Neutral Pressure Measurement in an Ion Thruster Discharge Chamber

IEPC-2013-106

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

Yoshinori NAKAYAMA[1] and Keninchi NARISAWA[2]
Department of Aerospace Engineering, National Defense Academy of Japan
1-10-20, Hashirimizu, Yokosuka, Kanagawa 239-8686, Japan

Abstract: Investigation of propellant distribution within discharge chamber is important to develop ion thrusters with more efficient and long durability. However, although the pressure measurement is necessary for the investigation, few measurement systems can detect the propellant pressure with sufficient validity because the pressure is rarefied. In order to measure the pressure, in this study, a low pressure measurement system with a differential pressure gauge was developed and evaluated. Through the evaluation, it was confirmed that this measurement system had a measurement error of approximately 5% in the pressure range of 0.01 Pa to 1 Pa. This detectable pressure range covers that of typical ion thruster discharge chamber. Since this system was also applicable to measure the pressure distribution within an ion thruster discharge chamber, the low pressure measurement system with differential pressure gauge seems to be useful for the investigation of propellant distribution.

I. Introduction

ION thruster has a discharge chamber for ion production, a grid system for ion acceleration, and a neutralizer for spacecraft potential regulation. Since highly efficient plasma production and ion acceleration have been achieved by great efforts of many researchers, at present, many ion thrusters are installed in various satellites and spacecrafts as attractive space propulsion systems. The ion thruster installation was associated with the first successful of the asteroid sample return probe "Hayabusa" mission1). It is safely to say that the embarking days of the initial development are gone, and the maturation days are coming. The investigation of propellant distribution within ion thruster seems to be necessary for the maturation. This is because it was reported that thruster performance was influenced by the propellant gas flow pattern: for example, inlet-locations, inlet-directions of inlets, and flow distribution ratio2). However, the propellant pressure measurement is difficult because few measurement systems can detect the propellant pressure with sufficient validity. This is because the propellant particle is non-charged, and the neutral pressure of typical ion thruster discharge chamber is approximately from 0.02 Pa to 0.1 Pa : rarefied gas3-6). This pressure range is between upper limit of vacuum gauge detectable pressure and lower limit of general gauge detectable pressure with high precision.

In order to investigate the propellant distribution of ion thruster discharge chamber, in this study, an application of a differential pressure gauge was considered. This is because differential pressure gauges with high resolution have been developed. The measurement resolution of a differential pressure gauge is less than 0.01 Pa. Since this resolution is lower than the typical ion thruster internal pressure as mentioned above, the gauge may be useful for the investigation.

The objectives of this study are (1) to design and develop a low pressure measurement system, (2) to evaluate the validity, and (3) to measure in an ion thruster discharge chamber with the system for the evaluation of the system usability.

II. Rarefied Gas

A. Propellant Flow

Propellant particle of ion thruster flows from one or a few inlets, passes through the baffle, and flows into the discharge chamber. Most of the propellant particles flows into discharge chamber reflect several times on the surface of the discharge chamber wall and/or the grids. After that, the particle goes through the grid holes and flows to the downstream of the grid sytem.

Figure 1 indicates the internal pressure of typical ion thrusters[3-6)]. The pressure range is from 0.02 Pa to 0.1Pa (from 20 mPa to 100 mPa), as shown in this figure. In some thrusters, the pressure near the inlets is larger than 1 Pa. The mean free path in such pressure range is approximately from 350 mm to 3.5 mm, and the Knudsen number is from 0.1 to 10. That is, intermediate flow (or transitional flow) between free molecular flow and viscous flow is formed in the discharge chamber. The inner wall of discharge chamber is composed of many parts with a variety of surfaces. As mentioned above, typical ion thrusters have one or a few propellant inlets. This give rises to the complex flow within the discharge chamber. Therefore, the neutral density distribution within the chamber is not uniform.

Non-uniform distribution of neutral density affects the plasma generation and ion beam optics. These are because neutral particles are the dominant on the production of rarefied weakly-ionized plasma, and non-uniform plasma causes the non-uniform ion emission and charge-exchanged ion production. Therefore, the non-uniform distribution brings about the deterioration of thruster duration.

