Rarefied Propellant Flow Analysis and Measurement for Electric Propulsion

IEPC-2017-558

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: **In order to know the propellant flow in 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 on the order of 0.01 mPa. Pumping flow vector caused by 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, 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 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 evaluation of the propellant flow within vacuum chamber is significant. However, the principal propellant particles staying in the vacuum chamber are neutral particles without electric charge. In addition,

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the average pressure within the vacuum chamber is rarefied and is approximately mPa-order (10^{-3} Pa-order). Moreover, the neutral propellant has its thermal velocity. Therefore, the 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.[1-6] In my previous work, the static or total pressure within a vacuum chamber had been measured with a fine differential pressure gauge within a vacuum chamber.[7] 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 is proposed. The objectives of this research are to design and manufacture measuring instruments of new idea, to evaluate its measurement validity and accuracy, and to evaluate the measurement significance by measuring the propellant flow in the vacuum chamber.

II. Dynamic Pressure Measurement Device and Code

A. Rarefied Propellant Flow

Operating of electric propulsion in 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

This instrument is referred to as DPVD, in this study. Figure 2 depicts the schematic of the DPVD. The DPVD 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.

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.

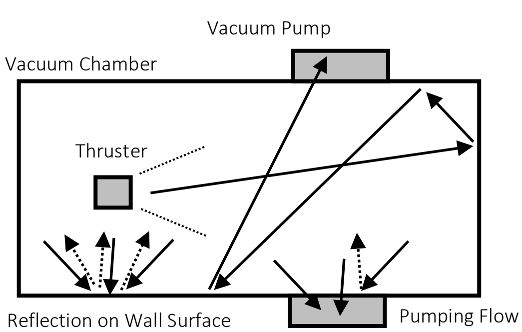

Fig. 1. Propellant flow with vacuum chamber.

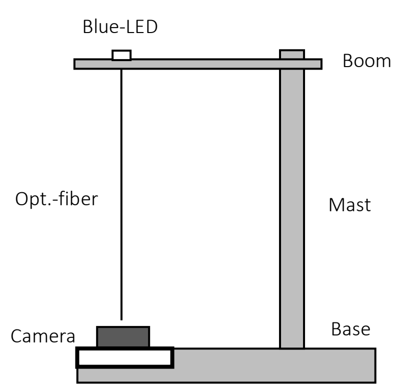

Fig. 2. Schematic of the DPVD.

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

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

$$p_f = F_f / (C_d \cdot d \cdot L) \quad (2)$$

, 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. Design and Fabrication

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 65 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 optical fiber light guiding. Moreover, a general-purpose USB camera was adopted as a small camera. Considering the time resolution and spatial resolution as the DPVD, JPEG format of 1600 × 1200 pixels was selected as the camera image data file.

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.

$$\bar{r}_c = \frac{\sum r \cdot c}{\sum c} \quad (8)$$

, 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.

III. Experimental Method and Procedure

A. Validity Evaluation Experiment

This experiment was conducted to evaluate the measurement validity and sensitivity of the DPVD. The schematic of the experiment is shown in Fig. 3. Both ends of a 3.5 m U-shaped angle bar were supported by a jack, and the DPVD was installed in the center of the angle bar. The jack on one side was raised by 1 mm up to the height of 7 mm and the center-position with respect to the inclination of the angle bar was imaged and calculated. The error of the jack height is 0.01 mm or less. For a jack-up height of 1 mm, the slope is about 0.017 degrees. The measurement validity and sensitivity of the DPVD were evaluated from the relationship between this displacement (mm) and the displacement on image (pixel).

This experiment was conducted in the atmosphere because of the long angle bar. Since the sensitivity of the DPVD is very high, it was measured so that the air does not flow directly to the DPVD.

B. Dynamic Pressure Measurement Experiment

This experiment was conducted to evaluate the propellant flow (dynamic pressure, "emitting-flow") and the influence of the vacuum pump (dynamic pressure, "pumping-flow"). 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

* In previous works, an optical fiber with length of 105 mm had been used (Ref. 8).

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.

A linear slider with a stroke distance of 500 mm was installed at the center of the lower surface of the vacuum chamber via two vibration suppression material plates. The DPVD was installed on the strut so that the center of the DPVD optical fiber is on the center axis of the vacuum chamber. The linear slider was settled every 50 mm, and a total of 11 points were measured. In order to avoid the influence of distortion of the linear slider, flat surface accuracy of the vacuum tank, and thermal distortion, the displacement was calculated from the difference between the center-position with the propellant flow and the center-position without the flow, at each measurement point.

