Three-dimensional Vector Measurement of EP Propellant Flow within a Vacuum Chamber

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Abstract: In order to know the propellant flow in a ground test facility, a dynamic pressure measuring device using linearly machined optical fiber was designed and fabricated. Propellant flow vector within a vacuum chamber was measured using this measuring device, and it was confirmed that the dynamic pressure vector can be measured with an accuracy of less than 0.01 mPa. Through the horizontal and vertical propellant flow measurements within a vacuum chamber, pumping flow vector caused by the vacuum pump could also be measured. By using this measuring device, it can be expected that it will be useful for compensation of experimental durability evaluation of electric propulsion system.

Nomenclature

c	=	luminance
C_d	=	drag coefficient
d	=	diameter
F	=	force
g	=	acceleration of gravity
h	=	displacement
L	=	length
m	=	mass
p	=	pressure
r	=	position (vector)
ρ	=	density
θ	=	angle
subscript		
b	=	angle bar
c	=	center
f	=	fiber

I.Introduction

FOR research and development of electric propulsion thruster, ground test facility, that is, the vacuum chamber is required. When the thruster is operated in the test facility, the propellant is reflected on the wall surface of the vacuum chamber until it is exhausted by the vacuum pump. This causes pressure to rise around the propulsion unit and backflow into the thruster. Then, it affects the performance evaluation and the durability evaluation of the thruster more or less, giving rise to a difference (performance estimation error) from that at the time of space operation.

In order to reduce this estimation error as much as possible, a more appropriate ground test evaluation is necessary. It seems that the evaluation of the propellant flow within the vacuum chamber is significant. However, the principal

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propellant particles staying in the vacuum chamber are neutral particles without electric charge. In addition, the average pressure within the vacuum chamber is rarefied and is approximately mPa-order (10^{-3} Pa-order). Moreover, neutral propellant has its thermal velocity. Therefore, detection is extremely difficult.

In the rarefied gas flow, the static pressure and dynamic pressure are regarded as the magnitude of the particle number density and the anisotropy (inhomogeneous distribution) of the particle group velocity, respectively. For the measurement of the static pressure, in some studies, ionization vacuum gauges are installed in the near thruster.[1-7] In my previous work, the static or total pressure within a vacuum chamber had been numerical-simulated and measured with a fine differential pressure gauge within a vacuum chamber.[8-9] Meanwhile, the dynamic pressure could not be measured, and the propellant flow in the vacuum chamber was not reasonably evaluated.

In this research, a new method of suspending the optical fiber and taking the light guided from its upper end from the lower end side has been proposed and evaluated. However, the vertical propellant flow was not able to be evaluated. The objectives of this research are to re-design and manufacture measuring device, to evaluate its measurement validity and accuracy, and to evaluate the measurement significance by measuring the horizontal and vertical propellant flow in the vacuum chamber.

II. Dynamic Pressure Measurement Device and Code

A. Rarefied Propellant Flow

Operating of electric propulsion in the vacuum chamber, the neutral propellant emitted from thruster is reflected on the vacuum chamber wall surface until it is exhausted by the vacuum pump, such as shown in Fig.1. Then it is retained in the vacuum chamber. Depending on the propellant type and flow rate, the average pressure in general ground test facilities for electric propulsion is approximately 0.5 to 5 mPa and the Knudsen number is approximately 0.5 to 5. Therefore, the propellant in the vacuum chamber forms a molecular flow which is strongly influenced by the wall reflection.

The vacuum pump is a device that exhausts incident particles outside the chamber without reflecting it into the chamber. In the near vacuum-pump, the number of reflection particles from the pump is smaller than the number of particles incident on the pump, and then the number density decreases and an anisotropic flow to the pump occurs.

However, there are no significant measuring instruments that can detect this dynamic pressure in the vacuum chamber. In addition, because reasonable physical property values such as propellant particle wall surface reflection, inter-particle collision, vacuum pump exhaust efficiency, and so on are not obtained, propellant flow analysis in the vacuum chamber has been limited to qualitative evaluation at present.

B. Basic Concept[10)]

Figure 2 depicts the schematic of the device as called “RFVD” (former name is DPVD). The RFVD consists of an optical fiber, a compact camera, an ultra-small LED, structural material (boom, strut, base). The linearized optical fiber is suspended vertically from a hole with the boom. A LED is provided at the upper end of the optical fiber, and the miniature camera is provided at the lower end of the optical fiber with its upper end facing upward. Assuming that the fiber is not deformed by the rarefied propellant flow, the fiber moves as a bar pendulum.