B. Conventional Evaluation Method

Conventional pressure measurement methods are roughly classified into two types; gauge measurement and spectroscopic measurement. The pressure gauges are also classified into two types; vacuum gauge and pressure gauge. Vacuum gauge can detect the pressure in a free molecular flow and pressure gauge can detect the pressure in a viscous flow. However, there are few gauges which can measure the pressure in an intermediate flow and its precision is worse than 30%. Although relative validity of spectroscopic measurement is confirmed, the absolute validity is insufficiently confirmed[7-9)].

As for other evaluation, the DSMC (Direct Simulation of Monte Carlo) method is used for numerical analysis of rarefied gas. Despite of many numerical analyses[10-12)], the sufficiently correct distribution in the discharge chamber cannot be obtained because it is not clear that the surface conditions of many parts, especially, reflection ratio. This reflection ratio influences not only propellant distribution, but also the transparency coefficient of grid holes. Figure 2 depicts the schematic of transparency coefficient (ξ). Since some propellant particles are reflected on the barrel surface of the grid as shown in this figure, the apparent grid area is narrower than the actual grid are. The transparency coefficient is equivalent to the ratio of the apparent are to the actual area, and expressed in the following equation with the flow-in-particle number (N_{in}), the flow-out-particle number (N_{out}) and the flow-back-particle number (N_{back}):

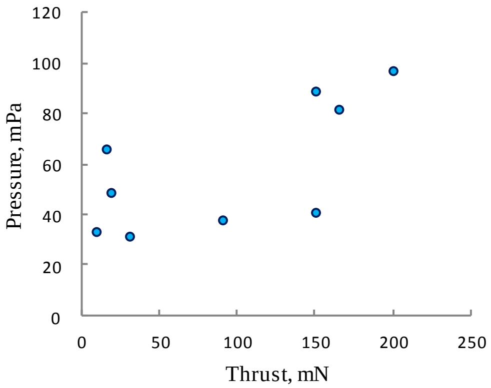


Fig. 1. Internal pressure of typical ion thrusters

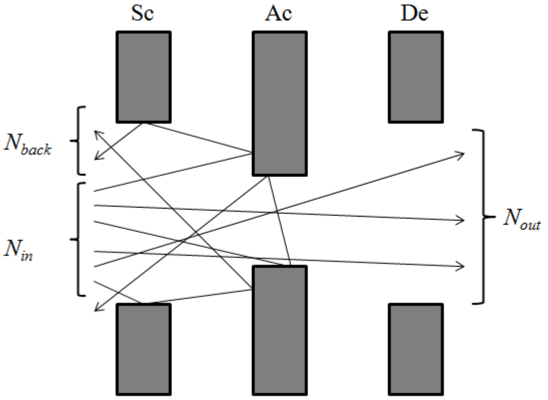


Fig. 2. Schematic of transparency coefficient

$$\xi = \frac{N_{out}}{N_{in}} = \frac{N_{out}}{N_{back}+N_{out}} \tag{1}$$

This transparency coefficient significantly influences the internal pressure. However, at present, it is difficult the transparency coefficient is obtained from numerical simulation and/or experimental measurement.

Accordingly, in the conventional researches and developments of ion thruster, the discharge chamber pressure is regarded as uniform and is estimated from theoretical calculation with conductance of grid system.

C. Differential Low Pressure Gauge

A schematic of differential pressure gauge is depicted in Fig. 3. A very thin diaphragm divides into two chambers within the gauge, and is slightly deflected by the pressure difference between the chambers. The value of differential pressure is determined by the deflection. This differential pressure gauge has the (1) unnecessity of bypass flow, and (2) unnecessity of gas conversion factor.

As mentioned above, the intermediate flow is formed in the discharge chamber. The intermediate flow is susceptible to the pressure change such as a bypass flow. Therefore, the former can prevent excrescent disturbance in the discharge chamber flow. In addition, almost vacuum gauges are susceptible to the gas species. For the use of these gauges, the conversion factor is necessary to measure correct pressure. This factor is a kind of compensation factor, and is an uncertain parameter. Therefore, the latter can reduce an uncertain parameter on account of the pressure measurement. Considering these, it seems that differential pressure gauges are appropriate for the measurements of the discharge chamber pressure.