The propellant flowed out from a one-eighth stainless-steel tube at the point-A or the point-B, toward the center of the vacuum chamber. Both points are placed at 28 cm from the center axis of the chamber. In order to measure only the effect of the vacuum pump, the propellant was emitted from the spherical porous body so as to isotropically (homogeneously) diffuse from the point C at the center of the upper surface.

The propellant was argon and the flow rate was 7.0 sccm (about 0.04 mg/s) with the temperature of 298 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.

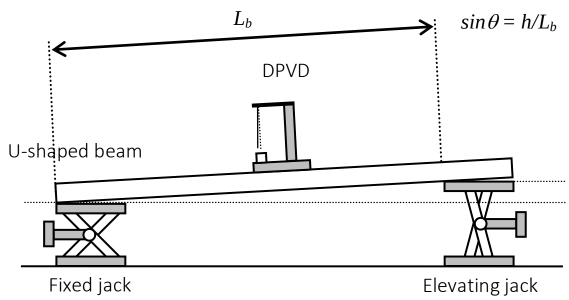

Fig. 3. Schematic of validation evaluation experiment.

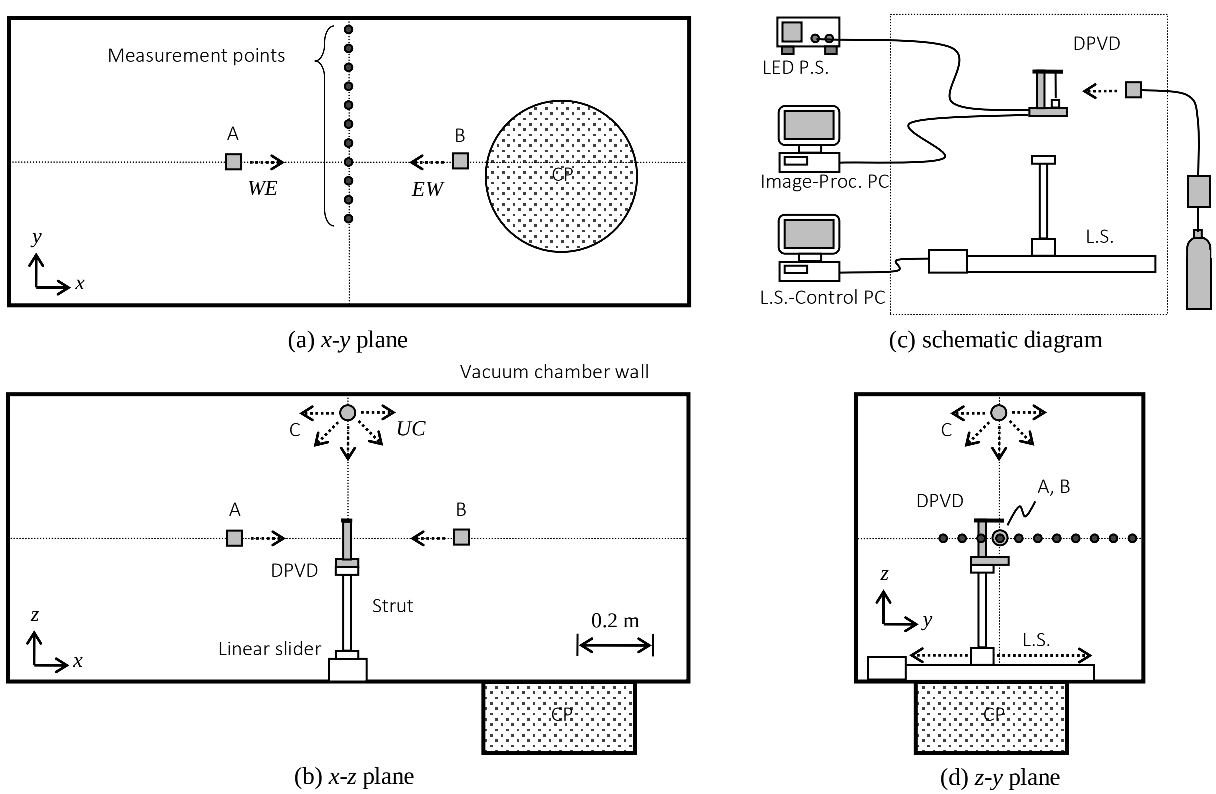

Fig. 4. Schematic of dynamic pressure measurement experiment.

IV. Results and Discussion

A. Validity Evaluation Experiment

The displacement of the center-position is shown in Fig. 5. The horizontal axis represents the displacement (set value, mm) of the center-position resulting from the inclination of the angle material, and the vertical axis represents the displacement (measurement value, pixel) on the image captured by the small camera. It can be seen from this figure that the measurement value of the center of the lower end of the fiber is approximately proportional to the set value. Further, reproducibility was also recognized.