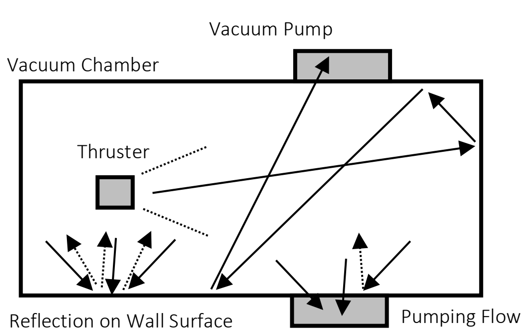

Fig. 1. Propellant flow with vacuum chamber.

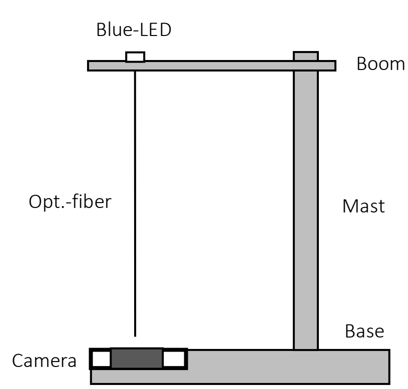

Fig. 2. Schematic of the RFVD.

The emission of the LED is photographed by the camera via the optical fiber, and the center position of the lower end of the optical fiber is calculated from the bright spot distribution. The force F_f acting in the horizontal direction on the fibers of length L_f, diameter d, and density ρ is expressed by the following equation using the fiber tip displacement h.

$$F_f = mg\sin\theta \approx \frac{\pi}{4} d^2 L_f \rho g \frac{h}{L_f} = \frac{\pi}{4} d^2 \rho g h \tag{1}$$

Assuming that the propellant uniformly collides with the fiber, the dynamic pressure p_f detected by the fiber is expressed by the following equation.

$$p_f = F_f / (C_d \cdot d \cdot L) \tag{2}$$

, where C_d is the drag coefficient. Assuming that the colliding particles are perfectly irregularly reflected on the cylindrical fiber surface, C_d becomes 1.785 under the molecular flow. Dynamic pressure vector in the horizontal direction can be measured from the displacement on the image and these equations.

C. Re-Design and Fabrication[11-12)]

Shortening the fiber length improves the spatial resolution but reduces the dynamic pressure resolution. Considering the size of the vacuum chamber and the magnitude of the dynamic pressure, the length of the optical fiber was designed to approximately 60 mm which is equal to approximately one-eleventh of the height of the vacuum chamber used in this study. The optical fiber adopted was polyethylene filament without coating, and linear treatment was performed. The diameter after treatment was 0.289 mm, and the average density was about 900 kg/m^3 was confirmed using an optical microscope and an electronic balance.

In addition, because it is installed on the boom, a surface mount type (approximately 1 × 1 × 2 mm) blue LED was adopted for the optical fiber light guide. Although general-purpose USB camera was adopted in the previous works, in this study, a small camera with ROI (Region-Of-Interest) function in order to capture the fiber edge regardless of the RFVD attitude and to improve the temporal resolution.

The dimension of this re-designed RFVD is 20 mm in width, 45 mm in length, and 76 mm in height. The volume is approximately one-sixth of that of the former RFVD. This miniaturization is considered useful because the volume of the device may affect the flow. Figure 3 shows a photograph of the re-designed RFVD. More details are described in the references.

Fig. 3. Re-designed RFVD.

D. Image Processing Code

The code developed for this measurement is called "CamCap." The images captured by the camera are JPEG converted in the camera and imported into a computer by USB communication. The CamCap converts the image data to RGB color data with 256 gradations and excludes LED light other than the color gamut setting. The luminance distribution center of this image is calculated using the following equation.

$$\bar{r}_c = \frac{\sum r \cdot c}{\sum c} \tag{3}$$

, where r is position and c is luminance. The theoretical calculation resolution is inversely proportional to the product of the pixel number and the color gamut gradation. This point is the center position of the lower end of the optical fiber (hereinafter referred to as the "center-position"). In order to improve its S/N ratio, some noise filter such as band-path-filter and median-filter are applied.

E. Validity Evaluation

To evaluate its measurement validity and accuracy, the preliminary experiment with a 3.5 m U-shaped angle bar had been performed. Through the detection of the slightly artificial horizontal tilt of the bar, it was confirmed that the pressure sensitivity is about 0.374 mPa/pixel. More detail of validity experiment was described in reference 10 and 11. By statistical processing of measured values with noise filters, the significant measurement accuracy was approximately 0.01 pixels (including measurement experiments to be described later). Therefore, the measurement resolution of the RFVD is approximately 0.004 mPa. Since it is sufficiently smaller than the pressure in the vacuum chamber (mPa-order, static), it is considered that the RFVD dynamic pressure measurement resolution is sufficient to evaluate the dilute flow in the vacuum chamber.