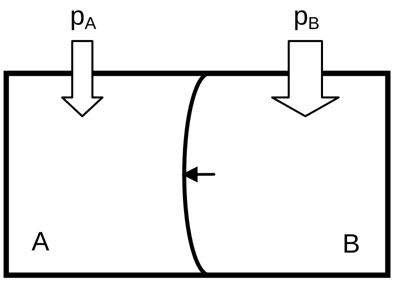
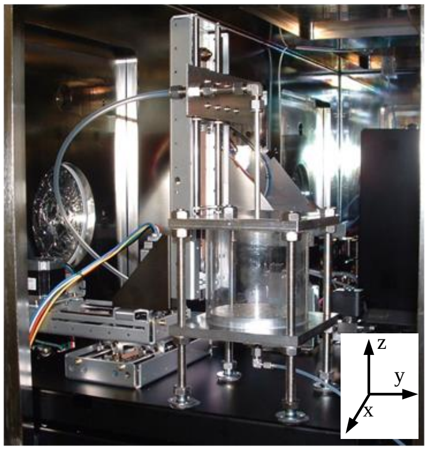
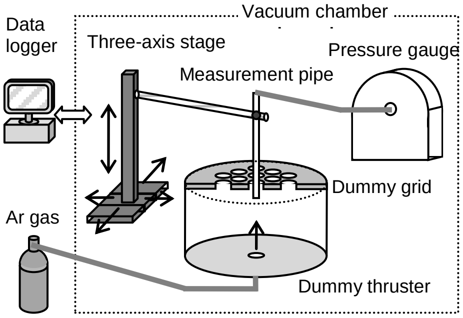


Fig. 3. Schematic of differential low pressure gauge



a) photograph



b) schematic

Fig. 4. Pressure measurement system

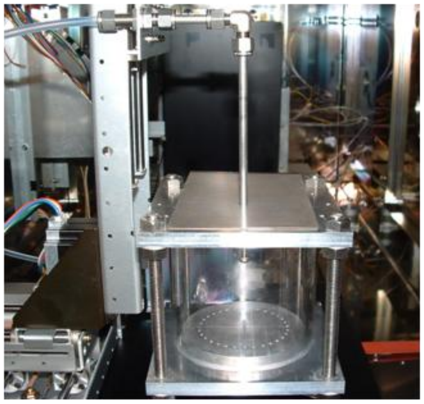


Fig. 5. Dummy thruster, dummy grid, distributor and insertion tube

III. Experimental Apparatus and Procedure

A. Measurement System

In this study, a fine differential pressure gauge is applied. The upper limit of pressure measurement of this gauge is 10 Pa. The certified resolution is less than 0.25%.

In the measurement with differential pressure gauge, the higher the resolution, the more sensitive the gas leak. Since the pressure range of the discharge chamber is approximately from 0.02 Pa to 0.1 Pa, even slightly gas leak affects the measurement. The concern is greatest for the gas leak on the pipe fitting. Accordingly, in this study, the gauge is not installed at the outside of vacuum chamber, but installed in the chamber. This is because the inside installation reduces the difference in pressure inside and outside.

Figure 4 shows the pressure measurement system in this study. The differential pressure gauge detects the pressure via a stainless steel tube and a PFA (a copolymer of tetrafluoroethylene and perfluoroalkoxyethylene) tube. The outside diameter of each tube is 1/4 inch. The stainless steel tube is inserted with a three-axis stage into the discharge chamber of the dummy thruster, as hereinafter is described in detail. The PFA tube connects between the stainless tube and the gauge. Since the PFA tube has an appropriate bendability, this tube can absorb the displacement of stainless tube. That is, the displacement does not affect the pressure measurement.

B. Dummy Thruster

In this study, a cylindrical vessel is applied as a measuring object; hereinafter called "dummy thruster." The inside diameter is 100 mm, and the length is 100 mm. This size is equivalent to a 10 mN-class ion thruster, for example, μ10 ion thruster installed in the HAYABUSA asteroid probe. The characteristic length of this thruster for the determination of Knudsen number is 100 mm.