Therefore, the DPVD optical fiber was found to swing (displace) as a pendulum in proportion to the force received in the horizontal direction. From this figure, the proportional coefficient is calculated to be approximately 50.2 pixel/mm (0.020 mm/pixel). From this proportional coefficient, force sensitivity of the DPVD is approximately 11.5 nN/pixel and pressure sensitivity is about 0.213 mPa/pixel. By statistical processing of measured values with noise filter, the significant measurement accuracy was approximately 0.05 pixels (including measurement experiments to be described later). Therefore, the measurement resolution of the DPVD is approximately 0.5 nN (0.01 mPa).

Since it is sufficiently smaller than the pressure (static pressure) in the vacuum chamber, it is considered that the DPVD dynamic pressure measurement resolution is sufficient to evaluate the dilute flow in the vacuum chamber.

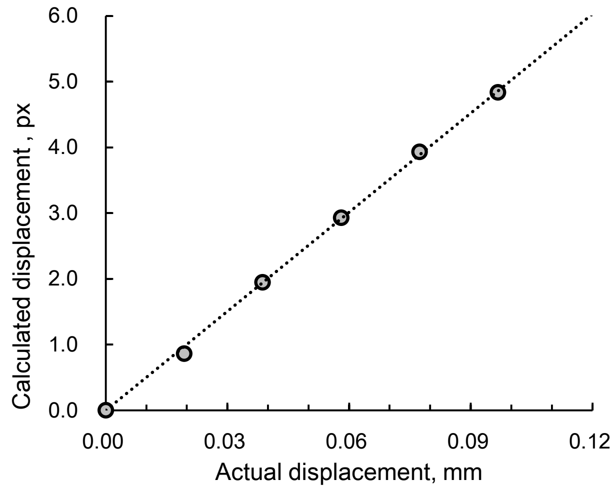

Fig. 5. Calculated vs. actual displacement.

B. Dynamic Pressure Measurement Experiment

The experimental results are shown in Fig. 6 (black solid line). Here, the propellant-supply from the point-A is denoted as "WE," the propellant-supply from the point-B as "EW," and the propellant-supply from point C as "UC." In the experiment of UC, it seems that it shows the influence by the exhaust as it does not collide directly with the DPVD and the density distribution within the vacuum chamber is emitted uniformly.

A comparison with the numerical analysis result by a DSMC method code is also shown in this figure (blue dot line). This code had been basically confirmed in my previous work.[9)] Since the physical property values such as the wall reflection and the exhaust efficiency were not acquired as described above, the numerical analysis result is a reference value, but it is qualitatively roughly agreeing and it suggests the validity of this experiment measurement.

Figure 7 also shows the result of subtracting the result of UC from the results of WE and EW. It can be seen that these figures coincide well. That is, the propellant flow within the vacuum chamber is found to be the sum of the exhaust flow vector from the engine and the exhaust flow vector by the vacuum pump: pumping-flow.

Furthermore, assuming that the propellant diffuses in a hemispherical shape from the dummy-engine, the theoretical dynamic pressure of 28 cm downstream (corresponding to $y = 0$ mm position) from the point-A or the point-B is calculated to be approximately 0.17 mPa. The pressure calculated from the fiber displacement at $y = 0$ is approximately 0.20 mPa, which can be said to be roughly in agreement quantitatively.

C. Applicability and Future Works

From the results and discussion above, it can be considered that the validity of performance evaluation of the electric propulsion system can be improved by directly evaluating or correcting the flow of the electric propulsion propellant using this DPVD. Although we have conducted excessive durability tests and performance evaluations with sufficient margins in anticipation of performance estimation errors, it is presumed that this will lead to reducing the time and cost associated with them.

Future works include more detailed measurement validity evaluation and improvement of measurement accuracy. The DPVD can be applied to other space engineering experiments and is considered to be useful for verifying the validity of dilute flow analysis such as DSMC method.

It also seems that three-dimensional measurement with this DPVD or modified DPVD within a whole of vacuum chamber is useful for estimation of vertical propellant flow. Furthermore, by evaluating it together with the static pressure (total pressure) measurement of the rarefied flow, it is considered that more detailed evaluation of the propellant flow in the vacuum tank and physical property values such as wall reflection and exhaust efficiency can be achieved.

