^{-32} m^2/sr, observed length along the probe beam of 2 mm, solid angle of 0.18, optical system efficiency of 0.06, and quantum efficiency of the PMT of 0.1. This estimate is in approximate agreement (within a factor of two) with the obtained result.

The S/N ratio is better with the 3 ns pulse duration than with the 6 ns pulse. The minimum detection limits at pulse durations of 3 ns and 6 ns are estimated to be 0.05 Pa and 0.08 Pa, respectively, because the reducing the detection duration from 10 ns to 5 ns reduces the chance of incidence of stray light on the chamber surface. The difference in the slope, which corresponds to the sensitivity of the system, is due to inaccuracies in the optical system and a difference in beam divergence (the diameters of the probe laser beam at the measurement position are 100 mm and 150 mm, respectively, for the 3 ns and 6 ns lasers.

We measured the neutral particle atom number density by Rayleigh scattering under high vacuum conditions; xenon atom number density was measured on the axis 6 mm downstream of the miniature Hall thruster, using the same method. The 3 ns pulse width laser was used, since it has a better S/N ratio. Figure 4 shows the estimated xenon atom number density for four mass flow rates through the miniature Hall thruster without plasma discharge (cold flow conditions). The number density at that position was 2.3×10^{19} m^{-3}. This is in good agreement with the number density from a 1D calculation of 2.9×10^{19} m^{-3} (the flux tube cross section is estimated as a circle of diameter 19 mm, and the temperature of the xenon atom is estimated to be 294 K), considering the divergence of the neutral atoms from the acceleration channel of the thruster. The large uncertainty is due to stray light; for lower density measurements (below 10^{19} m^{-3}), the incidence of stray light will need to be reduced.

4. Conclusion

The neutral number density of a miniature Hall thruster was successfully measured under cold flow conditions using the nonintrusive laser Rayleigh scattering optical method. Pressure estimated from Rayleigh scattering shows a linear relation to the pressure measured by an ion gauge under high vacuum (0.2–1.3 Pa). The adoption of a short laser pulse width improves the S/N ratio, that is, it improves the detection limit for the neutral atom number density; the detection limit of current system is 1.7×10^{19} m^{-3}. The adoption of a short wavelength laser also improves the sensitivity of the system, since the scattering cross section is inversely proportional to the biquadrate of the laser wavelength. A demonstration measurement of the neutral atom number density at 6 mm downstream of a miniature Hall thruster was performed; at a xenon mass flow rate of 0.2 mg/s, the xenon atom number density was estimated to be $(4 \pm 1.5) \times 10^{19}$ m^{-3}.

The present results prove that the Rayleigh scattering method will be useful for measuring the neutral atom number density in the plume region, with further improvement of the detection limit. This method could be used to reveal vacuum facility effects on electric propulsion system performance, and further illuminate the physics behind electric propulsion. In future work, we plan to further improve the detection limit by using a laser with even shorter wavelength and pulse width.

Acknowledgments

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