A propellant inlet is located at the center of the upstream plate of dummy thruster. The diameter of inlet is 1/8 inch. A distributor with 32 annularly-distributed inlets can be installed on the upstream plate. The thickness of distributor is 10 mm. In this paper, the no distributer case is called as "center-inlet" case, and the distributer installation case is called as "annular-inlets" case.

Argon gas is applied for the "dummy propellant gas." The neutral particle, propellant, flows into the dummy thruster via the center inlet in the center-inlet case, or via the annularly-distributed inlets in the annular flow case, and flows out from one of downstream plates of dummy thruster. There are two-type downstream plates; an orifice plate with a 13.9 mm diameter hole, and a perforated plate. The perforated plate, hereinafter called "dummy grid," has aperture ratio of 18.7% that is almost equivalent to the acceleration-grid of typical ion thruster. Each plate has a 6.4 mm diameter hole for the insertion of 1/4 inch stainless steel tube. Figure 5 shows the dummy thruster, the dummy grid, the distributor and the stainless steel tube for the pressure measurement. Since this dummy thruster has no anodes and no magnets, the propellant flow is relatively simple compared with the typical ion thruster discharge chamber.

C. Experimental Apparatus and Accuracy

The dimensions of the vacuum chamber used in this study are approximately 0.8 m × 0.8 m × 1.6 m. This vacuum chamber has five oil-free pumps; three scroll pumps with pumping speed of 525 L/min, a turbo molecular pump with pumping speed of 2,050 L/s, and a cryogenic pump with pumping speed of 5,000 L/s. The minimum pressure is lower than 0.001 Pa (1 mPa). In order to prevent the influences of back pressure in the vacuum chamber, each experiment is carried out after more than five hours pumping.

The propellant is supplied via a mass flow controller. The maximum argon flow rate of this controller is 7.0 sccm (0.21 mg/s). Since the setting error of flow rate is 1.5% F.S., the compensation coefficient had been determined in preliminary experiment with "blow-down" method; measurement of decreasing pressure rate of upstream tank against set flow rate. Figure 6 indicates the compensation coefficient of flow rate.

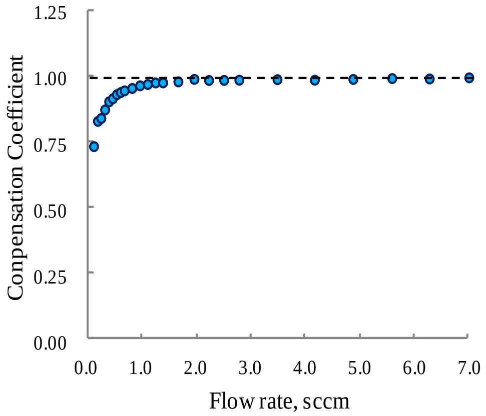


Fig. 6. Compensation coefficient of flow rate

The location error of three-axis stage is approximately 0.1 mm, and the compensated flow rate error is less than 5%.

D. Experimental Procedure

In this study, the following experiments are implemented:

1) Measurement Validity Evaluation

The orifice plate is set on the dummy thruster downstream side. The pressure located at x=25, y=0, z=60 mm is measured against the flow rate. The pressure of this measurement point is almost equivalent to the average pressure in the thruster, because the point is the midpoint of between upstream plate and downstream plate, and between the center axis and the wall surface. This was predetermined with preliminary numerical analysis.

2) Internal Distribution Measurement

The dummy grid is set on the dummy thruster downstream side. Pressure is measured every 10 mm in radial direction (x) and in axial direction (z). Since it takes from 10 to 30 seconds for the pressure equilibrium, the time interval is over 30 seconds. The flow rate is set at 0.13 sccm (0.04 mg/s). The average pressure with this flow rate is approximately 15 mPa that is theoretical calculated on the assumption of free molecular flow. The same experimental procedure is also implemented in the distributor installation case: “annular-inlets” case.