III.Experimental Procedure, Results, and Discussion

A. Experiment Procedure

The schematic of the experiment is shown in Fig. 4. The vacuum chamber used in this study has a rectangular parallelepiped shape of 0.76 × 0.76 × 1.80 m, and one cryopump with a diameter of 0.40 m is installed at a position slightly displaced from the central axis. The pumping speed (catalog value) is approximately 5 kL/s.

For both the horizontal and vertical measurement of the propellant flow within the vacuum chamber, two re-designed RFVDs were set on a movement mechanism consisted of two linear sliders. The propellant gas was emitted from a one-eighth stainless steel tube located at the center axis of the vacuum chamber as shown in Fig. 4. The propellant was xenon and the flow rate was 6.9 sccm (about 0.69 mg/s) with the temperature of around 295 K. The average static pressure within the vacuum chamber with the propellant flow was approximately 6 mPa. In order to avoid the influence of discharge gas from the vacuum chamber wall surface material, the measurement experiment was started after 12 hours or more after reaching 0.5 mPa or less.

B. Horizontal Propellant Flow

Figure 5 shows the horizontal flow vector on the horizontal middle plane of the vacuum chamber. As shown in this figure, the propellant flow is a convex symmetrical flow in the near gas injector. The diffusion angle with covering 95% of the dynamic pressure was calculated to be approximately 60 degrees. This figure indicates that the dynamic pressure is uniform in the center region of the chamber, which is considered to be combined with both the directly emitted flow and the flow reflected on the vacuum chamber walls. This figure also shows the closer to the vacuum-pump, the smaller the dynamic pressure. It seems that these imply that the propellant flow is influenced by the reflection on the chamber wall and the evacuation of the vacuum chamber.

C. Vertical Propellant Flow

Figure 6 shows the vertical flow vector on the vertical middle plane of the vacuum chamber. This figure also shows that the propellant flow is a convex symmetrical flow in the near gas injector and that that the dynamic pressure is uniform in the center region of the chamber. In contrast to the horizontal flow, however, this figure shows that the closer to the vacuum-pump, the larger the dynamic pressure.

Since the number of the particle reflected on the vacuum-pump is smaller than that of the flowing to the pump, this flow phenomenon seems reasonable. Since the inverse ratio of the square root of the displacement is proportional to the distance from the propellant gas injector without the effect of the vacuum chamber, the ratio implies isotropic diffusion of the propellant gas. Judging from the inverse ratio, it was also confirmed that the propellant flow significantly affected by the vacuum-pump, especially in the near vacuum-pump region.

D. Future Works

In this paper, the dynamic pressure (flow vector) on both the horizontal and vertical middle plane of a parallelepiped vacuum chamber. In the near future, the three-dimensional measurement of the more measurement points within the vacuum chamber will be performed to discuss the influence of the vacuum chamber (test facility effect). In addition, further miniaturization and higher accuracy are useful for more precise measurement. Moreover, to discuss the influence of the propellant flow more detail and in various cases, the measurements with this re-designed RFVDs in a variety of vacuum chambers seems to be useful.

IV.Concluding Remarks

In order to three-dimensional measure the dynamic pressure of rarefied propellant flow within a parallelepiped vacuum chamber, the RFVD using optical fiber was re-designed, and the following remarks were obtained:

- The re-designed miniatured RFVD can reasonably measure the rarefied dynamic pressure vector regardless of the attitude.
- The dynamic pressure resolution of the RFVD is approximately 0.004 mPa, at the present status.
- Vacuum evacuation (pumping-flow) has a strong influence on propellant flow.
- It is useful for other space engineering experiments and evaluation of rarefied flow analysis.
- Further miniaturization and higher accuracy are useful and further detailed measurement is to be carried out in the future.

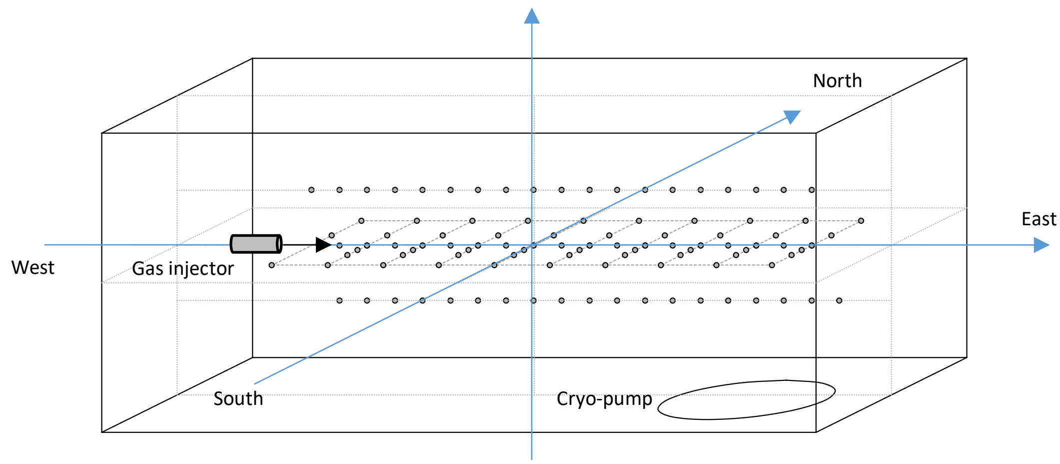

Fig. 4. Schematic of vacuum chamber and measurement-points.