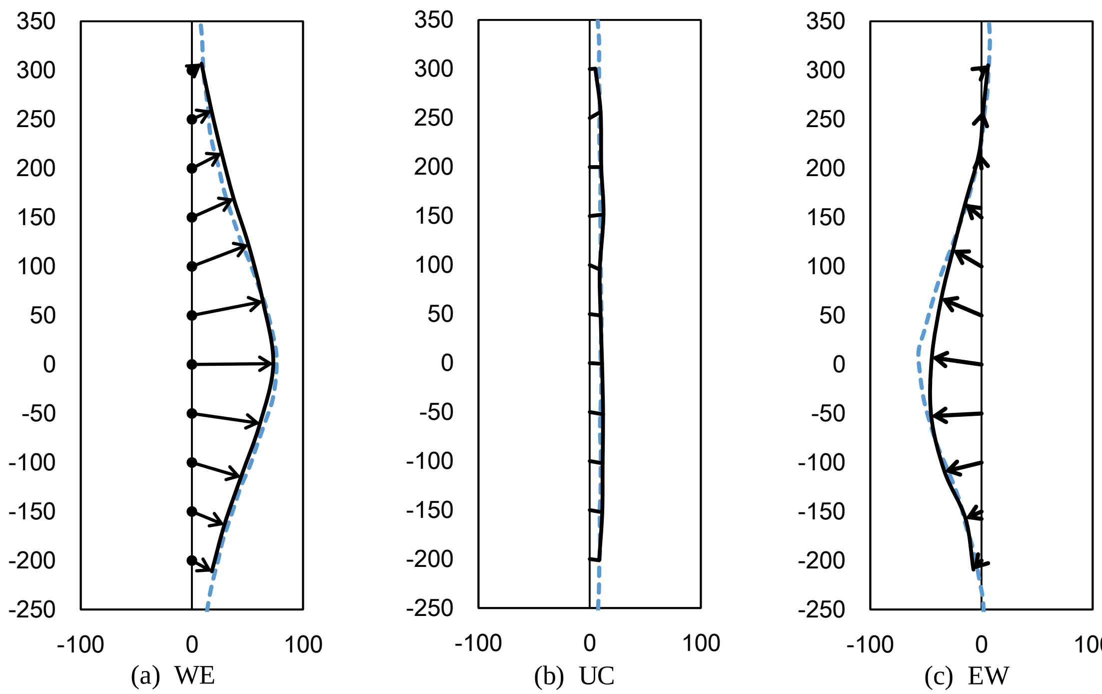

Fig. 6. Flow vectors of experimental measurement (black-solid) and numerical analysis (blue-dot).

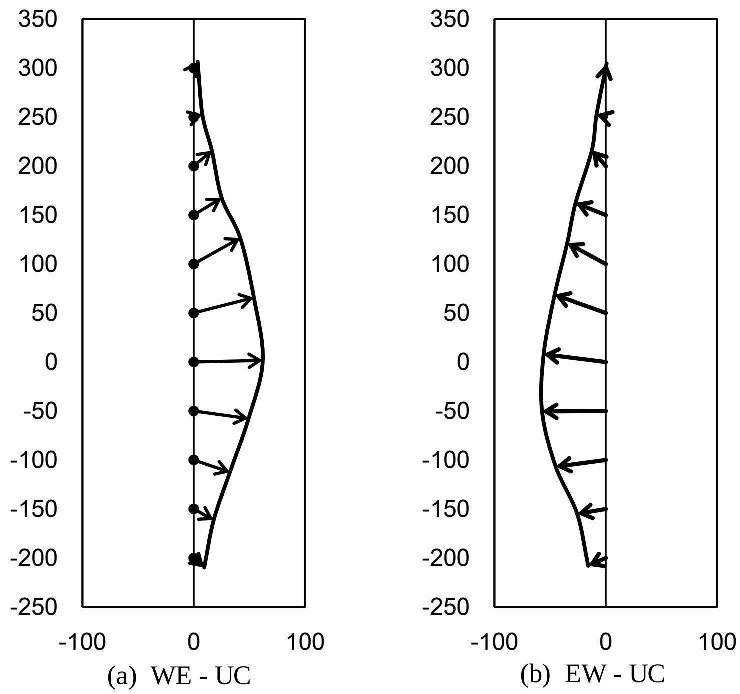

Fig. 7. Compensated flow vectors with pumping flow vector (UC-results).

V. Concluding Remarks

In order to measure the dynamic pressure of rarefied flow, the DPVD using optical fiber was designed, and the following remarks were obtained:

- The DPVD can reasonably measure the rarefied dynamic pressure vector.
- The dynamic pressure resolution of the DPVD is less than 0.01 mPa, at the present status.
- Vacuum exhaust (pumping-flow) has a strong influence on propellant flow.
- By measuring and evaluating the influence of vacuum equipment in advance, it is possible to acquire a proper propellant flow regardless of vacuum test facility.
- It is useful for other space engineering experiments and evaluation of rarefied flow analysis.
- Further miniaturization and higher accuracy are required and further detailed measurement is to be carried out in the future.

Acknowledgments

The author thanks Mr. Koki Hocchi of undergraduate student of National Defense Academy for his experimental assistance.

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