IV. Results and Discussion

A. Measurement Validity

Figure 7 indicates the measured pressure, the theoretical calculated pressure, and the simulated pressure against the compensated flow rate. The simulated pressure data were derived from the three-dimensional DSMC method simulation. The transparency coefficient of the orifice plate is 1.0 because the barrel surface area of the orifice plate is almost zero. That is, the propellant flow can be simulated without the transparency coefficient.

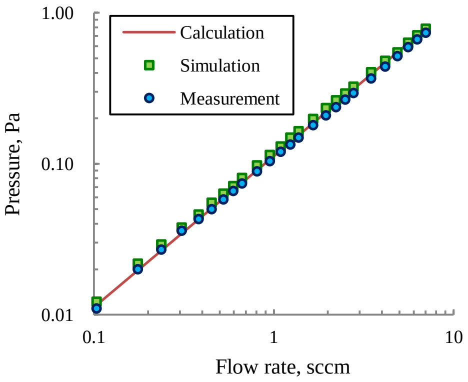


Fig. 7. Measured, simulated and calculated pressure

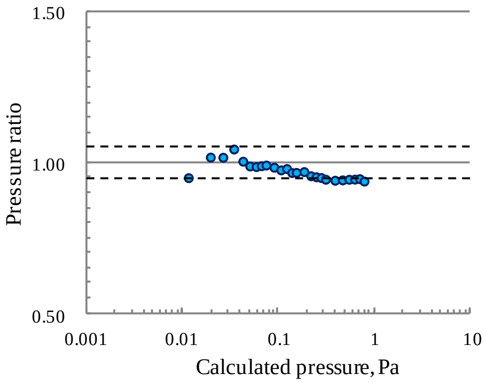


Fig. 8. Pressure ratio against calculated pressure

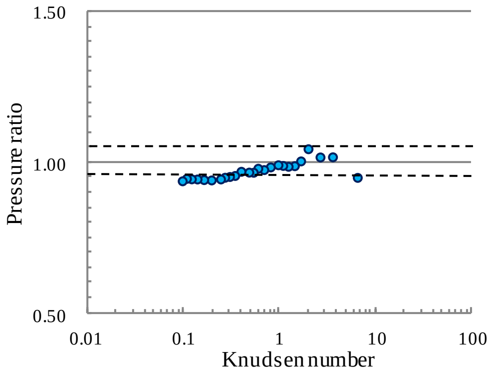


Fig. 9. Pressure ratio against Knudsen number

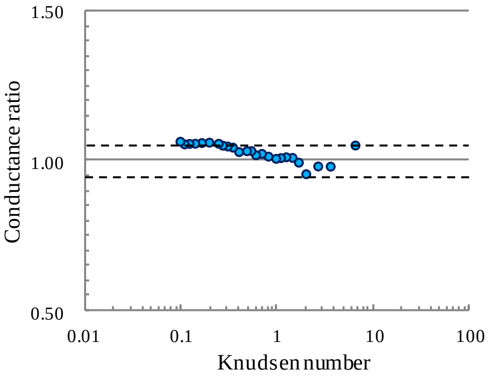


Fig. 10. Conductance ratio against Knudsen number

As shown in this figure, it was confirmed that the measured data almost agree with both the calculated data and the simulated data. Figure 8 indicates the pressure ratio against the calculated pressure. The pressure ratio is defined as the ratio of the measured pressure to the calculated pressure. Figures 9 and 10 indicate the pressure ratio and the conductance ratio against the Knudsen number. The conductance ratio is defined as the ratio of the conductance calculated from the measurement pressure divided by that from the calculated pressure. It seems that these results derive the followings:

1) The measurement error is less than 5% in the pressure range of from 0.01 Pa to 1 Pa. This pressure range includes that in the typical ion thruster discharge chamber. The Knudsen number in this range is from 0.1 to 10.
2) The measurement error of 5% is significantly lower than that of 30% with conventional measurement methods.

In addition, through the some experiments, the measurement reproducibility had been confirmed. Judging from these, it seems that the differential pressure gauge is significantly useful to measure the pressure in the ion thruster discharge chamber, with good validity.