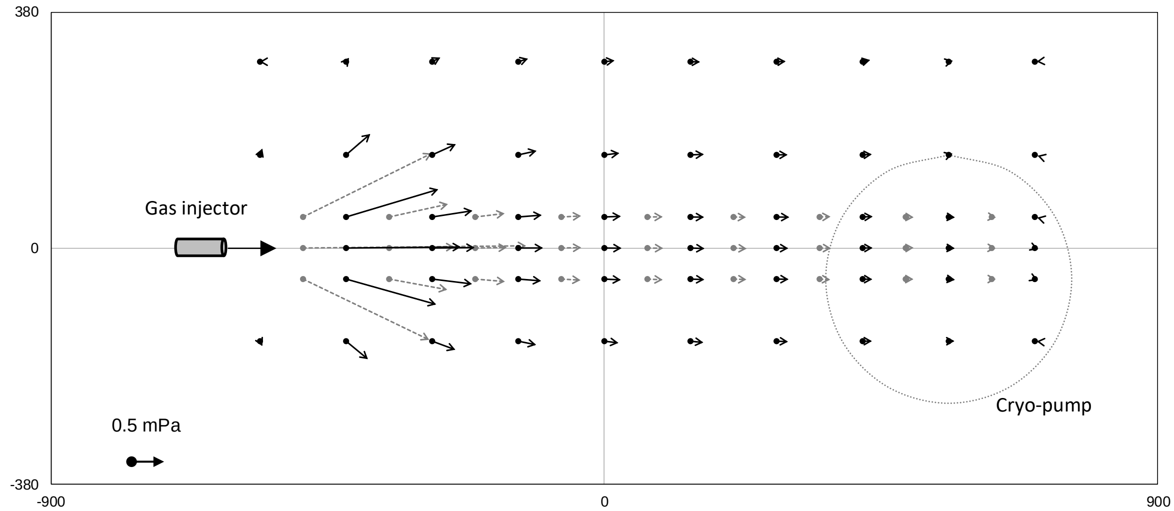

Fig. 5. Horizontal flow vector on the horizontal middle plane.

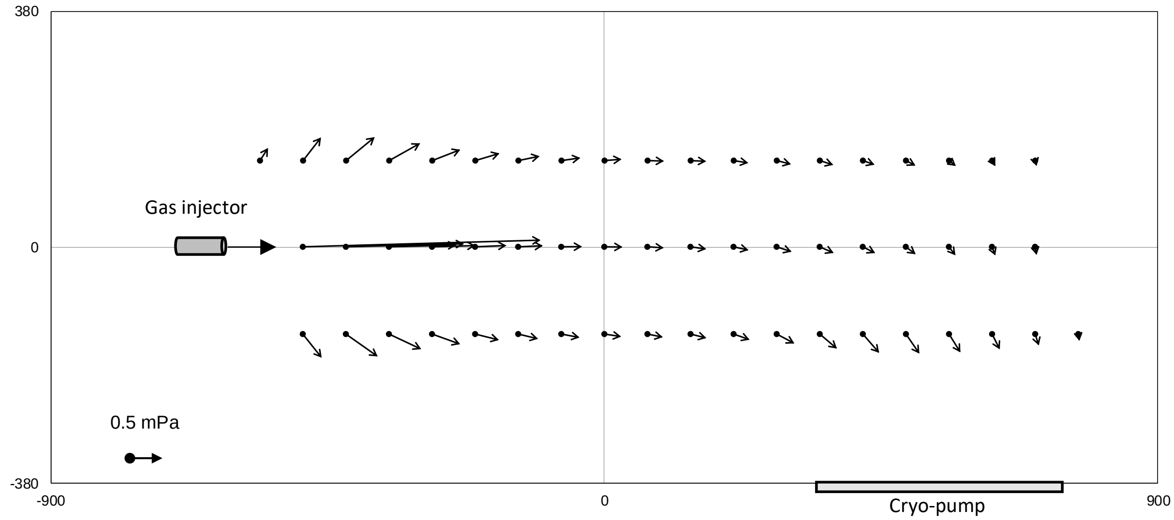

Fig. 6. Vertical flow vector on the vertical middle plane.

Acknowledgments

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