B. Internal Pressure Distribution

Figure 11 indicates the measurement points of this experiment. The pressure distributions within the discharge chamber are shown in Fig. 12. In this figure, the data on the left area of the center axis ($x<0$) are axisymmetrically-duplicated with the data on the right area ($x>0$). The average pressure within the discharge chamber in the center-inlet case is approximately 19.6 mPa, and that in the annular-inlets case is approximately 21.2 mPa. That is, the average pressure in the annular case is higher than that in the center case. Judging from these, the followings are derived:

a) *In the center-inlet case*, the neutral particles are non-uniformly distributed within the dummy thruster. The pressure near the center inlet is extremely high. The particles spread diffusely from the central inlet. The volume with below average pressure accounts for more than two-third of the dummy thruster. The occurrence of particle reflection on the inner wall surfaces (upstream plate, side wall and grid) is relatively low. The average residence time of the particle within the dummy thruster is also relatively short.

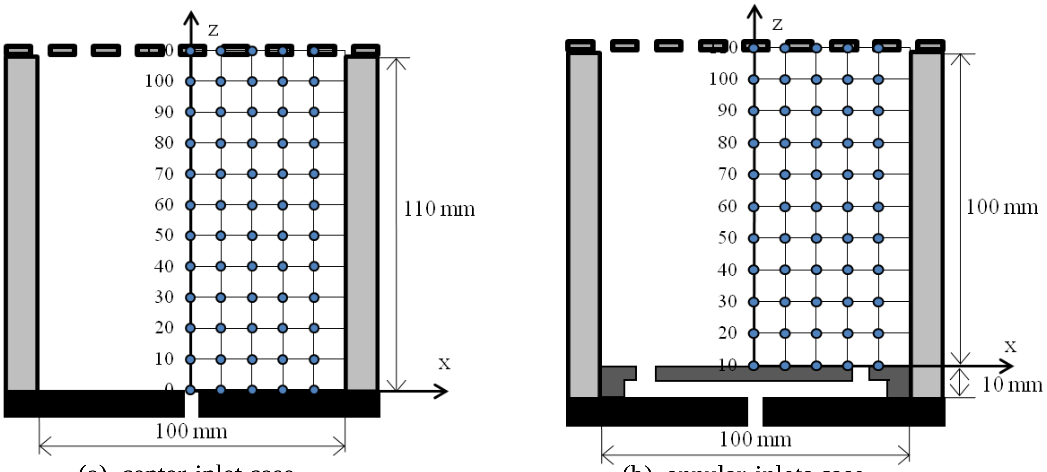
b) *In the annular-inlets case*, the neutral particles are almost uniformly distributed within the dummy thruster. The pressure near the side wall is slightly high. The occurrence of particle reflection is relatively high and the average residence time is relatively long. The longer average residence time brings about the higher the ionization probability.

Since high ionization probability gives birth to low ionization cost and high propellant utilization ratio, it seems that the thruster performance in the annular flow case is higher than that in the center-inlet case. As reported in Ref. 2, the thruster performance of modified μ10 ion thruster installed in the HAYABUSA-2 asteroid probe can be improved because of the modification of propellant flow paths; adding of annular inlets on the chamber wall. This improvement advocates the discussion in this paper.

C. Measurement System Usability

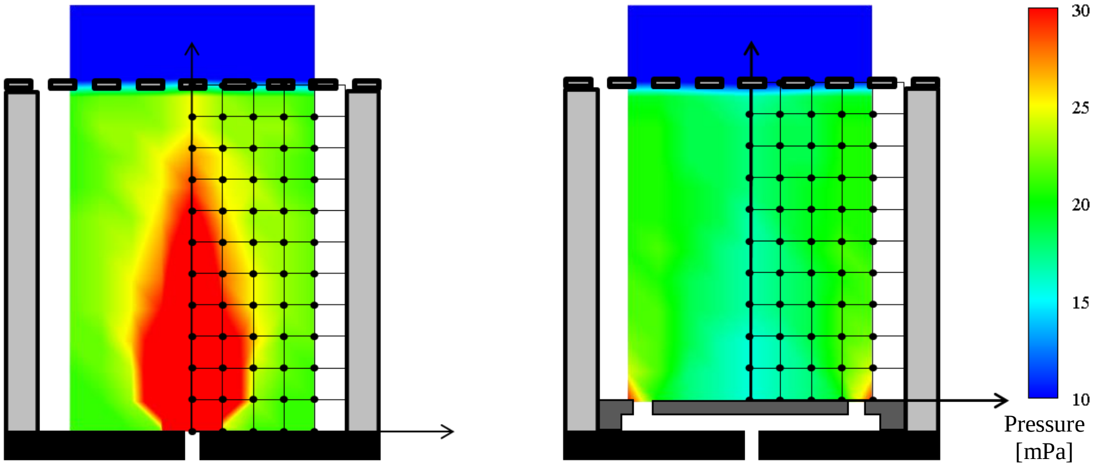
It has been confirmed that the measured average pressure within the dummy thruster discharge chamber was approximately 20 mPa in the section IV-B. The calculated average pressure is approximately 15 mPa with the dummy grid aperture ratio and the conductance as an orifice. Accordingly, the transparency coefficient of the dummy grid is equal to the ratio of the calculated pressure to the measured pressure: 15/20=0.75. With this coefficient, the simulated pressure distributions can be obtained as shown in Fig. 13. Although the partial difference between the distributions can be confirmed, both are in rough agreement each other. Since it was difficult to determine the transparency coefficient with conventional methods as mentioned in the section II-B, it seems that the low pressure measurement system with the high-resolution differential pressure gauge is useful for the investigation of the propellant distribution within ion thruster.

For more detailed evaluation of neutral density, the reduction of measurement error is necessary. It seems that high precision control of propellant flow rate contribute to the reduction. The evaluation with the modified measurement system is also useful for the other electric propulsion system, especially Hall-effect thruster. These are addressed in our future works.



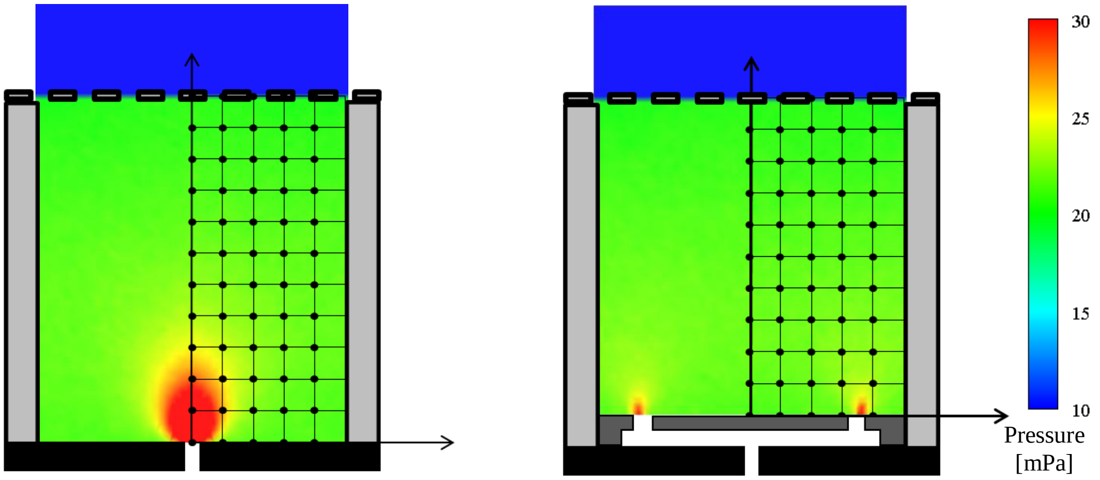
(a) center-inlet case (b) annular-inlets case

Fig. 11. Measurement points



(a) center-inlet case (b) annular-inlets case

Fig. 12. Measured pressure distribution



(a) center-inlet case (b) annular-inlets case

Fig. 13. Simulated pressure distribution

V. Concluding Remarks

Through low pressure measurements within an ion thruster discharge chamber with a differential pressure gauge, the following remarks have been obtained:

1) The measurement error is less than 5% in the pressure range of from 0.01 Pa to 1 Pa. This pressure range covers that in the typical ion thruster discharge chamber; from 0.02 Pa to 0.1 Pa.
2) In the center-inlet case, the particle distribution was non-uniform, and the average pressure is relatively low. In contrast, in the annular-inlets case, the neutral particles are almost uniformly distributed. The occurrence of particle reflection is relatively high and the average residence time within the discharge chamber is relatively long. Since long residence time gives birth to high efficient ionization, it seems that the thruster performance in the annular-inlets case is higher than that in the center-inlet case.
3) The transparency coefficient of grid hole can be determined with the pressure measurement system.
4) The pressure measurement system with differential pressure gauge is useful for the evaluation of the neutral density in the ion thruster discharge chamber.

Acknowledgments

This work was supported by MEXT KAKENHI Grant Number 24560983.

References

[1] Nishiyama, K. and Kuninaka, H., “Discussion on Performance History and Operations of Hayabusa Ion Engines,” *Transactions of JSASS Space Technology Japan*, Vol. 10, Pb.Tb_1-Tb_8, 2012.

[2] Nishiyama, K., Hosoda, S., Ueno, K. and Kuninaka, H., “The Ion Engine System for Hayabusa2” *32th International Electric Propulsion Conference*, IEPC-2011-309, Germany, 2011.

[3] Kuriki, K. and Arakawa, Y., *Ion Engine for Powered Flight in Space*, *Introduction to Electric Propulsion*, University of Tokyo Press,, Tokyo, 2003, pp115,234-236 (in Japanese).

[4] Arakawa, Y., Kuninaka, H., Nakayama, Y. and Nishiyama, K., *Ion Engine for Powered Flight in Space*, Corona, Tokyo, 2006 (in Japanese).

[5] Goebel, D., Polk, J., Sandler, I., Mikellides, I., Brophy, J., Tighe, W. and Chien. K., “Evaluation of 25-cm XIPS© Thruster Life for Deep Space Mission Application,” *31th International Electric Propulsion Conference*, IEPC-2009-152, USA, 2009.

[6] Gonzalez, J. and Saccoccia, G. “ESA Electric Propulsion Activities”, *32th International Electric Propulsion Conference*, IEPC-2011-329, Germany, 2011.

[7] Tsukizaki, R., Koizumi, H., Nishiyama, K., and Kuninaka, H., “Number Density Measurement of Xe I in the ECR Ion Thruster µ10 Using Optical Fiber Probe,” *32th International Electric Propulsion Conference*, IEPC-2011-318, Germany, 2011.

[8] Eichhorn, C., Lohle, S., and Fasoulas, S. Leiter, H., and Auweter-Kurtz, M. “Two-Photon Spectroscopy on Neutral Xenon in the Plume of the Radio-Frequency Ion Thruster RIT-10”, *32th International Electric Propulsion Conference*, IEPC-2011-302, Germany, 2011.

[9] Yamamoto, N., Sugita, K., Kurita, T., Tomita, K., Uchino, K. and Nakashima, H. “Measurement of Plasma Property in an Ion Thruster using Laser Thomson Scattering Technique” *32th International Electric Propulsion Conference*, IEPC-2011-200, Germany, 2011.

[10] Boyd, I. D. “Numerical modeling of spacecraft electric propulsion thrusters,” *Progress in Aerospace Sciences*, Vol. 41., No. 8., 2005, pp.669-687.

[11] Mahalingam, S., Choi, Y., Loverich, J., Stoltz, P. H., Bias, B., and Menart, J. A. “Fully Coupled Electric Field/PIC-MCC Simulation Results of the Plasma in the Discharge Chamber of an Ion Engine,” *47th AIAA Joint Propulsion Conference*, AIAA-2011-6071, USA, 2011.

[12] Miyasaka, T., Kobayashi, T., and Asato, K. “Characteristics of ions impacting grid surfaces in an ion engine,” *Vacuum*, Vol. 85., No. 5., 2010, pp.585-590.